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Energy Loss Estimation in Distribution Networks for Planning Purposes

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***Abstract*--Because of increasing economical pressures on network operators, the losses in the subtransmission and distribution systems are becoming more and more important. It is usually not economical to exchange equipment for the sole purpose of reducing losses; however, it is an important criterion when deciding to implement changes in the network. The computation of the energy loss with a network simulation program is very laborious and the required data is usually not available.**

In the paper, an energy loss estimation method based on readily available data (i.e. peak power, average power, power loss at peak load) will be derived and implemented. For this purpose already developed approximation formulas will be reviewed for the use in current networks with today's load characteristics. The estimation is used to obtain the energy loss for different networks as well as for the possible reduction of energy loss due to reconfiguration of existing networks.

To compare and verify the results of the energy loss estimation, a computation of the losses with a network simulation program is implemented and a time period of one year is analyzed.

***Index Terms*--energy loss, energy loss estimation, loss analysis, loss factor, load factor, network planning**

I. Introduction

Different network configurations are taken into consideration during the planning process of distribution networks. The challenge in the process is to observe all standards and criteria. This comprises for example voltage limits, current carrying capability of the equipment and the correct settings for the relays. Important focus of the engineering process should also be on reliability goals and economic operation of the network with little energy losses. Therefore, it is necessary to evaluate the losses in terms of costs, but costs can only be linked to energy losses and not to power losses. The costs of the losses have to be weighed up against investments as well as operation costs. Consequently, knowledge about the magnitude of the energy loss is important for the over-all comparison of different network configurations and should not be neglected.

There are different ways for the evaluation of energy loss, but regardless of the method used, it is difficult to determine the costs exactly. One reason is the diversity of the losses in an electrical system. They can be generally divided into technical losses and non-technical losses. Technical losses are caused by current and resistance (I^2R), hysteresis, eddy currents and dielectric losses (corona). Non-technical losses are for example due to metering errors, unmetered company or customer use and billing cycle errors. The complexity of the causes of the losses presents the difficulty of calculating them. Therefore an estimation based on proper reasoning meets certainly the needs for the network planner. Non-technical losses are not considered since they cannot be modelled and the network planner does not have direct impact on their magnitude.

The paper describes an energy loss estimation method for network planning based on readily available data. The results of the energy loss estimation are verified with the results of the computation with a network simulation program.

II. Determination of Energy Loss

The determination of energy loss of a network can be done in many ways. The methods distinguish each other in terms of complexity, data acquisition, accuracy and whether the period under review is in the past or future.

A. Measurement of Energy Loss

Determining energy loss is theoretically a simple task for existing networks, but it can only be applied to past periods. The sold energy has to be subtracted by the bought energy to obtain the energy loss. This includes all technical as well as non-technical losses. The difficulty remains in the data acquisition for a specific date. This method cannot be applied to network planning since only the past can be reviewed.

B. Computation of Energy Loss with a Network Simulation Program

The computation of the energy loss is done by dividing the time period under review (e.g. 1 year) into time segments (e.g. 15 minutes), obtaining the data for the loads for each time segment and computing the power loss for each time segment with a network computation program. The power loss is multiplied by the considered time segment and summed up, which yields the energy loss. The summation approaches the

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integral of the power loss of the time period under review.

For this computation many data are necessary and the collection of the data is very laborious, more often than not impossible. Very often generic data have to be applied since the actual data are not available. For such a simulation in a distribution network the load curves for all customers in low voltage networks and for all ring main units for medium voltage networks are needed. Usually this information is not available. In medium voltage networks typically only the load curve in the incoming transformer is measured. In the ring main units only the peak current is measured by non-return pointers. In low voltage networks very often there is no current measurement at all.

Only technical losses are considered in the computation and the time period under review can be in the past or future. This method is used in this paper to verify the results of the developed loss estimation method.

C. Energy Loss Estimation Method

The energy loss estimation method is based on the approximation of the loss factor by the load factor. For the approximation only information about the peak power, average power and power loss at peak load is needed. After all, only one load flow calculation has to be performed for the load losses and one for the no-load losses. This makes it easy to estimate the energy loss caused by technical losses with available data and in a very short time. The time period under review can be in the past or future.

The theory and its application to network planning will be explained in the following sections.

III. LOSSES, LOSS FACTOR, LOAD FACTOR AND THEIR RELATION

A. Definition of Technical Losses

Technical losses are typically divided into load losses (e.g. copper losses) and no-load losses (e.g. iron losses). Load losses are a function of current and no-load losses are a function of voltage.

Since the grids are run nearly at constant voltage, the no-load losses are also nearly constant. They can be calculated with one load flow calculation under the assumption that all units are in normal operation and all loads are switched off. The no-load losses include hysteresis, eddy currents and dielectric losses as well as I^2R losses due to no-load currents.

In contrast, the load losses are not constant and vary according to the loading of the equipment. They consist of heat losses in the conductors caused by the load cur-rent. The main focus for the energy loss estimation method is on the load losses since their computation is very difficult and they are differing in a wide range depending on the load characteristic.

B. Loss Factor

The loss factor F_s is defined as the average load loss $P_{\text{load loss}}$ to the load loss $P_{\text{load loss}}(S_{\max})$ at peak load $S_{\max}$ occurring in that period T. The relationship between the load loss and the load current is illustrated in figure 1.

$$F_s = \frac{\int_0^T P_{\text{load loss}} \cdot \mathrm{d}t}{T \cdot P_{\text{load loss}}\left(S_{\max}\right)} \tag{1}$$

Peak load $S_{\max}$ is the instant when the point of delivery supplies the peak load to the net and not the peak load of each customer.

Equation (1) can be rewritten considering current and resistance (I^2R), which cause the load losses. This gives equation (2), where I_{load} is the load current during a specific time period T and $I_{\text{load}}(S_{\max})$ the load current occurring in that period T at peak load $S_{\max}$. The link to load losses is the resistance R. The transmitted power S is proportional to the load current I_{load}. This relationship is also used in equation (2) to link the loss factor to the transmitted power.

$$F_s = \frac{\int_0^T R \cdot I_{\text{load}}^2 \cdot \mathrm{d}t}{T \cdot \left(R \cdot \left(I_{\text{load}}\left(P_{\max}\right)\right)^2 \right)} = \frac{\int_0^T S^2 \cdot \mathrm{d}t}{T \cdot S_{\max}^2} \tag{2}$$

The loss factor is also known as equivalent hours loss factor and can be interpreted as amount of time to give the same losses at peak load as that produced by the actual variable load over the time period under review [1], [2]. The period under review for network planning is usually one year.

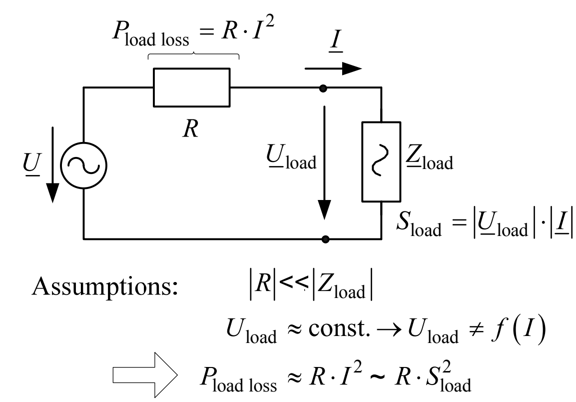

Fig. 1. Single-line diagram to illustrate the relationship between load loss and magnitude of load

C. Load Factor

The load factor F_d is the ratio of average load S to the peak load $S_{\max}$ during a specific period T. It is assumed that the power factor $\cos(\varphi)$ of the loads is constant.

$$F_d = \frac{\int_0^T S \cdot \mathrm{d}t}{T \cdot S_{\max}} \tag{3}$$

It can be seen that the definitions of load factor (eq. (3)) and loss factor (eq. (2)) are quite similar. However, there is also a relationship between the two factors which depends on the shape of the load curve. The estimation of this relationship is used for the energy loss estimation method.

D. Boundaries of the Relationship between Load Factor and Loss Factor

The relationship of the two factors depends on the shape of the load curve. Two extremely theoretical load curves S_A and S_B described by equation (4) are shown in figure 2.

$$S_A = \begin{cases} S_{max} & \text{for} \quad 0 \le t \le F_d \cdot T \\ 0 & \text{for} \quad F_d \cdot T < t \le T \end{cases}$$
$$S_B = \begin{cases} F_d \cdot S_{max} & \text{for} \quad 0 \le t \le 0.5 \cdot T - \Delta\tau \\ S_{max} & \text{for} \quad 0.5 \cdot T - \Delta\tau < t \le 0.5 \cdot T + \Delta\tau \\ F_d \cdot S_{max} & \text{for} \quad 0.5 \cdot T + \Delta\tau < t \le T \end{cases} \tag{4}$$

Load curve S_A has two extremes, peak load or no load. The load factor depends on the length of the time intervals. This represents start-stop operation.

In contrast to that is the continuous load curve S_B. Only for a very short time interval it reaches the peak load S_{max}. The time interval of peak load has the length of $2 \cdot \Delta\tau$ (with $\Delta\tau << T$). This represents no-stop operation.

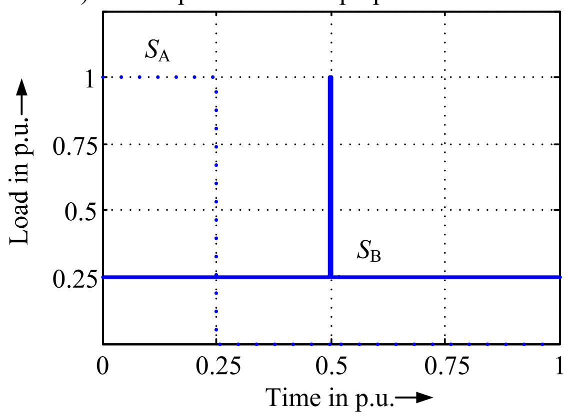

Fig. 2. Theoretical load curves ($F_d = 0.25$) to show the boundaries for the relationship between load factor and loss factor

At load curve S_A the load is either at peak load or at zero. In this case the load factor equals the loss factor. For load curve S_B the load is constant over the whole period of time except for a very short interval when it reaches the peak load. For this situation the loss factor is the square of the load factor. The derivation of these relationships is shown in equation (5) on basis of equation (2) with the load curves from equation (4). For the load curve S_B the interval of peak load is neglected. This is feasible since the interval is very short in comparison to the time period and therefore negligible.

$$F_{s\,A} = \frac{\int_0^{F_d \cdot T} (S_{max})^2 \cdot dt}{T \cdot S_{max}^2} = \frac{F_d \cdot T \cdot S_{max}^2}{T \cdot S_{max}^2} = F_d$$
$$F_{s\,B} = \frac{\int_0^{T} (F_d \cdot S_{max})^2 \cdot dt}{T \cdot S_{max}^2} = \frac{F_d^2 \cdot S_{max}^2 \cdot T}{T \cdot S_{max}^2} = F_d{}^2 \tag{5}$$

The two theoretical load curves are the boundaries for the relationship between load factor and loss factor. This is shown in figure 3 [1].

It can be seen that the loss factor has to lie in the shaded area between the limiting boundaries. Boundary S_A indicates the loss factor when directly proportional to the load factor and boundary S_B the loss factor when proportional to the square of the load factor.

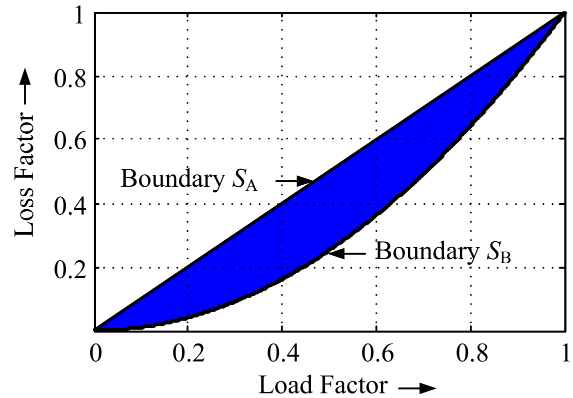

Fig. 3. Boundaries of the relationship between load factor F_d and loss factor F_s with the possible range being shaded

As explained later, the loss factor is closer to boundary S_B than to boundary S_A. This is due to the fact that for load curves with distinct base loads the peak loads have relatively low impacts on the losses.

IV. Approximation of the Loss Factor

A. Review of Different Approaches to the Approximation of the Loss Factor

Several approaches for the determination of the relationship between load factor F_d and loss factor F_s have been developed in the past. For example one approach is based on empirical relationships between load and loss factor. Another is based on mathematical approximations of load duration curves. The load duration curve is a descending sorting of a load curve.

Many approximation formulas are based on two different assumptions for the form of the functions. One is the polynomial function approach:

$$F_s = A \cdot F_d + B \cdot F_d{}^2 + C \cdot F_d{}^3 \tag{6}$$

and the other one is the power function approach:

$$F_s = F_d^{D} \,. \tag{7}$$

The summation of the parameters A, B and C of equation (6) has to sum up to 1 and the domain of exponent D of equation (7) has to be between 1 and 2.This also means that if the load factor equals zero the loss factor has to be zero and if the load factor equals one the loss factor has to be one and the function of the relationship between load and loss factor has to lie within the boundaries shown in figure 3.

The approximation formulas based on mathematical approximation of the load duration curve (e.g. Sochinsky, [3]) are not based on one of the functions mentioned above.

The approximation formula by Dewberry [4] is derived under the assumption that the load duration curve indicates a normal distribution for relatively long periods. It includes also the load ratio defined as minimum load S_{min} to peak load S_{max}. It should be noted that this approximation should only be used for load factors F_d under 0.8.

B. Selection of Common Approximation Formulas

A selection of different approximation formulas with the references where they had been published is given in table I. They are the most common formulas, and are still used in practice [8], [9]. The identifier for each formula in this paper usually corresponds to the respective author who published it first.

There are also many other approximation formulas. Often they are very similar to one of the formulas in table I.

It is important to notice that the time span of the publication dates of the presented approximation formulas is about 50 years. Therefore the here presented study will show which approximation formulas meet best the today's load curves in current networks.

TABLE I
COMMON APPROXIMATION FORMULAS WITH REFERENCES AND IDENTIFIERS

$F_s=$	Reference Identifier
$0.3 \cdot F_d + 0.7 \cdot F_d^2$	[1], Buller
$0.2 \cdot F_d + 0.8 \cdot F_d^2$	[6] CitiPower
$0.15 \cdot F_d + 0.85 \cdot F_d^2$	[7] Gangel
$0.083 \cdot F_d + 1.036 \cdot F_d^2 - 0.119 \cdot F_d^3$	[3] Wolf
$0.08 \cdot F_d + 0.92 \cdot F_d^2$	[3] Gustafson I
$F_d^{1.8}$	[3] Junge
$F_d^{1.912}$	[3] Gustafson II
$\dfrac{F_d^2 \cdot \left(2 + F_d^2\right)}{1 + 2 \cdot F_d}$	[3] Sochinsky
$F_d^2 + 0.273 \cdot \left(F_d - \dfrac{S_{min}}{S_{max}}\right)$	[4] Dewberry

Figure 4 shows three exemplary plots of loss factor versus load factor. It can be seen that the shown curves are closer to the boundary S_B than to the boundary S_A.

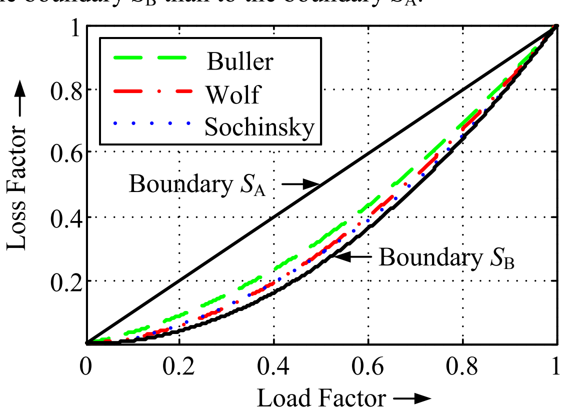

Fig. 4. Examples of common approximations for the loss factor versus load factor

V. Energy Loss Estimation for Network Planning

A. Necessary Data for the Calculation of the Load Factor

The evaluation of the relevant load data is the first step when taking energy loss into consideration for the network planning. To calculate the load factor with equation (3) information about the average load as well as peak load has to be determined. This data usually is readily available. The load factor can then be calculated.

B. Approximation of the Loss Factor

With the load factor and the approximation formulas in table I, the loss factor can be approximated. For the use of some approximation formulas additional data is needed. For example the minimum load has to be identified to use the formula by Dewberry. Also the limits of the formulas have to be taken into consideration. Most of the approximations were developed for distribution networks and are therefore applicable only to distribution network planning. Still the loads should represent the typical characteristic of loads in distribution networks.

C. Necessary Load Flow Calculations

Only two load flow calculations have to be performed for the energy loss estimation. One is done when all consumer loads are turned off to get the no-load losses and the other one is done at the instant when the point of delivery supplies the maximum load to the net to get the load losses at peak load.

D. Energy Loss Estimation

The estimation of the energy loss W_{loss} for a network can be done by multiplying the loss factor with the load losses at peak load and the time period T and adding the no-load losses multiplied by the same time period.

$$W_{loss} = F_s \cdot T \cdot P_{load\ loss}\left(S_{max}\right) + T \cdot P_{no\text{-}load\ loss} \quad (8)$$

E. Application to Network Planning Purposes

During the planning process of a network development many steady state, fault as well as transient calculations have to be performed. Within the process different network configurations are compared, taking the many results into consideration to find the best fit. With the shown easy to use estimation it is also possible to take the energy loss into consideration for network comparisons. This is done by determining the possible reduction by subtracting the energy loss for the planned reconfiguration from the energy loss for the actual state. Both energy values are a result of estimation. This leads to the question whether the results of the energy loss estimation method are useful or not.

In the next section the feasibility of this approach is examined by applying the method to three networks and comparing the results with calculated energy losses of a network simulation program.

VI. Verification of the Results of the Energy Loss Estimation

A. Overview

To show that the energy loss estimation can be used for distribution network planning processes three real distribution networks (0.4 kV and 20 kV) are selected. These networks are analyzed under the aspect of energy loss for their actual state and for a planned reconfiguration. The energy loss is computed with a network simulation program and estimated with the approximation formulas. For comparison reasons, the same load curve is taken for all investigations.

Table II shows an overview of the 3 networks with information about the loads.

TABLE II
OVERVIEW OF THE EXAMINED DISTRIBUTION NETWORKS

Network	1	2	3
Voltage level in kV	20	20	0.4
Number of loads	36	155	152
Peak load in MW	5.1	26.0	4.2

B. Computation of Energy Loss and its Reduction by Reconfiguration with a Network Simulation Program

For the computation with the network simulation program a time period of one year is examined and segmented into 15 minute intervals. Therefore, 35,040 load flow computations are needed in order to compute the total energy loss for one year. The challenge of doing a computation like this is mainly the data availability but it is also the data handling. First of all, the data of the loads have to be determined and stored. In case of network 2 it adds up to around 11 million values for the 155 loads and 35,040 time intervals considering active and reactive power. This amount of data must be gathered from an existing network requiring an extensive effort in measurement or it has to be assumed based on typical customer load curves. After all, the time demand for the simulation is about 10 hours if one computation with the data handling has a duration of 1 second. This shows how laborious the calculation of the energy loss with a network simulation program is.

The results of the computation of the total energy loss are shown in table III. It contains the lost energy for the actual state and for a planned reconfiguration as well as the possible reduction obtained for one year. They are the reference for the verification of the results of the energy loss estimation method.

TABLE III
COMPUTED ENERGY LOSS W_{LOSS} WITH A NETWORK SIMULATION PROGRAM AND POSSIBLE REDUCTIONS DUE TO A NETWORK RECONFIGURATION

Network		1	2	3
Actual state	W_{loss} in MWh / a	9.05	480.6	59.66
Planned		5.96	333.9	52.78
Reduction		34 %	30 %	11 %

C. Energy Loss Estimation and the Estimation of Reduction with Approximation Formulas

The load losses occurring at peak load are important for the energy loss estimation method. This is computed for the 3 networks. The results are summarized in table IV.

TABLE IV
RESULTS OF THE LOAD LOSSES $P_{LOAD\,LOSS}(S_{MAX})$ OCCURRING IN THE PERIOD UNDER REVIEW AT PEAK LOAD

Network		1	2	3
Actual state	$P_{load\,loss}(S_{max})$ in kW	4.92	269.84	33.04
Planned		3.13	197.28	29.23

TABLE V
CALCULATED LOSS FACTORS F_S FROM THE RESULTS OF THE SIMULATIONS

Network		1	2	3
Actual state	F_s	0.210	0.203	0.206
Planned		0.217	0.193	0.206

The load factor for this study is 0.42 for all networks. The average loss factor for the simulations calculated from the results of table V is 0.206. This confirms the nearly quadratic function as for the simulations the following relationship can be found:

$$F_s = F_d^{1.82} \tag{9}$$

With the computed losses from table IV and the approximation formulas from table I the loss factors are approximated and the energy loss W_{loss} can be estimated with equation (8). The results for the loss factors as well as for the reduction of the energy loss for all 3 networks are combined in table VI. The loss factor is for all networks the same because the load factor is constant.

TABLE VI
RESULTS FOR THE LOSS FACTORS

Identifier	$F_s =$	Identifier	$F_s =$
Network computation	**0.206**	Gustafson I	0.195
Buller	0.249	Junge	0.209
CitiPower	0.225	Gustafson II	0.190
Gangel	0.213	Sochinsky	0.208
Wolf	0.208	Dewberry	0.203

D. Comparison of the Results

An overview of the average errors and maximum deviations for the energy loss estimation method are shown in figure 5 and 6. The results of the network simulation program are taken as true value and therefore as reference for the relative errors.

Figure 5 presents the errors of the energy loss estimation for each of the 3 networks in the actual state as well as for the planned reconfiguration and figure 6 the possible reduction of energy loss after network reconfigurations for the 3 networks.

The results are shown for all approximation formulas presented in this paper.

The oldest approximation formula (Buller) for the loss factor has in both cases the largest error. All other approximations have an average error smaller than 15 %.

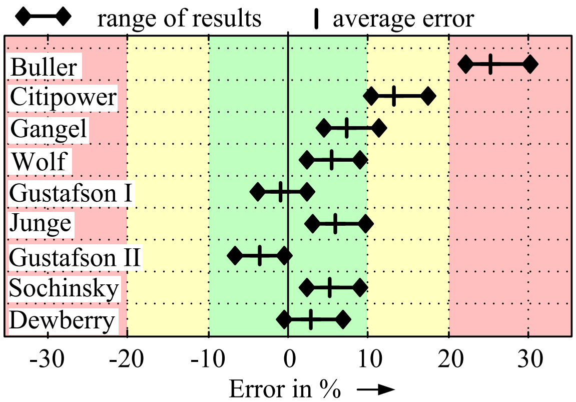

Fig. 5. Errors of the energy loss estimation for the examined approximation formulas

It can be seen that some approximations have negative and the other positive errors. However, figure 5 also shows that most of the approximation formulas provide sound results for the energy loss estimation having all errors in the range of ±10 %.

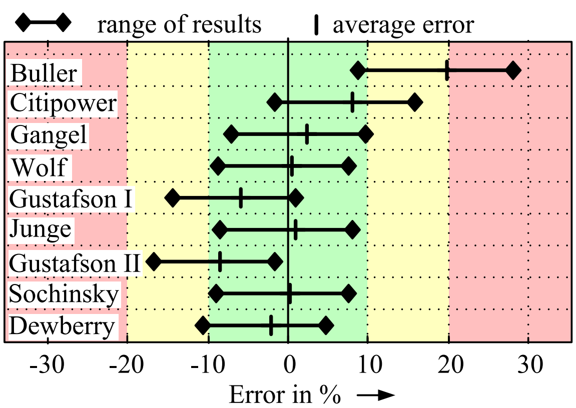

Fig. 6. Error of the estimated reduction of energy loss for the 3 networks for the examined approximation formulas

The deviation of the errors increases for the estimation of the reduction of energy loss (figure 6) compared to the energy loss estimation for a network (figure 5). This appears comprehensible because the estimation of the reduction uses two energy loss estimations for a network. The width of the range of results for the estimation varies between 6.0 % and 7.9 % for figure 5 and between 15.0 % and 19.3 % for figure 6.

However, most of the results for the possible reduction are still in the range of ±10 %. The approximation formulas by Wolf, Junge, Sochinsky and Dewberry yield the best results. The performance is satisfactory taking into account the straightforward and timesaving energy loss estimation method.

This shows that the estimation of possible reductions of energy loss with the approximation of the loss factor is possible for the network planning process. The savings in terms of time demand of the computation as well as data acquisition are large compared to the expected errors.

VII. Conclusion

The importance to evaluate energy loss increases not only during operation of networks, but also in the network planning process. This task has to be performed in a reasonable time while having the needed data available. Especially the reduction of energy loss for a network reconfiguration is of interest. With the described method the network planner can quickly give reliable results with the energy loss estimation method during the network planning process.

It could be shown that the comparison between different network configurations with the estimation is possible and in addition timesaving.

The shown procedure for the energy loss estimation method is sufficiently good to be used in the network planning process in practice.

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