A COMPREHENSIVE EVALUATION OF THE ENERGY LOSSES IN DISTRIBUTION SYSTEMS WITH HIGH PENETRATION OF DISTRIBUTED GENERATORS

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ABSTRACT
The accurate evaluation of grid losses is important for grid operators, especially in the era of high penetration of distributed generations (DGs). However, determining distribution grids’ losses in large scales is a difficult task. An advanced methodology for evaluation of energy losses in large distribution systems is developed in this work. Evaluation results are presented for the supply areas of four of the largest German distribution system operators (DSOs). Additionally, other related issues such as the impact of DG on grid losses and loss reduction measures are discussed in detail.

INTRODUCTION
Grid losses are considered as one of the key performance indicators for the evaluation of power systems. Therefore, the importance of an effective and accurate determination of grid losses is widely recognized by DSOs and regulatory authorities. However, determining the exact amount of energy losses of large distribution systems is a challenging task. Due to the incomplete measurements (mainly at low and medium voltage level) and the huge amount of grid assets, DSOs often have very limited possibilities in determining the exact grid losses. Currently, DSOs rely on the system energy balancing method to determine grid losses, which provides no insights concerning their source and allocation. In addition, this method is difficult to validate, as its evaluation completely depends on the quality of the measurements and ignores grid specific characteristics.

Another difficulty is the proper monitoring and understanding of the development of system losses in the era of high penetration of distributed generators, especially at the medium and low voltage (MV and LV) levels. Due to the rapid increase of DG installation for over a decade, significant amounts of DG are already accumulated in some supply areas of German DSOs [1]. Furthermore, the integration of DG will continuously increase in the next years. The energy feed-in by DG may have a strong impact on grid losses and will keep challenging the planning and operation for system operators.

To address the problem of technical evaluation of system losses, we conducted a 2-year project in cooperation with four of the largest German DSOs – Schleswig-Holstein Netz AG (SHNG), Avacon Netz GmbH (AVANG), Bayernwerk Netz GmbH (BAGE) and E.DIS Netz GmbH (EDIN). On the basis of the existing approach at Fraunhofer IEE, proposed in 2013 [2], diverse improvements are achieved with a new research methodology. By applying these improvements, approximately 100,000 grids (from 0.4 kV to 110 kV) are evaluated individually with time series simulations in this project. In this research paper, we present the major methodological developments and the detailed implementations with representative results of real grid data. The focus will be set on selected contributions described in the following:

- Allocation of system energy losses at all distribution grid levels for a full system coverage,
- Evaluation based on reference grid models of LV grids and complete annual power flow simulations at higher voltage levels in 15-min steps,
- Inherent validation based on simulation results of MV grids and the measured transformer power profiles,
- Comparison against the existing system energy balancing method.

The contributions in determining the system losses are highly relevant for any distribution system with high DG penetrations. The lessons learned for evaluating a huge amount of grid and metering data are valuable for future analyses related to distribution systems on a large scale.
GERMAN REGULATIONS ON GRID LOSSES AND INVESTIGATED DISTRIBUTION GRIDS

In Germany, the federal network agency currently regulates the amount of grid losses in distribution systems based on a 5-years regulation period and the purchase price of grid losses on a yearly base. DSOs are responsible for procurement, monitoring and reporting of their grid losses. By setting benchmark values of losses per grid level, the regulator encourages DSOs to achieve lower level of losses and improve the efficiency of their systems.

To obtain an accurate evaluation of grid losses, a large number of real grids and grid assets in combination with real measurement data are analyzed in this study. Fig. 1 illustrates geographies of the supply areas covered by the four partner DSOs.

Fig. 1 Supply areas of the partner DSOs (The supply area of Avacon Netz GmbH is presented primarily based on the 110 kV level.)

All the four DSOs share certain similarities. For instance, their LV grids are primarily located in rural, suburban and small-to-medium size cities. Consequently, the grids tend to use long feeders and low load density per substation. Driven by the political promotion and incentives for over a decade, high DG penetrations are observed in the supply areas of all these DSOs. However, different generation (and consumption) patterns are developed due to the regional climatic advantages. While the northern DSO SHNG is facing high amount of power feed-in by large wind parks, the southern DSO BAGE dominantly hosts the small to medium size PV generators. Besides the mixed structure of both solar and wind power, AVANG and EDIN also provide grid connections to substantial amounts of Combined Heat and Power and Biogas generations.

METHODOLOGY: DETERMINE ANNUAL GRID LOSSES AND THEIR ALLOCATION TO GRID LEVELS

The complete evaluation of distribution systems’ losses is carried out in a top-down and bottom-up scheme. As presented in Fig. 2, the assessment starts upwards from the LV level, so that the energy flows in the distribution system can be correctly built, up to the interface between the high voltage (HV) and MV levels. As all HV/MV transformers are equipped with power measurement devices, the power exchange profiles are available for an inherent validation of this methodology. If required, losses of HV grids are also calculated based on these power measurements. In this section, the detailed evaluation approach is presented for each grid level.

Fig. 2 Overview of the new research methodology

LV grids

The partner DSOs provided the complete database of pre-selected, representative areas. To better explore this huge amount of data, we followed the reference grid modelling principle and developed the following investigation procedure. The general evaluation workflow in the LV level is shown in Fig. 3.

Fig. 3 Workflow for evaluation of LV grid losses

Major steps are briefly described as follows:

A. Evaluations begin with the automatic generation of LV grid models. Firstly, the grid topology is created by analyzing the GIS database. Then, the electrical components in the grids are parameterized according to DSOs’ assets database. Finally, loads and DG are modelled with customers’ annual metering data and
the standard load profiles (SLP) [3]. This step yields power flow models of all investigated LV grids.

B. All LV grid models are implemented in a python-based tool pandapower [4]. The complete calculation of all LV grids is unnecessary. A part of the grids are selected. Their energy losses are determined by exhaustive annual power flow simulations in 15-min steps. The losses of the rest grids are determined by means of clustering analysis.

C. Important grid features are also evaluated for each grid based on these grid models. This dataset of features represents grid characteristics that relate to grid losses. For instance, typical features are total annual energy consumption and generation, total feeder length, transformer rating and DG penetration.

D. The dataset of grid features is subsequently normalized and analyzed using the k-Means clustering [5] method, which is an efficient, distance-based clustering algorithm. To enhance evaluation efficacy, the principle components analysis (PCA) [6] is additionally implemented as a pre-processing step. It selects and relates feature data to the grid losses. Reference grid models, i.e. representative samples, are identified for each cluster in this step.

E. For any further grids, the trained clustering model can be applied in order to associate them to similar reference grids. Their energy losses and power flow patterns are estimated using corresponding behavior of the reference grids.

**MV/LV transformers**

The input of the MV/LV level is composed of the results of the LV-level, the asset database and the customers directly connected to the LV/MV transformers. The calculation of transformer power losses follows the quadratic relationships between the iron losses and the voltage and between the copper losses and the current. The nominal transformer parameters can be derived from the DSO database, while the voltage and current are determined based on the results in the LV level. Through this simplification, the losses for all transformers are calculated with a time resolution of 15 minutes.

**MV grids**

Detailed MV grid models are provided by DSOs. Therefore, the losses in the MV level could be directly calculated for all the MV grids. MV grid models are converted from commercial software, such as PowerFactory and Sinical, to pandapower format using an automated approach.

Power consumption and generation of large customers above MV level are often measured as time series. The allocation of a power profile to its corresponding bus in the MV grid requires additional efforts. This problem is solved 1) based on the comparison of address data, 2) by calculating geographical coordinates and assigning to the nearest bus or 3) by consultation with DSO experts. By applying these three options, all customers can be allocated close to their allocation in reality. By integrating the aggregated load profiles of the LV grids, realistic power flows can be performed in the MV level. The losses are calculated using time series simulation of the whole year on 15-min steps. The calculations are executed with the power factor of 0.9, 0.95, 0.97, in case of customers modeled by the SLP profiles, and the exact measured power profiles for all large customers in order to estimate its influence on the grid losses.

**HV/MV transformers**

At the HV/MV level, we switch from the bottom-up to the top-down approach, i.e. instead of the input of the MV level, we use the measurements directly conducted at the primary side of the transformers. The mathematical background for calculating the grid losses is equal to the approach of the MV/LV level. The main differences to the MV/LV level are the calculation of both two-winding and three-winding power transformers. Furthermore, a sensitivity analysis of the power factors is not required, as both active and reactive power profiles are measured.

**HV grids**

In case of the HV grids (optional, primarily concerning the EDIN), the data for consumption and generation is based on two sources. The measured profiles that are used for energy accounting have the highest accuracy among all available data of time series. The measurements are mostly located at the transformers that belong to the customers and third-party DSOs. Alternatively, the operational measurements of the DSO are considered.

Due to deviations in the measurements, incomplete data sets and errors in profile allocations, the load flow model of the HV grid shows a deviation compared to the measurements at the EHV/HV transformers. In order to compensate the discrepancies between the load flow and the real measurements, a distributed slack approach is chosen to adjust the loads and generation iteratively to ensure that the load flow from the grid calculation through the EHV/HV transformers becomes consistent with the actual measurements. In addition, voltage measurements at the EHV/HV transformers are implemented to model the tap position of the EHV/HV transformers in the grid simulation, which is especially important in the case of a meshed topology of the HV grids.

Same as for the MV grids, the HV grid losses are also calculated for every 15-min interval of the year, using a distributed slack approach to every step.

**Additional loss components**

The symmetrical power flow model only determines the thermal losses of lines and transformers. In addition to these, diverse loss components are further evaluated, as suggested by relevant literature. We accordingly applied loss factors that represent energy losses in metering devices [7], energy losses of cable joints and fuses [8], underestimation of losses due to asymmetrical loading [9] and averaging effect by using SLP and 15-min profiles [9].
RESULTS AND DISCUSSIONS

In this section, the evaluation results and the validation are presented. In addition, the impact of DG on grid losses and relevant loss reduction measures in systems with high DG penetration are discussed.

Results of loss evaluation and comparison to the system energy balance method

The evaluation results of the grid losses for the four DSOs are summarized in Fig. 4. Here, the percentage of grid losses, determined by the ratio between the loss energy and the total amount of feed-in energy, are presented for each grid level of each DSO. According to a recent survey of European DSOs [10], all four investigated DSOs operate their systems in an efficient manner. Especially, the losses at interface levels HV/MV, MV/LV and MV grids show low discrepancy among the DSOs. In the LV sector, the DSOs are also able to keep losses within the range of approximately 3-4%.

![Fig. 4 Grid losses per grid level and the comparison between system energy balance and technical assessment methods](image)

In addition, total amount of loss energy, determined by these two methods, are almost equal in absolute values for each DSO. Due to the lack of measurements on energy flows between MV and LV, the current implementation of the energy balance method underestimates the energy exchange between the two levels. Accordingly, grid losses in percentage are overestimated for the same amount of absolute loss energy. Therefore, comparing the results determined by the technical assessment comparing against the energy balance method, decreases of percentage losses are observed in almost all grid levels. This analysis confirms the energy balance method in determination of the absolute level of losses. It also shows the advantage and the necessity of our technical evaluation study.

Validation of the evaluation methodology

As previously mentioned, the validation of the evaluation model takes place at the interface level between HV and MV levels on a yearly basis. Fig. 5 shows a comparison of actual measured power profile and the simulation results at an exemplary HV/MV transformer on several days. The good agreement of two curves indicate that both the power-measured customers and the aggregated generation and consumption in the LV grids are allocated in a complete and adequate manner. This approach guarantees a realistic representation of the loading situations of the grids over the investigation period. The evaluation, following our proposed methodology, provides therefore realistic results concerning the grid losses and their distribution among grid levels.

![Fig. 5 Comparison of measured power profile and the simulation results at an exemplary HV/MV transformer of selected days](image)

Impact of DGs on grid losses (LV)

In order to analyze the impact of DG on grid losses, a comparison between the DG penetrations, defined as the ratio of the annual feed-in energy w.r.t. the annual consumption, and grid losses is presented in Table 1.

<table>
<thead>
<tr>
<th>DSO</th>
<th>Total DG penetration of the LV level</th>
<th>LV grid loss [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHNG</td>
<td>0.24</td>
<td>3.9</td>
</tr>
<tr>
<td>BAGE</td>
<td>0.38</td>
<td>2.8</td>
</tr>
<tr>
<td>AVANG</td>
<td>0.14</td>
<td>3.2</td>
</tr>
<tr>
<td>EDIN</td>
<td>0.09</td>
<td>3.6</td>
</tr>
</tbody>
</table>

This analysis is carried out at the LV level for each DSO. The comparison of AVANG, EDIN and SHNG complies with the general conception, i.e. the developments of grid losses tend to reduce at lower DG penetration and increase again at a higher penetration level, as the DG penetration increases. However, the comparison between SHNG and BAGE show that high level of penetration may also yield relatively lower losses. Hence, a technical, comprehensive evaluation based on the complete grid data and the modeling of yearly power flows is necessary for a realistic and accurate representation of this subject.

Impact of DGs on grid losses (HV)

In the HV level, the impact of DG on (line) losses, regarding to the aggregate power of the consumption and generation, is illustrated in Fig. 6. The color represents the number of occurrences, while the dashed line is a fitted curve of all data points using a quadratic function. Negative power values correspond to grid situations of generation higher than consumption, while positive values indicate periods characterized by consumptions. The results show that the power losses within a range of 5-10 MW can be associated with either the load case or the generation case. A divergence of the losses can be observed for the load cases. There is a subset of time intervals with high load that have low losses, and a subset...
with the same value of aggregate power with higher losses. It is evident that the actual line losses depend on the specific load flow situation, e.g. the load positions, in the grid. Thus, general conclusions and the application of energy balance method may lead to over simplified results concerning the impact of DG on losses.

**Discussion on loss reduction measures**

The technical assessments on losses can contribute to the identification of critical grid assets and/or critical operation periods, so that the grid planning and operational decisions can be optimized. Further, measures are also relevant to the reduction of total losses:

- Coordinated planning of DG and grid extension
- Increase of local consumption
- Reactive power compensation
- Optimized control of switches (re-configuration)
- Dedicated implementation of OLTC and smart meter technologies to ensure reduction of losses
- Reduction of transit flows in the HV level

Principally, the reduction of grid losses can be achieved by means of additional investments in grid assets. Proper grid reinforcement, such as an increase in cable diameter or transformer capacity, will help to mitigate high loading situations in the system and thus lead to a reduction of physical losses. However, reducing losses in individual grids should not be considered as the primary objective for a DSO. The solely emphasis on grid losses may lead to an overinvestment in grid assets, which in fact contradicts to the overall objective, i.e. achieving an efficient and sustainable energy system. Therefore, a holistic and coordinated cost-benefit optimization to improve the overall efficiency on a scale of the whole system should be preferred. Based on this consideration, we suggest the regulators to benchmark the efficiency of distribution systems instead of the grid energy losses separately.

**CONCLUSIONS**

In this work, we presented a comprehensive study on grid losses of four large German DSOs hosting high amount of distributed generations. Beside the presentation of diverse methodological aspects, we compared the proposed technical evaluation method to the state-of-the-art method of system energy balancing. In addition, analysis of the impact of DG on grid losses and the reduction of losses are also discussed. These results and discussions demonstrated the importance and the necessity of such kind of technical assessment. Our future research activities include the evaluation of new technologies concerning grid losses, e.g. on-load tap changer and smart metering, further validations using field measurements and integration of the evaluation method into operational processes of DSOs.

**REFERENCES**


