LOSS CHARACTERISTICS OF LOCAL-DELIVERY DISTRIBUTION SYSTEMS

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ABSTRACT

In the North America and around the world, there is an increasing focus on energy efficiency, conservation and demand reduction. Technical losses within distribution systems are under increasing scrutiny by utility companies and regulatory agencies. One of the key issues is where losses occur along a “typical” feeder and what aspects of feeder engineering and construction contribute to or mitigate losses. This paper examines the breakdown of technical losses in distribution systems based on the “local delivery” concept, considering a range of urban, suburban, and rural feeders. The differences between local delivery systems and European-style central distribution systems are highlighted, and impacts of diversity are discussed.

INTRODUCTION

Electric utilities today are under considerable pressure to increase the energy efficiency of both their own operations and those of their customers. For electric utilities, this has translated into more awareness around how to design and build energy delivery systems to be more efficient and reduce technical losses. In power delivery, losses can be considered the “cost of doing business” in the sense that it takes power to deliver power. In addition to no-load (core losses of transformers), movement of power through any device incurs load losses that can be assessed and minimized but never eliminated.

One of the key issues with regard to loss minimization is where losses occur along a “typical” feeder and what aspects of feeder engineering and construction contribute to or mitigate losses. A first step is to identify the magnitude of these losses through the distribution system, with respect to the equipment and various size conductors operating at primary and secondary voltages.

Prior literature has discussed the breakdown of losses for the central distribution concept of system design, widely used in Europe. In North America, the “local-delivery” concept is extensively used, which leads to very different loss characteristics than European systems.

North American Delivery Systems

A major factor influencing losses is system design, and the fundamental design concepts of North American systems differ substantially from typical UK/European practices. In most European urban or suburban systems, a low-voltage, (380Y/220 or 416/240 volts) three-phase “distribution transformer” rated between 300 and 1000 kVA serves 100 to 300 dwellings. Primary (MV) feeders each interconnect a number of these distribution transformers to the supply substation. These feeders are often configured in ring-main networks.

In contrast, most North American distribution systems use a very different design approach, called the “local delivery” concept that brings the MV system very close to each and every customer. Local delivery systems use single-phase distribution transformers to provide residential loads with 120/240V service, most commonly in the range of 10 to 75 kVA. Typically, one to ten homes (most commonly, four homes) are served by radial service cables that are usually less than thirty or sixty meters in length. In rural areas, individual homes and farms tend to be served by a dedicated transformer. In more dense urban construction, secondary mains (typically larger than service cables) may run from the transformer along a street and several service cables are tapped off to serve customers (see Figure 1). Commercial loads, such as large stores, schools, etc., are usually supplied three-phase 208V or 480V service by a dedicated three-phase transformer, ranging from 75 kVA to 2500 kVA in size.

Medium voltage feeders are configured in a radial, branching, topology to serve several hundred distribution transformers per feeder. The medium voltage feeders have many branches, called “lateral”, and these laterals usually consist of just one phase. Figure 2 shows the layout of a typical U.S. radial distribution feeder, from substation to service transformer. While always operated radially, with a single point of supply, many feeders in urban and suburban areas have normally open interties with other feeders to permit service restoration. A number of nominal primary feeder voltages are used in North America. The largest number of feeders are in the 15kV class, 12.47, 13.2, and 13.8 kV the most common nominal voltages. Distribution feeders in the 25kV and 35kV class are also common.

![Figure 1. US service configuration showing secondary mains and service drops](image-url)
Due to the fundamental differences in distribution design, the loss profiles of these disparate systems are very different and strategies to mitigate losses on one system may not be as effective on another. Examination of the loss contribution along the feeder, and the sensitivity to design parameters provides valuable insight into how to effectively improve energy efficiency.

**Literature Review**

This paper examines the breakdown of technical losses in distribution systems based on the “local delivery” concept, considering a range of feeders operated at various nominal voltage levels. This type of loss investigation has substantial precedent. Indeed, several prior works have recognized the importance of characterizing losses at various levels of the system. But the approach taken in this work provides a more complete picture, especially on the secondaries and services. For example, the investigation in [1] concludes that the relative magnitude and sources of distribution system energy losses must be considered before initiating loss reduction measures. A common approach ([2] and [3]) is to use simulation models to analyze system losses at each level of the distribution system, and examine the sensitivity to various design and operation parameters. However, since these models do not adequately account for the impact of intra-hour diversity on loss factors, they tend to underestimate losses farther along the feeder, especially on the low-voltage system.

Lack of data, especially at the customer level, is one of the reasons losses have been frequently underestimated. In [4] metering was installed at customer and system locations and information related to load and losses was captured and compared to calculated data. The measured losses at the service level were much higher (more than twice on average) than calculated losses using traditional load factor and loss factor calculations. However, in lieu of trying to determine or explain the discrepancy the authors of that work adjusted the formulas to account for the difference. Another work, [5], also indicates that the losses at the service voltage level are actually higher than what is typically calculated but, also does not present a reason for the discrepancy.

Ultimately, the goal is to determine the most cost-effective ways to reduce losses. As explained in [6], for most North American utilities, a 1% - 2% loss reduction would provide significant savings, and better accommodate customer load growth. While this paper provides a good summary of solutions for loss reduction at the primary voltage level, it does not discuss the low-voltage, service level solutions.

The loss analysis performed in this work, and partially presented in the next section uses “typical” feeder models to determine where technical losses occur on a local-delivery system. The paper investigates how the losses vary with selected parameters, and discusses the often-observed discrepancy between observed losses and calculated losses on the low-voltage side.

**LOSS ANALYSIS**

To analyze the loss characteristics of local delivery systems, a variety of prototypical feeder types were selected and modeled in a standard distribution analysis package.

**Urban** - representative of a large city distribution system, (excluding UG secondary networks); characterized by high customer density, and small lots with a low per-customer kW peak demand contribution.

**Suburban** - represents typical subdivision developments in the US; larger lots than urban design, higher kW/customer, less customers per transformer, longer primary runs.

**Rural** – typical of systems in rural areas served by cooperative utilities; much lower customer density, decreasing away from the substation; far more single phase primary; no secondary mains; low transformer utilization.

**Semi-Rural** - in between rural and suburban types; similar to suburban closer to the substation but becomes more rural in nature further along the feeder.

For each feeder type above, the kW losses at peak feeder load are quantified at the following levels, for a variety of
parametric variations:
- Three phase primary segments
- Single phase laterals
- Service transformers
- Secondary mains (urban models only)
- Service wires

**Base Model**
Base models for the four selected feeder types were constructed and analyzed at typical U.S. primary voltage levels. The models reflect standard design and construction practices used in North America. Table 2 shows the breakdown in losses for a 12.47 kV feeder. The losses are quantified as a percent of total feeder kW. Figure 3 shows the losses at each level as a percent of total losses.

**Table 2. 12-kV Base Case Loss Summary**

<table>
<thead>
<tr>
<th></th>
<th>Urban</th>
<th>Suburban</th>
<th>Semi Rural</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-ph Feeder</td>
<td>1.39%</td>
<td>2.68%</td>
<td>2.23%</td>
<td>8.71%</td>
</tr>
<tr>
<td>1-ph Laterals</td>
<td>0.20%</td>
<td>0.37%</td>
<td>0.26%</td>
<td>1.86%</td>
</tr>
<tr>
<td>Transformers</td>
<td>1.51%</td>
<td>1.16%</td>
<td>1.14%</td>
<td>1.12%</td>
</tr>
<tr>
<td>Second. mains</td>
<td>0.15%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Services</td>
<td>0.37%</td>
<td>0.62%</td>
<td>0.57%</td>
<td>0.59%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3.63%</td>
<td>4.83%</td>
<td>4.21%</td>
<td>12.29%</td>
</tr>
</tbody>
</table>

**Figure 3. Loss distribution in base case by system level**

In Table 2 the total losses are significantly higher in the rural case, and Figure 3 shows that this is driven primarily by losses on the three-phase feeder. This is not unexpected, due to the length of rural feeders on typical North American systems. Conversely, total losses are the least on urban systems, which again follows from typical local-delivery urban systems which tend to have relatively shorter three-phase feeders than urban systems. Transformer losses are greater due to the fact that they are more heavily loaded.

For the base, models, the power factor ranges from .85 to .88 which can be easily improved with capacitors.

**Power factor Correction**
Capacitors were added to each base case feeder to correct the power factor to 0.97 and bring the voltage within 5% of nominal at the customer meter point. Voltage regulators were required for the semi-rural and rural models to bring the voltage profile within ANSI C84.1 standard limits. The following table shows the resulting impact on losses for the 12-kV case.

**Table 3. 12-kV Corrected Case Loss Summary**

<table>
<thead>
<tr>
<th></th>
<th>Urban</th>
<th>Suburban</th>
<th>Semi Rural</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-ph Feeder</td>
<td>1.02%</td>
<td>1.99%</td>
<td>1.68%</td>
<td>5.65%</td>
</tr>
<tr>
<td>1-ph Laterals</td>
<td>0.31%</td>
<td>0.35%</td>
<td>0.25%</td>
<td>1.41%</td>
</tr>
<tr>
<td>Transformers</td>
<td>1.50%</td>
<td>1.13%</td>
<td>1.13%</td>
<td>1.07%</td>
</tr>
<tr>
<td>Second. mains</td>
<td>0.14%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Services</td>
<td>0.37%</td>
<td>0.59%</td>
<td>0.55%</td>
<td>0.52%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3.33%</td>
<td>4.06%</td>
<td>3.61%</td>
<td>8.66%</td>
</tr>
</tbody>
</table>

The addition of capacitors mostly affects the three phase sections of the feeders, which is expected. Power factor correction reduces losses significantly. The slight variations in losses at the single phase, transformer, and service levels are due to changes in voltage profile resulting from the application of capacitors and regulators. The breakdown of losses remains essentially unchanged across feeder types.

**Load Balance**
North American utilities allocate single-phase loads to phases in an effort to promote balance. However, the actual balance often falls below desired objectives. Therefore, many utilities have feeder balancing programs, and the usual objective of these programs is minimizing current imbalance as measured at the substation (head) end of the feeder.

The corrected case was “balanced” so as to minimize the percent difference between the highest or lowest phase current and the average of all three phases. Initially, the average the imbalance was 12.4% for the 12-KV. This was reduced to 3.9% by moving laterals and single-phase transformers from the most loaded phase to other phases.

The results in Table 4 do not show a conclusive loss benefit due current balancing, which is understandable since this is primarily done for improved capacity utilization. The only opportunity to reduce losses by balancing is along the three phase main sections. But balancing currents at the head of the feeder does not necessarily improve the balance further along the feeder. The voltage balance at the end of the feeder might be a better metric for balancing the feeder to reduce losses.

**Table 4. 12-kV Impact of Current Balancing on Losses**

<table>
<thead>
<tr>
<th></th>
<th>Urban</th>
<th>Suburban</th>
<th>Semi Rural</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in total losses</td>
<td>-5.41%</td>
<td>-2.46%</td>
<td>-1.94%</td>
<td>5.2%</td>
</tr>
<tr>
<td>Cur. balance at feeder head</td>
<td>4.09%</td>
<td>0.95%</td>
<td>1.38%</td>
<td>9.06%</td>
</tr>
</tbody>
</table>
COMPUTING LOSS ENERGY

In the final analysis, the important metric is the cumulative energy loss over the year and not just the losses at peak. The typical approach to computing energy loss, given the loss at peak, is to apply a loss factor computed as the mean square of the feeder hourly load profile. Embedded in this computation is an implicit assumption of load homogeneity. In other words, the random nature of loads at various times over the load cycle and load diversity are not accounted for by applying a uniform loss factor to the snapshot of peak load losses.

Toward the end of the feeder, and particularly on the low-voltage system, the load currents are significantly less diversified than the total feeder current. Peak currents on non-diversified branches are greater than the currents on these branches coincident with the time of feeder peak current. Although the loss factors of these branches, relative to their individual peak loadings, are less than the diversified feeder loss factor, the net result of increased peak current and slightly lower loss factor is a loss that is greater in actuality than applying the feeder loss factor to the individual non-diversified branch loading at the time of feeder peak. Therefore, adjustment factors for each tier of the network topology are required. The conduction loss in each branch at the time of feeder peak is multiplied by the diversified loss factor for the feeder times the diversity adjustment factor. Adjustment factors, as a function of the number of loads served via a given branch, are shown in Figure 4. These factors are for a feeder serving relatively homogenous residential customers. A feeder serving a mix of customer types will have greater factors. These factors only need to be applied for relatively undiversified branches, as the adjustment factor is essentially unity for ten or more loads served.

Loss factors, and the diversity adjustments, can only be applied to series losses. Transformer core excitation loss is essentially independent of loading level, except to the extent to which loading affects voltage magnitude, which in turn creates a variation in core loss. Therefore, to calculate average power loss from a load-flow analysis of a distribution system, the transformer core loss must be deducted from the total loss, the loss factor, including diversity adjustments, is applied to the series losses, and the core loss is then added back in. The average loss is multiplied by 8760 hours per year to determine total energy loss.

Figure 4. Adjustment factor to compensate for increased losses in less diverse branches

CONCLUSIONS

The losses of local-delivery distribution systems are dominated by medium voltage feeder and distribution transformer losses. Lack of diversity in local-delivery system branches serving few customers, such as distribution transformers, secondary mains, and service cables, tends to increase the energy losses above that estimated by conventional analysis.

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REFERENCES