The Breakdown and Mitigation of Technical Losses on Distribution Power Systems

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Abstract: There has been an increasing focus on energy efficiency and demand reduction among utility companies and regulatory agencies in the United States. Technical losses within distribution systems are under increasing scrutiny. One of the key issues is to understand where losses occur along a “typical” feeder and what aspects of feeder engineering and construction contribute to or mitigate losses. In a recent project[1], the DSTAR utility research consortium looks for answers to both questions. This paper summarizes approaches and findings from the project.

Four feeder models are developed representing typical urban, suburban, semi-rural and rural feeders, which are used as a platform to examine the breakdown of technical losses in distribution systems. Two attributes are evaluated to illuminate the characteristics of technical losses: peak power loss and yearly energy loss. Power losses are analyzed assuming system loading at close to its thermal limit and are summarized for each system level, i.e. main feeder (three phase), laterals, distribution transformers, secondary mains, and service drops. The levels contributing the most to system losses are highlighted and the sensitivity of each level is discussed considering various design and operational characteristics, such as power factor correction and load balancing.

Given power loss at peak loading, the typical approach to calculate energy losses is to apply a loss factor, computed as the mean square of the feeder hourly load profile, to a model of the feeder representing maximum coincident loading conditions. This approach yields a relative breakdown of series losses (excluding transformer no-load losses) that are identical for losses at peak loading and total annual energy loss. Because of varying levels of load diversity at different points in the system, the true loss factor varies for different components of the feeder. Thus, the relative breakdown for peak power and annual energy losses are substantially different. The paper quantifies diversity, based on actual load data for a number of residential and non-residential loads, and applies the resulting correction to loss factors to reveal an accurate breakdown of energy loss.

The paper concludes with a summary of design and operating measures that can be applied to mitigate losses.

1 INTRODUCTION

Electric utilities today are under considerable pressure to increase the energy efficiency of both their own operations and those of their customers. It is known that utilities have long had consumer energy awareness programs, to reduce or shift demand and generally delay

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[1] The work in this paper is funded by DSTAR (Distribution System Testing, Analysis and Research) under Program 12 Project 5. DSTAR is funded by utilities scattering around US and managed by GE Energy in Schenectady, NY. For more information about DSTAR see www.dstar.org

infrastructure investment. But there is now more political, regulatory, and societal pressure to design and build distribution system with more attention to efficiency. For example, since the DOE is requiring utilities to purchase more efficient transformers, loss evaluation will attract a higher level of interests among utilities.

Much work has been done over the years concerning technical losses in the distribution systems. A key issue with regard to loss assessment and mitigation is to understand where losses occur and to what extent various system components contribute to the loss profile. Prior works have recognized the importance of characterizing losses at various levels of the system [1-3]. Chen and Orillaza take it a step further and show the sensitivity of losses to various design and operation parameters [2-3]. However, none of these works adequately account for the impact of intra-hour diversity on loss factors, which cause losses to be underestimated further down the feeder, especially on the low-voltage system. Negendra Rao affirms this underestimation and finds that 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 [4]. A paper by Eckles investigates reactive power compensation with capacitors [5]. A base case feeder with no capacitor compensation is used as the starting point. When capacitors are added, the voltage is reduced to quantify the released capacity. However, Eckles computes losses only for the main feeder and does not attempt to quantify the losses on laterals or secondary mains and services.

This paper examines the breakdown of technical losses in distribution systems based on the "local delivery" concept used in North America, considering a range of feeders with various load densities and feeder lengths. A similar approach as in [5] is used here, but this work provides a more complete picture, especially of the secondary and service losses. Specifically this paper discusses the often-observed discrepancy between measured losses and calculated losses on the low-voltage side. The rest of this paper is organized as follows. Section 2 specifies characteristics of distribution system models used in this study and defines various system components for which losses are classified. Section 3 discusses power and energy losses for four generic feeder types. Section 4 explores measures that can impact technical losses and also discusses loss reduction strategies. Section 5 concludes the paper with a summary of loss mitigation measures.

2 CLASSIFICATION OF LOSSES BASED ON SYSTEM STRUCTURE

The architecture of the distribution system can have a huge impact on the magnitude and distribution of losses. In most European urban or suburban systems, primary (MV) feeders connect a number of large distribution transformers to the supply station. These feeders are often configured in ring-main networks. A low-voltage, (380Y/220 or 416/240 volts) three-phase "distribution transformer" rated between 300 and 1000 kVA serves 100 to 300 dwellings. The fundamental design of US distribution system, however, is substantially different from common UK/Europe practices.

2.1 Typical US Feeder Structure

Most North American distribution systems use 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, which are usually less than thirty to 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.

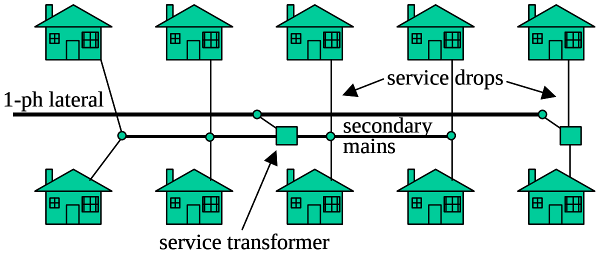

Figure 1 US service configuration showing secondary mains and services

2.2 Four Feeder Types

To analyze the loss characteristics of local delivery systems, four prototypical feeder types were selected and modeled in a standard distribution analysis package. Each type differs in backbone feeder length and customer density, but overall they reflect standard design and construction practices used in North America.

Urban - representative of a large city distribution system, (excluding underground secondary networks); characterized by high customer density, and small lots with a low per-customer kW peak demand contribution. This model includes a main feeder of two circuit-miles and a secondary system where each service transformer supplies a secondary conductor, which in turn feeds eight individual services. There is an even distribution of customers along the three phase mains and single-phase laterals.

Suburban - represents typical subdivision developments in the U.S.; larger lots than urban design, higher kW/customer, less customers per transformer, longer primary runs. There is also an even distribution of customers along the three-phase backbone feeder, which is 3.25 circuit-miles long, and the single phase laterals.

Rural – typical of systems in rural areas served by cooperative utilities; characterized by much lower customer density, decreasing away from the substation; far more single phase primary; no secondary mains; and low transformer utilization. The rural feeder modeled in this study is ten circuit-miles long.

Semi-Rural - in between rural and suburban types; similar to suburban close to the substation but becomes more rural in nature further along the feeder. There is a heavier concentration of customers along the first half of the feeder with a lower concentration of customers on the second half, matching that of the rural model. The semi-rural feeder is modeled as a six-mile circuit.

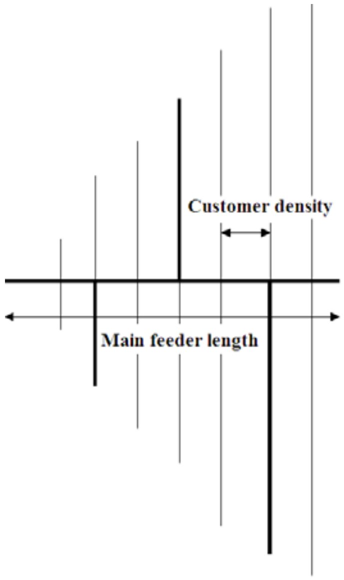

Figure 2. General layout of four feeder models

2.3 Loss Classification

For each feeder type above, the kW losses at peak feeder load are quantified at the following locations:

- Three phase primary segments
- Single phase laterals
- Service transformers
- Secondary mains (urban models only)
- Service wires

This paper studies both power losses at peak demand for each of the four feeder types and their annual energy losses considering yearly load variation.

3 LOSS ANALYSIS AND BREAKDOWN

Technical losses are defined to include two components: power loss and energy loss. Power loss is associated with the conductor or transformer and is proportional to the square of current. Therefore, more losses occur when the feeder is heavily loaded. The generic feeder models developed in Section 2 are heavily loaded, with peak loads on the order of 80% of conductor thermal limits.

3.1 Base Case

Base models for the four selected feeder types were constructed and analyzed for a typical U.S. primary voltage level. In the base cases there is no VAR compensation modeled on the feeders.

Table 1 shows the breakdown in peak power losses for the prototypical 12.47 kV feeders. The losses are quantified as a percent of feeder peak kW loading. Figure 3 shows the losses at each level of the system as a percent of total losses.

Table 1. 12-kV Base Case Loss Summary - Power Loss at Peak Coincident Loading

	Urban	Suburban	Semi Rural	Rural
3-ph Feeder	1.39%	2.68%	2.23%	8.71%

1-ph Laterals	0.20%	0.37%	0.26%	1.86%
Transformers	1.51%	1.46%	1.52%	1.12%
Second. mains	0.15%	N/A	N/A	N/A
Services	0.37%	0.31%	0.28%	0.59%
Total	**3.63%**	**4.82%**	**4.30%**	**12.29%**

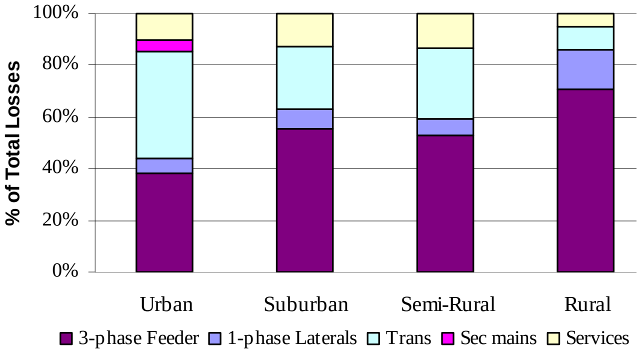

Figure 3. Loss distribution in base case by system level

Table 1 shows that the total losses are significantly higher in the rural case while Figure 3 shows that this is driven primarily by losses on the three-phase feeder. This is not unexpected, due to the typical length of North American rural feeders. Conversely, total losses are the lowest on the urban feeder. Urban systems tend to have much shorter three-phase runs than rural systems. Transformer losses are greater on the urban feeder due to the fact that transformers on this type of feeder tend to be more heavily loaded.

For the base models, the power factor ranges from 0.85 to 0.88, which can be easily improved with capacitors.

3.2 Compensated Case

Capacitors were added to each base case feeder to correct the power factor to 0.97 while maintaining the voltage within 5% of nominal at the customer meter point. Capacitor banks were only applied to the three-phase backbone sections of the feeder. The following table shows the resulting impact on losses for the 12.47-kV case.

Table 2. 12.47-kV Corrected Case Loss Summary - Power Loss at Peak Coincident Loading

	Urban	Suburban	Semi Rural	Rural
3-ph Feeder	1.02%	1.99%	1.68%	5.65%
1-ph Laterals	0.21%	0.35%	0.25%	1.41%
Transformers	1.50%	1.39%	1.49%	1.07%
Second. mains	0.14%	N/A	N/A	N/A
Services	0.37%	0.29%	0.28%	0.52%
Total	3.24%	4.02%	3.70%	8.66%

The addition of capacitors mostly affects the three phase sections of the feeders, as expected, where it results in significant loss reduction. The slight variations in losses at the single-phase lateral, transformer, and service levels are due to changes in the voltage profile, and the consequent changes in load demand, resulting from the application of capacitors and voltage regulators.

4 ENERGY LOSS BASED ON LOADING FACTOR

In contrast to the previous section, this section will examine the accumulation of losses over time. The power losses at Section II show that 3-phase line loss and transformer losses are the major loss contributors. Meanwhile, the breakdown of energy losses is expected to be different due to the decreased significance of series loss and increased significance of transformer core-losses.

4.1 Loss vs. Loading

A distribution system has two types of power losses: load-related loss and no-load loss. The former is also called series or ohmic loss and is due to the resistance of a conductor or device, and increases as the square of the load – i.e. doubling the power flow through a device quadruples the losses. No-load loss is associated with shunt-connected inductive equipment, i.e. transformers and regulators. No-load loss is nearly independent of loading (the only variation in no-load loss with respect to loading is indirectly due to the variation of applied voltage). When examining loss variation with loading, no-load loss should be excluded. Figure 4 shows the load-related loss variation versus feeder loading for the four feeder types. The horizontal axis is per unit feeder loading based on peak load (90% of thermal limit) and the vertical axis is per unit feeder series loss based on loss under peak load. Figure 4 provides a way of estimating series loss given the loading level. It is also clear that the normalized series losses and loading of the four different feeder types have a very similar quadratic relationship. While this conclusion may seem obvious, it is important to note that shunt capacitor banks switched and voltage regulators changed taps through these loading ranges. The quadratic regression coefficients indicate that these non-linear changes are virtually insignificant to the series loss versus loading relationship. Thus, the assumption that series loss varies with the square of loading is a very accurate approximation.

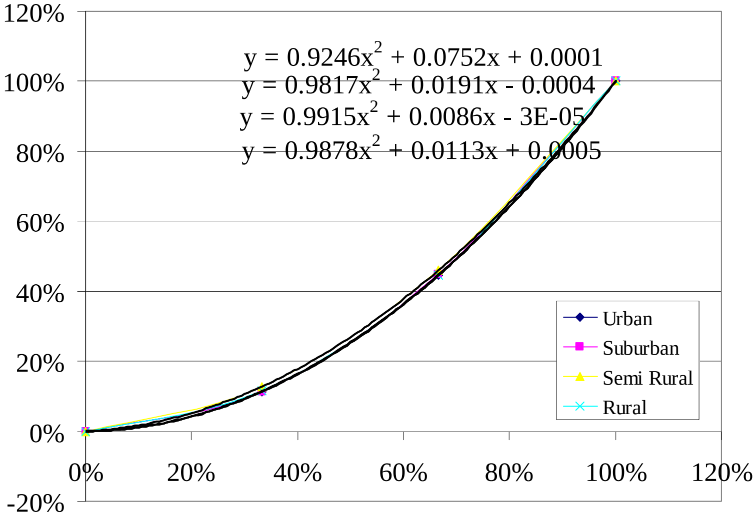

Figure 4. Load-related loss vs. feeder loading

4.2 Load Profile

Distribution system losses accumulate continuously, and loading at times other than peak must be considered in defining annual energy losses. Actual hourly customer load profiles over a one-year period were used to model aggregate feeder loading curves. The load on the feeders was considered to comprise three customer classes: 20% commercial, 20% all-electrical residential (AE), and 60% non all-electrical residential (NAE). Each class came from a variety of customers located in the Southeastern United States. Commercial loads are from a mix of various load types, e.g. high school, grocery stores, and office buildings. The load duration curve in Figure 5 shows utilization of system capacity over time, with the load variation on the vertical axis normalized to the feeder's peak load. The feeder is loaded below 65% of its peak demand 90% of the time.

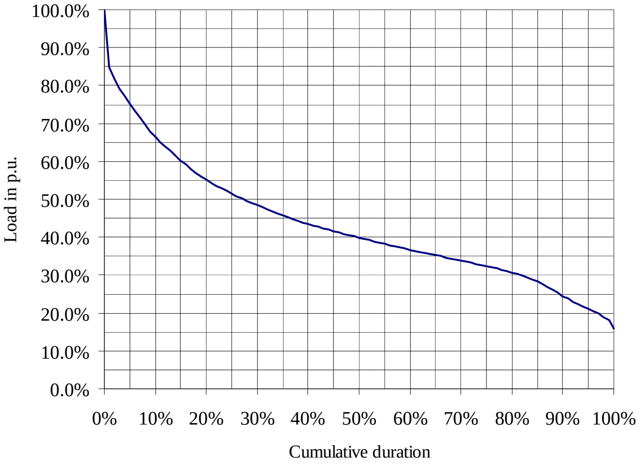

Figure 5 Normalized load duration curve

4.3 Energy Loss

Energy loss can be estimated via a loss factor, which is calculated for a given annual load profile if the loss variation with loading level known. Loss factor (LF) is defined in Equation (1)

$$\mathrm{LF} = \frac{\mathrm{Avg}(P_{\mathrm{series\_loss@loadinglevel}})}{P_{\mathrm{series\_loss@peakload}}} \quad (1)$$

The loss factor can only be applied to load-related (series or ohmic) losses. Transformer core excitation loss is essentially independent of loading level, except to the extent that 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 subtracted from the total losses. 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, as shown in (2).

$$\mathrm{Energyloss} = \mathrm{LF} \times P_{\mathrm{series\_loss@peakload}} \times 8760 + P_{\mathrm{core\_loss}} \times 8760 \quad (2)$$

Table 3 shows energy losses for the four feeder types based on the load profile in Figure 5. The total energy losses for all four prototypical feeders are below 6% of total energy consumption. The rural feeder has the most energy loss because it serves widely distributed customers via a long circuit. In the rural model, the three-phase backbone feeder conductors are the major contributors, representing more than half of the total energy loss. However, for all the other feeder types investigated (urban, suburban and semi-rural), distribution transformers were found to be the dominant contributor to energy losses (in contrast to the three-phase backbone for power losses in Table 2). The core and winding loss contributions to total transformer energy loss are roughly comparable in all of the scenarios.

Table 3. Energy loss summary for 12.47 kV corrected case

	Urban	Suburban	Semi Rural	Rural
3-ph Feeder	0.59%	1.17%	0.97%	3.23%
1-ph Laterals	0.12%	0.20%	0.15%	0.81%
Transformers	1.29%	1.3%	1.43%	1.48%
Second. Mains	0.09%	N/A	N/A	N/A
Services	0.31%	0.25%	0.23%	0.43%
Total	2.40%	2.93%	2.78%	5.95%

5 LOSS MITIGATION

The understanding of loss breakdown and the distribution of losses on different types of feeders can lead to more effective loss reduction techniques. From the loss analysis described in this paper, it is found that the largest contributors to distribution system losses are distribution transformers and primary three-phase conductors. Depending on the ultimate objective of the loss mitigation, the most effective strategy can vary. If the contribution of losses to system peak demand is the most important objective, then attention needs to be focused on the largest contributors to power loss at system peak. On the other hand, if energy conservation is the driving objective, then focus needs to be on the dominant contributors to cumulative energy losses. For the urban feeder scenario described in this paper, distribution transformer losses dominate both peak power and energy losses. Peak power losses are dominated by three-phase primary conductor losses, but energy losses are dominated by the distribution transformer losses for the suburban and semi-rural feeders. Only in the rural feeder do feeder conductor losses dominate both power and energy loss totals.

Loss reduction is most easily and effectively addressed during initial design of a feeder, when an existing feeder is being extended or reconfigured, when transformers are procured for new customer additions, or when transformers are being replaced due to failure or load growth. For existing feeders, the most economically efficient means for reducing losses is by installing adequate power factor compensation, and then controlling the compensation so that the most effective loss reduction is achieved.

5.1 Distribution Transformer Losses

Loss evaluation of distribution transformers had become a widespread practice in the utility industry by the early 1990's. Loss evaluation assigns a value to the cost of no-load losses (A factor) and load losses (B factor). The product of the A and B factors times the transformer losses are added to the selling price of the transformer to determine the total owning cost. Where the A and B factors fairly and accurately represent the cost of losses, this practice tends to promote procurement of efficient distribution transformers. The turmoil of utility industry deregulation induced many utilities to abandon loss evaluation in the latter half of the 1990's. The US Department of Energy has recently promulgated mandatory minimum distribution transformer efficiency requirements. New transformers meeting these new rules will be more efficient than many transformers purchased in the past, but may still not achieve a level of efficiency consistent with the value many utilities place on efficiency, as imputed by the investments these utilities make in other energy efficiency initiatives. In other words, a return to distribution transformer total owning cost evaluation may be more economically efficient than many other investments utilities, which are currently making to conserve energy and reduce demand.

A common practice is to size transformers primarily on the basis of voltage drop and flicker constraints rather than for simple load capacity. This creates a tendency toward oversized transformers, which in turn affects the no load and load-related losses such that the net energy losses are increased. This is because the no-load energy loss component increases at a greater rate for increased transformer rating than the load-related energy loss component decreases. (Peak loss actually decreases for increased transformer size, but the relatively low loss factor of residential distribution transformer applications results in an opposite trend in energy loss.) Where voltage drop and flicker are constraining, the greatest efficiency can be realized by specifying the constraint to the transformer manufacturers along with the A and B loss factors. The transformer designer can perform the tradeoffs yielding the economically efficient transformer design; e.g., the transformer designer may be able to meet these constraints by reducing the transformer impedance rather than providing an over-rated design with greater core loss.

5.2 Primary Conductor Losses

The most direct way to reduce conductor losses on the primary is to reduce the conductor resistance. Loss evaluation procedures, similar to those sometimes used for transformer procurement, can be used to select optimal feeder conductor sizes, considering the life-cycle cost of losses. Incremental costs of supporting structures (poles, conduits, etc.) and hardware for larger conductor and cable sizes, however, must necessarily be part of the analysis. Because of the high cost of reconductoring an existing feeder, loss reduction is rarely the sole justification for feeder reconductoring projects. However, when reconductoring or line relocation is required for other reasons, such as increased demand, highway widening projects, etc., it is prudent to design the reconductored or replaced feeder considering the costs of losses.

There are other ways to reduce the effective resistance of a feeder, and one way is by minimization of route length. New substations should ideally be located at or very near the center of the load they are serving to reduce the length of the main feeder. Feeder routing can also impact losses, so this should be a consideration when routing is determined.

The selection of the primary voltage level also has a significant impact on feeder conductor losses, especially with longer (rural) feeders. The three phase feeder conductor losses vary by a factor of four when voltage level doubles. Voltage level is not only a consideration for new feeders, but also when an existing feeder may be upgraded to a higher nominal voltage. As in the case of reconductoring, voltage upgrading is rarely justified by loss reduction alone, but is a supplemental benefit when considering upgrading for other reasons such as increased capacity.

Power factor compensation reduces feeder conductor losses by reducing the magnitude of current flow. Ideally, the greatest efficiency is achieved by maintaining unity power factor for current flow throughout the distribution system at all times. To do so would require dispersing capacitive compensation to every point in the system where load is connected, and continuously varying the compensation at each point. Neither is practically achievable. For economic reasons, capacitors are available only in discrete switchable bank sizes that are located at a limited number of locations on the feeder, typically on the three-phase primary. Maximum efficiency is realized by optimizing the location and rating of individual capacitor banks, and by implementing a control scheme that deploys the capacitors such that the conductor losses are minimized. Recent development of smart integrated volt/var control systems offer the opportunity to reduce losses to a greater extent than possible with conventional local voltage, time, temperature, current magnitude, or reactive power based capacitor bank controls.

Unbalanced loading causes increased losses due to the nonlinear relationship between current flow and losses, and due to currents flowing in the ground and in more resistive neutral conductors. Maintaining balanced flow through the whole system reduces losses, but simply balancing the total feeder current from the substation does not necessarily achieve this result. Some commercial distribution planning software tools have load-balancing algorithms that are based on achieving total current balance. Such a tool was tested on the prototypical feeders described in this paper, with negligible impact on loss reduction. In one case, the loss actually increased in the feeder after “balancing”. In this case, current balance was achieved in the feeder breaker current while current imbalance was increased downstream.

5.3 Secondary Service Design

When a distribution transformer serves a single load (e.g., large commercial three-phase service), locating the service transformer as close to the load as practical serves to keep the service conductor resistance to a minimum, thereby minimizing the losses on that component. The opportunities to reduce losses in this way may be limited by other considerations such as easement acquisition and the cost of additional primary extension.

For urban and suburban residential applications, the number of customers served from a single distribution transformer has a complex effect on losses. A greater number of customers served from one transformer implies longer secondary service cables with more loss, but also implies a larger distribution transformer that has greater efficiency. Transformer efficiency increases with transformer kVA rating, and the capacity of a transformer is more effectively utilized by the more diverse load of a larger number of connected customers. Transformer and service cable losses change in opposite directions with the number of served customers, and the optimum amount from an energy efficiency standpoint is very dependent on the specific situation**.**

5.4 Demand Management

A feeder load curve with less severe peaks (high load factor) will generate less losses than a curve delivering the same energy with more pronounced peaks. There are various measures that are being applied or considered to smooth utility demand curves, ranging from rate incentives to direct load control. Many utilities have special rates that give customers incentive to reduce their demand and usage or to reduce these during peak hours. The primary motivation for these demand response programs is usually related to deferral of additional generation capacity additions or minimization of power purchases when the market price is high. A secondary benefit of these peak reduction programs is reduction of distribution system losses.

6 CONCLUSIONS

This paper has presented some of the results of a recent comprehensive DSTAR study to examine the breakdown and mitigation of losses on U.S. distribution systems. There is a large amount of literature on technical losses, the breakdown of losses on various segments of the distribution system, and the impact of reactive compensation on losses. However none of these works adequately account for the effect of intra-hour diversity on loss factors, which cause losses to be underestimated toward the low-voltage side of the feeder. The DSTAR study analyzes this issue and develops methods to adjust results of typical loss calculation performed by utilities.

In this paper, power losses were calculated and compared on four prototypical feeders (urban, suburban, semi-rural, and rural) for an uncompensated case and a reactive power compensated case, and then the breakdown of cumulative energy losses for the corrected case was contrasted against the power loss at peak.

This slice of the larger study confirmed several expected results and raises a few key issues. Firstly, the benefit of var compensation is seen in the difference in power loss between the uncompensated and compensated systems. The loss reduction shows up almost exclusively on the three-phase primary (which is expected since three-phase capacitors where applied), and consequently the rural feeder with long primary runs benefited more, dropping from 12.29% to 8.66% of peak load. An interesting contrast was observed with regard to energy losses, which were calculated based on a computed loss factor. The total energy losses for all four prototypical feeders are below 6% of total energy consumption, but in this case the distribution transformers were found to be the dominant contributor to energy losses.

A complete understanding of loss breakdown and the distribution of losses on different types of feeders can lead to more effective loss reduction techniques. The full DSTAR report examined loss mitigation in the light of the loss analysis and some of the key findings are discussed in this paper. For example, the study has confirmed that if energy conservation is a goal, improving transformer efficiency should be part of the solution. Despite the fact that the US DOE now mandates minimum distribution transformer efficiency, a return to distribution transformer total owning cost evaluation may be more economically efficient than many other investments utilities are currently making to conserve energy and reduce demand. Additionally, where voltage drop and flicker are constraining for transformer application, the greatest efficiency can be realized by specifying the constraint to the transformer manufacturers along with the A and B loss factors.

These transformer efficiency measures and several other mitigation techniques regarding primary conductor losses, secondary service design, and demand side management are discussed with reference to the loss analysis results. Distribution utilities can benefit from the analyses and discussions presented in this paper, and the more in-depth analyses and discussions in the DSTAR energy efficiency report on which this paper is based.

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