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Time-varying cost of loss evaluation in distribution networks using market marginal price

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ABSTRACT

In the electric power system planning process, engineers seek to identify the most cost-effective means of serving the load within reliability and power quality criteria. In order to accurately assess the cost of a given project, the feeder losses must be calculated. In the past, it was necessary to estimate the feeder losses based upon the peak load and a calculated load factor for the year. The cost of these losses would then be calculated based upon an expected, fixed per-kW h generation cost. This paper presents a more accurate means of calculating the cost of losses, using hourly feeder load information and time-varying electric energy cost data. This paper attempts to quantify the improvement in accuracy and presents an example where the economic evaluation of a planning project requires the more accurate loss calculation.

Introduction

In almost any power system planning project, the cost of electric energy losses represents a significant cost factor, whether the planning engineer faces the task of laying out new feeders or resolving an overload or low voltage on an existing feeder. When laying new conductor or reconductoring, the lower losses of a larger conductor may offset the cost of the larger conductor. When evaluating a phase move to reduce flow imbalance on an existing feeder, the reduction of losses alone may be sufficient reason to perform the phase move. On the other hand, if losses are not calculated correctly, planning engineers may make poor choices of conductor size or may make the wrong decision whether to go ahead with a phase move or not.

In calculating losses accurately, two quantities must be known: the energy (kW h) of the losses and the cost of those losses ($/kW h). Methods for cost of loss calculation are well-established in literature. In the past, planning engineers often only had estimates of the peak load on a feeder and the total annual consumption on the feeder. With only this information, the total annual losses were calculated based upon the peak losses and a load factor calculation [1]. Furthermore, many distribution utilities also owned their own generation or else had fixed per-kilowatt-hour costs of electric energy. In [2], authors use peak load losses and diversity factor for loss cost calculation. Authors in [3] used average loading on transformers for the cost of loss calculations to avoid using the peak load approximation. In [4], the costs of losses are divided in two categories, fixed loss and dynamic loss. Fixed loss is independent of the load level and variable loss depends on the square of the load profile. A statistically based method is presented in [5] to calculate loss with the help of Time of Use (TOU) tariffs and daily load profiles. Ref. [6] explains a marginal loss calculation that used an incremental approach and Newton's method.

In the past decade, two changes have brought about the need for more detailed loss calculations. First, advancements in telecommunication and computing technology have made it much less expensive for utilities to acquire hourly flow measurements at each of their feeders and make these measurements available to their engineers [7,8]. These hourly feeder flow measurements can greatly improve the calculation of losses at each hour of the year. Second, the deregulation of the industry has changed the way many power distribution companies pay for the energy they deliver to their customers. The actual price of energy is no longer fixed, but rather changes hourly (or more often), determined by the

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Nomenclature

P_{avg}	average load (kW)
E_{annual}	the total annual energy consumption (kW)
8760	total number of hours in a year
P_{peak}	peak load (kW)
LF	load factor
$Loss_{peak}$	peak loss (kW)
$Loss_{avg}$	average loss (kW)
$Loss_{total}$	total loss (kW)
$C_{expected}$	the expected cost of a kilowatt of energy ($/kW h)
C_{total}	total cost of losses ($)
C^{i}_{alpha}	the coefficient for each customer type
$C_{kW\ h}$	the monthly consumption (kW h)
$C^{expected(i)}_{kW\ h}$	the expected hourly demand for customer (kW h)
$Fkw^{i}_{expected}$	total expected feeder demand at a given hour (kW h)
$Fkw^{i}_{measured}$	the measured demand at the start of the feeder (kW h)
$Ckw^{i}_{expected}$	the expected customer's demand (kW h)
Ckw^{i}_{scaled}	the scaled customer's demand (kW h)
P_{loss_i}	the losses at hour t (KW)

real-time bidding managed by the regional transmission organization (RTO) or independent system operator (ISO) and are published as the real-time locational marginal price (LMP) [9]. Authors in [10] used hourly power flow analysis and hourly load data to calculate annual line loss cost. Ref. [11] explains marginal loss calculation that is independent of reference bus.

Thus, to get a more accurate evaluation of the annual losses on a feeder, the losses may be calculated for every hour of the year and then paired up with hourly energy prices to determine the actual cost of the losses.

This paper is organized as follows: Comparison of old and new methodology is discussed in section 'Old methodology and new methodology'. The differences in accuracy are quantified for a 31-feeder system in section 'System model'. In section 'Quantification of differences between loss and cost calculations' an example is presented of how calculating the cost of losses more accurately may sway the decision to accept or reject a project. Finally, conclusions are drawn in section 'An investigation of the impact of cost calculation accuracy on electric power distribution system planning decisions'.

Old methodology and new methodology

Load factor loss (LFL) method

With only peak demand information and annual energy consumption information available, the planning engineer may use a method of calculating losses that is designated the "load factor" method. The method works as follows. The total annual energy consumption (total kilowatt-hours consumed by all customers on the feeder during the course of a year) is determined by totaling the meter readings of all customer meters on the circuit. This energy consumption is then divided by the number of hours in a year (8760 if not a leap year) to get the average load:

$$P_{avg} = \frac{E_{annual}}{8760} \quad (1)$$

For a long time, for many feeders, the only demand data available to a planning engineer was the maximum demand on the feeder (taken from the maximum value on a circle chart reading), and perhaps the maximum demand at certain large customers who had demand meters. With the peak load known, a "load factor" may be calculated as follows:

$$LF = \frac{P_{avg}}{P_{peak}} \quad (2)$$

A load flow analysis program can calculate the losses on the feeder at peak. Since the losses through a conductor are proportional to the square of the current, the average losses are estimated using the square of the load factor.

$$Loss_{avg} = Loss_{peak} * LF^2 \quad (3)$$

Then, the total losses may be calculated by multiplying the average hourly losses by the number of hours in the year.

$$Loss_{total} = Loss_{avg} * 8760 \quad (4)$$

Finally, the cost of these losses would be calculated based upon the expected cost of a kilowatt of energy which is the LMP in this paper. $C_{expected}$ in $/kW h

$$C_{total} = Loss_{total} * C_{expected} \quad (5)$$

The most significant problem with this calculation appears in Eq. (3). Willis notes that this equation will "underestimate losses' costs slightly" [12]. Although Willis himself does not stop to explain the reason for his statement, the reason may be seen as follows. While it is true that the losses are proportional to the square of the current, accurately calculating the total losses would require applying the square at each hour and then averaging the results (square-then-average), rather than the opposite sequence of average-then-square used in the load factor calculation. The difference in computation can be seen in Table 1.

Averaging and then squaring can be proven by Jensen's inequality [13] to produce a smaller value than squaring and then averaging, as illustrated in Eq. (6).

$$\frac{\sum x_i^2}{n} \geqslant \left(\frac{\sum x_i}{n}\right)^2 \quad (6)$$

Measurement based loss (MBL) calculation

To avoid the problem of averaging-then-squaring, one would simply need to calculate the losses at every hour. With all of these "square" terms, one could use equation 4 above to calculate the total annual losses. Of course, there is no need to average and then multiply by the number of hours—one could sum the individual hourly losses directly to get the same result.

Of course, calculating the losses at every hour would require knowing the load at every hour. While a small yet growing number of feeders have advanced metering infrastructure which provides the demand at each load point at each hour (or higher resolution), such detailed load information will not be available on all feeders

Table 1
Comparison of methods.

Method	Formulation
Square-then-average	$\frac{\sum x_i^2}{n}$
Average-then-square	$\left(\frac{\sum x_i}{n}\right)^2$