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Probabilistic methodology for Technical and Non-Technical Losses estimation in distribution system

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ABSTRACT

This work contemplates the development and application of a probabilistic methodology for the Technical and Non-Technical Losses estimation in a feeder in the presence of load variations of a large distribution system. Due to such variations in load, the feeder losses are also characterized as random variables which are related to statistical moments, such as mean and variance. Comparing the Measured Energy consumption in the feeder with the Billed Energy by the utility plus the Technical Losses, the energy balance is made and the Non-Technical Losses are estimated. Along a feeder, meters are installed allowing its division into sub-networks, therefore, the Non-Technical Losses of each circuit are estimated with greater precision. This methodology is useful in countries that Smart Grids are far from reality and the resources are scarce. A real system was used as a case study for the Probabilistic Energy Balance developed.

1. Introduction

The electrical losses represent a significant share in the cost matrix of distribution systems and, therefore, have always had major highlight in planning studies. For utilities, due to the management model which emphasizes the productivity and profitability, a reduction in the costs can be achieved by improving the system performance. In this sense, the decrease of Technical Losses of the system, as well as improving the efficiency of system operation are desired goals for utilities and are required by the Regulatory Agency. Therefore, Technical Losses should be reduced to its optimal level, i.e. the level at which no additional investment is economically justified.

Thus, this work aims to develop a new methodology for the probabilistic estimation of Technical[1] and Non-Technical[2] Losses in a feeder in the presence of load variations of a large distribution system. The proposed model determines the sensitivity of voltage and Technical Losses variations in each bus without the need of a new power flow solution. After determining the actual amount of Technical Losses from periodic measurements, the Non-Technical Losses can be segregated of the total system losses. Since both the demand and the Technical Losses are being modeled as random variables, the separation of the Non-Technical Losses results in a relation of probability density functions involving convolution operations between these functions.

In Section 2, a brief state-of-the-art review on Losses Calculation is presented. Section 3 details the developed probabilistic methodology that is applied, in Section 4, in the study case of a real system. Lastly, Section 5 presents some conclusions.

2. Losses Calculation

Regarding the methods for determining losses in transmission and distribution systems, there is a wide variation in the processes adopted. In transmission systems, losses are estimated mainly by power flow studies or energetic balance. In distribution systems, the vast majority of utilities use procedures such as network management, power flow, statistical processes, and geometric models, among others [1].

According to [1,2], the choice between a more developed and a simplified methodology depends both on the available data and the objective. The more elaborate methods (network management and load flow, for example) present results that should be closer to reality, and can even be used for individual and localized analysis, but they require an extensive database and constantly updated

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[1] Technical Losses occur naturally and consist mainly of power dissipation in electricity system components such as transmission and distribution lines, transformers, and measurement systems.

[2] Non-Technical Losses are caused by actions external to the power system and consist primarily of electricity theft, non-payment by customers, and errors in accounting and record-keeping.

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records. The simplified methods (statistical processes, geometric model, etc.) require a reduced volume of data and provide the estimated loss quickly; however tend to produce satisfactory results only when applied in a general form.

Several simplified models of loads and respective modes of loss calculation by distributed load and geometric areas modeling (rectangular, triangular, and trapezoidal) with constant load density are developed in [3]. Such techniques are useful for rapid calculations, obtaining estimated values. The methodology used by several Brazilian utilities consists in calculating the Technical Losses by segment in the distribution system within a policy of periodical calculations (monthly) with the use of a software, as stated in [4].

In any system, making the difference between Total Loss and Technical Loss (calculated/estimated) returns an estimation of the Non-Technical Losses [1,2,4].

3. Probabilistic methodology

In this work, the development of a new analytical model of the Technical Losses variation versus load change is proposed. This model estimates adequately the sensitivity of the voltages and their respective angles to the variation of the load including the electrical losses, and also includes a new analytical formulation sensitivity to losses with the variation of load. Thus, through the variation of the loads, the variation in the Technical Losses can also be estimated, which is used in the Probabilistic Energy Balance for calculating the Non-Technical Losses.

3.1. Installation of meters

Once defined the feeder to be studied, strategic points for the installation of meters are chosen. In a general way, being M the number of meters installed, the network can be divided into M sub-networks. Each sub-network has as a start point one of the meters, being the meter downstream, modeled as a load.

3.2. Network reduction and sorting routine

In order to apply the methodology in larger distribution networks, algorithms to reduce the number of electrical points (nodes) were developed. It consists of grouping the points where there is no load, which serves only to denote the spatial layout of the feeder or consist in some equipment with no influence in this analysis, such as switches or fuses. The lengths of the grouped sections are combined to maintain the real values of resistance and reactance of the total section. After the reduction, a reordering of the points is made in order to optimize the performance of back/forward sweep methods – as the DistFlow method [5–7] – which was used in this work.

With the use of these network reduction and sorting routines a high gain in computational time and processing is obtained without altering the results.

3.3. Sensitivity matrix of voltages in relation to the load variation

The objective is to calculate the voltage variation sensitivity in each distribution network bus (node) when there is a variation in its demand, without requiring a new power flow solution.

The analysis of the voltage sensitivity in relation to the load variation is based on the DistFlow method and was developed by [8]. In order to improve the accuracy of results and reduce the computational time, some modifications and optimizations were introduced, such as the use of graph theory [9] and inclusion of losses in the calculation.

The voltage sensitivity calculation with the load variation without losses is used as an initial step for the iterative calculation of a new sensitivity matrix with the inclusion of the loss (named MSit). Therefore, the next step is to establish the desired accuracy for the update of the losses of MSit. The accuracy influences considerably in the computational time that the algorithm takes to be executed.

The iterative process consists of n backward iterations, through the end of the feeder to the beginning, in order to update $\partial Pac_i/\partial P_j$ and $\partial Qac_i/\partial Q_j$, which in the sensitivity matrix without losses were binary matrices equal to the Reachability Matrix [9], and $\partial Qac_i/\partial P_j$ and $\partial Pac_i/\partial Q_j$ that previously were null matrices. The accumulative active (Pac) and reactive (Qac) powers are given by:

$$Pac_i = P_i + Pac_{i+1} + LPac_{i+1} \quad \text{and} \quad Qac_i = Q_i + Qac_{i+1} + LQac_{i+1} \tag{1}$$

Differentiating these expressions in relation to the active power (P) results in:

$$\frac{\partial Pac_i}{\partial P_j} = \frac{\partial (P_i + Pac_{i+1} + LPac_{i+1})}{\partial P_j} = \frac{\partial P_i}{\partial P_j} + \frac{\partial Pac_{i+1}}{\partial P_j} + \frac{\partial LPac_{i+1}}{\partial P_j} \tag{2}$$

$$\frac{\partial Qac_i}{\partial P_j} = \frac{\partial (Q_i + Qac_{i+1} + LQac_{i+1})}{\partial P_j} = \frac{\partial Q_i}{\partial P_j} + \frac{\partial Qac_{i+1}}{\partial P_j} + \frac{\partial LQac_{i+1}}{\partial P_j} \tag{3}$$

where the active ($LPac$) and reactive ($LQac$) losses are given by:

$$LPac_i = \frac{R_i \cdot (Pac_i^2 + Qac_i^2)}{V_i^2} \quad \text{and} \quad LQac_i = \frac{X_i \cdot (Pac_i^2 + Qac_i^2)}{V_i^2} \tag{4}$$

so:

$$\frac{\partial LPac_{i+1}}{\partial P_j} = R_i \cdot \left(\frac{2}{V_i^3}\right) \left[\left(Pac_i \cdot \frac{\partial Pac_i}{\partial P_j} + Qac_i \cdot \frac{\partial Qac_i}{\partial P_j} \right) \cdot V_i - (Pac_i^2 + Qac_i^2) \cdot \frac{\partial V_i}{\partial P_j} \right] \tag{5}$$

$$\frac{\partial LQac_{i+1}}{\partial P_j} = X_i \cdot \left(\frac{2}{V_i^3}\right) \left[\left(Pac_i \cdot \frac{\partial Pac_i}{\partial P_j} + Qac_i \cdot \frac{\partial Qac_i}{\partial P_j} \right) \cdot V_i - (Pac_i^2 + Qac_i^2) \cdot \frac{\partial V_i}{\partial P_j} \right] \tag{6}$$

Similarly, the accumulated active and reactive powers derivatives in relation to the reactive power (Q) can be calculated. The process continues until there is convergence of the voltage derivatives ($\partial V_i/\partial P_j$ and $\partial V_i/\partial Q_j$) to the accuracy set.

3.4. Loss sensitivity in relation to the load variation

In order to determine a relationship that denotes the sensitivity of the total Technical Loss in the feeder to the load variation, the total Technical Loss, LS, is given by:

$$LS = LP + j \cdot LQ = \sum z_i \left|\left| \frac{E_{i-1} - E_i}{z_i} \right|\right|^2 = \sum y_i^* ||E_{i-1} - E_i||^2 \tag{7}$$

where z_i is the impedance between the buses $i-1$ and i, and y_i is the admittance between the buses $i-1$ and i. Separating the above expression in their real and imaginary parts, since $y_i = g_i + j \cdot b_i$ results in:

$$LP = \sum g_i ||E_{i-1} - E_i||^2 \quad \text{and} \quad LQ = \sum b_i ||E_{i-1} - E_i||^2 \tag{8}$$

where g_i is the conductance between the buses $i-1$ and i, and b_i is the susceptance between the buses $i-1$ and i. Now, notice that the square of the voltage drop modulus in the lines is given by:

$$||E_{i-1} - E_i||^2 = V_{i-1}^2 + V_i^2 - 2V_{i-1} \cdot V_i \cdot \cos \beta_i \tag{9}$$

Differentiating the above expression in relation to P_m and Q_m: