Electric power losses in distribution networks

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Abstract: According to international organizations such as the Energy Information Agency (EIA) and the Inter-American Development Bank (IDB), reducing electricity losses can contribute to achieving the objective of universal access to modern energy sources. The reduction in the levels of losses would also imply a reduction in greenhouse gas emissions, as well as a reduction in electricity tariffs for the final consumer. This research seeks to analyze the levels of electrical energy losses in distribution networks in order to propose possible solutions that allow the electrical power system to provide stability in the equipment that is part of the network, leading to a cost analysis in the future within the planning of the country's electrical network.

Keywords: energy, system, level, network, stability, stability, analysis, tariff.

1. Introduction

The losses of electrical energy in distribution networks have had a significant value, within the decompensation of power systems, and in the great majority of cases, they have not been treated in the best possible way. These losses represent short and long term, operational failures of distribution systems, which cause higher internal costs thus generating a serious impact on electricity rates and on the economy of the companies; That is why this research proposes an initial diagnosis from energy variables within a system under study, in order to identify the possible causes that produce losses, and then make a quantitative assessment and control that leads to propose necessary considerations to reduce the levels of losses in the distribution network (S. P. Cañar Olmedo,2007).
The investigation of electrical energy losses is carried out for the optimization of network operators, which takes into account compliance with the conservation of energy from the power supply to the final consumer who are the customers, thus seeking to generate strategies to mitigate this energy difference between the start process to the end of each circuit of the system (Toledo, 2012).

2. Methodology for analysis and definition of energy losses in distribution networks

This section presents the aspects to be considered in the analysis and definition of technical and non-technical electrical energy losses, analyzes the mathematical methods of analysis such as simple random sampling, measurement of variables and multiple linear regression model in order to propose possible measures for their mitigation, and establishes a methodological design where, through the study of information, an analysis of both technical and non-technical losses will be carried out.

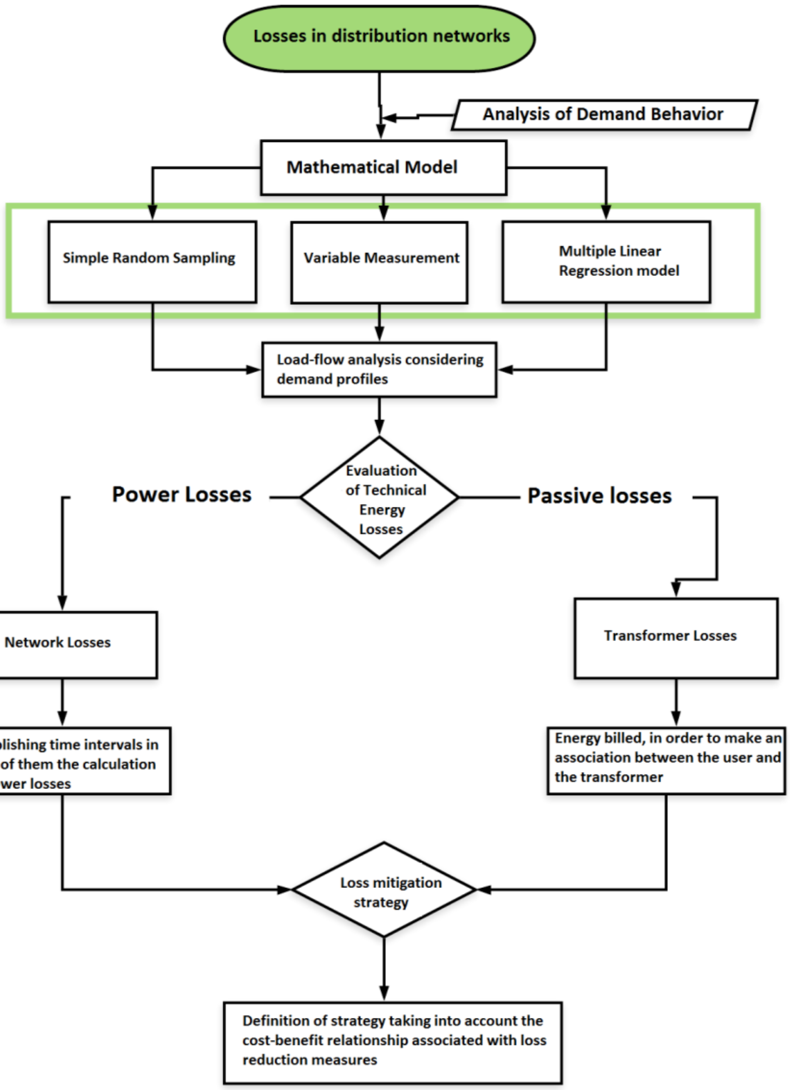

Figure 1. Flowchart of losses in distribution networks

Simple Random Sampling

In this methodology, the population to be sampled is represented by the total number of electrified sectors, being an electrified sector, an entire low voltage network fed by a distribution transformer. In an electrified sector there are services to users (customers) and people without contracts with the company connected to the power grid (non-customers), therefore the measurement of variables in the sampling is directed to any point of consumption of electricity, whether or not a customer of the company[1]

The following terms are defined for the sample, as shown in Figure 2:

- Service: Interconnection contract with energy meter.
- Theft or robbery: Users connected to the low voltage network but who do not have a valid interconnection contract, i.e., they do not have an energy meter, or they have an energy meter but no interconnection contract.

- Fraud: Users connected to the low voltage network who have a valid interconnection contract, but whose electrical installation or meter is altered in such a way that the energy measured is less than the actual energy consumed by the user.
- Dwelling: Place with domicile where none, one or more services are located.
- Sector: A low voltage network that is fed by a transformer. This sector interconnects dwellings, workshops, houses, etc., with or without interconnection services.

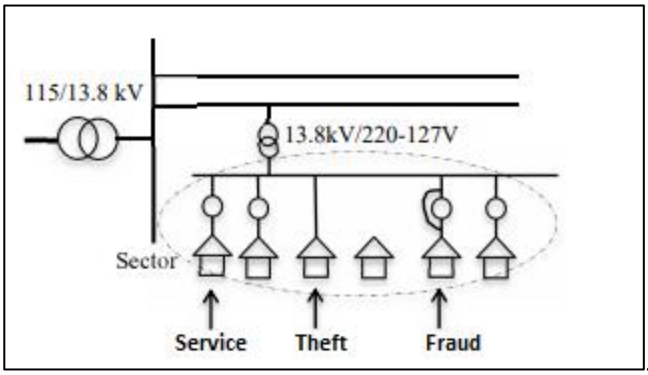

Figure 2. Distribution system schematic [2]

To determine what proportion of thefts and/or frauds are committed in the company, and considering these variables with normal distribution, the sample size is given by:

$$n = \frac{\left(Z\frac{\alpha}{2}\right)^2 \text{ pq N}}{\left(Z\frac{\alpha}{2}\right) \text{ pq} + E^2(N-1)} \quad (2)$$

where n is the sample size, Zα / 2 is the value of Z to the right of which there is an area α / 2 for normal distribution, being normally α =0.05 for a confidence level of 95%, p is the value of the proportion of theft and/or fraud in the company and q=1-p ; N is the total number of elements in the population (electrified sectors) and E is the specified sampling error, which usually takes a value less than 0.10, and is often set between 0.03 and 0.04 (3% and 4%). In case the p value is not known, the result of a previous sample, a pilot study, or the value of 0.5 can be used, which guarantees that the greatest variance of the proportion is obtained, therefore, the largest possible sample size[2].

If the company has different service areas, the sample size in each area is obtained proportionally to the number of electrified sectors in each one of them.

Measurement of variables

The measurement of variables is carried out only in low voltage networks, discarding medium and high voltage electrical systems since it is difficult to commit fraud or energy theft at these voltage levels. The variables to be measured for each electrified sector are shown in Table 1. Table 2 presents the classifications of categorical variables, knowing that binary variables have only two possible values: 1 if the condition exists, and 0 if it does not exist.

Table 1. Variable to be measured by electrified sector

Name	Description	Type
$y1$	Thefts by sector	Continuous
$y2$	Fraud by sector	Continuous
$x1$	Type of network	Categorical
$x2$	Network conditions	Categorical
$x3$	Meters with seals	Continuous
$x4$	Meters without seals	Continuous
$x5$	Damaged meters	Continuous
$x6$	Homes with access to the network	Continuous
$x7$	Type of population	Categorical
$x8$	Socioeconomic level	Categorical

Table 2. Classification of categorical variables

Name	Description	Classification
$x1$	Type of network	Bare (1), isolated (2) and underground (3)
$x2$	Network conditions	Good (3), regular (2) and bad (1)
$x7$	Type of population	Urban (3), suburban (2) y rural (1)
$x8$	Socioeconomic level	High (1), Mean (2) and low (3)

The variables x'_s are measured to explain y'_s (energy theft and fraud), i.e., for this study, the x'_s are the independent variables and the variables y'_s are the dependent variables. The first 6 variables x'_s are controllable by the company, while the last 8 are beyond the company's control[3]

In the selected electrified sectors, it is advisable to make revisions only in the measurement equipment that shows evidence of possible fraud, such as those with broken seals. The measurement of some categorical and binary variables is subjective and depends on the criterion of the personnel in charge of measuring the sample[4].

In order to keep track of the measurements taken during sampling, it is necessary to record certain general data of the energy consumption points that are sampled, such as: name of the person where the sample is taken, home address, town, tariff (if applicable) and meter number (if applicable)[2].

Multiple Linear Regression Model

Prior to the regression study, a correlation analysis must be made between the measured variables in order to discard those variables that are not independent of each other, to avoid noise in the mathematical model obtained. This study is done by determining the correlation coefficient between each pair of variables; and in case this value is higher than 0.7, a detailed review between the two variables should be made to rule out dependence between them. If there is dependence between a pair of variables, one of them should be discarded for the linear regression analysis.

With a linear regression equation, for any given set of values, for any given set of values $X_{1,}X_2, \ldots, X_r$, the mean of the distribution of the Y_I is given by:

$$Y_{I=}\,\beta_o + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_r X_{ir} + u_i \quad (3)$$

Where u_i is a normal random error variable with zero mean and constant variance for all i. The errors are independent of each other. The model to be used for the multiple linear regression is done using matrix notation, leaving eq. (3) as follows:

$$Y = X\beta + U \quad (4)$$

Proceeding to write the estimators to approximate the true population equation as shown in eq. (4), it is found that the variances are given by:

$$e^T = [\ e_1 \quad e_2 \ldots e_n] \quad (5)$$

Where the elements of the vector e are given by $e_i = Y_i - ý_i$. Then the problem of obtaining the ordinary least squares estimators is solved by minimizing the $Error = e^T e$ with respect to variable b (predictor of β). In developing the above, the following normal equation is found:[5]

$$X^T Y = X^T X b \quad (6)$$

Solving eq. (6) for the variable b, it was found that:

$$b = (X^T X)^{-1}\, X^T Y \quad (7)$$

Where b is a column vector containing the n least-squares estimators of the multiple linear regression.

To determine the quality of the model found it is necessary to find the adjusted coefficient of determination (RAdj), which if it is higher than 0.7 is acceptable. This coefficient is defined by:

$$R^2{}_{Adj} = 1 - \frac{(n-1)\sum_{i=1}^{n}(Y_i - ý_i)^2}{(n-r-1)\sum_{i=1}^{n}(Y_i - \bar{y}_i)^2} \quad (8)$$

Where ȳ is the arithmetic mean, n is the number of data and r is the number of parameters β, including β0.Having a good coefficient of determination to know how adequate the obtained regression model is, is necessary but not sufficient. Hypothesis tests must be performed on the values of the estimator coefficients to determine their validity, there are hypothesis tests with the t-statistic or with the p-value[2].

In this case, there are two output variables such as energy theft (y1) and energy fraud (y2) and 14 independent variables x'_s . Mathematical models can be obtained for each output variable independently or for the sum of both variables, which implies a large number of possible mathematical models, but only those with higher determination coefficients are taken. The regression analysis process starts by considering only one independent variable at a time, recording the coefficients of determination for each case. Then it continues with two independent variables, and so on until all the independent variables are considered at the same time[2].

3. Aspects to evaluate in the analysis of technical energy losses:

The methodology for the evaluation of technical losses allows to have the physical situation of the system, a study of technical losses in a feeder includes the following aspects:

- Losses in primary networks
- Losses in secondary networks
- Losses in distribution transformers
- Losses in other components (service connections, street lighting and meters)

The evaluation of technical losses depends on the component under study, for example, for medium voltage lines within the feeder, it is based on power flows and calculations using their load curve; for distribution transformers, the results of manufacturers' tests, the use of recording equipment and calculations according to their behavior will be used; for the other components involved, their physical effects will be analyzed[1].

For the power losses, the procedure of the voltages at the feeder nodes is followed, performing power flows and a comparison with the historical power data of the system. The resistive losses in energy, from the power losses, can be obtained from the information of losses at maximum demand, calculating the losses at other values of demand with the following expression:

$$PLi = \left[\frac{(DDi)(cos\emptyset\ max)}{D\ max(cos\emptyset i)}\right]^2 PD\ max \quad (9)$$

Where PLi the losses of the demands of the interval i, DDi is the demand in the interval i, $D\ max$ Maximum demand, $cos\emptyset\ max$ is the power factor at maximum demand, $cos\emptyset i$ is the power factor in the interval i and $PD\ max$ losses at maximum demand.

On this basis, a load curve of the losses is obtained from which the loss energy is obtained. For a correct evaluation of losses, measurements must be taken at different points of the system and load profiles are used, which are nothing more than records of demands over long periods of time.

Losses in primary networks

Losses in a medium voltage or primary network are determined by establishing time intervals and in each of them the calculation of power losses, the contribution of each interval allows determining the total energy losses[1].

The following expression is used for technical energy losses:

$$L_{TP} = \sum_{j=1}^{Nd}\sum_{K=1}^{24} W_{PjK} \quad (10)$$

Where L_{TP} are the technical losses in primary circuits [kWh], W_{PjK} are the Technical Losses in primary circuits for a day j and an hour k [kW], *Nd* is the number of days of the study considered, K is the number of hours, j is the number of days.

his method can be applied for different day and any time, which allows to make relationships for different days in a month if it is the case, and thus a comparison, of the losses for different days.
By means of a flow made in the study, which is an annual flow, it will allow to know more precisely the behavior of the feeder, its voltage drops, load balance and losses, this behavior of the load will indicate in which place the highest rate of losses is produced.[6]

Losses in secondary networks

For the evaluation of losses in secondary networks, the same criteria are used as for primary or medium voltage networks, i.e., to evaluate them based on the maximum demand. With the same methodology of a primary system, i.e., based on energy consumption at different points of the system at maximum demand, the study can be performed in the secondary network.[3]

First, a single-line diagram of the secondary networks of the feeder's study groups is obtained, in which the electrical parameters are specified, such as number of phases, conductor size, etc. This topology is provided with the SID program which provides a geographic base of the feeder with its characteristics.

For an evaluation of a secondary network, the maximum demand of the distribution transformer (W, VAR) is necessary for the realization of the load flows. Estimate the maximum demand at each point of the secondary circuit associated with the transformer.[7]

After the above-mentioned procedures, the voltages of the different points and the losses of the circuit (use load flows) are calculated. The energy losses are calculated by means of:

$$L = F_L {P^{max}}_L \; T \quad (11)$$

Where L is the energy loss [kWh], F_L loss factor, ${P^{max}}_L$ the power losses at maximum demand [W], T is the time period [h].

Distribution transformer losses

It is very common to calculate the losses of transformers associated with primary or secondary circuits, using the energy billed to make an association between the user and the transformer.

For a loss estimation in distribution transformers, a methodological procedure is necessary as follows:

The starting data is the result of transformer laboratory tests concerning core losses and resistive losses, i.e., the information from the results of no-load and loaded tests. The tests are represented as follows:

Specified losses for the measurement test due to load.

Table 3. Resistive losses in Transmission and Distribution

Nominal Power [KVA]	10	15	25	37.5	50
Specified losses [W]	164	262	392	466	895

A frequent cause of failure is due to high heating as a result of: Tap changer not in the rated position, loose connections inside the transformer, insufficient conductor cross-section to short-circuit the low-voltage winding.

4. Strategies for loss reduction and control.

A list of conventional and smart grid approaches to technical loss reduction is presented. Methods to reduce losses at the distribution level are numerous, e.g., capacitor placement, reconductoring, voltage upgrading, transformer load monitoring, and reconfiguration, among others. Table 4 provides information on the benefit/cost ratio associated with various loss reduction measures. From Table 4, it is evident that both distribution transformer load management and reconfiguration offer the highest benefit/cost ratio as they are implemented with minimal expense, however, it is important to note that the actual ratios are highly system dependent[8]

Table 4. Benefit/cost ratio for different loss reduction measures

Measure	Benefit/cost ratio
Compensation reactive	2 a 8
Reconductive	0.6 a 7
Voltage enhancement	1.5 a 3
Load management transformer	1 a 15

Distribution system load losses are a function of the square of the current. Therefore, one way to reduce technical losses is to reduce the absolute value of the line current by reducing its reactive component, i.e. improving the power factor. This can be achieved by installing fixed and switched capacitor banks. This procedure is commonly known as reactive compensation. Since capacitors can decrease the reactive power demand by supplying VARS locally, line currents are reduced from the capacitor bank locations to the generation equipment, which generates the following economic benefits:[3]

- Generation capacity released.
- Transmission capacity released.
- Distribution substation capacity released.
- Reduced energy losses.
- Reduced voltage drop and, consequently, better voltage regulation.
- Released feeder and associated apparatus capacity.
- Deferred capital expenditures due to system upgrades and/or expansions.
- Increased revenue due to voltage improvements.

Conventional switched capacitor banks allow for stepped reactive power compensation. Distributed generators (DG) and devices such as SVC and STATCOM can allow more versatile and continuous (after reactive power charging) voltage compensation and control (even during dynamic conditions). Although voltage regulation using DG is not widely used or allowed by some of the existing regulations, there is a lot of activity in this area, including ongoing research and revisions to the standard. Therefore, it has the potential to become a more common distribution system operating practice.[8]

For the reconduction of primary and secondary lines it is noted that the distribution load losses are directly proportional to the series resistance (R) of the system components, another way to reduce the technical losses is to reduce R. This can be achieved by replacing the existing primary and secondary lines with conductors of larger cross section. This procedure is commonly referred to as reconductoring. For example, the experience of a municipal utility that implemented a reconductoring project. The total losses reported by this utility are approximately 2%. This value is considerably lower than that of most utilities in the same region, which ranges from 4 to 13%. The benefit/cost ratio associated with reconductoring depends on the system. Additional benefits provided by reconductoring are the improvement of the voltage profile due to the reduction of voltage drop along the feeder and the availability of additional capacity for load transfer, either from or to neighboring feeders. The latter also has a positive impact on system reliability[8].

Distribution system losses can also be reduced by increasing the primary line voltage; this is known as voltage upgrade or voltage conversion. Fig.6, shows an example of the estimated line current and active power losses for different operating voltages, current and loss reductions are evident. Additional benefits include increased feeder capacity and reach, i.e., greater ability to serve customers located at farther distances from the substation. A potential drawback is decreased reliability, particularly in rural and wooded areas. In addition to requiring higher voltage class insulation, the voltage upgrade may also involve replacement of cross arms, poles, etc.

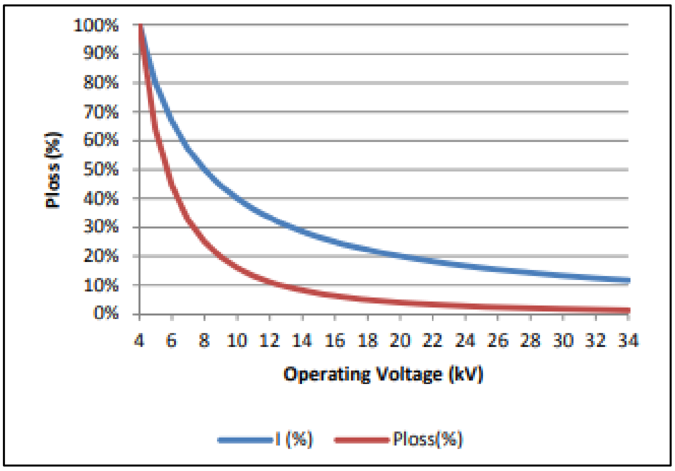

Figure 2. Line current and active power losses (%) as a function of operating voltage (kV)[8]

In the case of reducing non-technical losses, these are mainly due to electricity theft, meter tampering and commercial system inefficiencies. These include: a) unmetered energy consumption (e.g., bypassing existing utility meters or directly touching secondary lines); b) meter accuracy tampering, e.g., by manipulating power and instrument transformer wires; and c) meter reading and billing errors, e.g., inaccurate estimation of energy consumption of customer facilities located at remote sites, unmetered utility facilities (substations and power plants), etc.

Alternatives to reduce technical losses through more efficient and widespread metering include: Installation of meters for all customers and facilities, regardless of customer type, facility type (e.g., ancillary services, substations, etc.), or tariff type (there may be customers with special tariffs, e.g., free). This allows all energy delivered by the system to be measured and losses to be accurately calculated. Also Installation of prepaid meters. More than 40 countries have implemented prepaid meters in their markets. Examples include the United Kingdom, with approximately 3.5 million consumers, and South Africa, with more than 6 million meters. Prepaid meters allow customers to purchase in advance the monetary equivalent of the amount of energy to be consumed. The meters inform consumers when most of the credit energy has been consumed, and then the consumer purchases additional energy. International experience has shown that prepaid meters are a good alternative to reduce non-technical losses due to billing and commercial irregularities[8].

Finally, installation of macro-metering to measure and calculate technical and non-technical losses. The macro-metering strategy (also known as collective metering, master metering or totalizing metering) requires the installation of global meters (e.g., on the low voltage side of distribution transformers). In this way, the total energy delivered can be compared with the energy billed by the utility, a solution known as energy balancing, which allows the utility to locate, detect and control non-technical losses. International experience with macro-metering has been very satisfactory. For example, an 8% reduction in non-technical losses (from 25% in December 2003 to 17% in June 2006) by implementing a meter totalizer project has been very satisfactory[9].

In the case of secondary lines and service drops, the replacement of conventional cables with anti-fraud conductors, the objective of this alternative is to restrict or make it difficult for consumers to access secondary lines. For example, in areas known for electricity theft, low-voltage coaxial or preassembled cables are used instead of conventional conductors. In addition, service drops are replaced by an anti-fraud cable, preventing access to the phase conductor by piercing or cutting the insulation. The phase conductor is protected by the neutral conductor, which has a concentric pattern around the insulation. Therefore, if an unauthorized connection is attempted, a short-circuit occurs, interrupting the service. This cable is mainly used for single-phase loads, and its effectiveness has been reported in international literature. For example, the reduction of total losses by approximately 16% by implementing a portfolio of solutions that included the use of anti-fraud cable[8].

In utility information systems, georeferencing the distribution system with standard GIS software and Customer Information Systems (CIS) is vital to the reduction of non-technical losses. Through GIS, the utility can geographically relate each customer to its respective secondary system, distribution transformer, feeder and distribution substation. CIS handles customer energy consumption and billing information[10]. Both systems facilitate the calculation of accurate energy balances and the monitoring and location of system losses. In addition, utilities are moving towards the implementation of DMS, which allows optimizing system operation to minimize technical losses, as well as collecting data that can be used to estimate and locate non-technical losses. For example, it presents the application of a state estimator (integrated in a DMS) to determine the areas with the highest amount of non-technical losses in a radial distribution feeder.[11]

5. Conclusions

The efficiency of the distribution system can be significantly improved by controlling and reducing technical and non-technical losses. Furthermore, in a company, distribution engineering is of great importance for the optimization of the electrical system, since having a certain operation, design and planning of the networks improves efficiency and increases income.[12]

On the other hand, with these models the most influential variables in the existence of theft and fraud in the company are known, which allows establishing strategies to minimize the impact of these illicit activities and to control or reduce them in the case of non-technical losses. In addition, the level of system losses differs in industrialized and developing countries. Interestingly, non-technical losses are not a problem exclusive to developing countries. Given the higher energy consumption, the relatively low rates and system losses in an industrialized country may have a similar absolute monetary value to that due to high system losses in a developing country. For example, electricity theft accounts for 3% of system losses and approximately $6 billion annually in the United States, while in India it corresponds to 30% and $4.5 billion.[9]

On the technical losses side, the analyses carried out with the purpose of improving the operation of the network will also allow generating the loss indexes for the diagnosis and discrimination of technical losses in each component of the network, so it is possible to propose reduction plans for each subsystem, as has been demonstrated with the study presented. Therefore, the improvement in the energy efficiency of the industry had the advantage of the approach suggested above, which can be quantified with a study of the distribution system from transformer, feeder and even the utility.

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