Technical and Economic Analysis for the Reduction of Losses in Distribution Systems

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***Abstract*—This paper presents the results achieved following the application of a new methodology for the calculation of technical losses in segments of the distribution system and compares them to the results achieved through other methodologies. The article presents a comparison between the direct calculation of energy loss based on the load curve and the indirect calculation based on the maximum loss demand and on the loss factor, thus showing how the indirect method can lead to meaningful errors. Moreover a software to perform a technical-economic analysis of possible interventions in the network was developed through graphic displays, aiming at the reduction of losses.**

***Index Terms*--demand losses, energy losses, technical losses, load curve.**

I. Introduction

On previous papers [4] [5], the authors presented a new methodology for the calculation of technical energy losses and demand in segments of the distribution system.

A new computational system enclosing two main modules was developed. The first one is used for the calculation of technical losses in specific networks. The calculation is hierarchically carried out, e.g. once a given substation is selected, the losses within that substation and in every other downstream component are calculated.

By applying such module either for the whole company's distribution system or for a meaningful part of it, a loss index is obtained for each segment. Such indices are then transferred on to the second module, which in turn aims at carrying out the balance of the overall system energy by making use of the energy data on the supplying borders and the total billed energy monthly. Energy losses are thus obtained for each system segment and non-technical losses are estimated.

Technical losses are obtained with the help of specific procedures for each component, using recorded network data, billing data and typical load curves. Typical load curves were determined in a former study [2], where residential consumers were divided into consumption groups while commercial and industrial consumers were divided into their lines of business. For each consumption group and each line of business, a typical pu load curve was established for the monthly average demand, which allows for obtaining a load curve from the monthly energy.

This article shows the results achieved by applying the methodology to a real distribution system, and the comparisons to the results achieved by other methodologies. It will analyze the comparison between the direct calculation of energy losses to those indirectly achieved by the estimate of the loss factor based on the load factor, generally used by other methodologies. As will be later seen, the use of indirect methods may lead to meaningful errors when obtaining losses in energy terms.

The application of this methodology may allow for identifying regions and/or components, which bear high losses. Aiming at performing technical-economic analysis of possible interventions to reduce losses, a software to simulate some works within the network was developed.

II. Methodology

A. Calculation of Losses in each Segment

The methodology is hereinafter presented for the calculation of the technical energy losses in each segment of the distribution system. It may be found in details in other papers [4] [5] [6].

1) Energy Meters

The losses in energy meters are basically iron losses in voltage coils and might thus be considered approximately constant, for they do not depend on the load.

This way, the energy loss in meters (e_{em}) will be obtained by:

$$e_{em} = \frac{p_{avg} \cdot N_{em} \cdot (i_1 + 2i_2 + 3i_3) \cdot T}{1000} \text{ [kWh]} \quad (1)$$

where:

p_{avg} - average loss in each element (voltage coil) of the energy meter [W];

N_{em} - total number of meters;

i_1 - percentage of single phase meters;

i_2 - percentage of double phase meters;

i_3 - percentage of three phase meters;

T - given time interval [h].

2) Customer Connections

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In order to calculate losses along customer connections, a typical connection line according to the corresponding consumption class was defined, at a pre-established resistance and length for the conductors.

Thus, the daily energy loss (e_{cc}) along the connection line of a consumer will be obtained by:

$$e_{cc} = \frac{n \cdot R \cdot L \cdot \Delta t \cdot \sum_{t=1}^{N_t} I_t^2}{1000} \text{ [kWh]} \quad (2)$$

where:

n - number of conductors in the customer connection, where there is current flowing in normal conditions;

R - resistance in the typical line [Ω/km];

L - average length of the typical line [km];

I_t - current along the line over the t period of day [A];

Δt - interval span of the load curve [h];

N_t - the number of intervals in a day.

The current value for each period of the day will be obtained based on the monthly energy consumption of the consumer and his/her typical daily load curve.

The k value depends on the consumer’s type of connection (single phase, double phase or three phase) and on the connection of the transformer feeding it.

3) Low voltage network

The model proposed allows for evaluating the losses along all branches within the low voltage network, according to both the phase and the loading on the distribution transformers.

In order to obtain the currents on each phase for each branch within the network at a given moment of the day, the previously calculated consumers’s currents are accumulated. Following that, the daily energy losses within each network branch (e_{lv}) are obtained by

$$e_{lv} = \frac{1}{1000} \cdot \sum_{t=1}^{N_t} \left(\sum_{i=1}^{N_{cond}} \left(R_i \cdot I_{i,t}^2 \right) \right) \cdot \Delta t \text{ [kWh]} \quad (3)$$

where:

R_i - resistance of conductor i [Ω];

$I_{i,t}$ - current on i conductor within time interval t [A];

Δt - interval span of the load curve [h];

N_{cond} - number of conductors in the branch (including phase and neutral conductors);

N_t - the number of intervals in a day.

4) Distribution Transformer

After calculating the losses in the low voltage network, which has accumulated currents from the final branches to the start of the network, one determines the loading of each phase of the transformer regarding the daily load curve.

Given the rated power, the rated loss in the iron and the rated loss in the copper at full load for each transformer, one calculates the daily energy loss (e_{DT}) by:

$$e_{DT} = p_{fe} \cdot S_N \cdot 24 + p_{cu,pc} \cdot S_N \cdot \sum_{t=1}^{N_t} \left(\frac{S_t}{S_N} \right)^2 \cdot \Delta t \text{ [kWh]} \quad (4)$$

where:

S_N - rated power of the transformer [kVA];

S_t - transformer loading within interval t of the load curve [kVA];

p_{fe} - rated loss in the iron [pu];

$p_{cu,pc}$ - rated loss in the copper at full load [pu];

Δt - interval span of the daily load curve [h];

N_t - the number of intervals in a day.

It is major to highlight that each transformer may have a different type of connection, thus needing some specific formulation. Reference [6] presents some specific formulation for each distribution transformer according to its connection type.

5) Medium voltage network

The methodology proposed for the calculation of losses within the medium voltage network is analogous to that presented for the low voltage network.

In order to attribute the load to the medium voltage network phases, one needs the calculated load curve data for the distribution transformers, the load curves for the primary consumers and the load of public lighting. In order to calculate the power flow, one still needs data for capacitor banks, i.e. the connection point to the network, the rated power and the utilization span over the day.

Computation of daily energy losses for each branch of the medium voltage network is then given by equation (3).

6) Distribution Substation

The electric calculation of the medium voltage network results in the daily load curve of the feeder. The composition of the load curves of all feeders results in the load curve of substation transformers.

Given the transformer where each circuit of a substation is connected, one determines the load curve (by phase) for each transformer.

Given the rated power, rated loss in the iron and the rated loss in the copper at full load for each transformer, one calculates the energy losses in the distribution substations as in equation (4).

7) High Voltage Network

Losses within high voltage networks are calculated based on energy balance, from losses index determined by the application of a power flow program, using network-planning data. Such power flow calculation is to be carried out periodically in order to update the level of energy losses within the high voltage network.

8) Other Segments

The energy losses in other segments such as equipment (voltage regulators, capacitor banks), connections, losses due to leakages in insulators and to corona effect, among others, are evaluated as some percentage of the total technical losses calculated within the previous segments. Losses within these segments generally vary from 5 to 10% of the total technical losses.

B. Calculation of Loss Indices

After calculating energy losses in kWh, one can determine energy loss indices in each segment.

The loss index is always calculated either in relation to the energy entering the segment (upstream energy) or in relation to the energy leaving the segment (downstream energy) plus the energy loss within the segment as shown in (5). Figure 1 illustrates the energy flow through a segment.

$$e_L = \frac{E_L}{E_{upstream}} \cdot 100 = \frac{E_L}{E_{downstream} + E_L} \cdot 100 \ [\%] \qquad (5)$$

where:

E_L - energy losses [kWh];

$E_{upstream}$ - upstream energy (energy entering segment) [kWh];

$E_{downstream}$ - downstream energy within segment (energy leaving segment) [kWh];

e_L - energy loss within segment [%].

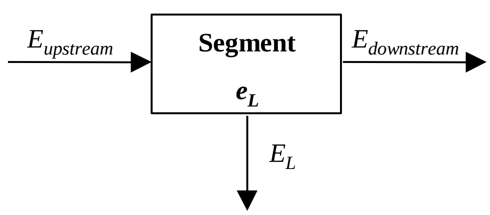

Fig. 1. Energy flow through segment.

III. Results and Comparison to Other Methods

The methodology developed was applied to a real distribution system composed of about 90,000 distribution transformers and low voltage networks and about 1,200 primary circuits.

Based on the results achieved, a comparative analysis was proceeded following other methodologies for the calculation of losses. The calculation of losses is generally carried out for the peak load in the network (demand losses). Later, energy losses are obtained in an indirect way as a function of the demand losses and the loss factor. For that matter, one looks into evaluating the loss factor through the load factor. An analysis over the influence of loss factor on the indirect calculation of energy losses, was performed by evaluating the adequacy and the errors derived from its application.

A. Energy Losses in each Segment

Table I shows the technical losses obtained in each segment, by applying the methodology described in this paper. The demand loss shown is the non-coincident demand loss, i.e. it represents the sum of maximum demand losses in each component considered.

TABLE I
TECHNICAL LOSSES IN EACH SEGMENT

Segment	Energy Loss (%)	Demand Loss (%)
Energy Meter	0.56	0.29
Customer Connection	0.27	0.83
Low Voltage Network	0.95	1.47
Distribution Transformer	2.75	2.45
Medium Voltage Network	0.94	1.43
Substation Distribution	0.59	0.57

B. Direct Calculation X Indirect Calculation

As mentioned before, methodologies generally calculate energy losses in an indirect way, i.e. from the demand loss at the peak hour and the loss factor. The loss factor (f_p) is estimated from the load factor (f_c) by

$$f_p = k \cdot f_c + (1-k) \cdot f_c^2 \qquad (6)$$

For load curves at a constant value over the day, $f_p = f_c$. For load curves bearing short duration of peak load, $f_p = f_c^2$. Real load curves lie within these two extremes. Industrial consumers tend to present f_p closer to f_c. Residential consumers in turn tend to present f_p closer to f_c^2. One often uses values between 0.15 and 0.30 for k. Equation (6) is only valid for each network interval and not for the network as a whole. In fact, each network branch bears a different loss factor, for each branch is submitted to a different load curve. When calculating the loss factor by equation (6), one incurs into errors, once the equation may not be applied for the whole circuit.

From the results obtained from the methodology described – which carries out energy loss calculation in a direct way, i.e. from the load curve in each component – this paper shows how the indirect calculation may cause errors to come up in the final results of energy loss. In other words, the loss factor may influence the results of the energy losses when indirect calculation is carried out.

The analysis of such influence was performed for the segments: low voltage network, distribution transformer and medium voltage network.

Given the calculation results for several components for each segment, it was possible to calculate, for each component, the load and the loss factors. Consequently, the k value was to be used in equation (6) in such a way indirect calculation produced the same result deriving from direct calculation: the energy loss by indirect calculation from the demand loss (resulting from the direct calculation by the methodology described in this article), by using k = 0.15 and k = 0.30 (ordinary values used in the Brazilian electric sector); the energy loss index obtained by indirect calculation in relation to the energy loss index obtained by the direct calculation and the mean k value for the segment.

1) Low voltage network

In the segment of low voltage networks, the analysis considered 20,000 feeders. Table II shows the results obtained for some of such networks.

TABLE II
ENERGY LOSSES IN LOW VOLTAGE NETWORKS

Low Voltage Network	Energy Losses (kWh)			Correct Value for k	Errors (%)	
	Direct Calculation	Indirect Calculation				
		$k = 0.15$	$k = 0.30$		$k = 0.15$	$k = 0.30$
1	604.36	720.50	768.96	-0.21	19.22	27.24
2	193.50	203.64	220.09	0.06	5.24	13.74
3	266.42	203.98	225.15	0.59	-23.44	-15.49
4	219.11	207.43	223.06	0.26	-5.33	1.80
5	482.86	488.05	520.80	0.13	1.08	7.86
6	96.41	110.93	119.57	-0.10	15.06	24.02
7	113.67	48.06	59.38	1.02	-57.72	-47.77

One should notice how the k value varies from component to component, where even values below zero and above 1.0 come up, what indicates that the loss factor f_p is not within $f_c^2 \leq f_p \leq f_c$. That is due to the fact that such conclusion is only valid for each network branch and does not apply to the network as a whole as mentioned before.

The figures hereinafter better illustrate the results obtained for the low voltage networks considered for this analysis. Figure 2 shows a dispersion graph with k values for each low voltage network. The horizontal line indicates the mean value obtained for k. The mean value found was 0.13 with standard deviation 0.17. Figure 3 shows how k values distribute along 20 groups. The most frequent k values lie between 0.10 and 0.18, representing 38.91% of the analyzed low voltage networks.

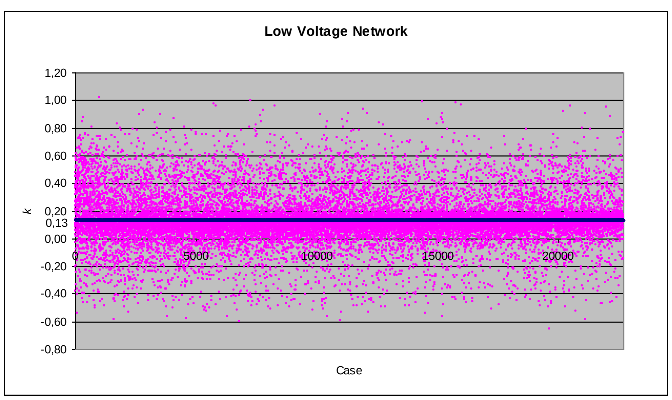

Fig. 2. Dispersion graph (k values for each low voltage network).

A total of 64.63% low voltage networks accused reasonably low errors, between -8.04% and 7.25%, when k is taken as 0.15 in the indirect calculation of energy losses. Other low voltage networks (35.37%) accused higher errors, between -8.04% and -57.72% or between 7.25% and 56.93%.

Similarly, only 24.95% low voltage networks accused errors between -10.35% and 10.44% when k was taken as 0.30 in indirect calculation of energy losses. Most networks (75.05%) accused high errors, between -10.35% and -47.77% or between 10.44% and 76.96%. That was expected once the mean k value found among the cases analyzed was 0.13.

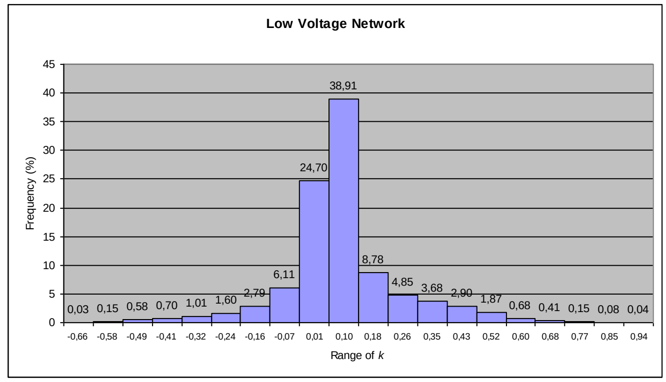

Fig. 3. Distribution of k values along 20 groups.

When taking k as 0.15, one makes lower mistakes. Notwithstanding, one should notice than in many cases the error observed may be notably high.

2) Distribution Transformers

Within the distribution transformer segment, about 20,000 transformers were analyzed. Table III shows the results obtained for seven transformers. Figure 4 shows a dispersion graph where there are k values for each transformer. The line indicates the mean value found for k, which was 0.19 with standard deviation 0.14. Figure 5 shows how k values distribute along 20 groups. Most frequent k values lie between 0.10 and 0.15, representing 40.47% of the transformers analyzed.

TABLE III
ENERGY LOSSES IN DISTRIBUTION TRANSFORMERS

Distribution Transformer	Energy Losses (kWh)			Correct Value for k	Errors (%)	
	Direct Calculation	Indirect Calculation				
		$k = 0.15$	$k = 0.30$		$k = 0.15$	$k = 0.30$
1	551.99	417.20	462.71	0.59	-24.42	-16.17
2	97.02	98.33	108.99	0.13	1.35	12.34
3	186.28	168.89	182.54	0.34	-9.33	-2.01
4	14.66	12.42	13.61	0.43	-15.25	-7.18
5	335.63	327.28	349.24	0.21	-2.49	4.05
6	193.94	161.18	176.90	0.46	-16.89	-8.79
7	103.63	102.18	110.14	0.18	-1.40	6.28

For the mean k value found among the cases analyzed (0.19), one makes lower mistakes when taking k as 0.15 in the indirect calculation of energy loss.

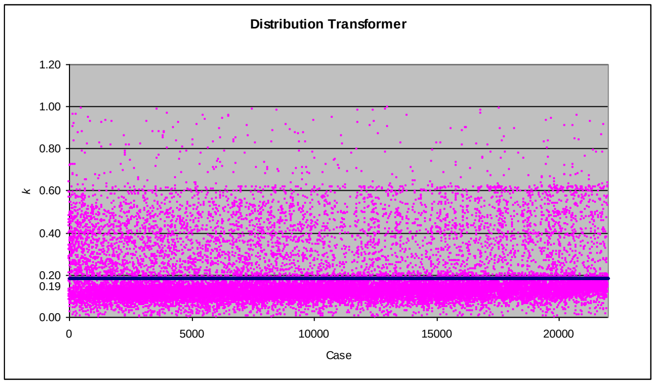

Fig. 4. Dispersion Graph (*k* values for each transformer).

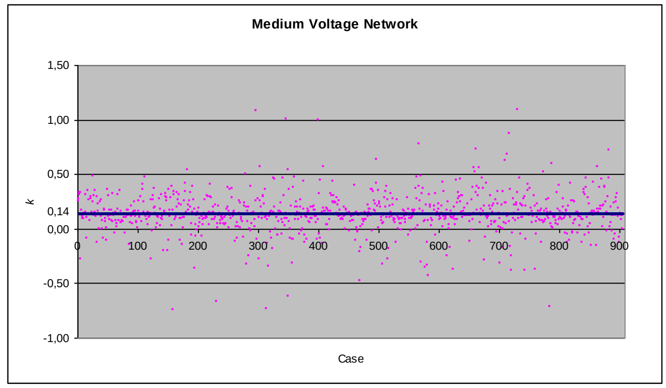

Fig. 6. Dispersion Graph (*k* values for each medium voltage network).

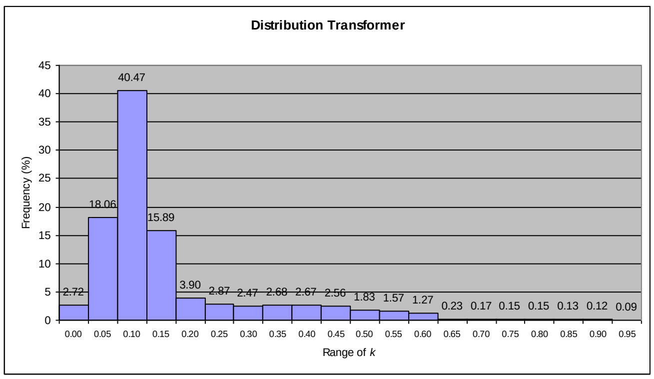

Fig. 5. Distribution of *k* values along 20 groups.

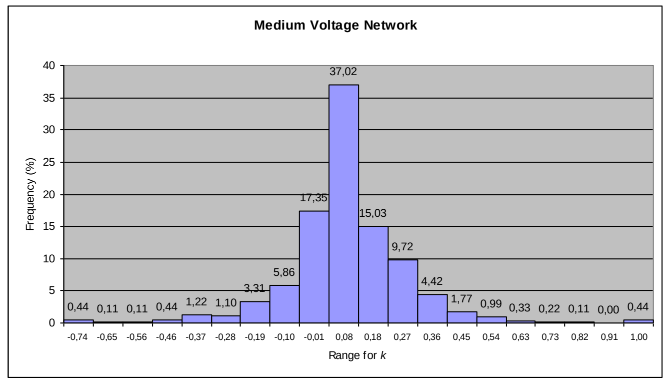

Fig. 7. Distribution of *k* values along 20 groups.

3) *Medium voltage network*

In the medium voltage network segment, 905 primary feeders were analyzed. Table IV shows the results obtained for some networks. Figure 6 shows a dispersion graph where *k* values lie for the network. The line indicates the mean value found for *k*, which was 0.14 with standard deviation 0.18. Figure 7 shows how *k* values distribute along 20 groups. Most frequent *k* values lie between 0.08 and 0.18, representing 37.02% of the networks analyzed

TABLE IV
ENERGY LOSSES IN MEDIUM VOLTAGE NETWORKS

Medium Voltage Network	Energy Losses (kWh)			Correct Value for k	Errors (%)	
	Direct Calculation	Indirect Calculation				
		k = 0.15	k = 0.30		k = 0.15	k = 0.30
1	693.92	679.30	699.72	0.26	-2.11	0.84
2	494.66	470.89	499.68	0.27	-4.81	1.02
3	975.87	923.62	968.04	0.33	-5.35	-0.80
4	210.46	255.24	270.82	-0.28	21.28	28.68
5	958.84	1132.62	1244.25	-0.08	18.12	29.77
6	2.75	2.13	2.40	0.48	-22.59	-12.42
7	3322.88	2603.07	2718.57	1.08	-21.66	-18.19

For the mean *k* value found among the cases analyzed (0.14), one makes lower mistakes when taking *k* as 0.15 in the indirect calculation of energy loss.

Having stated that, when carrying out an indirect calculation of energy losses, one might incur in considerable errors in several components of each segment.

One should also notice the *k* value, which might show different values for each segment. In the analysis here performed, the differences observed among the three segments were small and the results obtained may vary a little depending on the universe chosen for the analysis.

The *k* value also varies a lot from component to component within the same segment, what leads to large variations in loss factor and, consequently, in energy losses.

Therefore, when one looks into a more precise calculation of energy losses, the best possible option is using direct calculation in case one is presented with load curves in each distribution system component.

IV. TECHNICAL AND ECONOMIC ANALYSIS

With the help of the above described load curve methodology and the computational system developed, it is possible to identify the segments which most contribute for total technical losses. It is also possible to identify the components of a given segment with a loss index, high above the average.

For the low voltage network segments and the distribution transformer, it is possible to simulate the carrying out of interventions with the help of a software. The software developed allows for simulating the carrying out of works such as replacing transformers, recabling the network and splitting the network. Figure 8 shows the graphic interface of the software developed. It also shows a low voltage network with its poles, branches and distribution transformer drawn on a cartographic basis.

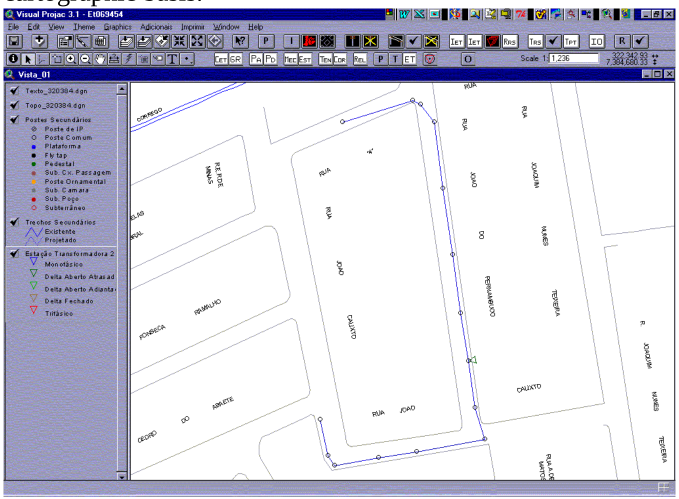

Fig. 8. Software to simulate some works within the network.

When simulating, losses are calculated before and after the intervention in such a way it is possible to calculate the loss reduction in the network when carrying the work out. Given the intervention cost, the software calculates an Investment Profitability in Loss Reduction (*RIRP*) given by equation (7) to evaluate the economic feasibility of the work.

$$RIRP = \frac{B}{CAE} \qquad (7)$$

where:

B - benefit in loss reduction [U$];

CAE - equivalent annual cost [U$].

The benefit in loss reduction (*B*) and the equivalent annual cost (*CAE*) are obtained by equations (8) and (9), respectively.

$$B = \Delta pe \cdot CE + \Delta p \cdot CP \qquad (8)$$

where:

Δpe - energy loss reduction [MWh];

CE - unitary cost of avoided energy [U$/MWh];

Δp - reduction in maximum demand loss [kW];

CP - unitary cost of avoided demand [U$/kW].

$$CAE = (FRC + DE) \cdot CT \qquad (9)$$

where:

FRC - capital recovery factor;

DE - annual expense rate of exploring the work [U$/MWh];

CT - total investment cost for the intervention [U$].

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VI. Biographies

André Méffe was born in São Paulo, Brazil, on April 23, 1976. He graduated from University of São Paulo in 1998. He received the M. Sc. degree from University of São Paulo in 2001. Since 1999, he has been with the Department of Electrical Engineering at the University of São Paulo, where he works with researches related to electric distribution systems. His current research interests include electrical power distribution planning and methodologies for calculating technical losses.

Carlos César Barioni de Oliveira was born in São Paulo, Brazil, on August 18, 1962. He graduated from School of Engineering of São Carlos (University of São Paulo) in 1985. He received the M. Sc. and Ph.D. degrees from University of São Paulo in 1993 and 1997, respectively. Between 1991 and 1995, he worked for E. J. Robba Consultoria & Cia. Ltda., a leading consulting company in São Paulo, where he developed computational models aiming at distribution system planning and operation. Since 1990, he has been with the Department of Electrical Engineering at the University of São Paulo, where he teaches power system basics. His current research interests include the application of optimization techniques and artificial intelligence in distribution system problems.

Nelson Kagan was born in São Paulo, Brazil, on October 8, 1960. He received his MSc in Electrical Engineering from the University of São Paulo, Brazil, in 1988 and his Ph.D. in Electrical Engineering from the University of London in 1993. He lectures at the Department of Electrical Engineering at the University of São Paulo since 1983. After presenting his post-doctoral thesis in 1999 he became an Associate Professor. Most of his research work concerns electrical power distribution planning. His interests in this area are related to the application of optimization and intelligent systems so that more important issues like multiple objectives (power quality, environment and operation issues) and uncertainty (probabilistic and possibilistic models) can be represented into the modeling. His works have been implemented in many utilities in Brazil.