A NEW METHOD FOR THE COMPUTATION OF TECHNICAL LOSSES IN ELECTRICAL POWER DISTRIBUTION SYSTEMS

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ABSTRACT

This paper aims at presenting a new method for the evaluation of technical (demand and energy) losses in electrical power distribution systems. A computational tool was developed and implemented at Eletropaulo, the largest distribution company in Brazil. The methodology divides the distribution system into eight different segments, namely: energy meters, customer connections to the network, low voltage network, distribution transformers, medium voltage network, distribution substations, subtransmission system and other technical losses. The latter segment includes equipment losses in capacitors, voltage regulators, connectors, insulators and so forth. The computational tool comprises two modules. The first one determines technical losses in specific networks in a hierarchical way. From the evaluation of losses in a representative part of the distribution system, per unit loss indices for each segment are readily computed. Such indices are transferred to a second module, which is responsible for the assessment of a global energy balance for the overall distribution system.

1. INTRODUCTION

The evaluation and reduction of energy losses represent important challenges for distribution companies in Brazil. Privatisation and deregulation, linked to competitive markets, have led distribution companies to search for more efficiency in their technical and commercial processes.

Energy losses are commonly classified into technical and non-technical losses. Technical losses are due to the transport of electrical power energy, related to the characteristics of the distribution system, the supplied demand and types of equipment in use. They are generally determined in terms of demand (maximum losses) and energy, either as absolute (in kW and kWh) or relative (in relation to the supplied demand and energy) parameters. Non-technical losses are usually named commercial losses. The global amount of losses can be easily computed by the difference between the supplied energy and the billed energy. Since global losses comprise technical and non-technical parcels, the latter can be obtained as the difference between the measured global losses and estimated technical losses.

The evaluation of technical losses for each distribution system segment allows for the identification of areas and equipment that most contribute to the respective indices. Thus it is straightforward to prioritise actions for losses reduction. A segment is simply defined as "the set of components that play the same role in the electrical power distribution system". Segments considered in this paper, as illustrated in fig. 1, are the following ones:

- Subtransmission network;
- Distribution substations;
- Medium voltage (MV) network;
- Distribution transformers (DT);
- Low voltage (LV) network;
- Customer connections;
- Energy meters;
- Others (capacitors, voltage regulators, insulators, etc.).

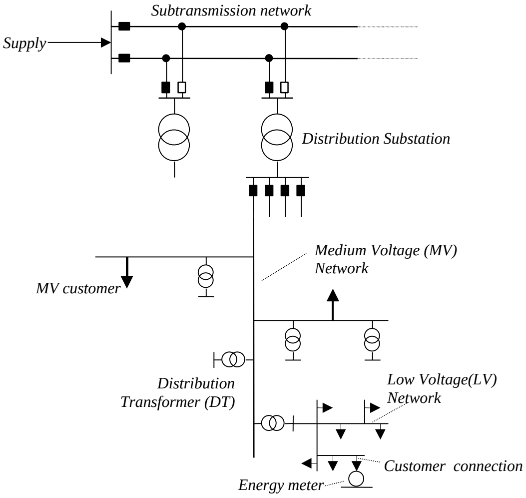


Figure 1 – Segments in the distribution system

Table 1 shows typical ranges for the energy technical losses indices estimated in Brazilian distribution systems.

Table 1 – Estimated energy losses in Brazil

Segment	Energy losses (%)
Subtransmission	2,0 - 3,0
Distribution substations	0,5 - 2,0
MV network	0,5 - 2,5
Distribution transformers	1,0 - 2,0
LV network	0,5 - 2,0
Customer connections	0,05 - 0,15
Energy meters	0,2 - 0,4
Others	0,2 - 0,8

2. METHODOLOGY

The proposed methodology for the computation of technical losses in the various distribution system segments is detailed in the following sub-items. The overall procedure is according to the steps below:

a) Each energy meter is assigned a fixed value of losses (according to its type).
b) Losses in customer connections are estimated by assuming typical parameters, such as length and electric resistance of standardised conductors, and by using typical customer daily load curves.
c) For each LV network connected to a distribution transformer, energy and demand losses are determined by a three-phase load flow method for each instant in the daily load curve.
d) Losses in each distribution transformer (including bank of single phase distribution transformers) are computed, taking into account iron and copper losses. Such indices are obtained from the rated transformer parameters and from their respective load curves, determined by the aggregation of daily curves of each customer connected to the transformer through the LV network.
e) Technical losses in MV distribution feeders are evaluated by a three-phase load flow, by using the aggregated transformer load curves seen on the primary side. The MV feeder load curve at the substation is also determined by the three-phase load flow program.
f) The above steps are carried out for all MV outcoming feeders of a distribution substation. Iron and copper losses are then computed for each power transformer by using the substation load curve, obtained from the aggregation of the corresponding feeder load curves.
g) Energy losses are then computed at the substransmission network, considering the customers supplied at this level.
h) The difference between the energy measured at supply points and the sum of billed energy and energy losses is equal to the non-technical losses added to other losses (capacitors, insulators, network connections, etc.).

2.1 Load modelling

Load modelling is primordial in this new approach to the estimation of technical losses. It includes the representation of low and medium voltage customers as well as public lighting models.

Low voltage customers are represented by typical daily load curves. Eletropaulo has a data base of typical load curves, obtained as the result of an extensive measurement campaign in residential, commercial and industrial low voltage customers [7,8].

As far as residential customers are concerned, typical load curves are obtained for four monthly energy ranges, namely from 0 to 200 kWh, from 200 to 400 kWh, from 400 to 500 kWh and above 500 kWh. Fig. 2 shows a daily load curve for the second range.

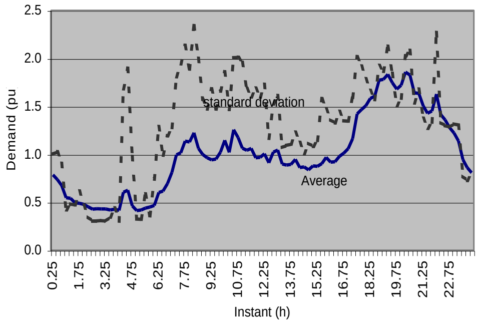


Fig. 2 – Typical daily load curve for a 200-400kW range residential customer

Daily load curves for commercial and industrial customers are known according to their respective activity. Commercial customers were divided into 47 categories whereas industrial customers were divided into 26 main activities. Fig. 3 shows a daily load curve for a given industrial activity.

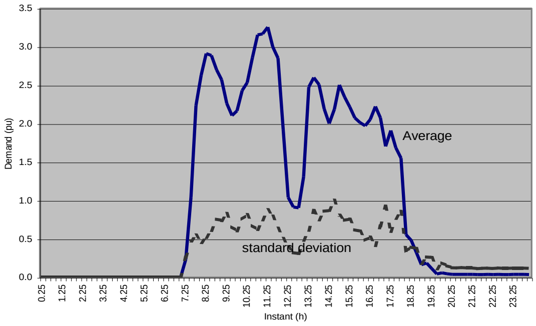


Fig. 3 – Typical daily load curve for an industrial customer (production of wood structures)

As seen in figures 2 and 3, typical daily load curves present average and standard deviations on the demand for 15 minute intervals. That is, for a given interval, demand is a random variable, for which the probability distribution is well known. For the evaluation of distribution transformer loading it is sufficient to utilise a deterministic approach in which the customer demand for a given interval, $D_{i,t}$, is given as:

$$D_{i,t} = D_{av_{i,t}}\left(1+\frac{k\sigma_{DT,t}}{D_{av,DT,t}}\right) \qquad (1)$$

where:

$\sigma_{DT,t}$ - standard deviation for the distribution transformer load demand (kW), interval t, estimated from customer standard deviations as: $\sigma_{DT,t} = \sqrt{\sum_i \left(\sigma_{i,t}{}^2\right)}$;

$D_{av,DT,t}$ - distribution transformer average demand (kW), , interval t, estimated by the sum of individual customer average demands: $D_{av,DT,t} = \sum_i D_{av_{i,t}}$;

k - multiplying factor, applied to the standard deviation. For a gaussian probability distribution, k = 1.28 ensures 90% probability that the demand does not exceed a $D_{i,t}$ value. For energy losses computation k is assumed *0* since the aggregated standard deviation for many customers is reduced and the results for the computation of the global supply energy are more accurate.

As shown in figs 2 and 3, interval demands are expressed in pu. Given the customer monthly energy, E_i (in kWh), and its typical daily curve, the demand (in kW) for interval *t* is determined as:

$$D_{i,t}(kW) = \frac{E_i}{720} d_{i,t}(pu) \qquad (2)$$

MV customers are dealt with in a similar way as LV customers. They are basically divided into six different categories. Public lighting is represented by a daily load curve, in kW, constant for specific intervals.

2.2 Losses in energy meters

Losses in energy meters are basically due to iron losses in the voltage coils and may be assumed as constant, since they do not depend on the power flow. Thus, according to [1], energy losses in meters (e_m) can be obtained, in *kWh*, by:

$$e_m = \frac{p_m \cdot N_m \cdot (i_1 + 2i_2 + 3i_3) \cdot T}{1000} \qquad (3)$$

where:

p_m - average demand losses for each voltage coil of the meter (W);
N_m - total number of energy meters;
i_1 - percentage of single-phase meters;
i_2 - percentage of double-phase meters;
i_3 - percentage of three-phase meters;
T - time interval considered (720h for a month);

According to laboratory tests made by Eletropaulo, their energy meters present average losses equal to 1.2 W per voltage coil.

2.3 Losses in customer connections

The computation of losses in customer connections was based on the assumption of a typical lateral, for each customer category, presenting length and electric resistance previously defined. Daily energy losses (e_r) in customer connections are then given by:

$$e_r = \frac{k \cdot R \cdot L \cdot \Delta t \cdot \sum_{i=1}^{N_t} I_t^2}{1000} \qquad (4)$$

where:

k - number of conductors in the customer connection where there is current flowing under normal conditions (*k=2* for single and double phase customers and *k=3* for three-phase customers);
R - conductor electric resistance (Ω/km);
L - average lateral length (km);
I_i - electric current on the lateral for interval t (Ampere);
Δt - interval duration (e.g. 0.25h=15min);
N_t - number of daily intervals (e.g. 96 intervals).

A constant current model is assumed, i.e. it is assumed that the absorbed current does not vary with the supplied voltage. It means that the current can be evaluated as a function of the interval demand (eq. 2) and the rated voltage.

2.4 Losses in the low voltage network

Given the load demands (and corresponding currents) for each interval *t* and the low voltage network configuration, it is possible to run a three-phase load flow model for the evaluation of network losses in all its branches. The three-phase load flow model is fairly simple, since, for Eletropaulo, the LV network is radial. Moreover, network branches are represented by three phase conductors and a ground conductor, as shown in fig. 4. Phase and ground load currents (I_A, I_B, I_C ,I_N) are obtained as explained in section 2.3. Branch currents result from the first Kirchhoff's law applied to each network node in an ordered way (from demand nodes towards the distribution transformer node). Daily energy losses for a given network branch (e_s) can be evaluated by:

$$e_s = \frac{1}{1000} \sum_{t=1}^{96} \left(\sum_{i=1}^{N_{cond}} \left(R_i \cdot I_{i,t}^2 \right) \right) \cdot \Delta t \qquad (5)$$

where:

R_i - conductor *i* electric resistance (Ω);
$I_{i,t}$ - electric current on the conductor *i* for interval t (Ampere);
Δt - interval duration;
N_{cond} - number of conductors (phase and ground) for the branch.

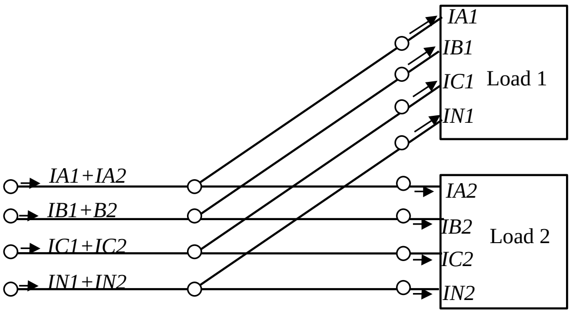


Fig. 4 – Low voltage networks

2.5 Losses in distribution transformers

As explained in the previous item, network currents are determined for all branches ending up at the distribution transformer node. Therefore the currents for phase and ground conductors, for every interval *t*, at the transformer units result from the three-phase load flow model applied to the LV network. Given the rated transformer data, daily energy losses for a distribution transformer are given by:

$$e_t = p_{fe} \cdot S_N \cdot 24 + p_{Cu,pc} \cdot S_N \cdot \sum_{t=1}^{96} \left(\frac{S_t}{S_N} \right)^2 \cdot \Delta t \qquad (6)$$

where:

S_N - transformer rating (kVA);

S_t - transformer loading for interval *t* (kVA);

p_{fe} - rated iron losses (pu);

$p_{cu,pc}$ - rated copper losses (pu);

Δt - interval duration (h).

2.6 Losses in the MV network

Computation of MV network losses are analogous to the method developed for LV networks. The basic difference is that demand loads are due to distribution transformers, MV customers and public lighting transformers. Load modelling for such categories have been addressed in section 2.1. The three-phase load flow model also considers capacitor banks installed along the network and estimates demand losses for every interval *t* in the daily load curves.

2.7 Losses in distribution substations

Feeder load curves are obtained as a result from the application of the three-phase load flow model to the MV network. The aggregation of load curves of the substation outcoming feeders leads to the substation load curve. Given the rated data of the substation transformers, the corresponding daily energy losses can be determined as shown in eq. 6, section 2.5.

2.8 Losses in the subtransmission network

Losses in the subtransmission network are estimated by the use of a percentual index, obtained by the application of a load flow model to a given system configuration. Such index is regularly computed and updated according to possible changes in the system configuration or load patterns.

2.9 Energy balance for the overall distribution system

Applying the proposed losses evaluation method (sections 2.2 to 2.8) for the entire or for a representative portion of the company's distribution system makes possible to estimate losses indices for each segment considered. The losses index for a given distribution system segment is defined by the following expression:

$$e_p\,(\%) = \frac{E_p}{E_{supplied}}\,100 = \frac{E_p}{E_{following} + E_p}\,100 \qquad (7)$$

where:

E_p : energy losses in the segment (kWh);

$E_{supplied}$: energy supplied to the segment (kWh);

$E_{following}$: energy supplied to the following segment.

A good estimation for the overall energy flow in the distribution company can be obtained from the computed losses indices per segment, the energy supplied (measured on the supply nodes) and the billed energy. The energy balance equation can by obtained by:

$$E_{total} = E_{con} + E_{p,tec} + E_{p,com} \qquad (8)$$

where:

E_{total} : total energy supplied to the distribution company;

E_{con} : total billed energy, considering low and medium voltage customers as well as subtransmission customers;

$E_{p,tec}$: technical losses for the distribution system by adding up energy losses in all segments considered;

$E_{p,com}$: commercial (non-technical) losses for the company's distribution system.

Eq. 8 provides a good estimation for the commercial losses, $E_{p,com}$, and the corresponding percentual index is given by:

$$e_{p,com}\,(\%) = \frac{E_{p,com}}{E_{total}}\,100 \qquad (9)$$

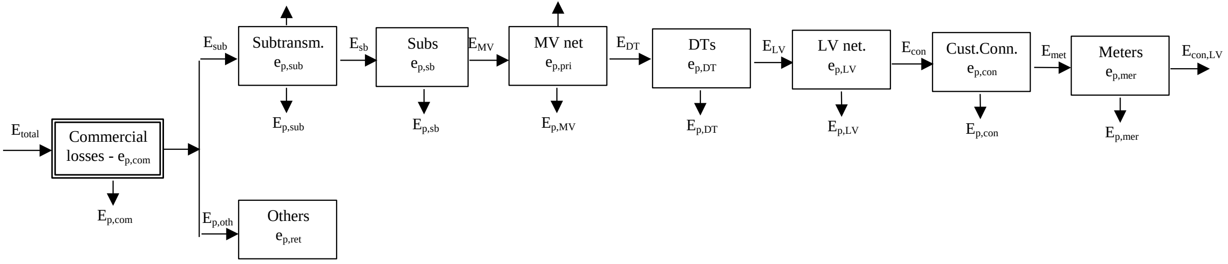
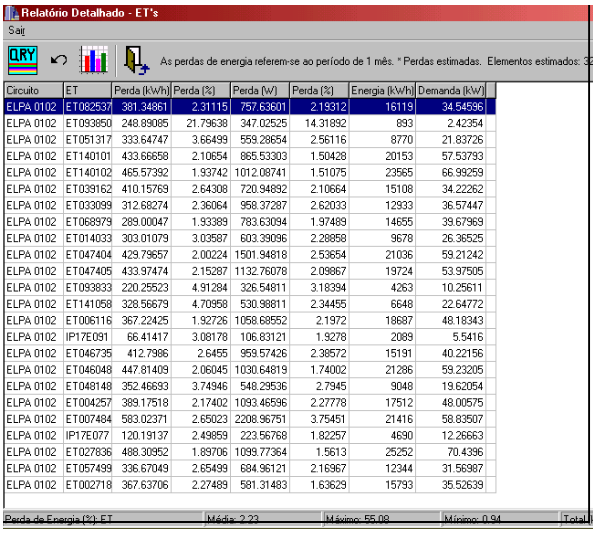


Fig. 5 – Energy balance

3. CASE STUDY

PERTEC is the computational system developed for losses evaluation in distribution systems according to the methodology described in the previous section. For illustration, fig. 6 shows energy and demand losses (*Perda* in the figure stand for *losses*) for the distribution transformers located in a specific MV feeder (ELPA0102). For instance, the distribution transformer ET082537 presents 381.35 kWh monthly energy losses or a 2.31% losses index. Fig. 7 shows results for losses evaluation in 4 medium voltage feeders.

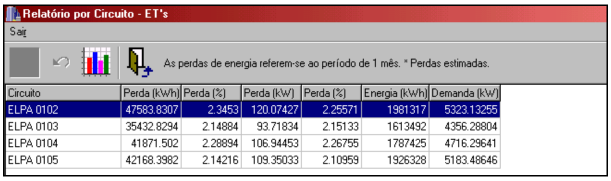


As perdas de energia referem-se ao período de 1 mês. * Perdas estimadas. Elementos estimados: 3

Circuito	ET	Perda (kWh)	Perda (%)	Perda (W)	Perda (%)	Energia (kWh)	Demanda (kW)
ELPA 0102	ET082537	381.34861	2.31115	757.63601	2.19312	16119	34.54596
ELPA 0102	ET093850	248.89085	21.79638	347.02525	14.31892	893	2.42354
ELPA 0102	ET051317	333.64747	3.66499	559.28654	2.56116	8770	21.83726
ELPA 0102	ET140101	433.66658	2.10654	865.53303	1.50428	20153	57.53793
ELPA 0102	ET140102	465.57392	1.93742	1012.08741	1.51075	23565	66.99259
ELPA 0102	ET039162	410.15769	2.64308	720.94892	2.10664	15108	34.22262
ELPA 0102	ET033099	312.68274	2.36064	958.37287	2.62033	12933	36.57447
ELPA 0102	ET068979	289.00047	1.93389	783.63094	1.97489	14655	39.67969
ELPA 0102	ET014033	303.01079	3.03587	603.39096	2.28858	9678	26.36525
ELPA 0102	ET047404	429.79657	2.00224	1501.94818	2.53654	21036	59.21242
ELPA 0102	ET047405	433.97474	2.15287	1132.76078	2.09867	19724	53.97505
ELPA 0102	ET093833	220.25523	4.91284	326.54811	3.18394	4263	10.25611
ELPA 0102	ET141058	328.56679	4.70958	530.98811	2.34455	6648	22.64772
ELPA 0102	ET006116	367.22425	1.92726	1058.68552	2.1972	18687	48.18343
ELPA 0102	IP17E091	66.41417	3.08178	106.83121	1.9278	2089	5.5416
ELPA 0102	ET046735	412.7986	2.6455	959.57426	2.38572	15191	40.22156
ELPA 0102	ET046048	447.81409	2.06045	1030.64819	1.74002	21286	59.23205
ELPA 0102	ET048148	352.46693	3.74946	548.29536	2.7945	9048	19.62054
ELPA 0102	ET004257	389.17518	2.17402	1093.46596	2.27778	17512	48.00575
ELPA 0102	ET007484	583.02371	2.65023	2208.96751	3.75451	21416	58.83507
ELPA 0102	IP17E077	120.19137	2.49859	223.56768	1.82257	4690	12.26663
ELPA 0102	ET027836	488.30952	1.89706	1099.77364	1.5613	25252	70.4396
ELPA 0102	ET057499	336.67049	2.65499	684.96121	2.16967	12344	31.56987
ELPA 0102	ET002718	367.63706	2.27489	581.31483	1.63629	15793	35.52639

Perda de Energia (%): ET | Média: 2.23 | Máximo: 55.08 | Mínimo: 0.94 | Total (k

Fig. 6 – Losses in distribution transformers



As perdas de energia referem-se ao período de 1 mês. * Perdas estimadas.

Circuito	Perda (kWh)	Perda (%)	Perda (kW)	Perda (%)	Energia (kWh)	Demanda (kW)
ELPA 0102	47583.8307	2.3453	120.07427	2.25571	1981317	5323.13255
ELPA 0103	35432.8294	2.14884	93.71834	2.15133	1613492	4356.28804
ELPA 0104	41871.502	2.28894	106.94453	2.26755	1787425	4716.29641
ELPA 0105	42168.3982	2.14216	109.35033	2.10959	1926328	5183.48646

Fig. 7 – Losses in MV feeders

PERTEC also determines the energy balance as mentioned in section 2.9. Fig. 8 shows a graphical display of such computation for an illustrative example.

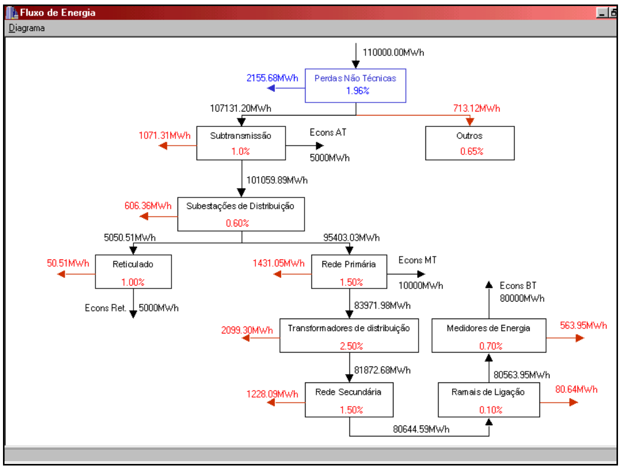


Fig. 8 – Energy balance

4. CONCLUSIONS

A novel approach for the computation of technical (energy and demand) losses in distribution systems, classified into 8 segments, is presented in this paper. Technical losses are determined in a detailed way, by eliminating simplifying assumptions which were necessary in previous works. The estimation of energy losses by using typical daily load curves has proven very accurate, mainly when compared with models based on loss factors determined as a function of load factors.

The application of this methodology demands adequate corporate data bases, since the models are based on the network topology and absorbed (billed) monthly energy in each customer. Moreover it is based on typical daily load curves, obtained from extensive measurement campaigns and statistical analysis.

A software named PERTEC was installed in Eletropaulo and is currently being used for evaluation of technical losses in its overall distribution system. The computational system allows for various studies, such as evaluation of critical areas and corresponding action plans for losses reduction in specific areas and distribution system segments.

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