A QUALITY DRIVEN SOFTWARE FOR EXPANSION PLANNING IN AN OPEN REGULATED ELECTRICITY MARKET

N. Kagan M.R. Gouvêa C.M.V. Tahan C.C.B. Oliveira H. Arango
Universidade de São Paulo
Av. Prof. Luciano Gualberto, trav. 3, n. 158
CEP 05508-900 - São Paulo – SP - Brazil
PHONE: +55 11 818 5473 FAX: +55 11 210 5820
e-mail: nelsonk@pea.usp.br

SUMMARY

This paper deals with a methodology, named SISPAI, to assess quality indices as a function of investments related to the expansion of electric power distribution systems. SISPAI is able to handle the entire area of a distribution company, by using statistic and clustering analysis to represent the distribution network and to assess their main parameters, such as voltage drops, network losses and reliability indices. Also the effects of data uncertainty on the system results can be rapidly assessed, thus permitting the development of a risk analysis to control the quality level related to a given budget profile. Some applications illustrate the proposed methodology.

1. INTRODUCTION

Brazil is on its way to install an open market as regard with electrical energy viewed as a commodity. During the last few years, several universities and power utilities have been involved in the development of planning tools and methodologies able to indicate an optimal pattern of investments to be allocated in electrical power distribution systems. The developed tool to be shown in this paper works upon a goal function taking into account not only the costs paid by the utility, but also the costs related to imperfections in the supplied energy that are still paid by the consumers.

Based on a first paper developed by EDF [1], conceptual basis of a new investment planning model [2] was devised, taking into consideration the characteristics of the distribution systems existing in Brazil and the various engineering practices adopted by utilities throughout the country.

The methodology was made available through a software, entitled SISPAI [3], which is being utilised or implanted in many distribution companies within Brazil. The model and corresponding computational tool were developed as part of an agreement involving the University of São Paulo and the ABRADEE, an association that represents most distribution companies in Brazil.

The process starts from clustering the distribution units into groups in order to decrease the problem complexity. In a second stage, it simulates the demand growing in such units by using statistical laws that relate technical indices to the cluster attributes. Such statistical laws are determined by a procedure that incorporates the Monte Carlo method followed by a regression analysis that determines the main indices (voltage, losses, reliability indices and so on) as a function of given attributes.

A main module evaluates the best measures that meet the technical criteria for each cluster by computing the cost-benefit indices (CBI). Such measures, for a given year, are ordered by their corresponding CBIs until the budget is about to be exceeded.

Uncertainties arising in the process of planning are considered by means of a probabilistic generation of distinct scenarios involving technical, social, economic and financial considerations.

The software can be used as a management and decision-making tool by means of a graphic interface which shows the reactions of the system to different strategies of the electrical market development, from the point of view of utilities, consumers or regulation agencies. It can thus be used to evaluate marginal costs and to serve the open market as an efficient price-energy allocation tool.

2. METHODOLOGY

2.1 Network representation by clusters

The model considers investments regarding the distribution system expansion, namely distribution substations (S/Es) – transforming subtransmission voltage levels (69 to 138kV) to primary voltage levels (13.8 to 34.5kV), subtransmission laterals – interconnecting the S/Es to the transmission system and medium voltage (primary) distribution feeders.

Each set – comprising a S/E, a subtransmission lateral and primary feeders – defines a EDS – Elementary Distribution System. The model considers two different types of EDS. The first one is applied to rural regions or low load density areas, where each S/E can be considered as isolated, i.e., there is no significant load exchange capabilities amongst neighbouring S/Es. The second one comprises EDSs in urban areas, that is in high density areas, where there is a strong interaction amongst neighbouring S/Es.

The investment planning process can be carried out in a global way, that is, by considering a total universe of the existing substations and feeders within the utility. Otherwise, a decentralised representation of the utility can be used.

Given a universe under study, a clustering and grouping process of substations and feeders is taken place, following some criteria and by considering most attributes regarding EDSs. The process begins by forming groups of substations through a hierarchical classification procedure, which takes into consideration the following attributes:

- Rated voltage at subtransmission level;
- Rated voltage at primary level (medium voltage);
- Transformer rating;
- Number of transformer units;
- Number of outcoming primary feeders;
- Utilisation factor (relation maximum demand / capacity);
- Load growing rate;
- Load factor.

A representative EDS is associated with each group. Such representative is a fictitious S/E with a series of descriptors, obtained from the average or most frequent values of the parameters related to the existing S/Es.

As urban S/Es regard, they are grouped using such hierarchical method as well, though incorporating geographic information. Such information is given by the planner, who identifies which substations is close and allow load transfer to each other.

In sequence, a clustering of existing distribution feeders that form each group of substations is carried out. Each one of such groups will constitute a universe, for which representative feeders will be determined. A statistic process [2,3] based on Euclidian distance deals with feeder clustering. The following attributes are considered to determine groups of feeders:

- Network length;
- Number of load points served;
- Action angle;
- Maximum demand;
- Load factor;
- Vertical loading growth rate;
- Horizontal loading growth rate;
- Power factor.

2.2 Statistic equations to assess EDS performance

The investment planning model aims at relating investment to quality levels, by considering a number of scenarios that take into account uncertainties due to financial, technological and social-economical aspects. In order to do so, the model must be fast enough to assess such combinations of multiple scenarios. The assessment of network performance regarding component loading, voltage drops, losses and other quality indices are evaluated in a statistical manner. They are determined based on the information of existing network characteristics as well as utility technical standards. Therefore it is not necessary to particularise such evaluation for an individual feeder or substation.

Statistic equations allow for the rapid computation of operational and topological network parameters as functions of EDS group descriptors.

Fictitious radial networks are randomly generated by the Monte Carlo Method, bearing technical, topological and load characteristics previously defined so that the universe of EDSs is represented. Such characteristics comprise the independent variables. The randomly generated networks have their main technical parameters (dependent variables) evaluated by the conventional way, that is, a load flow computing voltage drops, component loading and losses; this procedure is very efficient for it deals with radial networks only. Quality indices (energy not supplied and other customer interruption indices) are determined based on average failure rates, restoration times as well as some general criteria that incorporate utility practices concerning protective and switching equipment allocation along the network.

The methodology can be described according to the following steps:

i. Generate a radial network feeder randomly, according to a set of attributes (demand, number of load points, feeder angle and area, lateral and main conductor types, etc.)
ii. Evaluate the parameters (network length, voltage drops, losses, energy not supplied, interruption indices) by the use of direct methods;
iii. Repeat steps i. and ii. for N simulations. N is fixed in such a manner that it can be assured, within a given probability, that the maximum confidence interval in relation to the mean value of each parameter is not exceeded;
iv. Repeat steps i. to iii. for many combinations of input attributes;
v. Based on the results obtained in the previous steps, determine statistical equations by regression analysis in a n-dimension space, i.e. dependent variables will be given as functions of the independent variables.

This procedure leads to the evaluation of the following statistical equations:

$$
\begin{aligned}
L_T &= \alpha_1 N_d^{\beta_1} N_P^{\delta_1} Z_d^{\gamma_1} \\
L_{tr} &= \alpha_2 N_d^{\beta_2} N_P^{\delta_2} Z_d^{\gamma_2} \\
\Delta_V &= (P.L_T) \Big/ \left(\alpha_3 N_d^{\beta_3} N_P^{\delta_3} Z_d^{\gamma_3}\right) \\
P_{er} &= \left(P^2.L_T\right) \Big/ \left(\alpha_4 N_d^{\beta_4} N_P^{\delta_4} Z_d^{\gamma_4}\right) \\
END &= \alpha_5 \, P^{\beta_5} L_T^{\delta_5} \lambda_f \, f_c \\
FEC &= \alpha_6 \, P^{\beta_6} L_T^{\delta_6} \lambda_f \\
DEC &= END / (f_C P)
\end{aligned}
\tag{1}
$$

where:

L_T : total feeder length;

L_{tr} : main feeder length;

Δ_V : maximum voltage drop along the feeder;

P_{er} : feeder losses;
END : not supplied energy;
FEC : equivalent failure rate per customer;
DEC : equivalent duration of interruptions per customer;
$\alpha_i, \beta_i, \delta_i, \gamma_i$: regression coefficients;
$N_D = 360/\theta$, where θ is the action angle of the feeder;
N_P : Number of load points (transformers) along the feeder;
Z_d : feeder area;
P: feeder demand;
λ_f : feeder failure rate;
f_c : load factor.

When applying the Monte Carlo method, load points are generated such that the load density along the feeder is given by:

$$D_r = D_0 . r^{\sigma} \quad (2)$$

where:

D_r : Load density for a radius r related to a circular sector defined by the action angle and the feeder area;
D_0 : Load density for $r=0$;
σ : Exponent defining the variation of the load density along the radius r.

By varying the values of σ , urban and rural feeders can be fairly well represented, by assigning values around 0 (uniform distribution) and –1 (load density decreases with the distance from S/E), respectively. Long feeders, supplying load at distant locations (also called express feeders) can be represented by assigning $\sigma \geq 2$.

2.3 Network Expansion and Facilities Ranking

The analysis of network expansion is carried out by simulation, year by year. Both urban and rural EDSs and corresponding load growths are considered. The model aims at determining the best strategy to serve the demand market, by taking into account technical and economical criteria. In this process, investment amounts related to the desired quality of service levels should be determined. Annual investments are subject to financial constraints.

Also, technical constraints must be met accordingly, namely limits on transformer and feeder loading, voltage drop and quality indices. Such criteria can be represented as goals to be met, fixed for each year. The following facilities are evaluated as candidates for the expansion process: new substations, expansion of existing substations, installation of new outcoming feeders, feeder recabling, voltage regulators, and switching devices. Unit costs are represented as modular costs.

Candidate facilities, for each year and each group of EDSs, are classified into two categories, namely mandatory and improvement ones. All facilities are given a cost-benefit index. A given facility k, having annual cost given by C_annual_k, and leading to annual benefits measured by losses reduction ($\Delta_{per,k}$), reduction in the energy not supplied ($\Delta_{END,k}$), and improvement in the voltage profile ($\Delta_{\Delta V,k}$), will have a cost-benefit index (CB_k) evaluated by the following expression:

$$CB_k = \frac{Benefit_k}{C\_annual_k} = \frac{\Delta C_{per,k} + \Delta C_{END,k} + \Delta C_{\Delta V,k}}{C\_annual_k} \quad (3)$$

The ranking process starts from an initial selection of those facilities in which the system meets technical criteria (mandatory facilities). If there is budget for that specific year, additional facilities are selected, aiming at improving quality indices.

The system performance, i.e. the technical assessment of each EDS representative of a group, is evaluated by using the statistical equations described in sub-section 2.2. Feeders and substation transformers are assessed by comparing their loading values with their maximum capacities. Such capacities are determined by some utility criteria, such as capacity reserves, contigency criteria, etc.

The system, represented by the groups of EDSs, is updated for each year according to the selected facilities.

Figure 1 illustrates the computation of the voltage profile costs. It considers an increasing penalty (linear or not) starting from a given value ($V_{min,pen}$), normally higher than the minimum voltage in the system value ($V_{min,crit}$). Customers which are below a given critical level (V_{inter}) are penalised by the interruption cost, C_{END}.

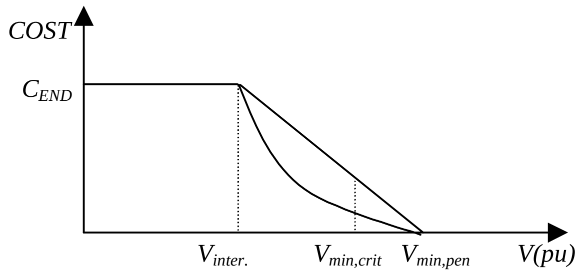

Figure 1 – Voltage profile cost

2.4 Uncertainties

In long term planning, the consideration of uncertain factors is very important, since they provoke serious consequences in the evaluation of investment amounts and in the overall quality of service levels. The SISPAI model handles financial, technological and social-economical uncertainty aspects. This is realised by the evaluation of all possible scenarios which are defined by the combination of the following factors:

- Financial aspects: variation of interest rates;
- Technological aspects: variation of unitary equipment costs;
- Social and economical aspects: variation of the load growth rates.

Optimistic, pessimistic and medium figures of each one of the three factors above (with corresponding probabilities) combine to generate the possible scenarios. Also, different sets of annual budgets are simulated. This allows for the simulation of relaxed and tight budgets, which leads to installation of different facilities along the system. Therefore different quality – budget pairs will be obtained composing a corresponding curve. Such quality – budget curve can be obtained for each scenario *j*, having a probability associated p_j. Figure 2 shows the curves obtained by the model. Such curves might answer some interesting questions such as: What is the risk of not reaching a given minimum quality index?

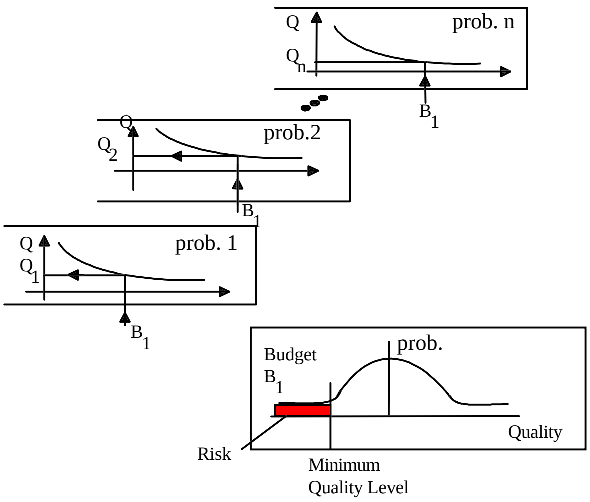

Figure 2 – Quality versus Budget

3. SYSTEM APPLICATION AND RESULTS EVALUATION

3.1 General Considerations

The software SISPAI is being used by many electric power distribution companies in Brazil. A total of 16 utilities will have the software and corresponding methodology implanted in the next 2 years. Reference [4] shows a few initial results determined by the application of the software in three of the largest distribution companies in Sao Paulo State, namely CESP (148 distribution substations and 537 feeders in 1996), CPFL (213 substations and 1044 feeders) and ELETROPAULO (188 substations and 1653 feeders).

3.2 Case Study

This section concerns the application and results regarding simulations using SISPAI in a distribution company having 40 substations and 160 feeders, what amounts a total of 650MVA rated power.

According to the methodology described, the system determined 13 groups of EDSs. Three sets of statistical equations were devised to assess the feeders performance. Such equation differ from each other due to the load density, where the parameters σ (cfr. eq 2, section 2.2) were adjusted to the following values:

- Urban feeders: $\sigma = -0,5$
- Rural feeders: $\sigma = -1,0$
- Express feeders: $\sigma = +8$

Scenarios representing uncertainties regarding financial, economical and technological aspects are shown in figure 3. Such aspects are represented by the multiplying factors and associated occurrence probabilities concerning interest rates, load growth rates and unitary equipment costs.

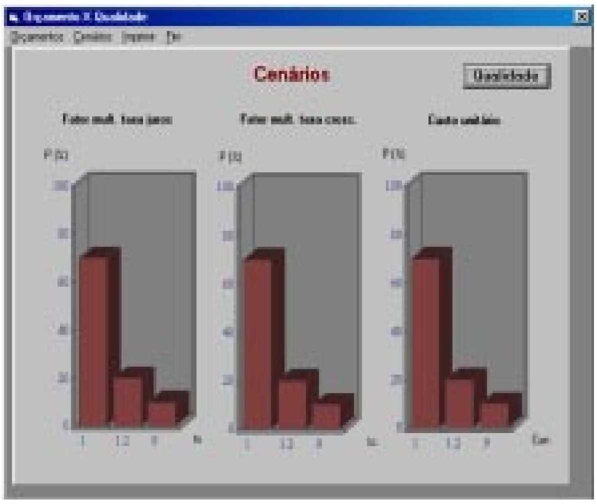

Figure 3 – Scenarios

Table I presents global results obtained for the first of the scenarios, which is the base case (highest probability). This scenario presents multiplying factors equal to 1 for all the three parameters, and a probability of occurrence equal to 34.3% (probability 70% for the three parameters).

Results correspond to a 10 year period and two simulations. The first simulation was designed to determine mandatory facilities only (i.e. to attend a minimal set of criteria). The second simulation determined quality improving facilities, by imposing a benefit/cost index higher than 1, disregarding any budget limitation.

The impact resulting from such quality improving facilities can be seen in Table I. Additional facilities were suggested, namely 18 feeders and 32 voltage regulators, since they basically improve voltage and reliability indices.

TABLE I - Mandatory and quality improving facilities for the base case scenario

	Base case (mandatory facilities)	Quality improving facilities
Feeders	51	69
Voltage regulators	26	58
Substation transformers	5	5
New substations	17	17
Present Worth (kUS$)	31900	33470

Table II shows along with the base case - considering mandatory facilities only - another simulation considering budget limitation.

Results show a 12% variation as investment regard. Such reduction is mainly due to the suggestion for the installation of lower budget facilities (total of 17 substations in the base case reduced to 10 substations). When a more relaxed budget is proposed, the global expansion plan leads to a system bearing higher values of quality indices. The tighter budget case, representing financial limitations, considers facilities bearing lower costs, which end up by worsening the system quality level.

TABLE II - Budget limitation effects

	Base case Unconstrained budget (mandatory facilities)	Constrained budget Case (mandatory facilities)
Feeders	51	57
Voltage regulators	26	30
Substation transformers	5	11
New substations	17	10
Present Worth (kUS$)	31900	28090

Table III shows some alterations in the investment profile due to changes in technical criteria, specifically maximum reliability indices, i.e. annual interruption duration (DEC) and frequency (FEC) per customer. Maximum limits for the base case were fixed at 10 hours/yr and 10 interruptions/yr, respectively. Another case was run by setting targets, with gradual decrease of these indices, aiming at average values of 5 hours/yr and 5 interruptions/yr for the final year (planning horizon). Such simulation represents a critical case, since such targets are really very hard to be achieved by the possible expansion facilities considered by the SISPAI model. Such limits can be obtained by additional measures, such as efforts to reduce restoration times following contingencies in the network, tree trimming programs to reduce failure rates in overhead systems, and so forth. Such measures could be incorporated in the software by the determination of new statistical equations, as described in section 2.2.

TABLE III – Effect of changes in DEC and FEC limits

DEC/FEC (max./yr.)	Feeders	Voltage Regulators	Trans-formers	New S/Es	Investment (kUS$)
10/10	51	26	5	17	31900
5/5 (target)	87	4	3	73	103000

In order to assess the impact of data uncertainty, various scenarios were sequentially simulated by SISPAI. Present worth values of total investment in the system throughout the planning period varied within the interval ranging from 27025 kUS$ (lowest load growth rates, lowest interest rates and lowest unitary costs) up to 42225 kUS$ (highest values of load growth rates, interest rate and unitary costs). Such results prove the relevance of considering the assessment of different scenarios and perform risk analysis as an aid to management decisions.

SISPAI allows displaying quality indices and economic benefits due to suggested facilities, when multiple scenarios are considered. For the sake of illustration, figure 4 shows the distribution of present worth values of total economic benefits and the corresponding probabilities of occurrence in each interval.

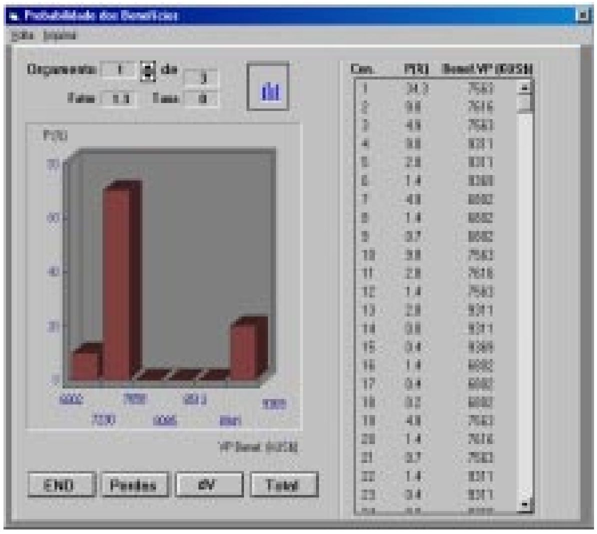

Figure 4 – Probability distribution of benefits

SISPAI also provides graphic visualisation of the main quality indices, for each EDS group and for the whole system. The main parameters considered are as follows: losses, voltage drop, feeder and substation loading and reliability indices: DEC, FEC and END (energy not supplied). Two different types of curves are presented for the user:

- Evolution of the parameter, year by year, for a given scenario;
- Probability distribution for each budget, considering all scenarios and all years within the planning period.

Figure 5 shows the evolution of the maximum voltage drop determined for the feeders of a given EDS. The values increase until the 8^{th} year due to the load growth. From the 8^{th} to the 9^{th} year there is a strong reduction in voltage drop, explained by the installation of new facilities that alleviate the loading in feeders belonging to this EDS.

Figure 6 depicts the probability distribution curve regarding the average value of a reliability index (DEC – average duration of interruptions per customer, per year). By analysing the figure, it is seen that due to data uncertainty the risk of average DEC in feeders exceeding 6.4 hours/yr, for the given budget, is 12.8%.

4. ADDITIONAL APPLICATIONS

Cases studied in the previous section illustrate the potential of SISPAI. It represents a powerful tool to managers in their decision making regarding investment plans. The system is designed to rapidly assist decision makers in evaluating the impact of different scenarios, i.e. answering a number of 'what if' questions. Such scenarios consider financial, technological and load forecasting aspects, making sure that the selected facilities ensure the set of technical criteria. Sensitivity analysis regarding changes in the values of the parameter limits, by setting different targets, can be easily executed. Examples of such analyses would be reduction of maximum voltage drop, reduction of DEC and FEC limits and inclusion of different network standards. Different risk analyses can be performed, assessing the impact of financial constraints in quality indices. Examples of such questions would be (i) what is the probability of the losses exceeding a specific amount? (ii) what is the risk of not achieving the yearly DEC and FEC targets?

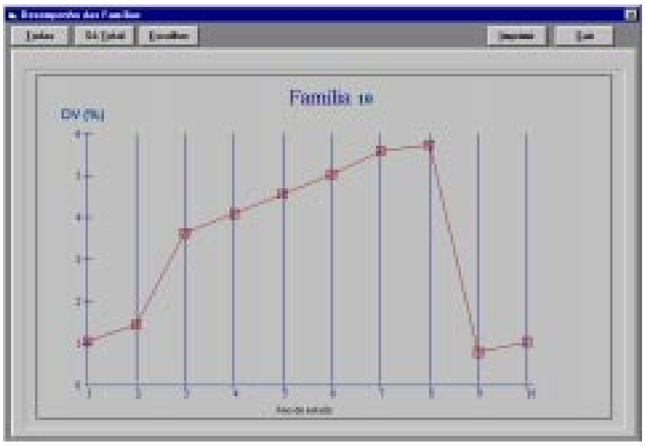

Figure 5 – Voltage drop evolution

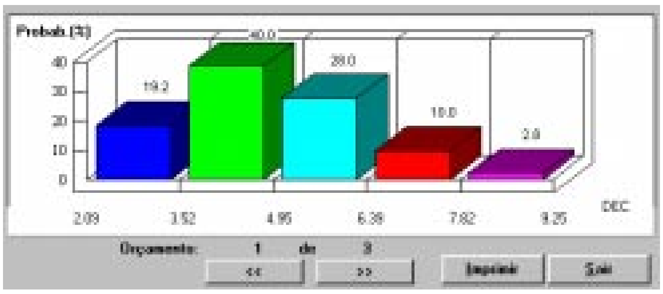

Figure 6 – Risk analysis for DEC reliability index

Results obtained by the software can be quite useful for other studies. The necessary investment figures are determined for the overall system or for specific EDS groups. Such investments represent the total costs due to the installation facilities in the subtransmission system (laterals), in substations, and in the primary distribution network. Also, investments are directly related to the load growth for the overall system or for given parts of the system.

These results allow for the computation of marginal costs related to the system expansion. SISPAI should be used as an important tool to assist the evaluation of electric energy prices and tariffs.

5. CONCLUSION

The methodology developed and incorporated in the software SISPAI allows for a variety of strategic studies, related to long and medium term planning. The basic objective is to associate investment figures to quality levels. Utility practices can be assessed and new standards and technical criteria can be proposed when they are proven convenient with respect to technical and economical aspects.

The effects of data uncertainty implicit in the long term planning problem can be rapidly determined and displayed with the help of an interesting graphic interface.

Also, SISPAI can be used to evaluate marginal costs and to serve the open market as an efficient price-energy allocation tool.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to ABRADEE – Association of Electric Power Distribution Companies in Brazil and to the working groups that have helped in constantly improve the SISPAI methodology.

REFERENCES

[1] ELECTRICITE DE FRANCE, *Planification des Réseaux de distribution*, France, 1989 (E.D.F. Rapports, R1-R5).

[2] Gouvêa, M.R., *Bases conceituais para o planeja-mento de investimentos em sistemas de distribuição de energia elétrica*, São Paulo, 1993. 109p. Thesis (Ph.D.). Universidade de São Paulo.

[3] Gouvêa, M.R.; Kagan, N.; Arango, H., "A methodology for planning electricity supply systems on aggregated basis", in *Proceedings 13th International Conference on Electricity Distribution*, vol. 1, Session 6, pp. 6.32.1-6.32.5, 1995.

[4] Oliveira, C.C.B.; Tahan, C.M.V.; Schmidt, H.P.; Antunes, A.U., "Application of an aggregated planning model to electric utilities in São Paulo State: preliminary results", in *Proceedings III Congresso Latino Americano de Distribuição de Energia Elétrica*, pp. 238-243, 1998.