IV SEPOPE

IV SIMPÓSIO DE ESPECIALISTAS EM PLANEJAMENTO DA OPERAÇÃO E EXPANSÃO ELÉTRICA

IV SIMPOSIUM OF SPECIALISTS IN ELECTRIC OPERATIONAL AND EXPANSION PLANNING

MAIO - 23 - 27 / 1994
MAY - 23 - 27 / 1994

SP 13

FOZ DO IGUAÇU - BRASIL
FOZ DO IGUAÇU - BRAZIL

REGIONAL TRANSMISSION SUBSYSTEM PLANNING

Edson da Costa Bortoni[1]
QUADRANTE SOFTWARES ESPECIALIZADOS LTDA.

Sérgio Valdir Bajay, Paulo de Barros Correia
AIPSE/FEM/UNICAMP

Afonso Henriques Moreira Santos, Jamil Haddad
EFEI

ABSTRACT

This work presents an approach for the planning of transmission systems by employing mixed-integer linear programming to obtain a cost and operating characteristics optimized system. The voltage loop equations are written in a modified form, so that, at the end of the analysis, the model behaves as a DC power flow, with the help of the two Kirchhoff's laws, exempting the need of interaction with an external power flow program for analysis of the line loading. The model considers the occurrence of contingencies, so that the final result is a network robust to the most severe contingencies. This whole technique is adapted to the regional electric power transmission subsystems.

1. INTRODUCTION

The planning of transmission systems is performed in order to get, at the end of the exercise, a robust transmission network, able to carry all the energy generated to attend the demand, within the planning horizon.

In the other hand, there is a growing concern towards the allocation of resourses in transmission and subtransmission and, in the last two decades, the optimized planning of electric power transmission networks has been the subject of many works which employ mathematical programming and optimization techniques [1-4].

Two main approaches are usually found, that is, either it is sought to obtain a network whose reliability levels in the most important load buses are larger than a pre-specified minimum value, or it is built a network resistant to the most severe contingencies which, in general, consist in losses of important transmission lines.

In both cases, the objective function to be minimized must include, for a correct simulation, the investment costs, as well as the operating costs due to losses in the transmission. Whereas the investment in lines present threshold characteristics, the operating costs are generally represented by a second order polinomial function. The constraints of such models try to simulate the systems operation and they are represented by the power flow equations in its complete or linearized form.

2. DEVELOPMENT OF THE SYSTEM MODELLING

2.1. Objective Function

The objective function to be minimized includes the investment and the operation costs for the proposed lines, as well as the operating costs for the existing lines, as follows [5].

$$Min\ F = \sum_{i=1}^{M1} \sum_{j=1}^{NS(i)} (C_{ij}\, Z_{ij} + S_{ij} P_{ij}) + \sum_{i=1}^{M2} W_i\, PR_i$$

where:
F = objective function;
M1 = number of proposed lines;
NS(i) = number of states considered for line i;
Cij = investment cost of state j for proposed line i;
Zij = integer variable (0/1) connected to state j of line i;
Sij = cost coefficient, linearized for losses, in state j for proposed line i;
Pij = power flow in state j for proposed line i;
M2 = number of existing lines;
Wi = cost coefficient, linearized for losses, of existing line i;
PRi = power flow in existing line i.

The consideration of different kinds of transmission lines as variables in the optimization problem can bring about big troubles with respect to the increasing number of variables involved.

In this case, the modelling presented treats the capacity to be added as a unic variable in each line, reducing the complexity of the problem. This way, each line will present one characteristic of the graph below. This graph represents the alternatives of each option for construction of the line [2]. Only one of these thresholds (states) will be chosen and cost, reactance, linearized loss coefficient and maximum capacity will be defined for each.

---

[1] **Rua Major Belo Lisboa, 22 - sala 52 - 37500-000 - Itajubá/MG - Phone: (035) 622-2630**

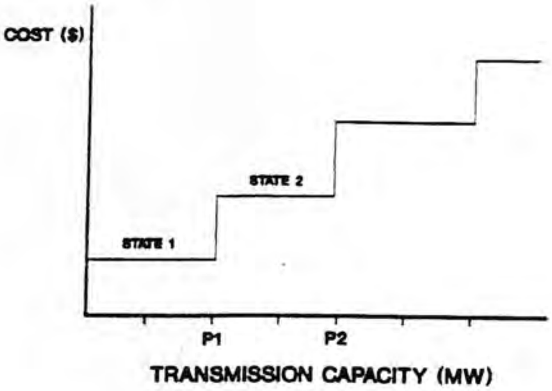


Figure 1. Possible states for the line proposed

The linearized loss coefficient is determined so as to represent the quadratic function of losses in the transportation of electrical power, within the linear model.

As the losses in transmission correspond to a small part of the total transmitted power and, since that, for any state of the line operation, its lower and upper limits are known, the linearization can be performed within this interval, as shown in figure 2, reducing the errors of this approach.

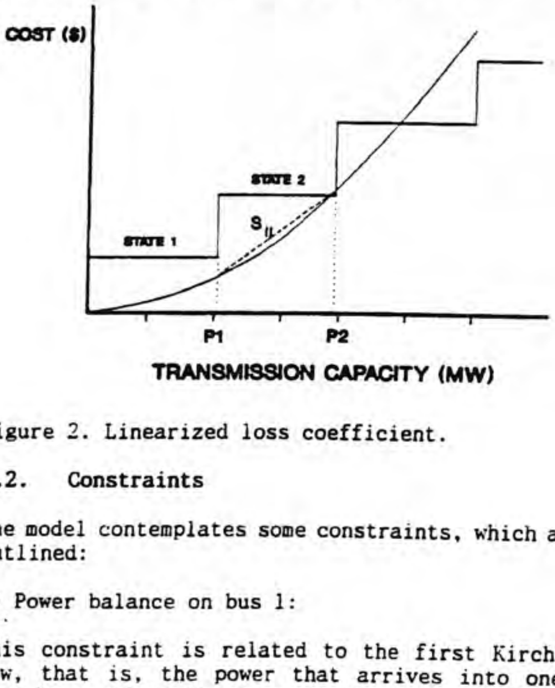


Figure 2. Linearized loss coefficient.

2.2. Constraints

The model contemplates some constraints, which are now outlined:

a) Power balance on bus 1:

This constraint is related to the first Kirchhoff's law, that is, the power that arrives into one node must be equal to the power that leaves it. Thus:

$$\sum_{i\in k_1(l)} \sum_{j=1}^{NS(i)} P_{ij} + \sum_{i\in k_2(l)} PR_j = H_l$$

where:
$k_1(l)$ = set of proposed lines connected to bus 1;
$k_2(l)$ = set of existing lines connected to bus 1;
H_l = power injected in bus 1.

b) Loop equations containing only existing lines:

According to the second law of Kirchhoff, the sum of the voltages around a loop must be equal to zero. In this case, for loops containing only existing lines:

$$\sum_{i\in L_1(j)} Xe_i \; PR_i = 0$$

where:
$L_1(j)$ = set of existing lines which form a basic j loop;
Xei = reactance of the existing line i;
LB1 = number of basic loops containing only existing lines.

c) Loop equations containing only one proposed line:

Some attention must be taken when ellaborating this constraint, since that it must be valid only if the line proposed is actually selected. Thus, a device is used employing integer variables, representing the line choice, as shown below:

$$\sum_{k\in L_2(j)} Xe_k \; PR_k + \sum_{k=1}^{NS(i)} XP_{ik} \; P_{ik} \le M \; (1 - \sum_{k=1}^{NS(i)} Z_{ik})$$

$$\sum_{k\in L_2(j)} Xe_k \; PR_k + \sum_{k=1}^{NS(i)} XP_{ik} \; P_{ik} \ge M \; (\sum_{k=1}^{NS(i)} Z_{ik} - 1)$$

where:
L2(j) = set of existing lines which form a basic loop j containing a proposed line i;
XPij = reactance in the state j of the proposed line i;
M = very large integer number (big M);
LB2 = number of basic loops containing existing lines and only one proposed line;
Zij = integer variable for state j of line i.

In this case, the second law of Kirchhoff for loops containing only one proposed line has been decomposed into two equations. This allows for the validity of this law in the presence of the proposed line ($\Sigma Zik=1$) and, in the other hand, makes the constraint idle in the absence of the line ($\Sigma Zik=0$).

The value of M must be large enough to make the constraint idle, but precaution must be taken so as not to fall in a numeric instability, resulting from different orders of magnitude among the variable coefficients.

d) Constraint of exclusivity for each line proposed:

As the modelling permits to choose the line through operation in a certain state, as shown in figure 1, only one of these states must be chosen. This can be translated by the following constraint:

$$\sum_{k=1}^{NS(i)} Z_{ik} \le 1$$

e) Capacity constraint for each existing line i:

The maximum capacity of each line must be respected, that is:

$$PR_i \le QM_i$$

where:

QM_i = overload limit of line i.

Naturally, this constraint can be implemented as an upper limit for the variable, increasing the efficiency of the mixed integer linear programming algorithm.

f) Constraint of overload for the proposed lines

Just like the previous constraint, the proposed lines also have their overload limits, but they depend upon the operating state chosen for the line during the optimization process. This constraint is also important for controlling the value of the flow variable of the proposed line and the integer variable associated, as shown below:

$$P_{ij} - PM_{ij} Z_{ij} \le 0$$

where:
PM_{ij} = overload limit of line i operating in state j.

g) Availability constraint in each bus

This constraint can be used to provide a minimum number of lines that arrive at a certain bus, translating some reliability criteria:

$$\sum_{k \in E_1(l)} \sum_{j=1}^{NS(k)} Z_{kj} \ge NB_l$$

3. ADAPTATIONS FOR REGIONAL SUBSYSTEMS

Assessing the transmission systems under a regional scope, some of their peculiarities with respect to large size transmission systems must be highlighted [6]. There are two major peculiarities, technical ones.

The first one concerns the system topology, that is, in large electric power transmission systems, the networks are strongly meshed, what is not common in regional systems, where long radial branches are usual. As a consequence, this can bring about some implications in the methods of evaluating such systems, as in the calculation of power flow, since the radial systems are part of the set of the so-called ill-conditioned systems.

The second one concerns the capacity of the power transmitted, as far as the voltage level of these systems is concerned. In large transmission systems there are voltages ranging from 230 to 750 kV. In regional systems, the voltage levels range from 13.8 to 138 kV, including the 34.5 and 69 kV thresholds. Voltages lower than these are left only to distribution systems.

3.1. Reliability criteria

The planning of transmission systems can be defined as the determination of the capacity of several system components, so that the demand is attended appropriately in the main load points [4,7].

The use of reliability indexes allows the determination of the points in which the allocation of investment is desirable, while keeping the risk levels within acceptable limits in the most important load buses.

The most used indexes are the LOLP and the EDNS. LOLP is a function of the rates of forced outage of each element of the system, while EDNS is a function of both the rates of forced outage and the capacity of each element.

When the reliability criterion is used for the transmission planning, sensibility coefficients can be calculated, given by the partial derivatives of the EDNS with respect to the capacity of the system components, allowing the determination of where it is more attractive to add an incremental transmission capacity. This procedure is repeated until the value of EDNS is equal to or less than the one initially specified.

3.2. Contingencies criteria

An electrical system is considered safe with respect to contingencies of order n if the loss of any n lines belonging to the transmission network does not cause overloads to the remaining lines and if the loads are attended satisfactorily [8].

By using the expansion method presented, a more complete modelling can be developed permitting to obtain in the end of the process, a robust network, resistant to the first order contingencies [6].

This is done by removing temporarily one line of the network, obtaining a new set of constraints, different from the initial ones, reflecting the change suffered by the system. The line removed must be restored to the system before a new line is considered for a new change of the constraints.

This process is repeated until all the desired contingencies are evaluated. The different constraints obtained through this process are concatenated, resulting in the final modelling. The main contingencies to be assessed can be obtained through a very simple process, employing the nodal impedance matrix of the system, used in the calculation of the linearized power flow, as shown in [6].

The final modelling will present the characteristic shown in figure 3, i.e., the typical form of a dual angular block. It is important to observe the coupling existing among the constraints through the integer variables, what brings immediately the Benders' decomposition method as the most attractive for the solution of large size problems.

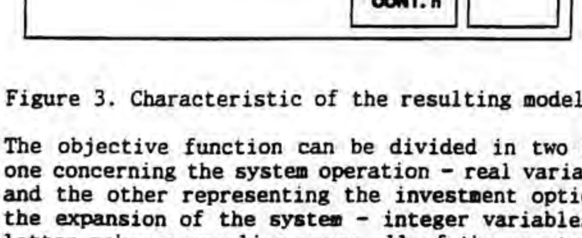


Figure 3. Characteristic of the resulting model.

The objective function can be divided in two parts, one concerning the system operation - real variables - and the other representing the investment options in the expansion of the system - integer variables. The latter makes a coupling among all of the constraints.

In this case, the optimization process is carried out in two stages; in the first one, a network able to attend the demand without any contingency being considered is determined. In the second stage, with the same set of lines proposed in the first one, it is determined which are the reinforcements that attend the first order contingencies at a minimum cost.

This modelling can be used for the expansion of an existing network with first order analysis or multiple contingencies. Since the reliability can be related to the output of any line, the method can also be employed to determine which is the best reinforcement for the system, during the occurrence of a particular contingency.

4. A STUDY CASE

One of the first authors to present the optimized planning of transmission networks was L.L. Garver in 1970. Since then, practically every work in the same area presents the same study case for comparison of the methodologies proposed. So, the same example is applied here and its data is outlined in his work [1].

In this case, some considerations are pertinent with respect to the proposed lines, so that the example mentioned can be applied, that is, it is assumed five thresholds for the lines, the costs and capacity of which vary linearly with the level of the threshold and with its lenght. The effect of the transmission losses are neglected.

It was sought to develop a numerical procedure which, from the current network data and for the lines proposed, can generate the expansion model automatically, the solution of which can be obtained by any computational package specialized in the solution of optimization problems. Hence, it is necessary to make the network equations explicit, such as the equations of buses, of the existing loops and of the loops involving the proposed lines. This can be done by using the network incidence matrices and basic loops matrices, as outlined in [9].

Figure 4a presents the original network, as well as the proposed lines. Figure 4b shows the result of the first expansion stage. Figure 5a shows the lines proposed for the second stage and, finally, figure 5b presents the network obtained, considering the criteria of first order contingencies.

Notice that the results found are just the ones obtained by Lee et alii [2], Monticelli et alii [3] and Seifu et alii [8], confirming the efficiency of this new method.

5. CONCLUSIONS

The model proposed has been easily implemented in personal computers, what enable it to be used by small utilities.

It is suggested the use of the Benders' decomposition for large systems. In the case of regional systems, the branch-and-bound method can be applied, without additional problems. The application of the modelling to a test system has shown its efficiency, when compared to other prominent methods.

6. REFERENCES

[1] Garver, L.L.; "Transmission network estimation using linear programming" - IEEE Trans. on PAS, Vol 89, No 7, pp 1688-1697. (1970)

[2] Lee, S.T.Y.; Hicks, K.; Hnyilieza, E.; "Transmission expansion by branch-and-bound integer programming with optimal cost capacity curves" - IEEE Trans. on PAS, Vol 93, pp 1390-1399. (1974)

[3] Monticelli, A.; Santos Jr., A.; Pereira, M.V.F.; Cunha, S.H.; Parker, J.C.G.; Praça, J.C.G.; "Interactive transmission network planning using a least-effort criterion" - IEEE Trans. on PAS. Vol 101, No 10, pp 3919-3925. (1982)

[4] Hsu, Y.Y.; Chan, W.C.; "Optimal expansion planning for electric power systems" - Electric Power Systems Research, No 9, pp 141-148. (1985)

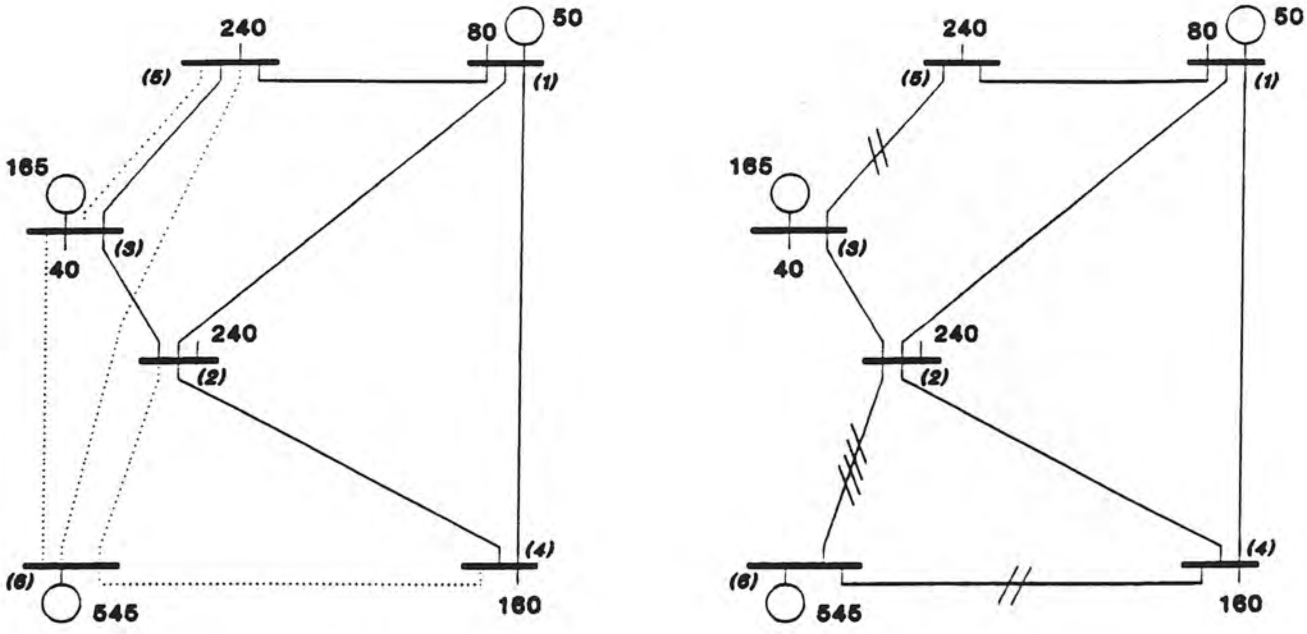
[5] Farrag, M.A.; El-Metwally, M.M.; "New method for transmission planning using mixed-integer programming"- IEE Procedings, Vol 135, Pt C, No 4, pp 319-323. (1988)

[6] Bortoni, E.C.; "Planejamento de sistemas elétricos regionais considerando a contribuição da geração descentralizada"- Dissertação de mestrado apresentada à AIPSE/FEM/UNICAMP. (1993)

[7] Sharaf, T.A.M.; Berg, C.J.; "Reliability optimization for transmission planning" - IEEE Trans. on PAS, Vol 101, No 7, pp 2243-2248. (1982)

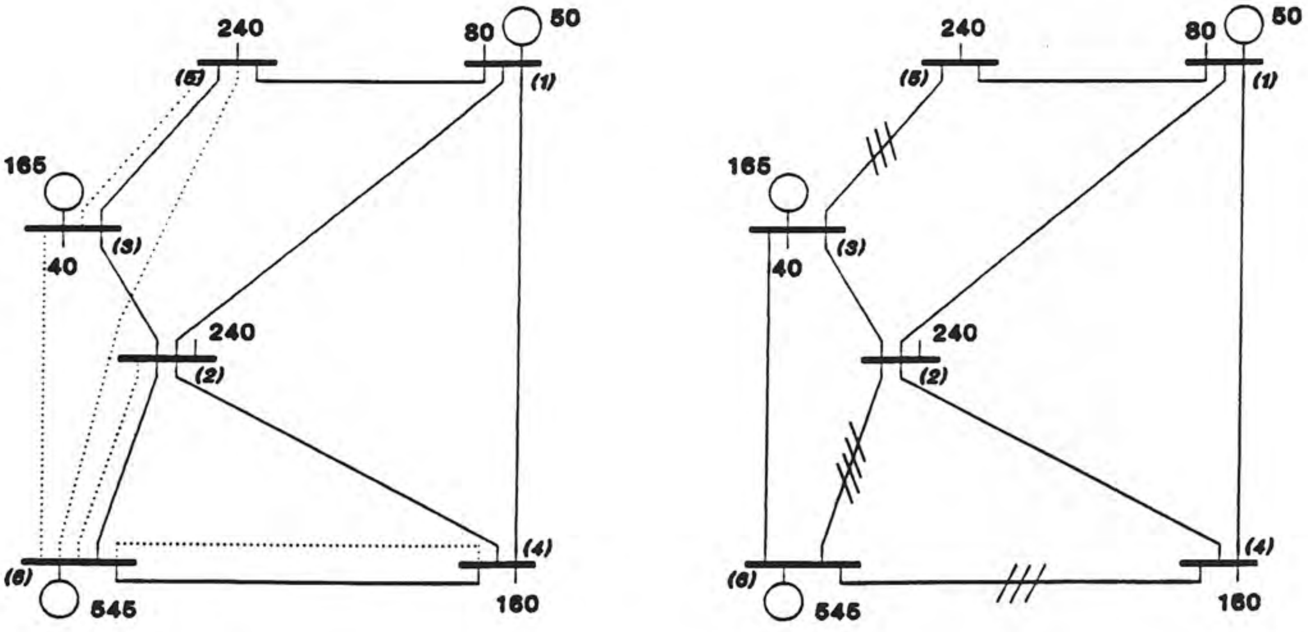
[8] Seifu, A.; Salon, S.; List, G.; "Optimization of transmission line planning including security constraints" - IEEE Trans. on PWRS, Vol 4, No 4, pp 1507-1513. (1989)

[9] Brameller, A.; Allan, R.N.; Homam, Y.M.; "Sparsity" - Pitman Publishing. (1976)



(a) (b)

Figure 4: Study case of an electrical system - first stage.



(a) (b)

Figure 5: Study case of an electrical system - second stage.