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TRANSMISSION EXPANSION PLANNING CONSIDERING THE COST OF SERVICE INTERRUPTIONS FOR THE CUSTOMERS

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ABSTRACT

This paper presents a methodology for the long term planning of power transmission systems that includes in the optimization problem the cost of service interruptions for the customers. Thus, the classic transmission expansion planning and the value based reliability planning are integrated.

The proposed methodology combines the Chu-Beasley specialized genetic algorithm for solving the nonlinear integer mixed optimization problem corresponding to the expansion planning analysis, the sequential Montecarlo simulation method to assess the reliability of the alternatives considered in the expansion planning analysis, and the AC power flow to assess the system electrical performance of the operative states corresponding to the expansion alternatives. As result, this methology allows the explicit (objective, quantitative) assessment of the three aspects that define from a technical point of view the service quality: reliability, security and power quality.

This methodology is tested on a real power system using customer damage functions obtained from a study based on personal interviews. Conclusions are: (1) The results obtained by means of the traditional expansion planning analysis that is based on the DC power flow and the $n-1$ loss of component criteria are very different to those obtained by means of an detailed analysis as the proposed in this paper that includes an explicit asessement of the reliability, security and power quality aspects and the cost for the customers of the service interruptions. (2) It is possible to integrate the transmission expansion planning with the reliability planning, two important technical fields that have traditionally been worked independently. (3) More research is needed to reduce the computational time required by the proposed methodology, a very important aspect for its application on large power systems. (4) For the system under study, is observed that the reduction on the cost for customers due to service interruptions is a very small part of the required investment to improve the reliability.

KEYWORDS

Power system reliability, power system planning, optimization, Montecarlo simulation, value-based reliability planning, genetic algorithms.

1. INTRODUCTION

Under a competitive electricity market environment is necessary to evaluate the economic impact of service unreliability in a more detailed way than it has been performed in traditional planning studies. In adittion, the evaluation of other technical aspects directly related to service quality, like voltage regulation, it is a must due to its impact on other operational aspects, like energy lossess, and its high correlation with customer satisfaction with the service.

Service reliability can be incorporated in the power system planning problem formulation as a constraint or as part of the objective function. When it is incorporated as a constraint it is generally expressed as operational targets like a maximum failure frecuency, maximum hours of service unavailability, maximum loss of load or maximum energy not served. On the other hand, when it is incorporated as part of the objective function it is expressed as the cost of service interruptions.

The cost of service interruptions has two different points of view: The cost for the utility and the cost for the customers. The current trend in power system planning studies is to use the cost of service interruptions for the customer and this kind of analysis is called "value-based reliability". This means the mathematical problem of a power system will seek the minimization of investment costs, operational costs and costs for customers due to service interruptions.

The cost for customers due to service interruptions is defined as all the expenses the customers have to do due to blackouts. For example, if a blackout occurs and a customer buys a battery to power a radio to listen to the news, this expense is a cost directly related to the electricity service interruption and is the minimum value the customer accepts to pay to recover one of the services supplied by electricity. From a theoretical point of view, is expected that the cost for customers due to service interruptions can be translated into investmens for reliability improvements.

The most common way to model the cost for customers due to service interruptions is a function of cost versus interruption duration that is called "customer damage function". This function can be obtained fitting a function, by means of regression analysis, to the average cost reported by the customers for different interruption durations that were asked to them in interviews.

2. TRANSMISSION SYSTEM EXPANSION PLANNING FORMULATION

The transmission system expansion planning problem considering the cost of service interruptions for the customers is expressed as the optimization problem (1) - (10).

$$\min\ v = \sum_{(i,j)} C_{ij} n_{ij} + \overline{SIC} \qquad (1)$$

Subject to:

$$P_i(V,\theta,n) - P_{G_i} + P_{D_i} = 0 \qquad (2)$$

$$Q_i(V,\theta,n) - Q_{G_i} + Q_{D_i} = 0 \qquad (3)$$

$$P_{G_k}^{\min} \le P_{G_k} \le P_{G_k}^{\max} \qquad (4)$$

$$Q_{G_k}^{\min} \le Q_{G_k} \le Q_{G_k}^{\max} \qquad (5)$$

$$0 \le \overline{VDV} \le \overline{VDV}^{\max} \qquad (6)$$

$$0 \le \overline{LC} \le \overline{LC}^{\max} \tag{7}$$

$$(n_{ij} + n_{ij}^{o})S_{ij}^{from} \le (n_{ij} + n_{ij}^{o})S_{ij}^{\max} \tag{8}$$

$$(n_{ij} + n_{ij}^{o})S_{ij}^{to} \le (n_{ij} + n_{ij}^{o})S_{ij}^{\max} \tag{9}$$

$$0 \le n_{ij} \le n_{ij}^{\max} \tag{10}$$

Where: $ij \in \Omega$, $i \in B$, $k \in \Gamma$

C_{ij} : Cost of a circuit that can be added in the right-of-way ij
n_{ij} : Number of circuits added in the right-of-way ij
$\overline{SIC}$: Cost of service interruptions for the customers
$n_{ij}^{\max}$: Maximum number of circuits to added in the right-of-way ij
P_{G_i} , Q_{G_i} : Real and reactive power generated at bus i
P_{D_i} , Q_{D_i} : Real and reactive load at bus i
$P_{G_k}^{\max}$, $P_{G_k}^{\min}$: Maximum and minimum active power generation limits at bus k
$Q_{G_k}^{\max}$, $Q_{G_k}^{\min}$: Maximum and minimum reactive power generation limits at bus k
$\overline{VDV}$: Expected number of voltage violations
$\overline{VDV}^{\max}$: Maximum number of voltage violations
$\overline{LC}$: Expected value of the active load curtailed
$\overline{LC}^{\max}$: Maximum active load curtailment
S_{ij}^{from} , S_{ij}^{to} : Power flow in right-of-way ij , both ≥ 0
$S_{ij}^{\max}$: Maximum power flow in right-of-way ij
B : Number of buses
Γ : Number generation buses

Equations (2) and (3) represent the AC power flow equations, where:

$$P_i(V,\theta,n) = V_i \sum_{j \in B} V_j [G_{ij}(n_{ij})\cos\theta_{ij} + B_{ij}(n_{ij})\sin\theta_{ij}] \tag{11}$$

$$Q_i(V,\theta,n) = V_i \sum_{j \in B} V_j [G_{ij}(n_{ij})\sin\theta_{ij} - B_{ij}(n_{ij})\cos\theta_{ij}] \tag{12}$$

Where:

V , θ : Voltage magnitude and phase
B_{ij} , G_{ij} : Conductance and susceptance matrixes

The set of all possible expansion alternatives defines the solution space Ω of the optimization problem.

This formulation is a non-convex mixed integer non-linear problem that includes an explicit (objective, quantitative) assessment of the three aspects that define from a technical point of view the quality of the service:

- Reliability: By means of the minimization of the cost for the customers of service interruptions and the maximum value for the total load curtailed.

- Power quality: By means of the assessment of voltage regulation and the maximum value for voltage violations

- Security: By means of the convergence of the power flow that is performed for the proposed expansion alternatives.

Even for systems with very few components, the solution space Ω is of huge order. On the other hand, in a strict sense, for every expansion alternative in Ω is mandatory to evaluate the system electrical performance of every operative state, i. e. all the states resulting from the loss of the components. Thus, the combination of all the expansion alternatives of the solution space and all the operative states of the expansion alternatives leads to a "combinatorial explosion" that makes the power system expansion planning problem a task almost impossible to solve in a rigorous way for real power systems.

The strategy to overcome the problem of combinatorial explosion is to reduce the number of cases to be studied i. e. the analysis will seek for a good credible solution not for the best one. The most common approach that have been applied since long ago is to evaluate a small set of expansion alternatives defined by an expert (engineeging judgment) and for them to evaluate the system electrical performance of the operative states defined by the very known $n-1$ loss of component criteria by means of DC load flow.

3. PROPOSED METHODOLOGY

The methodology proposed in this paper combines:

- A genetic algorithm (GA) to search in Ω for a good expansion alternative. In this procedure the expansion alternatives are called "individuals". The Chu-Beasley Specialized Genetic Algorithm (CBGA) is used because it is more efficient than the traditional GA algorithm: CBGA replaces per iteration only one individual that has been improved what is very different to the conventional GA algorithm that replaces all the population of individuals per iteration. Thus, CBGA keeps constant the size of the alternatives population which improves the convergence process and reduces the homogeneity of the population. Details of CBGA are in [8], [10].

- The sequential Montecarlo simulation method (SMSM) to assess the reliability of the expansion alternatives selected by the CBGA: A simulation consists of N iterations or artificial observations of one year of system operation under the conditions specified by a scenario defined by the expansion alternative that is selected by the CBGA and the system maximum demand. Within iterations, the sequence of component outages and restorations is generated. Details of SMSM are in [4], [6], [7].

- The AC power flow to assess the system electrical performance of the operative states of the expansion alternatives selected by the CBGA: The AC power flow is performed for the periods when a component is lost. There will be a "failure" on a load point if: 1. it is isolated, 2. load curtailment is applied, 3. there are voltage violations ($0.95 \leq V_{p.u.} \leq 1.05$). Details of this procedure are in [4], [6], [7].

Figure 1 shows the flowchart of the proposed methodology

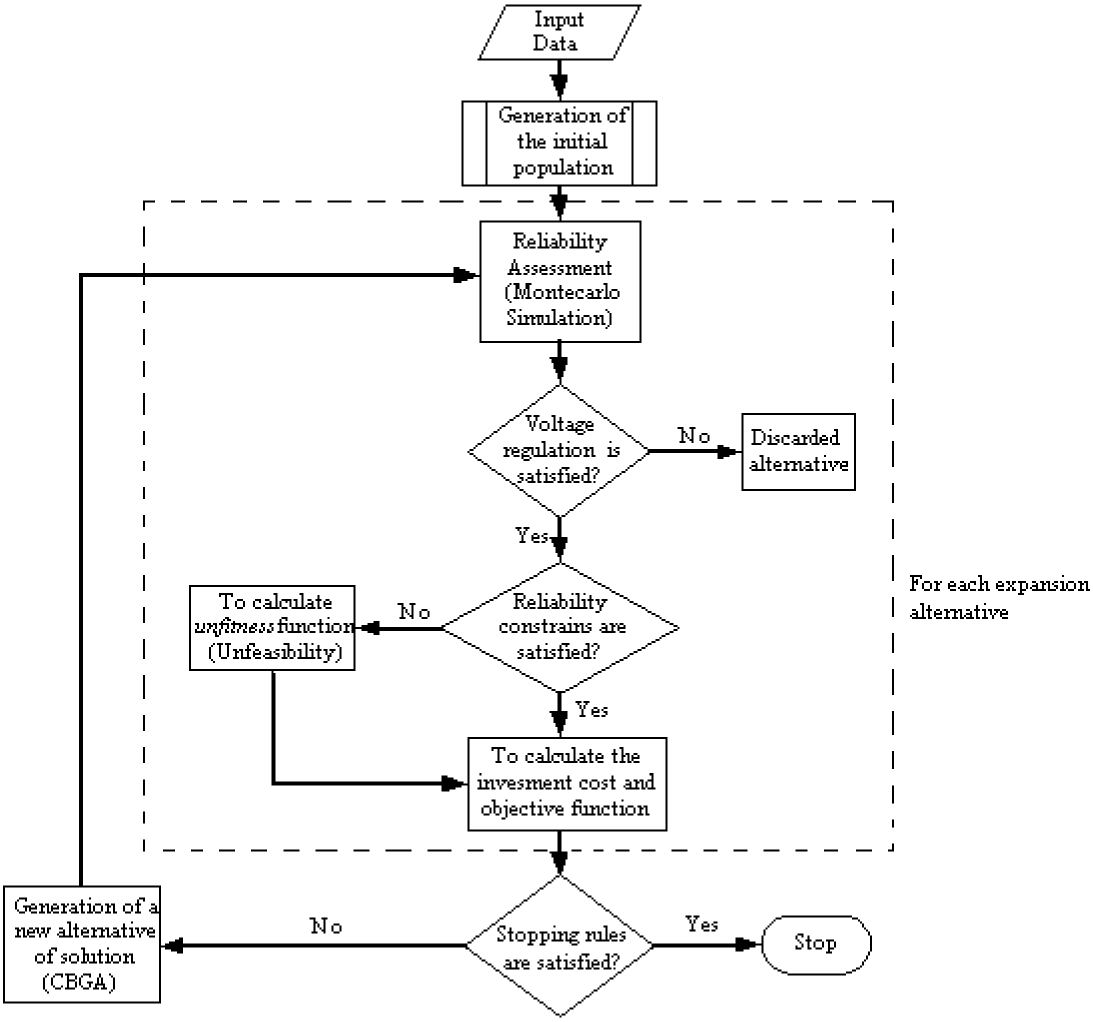

Figure 1. Flow chart of the proposed methodology

The modeling of the system includes: load point hourly active and reactive demand for ordinary days and holidays, two state probability models for all system components, internal generationg dispatch taking into account the availability of the primary energy resources and generator capability curve, randomness on the availability of the support that external systems can give and operative actions such us load shedding and adjustment of reactive equipment. These operative actions are applied when there is abnormal system operative conditions like overloads of busbar voltages out of limits. More details are given in [4], [6], [7].

The CGBA uses the objective function (*fitness*) and an unfeasibility function (*unfitness*). The unfitness function correspond to a penalty when the reliability constrains are not met. The value of the objective function is used to implement the selection procedure and in the substitution of an individual in the population when all members of the population are feasibles. The unfeasibility is used to substitute an individual in the population when there are proposals of unfeasibles solutions in the initial population. More details are given in [8], [10].

The process finishes when the pre-specified number of iterations is satisfied or if the better solution obtained do not vary in a pre-especified number of iterations.

4. EXAMPLE AND RESULTS

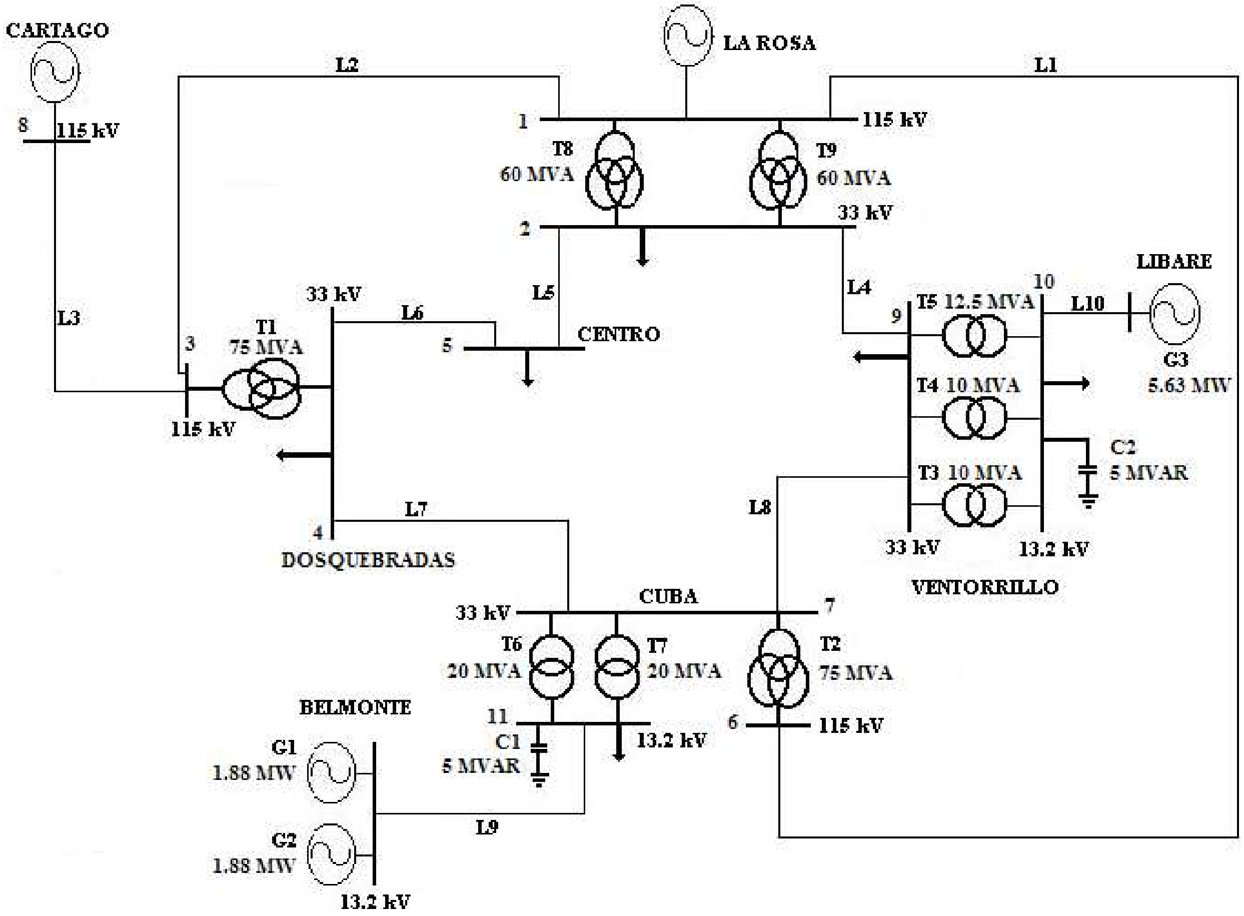

Figure 2. Power system of the city of Pereira

The proposed metodologhy was applied to a power system that serves approximately 115,000 customers in Colombia. See Figure 2. Data of this system is given in [4], [5], [6], [7]. The customer damage functions (13) and (14) were taken from [2], [3]. These functions were obtained by means of a survey based on personal interviews.

Day: $$\overline{C} = (-0.0092T^2 + 13.407T - 181.47)/2310.56 \quad (US\$/Kw) \qquad (13)$$

Night: $$\overline{C} = (-0.0074T^2 + 12.159T - 80.288)/2310.56 \quad (US\$/Kw) \qquad (14)$$

Where: $\overline{C}$: Average cost of service interruptions per kW of customer demand
T : Average time to restoration of the element that is considered lost

An expansion planning study was performed for a year with a maximum system demand of 100 MW. Only single outages on transmission components are considered although the methodology can also consider double outages on any kind of component. The cases of study shown in Table 1 were defined to compare the proposed methodology with others more simplistic. The global results for the test system are shown in Table 2. The upper indexes in the components to be added indicate the number of transmission lines required in a given right of way.

Table 1. Cases of study for the test system

Case	Description	Observations
I	System without expansion	Solved using sequential Montecarlo Simulation, AC power flow, and single outages on transmission components.
II	Expansion obtained by means of GRASP	This method adds components until there are no overloads. It uses DC power flow.
III	Expansion obtained by means of the methodology proposed in this paper	$\overline{LC}^{max} = 5\%$, $\overline{VDV}^{max} = 40$, 100 iterations

Table 2 – Results of the expansion study for the test system

Results	Case I System without expansion	Case II Expansion obtained by means of GRASP	Case III Expansion obtained by means of the proposed methodology
Components to be added	-----------	--------	1-3^1 , 1-6^1, 3-8^2, 4-5^2, 6-7^1, 7-11^1
Load curtailment [MW/year]	1322.65	0.00	0.59
Voltage Violations [event/year]	19.02	Not calculated	1.66
Investment Cost [USD$]	0.00	0.00	7’000,000.00
Cost of interruptions for custormers [USD$/year]	588,550.00	Not calculated	510.26
Required computational time [hours]	0.6	1.5	900

5. CONCLUSIONS

1. The results obtained by means of the traditional expansion planning analysis that is based on the DC power flow and the $n-1$ loss of component criteria are very different to those obtained by means of a detailed analysis, as the proposed in this paper, that includes an explicit asesseement of the reliability, security and power quality aspects and the cost for the customers of the service interruptions. For the conditions defined for the expansion planning of the system under study, the results of the simplified approach are misleading because they show that expansion is not required.

2. It is possible to integrate the transmission expansion planning with the reliability planning, two important technical fields that have traditionally been worked independently.

3. More research is needed to reduce the computational time required by the proposed methodology, a very important aspect for its application on large power systems.

4. For the system under study, is observed that the reduction on the cost for customers due to service interruptions is a very small part of the required investment to improve the reliability. However, this result depends on the specific economic conditions of the customers and cannot be generalized to power systems of other countries or regions with very different economic development.

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