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SOLUTION METHODOLOGY FOR TRANSMISSION PLANNING CONSIDERING DEMAND UNCERTAINTY AND DIFFERENT CONDUCTOR PROPOSALS

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ABSTRACT

This paper presents a methodology for solving the static planning problem in electrical energy transmission networks considering demand uncertainty and conductor selection for the transmission lines that belong to new paths. The optimization problem is solved using a specialized genetic algorithm which uses the logic of the genetic algorithm proposed by Chu and Beasley, combined with exact optimization. The testing bench chosen for the proposed methodology was the Colombian power system of 93 nodes and 155 candidate lines. The results obtained improve the static planning solution for the Colombian power system.

KEYWORDS: Genetic algorithm; Optimization; High temperature low sag (HTLS) conductor; Transmission planning; demand uncertainty .

METODOLOGÍA DE SOLUCIÓN PARA PLANEAMIENTO DE LA TRANSMISIÓN CONSIDERANDO INCERTIDUMBRE EN LA DEMANDA Y PROPUESTAS DE DIFERENTES CONDUCTORES

RESUMEN

En este artículo se presenta una metodología de solución para resolver el problema de planeamiento estático de redes de transmisión de energía eléctrica, considerando incertidumbre en la demanda y selección de conductores en las líneas de transmisión que hacen parte de los nuevos corredores. Este problema de optimización se resuelve usando un algoritmo genético especializado que utiliza la lógica del algoritmo genético propuesto por Chu y Beasley, combinado con una técnica exacta. La metodología se prueba sobre el sistema eléctrico colombiano de 93 nodos y 155 líneas candidatas. Los resultados obtenidos mejoran la solución para el planeamiento estático del sistema eléctrico colombiano.

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PALABRAS CLAVE: algoritmo genético; optimización; conductores de alta temperatura y baja dilatación; planeamiento de la transmisión; incertidumbre en la demanda.

METODOLOGIA DE SOLUÇÃO PARA PLANEJAMENTO DA TRANSMISSÃO CONSIDERANDO INCERTEZA NA DEMANDA E PROPOSTAS DE DIFERENTES CONDUTORES.

RESUMO

Neste artigo apresenta-se uma metodologia de solução para solucionar o problema de planejamento estático de redes de transmissão de energia elétrica, considerando incerteza na demande e seleção de condutores nas líneas de transmissão que fazem parte dos novos corredores. Este problema de optimização se soluciona usando um algoritmo genético especializado que usam a lógica do algoritmo genético proposto por Chu y Beasley, combinado com uma técnica exata. A metodologia se experimenta sobre o sistema elétrico colombiano de 93 nodos e 155 linhas candidatas. O resultados obtidos melhoram a solução para o planejamento estático do sistema elétrico colombiano.

PALAVRAS-CHAVE: Algoritmo genético; Optimização; Condutores de alta temperatura e baixa dilatação; Planejamento da transmissão; incerteza na demanda.

1. INTRODUCTION

The traditional problem of expansion planning for electrical energy transmission networks determines new investments in transmission lines and high voltage AC substations, which are necessary for the adequate transfer of electrical energy between different points on a power system, both in terms of current operation and future operation. The options associated with this problem are characterized by their high investment costs, their long construction periods, and their delayed return on investment. Planning studies take the current network as a point of reference and consider the increased demand at system nodes, the alternatives for new generation, and repowering existing generation on a time horizon that is generally of 10 or more years.

Static planning determines the minimum-cost solution through a mathematical optimization problem that considers the existing network as part of the future solution; that is, it does not consider the possibility of reiterating, moving, or permanently disconnecting elements that are operating in the current network. It also assumes that a planning agent has previously established the following aspects: 1) demand growth in the system's nodes; 2) location and quantity of demand in new nodes; 3) amount and location of new generation; 4) additional capacity of existing power plants that are being or will be repowered; 5) geographical location, cost, and electrical characteristics of new transmission paths; 6) cost associated with additional circuits that may be connected in parallel with already established circuits on existing paths; 7) location, size, and cost of new substations; 8) voltage levels at which new and existing paths operate; and 9) voltage levels associated with new substations. It is important to clarify that static planning does not apply to systems with an electricity market. In the case of unregulated systems, the methodology must consider aspects associated with open access which are not are not taken into account in this study.

The problem of planning for electrical energy transmission networks is a nonlinear mixed-integer problem (NMIP) and it can also be an NP-complete problem. It has been shown to be a multimodal non-convex problem that cannot be successfully solved using exact optimization techniques when the system is large and has a large number of isolated nodes. In small and medium-sized systems, the optimal solution is found with methods like branch and cut or branch and bound (Bahiense et al., 2001; Sousa & Asada, 2011). In these cases, it has been found that the computational systems require a great deal of calculation time compared to those required by metaheuristic techniques like tabu search (TS) or the genetic Chu-Beasley algorithm, GCBA, (Beasley & Chu, 1997). Problems that are simultaneously NMIP and NP-complete are characterized as being the most difficult to solve. The problem of planning is made up of linear and nonlinear functions that include continuous variables (angular difference, power flow along lines, etc.) and integer variables (number of lines or transformers that must be added to the network). Real-life systems can include hundreds or thousands of variables and restrictions.

To solve the expansion planning problem, different solution methodologies ranging from heuristic techniques and exact NMIP methods to metaheuristic techniques have been used. An initial approach to the planning problem was made by Garver (1970). This approach was founded on the principles of linear programming. Other techniques have been based on nonlinear programming (Sanchez et al., 2005), heuristic techniques (Monticelli et al., 1982), and metaheuristic techniques (Gallego, 1997).

A review of the publications and models that have been used for planning problems can be found in Latorre, Cruz & Areiza (2003) and in Romero, García & Haffner, (2002). Sum-Im et al. (2006) include a review of the types of proposals, and Lee et al. (2006) present a classification of the algorithms used. Escobar (2008) and Hemmati, Hooshmand & Khodabakhshian (2013) also present a review of the different studies completed regarding transmission planning.

This study presents a solution methodology that differs from the model traditionally used to solve the static planning problem for expansion in two regards: 1) it allows for selection of the most appropriate conductor for new transmission paths, and 2) it takes demand uncertainty into account. The second aspect is related to the fact that in long-term planning, the future demand is obtained through a process of demand projection that determines three scenarios: one pessimistic, one optimistic, and one intermediate and deterministic. Traditional planning uses the deterministic demand value. However, demand can be thought of as a variable that can assume a value within a defined range between the pessimistic and the optimistic scenarios. This variability can be taken advantage of in the optimization process since the long-term future network may be considered appropriate if it attends to a demand in each bar of the system found within the range of uncertainty. This condition can avoid high-cost investments that are made to attend to small deferrals in uncertain future demands with very low benefit-cost ratios. Some studies in which demand is considered a variable in the planning problem can be found in Bolaños, Correa & Escobar (2008), Escobar, Romero & Gallego (2008), Silva et al. (2005), and Silva et al. (2006).

In addition to demand uncertainty, this study also considers selection of the most appropriate conductor for each new transmission path. Therefore, caliber and construction technology are also considered to be variables. The goal is to benefit from new production technologies to increase transmission capacity in order to have a positive impact on the system's security and take advantage of the economies of scale that appear when using higher-capacity conductors in structures similar to those used for traditional conductors in the investment plan.

In the solution technique, a genetic Chu-Beasley algorithm is used. In its coding, this algorithm uses a chromosome with two components. The chromosome's first component defines *what*, *where*, and *how many* additions must be made; and the second component selects the conductor that must be used for each line in the system for the case of new transmission paths. The solution achieved through this optimization process must guarantee adequate operation in a long-term future generation-demand scenario.

This study uses the Colombian transmission system as a reference. This system contains 93 nodes and 155 paths and is modified to consider inclusion of high temperature low sag (HTLS) conductors in the investment proposals for new transmission paths. It also considers an uncertainty of ±5% in deterministic demand. The results obtained create a relevant economic benefit in terms of investment costs.

2. PLANNING PROBLEM MODEL

The mathematical model used to solve the static planning problem for transmission with demand uncertainty and proposals for conductors of different caliber and technology is presented below. It is derived from the DC model (Escobar, Gallego & Romero, 2010), which is considered ideal for long-term transmission planning projects.

$$
\begin{array}{l}
\min \;=\; \sum_{(i,j)\in\Omega_2} C_{ij} n_{ij} + \sum_{(i,j)\in\Omega_3} C''_{ij} n''_{ij} + \alpha \sum_{i\in\Omega_1} r_i + \beta \sum_{i\in\Omega_1} \left| d_i - d_{i0} \right| \\
s.a. \\
S^0 f^0 + S' f' + g + r - d = 0 \\
f^0_{ij} - (\theta_i - \theta_j)(n_{ij} + n^0_{ij})\gamma_{ij} = 0 \qquad \forall\ (i,j)\ \in\ \Omega_2 \\
f'_{ij,k} - (\theta_i - \theta_j) n'_{ij,k} \gamma'_{ij,k} y_{ij,k} = 0 \qquad \forall\ (i,j)\ \in\ \Omega_3,\ k = 1,\ldots,nk \\
\sum_{k=1}^{nk} y_{ij,k} = 1 \ \ \forall\ (i,j)\ \in\ \Omega_3 \\
n''_{ij} = \sum_{k=1}^{nk} n'_{ij,k} y_{ij,k};\ \ C''_{ij} = \sum_{k=1}^{nk} C'_{ij,k} y_{ij,k} \\
f'_{ij} = \sum_{k=1}^{nk} f'_{ij,k}; \\
\left| \theta_i - \theta_j \right| \le \dfrac{\overline{f_{ij}}}{\gamma_{ij}} \qquad \forall\ (i,j)\ \in\ \Omega_2 \\
\left| \theta_i - \theta_j \right| \le \min \left\{ \left(\dfrac{\overline{f_{ij,1}}'}{\gamma'_{ij,1}} + M(1 - y_{ij,1}) \right), \ldots, \left(\dfrac{\overline{f_{ij,nk}}'}{\gamma'_{ij,nk}} + M(1 - y_{ij,nk}) \right) \right\} \ \forall\ (i,j)\ \in\ \Omega_3 \\
0 \le g \le \overline{g} \\
d_{\min} \le d\ \le d_{\max} \\
0 \le n_{ij} + n^0_{ij} \le \overline{n_{ij}} \\
0 \le n''_{ij} \le \overline{n_{ij}} \\
0 \le r \le \overline{r} \\
y_{ij,k} \in \{0,1\},\ \left\{ \mathrm{n}_{ij}, n^0_{ij}, n'_{ij,k}, n''_{ij} \right\}\ \mathit{Entero},\ \left\{ \gamma_{ij}, \gamma'_{ij,k} \right\}\ \mathit{Discreto},\ \left\{ f^0_{ij}, f'_{ij,k}, g_i, \theta_j \right\}\ \mathit{Irrestricto}
\end{array}
\tag{1}
$$

In the model above, C_{ij} is the cost of adding a circuit to branch *i-j* of an existing path; $C'_{ij,k}$ is the cost of adding a circuit with a type *k*,conductor in branch *i-j* of a new path; C''_{ij} is the cost of adding a circuit in branch *i-j*, in a new path; Ω_2 and Ω_3 rerepresent the set of existing and new transmission paths, respectively; Ω_1 is the set of load node; α is a penalty parameter associated with unserviced power; β is a penalty parameter associated with deferral of serviced demand with regards to the deterministic demand; *r* is the artificial generators vector; d_{io} is the deterministic demand at node *i*; d_i is the serviced demand at node *i*, and it must be found within ±5% with regards to d_{io}; S^0 and S' are node-branch incidence matrices for the electricity system in the base network and the new network, respectively; f^0 and f' are flow vectors whose elements represent the total flow in path *i-j* in the base network (f_{ij}^0) and in the new network (f'_{ij}) for a type *k* conductor, *g* is the nodal generation vector, *d* is the nodal demand vector, γ_{ij} and $\gamma_{ij,k}$ are the susceptances of each circuit in path *i-j* in the base network and in the new network for type *k* conductors; θ is the nodal angle vector; $\overline{f}_{ij}$ and $\overline{f}_{ij,k}$ are the maximum allowed flow for a circuit in path *i-j* in an existing path and in a new path that uses a type *k* conductor, respectively; $\overline{g}$ is the vector of maximum node generation d_{min} is a vector that contains the minimum demand that must provided at each node, d_{max} is a vector that contains the maximum demand that must be provided in each node; n_{ij} is the number of additional reinforcements in branch *i-j* of the base network; $\overline{n}_{ij}$ is the maximum number of circuits that can be added to branch *i-j*; n^0_{ij} is the number of existing circuits in branch *i-j* of the base network; $n'_{ij,k}$ is the number of circuits added to branch *i-j* using a type *k* conductor; and $y_{ij,k}$ is a binary variable that allows for selection or no selection of the type *k* conductor for the new *ij* path. The objective function is composed of three terms: the first represents the sum of the costs for additional reinforcements to existing paths, the second term represents the sum of the costs of elements added to the new paths, and the third term represents the sum of the unserviced demands in the load nodes. The following clarifications must be made for the model: 1) *M* eis a large sized parameter that relates the maximum allowed angular aperture for new transmission paths with the susceptance and maximum capacity for the selected type *k* conductor; 2) the groups of restrictions $f'_{ij,k} - (\theta_i - \theta_j) n'_{ij,k} \gamma'_{ij,k} y_{ij,k} = 0$, represent the second law of Kirchhoff applied to the set of reactances for each new transmission path, connected between nodes *i-j* and using a type *k* conductor. If the type *k* conductor is selected, the value $y_{ij,k}=1$, and the power flow for the new path *ij* will be related to the angular aperture and the susceptance of the type *k* conductor. If $y_{ij,k}=0$, the flow $f'_{ij,k}$, is zero; 3) the restriction $\sum_{k=1}^{nk} y_{ij,k} = 1$ guarantees that for every new transmission path *i-j*, only one type of *k* conductor can be selected from the possible *nk*; 4) there are two types of restrictions for angular aperture. The first applies to paths in the existing network and is traditional. The second applies only to new paths and contains the term $M(1-y_{ij,k})$**,** which, for $y_{ij,k}=1$ creates the restriction $|\theta_i - \theta_j| \leq \overline{f_{ij,k}}' / \gamma'_{ij,k}$, for path *i-j* and the selected type *k* conductor. 5) The equation system (1) does not consider modifying the type of conductor in the paths of the existing network and considers demand uncertainty in all load nodes.

3. HIGH TEMPERATURE LOW SAG CONDUCTORS

LoHigh temperature low sag (HTLS) conductors have a greater current capacity than conventional conductors and can operate at high temperatures with low thermal sag, which allows them to transport more power while maintaining safe distances between conductors and the elements surrounding the transmission line (vegetation, etc.) (Thrash, 2001; Baker, 2001; Zamora et al., 2001; Mateescu et al., 2011; Chasipanta, 2012). They are made up of a core which can be steel, steel alloy, or a compound material surrounded by multiple layers of aluminum or aluminum alloy. Unlike conventional conductors, the properties of the aluminum layers are mechanically and electrically stable at temperatures between 200 and 250 degrees centigrade. In regards to conventional ACSR (Aluminum Conductor Steel Reinforced) conductors of the same external diameter, these conductors increase the current capacity by a factor of between 1.4 and 2. The following are HTLS conductors::

a. **ACSS (Aluminium Conductor Steel Suported).** It is formed by aluminum threads braided around an extra-high stress steel core. It is simple to install, but requires more care in installation because it contains annealed aluminum. The operation temperature is close to 200ºC, and when the core is covered by a layer of aluminum, it can reach 260ºC. If galvanized, it can operate at 245ºC. The installation method is the same as that used for ACSR conductors and the possibility of conductor failure due to wear is low. ACSS complies with ASTM (American Society for Testing and Materials) standards B856 and B857.
b. **(Z)TACIR (Super-Thermal Resistant Aluminum Alloy Conductor, Invar Reinforced).** Its construction is similar to that of ACSR. It has a core made of Invar alloy (steel with 36%-38% nickel, which gives it a very low dilation coefficient). The core is surrounded by (Z)TAL, an aluminum zirconium allow that resists temperatures of up to 200°C. Installation of (Z)TACIR is the same as for a conventional ACSR conductor.
c. **G(Z)TACSR (Gap-type Super-Thermal Resistant Aluminum Alloy Conductor, Steel Reinforced).** This conductor has a normal steel core, but during installation, its steel withstands any stress. It requires a special procedure and installation team. On the other hand, its installation is not recommended in areas with high loads of ice.
d. **ACCR (Aluminum Conductor Composite Reinforced).** It is made of aluminum zirconium alloy threads that are resistant to temperature, which allows for continuous operation at 210°C and emergency regimens of up to 240°C. The core is reinforced with ceramic fibers that are found within a matrix of pure aluminum filaments to improve conductivity. The ACCR conductor is certified under ASTM standard B976. The installation method

Table 1. HTLS conductor costs, installation, and accessories, compared to ACSR.

Conductor	ACSR	ACSS	GZTACSR	ZTACIR	ACCC	ACCR
Relative cost	1	1.1-1.5	2	3.5	5-7	10

is similar to the conventional one, and care must be taken not to bend and break the ceramic fibers. Installation time is 10% above that of conventional installation.

e. **ACCC (*Aluminum Conductor Composite Core*).** It is made of a core with carbon fibers and an aluminum coating. ACCC conductors use high-temperature annealed aluminum technology. Their core is 25% stronger than steel and 60% lighter, which allows for increasing the aluminum content by over 25% without increasing diameter or weight. It also has a higher roughness coefficient on the conductor's surface and lower losses due to the corona effect. Under normal conditions (up to 200°C), no plastic deformation is produced.

The relationship of HTLS conductor costs, their accessories, and their installation with regards to a conventional ACSR conductor is shown below (Mateescu et al., 2011).

4. SOLUTION METHODOLOGY

In this proposal, the mathematical optimization technique evaluates a larger solution space than that evaluated in traditional planning since it considers different types of conductors for each candidate circuit and selects those that minimize global investment costs for a future generation scenario. It also considers a percentage of demand deferral for each of the system nodes for the future demand projection. It is thereby possible to service a greater or lesser amount of the demand at each of the system's nodes depending on what is most advantageous for the cost minimization process.

In traditional planning, the organisms in charge of planning establish expected future demand and the type of conductor to be used in each new path a priori, which can lead to less than optimal solutions. This study considers that demand can vary by up to 5% below (lower limit) and above (upper limit) the deterministic value. Thereby, the optimization process selects the demand values that must be serviced between these minimum and maximum values, bearing in mind the network's configuration and the objective function. One relevant aspect is that there are HTLS conductors with a greater transportation capacity but with a diameter similar to that of ACSR conductors. They can also use the same structures and the majority of the accessories required for setup of ACSR conductors. Under these conditions, the cost overrun mainly affects the conductor, which is a fraction of the total path costs. This can produce low cost overrun factors when compared with total investment costs for circuits for different path options.

In a new project, approximately 30% of the total transmission line cost is associated with the conductor. This means that when increasing the cost of the conductor 1.5 times (ACSS vs. ACSR), the total cost for the line is increased approximately 1.15 times. The increase in cost is lower than the increase in the circuit's transmission capacity, which for an ACSS conductor is 1.8 that of an ACSR conductor. Therefore, there is a net benefit that favors using these conductors. It is also interesting in cases in which a single circuit with HTLS conductors allows for transporting the same power that two circuits with conventional conductors are able to transport. The decision of whether to use HTLS conductors is left up to a process of optimization in which different conductor proposals are considered for each network branch.

In order to consider replacing a conventional conductor with an HTLS conductor, the following conditions must be met: 1) for a given section of a network, the HTLS conductor must present a high-temperature dilation that is less than or equal to the dilation shown by a conventional conductor operating at a lower temperature. 2) The maximum horizontal stress must not exceed that of the conventional conductor by more than 10% (to avoid structure and foundation modifications). 3) The HTLS conductor must have a high damping coefficient. 4) The diameter must be equal to or less than that of a conventional conductor (to avoid modifications to the structure or other elements in the network). 5) It must have the same or lower electrical resistance so as not to significantly affect electrical losses.

The use of HTLS conductors incentivizes research into the problem of planning in electrical energy transmission network expansion given that economies of scale can be taken advantage of if these conductors are used. In 1998, CIGRE (International Council on Large Electric Systems) administered a survey regarding the conductors used in several countries in order to project the capacity of their networks into the future. The results of the survey showed that the majority of networks, nearly 82%, are built with ACSR conductors (CIGRE, 1998). It is therefore interesting to investigate the advantages of considering HTLS conductors among the alternatives for future investments.

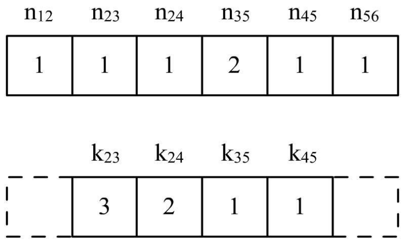
In this study, the optimization process that selects the best subgroup of transformers, transmission lines, and conductor types is a specialized genetic Chu-Beasley algorithm (GCBA). Each of the parts that make it up is described below:

a) Codification. The decision chromosome has two components. In the first component, the specialized GCBA must decide on the addition of circuits both on new paths and on existing ones. In the second component, in the case of new paths, it must decide on the type of conductor for its operation. **Figure 1** presents the codification scheme used.

In **Figure 1**, n_{12} y n_{56} are additions to substations. n_{23}, n_{24}, n_{35} and n_{45} are additions to transmission lines in new paths. k_{ij} defines the type of conductor proposed for the transmission lines. For example, in line *2-3*, a type 3 (k_{23}=3) conductor is selected, in line *2-4*, a type 2 (k_{24}=2) conductor is selected, in line *3-5*, a type 1 (k_{35}=1) conductor is selected, and in line *4-5*, a type 1 (k_{45}=1) conductor is selected. In the database, each type of conductor is related to its specific data. In an existing transmission path, reinforcements may only be installed using the same type of conductor already present in said path.

b) Initial population. The initial population for genetic algorithms is generally constructed randomly, which usually increases the computational effort and requires more time to find acceptable solutions. This problem can be improved with populations constructed heuristically or in a controlled random manner, including one or more sensitivity criteria. A summary of the most common techniques for constructing the initial population can be found in Escobar, Gallego & Romero (2011). Experimental tests have shown that by constructing one part of the population with constructive heuristic techniques and the other part in a controlled random manner, the optimization process's performance is improved.

Figure 1. Codification proposed in the methodology



c) Diversity criteria. During the entire GCBA optimization process, a distance of separation must be maintained between individuals within the population in order to guarantee the population's heterogeneity. The advantage of this criterion is that is assures a greater exploration of the solution space and avoids premature convergence, which is common in traditional genetic algorithms.

d) Selection operator. In GCBA, the selection process is completed by applying the tournament method. This technique selects *k* participants, where *k* varies between 2 and 4. The process is as follows: *k* individuals are randomly selected from the population. Then the individual with the best objective function is selected and denominated the first parent. Then the process is repeated to find the second parent, guaranteeing in the process that the two parents are different. Then the parents move on to the recombination phase.

e) Recombination operator. In this study, recombination is applied at one point. To do so, a number *p* is randomly selected between one and the number of transmission paths minus one. In the example shown in **Figure 2**, a number between 1 and 5 is selected.

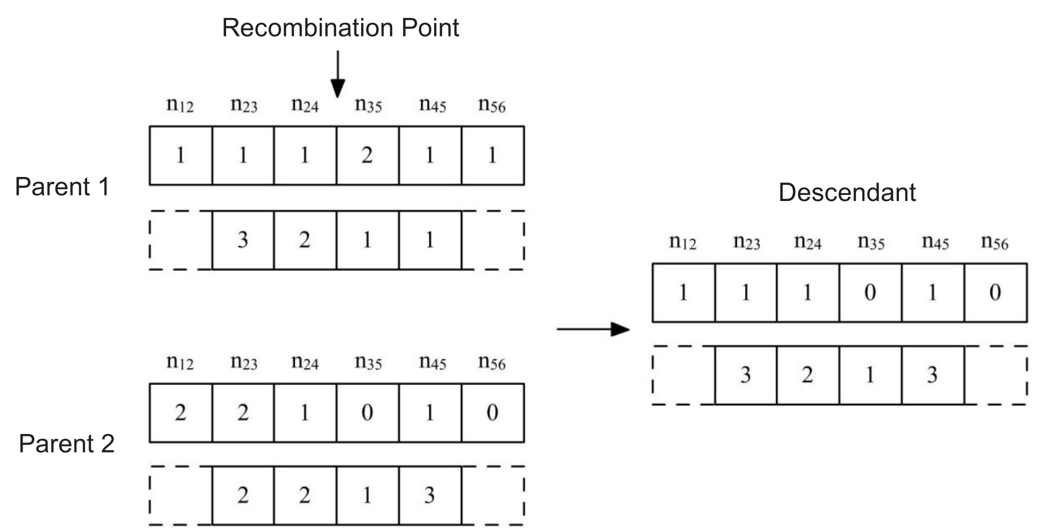
To create the descendant, the contents of the first p paths are taken from parent 1, and the last (*n-p*) elements are taken from parent 2. Since each new path associated with a transmission line is given a type *k* conductor, the type will always accompany the path in the exchange process.

f) Mutation operator. : Mutation in GCBA is exercised in only one individual and is defined as the alteration of 1 or more genes in the decision vector (the descendant obtained from the recombination process) according to the percentage or rate of mutation. In transmission planning, the mutation is carried out according to the rate that is fixed regarding mutation, and modification of the selected gene depends on the load cut. A maximum load cut limit (*maxcor*) is defined, then, if the proposal has a load cut greater than the maximum limit, a greater priority will be probabilistically given to adding circuits than to removing them. The conductor type k_{ij} will also possibly mutate randomly. **Figure 3** shows an example of the mutation operator when the load cut in the investment proposal is lower than the *maxcor*.

g) Local individual improvement. In transmission planning, after the mutation stage, the descendant may undergo a special analysis in which its objective function can be improved and/or its infeasibility can be reduced. Two improvement phases are used. The first phase uses sensitivity analyses, including a constructive heuristic technique based on the proposal made by Villasana-Garver-Salon (Villasana, Garver & Salon, 1985). The sensitivity indicator can identify several additions that may be of interest for improving the solution and select one of them, which may be the best, to add a circuit. The second phase is based on the identification of redundant circuits, that is, elements that, when removed, reduce the investment cost but do not alter the feasibility of the problem. To do so, the current proposal is successively solved by eliminating one added circuit at a time. The transmission lines removal process is completed in the order of greatest to least cost and only considers removal of one circuit at a time from each path.

h) Population modification. In the final stage, a descendant that fulfills diversity (a descendant that is different from all other individuals in the population) can replace one individual in the current population in the following cases. 1) The descendant is infeasible, and there are infeasible individuals in the population with greater infeasibility. In this case, the descendant replaces the most infeasible individual in the population. 2) The descendant is feasible, and there are infeasible individuals in the population. In this case, the most infeasible individual in the population is replaced. 3) The descendant is feasible, and there are only feasible individuals in the population,

Figure 2. Recombination in the methodology



though some are of poorer quality than the descendant. In this case, the descendant replaces the individual with the worst objective function. For all cases, if the descendant has a better objective function that the best in the population (incumbent) and does not fulfill diversity, the aspiration criterion is applied. The aspiration criterion allows for substituting that individual (descendant) for the individual that represents the best solution for the process in a given moment (incumbent). Likewise, all the individuals in the population that do not satisfy diversity with the new individual (descendant) must be eliminated. Then, in the following generations, the new population must be completed with new individuals that are the product of the selection, recombination, local improvement, and mutation stages.

5. RESULTS

The results obtained are given below. The Colombian electricity system with 93 nodes and 155 candidate lines is used as a reference. ACSS type HTLS conductors are proposed for new paths as an alternative to investment in traditional ACSR conductors. Although only one additional type of conductor is proposed, more types of conductors could be proposed. The Colombian system's data can be found in Escobar (2002). Based on this system, ACSS conductors are proposed for the new paths in the 500kV and 230kV transmission network. The data associated with ACSS conductors can be reviewed with the authors. In regards to demand uncertainty, a value of ±5% is used for each node to demarcate a minimum and maximum value based on the deterministic value.

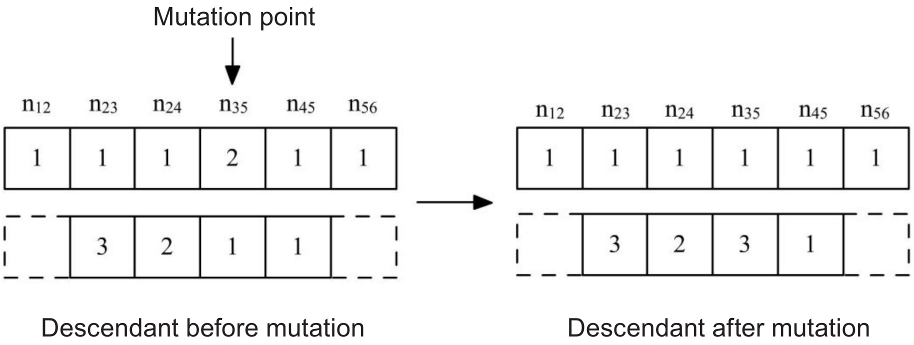
The transmission system planning problem is resolved by using the procedures described above in a computer program written in FORTRAN. Typical conductors for the Colombian transmission network are ACSR (nearly 80%) and AAAC (All Aluminum Alloy Conductor) (nearly 8%) (Mejía, 2008). Infocables (2007) states that the cost of ACSR and AAAC is approximately the same when compared with conductors of the same caliber (the same diameter).

In this study, a cost of 1.5 times more was considered for the ACSS conductor in regards to the ACSR conductor (worst case scenario). Meanwhile, according to the ACSS conductor's power capacity, it is understood that for 230 kV conductors, the increase is of approximately 84% with respect to the original, and for 500kV conductors, the increase is of approximately 80% with respect to the original. However, in this study, the power transport capacity is limited to 69% and 65% in circuits with 230kV and 500kV ACSS conductors, respectively, in order to gain an additional benefit in electrical security during operation and in order to reduce power losses.

5.1 Reference Solution: Traditional Colombian System

The reference for this study is the best known solution for this system with US$560.002 million and a load cut of 0.38MW, reported by Escobar (2002), found through traditional planning and made up of the following circuits:

Figure 3. Mutation in the methodology



$n_{43\text{-}88}$=2, $n_{15\text{-}18}$ =1, $n_{30\text{-}65}$ =1, $n_{30\text{-}72}$ =1, $n_{55\text{-}57}$ =1, $n_{55\text{-}84}$ =1, $n_{56\text{-}57}$ =1, $n_{55\text{-}62}$ =1, $n_{27\text{-}29}$ =1, $n_{29\text{-}64}$ =1, $n_{50\text{-}54}$=1, $n_{62\text{-}73}$=1, $n_{54\text{-}56}$=1, $n_{72\text{-}73}$=1, $n_{19\text{-}82}$=2, $n_{82\text{-}85}$= 1, y $n_{68\text{-}86}$=1.

In the solution above, n_{ij} is the number of additions in path *i-j*. The codification used in this case selects the necessary investments in transmission lines and transformers without including the conductor type for the lines as a variable. This solution will be called solution A.

5.2 Solution Using the Traditional Colombian System Network and Demand Uncertainty

This study includes the solution for the traditional Colombian system network, that is, without HTLS conductor proposals, using the genetic algorithm, and considering demand uncertainty. The best solution found was for US$295.665 million without a load cut, and this will be called solution B. This solution is made up of the following circuits:

$n_{43\text{-}88}$=1, $n_{73\text{-}82}$ =1, $n_{55\text{-}84}$ =1, $n_{27\text{-}64}$ =1, $n_{19\text{-}82}$=2, $n_{82\text{-}85}$= 1, y $n_{68\text{-}86}$=1

In the solution above, n_{ij} represents the number of additions to path *i-j*. The total demand met is 13,950.6MW, representing 95.82% of the mean expected demand or deterministic total, which has a value of 14,559MW. The codification used in this case selects the investments necessary in transmission lines and transformers without including the type of conductor for the lines as a variable.

Solution B reduces the cost to 52.7% of that of solution A and meets a demand equal to 95.82% of the deterministic demand. This is explained by the fact that solution B eliminates investments with a low benefit-cost relationship, which greatly increase the investment cost and produce very little impact on the demand met.

5.3 Colombian System Solution with Demand Uncertainty and ACSS Conductor Proposals

The ACSS conductor option is used with a cost of 1.5 times that of the conventional (ACSR) conductor and demand uncertainty. The GCBA finds to solutions with the same cost and meeting a different demand value. The solution found has a cost of US$294.031 million, hereafter called solution C. In a first solution with a load cut of 0.7MW and servicing 13,935.62MW, which represents 95.72% of the mean total expected demand. In the second solution without a load cut, a value of 13,887.58MW is met, representing 95.38% of the mean total expected demand. The additions required in the network when the ACSS conductor option is used are:

$n_{15\text{-}18}$ =1, $n_{55\text{-}84}$ =1, $n_{27\text{-}64}$ =1, $n_{19\text{-}66}$ =1, $n_{62\text{-}73}$ =1, $n_{19\text{-}82}$ =2, $n_{82\text{-}85}$=1, $n_{68\text{-}86}$ =1, $n_{43\text{-}88/ACSS}$ =1

In the solution above, n_{ij} is the addition of a circuit to path *i-j* and $n_{ij/ACSS}$ represents the addition of an ACSS type circuit to path *i-j*.

The solution obtained (B) with ACSS conductors improves solution B by US$1.634 million. It improves situation A by US$265.971 million.

The parameters used in the GCBA were: mutation rate between 3% and 5%, population size between 10 and 40 individuals, and a difference gene diversity factor between individuals in the population for the genetic algorithm. During the parameter calculation phase of the genetic algorithm, less than optimal alternatives are found, but in only a few generations, and long computation times were not needed. These solutions are used to generate to starting points.

Table 2 shows the difference between solutions A, B, and C.

In **Table 2**, the symbol «--» means that the circuit does not appear in the solution. The difference between the solutions can be seen, as well as the circuits they have in common. The low difference between solutions B and C is explained by the fact that both the uncertainty as well as the use of HTLS conductors have the same goal: eliminating high-cost investments associated with low benefit-cost relationships. Therefore, a significant part of the investments that are reduced by the use of HTLS conductors had already been dismissed by the solution that only considered demand uncertainty.

The solutions obtained show that when considering more variables in the transmission planning problem, investment costs can be reduced for an es-

Table 2. Comparison between solutions A, B, and C..

US$ 560,002	US$ 295,665	US$ 294,031
43-88 =2	43-88 =1	43-88/ACSS=1
55-84=1	55-84=1	55-84=1
19-82=2	19-82=2	19-82=2
82-85=1	82-85=1	82-85=1
68-86=1	68-86=1	68-86=1
15-18=1	--	15-18=1
--	27-64=1	27-64=1
--	--	19-66=1
--	--	62-73=1
--	73-82=1	--
30-65=1; 50-54=1	--	--
30-72=1; 62-73=1	--	--
55-57=1; 54-56=1	--	--
56-57=1; 72-73=1	--	--
55-62=1; 27-29=1	--	--
29-64=1	--	--

tablished time horizon. In the case of the Colombian system with demand uncertainty (A), a cost equal to 52.8% of the investment found with traditional planning is obtained. When ACSS conductors and demand uncertainty are considered (B), the cost represents 52.5% of the traditional cost.

The solutions found in B and C reuse circuits from the traditional solution (A) and avoid several investments with low benefit-cost relationships that are used to eliminate small rationings in the load nodes. These rationings are within the range of demand uncertainty.

The optimization process decides to change the 73-82 addition present in solution B for the proposed 43-88 circuit in ACSS and the addition of a circuit at 15-18, 19-66, and 62-73 to reduce the network cost by US$1.634 million. This is why it is important to propose conductors that use new technology.

The solutions found must undergo other analyses, such as for security (n-1 contingency) since some removed circuits could be relevant for obtaining a more reliable system. Electricity market aspects could also be considered. This type of study will be considered in future research.

6. CONCLUSIONS

Considering the technology of conductors to be used in the future transmission network allows for reducing the investment cost in the case of static problem planning. The HTLS conductor analyzed is more competitive in terms of investment cost than traditional ACSR conductors for some branches of the network that require new circuits.

Including demand uncertainty allows for network planning with a lower cost because it is possible to take advantage of the uncertainty associated with future demand projection and also to make additions assuming that any demand within the cone of uncertainty may arise with equiprobability.

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REFERENCES

Bahiense, L., *et al*., (2001). A Mixed Integer Disjunctive Model for Transmission Network Expansion. *Power Systems, IEEE Transactions on*, 16(3), pp.560-565.

Baker, G.C. (2001). Reconductoring Power Lines- an Example Exercise in Conductor Selection. *Rural Electric Power Conference*, April, pp.D1/1-D1/6.

Beasley, J. y Chu, P. (1997). A Genetic Algorithm for the Generalized Assignment Problem. *Computers Operations Research*, 24(1), pp. 17–23.

Bolaños, R. A., Correa, C. A., Escobar A. H. (2008). Planeamiento de la expansión de la transmisión considerando incertidumbre en la demanda y reprogramación de la generación. *Revista Scientia Et Technica*, XIV(40), December, pp. 13-18.

CIGRE, (1998). Survey on Future Use of Conductors. [Online] Available on: <http://www.nexans.us/US/2008/SurveyOnFutureUseOfConductors.pdf>. [Consulted October 19 2012].

Chasipanta J. A.; Canelos R. A. (2012). Estudio para repotenciación de la línea de transmisión Pucará - Mulaló a 138 kV utilizando el conductor más económico. Memorias de jornadas de ingeniería eléctrica y electrónica, Facultad de Ingeniería Eléctrica y Electrónica de la Escuela Politécnica Nacional [online]: Available on:

<http://bibdigital.epn.edu.ec/handle/15000/4902>. [Consulted 01 November de 2012].

Escobar, A. H. (2002). *Planeamiento dinámico de la expansión de sistemas de transmisión usando algoritmos combinatoriales*. Tesis de Maestría. Universidad Tecnológica de Pereira. Pereira.

Escobar, A. H. (2008). *Análise crítica de aspectos de modelagem matemática no planejamento da expansão a longo prazo de sistemas de transmissão*. Tesis Doctoral. Universidad Estadual Paulista Júlio de Mesquita Filho (UNESP), Campus de Ilha Solteira.

Escobar, A. H.; Romero, R. A.; Gallego, R.A. (2008). Transmission Network Expansion Planning Considering Uncertainty in Generation and Demand. *Transmission and Distribution Conference and Exposition: Latin America*, IEEE/PES, (August), pp.1-6.

Escobar, A. H.; Gallego, R. A.; Romero, R. A. (2010). *Modelos usados en el planeamiento de la expansión a largo plazo de sistemas de transmisión de energía eléctrica*. Risaralda, Pereira: Universidad Tecnológica de Pereira.

Escobar, A. H., Gallego, R. A.; Romero, R. A. (2011). Using Traditional Heuristic Algorithms on an Initial Genetic Algorithm Population Applied to the Transmission Expansion Planning Problem. *Revista Ingeniería e Investigación*, 31(1), April, pp. 127–143.

Gallego, R. A. (1997). *Planejamento a longo prazo de sistemas de transmissão usando técnicas de optimização combinatorial*. Tesis Doctoral. Universidad Estadual de Campinas (UNICAMP).

Garver, L. L. (1970). Transmission Network Estimation Using Linear Programming. *Power Apparatus and Systems, IEEE Transactions on*, 89(7), september, pp. 1688–1697.

Hemmati, R.; Hooshmand, R-A.; Khodabakhshian, A. (2013). State-of-the-art of Transmission Expansion Planning: Comprehensive Review. *Renewable and Sustainable Energy Reviews*, 23, pp. 312–319

Infocables (2007). Conductores de Aluminio: 1350, 6201 y serie 8000, la importancia de las puestas a tierra. Procables S.A. n. 5 (January), pp 3-9. [Online]: Available on: <http://www.procables.com.co/downloads/infocables_edicion_5.pdf >. [Consulted October 21 2012].

Latorre, G.; Cruz, R.; Areiza, J. (2003). Classification of Publications and Models on Transmission Expansion Planning. *Power Systems, IEEE Transactions on*,18(2), May, pp. 938–946.

Lee, C. W., *et al*., (2006). Transmission Expansion Planning from Past to Future. *Power Systems Conference and Exposition*, PSCE '06, IEEE PES, october, pp. 257–265.

Mateescu, E., *et al*., (2011). Reconductoring Using HTLS Conductors. Case study for a 220 kV double circuit transmission LINE in Romania. *Transmission and Distribution Construction, Operation and Live-Line Maintenance (ESMO)*,2011 IEEE PES 12th International Conference on, May, pp.1-7, 16-19.

Mejía, A. (2008). *Análisis técnico y económico de la repotenciación de líneas aéreas de alta tensión en un sistema de subtransmisión*. Tesis de Pregrado. Universidad Tecnológica de Pereira.

Monticelli, A., *et al*., (1982). Interactive Transmission Network Planning Using a Least-effort Criterion. *Power Apparatus and Systems*, *IEEE Transactions on,* 101(10) October, pp. 3919–3925.

Romero, R.; Garcia, A.; Haffner, S. (2002). Test Systems and Mathematical Models for Transmission Network Expansion Planning. *Generation, Transmission and Distribution, IEE Proceedings*, 149(1), January, pp. 27–36.

Sanchez, I. G., *et al*., (2005). Transmission Expansion Planning Using the DC Model and Nonlinear Programming Technique. *Generation, Transmission and Distribution, IEE Proceedings*, 152(6), November, pp. 763–769.

Silva, I.D.J., *et al.* (2005). Transmission Network Expansion Planning Considering Uncertainness in Demand. *Power Engineering Society General Meeting*. *IEEE*, 2 (June), pp.1424-1429.

Silva, Id.J., *et al.* (2006). Transmission Network Expansion Planning Considering Uncertainty in Demand. *Power Systems, IEEE Transactions on*, vol.21(4), November, pp.1565-1573.

Sousa, A.S.; Asada, E. N. (2011). A Heuristic Method Based on the Branch and Cut Algorithm to the Transmission System Expansion Planning Problem. *Power and Energy Society General Meeting, IEEE*, July, pp.1-6.

Sum-Im, T., *et al*., (2006). A Comparative Study of State-of-the-art Transmission Expansion Planning Tools. Universities Power Engineering Conference. UPEC '06. *Proceedings of the 41st International*, 1, September, pp. 267–271.

Thrash, F. R.Jr. (2001). ACSS/TW-an Improved High Temperature Conductor for Upgrading Existing Lines or New Construction. *Power Engineering Society Summer Meeting*, 1, July, pp.182-185.

Villasana, R.; Garver, L.; Salon, S. (1985). Transmission Network Planning Using Linear Programming. *Power*

Apparatus and Systems, IEEE Transactions on, 104(2) February, pp.349-356.

Zamora, I., *et al.*, (2001). High-Temperature Conductors: a Solution in the Uprating of Overhead Transmission Lines. *Power Tech Proceedings, IEEE Porto*, 4 September, pp.1-6.

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