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Transmission network expansion planning for the Colombian electrical system: Connecting the Ituango hydroelectric power plant

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ABSTRACT

The hydroelectric power plant HidroItuango represents a major expansion for the Colombian electrical system (with a total capacity of 2400 MW). This paper analyzes the possible interconnections and investments involved in connecting HidroItuango, in order to strengthen the Colombian national transmission system. A Mixed Binary Linear Programming (MBLP) model was used to solve the Multistage Transmission Network Expansion Planning (MTEP) problem of the Colombian electrical system, taking the N-1 safety criterion into account. The N-1 safety criterion indicates that the transmission system must be expanded so that the system will continue to operate properly if an outage in a system element (within a pre-defined set of contingencies) occurs. The use of a MBLP model guaranteed the convergence with existing classical optimization methods and the optimal solution for the MTEP using commercial solvers. Multiple scenarios for generation and demand were used to consider uncertainties within these parameters. The model was implemented using the algebraic modeling language AMPL and solved using the commercial solver CPLEX. The proposed model was then applied to the Colombian electrical system using the planning horizon of 2018–2025.

1. Introduction

Transmission network expansion planning (TNEP) defines where, when, and how many new transmission assets are necessary to ensure reliable and economical operation. Such an analysis is made using a predefined planning horizon. There must be flexibility in the planning process, allowing for the possibility of change and adaptation to an unpredictable environment. The most significant changes in TNEP solutions appear as a result of variations in demand growth and generation planning strategies [1].

This means that TNEP solutions must be flexible enough to allow the deployment of new facilities as required. If the TNEP utilizes just one stage of planning, it is called static planning, whereas if it uses several stages, it is called Multistage Transmission Expansion Planning (MTEP) [2]. In regards to the electricity market, there are two main objectives that need to be considered – power supply quality and competitive pricing [3]. In light of these considerations, an adequate infrastructure with minimal investment is required for long-term planning. For long-term MTEP, simplified mathematical models are usually used to represent the transmission network. Such models, however, only consider active power flows and angles of complex voltages. The transport model, the DC model, and a hybrid model are examples of simplified models used to solve long-term MTEP [4]. In subsequent planning phases, improved models for transmission grids are applied, resulting in more sophisticated analyses, as seen in reactive power planning and stability, among others [5].

Studies of MTEP using the N-1 safety criterion are scarce, though some contributions can be found in Refs. [6–10]. The N-1 safety criterion indicates that the transmission system must be expanded so that the system can continue to operate properly if an outage in a system element (within a pre-defined set of contingencies) occurs. Traditionally, MTEP that takes into account the N-1 safety criterion is carried out in two steps. In the first step, an MTEP problem is solved without consideration of safety criteria, while in the second step, the results of the first step are used and new elements added to the system until it operates properly under the N-1 safety criterion. The advantage of this strategy is that an expansion plan that includes the N-1 security criterion can be proposed with little computational effort. The main disadvantage of this strategy is that the expansion plan is not optimal. Furthermore, the expansion plan generated by the first step greatly influences the resulting expansion plan obtained using the two-step methodology that includes the N-1 safety criterion [9].

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Nomenclature

Ω_b	set of power buses
Ω_l	set of corridors (power lines and power transformers)
Y	set of transmission circuits
T	set of transmission planning stages
S	set of operating scenarios of generation and demand
$C = C^0 \cup C^1 \cup C^2$	set of all operating statuses (including contingencies) for each transmission corridor
C^0	set of operating statuses without branch outages
C^1	set of operating statuses for contingencies at existing branches (power lines and transformers)
C^2	set of contingencies at the candidate branches (power lines and transformers)
c_{ij}	construction cost of each branch (power lines and transformers) at corridor ij
n_{ij}^0	number of branches available at the base (without expansion)
$\bar{n}_{ij}$	maximum number of branches that can be added in transmission corridor ij
x_{ij}	reactance for branches in transmission corridor ij
$f_{ij,c,t,s}^0$	power flow for existing branches, transmission corridor ij, contingency c, planning stage t, scenario s
$f_{ij,y,c,t,s}$	power flow for new branches, transmission corridor ij, circuit y, contingency c, planning stage t, scenario s
$\bar{f}_{ij,c}$	maximum power flow allowed for contingency c at transmission corridor ij
α_t	discount economic factor for net present value (NPV) calculations at planning stage t
v	total investment required for branch (power lines and transformers) additions
$GSDDP_{i,t,s}$	power generation taking the form of SDDP® at bus i, stage t, scenario s
$D_{i,t,s}$	power demand at bus i, stage t, scenario s
$\theta_{i,c,t,s}$	phase angles at bus i, contingency c, stage t, scenario s
$\bar{\theta}$	maximum voltage phase angle
$w_{ij,y,t}$	binary variable representing circuit y in corridor ij in stage t
$N_{ij,c}^{\text{cont}}$	sparse matrix consisting of ones and zeros, if equal to 1 an outage anticipated for a circuit in corridor ij and scenario c. Otherwise, if equal to 0 the circuit is in normal operation

In addition, the approach can be seen as deterministic if all of the input information for the MTEP problem is known with 100% certainty. By contrast, if uncertainties exist in planning, it is said to be stochastic planning [11–15]. Forecasts of demand and generation may be formed using sets of scenarios with an associated probability of occurrence or degree of importance. These forecasts are able to model past experiences, future expectations, and uncertainties on the planning horizon. In terms of power grid stochastic planning, it is necessary to identify critical scenarios wherein a combination of factors (generation dispatch, load configuration, and so forth) produce inadequate network conditions (overloads, under voltages, among others). Thus, transmission reinforcements may be considered as a solution to these problems if they can be economically justified. These issues can be examined using stochastic programming, as discussed in the specialized literature on its application with regards to the following: reinforcing the network against deliberate attacks [11], integrated generation and transmission planning problems [12,13], hydrothermal planning under uncertainty [14], or the selection of the most flexible transmission expansion plan [15].

The main challenge facing developing countries like Colombia is economic development, along with the development of the electrical system. This development entails decision making, in order to connect energy sources with the centers of demand. Thus, the need for new transmission lines, transformers, and substations is greater than the need for Smart Grids or FACTS devices. Additionally, in Colombia the benefits of transmission networks are evaluated using hydrothermal models. These models use DC power flows and optimization as an approximation of market operations. Optimization models with AC power flows only allow for short-term analysis, which is insufficient for evaluating the benefits of network assets that must be paid over long periods of time.

In this paper, a Mixed Binary Linear Programming (MBLP) model is presented, in order to solve the MTEP in the Colombian electrical system; the model uses several scenarios for generation and demand and takes into account the N-1 safety criterion. The use of an MBLP model guarantees the convergence with the optimal solution and the MTEP using commercial solvers. The model is implemented using the algebraic modeling language AMPL and solved using the commercial solver CPLEX. The proposed model is then applied to the Colombian electrical system using the planning horizon of 2018–2025.

The main contributions of this paper are as follows:

- An MBLP model to solve the MTEP problem with various generation and demand scenarios using the N-1 safety criterion. The model result is a unique Transmission Expansion Plan valid in all generation-demand scenarios and grid contingencies.
- An analysis of the interconnections of the HidroItuango hydroelectric power plant within the Colombian electrical system.

2. MBLP model for multistage multiscenarios with safety criterion N-1

2.1. MBLP mathematical model for MTEP

The parameters of the MBLP model for solving MTEP are generated from generation-demand scenarios for each busbar. The solution obtained is a transmission expansion plan that has a minimum cost, and can be applied for safe and reliable operation (N-1 criterion) in every possible scenario. The full MBLP model is presented in (1)–(14):

$$\min v = \alpha_1 \sum_{ij \in \Omega_l} \sum_{y \in Y} c_{ij} w_{ij,y,1} + \sum_{t \in T, t>1} \alpha_t \sum_{ij \in \Omega_l} \sum_{y \in Y} c_{ij} (w_{ij,y,t} - w_{ij,y,t-1}) \quad (1)$$

subject to:

$$\sum_{ji \in \Omega_l} \left(\sum_{y \in Y} f_{ji,y,c,t,s} + f_{ji,c,t,s}^0 \right) - \sum_{ij \in \Omega_l} \left(\sum_{y \in Y} f_{ij,y,c,t,s} + f_{ij,c,t,s}^0 \right) + GSDDP_{i,t,s} = D_{i,t,s} \quad \forall i \in \Omega_b,\ \forall c \in C,\ \forall t \in T,\ \forall s \in S \quad (2)$$

$$f_{ij,c,t,s}^0 = (n_{ij}^0 - N_{ij,c}^{\text{cont}}) \frac{(\theta_{i,c,t,s} - \theta_{j,c,t,s})}{x_{ij}} \quad \forall i \in \Omega_b,\ \forall c \in C,\ \forall t \in T,\ \forall s \in S \quad (3)$$

$$\left| f_{ij,c,t,s}^0 \right| \le (n_{ij}^0 - N_{ij,c}^{\text{cont}}) \bar{f}_{ij,c} \quad \forall ij \in \Omega_l,\ \forall c \in C,\ \forall t \in T,\ \forall s \in S \quad (4)$$

$$\left| x_{ij} f_{ij,y,c,t,s} - (\theta_{i,c,t,s} - \theta_{j,c,t,s}) \right| \le 2\bar{\theta}(1 - w_{ij,y,t}) \quad \forall ij \in \Omega_l,\ \forall y \in Y | y > 1,\ \forall c \in C,\ \forall t \in T,\ \forall s \in S \quad (5)$$