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Transmission Network Expansion Planning Considering Repowering and Integration of Small-Scale Generation

Sergio D. Saldarriaga Zuluaga[1], **Jesús M. López-Lezama**[2]
and Juan C. Castro Galeano[3]

[1] Facultad de Ingeniería, Institución Universitaria Pascual Bravo
Medellín, Colombia

[2] Departameto de Ingeniería Eléctrica, Facultad de Ingeniería
Universidad de Antioquia, Calle 67 No 53-108, Medellín, Colombia

[3] Universidad Pedagógica y Tecnológica de Colombia (UPTC)
Sede Duitama Colombia

Abstract

This paper presents a new modeling approach for the transmission network expansion planning (TNEP) considering repowering of circuits and integration of small-scale generation. The TNEP consists on determining the new assets that will be needed in the network to meet a forecasted demand. Traditionally, the candidate solutions of this problem only consider the integration of new lines or transformers. In this paper we expand the candidate solutions to include repowering of circuits. Also, the integration of small-scale generation is considered. The TNEP problem is modeled as a mixed integer linear programming problem and solved using the software GAMS. Several tests are performed on the Garver system and IEEE 24 bus test system showing the applicability of the proposed model. Results show that circuit repowering in strategic corridors, combined with the installation of small-scale generation, contributes to a significant reduction of the cost of the TNEP.

Keywords: Transmission expansion planning, circuit repowering, small-scale generation, mixed integer linear programming

1 Nomenclature

The nomenclature used throughout the document is provided here for quick reference.

Sets:

Ω_b: Set of buses.
Ω_l: Set of lines.
Ω_g: Set of generators.
Ω_{ln}: Set of new lines.
Ω_{gn}: Set of new generators.
Ω_{le}: Set of existing lines.
Ω_{ge}: Set of existing generators.
Ω_{lr}: Set of existing repowered lines.
Ω_{lnr}: Set of new repowered lines.

Parameters:

d_i: Demand in bus i[MW].
$\overline{g}_k$: Maximum generation limit of generator k[MW].
c_l: Investment cost of line l[$].
cr_l: Repowering cost of line l[$].
cir_l: Investment cost of repowered line l[$].
c_k: Investment cost of generator k[$].
co_k: Operation cost of generator k[$/MW].
$\overline{f}_l$: Maximum power flow limit in line l[MW].
$\overline{fr}_l$: Maximum power flow limit in repowered line l[MW].
x_l^{pu}: Reactance of line l[p.u].
xr_l^{pu}: Reactance of repowered line l[p.u].
S_{base}: Base power [MW].
$\overline{\theta}$: Maximum angle limit [rad].
C_{UD}: Cost of unmet demand [$/MW].

Variables:

w_l: Binary variable indicating new line l.
r_l: Binary variable indicating repowered line l.
wr_l: Binary variable indicating new repowered line l.
z_k: Binary variable indicating new generator k.
UD_i: Unmet demand in bus i[MW].
g_{ki}: Active power generation of generator k in bus i[MW].
θ_i: Angle in bus i[rad].
f_{lij}: Power flow in line l connecting nodes i, j [MW].

2 Introduction

The transmission network expansion planning (TNEP) problem consists on determining the optimal set of elements (typically lines and transformers) that must be installed in a network in order to allow a feasible operation in a pre-defined time horizon at a minimum cost [1]. In general, the TNEP problem is a large-scale, mixed-integer, non-linear and non-convex optimization problem which solution is a challenging task. In practice, the TNEP problem is approached using a simplified network model (DC power flow) allowing to recast it as a Mixed Integer Linear Programming (MILP) problem which is tractable with commercially available software [2]. Solution approaches to the TNEP problem can be broadly classified as those based on classic mathematic programming such as decomposition methods [3] and metaheuristic techniques such as genetic algorithms [4], and particle swarm optimization [5], among others. The specialized literature provides several variants of the TNEP; for example, in [6] a probabilistic contingency analysis is incorporated considering wind power uncertainties. In [7] a stochastic model is proposed incorporating phase-shifting transformers as well as demand-side management. In [8] the authors propose a multi-objective probabilistic TNEP to include wind generation. In [9] the authors propose a two-stage robust optimization approach to deal with uncertain demand and generation capacity in the TNEP problem. An overview and comprehensive analysis of the major publications regarding the TNEP can be consulted in [10] and [11].

In recent years, the growing participation of renewable and small-scale generation has posed a major challenge to the TNEP. In [12] the authors propose a risk assessment model to evaluate the potential negative effects of renewable energy resources in the transmission planning. In [3] the uncertainty of renewable generation is modeled though a scenario generation method, and a chance-constraint approach to the TNEP problem is proposed. In [13] the authors propose a probabilistic TNEP considering distributed generation and demand response programs. Despite of the great number of model adaptations and solution approaches reported for the TNEP problem, to the best of the authors' knowledge, there is not a model that simultaneously considers the repowering of circuits and the inclusion of small-scale generation.

There are several types of generation technologies that can be used in small-scale applications; some of them are controllable, such as reciprocating engines, small hydro and micro turbines; while some others are non-controllable, such as photovoltaic and wind generation. For the sake of simplicity, the stochasticity associated with the energy production of these technologies is not taken into account. On the other hand, repowering of existing network assets (lines and transformers) is a common solution implemented in real power systems. Some examples of the implementation of this type of solution in the TNEP include repowering of circuits in Panama [14], Peru [15] and Brazil [16]. Despite of being common in real applications, repowering is not usually modeled in the classical TNEP problem. In [1] the authors propose repowering and reconfiguration as nonconventional solution candidates for the TNEP problem; however, they do not consider the inclusion of generation. On the other hand, in [17] and [18] repowering is restricted to the distribution expansion planning.

The remaining of this paper is organized as follows. Section 3 describes the proposed mathematical model; Section 4 presents the tests and results for two benchmark power systems and finally conclusions are presented in Section 5.

3 Mathematical Model

The proposed model of the TNEP problem, considering repowering and small-scale generation is given by (1)-(21). The objective function, given by (1), consists on minimizing the operation and investment costs associated to the expansion plan. The first term of the objective function represents the investment cost of new lines; the second term is the cost of repowering an existing line; the third term is the investment cost of a new circuit with the characteristics of a repowered one; the fourth and fifth terms represent the investment and operative costs of a new generator, respectively; finally, the sixth term is the cost of unmet demand. In this case, the binary variables z_k and w_l are used to indicate the existence of new generators and lines, respectively. On the other hand, binary variables r_l and wr_l are used to indicate the repowering of an existing line or the construction of a new line with the characteristics of a repowered one.

$$\begin{aligned}\text{Min: } f1 = &\sum_{l \in \Omega_{ln}} c_l w_l + \sum_{l \in \Omega_{ln}} cr_l r_l + \sum_{l \in \Omega_{ln}} cir_l wr_l \sum_{k \in \Omega_{gn}} c_k z_k + \sum_{k \in \Omega_g} co_k g_{ki} \\ &+ \sum_{i \in \Omega_b} UD_i C_{UDi}\end{aligned} \quad (1)$$

Subject to:

$$\begin{aligned}&\left(\sum_{l \in \Omega_{le}} f_{lji} + \sum_{l \in \Omega_{ln}} f_{lji} + \sum_{l \in \Omega_{lr}} f_{lji} + \sum_{l \in \Omega_{lnr}} f_{lji}\right) \\ &\quad - \left(\sum_{l \in \Omega_{le}} f_{lij} + \sum_{l \in \Omega_{ln}} f_{lij} + \sum_{l \in \Omega_{lr}} f_{lij} + \sum_{l \in \Omega_{lnr}} f_{lij}\right) \\ &\quad + \sum_{l \in \Omega_g} g_{ki} + UD_i = d_i\end{aligned} \qquad \forall i \in \Omega_b \quad (2)$$

$$\frac{f_{lij} x_l^{pu}}{S_{base}} - \left(\theta_i - \theta_j\right) \leq 2\bar{\theta} r_l \qquad \forall l \in \Omega_{le} \quad (3)$$

$$\frac{f_{lij} x_l^{pu}}{S_{base}} - \left(\theta_i - \theta_j\right) \geq -2\bar{\theta} r_l \qquad \forall l \in \Omega_{le} \quad (4)$$

$$\frac{\mathrm{f_{lij}xr_l^{pu}}}{\mathrm{S_{base}}} - \left(\theta_i - \theta_j\right) \leq 2\bar{\theta}(1 - \mathrm{r_l}) \qquad \forall \mathrm{l} \in \Omega_{\mathrm{lr}} \tag{5}$$

$$\frac{\mathrm{f_{lij}xr_l^{pu}}}{\mathrm{S_{base}}} - \left(\theta_i - \theta_j\right) \geq -2\bar{\theta}(1 - \mathrm{r_l}) \qquad \forall \mathrm{l} \in \Omega_{\mathrm{lr}} \tag{6}$$

$$\frac{\mathrm{f_{lij}x_l^{pu}}}{\mathrm{S_{base}}} - \left(\theta_i - \theta_j\right) \leq 2\bar{\theta}(1 - \mathrm{w_l}) \qquad \forall \mathrm{l} \in \Omega_{\mathrm{ln}} \tag{7}$$

$$\frac{\mathrm{f_{lij}x_l^{pu}}}{\mathrm{S_{base}}} - \left(\theta_i - \theta_j\right) \geq -2\bar{\theta}(1 - \mathrm{w_l}) \qquad \forall \mathrm{l} \in \Omega_{\mathrm{ln}} \tag{8}$$

$$\frac{\mathrm{f_{lij}xr_l^{pu}}}{\mathrm{S_{base}}} - \left(\theta_i - \theta_j\right) \leq 2\bar{\theta}(1 - \mathrm{wr_l}) \qquad \forall \mathrm{l} \in \Omega_{\mathrm{lnr}} \tag{9}$$

$$\frac{\mathrm{f_{lij}xr_l^{pu}}}{\mathrm{S_{base}}} - \left(\theta_i - \theta_j\right) \geq -2\bar{\theta}(1 - \mathrm{wr_l}) \qquad \forall \mathrm{l} \in \Omega_{\mathrm{lnr}} \tag{10}$$

$$-\bar{\mathrm{f}}_{\mathrm{l}}(1 - \mathrm{r_l}) \leq \mathrm{f_{lij}} \leq \bar{\mathrm{f}}_{\mathrm{l}}(1 - \mathrm{r_l}) \qquad \forall \mathrm{l} \in \Omega_{\mathrm{le}} \tag{11}$$

$$-\overline{\mathrm{fr}}_{\mathrm{l}}\mathrm{r_l} \leq \mathrm{f_{lij}} \leq \overline{\mathrm{fr}}_{\mathrm{l}}\mathrm{r_l} \qquad \forall \mathrm{l} \in \Omega_{\mathrm{lr}} \tag{12}$$

$$-\bar{\mathrm{f}}_{\mathrm{l}}\mathrm{w_l} \leq \mathrm{f_{lij}} \leq \bar{\mathrm{f}}_{\mathrm{l}}\mathrm{w_l} \qquad \forall \mathrm{l} \in \Omega_{\mathrm{ln}} \tag{13}$$

$$-\overline{\mathrm{fr}}_{\mathrm{l}}\mathrm{wr_l} \leq \mathrm{f_{lij}} \leq \overline{\mathrm{fr}}_{\mathrm{l}}\mathrm{wr_l} \qquad \forall \mathrm{l} \in \Omega_{\mathrm{lnr}} \tag{14}$$

$$\mathrm{wr_l} \leq \mathrm{r_l} \qquad \forall \mathrm{l} \in \Omega_{\mathrm{l}} \tag{15}$$

$$\mathrm{w_l} \leq (1 - \mathrm{r_l}) \qquad \forall \mathrm{l} \in \Omega_{\mathrm{ln}}, \forall \mathrm{l} \in \Omega_{\mathrm{c}} \tag{16}$$

$$0 \leq \mathrm{g_{ki}} \leq \bar{\mathrm{g}}_{\mathrm{k}} \qquad \forall \mathrm{k} \in (\Omega_{\mathrm{ge}}) \tag{17}$$

$$0 \leq \mathrm{g_{ki}} \leq \bar{\mathrm{g}}_{\mathrm{k}}\,\mathrm{z_k} \qquad \forall \mathrm{k} \in (\Omega_{\mathrm{gn}}) \tag{18}$$

$$-\bar{\theta} \leq \theta_i \leq \bar{\theta} \qquad \forall \mathrm{i} \in \Omega_{\mathrm{b}} \tag{19}$$

$$\begin{array}{llll} w_l\ binary; & z_k\ binary; & r_l\ binary; & \forall \mathrm{l} \in \Omega_{\mathrm{ln}}; \forall \mathrm{k} \in \Omega_{\mathrm{gn}}; \\ wr_l\ binary & & & \forall \mathrm{l} \in \Omega_{\mathrm{lr}}; \forall \mathrm{l} \in \Omega_{\mathrm{lnr}} \end{array} \tag{20}$$

$$\theta_i = 0 \qquad \forall \mathrm{i} \in \Omega_{\mathrm{b}}\ /\mathrm{i} = \mathrm{ref} \tag{21}$$

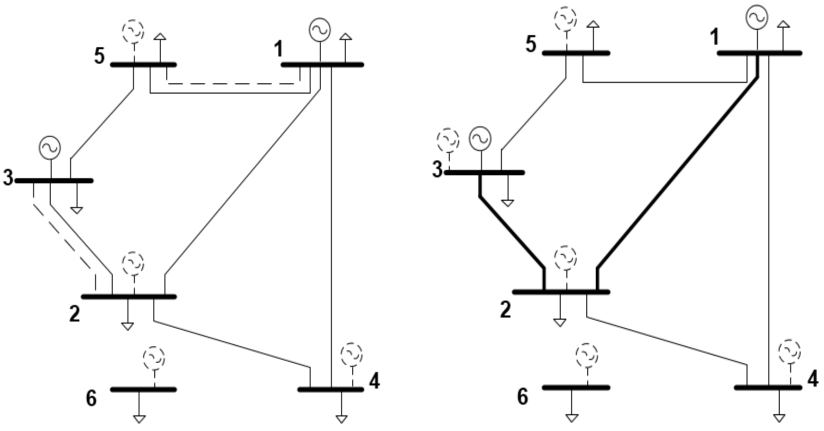
The TNEP problem must consider a large set of constraints regarding system limits. Equation (2) represents the nodal balance constraint. Equations (3) and (4) are used to model the power flow in existing lines, while (5) and (6) do the same for repowered lines. Equations (7) and (8) represent the power flow of new lines constructed in a traditional fashion, while (9) and (10) do the same for new lines that are constructed with the characteristics of repowered ones. Equations (11) and (12) represent the power flow limits of existing and repowered lines, respectively; while (13) and (14) represent the power flow limits of new lines and new lines with characteristics of repowered lines, respectively. Equation (15) guarantees that only new repowered lines are installed in a corridor if it already has one repowered line. Equation (16) prevents new lines to be constructed with the original characteristics of a repowered line. Equations (17) and (18) represent maximum generation limits of existing and new generators, respectively. Equation (19) represents the limits of bus angles; equation (20) indicates the binary nature of the decision variables, and finally equation (21) indicates that the angle in the reference bus must be set to zero. The model given by (1)-(21) allows to find an optimal expansion plan that takes into account repowering of circuits and the inclusion of new generators. This model is a MILP problem that can be solved using commercial optimization software.

4 Tests and Results

In order to demonstrate the applicability of the proposed model, several tests were run with the Garver system and the IEEE 24 bus test system. The proposed model was solved using GAMS under CPLEX solver. Also, for each node of the system the possibility of installing three types of small-scale generators, as part of the expansion plan, was considered. Generators were label as type 1, 2 and 3 with capacities of 10MW, 20MW and 30MW, respectively. Their investment cost was set to 1 Million $/MW. Repowered lines are supposed to be 50% less expensive than new lines in a given corridor.

4.1 Results with the Garver system

This system features 6 buses, two generators and 5 loads that add up 190MW. The future demand is 820 MW, so it is necessary to find the future infrastructure (lines, generators and transformers) that would meet such demand at minimum cost. All combinations of corridors are considered as viable expansion candidates. In this system it is possible to add up to 2 lines per corridor. Also, small-scale generation is considered viable in every bus. Investment cost of transmission lines were taken from [19]. Figure 1 illustrates the results with and without repowering. In both cases small-scale generation is considered as part of the expansion plans. New elements are marked in dashed lines, while repowered lines are in bold line.



(a) (b)

Figure. 1: Expansion plan for the Garver System: a) without repowering and b) with repowering.

The details of the expansion plans depicted in Figure 1 are presented in Table 1. The first column represents new and repowered lines labeled with the buses they interconnect. For example, L1-5 indicates the construction of a new line connecting nodes 1 and 5, while LR2-3 indicates that the line in corridor 2-3 must be repowered. The second column indicates new generators. The label Bus(MW) indicates the location and generation capacity of a generator. For example, N1(30) indicates that a generator of 30MW must be installed in bus 1. Note that the investment cost reduces from 200.057M$ to 180.057M$ (10% approximately) when repowering of circuits is considered. This is because it results less expensive to repower an existing line than to build a new one.

Table 1: Expansion plans for the Garver system reported in Figure 1.

Transmission Lines	Generators Bus(MW)	Cost ([M$])	Obs
L1-5, L2-3	N2(10), N2(20), N2(30), N4(10), N5(10), N5(20), N6(10), N6(20), N6(30)	200.057	Without repowering
LR1-2, LR2-3	N2(10), N3(10), N4(10), N5(10), N5(20), N5(30), N6(10), N6(20), N6(30)	180.057	With repowering

4.2 Results with the IEEE 24 bus power system

This system features 24 buses, 38 lines, 17 lines that add up 2850MW. The infrastructure of this system must be enhanced to attend a future demand of 8550MW. The data of this system can be consulted in [20]. In this case, all existing corridors plus seven more, as indicated in [19] were considered as candidate solutions for new and repowered lines. In this system it is allowed to build up to 2 lines per corridor. Also, for each node of the system, the possibility of installing small-scale generation, as with the previous system, was considered.

Figures 2 and 3 depict the results of the TNEP with and without repowering, respectively. Dashed lines indicate new elements (lines, transformers and generators), while repowering for lines and transformers is indicated in bold. It can be seen in Figure 2 that only repowered lines and transformers are considered in the expansion plan and small-scale generation was introduced only in 4 buses. On the other hand, when repowering is not considered, seven new lines are built and new generation is introduce only in 4 buses but different from those of the first case. The details of the expansion plan are presented in Table 2. Note that the cost of the expansion plan decreases from 502.589M$ to 332.598M$ (33% approximately) when repowering of circuits is considered. As explained before this is due to the fact that repowering a given line is considered to be less expensive than building a new one.

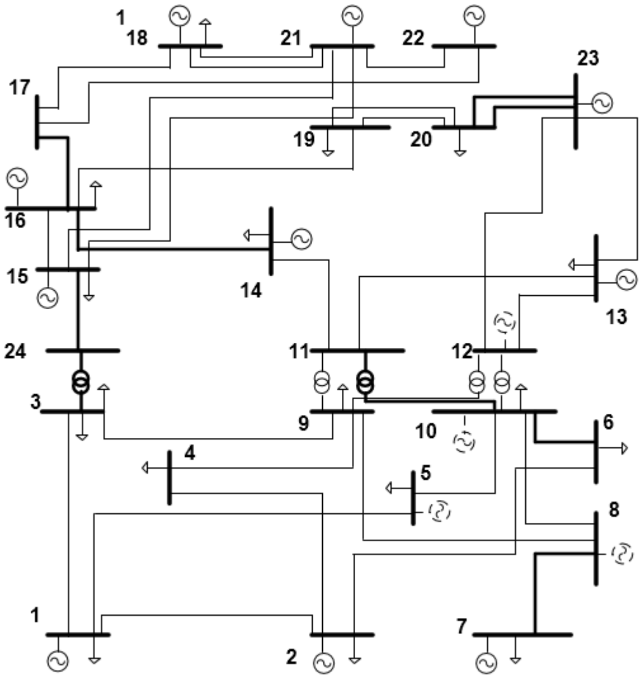


Figure 2: Expansion plan for the IEEE 24 bus test system with repowering.

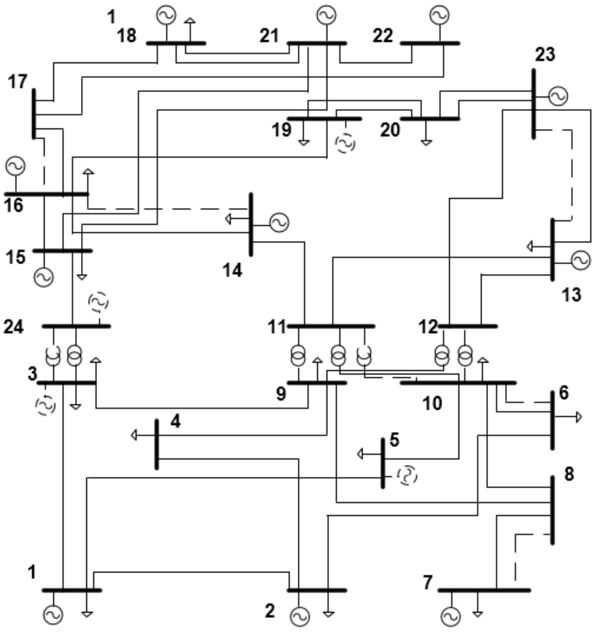


Figure 3: Expansion plan for the IEEE 24 bus test system without repowering.

Table 2: Expansion plan for the IEEE 24 bus power system.

Transmission lines	Generators Bus(MW)	Cost ([M$])	Obs
L3-24, L6-10, L7-8, L10-11, L13-23, L14-16, L16-17,	N3(10), N3(20), N3(30), N5(30), N19(10), N(24), N24(10), N24(20), N24(30),	502.589	Without repowering
LR3-24, LR6-10, LR7-8, LR10-11, LR14-16, LR15–24, LR16-17, LR20-23	N5(20), N8(10), N8(20), N10(10), N10(20), N10(30), N12(10), N12(20), N12(30),	332.598	With repowering

5 Conclusions

This paper presented a novel modeling of the transmission network expansion planning problem. The main features of this model consist on the consideration of circuits repowering and the inclusion of small-scale generation. The inclusion of repowering and small-scale generation as solution candidates in the TNEP problem allow to explore a larger search space and find solutions that result in less investment costs when compared to the traditional modeling that considers conventional candidates only.

Repowering of existing networks has proven to be a feasible solution in real power systems worldwide. Therefore, having an optimization model that considers such candidate solutions allows to find expansion plans that can be implemented in real life projects. In a future work more details regarding the modeling of small-scale generation and distributed generation will be explored.

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