A two-stage constructive heuristic algorithm to handle integer investment variables in transmission network expansion planning

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Tutorial test system – IEEE24

The IEEE 24-bus system in Fig. 1 has 38 circuits in its base topology, 41 paths candidate to expansion, and a forecasted load demand of 9550 MW. This system has been vastly used to validate results of new methodologies applied to the TNEP problem [1]. The IEEE 24-bus system presents five scenarios (IEEE24G0 to IEEE24G4) that do not allow generation redispatch. For this system, the expansion planning was obtained neglecting the transmission losses and the obtained results were compared with the ones provided by other approaches reported in the literature.

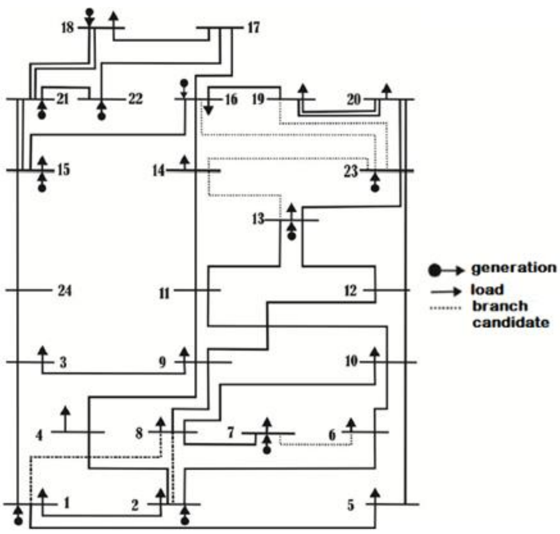

Fig. 1 - IEEE24-bus System.

1.1.1 Stage 1 - Construction phase – IEEE24G4 System

In this phase, ten simulations of the proposed methodology were performed. The most reduced expansion cost was obtained with an HTF^{1} sensibility (A^{1_Best}) equal to six, see Fig. 2. The expansion plan obtained in this phase is presented in Table 1. Fig. 3 presents the number of non-linear programming (NLP) problems solved for every value of the adjustment coefficient A^1.

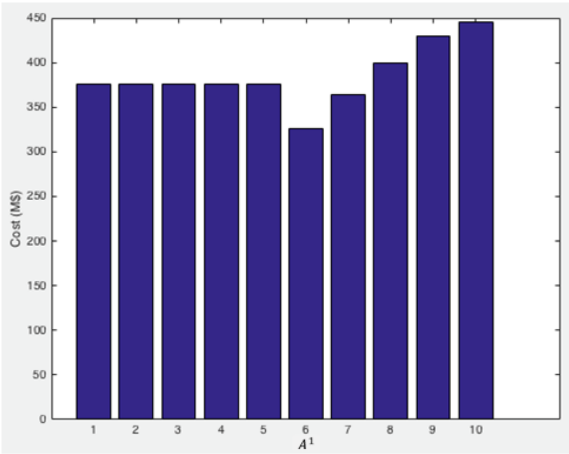

Fig. 2 - Histogram: Cost (M$) x Slope ($\boldsymbol{A^1}$) – Stage 1.

Table 1

Results – IEEE24G4 System – Stage 1 – $\boldsymbol{A^{1\_Best}}$= 6 - Losses neglected.

Selected path	Number of lines	Selected path	Number of lines
03-24	1	15-24	1
06-10	1	16-17	1
07-08	3	14-16	1
10-12	1	**Total Expansion Cost**	$326M

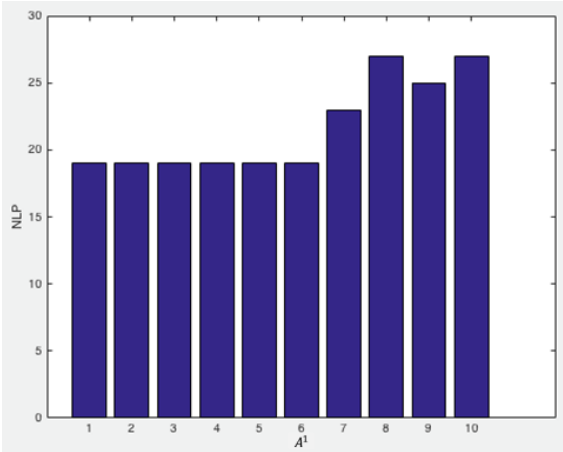

Fig. 3 - Histogram: NLP x Slope ($\boldsymbol{A^1}$) – Stage 1.

1.1.2 Stage 2 - Refinement phase – IEEE24G4 System

Once the construction phase is finished, it is performed the verification, or refinement phase of the expansion plan output from Stage 1. This phase has the goal of verifying the possibility of obtaining more economical expansion plans via a small variation of the optimal slope coefficient of the previous phase (A^{1_Best}), according to Eq. (16).

$$HTF^2 \rightarrow \begin{cases} x = [0.001:20] \\ A^2 = [(5.1):0.1:(6.9)] \end{cases} \qquad (16)$$

In this phase, nineteen simulations of the proposed heuristic methodology were performed, which allowed obtaining a more economical expansion cost compared to that obtained in Stage 1. To achieve such a cost, A^{2_Best}= 5.1 to 5.7, as observed in Fig. 4. The expansion plan obtained in this phase is presented in Table 2, which is more economical than that presented in the specialized literature. In fact, Table 3 presents the optimal results published in [2,3] for the aforementioned IEEE24 systems scenarios and the cost associated to the G4 scenario is 10% larger than the cost obtained with the proposed approach. Fig. 5 presents the number of non-linear programming (NLP) problems solved for every value of the adjustment coefficient A^2.

Table 2

Results – IEEE24G4 System – Stage 2 – $\boldsymbol{A^{2\text{-}Best}}$= 5.1 to 5.7 - Losses neglected.

Selected path	Number of lines	Selected path	Number of lines
03-24	1	15-24	1
06-10	1	16-17	2
07-08	2	14-16	1
10-12	1	**Total Expansion Cost**	$310M

Table 3

Best solutions published in the literature - IEEE24 Systems- Losses neglected [2,3].

Transmission Network	Optimal Expansion Cost
IEEE24G0	**$152M**
IEEE24G1	**$390M**
IEEE24G2	**$392M**
IEEE24G3	**$218M**
IEEE24G4	**$342M**

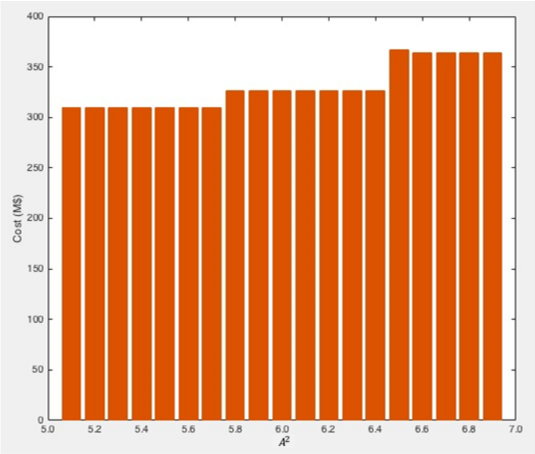

Fig. 4 - Histogram: Cost (M$) x Slope ($\boldsymbol{A^2}$) – Stage 2.

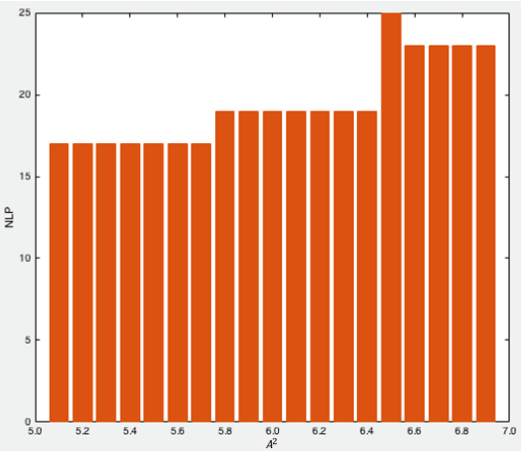

Fig. 5 - Histogram: NLP x Slope ($\boldsymbol{A^2}$) – Stage 2.

Fig. 6 presents a descriptive statistical analysis concerning the investment costs obtained in the construction (Stage 1) and in the refinement (Stage 2) phases, in which it is possible to observe some metrics regarding the obtained results. As notable, the second stage presents a smaller interquartile amplitude followed by less dispersion of the results when compared to the results obtained in the first stage. Such occurrences are due to the successful refinement around the best obtained solution, and the consequent improvement in the solutions' mean value during the second stage.

Therefore, it can be observed that the refinement phase provided better results, which indicates that the fine adjustment of the *HTF*'s slope had the desired outcome for the case here analyzed.

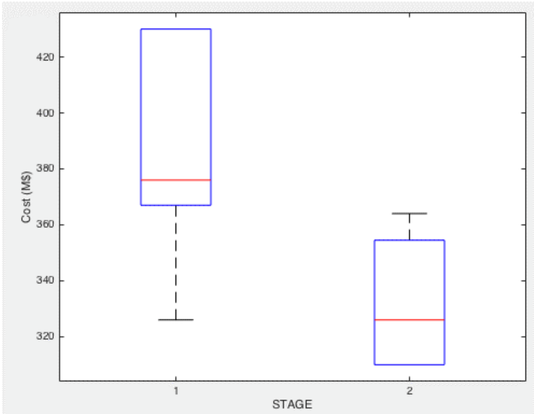

Fig. 6 - Dispersion of solutions: Stages 1 e 2 – IEEE24G4.

Table 4 presents the results provided by the proposed methodology for different generation scenarios and it includes the following information: (i) the total expansion cost obtained; (ii) number of performed non-linear programming problems both in Stages 1 and 2); (iii) slope of the hyperbolic tangent function that provided the best solution in the construction phase; (iv) slope of the hyperbolic tangent function that provided the best solution in the refinement phase; (v) percentage difference between the solution provided by the proposed methodology and the best solution reported in the literature so far.

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Table 4

Results provided by the proposed heuristic methodology- Losses neglected.

Systems	Expansion Cost	Total NLP	A^{1_Best}	A^{2_Best}	Difference (%) regarding the Expansion Cost
IEEE24G0	$152M	382	1	0.1 to 0.3	0
IEEE24G1	$370M	720	1	0.2	-5.1%
IEEE24G2	$390M	735	2	2	0
IEEE24G3	$218M	837	1	1	0
IEEE24G4	$310M	583	6	5.1 to 5.7	-9.3%

Given the results in Table 4, it is noteworthy that: (i) The proposed heuristic provided better (in two cases) or equal (in the remaining three cases) results as the ones reported in the literature; (ii) all expansion plans obtained through the proposed methodology presented no significant load shedding. It means that the proposed constructive heuristic has proved to be efficient since it found competitive solutions solving a relatively reduced number of primal-dual interior-point NLP problems [4] when compared to metaheuristic techniques [5] and integer non-linear programming [3,6].

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