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AN APPLICATION OF A COMBINATORIAL HYBRID HEURISTIC ALGORITHM TO TRANSMISSION EXPANSION PLANNING

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Abstract- Transmission Expansion Planning (TEP) is a non-convex optimization problem that can be solved via different heuristic algorithms. Varieties of classical as well as heuristic algorithms in literature are addressed to solve TEP problem. In this paper, a Constructive Heuristic Algorithm (CHA) is used for solving TEP problem. The basic idea comes from Garver's work applied to the transportation model. In this algorithm, CHA is applied to a linear model as hybrid model. This algorithm proposed by 'Villasana Garver Salon' (VGS) to the transmission system long-term planning. Simulation studies and tests results on the well-known transmission network such as: Garver and IEEE 24-bus 46-bus Sothern Brazilian and Southeast Network of Iran, systems are carried out to show the significant performance as well as the effectiveness of the proposed algorithm.

Keywords: Transmission Expansion Planning, Constructive Heuristic Algorithm, Hybrid Model.

I. INTRODUCTION

In recent years, by fast growing electric power consumption, new circuits must be added to the existing transmission network. Transmission Network Expansion Planning (TNEP) facilitate finding a plan that must specify the number and location of transmission lines transformers where power system can operate in a reliable as well as secure manner [1]. Since the transmission construction costs are very high, TNEP must minimize the total investment considering predefined time horizon. On the other hand, inherently a TNEP problem especially under large-scale interconnected transmission systems is a mixed integer nonlinear optimization problem, it desires the application of hybrid heuristic optimization techniques.

The initial information available for TNEP are base year topology, candidate circuits, forecasted demand and scheduled generation for predefined planning horizon as well as the investment budget [2-5]. In general, TNEP study can be managed by a static or planers should consider Single Stage Transmission Network Expansion Planning (STNEP), where the planning horizon is considered just in one stage and the number of circuits that should be added to the existing transmission network. It should be notified that the investment must be stated at the beginning of the planning horizon.

Multi stage dynamic planning considers the planning horizon as a multi-stage expansion starting from a base year and finishing at the end of planning horizon such that where and when the expansion should be happened [5-7]. Usually, long-term TEP is modeled by a mathematical formulation the so-called DC model, which is a Mixed Integer Non-Linear Problem (MINLP) that is hard to solve especially for large scale systems [7, 8]. DC model for TEP is formulated as follows:

$$\min v = \sum_{(i,j)\in\Omega} c_{ij} n_{ij} + \alpha \sum_{s} r_s \tag{1}$$

subject to:

$$sf + g = d \tag{2}$$

$$f_{ij} - \gamma_{ij}(n^0{}_{ij} + n_{ij})(\theta_i - \theta_j) = 0 \tag{3}$$

$$| f_{ij} | \le (n^0{}_{ij} + n_{ij}) \overline{f}_{ij} \tag{4}$$

$$0 \le g \le \overline{g} \tag{5}$$

$$0 \le n_{ij} \le \overline{n}_{ij} \tag{6}$$

where, n_{ij} is integer, f_{ij} and θ_{ij} unbounded $(i, j) \in \Omega$, v is present value of the expansion investment cost of the transmission system for a predefined planning horizon, c_{ij} is cost of a candidate circuit added to right of way i-j, n_{ij} is number of circuits added to the right of way i-j, n_{ij}^0 is number of circuits in primary network, γ_{ij} is susceptance of line i-j, θ_i is phase angle at bus i, f_{ij} is active power flow through line i-j, $\overline{f}_{ij}$ is maximum power flow through line i-j, g is a vector with elements g_k (generation at bus k), n_{ij} is number of transmission lines installed at line i, $\overline{n}_{ij}$ is maximum number of circuits added right of way i-j.

Equation (2) models Kirchhoff's Current Law (KCL) in equivalent DC network. Equation (3) is an expression of Ohm's law for equivalent DC network while Kirchhoff's Voltage Law (KVL) is implicitly taken into consideration. Since the third constraint is nonlinear, therefore DC model is a nonlinear problem where n_{ij} should be relaxed. Such Mixed Integer Nonlinear Problem (MINLP) is so complicated to be solved especially for large scale systems. In fact, there are some alternatives to DC models such as hybrid linear model and relaxed model [9]. The Hybrid Linear Model (HLM) is achieved via linearization the third constraint of DC model. Hence, the HLM is a Mixed Integer Linear Problem (MILP).

The HLM, which is formulated by 'Villasana Garver Salon' is as follows [10, 11]:

$$\min v = \sum_{(i,j)\in\Omega} c_{ij} n_{ij} + \alpha \sum_k r_k \tag{7}$$

subject to:

$$sf + s^0 f^0 + g = d \tag{8}$$

$$f_{ij} - \gamma_{ij}\left(n^0{}_{ij}\right)\left(\theta_i - \theta_j\right) = 0 \tag{9}$$

$$| f^0{}_{ij} | \le n^0{}_{ij} \overline{f}_{ij} \tag{10}$$

$$| f_{ij} | \le n_{ij} \overline{f}_{ij} \tag{11}$$

$$0 \le g \le \overline{g} \tag{12}$$

$$0 \le n_{ij} \le \overline{n}_{ij} \tag{13}$$

where, n_{ij} is integer, f_{ij} and θ_{ij} unbounded $(i, j) \in \Omega$, s^0 is the transpose incidence node branch matrix formed by circuits and buses of base topology, f^0 is vector of power flow through the circuits of base topology with elements of f_{ij}^0, s is transpose incidence matrix of entire system, f is vector of the power flows through added circuits with elements f_{ij}, Ω_0 is base case circuit indices and Ω set with indices of all circuits.

As it can be seen, Equation (7) includes two objectives that can be solved separately. First objective will handle the number and the location of new lines and second objective determines dummy generations equivalent to load shedding for a given network configuration. To solve dummy generation for a given network configuration, Equation (7) can be rewritten as the following LP problem.

$$w = \sum_k r_k \tag{14}$$

subject to:

$$s^0 + f^0 + g + r = d \tag{15}$$

$$0 \le g \le \overline{g} \tag{16}$$

$$| f^0{}_{ij} | \le n^0{}_{ij} \overline{f}_{ij} \tag{17}$$

where, n_{ij} is integer, f_{ij} and θ_{ij} unbounded $(i, j) \in \Omega$, w represents load shedding, $n_{ij}{}^0$ is the vector with the circuits in base topology, and r is the vector with artificial generators added in each load bus. If $w = 0$, the system is correctly operating.

II. VGS AS A HEURISTIC ALGORITHM

In this section fundamental components and main characteristic of VGS is presented. This algorithm is a CHA that is applied to HLM by 'Villasana Garver Salon'. In fact, VGS may find a good quality solution in an iterative process. It can be said that, main characteristic of VGS is fast and robustness convergence. In transmission network planning via sensitivity index, a selected circuit (transmission line) is added to system iteratively. Process will stop when a feasible high quality solution is obtained, while system load shedding must be zero [12, 13]. The algorithm may be summarized as follows:

Step 1: Assume the base topology as current topology and choose a mathematical model.

Step 2: Solve an LP to determine parameters used in the sensitivity index for a chosen CHA considering the operational conditions of the system.

If the LP solution indicates that, the system is adequately operating with the new additions, then STOP. Here a new solution for the model has been found. Then go to Step 4.

Step 3: Use a sensitivity index to identify the most attractive circuit. Update the current topology with the chosen circuit, and then go to Step 2.

Step 4: Sort the added circuits in decreasing order of costs. Verify by using an LP that calculate load shedding of given network, whether the removal of a circuit keeps the system in an adequate operational condition. If yes, remove the circuit otherwise keep the circuit. Repeat circuit removal simulation until all circuits have been tested. All added circuits that were not removed represent CHA's solution. The mentioned LP at Step 2 is slightly different from Equation (7) while it is as follows:

$$\min v = \sum_{(i,j)\in\Omega} c_{ij} n_{ij} \tag{18}$$

subject to:

$$sf + s^{01} f^{01} = g = d \tag{19}$$

$$f^{01}{}_{ij} - \gamma_{ij}(n^1{}_{ij} + n^0{}_{ij})(\theta_i - \theta_j) = 0 \qquad \forall (i,j) \in \Omega \tag{20}$$

$$| f_{ij} | \le (n^0{}_{ij} + n^1{}_{ij}) \overline{f}_{ij}, \qquad (i,j) \in \mathrm{IW} \tag{21}$$

$$| f_{ij} | \le n_{ij} \overline{f}_{ij} \quad \forall (i,j) \in \Omega \tag{22}$$

$$0 \le g \le \overline{g} \tag{23}$$

where, f_{ij}^{01}, f_{ij} and θ_j are unbounded, n_{ij}^1 is circuits that are added during the iterative process to base case, Ω_1 is the set of all added circuits during the iterative process and all prime circuits of base case, s^{01} is transpose incidence branch-node matrix of the base topology and added topology in previous iterations of algorithm, f_{ij}^{01} is power flow on path $(i, j) \in \Omega_1$. The sensitivity index is given by Equation (24).

$$IS = \max\left\{ IS_{ij} = n_{ij} f_{ij};\ nij \ne 0 \right\} \tag{24}$$

where, n_{ij} is answer of LP after relaxing integrality of n_{ij}. At the end of process the added circuits are stored in $n_1 = \left\{ n_{ij}^1 \right\}$. In addition, the mentioned LP at Step 4 is slightly different from Equation (15) while it is as follows:

$$w = \sum_k r_k \tag{25}$$

subject to:

$$sf + g + r = d \tag{26}$$

$$| f^0{}_{ij} | \le (n^0{}_{ij} + n^1{}_{ij}) \overline{f}_{ij} \tag{27}$$

$$0 \le g \le \overline{g} \tag{28}$$

where, θ_{ij} is unbounded $(i, j) \in \Omega$, n_{ij}^1 is the vector with the circuits added during the process.

The VGS algorithm avoids solving a nonlinear programming problem to DC model that is a Mixed Integer Nonlinear Problem (MINLP). Therefore, by considering Equation (18), VGS algorithm finds a set of variables $n_{ij} \neq 0$, which identifies the best investment proposal satisfying only KCL while these variables must satisfy both KVL and KCL constraints. Therefore, VGS algorithm cannot obtain the optimal solution [14, 15].

III. CASE STUDIES AND RESULTS ANALYSIS

In this section, simulation studies and tests results of the proposed method on 'Garver' and IEEE 24-bus systems are presented.

A. Garver's System

Garver's system includes six transmission lines and six buses with 760 MW demand for base topology, which is shown in Figure 1. The number of candidate lines is 15 circuits. The system data can be found in [11]. By applying the VGS algorithm to Garver's system considering generation rescheduling the obtained results are, total investment is 130 M$ with added circuits $n_{2\text{-}3} = 1$, $n_{2\text{-}6} = 1$, $n_{3\text{-}5} = 1$, $n_{4\text{-}6} = 2$. The solution details of the VGS algorithm are presented in Table 1 of five iterations. VGS algorithm converges after five iterations without removing any circuit in Step 4 are solved. The results VGS algorithm for Garver's system without generation rescheduling is as follows. Total investment is 200 M$ with added circuits, $n_{2\text{-}6} = 4$, $n_{3\text{-}5} = 1$, $n_{4\text{-}6} = 2$, also the solution details of the VGS algorithm are presented in Table 2. VGS algorithm converges after seven iterations without removing any circuit in Step 4 are solved.

Table 1. Results of Garver's system with generation rescheduling

Iteration No.	Added circuit	Selected circuit by IS	v
1	$n_{2-3} = 0.2146,\ n_{2-6} = 0.8878$ $n_{3-5} = 0.9854,\ n_{4-6} = 1.6122$	4-6	0
2	$n_{2-3} = 0.2586,\ n_{2-6} = 0.7009$ $n_{3-5} = 0.9414,\ n_{4-6} = 0.7991$	3-5	30
3	$n_{2-3} = 0.177,\ n_{2-6} = 1.0479$ $n_{3-5} = 0.023,\ n_{4-6} = 0.4521$	2-6	50
4	$n_{2-3} = 0.1818,\ n_{2-6} = 0.0273$ $n_{3-5} = 0.0182,\ n_{4-6} = 0.4727$	4-6	80
5	$n_{2-3} = 0.0575$	2-3	110
6			130

Table 2. Results of Garver's system without generation rescheduling

Iteration No.	Added circuit	Selected circuit by IS	v
1	$n_{2-6} = 2.1375,\ n_{3-5} = 0.6125$ $n_{4-6} = 3.3125$	4-6	0
2	$n_{2-6} = 2.1375,\ n_{3-5} = 0.6125$ $n_{4-6} = 2.3125$	4-6	30
3	$n_{2-6} = 2.1375,\ n_{3-5} = 0.6125$ $n_{4-6} = 1.3125$	2-6	60
4	$n_{2-6} = 2.486,\ n_{3-5} = 0.8373$	2-6	90
5	$n_{2-6} = 1.4860,\ n_{3-5} = 0.8373$	2-6	120
6	$n_{2-6} = 0.4860,\ n_{3-5} = 0.8373$	3-5	150
7	$n_{2-6} = 0.4860$	2-6	170
8			200

B. IEEE 24-Bus

IEEE 24-bus system consists of 24-bus, 41 right of ways for the addition of new circuits with 8550 MW demand for base topology which is shown in Figure 2. The data is available in [14]. By applying the proposed method to IEEE 24-bus system considering generation, rescheduling the obtained results are: total investment is 271 M$ with added circuits: $n_{3\text{-}24} = 1$, $n_{6\text{-}10} = 1$, $n_{7\text{-}8} = 1$, $n_{10\text{-}12} = 1$, $n_{14\text{-}16} = 1$, $n_{1\text{-}8} = 1$, $n_{6\text{-}7} = 1$. Table 3 shows solution details for IEEE 24-bus system. VGS algorithm converges after eight iterations with removing circuit 6-7 in Step 4 are solved.

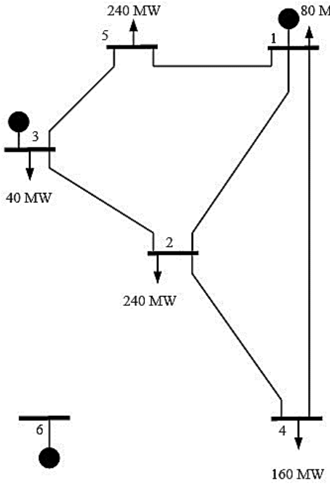

Figure 1. Garver system network [11]

Table 3. Results of IEEE 24-bus system with generation rescheduling

Iteration No.	Added circuit	Selected circuit by IS	v
1	$n_{1-5} = 0.2911,\ n_{3-24} = 0.4085$ $n_{7-8} = 0.8854,\ n_{10-12} = 0.4270$ $n_{14-16} = 2.4245,\ n_{6-7} = 2.6146$	6-7	0
2	$n_{1-8} = 0.3909,\ n_{3-24} = 0.3656$ $n_{7-8} = 2.3365,\ n_{10-12} = 0.8563$ $n_{14-16} = 2.310,\ n_{6-7} = 0.2737$	7-8	50
3	$n_{1-8} = 0.3909,\ n_{3-24} = 0.3656$ $n_{7-8} = 0.5865,\ n_{10-12} = 0.8563$ $n_{14-16} = 2.310,\ n_{6-7} = 0.2737$	14-16	66
4	$n_{1-8} = 0.3222,\ n_{3-24} = 0.1905$ $n_{7-8} = 0.5865,\ n_{10-12} = 0.7744$ $n_{6-7} = 0.3056$	10-12	120
5	$n_{3-24} = 0.0029,\ n_{6-7} = 0.9292$	6-7	170
6	$n_{6-10} = 0.3228,\ n_{8-7} = 0.2905$	6-10	220
7	$n_{3-24} = 0.1790,\ n_{6-7} = 0.1701$	3-24	236
8	$n_{1-8} = 0.2070$	1-8	286
9			321

C. Southern Brazilian System of 46-Bus

Southern Brazilian System has 46-bus, 79 right of ways for the addition of new circuits, and 6880 MW of demand, where the system data is available in [15]. The base topology of this system is shown in Figure 3. There is no limit for circuit additions in each right of way. In this system, the maximum generation capacity is equal to load, therefore there is only one possible generation pattern for this system. The proposed algorithm offered

the following results with considering the generation rescheduling. Total investment cost is 154420 M\$, with added circuits:
$n_{20\text{-}21} = 1$, $n_{42\text{-}43} = 2$, $n_{46\text{-}6} = 1$, $n_{19\text{-}25} = 1$, $n_{31\text{-}32} = 1$, $n_{28\text{-}30} = 1$, $n_{26\text{-}29} = 3$, $n_{24\text{-}25} = 2$, $n_{29\text{-}30} = 2$, $n_{5\text{-}6} = 2$.

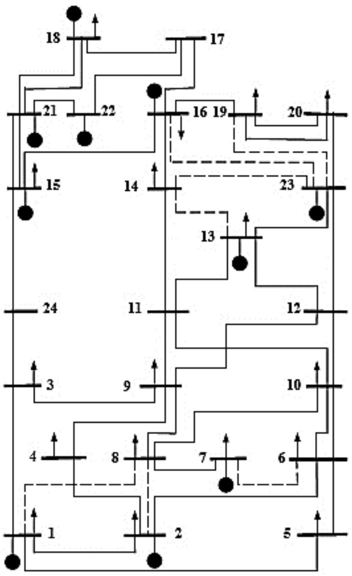

Figure 2. IEEE 24-bus system network [14]

The proposed method may find a better topology in comparison with the other algorithms applied to the same test systems, while the proposed algorithm deploys VGS algorithm in improvement stage that promote infeasible solutions with good quality. In summary, proposed algorithm has following characteristics. (a) effortless, reduces the number of LPs solved to reach the optimal solution of TENP problem, (b) high quality initial solution, by using transportation model to generate initial population with high quality, (c) robustness, to find good topology for medium and large scale system, and (d) extendable, it can be extended to multistage planning even considering dispersed generation.

D. Southeast Network of Iran

In this section, the proposed method is applied to the southeast network of Iran as a first attempt for TNEP. SNI is a part of interconnected electric power network in Iran, which is divided into 4 regions (provinces), Kerman, Yazd, Hormozgan and Sistan-Baluchestan. Southeast network of Iran procures electric power for an area about 381787 km^2. Main tie lines between southeast network and other regions are, four (2×400 kV and 2×230 kV) lines connected to Esfahan, 3 lines (2×400 kV and 1×230 kV) connected to Fars. The total length of 230 kV lines is about 2372 km and total length of 400 kV lines is about 4635 km. This system has 54 buses and 87 right of ways for the addition of new circuits and a total demand 10268 MW [16]. The base year topology is 2010 and the expansion is targeted for year 2016. Single line diagram of SNI is illustrated in Figure 4. By applying the proposed MSSA to SNI, two different topologies with similar investment costs are obtained as follows. Total investment is v = 339 M\$ added circuits are:

$n_{11\text{-}12} = 1$, $n_{12\text{-}26} = 2$, $n_{22\text{-}24} = 1$, $n_{18\text{-}1} = 1$, $n_{7\text{-}8} = 1$, $n_{39\text{-}35} = 1$, $n_{31\text{-}30} = 1$, $n_{53\text{-}33} = 1$, ($n_{30\text{-}33} = 1$ or $n_{27\text{-}28} = 1$).

Regarding convergence curve presented in Figure 4, MSSA gives good convergence rate for solving TNEP problem. The proposed method may find better topologies with regards to the other method applied to the same test systems, while the proposed method deploys VGS algorithm in the improvement stage that promote the infeasible solutions with good quality. In summary MSSA has following characteristics: (a) robustness, to find good topology for medium and large scale system, (b) effortless, reduces number of LP to solve TENP problem, (c) high quality initial solution, it uses transportation model to generate initial population with high quality and (d) extendable to multistage planning even considering dispersed generation.

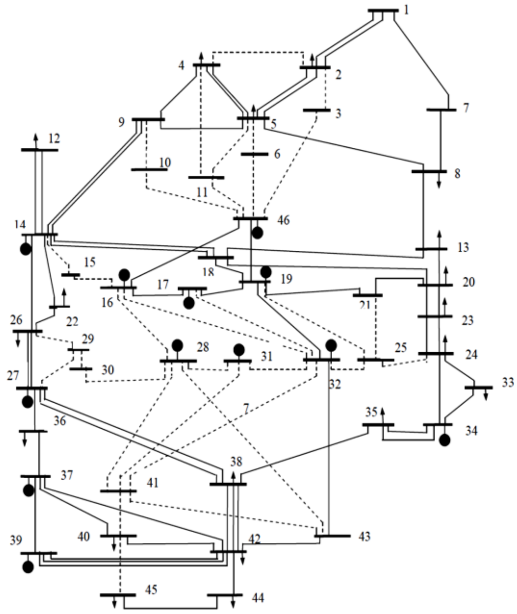

Figure 3. Southern Brazilian 46-bus system [15]

IV. CONCLUSIONS

This paper presents a combinatorial hybrid heuristic algorithm for transmission expansion problem associated with a hybrid linear model. The proposed algorithm incurs significant performance for systems with low, medium, and high complexity while DC model by itself may not be a proper model for systems with high complexity. The main advantage of the proposed algorithm is that it can be applied even to practical transmission network as well. The resulting information is of outstanding quality for use as a sensitivity index.

This algorithm is robust and reliable for large scale as well as complex systems and also it can be advised for the application to multistage transmission expansion planning. On the other hand, the proposed methodology can be combined with other meta-heuristic algorithm to get the advantage of those for finding the global optimal solution. The proposed methodology is tested on several standard as well as practical systems while the obtained results are promising and they offer a significant saving both from computational efforts as well as from investment.

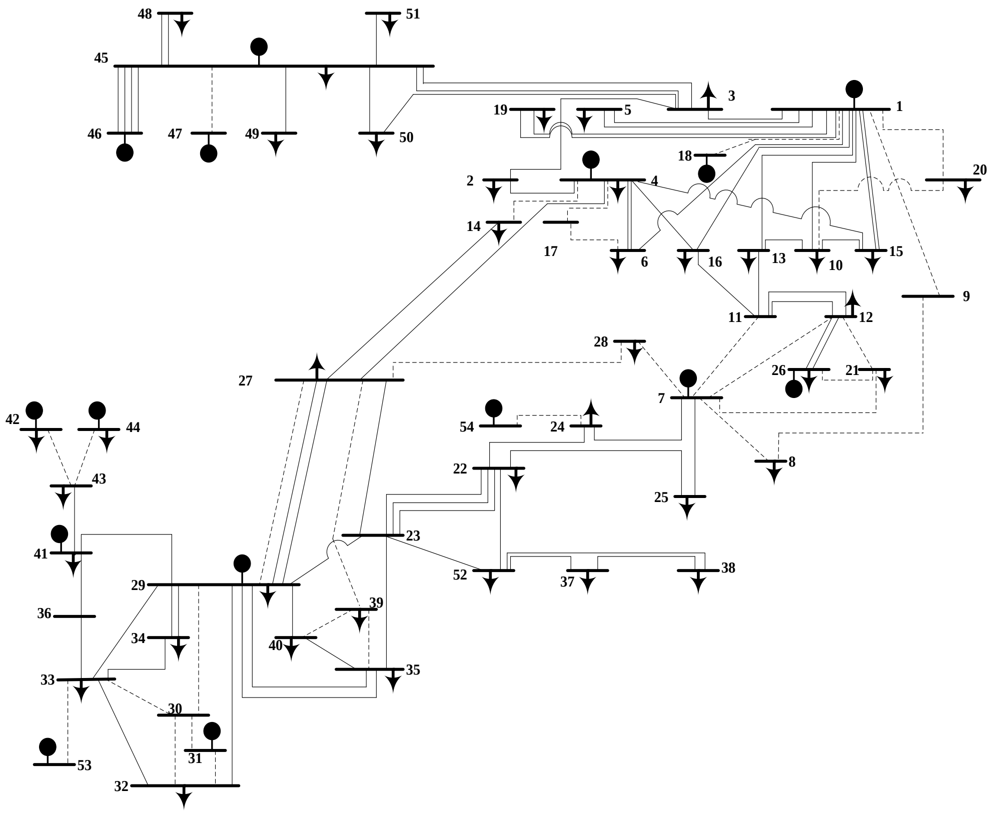

Figure 4. Single diagram of Iran southeast network [16]

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