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Transmission Network Expansion Planning – A Critical Review

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Abstract

Transmission Network Expansion Planning (TNEP) is determination of an optimal network configuration that satisfies the operational conditions for forecasted load growth under a particular generation expansion plan. TNEP may be broadly classified into static and dynamic network planning. Static TNEP (STNEP) deals with finding where and which type of new lines should be installed in an optimal way that minimizes the installation and operational cost. Dynamic TNEP (DTNEP) is more complex and aims at determining when to install the new lines (in addition to determination of where and which type of lines to be installed). Researchers have used mathematical optimization methods, heuristic methods and meta-heuristic methods to solve STNEP problem. DTNEP problem have been tackled using mathematical optimization methods and meta-heuristic methods by the researchers. This paper compiles the significant developments made in the area of TNEP using conventional (mathematical) optimization methods, and advanced (heuristic & meta-heuristic) optimization methods. After a thorough study of vast literature available on TNEP, critical comments and future scope have been presented to make the review study focused and useful for the researchers in this area.

Keywords: Dynamic Planning, Heuristic Methods, Mathematical Optimization Methods, Meta-Heuristic Methods, Static Planning, Transmission Network Expansion Planning

1. Introduction

Modern power systems are becoming more interconnected and are being subjected to heavily stressed conditions forcing to operate very near to loadability limit. Thus the complexity of planning and operation of large interconnected power systems is growing. The rapid increase in load demand has led to generation expansion, which in turn have made network planning an important part of power system planning. The allocation of transmission costs in a competitive environment requires careful evaluation of alternative transmission network expansion plans[1]. TNEP is an important part of power system planning which aims at determining an optimal network configuration according to load growth and a generation planning scheme for the planning period so as to meet the requirement of delivering electricity safely and economically[2]. In other words, TNEP can be said to be an optimization process in which the allocation (the sending and the receiving ends) and class (voltage level, number of conductors, conductor type) of new transmission elements together with their required availability times are specified[3]. TNEP is more complex as compared to generation expansion planning because

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it has to consider the practical network topology, and the Rights Of Way (ROW) must be treated as independent decision variables. Moreover, the constraints to be satisfied are more complex, including non-linear and differential equations. ROW is a strip of land used to construct, operate, maintain and repair the transmission line facilities by electrical transmission utility.

Generally speaking, the TNEP should answer the following questions[2]

(i) Where to build a new transmission line?

(ii) What type of transmission line to build?

(iii) When to build it?

TNEP may be studied by static or dynamic model[4]. A static model tries to find an optimal network structure for a given scenario of generation and load, and is known as STNEP. STNEP answers questions **(i)** and **(ii)** out of the three mentioned above. A dynamic model (known as DTNEP) is more complex and it aims at, besides answering the questions of where and what type of new line to build, defining when to install the new additions[2,4]. It therefore creates a plan of investment along successive period of time, and hence also called multi-stage TNEP.

Many mathematical optimization methods were developed to solve the TNEP problem. Though some of these techniques have excellent convergence characteristics, and various among them are widely used in the industry, they suffer with the following disadvantages as[5–7]:

1. They might converge to local solutions instead of global ones if the initial guess happens to be in the vicinity of a local solution.
2. They are developed with some theoretical assumptions, such as convexity, differentiability, and continuity, among other things.
3. They are weak in handling qualitative constraints.
4. They become too slow if number of variables is large.
5. They are computationally expensive for solution of a large system.

Since there are recent attempts to overcome the limitations of the mathematical optimization methods, the application of heuristic and meta-heuristic techniques to solve the TNEP problem has emerged. Some of such techniques are Simulated Annealing (SA), Tabu Search (TS), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony algorithm, Artificial Bee Colony (ABC) algorithm etc. are used often owing to their major advantages such as [5] –

1. They are relatively versatile for handling various qualitative constraints.
2. They have excellent convergence characteristic; in most cases they can find the global optimum solution.
3. They are fast in computation and possess learning ability.

A comparison between mathematical (conventional), and heuristic and meta-heuristic (advanced) optimization techniques is presented in Table 1[5,7].

The first relevant work with TNEP appeared in the early 1960s with the application of heuristic methods of optimization. In 1970s and 1980s, the heuristic techniques achieved significant improvement, and new applications to conventionally intractable problems were proposed[4].

In 1970, Garver presented the use of linear programming for network analysis to determine where capacity shortages exist and, most importantly where to add new circuits to relieve the shortages[8]. Garver's work became a milestone in TNEP and, since then every new TNEP algorithm differed from Garver's model just in three aspects: **(i)** the sensitivity index, **(ii)** the use of different mathematical models, and **(iii)** the use of a local optimization method[4].

In 1980s, several constructive algorithms employed the DC model to explore the information related to the power system performance indices as the sensitivity indicators. To solve TNEP problem, classical optimization has also been employed.

This paper presents review on different effective methodologies used to solve TNEP problem. It will provide a good starting reference and a rich resource for the power system planning researchers.

2. Problem Formulation

The network planning may broadly be divided into STNEP and DTNEP. STNEP gives the network connection scheme for a particular load horizon year and does not consider the transit problem of network connection schemes[2]. It is also called "horizon year planning", which does not consider when to build a new transmission line.

For a longer planning period it is divided into several horizon years in which the transit problem of each horizon year is considered. In such circumstances, one has to decide when and where to build a new line. Such a planning is called DTNEP or "long term planning"[2].

Table 1. A comparison between mathematical and heuristic and meta-heuristic optimization technique

Property	Heuristic & Meta-Heuristic	Mathematical
Search space	Population of potential solution	Trajectory by a single point
Motivation	Natural selection and Social adaptation	Mathematical properties (gradient, Hessian)
Applicability	Domain independent, Applicable to variety of problems	Applicable to a specific problem domain
Point Transition	Probabilistic	Deterministic
Prerequisites	An objective function to be optimized	Auxiliary knowledge such as gradient vectors
Initial guess	Automatically generated by the algorithm	Provided by user
Flow of control	Mostly parallel	Mostly serial
CPU time	Large	Small
Results	Global optimum more probable	Local optimum, dependant of initial guess
Advantages	Global search, parallel, speed	Convergence proof
Drawbacks	No general formal convergence proof	Locality, computational cost

2.1 Static Transmission Network Expansion Planning (STNEP)

The STNEP problem is formulated as a mixed-integer nonlinear programming problem in which the power network is represented by a DC power flow model[4]. The STNEP problem can be formulated as[9,10]:

Objective function:

$$\min v = \sum_{l \in \Omega} c_l \, \mathrm{n}_l \tag{1}$$

Subject to

$$S f^k + g = d \tag{2}$$

$$f_l^k \,| \le (\mathrm{n}_l^0 + \mathrm{n}_l)(\Delta\theta_l^k) = 0 \tag{3}$$

$$| f_l^k | \le (\mathrm{n}_l^0 + \mathrm{n}_l)\overline{f}_l \tag{4}$$

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

$$0 \le g \le \overline{g} \tag{6}$$

$n_l \ge 0$, and integer,

f_l and θ_j are unbounded

$l \in \Omega$ and $k = 0, 1 \ldots\ldots\ldots NC$

where,

$k = 0$, represents the base case without any line outage.

g: the vector of generation at each node,

d: the vector of corresponding demands at that node,

S: branch-node incidence matrix of the power system,

f^k: Vector with elements f^k_l,

Υ_l: Suceptance of the circuit that can be added to l^{th} right of way,

n_l: The number of circuits added in l^{th} right-of-way,

n^0_l: number of circuits in the base case,

$\Delta\theta^k_l$: phase angle difference in l^{th} right-of way when k^{th} line is out,

f^k_l: total real power flow by the circuit in l^{th} right-of-way when k^{th} line is out,

$\overline{f}_l$: maximum allowed real power flow in the circuit in l^{th} right of-way,

$\overline{n}_l$: maximum number of circuits that can be added in l^{th} right-of-way,

Ω : set of all right-of-ways,

nl: total number of lines in the circuit,

NC: number of credible contingencies

The STNEP performs all the expansions in a single stage of planning horizon. The DC power flow model is most widely used model. It is considered a reference because in general, networks synthesized by this model satisfy the basic conditions stated by operation planning strategies[4]. Considering the difficulties to deal with this problem, many times, relaxed version of DC models are used. The most used relaxed models are transportation model and the hybrid models. The transportation model was originally proposed by Garver[8], and from mathematical point of view, it is considered as a relaxed DC model.

2.2 Dynamic Transmission Network Expansion Planning (DTNEP)

Generally speaking, the DTNEP should answer three questions[2], **(i)** when (in which year/ horizon) to build new line? **(ii)** where (in which ROW) to build new transmission line? And **(iii)** how many new lines are to be built? DTNEP problem also uses the DC power flow model. The problem can be stated as[11]:

Objective function:

The objective function for DTNEP can be represented as –

$$\min v = \sum_{t=1}^{Y}\left(\frac{v^t}{(1+d)^{t-1}}\right) \tag{7}$$

$$v^t = \sum_{m=1}^{M} v_m^t \tag{8}$$

where,

v_m^t represents the expansion investment on the m^{th} right-of-way in the year t

v^t: investment cost in the year t

v: total investment cost referred to the beginning year of the planning horizon

d : discount rate

Y : total number of years

The DTNEP problem is subject to following constraints,

$$S^t f^{t,k} + g^t = d^t \tag{9}$$

$$f_{ij}^{t,k} - \gamma_j^t\left(n_j^0 + \sum_{m=1}^{t} n_j^m\right)\left(\theta_i^{t,k} - \theta_j^{t,k}\right) = 0 \tag{10}$$

(for $l \in$ *1, 2, ……, nl, and l* $\neq k$)

$$f_l^{t,k} - \gamma_l\left(n_l^0 + \sum_{m=1}^{t} n_j^m - 1\right)\left(\theta_i^{t,k} - \theta_j^{t,k}\right) = 0 \tag{11}$$

(for $l = k$)

$$\left|f_l^{t,k}\right| \leq \left(n_j^0 + \sum_{m=1}^{t} n_j^m\right)\overline{f_j}, \tag{12}$$

(for $l \in$ *1, 2, ……, nl, and l* $\neq k$)

$$\left|f_l^{t,k}\right| \leq \left(n_j^0 + \sum_{m=1}^{t} n_j^m - 1\right)\overline{f_j} \quad (\text{for } l = k) \tag{13}$$

$$\sum_{t=1}^{T} n_{ij}^t \leq \overline{n_j} \tag{14}$$

f_l^k and θ_l^k are unbounded

$t = 1, 2, \ldots, T$

k =0, represents the base case without any line outage

$k = 0, 1, \ldots, NC$

γ_{ij}^t : Suceptance of the circuit that can be added to right-of-way *i-j* in the t^{th} stage

n_{ij}^0 : number of circuits in the base case

$\theta_i^{t,k}$: phase angle at i^{th} bus in t^{th} stage when k^{th} line is out

$f_{ij}^{t,k}$: total real power flow in the circuit in ROW *i-j* in the t^{th} stage when k^{th} line is out

$\overline{f_{ij}}$: maximum allowed real power flow in the circuit in ROW *i-j*

S^t : branch-node incidence transposed matrix of the power system in the t^{th} stage

$f^{t,k}$: vector with elements $f_{ij}^{t,k}$

$\overline{n}_{ij}$: maximum number of circuits that can be added in ROW *i-j*

Equation (9) represents the conservation of power at each node. Equations (10) and (11) represent Ohm's law for equivalent network. Equations (12) and (13) satisfy the maximum allowed flow limit and equation (14) satisfies the total allowed number of lines in ROW *i-j*.

The problem of dynamic planning of a network is highly complex and large scale. It involves deriving a strategy for system expansion and not only arriving at a specific network design. It involves not only an optimization of the network design at a given moment but also taking into account the cross influence of decisions already taken and decisions to be taken in the future[4].

3. Solution Techniques

The TNEP problem is a large-scale, complex and nonlinear combinatorial problem of mixed integer nature. In this, the number of candidate solutions to be evaluated increases exponentially with the increase in the system size. In order to plan power systems in both an economic and efficient manner, accurate solution of the TNEP problem is essential. Therefore, applied optimization methods should be sufficiently efficient when solving such problems[10].

The algorithm proposed for solving STNEP and DTNEP problems can be classified in two types as conventional (mathematical) optimization methods, heuristic and meta-heuristic methods (advanced optimization methods).

A review of these methods used by different researchers is presented in following two sections.

4. Conventional Optimization Methods

TNEP by mathematical optimization formulates the design requirements of network planning as an operational mathematical planning model and is solved by an optimization algorithm such that an optimal planning scheme is obtained satisfying all constraints[2].

To solve TNEP problem, several methods have been proposed by researchers based on classical optimization techniques as presented in Table 2.

Table 2. Conventional (mathematical) optimization methods used to solve TNEP problem

Sr. No	Ref. No.	Method used
1	12	Dynamic programming
2	13	Hierarchical decomposition
3	14, 15, 16	Linear programming (LP)
4	17, 18	Non-linear programming (NLP)
5	19, 20	Bender Decomposition
6	21, 22, 23	Branch and bound algorithm
7	24, 25, 26, 27, 28	Mixed integer programming
8	29	NLP – Interior point method
9	30	Improved standard branch-and-bound algorithm

The conventional (mathematical) optimization model of network planning is comprised of variables, constraints and an objective function.

There are two groups of variables. A "decision variable" represents whether a transmission line is selected to join the network, and thus is an integer variable. A "state variable" represents the state of the system operation, such as line flows, nodal voltage etc. It is usually a real variable.

The constraints include construction conditions of decision variables, upper and lower limits of state variables and so on.

An objective function is a function of decision variables and state variables. It primarily consists of network construction investment costs and operational costs.

5. Advanced Optimization Methods

The advanced (heuristic and meta-heuristic) methods are based on intuitive analysis. They are relatively close to the way that engineer thinks. An advanced method can give a good design scheme based on experience and analysis[2]. However, it is not a strict mathematical optimization method.

In transmission network expansion planning heuristic and meta-heuristic methods find wide applications their straightforwardness, flexibility, speed of computation, and ability to obtain a comparatively optimal solution which meets practical engineering requirements.

The first relevant work with TNEP appeared in the early 1960s with the application of heuristic methods for optimization[4]. In 1970s and 1980s, the heuristic techniques achieved significant improvement, and new applications to conventionally intractable problems were proposed[4].

In 1970, Garver presented the transportation model and the solution algorithm based on a constructive heuristic algorithm[4,8]. The most relevant contribution of Garver was the application of constructive heuristic algorithm that employs a sensitivity index for guiding the search. Garver's work became a milestone in TNEP and, since then every new TNEP algorithm differed from Garver's model just in three aspects: **(i)** the sensitivity index, **(ii)** the use of different mathematical models, and **(iii)** the use of a local optimization method[4].

Several advanced (heuristic and meta-heuristic) methods to solve TNEP problem, have been proposed by researchers. Some of them are presented in Table 3.

Many algorithms based on heuristic and meta-heuristic techniques have been proposed. Generally, an advanced method to solve TNEP problem, consist of over load checking, sensitivity analysis and scheme formation.

Overload checking: It is to be carried out to check whether there is adequate transmission capacity, i.e. whether there are any lines overloaded under normal conditions or sometimes even under conditions where on line is out of service (N – 1 checking).

Table 3. Advanced (heuristic and meta-heuristic) optimization methods used to solve TNEP problem

Sr. No	Ref. No.	Method used
1	8, 31, 32	Constructive heuristic algorithm
2	33, 34, 35, 36	Genetic algorithm (GA)
3	37, 38, 39	Particle swarm optimization (PSO)
4	40, 41, 42	Harmony search algorithm
5	43, 44	Simulated annealing (SA) algorithm
6	45, 46	Tabu search algorithm
7	47	Greedy randomized adaptive search (GRAS)
8	9, 10	Artificial bee colony (ABC) algorithm
9	48	Ant Colony Optimisation
10	49, 50, 51	Differential evolution algorithm

Sensitivity analysis: When a line is overloaded, sensitivity analysis is used to expand the network with the most effective line in order to eliminate overloading.

Scheme formation: Possible additions may be arranged in order of their effectiveness determined by sensitivity analysis so that a network expansion scheme may be determined certain method.

6. Comments

1] Many mathematical optimization methods like, linear programming, dynamic programming, mixed integer programming, branch-and-bound method, non-linear programming etc. have been used for solving TNEP problem, however they have some practical limitations.
2] Compared with advanced methods, the mathematical optimization method takes into account the interaction between variables resulting in more strictness in theory.
3] Since the number of network planning variables is very large and constraints are very complex, the existing mathematical optimization methods find it very difficult to solve such a large-scale planning problem. Therefore, when formulating a model by the mathematical optimization method one has to make many simplifications for a practical problem.
4] Some planning decision factors are very difficult to describe by a mathematical model, and hence a mathematical optimal solution may, not necessarily, be a practical optimal solution.
5] The advanced method of optimization (based on heuristic and meta-heuristic algorithms) have many interesting features such as **(i)** they easily find optimal solution for small and medium system; **(ii)** they find sub-optimal solutions for very complex systems; **(iii)** they are robust i.e. they always find a feasible solution; and (iv) they are easy to program.
6] The advanced methods of optimization are not deterministic and in many cases their efficiency depends on several points, for instance, the tuning of control parameters, the problem formulation, and, mainly, the way that the problem can be tailored in the selected approach.
7] It is indicated in the literature that to solve TNEP problem, the Tabu search and its hybrid versions have a slight advantage over the other advanced methods due to their flexible characteristic to incorporate new intelligent strategies.
8] Since the network planning is a planning problem with a large number of variables and complex constraints, there exist enormous difficulties in both the formation of planning models and the solution to the problem.
9] Researchers have confirmed the superiority of the meta-heuristic approach in dealing with TNEP problem, which is, large size, complex, nonlinear, and combinatorial problem. These methods have shown ability to avoid getting entrapped into local optima, and despite large solution space, only a small fraction of alternatives are analyzed and the search is guided to better solutions.

7. Future Scope

After going through the literature in detail, it can be said, in general, that transmission network expansion planning is still in a developing stage. The existing planning methods can only be used as complementary tools in practical planning.

In future, studies in network planning should try to improve the planning quality, efficiency and practicality, such as,
1] While formulating the problem, more consideration should be given to operating and constructional

constraints, so as to ensure that it gives practically feasible optimal plan.

2] Many new modern optimization methods have come up which are more promising. These methods (such as, fire-fly algorithm, bat algorithm, gravitational search algorithm, teaching learning based optimization algorithm, Jaya algorithm etc.) should be tried up on the TNEP problem.

3] The man-machine interface could be reinforced. The planners' experience should be taken into consideration to improve the planning quality and practicality. It may be very difficult to mathematically model such factors.

4] Remarkable efforts should be taken to gain higher accuracy in achieving to the practically optimal solution for TNEP problem.

5] The development of effective network evaluation methods should quickly help to select an optimal scheme from a large number of alternatives and also provide information for further improvement.

6] To solve TNEP problem, new approaches should be proposed, which include hybrid algorithms that merge the best qualities of conventional optimization method and advanced optimization method.

8. Conclusions

The TNEP problem is a large-scale, complex and nonlinear combinatorial problem of mixed integer nature. Various conventional and advanced (heuristic and meta-heuristic) optimization techniques have paid a lot of attention for solution of such problems. This paper has taken review on the work reported in the literature, on various conventional and advanced optimization methods in the field of TNEP problem but still further improvement in algorithms are required.

For a network planning problem as a whole, there is no clear demarcation between the scheme formation and evaluation, and between the methods used in the scheme formation and evaluation. It is difficult to conclude which algorithm presents the best performance to the network planning.

The hybrid algorithms may prove to provide optimal network planning which will be practically feasible and optimal.

The best combination of methods and algorithms will point the way towards improved network planning.

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