Efficient Multi-Year Security Constrained AC Transmission Network Expansion Planning

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Abstract: Solution of multi-year, dynamic AC Transmission network expansion planning (TNEP) problem is gradually taking centre stage of planning research owing to its potential accuracy. However, computational burden for a security constrained ACTNEP is huge compared to that with DCTNEP. For a dynamic, security constrained ACTNEP problem, the computational burden becomes so very excessive that solution for even moderately-sized systems becomes almost impossible. Hence, this paper presents an efficient, four-stage solution methodology for multi-year, network N-1 contingency and voltage stability constrained, dynamic ACTNEP problems. In the first three stages of the proposed solution methodology, simpler versions of TNEP are solved. Several intelligent logical strategies are developed from the results of these stages. The developed strategies are then applied to solve multi-year, security constrained ACTNEP in the final stage. This results in substantial reduction in the overall computational burdens of solving the problems. The proposed methodology is applied to Garver 6, IEEE 24, South-Brazilian 46 and IEEE 118 bus systems to demonstrate its efficiency and ability to solve multi-year ACTNEP for varying system sizes.

Keywords: Transmission network expansion planning, multi-year planning, intelligent algorithms, network security constraints.

1. Nomenclature

A. Variables, Sets and Parameters Related to TNEP

v_d	Total investment cost referred to first year of planning
T_y	Total number of years in planning horizon
y	Year of planning
k	Contingency state, $k = 0$ denotes base case
$\forall$ year, y:	
C_d^y	Discount factor for investment cost
v^y	Total investment cost
v_{lc}^y	Line addition cost
l^y	Power corridor between two buses
Ω	Set of all power corridors
C_l^y	Cost of line addition in the l^{th} power corridor
n_l^y	Number of additional lines in the l^{th} power corridor
N_{ld}	Set of load buses of the system
$\boldsymbol{P}_{\boldsymbol{Dm}}^{\boldsymbol{y}}$	Vector of real power demand
$\boldsymbol{Q}_{\boldsymbol{Dm}}^{\boldsymbol{y}}$	Vector of reactive power demand
$\boldsymbol{q}_{\boldsymbol{rc}}^{\boldsymbol{y}}$	Vector of capacity of additional reactive sources
L^y	Base case L-index value of the system
$\forall$ year, y and $\forall$contingency, k:	
$\boldsymbol{P}_{\boldsymbol{in}_k^y}$	Vector of real power injections
$\boldsymbol{P}_{\boldsymbol{Gn}_k^y}$	Vector of real power generations
$\boldsymbol{Q}_{\boldsymbol{in}_k^y}$	Vector of reactive power injections
$\boldsymbol{Q}_{\boldsymbol{Gn}_k^y}$	Vector of reactive power generations
$\boldsymbol{V}_{\boldsymbol{k}}^{\boldsymbol{y}}$	Vector of bus voltage magnitudes
$\boldsymbol{n}_{\boldsymbol{k}}^{\boldsymbol{y}}$	Vector of bus voltage angles
$\boldsymbol{\theta}_{\boldsymbol{k}}^{\boldsymbol{y}}$	Vector of system circuits
S_{ly}^{kfr}	Sending end MVA flow in each line of l^{th} corridor
S_{ly}^{kto}	Receiving end MVA flow in each line of l^{th} corridor
$\bar{n}_l$	Maximum limit on new lines in l^{th} power corridor
ω_{cont}	Total number of contingencies in a system
N_{bus}	Set of all buses in a system

B. Parameters Related to Metaheuristic Algorithm

cs_N	Population/colony size
E_h	Number of neighbours
$iter$	Maximum number of iterations per trial
lim	Parameter for generation of scout bees
w_g	Parameter to control the effect of best solution
tp	Approximate time of solution per trial

2. Introduction

2.1. Background and Motivation:

Power system networks worldwide have encountered fundamental changes due to their unbundling and deregulation. In addition, environmental concerns to reduce greenhouse gas emissions are encouraging increasing the amount of integration of renewable energy sources (RES) after the enactment of Kyoto protocol [1]. This necessitates sufficient flexibility in the transmission planning to account for the uncertainties resulting from RES integration. Solution of multi-year, dynamic transmission network expansion planning (TNEP) can adequately address this by providing the network planners not only the information on which lines to construct, but also the time of its construction within the planning horizon so that the overall investment cost is minimized and the uncertainties in future load/generation can be adequately addressed. However, owing to its NP-hard, mixed-integer, combinatorial nature, solution to such an optimization problem is extremely complex. Often, it leads to a situation of “combinatorial explosion” which makes their solution computationally much intensive. In addition, the final planned network should be reliable enough to at least withstand a single line/equipment failure (N-1 contingency). In a multi-year dynamic TNEP, consideration of network contingencies is even formidable to solve.

Therefore, extensive research has been conducted on this topic in past few decades, although, with several simplifications. In existing literatures, researchers have mostly used approximated DC formulation to solve the problem within a manageable time frame [2]-[26]. Primary drawback of using DCTNEP plans is that, it completely neglects the system reactive power flows. As a result, direct application of the DCTNEP solutions to AC networks can cause line overloads, poor voltage profile and, in the worst case, in absence of proper reactive support, may lead to system voltage collapse. As in current deregulated scenario, maintaining an acceptable system voltage profile is a strict requirement, solution of ACTNEP is gradually gaining interest. Through ACTNEP, the final planning is quite accurate as the actual network power flow scenario, voltage profile and losses can be known. Although, solution of multi-year dynamic ACTNEP tremendously increases the computational burden compared to DCTNEP due to the requirement of repeated iterative solutions of non-linear AC power flow/ AC optimal power flow.

Therefore, most of the existing works [2], [27]-[34] consider approximated linearized solution processes of multi-year ACTNEP to tackle the issue of extreme complexity. In addition, most of them either completely ignore the network security aspects or only consider them in a limited manner. These aspects again result in approximate final investment plans, and their direct application to practical systems may cause unintentional security issues.

This brings to the motivation for this paper, which can be stated as follows:

i. To develop a computationally efficient solution methodology that can effectively and efficiently solve completely non-linear security constrained multi-year ACTNEP with much reduced computational burden.

ii. Demonstrate the applicability of methodology as a general tool for multi-year ACTNEP in a variety of test systems.

2.2. Literature Survey:

A detailed and comprehensive review of the existing TNEP literature is presented by the authors in [2]. It provides a holistic view of the different approaches considered by researchers for the solution of TNEP problems. Generally, metaheuristic methods are applied for the solution of TNEP [3] – [8]. Mixed integer linear programming (MILP) approach with DC model has also been used by several researchers to solve multi-year TNEP [9] – [14]. Also, dynamic generation and transmission expansion planning in a DC framework are solved in [15] – [17]. Due to increased computational burden experienced in solving multi-year TNEP even in DC framework, several strategies for effective reduction of the same have also been explored by researchers. Heuristic strategies to solve the problem is presented by authors in [18]. In [19], several strategies to reduce the combinatorial search space is proposed in solving multi-year TNEP; and, a two-stage solution methodology for solving similar problem is presented in [20].

Authors in [21] use a Reduced Disjunctive Model (RDM)-based methodology to solve DC N-1 contingency constrained multi-year TNEP in a MILP environment. The effectiveness of the methodology is in reducing the combinatorial search space compared to traditional Disjunctive Model. In [22] and [23], stochastic programming approaches are used to solve multi-stage electricity and natural gas co-planning problems in presence of various network uncertainties. As the solution methodologies proposed here are based on stochastic programming, the accuracy of the final solutions greatly depend on the number of scenarios considered for the uncertainties.

New options are also explored in recent literatures while solving multi-year TNEP. Likewise, network uprating options along with multi-year DCTNEP is solved in [24]. Ant Colony Optimization (ACO) is used here and efficiency of the methodology is shown compared to traditional MILP approach. Similarly, authors in [25] solve Particle Swarm Optimization (PSO)-based multi-year DCTNEP with consideration for line maintenance costs of existing and replaced lines. In [26], a Symphony Orchestra Search Algorithm (SOSA) is used to solve multi-period DCTNEP problem incorporating Unified Interphase Power Controllers (UIPCs) in the solution model. Here, one of the objectives is to reduce the short-circuit level of the final planned network.

Due to the shortfalls of the DC-based planning as described earlier, ACTNEP is becoming increasingly important. Solution of security constrained multi-year ACTNEP by MILP approach is explored in [27]. Here, an initial DC solution is reinforced to obtain security constrained AC results. Such a formulation, although very effective in reducing computational burden, leads to sub-optimal solutions. In [28], the author uses mixed integer conic programming (MICP), to solve static and multi-year ACTNEP, without consideration of network contingencies. Solution for a smaller system is obtained very quickly, however, solution time for a medium-sized (46 bus) system is found to be extremely large. Therefore, the author recommends the readers to explore different techniques which reduce the overall search space. In [29], MILP is used to solve a similar problem. Main drawback faced here is dealing with high dimensionality and computational burden. Also, in [30], a multi-objective dynamic ACTNEP is solved without consideration of security constraints by a new proposed Multi-Population and Multi-objective Evolutionary PSO (MEPSO-II) algorithm. Although it provided better results compared to existing methodologies, the solution time is found to be high. Security constrained, multi-year linearized ACTNEP is solved by MILP in [31]. However, here, the authors have considered a set of only a few selective contingencies instead of all possible contingencies for security studies. In [32], authors propose a two-stage methodology to solve multi-year ACTNEP with security constraints. Available search space is reduced in the first stage by applying Constructive Heuristic Algorithm (CHA). This forms a starting point for the second stage, which is solved by an evolutionary metaheuristic algorithm EPSO-μ. However, the overall computation time is still significantly high.

Combined Generation and TNEP (G&TNEP) problems in a dynamic, multi-year time-frame are also solved in recent literatures. A framework is proposed in [33] for the solution of multi-year combined Generation and TNEP (G&TNEP) in Multi Carrier Energy Systems (MCES) with linearized AC model. The results are then compared with that of DC model to establish its effectiveness. Authors in [34] solve pseudo-dynamic multi-stage/year TNEP with the primary aim of reducing impacts of a cascading failure. The most critical line is identified based on its ability to initiate and propagate a cascading failure in a network. Consequently, reinforcements of the entire network are performed by an iterative process.

2.3. Research Gaps and General Overview:

In the extensive literature present on TNEP studies, it can be observed that the most commonly used test networks range from 3 or 6 bus to 118 bus or similarly sized networks. Empirically, a small system may be assumed to have the total number of network buses less than or equal to 15. From 24 to about 57 bus systems, they may be assumed to be medium-sized, whereas from 96 bus to 118 bus systems, they may be considered to be large-sized systems. A very limited number of works [2] can be found to study TNEP for even larger systems. However, these studies primarily focus on DC based planning to reduce the computational requirement.

Further, from the above literature review it is clear that, most of the existing literature focus on solving multi-year TNEP with DC formulation. Due to huge computational burden in solving even DC problems, several strategies have been proposed previously. Also, it can be observed that in solving multi-year ACTNEP with security constraints, full non-linear formulation has not been attempted in the past to that extent. In addition, none of the existing literatures consider network voltage stability aspects while solving multi-year TNEP. This paper addresses the aforementioned research gaps by proposing a four-stage solution methodology which uses several intelligent strategies, to effectively reduce the overall computational burden for solving a full non-linear, network security and voltage stability constrained multi-year ACTNEP.

The methodology proposed in this paper depends on the fact that, the power corridors which will have new lines, and the total number of new lines in the final AC contingency constrained planning, can be very effectively estimated from: a) Contingency constrained DCTNEP and b) ACTNEP without considering contingencies. Therefore, the first three stages involve the respective solutions of: 1) Base case DCTNEP, 2) Base case ACTNEP, and, 3) Contingency constrained DCTNEP. Intelligent strategies are then formed based on these results to solve the fourth and final stage of contingency constrained or security constrained ACTNEP. It is to be noted here that, base case denotes a network condition where all the available power lines are assumed to be functional and there is no contingency. So, base case TNEP is solved assuming that all existing power lines will always be available. In other words, for base case TNEP, the contingency percentage of the lines is assumed to be zero. As a result, base case TNEP is much easier to solve and it always provides a lower investment cost compared to contingency constrained TNEP.

To demonstrate the potential of the developed framework, computational burden of a metaheuristic, modified artificial bee colony algorithm (MABC) [35], is compared with/without the proposed strategies. Here, MABC is only used as it has shown improved effectiveness in solving TNEP compared to other existing metaheuristic algorithms [35]. However, the strategies developed in this paper are generic enough to be applied with any other algorithm as per the wish of a user, and, their application is expected to provide similar reductions of computational burdens for all such algorithms.

In this paper, the solution methodology developed does not depend on a future load or generation profile of the network. Instead, the strategies are developed based on results obtained from simpler solutions of TNEP over the course of the multi-stage solution process (Stage 1 to Stage 3). Hence, the developed strategies are also applicable when load and generation uncertainties are considered. However, consideration of network uncertainties is bound to increase the computational burden by a large extent and development of additional strategies may be required for the efficient solution of uncertain dynamic ACTNEP problem within a suitable time-frame. A definite methodology for the solution of such problems is a matter of our active research which we hope to include in a future publication. Therefore, to primarily focus on the development process of a solution methodology for security constrained dynamic ACTNEP, network uncertainties have not been considered in this paper.

2.4. Contributions:

The primary contributions of this paper can be summarized as:

1) A novel four-stage solution methodology for the efficient solution of security constrained multi-year dynamic ACTNEP is developed.
2) The methodology is developed as a general tool, independent of any particular metaheuristic algorithm. Hence, a user can apply it to any algorithm as per convenience.
3) The proposed solution methodology is used to solve security constrained dynamic ACTNEP for a number of test systems so as to demonstrate its applicability and efficiency compared to conventional methods.

The novelty of this paper lies in the development of the intelligent strategies from solutions of TNEP of gradually increasing complexities, that enables a user to solve full non-linear security constrained dynamic ACTNEP for a network with substantially reduced computational burden compared to conventional techniques. Therefore, with the proposed solution methodology, it is now possible to solve security constrained dynamic ACTNEP for much larger systems with relative ease.

2.5. Paper Structure:

Rest of this paper is organized as follows: Section 3 provides the mathematical modelling, followed by a description of the solution technique used, in Section 4. Section 5 describes the proposed solution methodology. Section 6 provides detailed results of the test systems and relevant discussions. Finally, conclusions and future work are stated in Section 7.

3. Mathematical Modelling

In this paper, a multi-year dynamic ACTNEP problem is solved, with approximate Reactive Power Planning (RPP) being considered from the solution of static, sequential ACTNEP. Experience has shown that, the RPP of the final dynamic ACTNEP is not much different compared to the RPP obtained from the solution of relatively easy sequential planning. Therefore, such a consideration of approximate RPP reduces the complexity and computational burden in solving dynamic ACTNEP as will be discussed in detail in Section 5.

The objective thus becomes the minimization of total cost of line additions over the planning horizon [36]:

Minimize:

$$v_d = \sum_{y=1}^{T_y} (C_d^y \times v_{lc}^y) \tag{1}$$

where, ∀ y,

$$v_{lc}^y = \sum_{l^y \in \Omega} (C_l^y \times n_l^y) \tag{2}$$

In multi-year TNEP, cost of construction is referred to the first year with appropriate discount factors to account for cost depreciation. Therefore, the objective function for minimization is represented by (1), which is the sum of total investment cost per year multiplied by the respective discount factors, C_d^y. Cost of investment in each year, is the line investment cost, v_{lc}^y represented by (2).

In solving TNEP, 'power corridors' or transmission corridors [31] consist of a very important concept. It can be assumed to be a direct pathway for the flow of power between two buses. Physically, these corridors are the rights-of-way where new transmission towers and lines can be built. In each such power corridor, there may be several types of lines each with different parameters/properties. In this paper, each set of such similar types of lines within an actual physical power corridor are assumed to be separate sub-corridors for power flow. This consideration makes the planning convenient as each sub-corridor only has lines of similar properties. The real advantage for this type of modelling is that it can track the line contingencies of these different types of lines so that the final planning is adequately reliable and satisfies the important N-1 security criteria [36].

Therefore, C_l^y represents the cost of line addition in the l^{th} power corridor in the y^{th} year. Several constraints are required to be satisfied for each year y and for each contingency state k. The constraints that govern the above minimization problem can be grouped as follows:

3.1. Operational constraints:

These are network power balance constraints at all the buses,

$$\boldsymbol{P_{in}(V,\theta,n)_k^y} - \boldsymbol{P_{Gn}}_{\boldsymbol{k}}^{\boldsymbol{y}} + \boldsymbol{P_{Dm}^y} = 0 \tag{3}$$

$$\boldsymbol{Q_{in}(V,\theta,n)_k^y} - \boldsymbol{Q_{Gn}}_{\boldsymbol{k}}^{\boldsymbol{y}} + \boldsymbol{Q_{Dm}^y} - \boldsymbol{q_{rc}^y} = 0 \tag{4}$$

In addition, network voltage profile is required to be maintained within a specified upper and lower bound,

$$\boldsymbol{V_{Min}^y} \leq \boldsymbol{V_k^y} \leq \boldsymbol{V_{Max}^y} \tag{5}$$

As voltage stability of a system is a major concern in current deregulated scenarios, a good planning should provide adequate margin of the same. System L-index [37] value provides a fair estimate of its voltage stability. Ranging from 0 to 1, L-index value of 1 indicates system voltage collapse, whereas low values indicate a stable system. However, as L-index is highly nonlinear, accurate realization of network MW voltage stability margin is not possible only through its value. For obtaining an accurate voltage stability margin, proper RPP is required to be solved along with ACTNEP. In this work, a simplistic RPP is solved only to ensure system convergence and adequate reactive support. After an initial investment plan is obtained by the method proposed in this paper, a user can perform a proper RPP with consideration of an accurate voltage stability margin to obtain a final plan. Such a decomposed approach to the problem is essential for managing the computational burden involved in solving multi-year dynamic ACTNEP.

Therefore, with a simplistic RPP as is done here, to provide at least an approximate estimation of a good, voltage-stable system, a bound is set on its L-index value. If L-index value of a network is maintained within a low maximum bound (typically 0.4), it can result in an adequately voltage-stable system. Although the boundary value considered is not optimal, the model proposed is general enough, and users can define an optimal limit on L-index values according to their choice. It is enforced only for base case network, as similar enforcement even in the contingency cases may result in a significantly increased investment cost. Further, limiting base case L-index value of a system within a low bound obviously increases voltage stability margin even for contingency cases. Thus,

$$L_{Min}^y \leq L^y \leq L_{Max}^y \tag{6}$$

3.2. Equipment constraints:

Equipment constraints include real and reactive power generation limits of the generators and line power flow limits. The generator limits are provided by (7) and (8).

$$\boldsymbol{P_{Gn}}_{\boldsymbol{Min}}^{\boldsymbol{y}} \leq \boldsymbol{P_{Gn}}_{\boldsymbol{k}}^{\boldsymbol{y}} \leq \boldsymbol{P_{Gn}}_{\boldsymbol{Max}}^{\boldsymbol{y}} \tag{7}$$

$$\boldsymbol{Q_{Gn}}_{\boldsymbol{Min}}^{\boldsymbol{y}} \leq \boldsymbol{Q_{Gn}}_{\boldsymbol{k}}^{\boldsymbol{y}} \leq \boldsymbol{Q_{Gn}}_{\boldsymbol{Max}}^{\boldsymbol{y}} \tag{8}$$

Line power flow limits are considered as follows:

$\forall l^y \in \Omega\, ;\, l^y \neq k,$

$$(n_0^y + n_l^y) S_{l^y}^{kfr} \leq (n_0^y + n_l^y) S_{l^y{}_{Max}} \tag{9}$$

$$(n_0^y + n_l^y) S_{l^y}^{kto} \leq (n_0^y + n_l^y) S_{l^y{}_{Max}} \tag{10}$$

for $l^y = k,\, k \neq 0,$

$$(n_0^y + n_l^y - 1) S_{l^y}^{kfr} \leq (n_0^y + n_l^y - 1) S_{l^y{}_{Max}} \tag{11}$$

$$(n_0^y + n_l^y - 1) S_{l^y}^{kto} \leq (n_0^y + n_l^y - 1) S_{l^y{}_{Max}} \tag{12}$$

Here, constraints (9) and (10) denote the power flow constraints for the base case and for corridors without any contingency. Constraints (11) and (12) are for the power flow limitations on the power corridor with a line outage.

3.3. Physical constraints:

These constraints include physical limitations in a network planning, such as, limits on the maximum number of new lines per corridor:

$$\forall l^y \in \Omega, \quad 0 \leq \sum_{y=1}^{T_y} n_l^y \leq \bar{n}_l \qquad (13)$$

Further, an investment committed in a previous year should always be present in the consecutive years. This constraint is enforced by the following:

$$\forall l^y \in \Omega, \qquad n_l^y \geq n_l^{y-1} \qquad (14)$$

Here, $n_l^y \geq 0$ and integer $\forall l^y \in \Omega$ and $l^y \neq k$; $(n_0^y + n_l^y - 1) \geq 0$ and integer for $l^y = k$, $k \neq 0$. $k = 0,1, \dots \dots \omega_{cont}$, denotes the state of contingency, with $k = 0$ denoting the base case.

DCTNEP forms an important part of the solution methodology proposed in this paper for the solution of complex ACTNEP. Hence, for completeness of discussion, a brief description of DCTNEP is provided here with its differences from ACTNEP:

DCTNEP is actually a simplified version of the complex ACTNEP. In DCTNEP, the network is considered to be completely reactive, without resistive elements. Network losses and reactive power flows are neglected. Further, network constraints are linearized, with an assumption of uniform unity voltage profile throughout the network. Therefore, the reactive power balance and its associated constraints, that is (4), (6) and (8) are not present. Also, as unity voltage profile is assumed, constraint (5) is absent. Apparent power flows through the lines become equal to the real power flows. In the absence of network losses, (9) and (11); and (10) and (12) become same. Such simplifications lead to non-iterative solution of DC power flow, and hence result in substantially low computational burden when solving DCTNEP. All other physical constraints of ACTNEP are also present in DCTNEP. As a result, solution of DCTNEP is able to provide vital information regarding the power corridors and new lines for the solution of ACTNEP.

As the RPP used for dynamic ACTNEP is considered same as what have been obtained in sequential ACTNEP, the constraints for the former do not include the usual constraints related to the additional reactive sources. However, these omitted constraints are completely considered [36] when solving sequential planning.

Additionally, in recent times, there has been an increased importance for the consideration of environmental pollution constraints in TNEP studies. However, in a majority of the existing literature, the primary objective of TNEP is the minimization of line investment costs. Therefore, in this paper also, to keep the formulation simple and to have a fair comparison with the existing works, environmental pollution constraints have not been considered. It should be noted here that, the solution methodology developed in Section 5 is independent of the problem constraints; and hence a user can also incorporate the environmental pollution constraints in the studies to obtain a similar reduction in computational burden compared to conventional solution methodology.

4. Solution Technique

ACTNEP is a NP-hard problem with both integer and continuous variables which can be differentiated as:

$\forall\, y$, and $\forall\, k$, State variables: ${V_k^y}_i$ ($\forall i \in N_{ld}$) and ${\theta_k^y}_i$($\forall i \in N_{bus}$, $i \neq$ slack); Control variables: ${P_{Gn}}_{k\,i}^{y}$ ($\forall i \in N_{pvbus}$ $i \neq$ slack), ${V_k^y}_i$ ($\forall i \in N_{pvbus}$) and n_l^y ($\forall l^y \in \Omega$); and Fixed variables: $P^y_{Dm_i}$($\forall i \in N_{ld}$), $Q^y_{Dm_i}$($\forall i \in N_{ld}$), $q^y_{rc_i}$ ($\forall i \in N_{ld}$), and ${\theta_k^y}_i$ (i =slack).

Solution of such a problem while considering all the variables as a single set is computationally intensive. However, computational complexity can be substantially reduced by suitable truncation of these variable sets and their successive solution. In this paper, it has been divided into two parts: a) investment variable part and b) operational variable part.

Line additions in a power corridor (n_l^y), which determine the investments and network topology, are obtained by MABC. Network reactive power addition ($q^y_{rc_i}$ and α_i^y) are assumed to be known previously from sequential TNEP, as will be elaborated in section 5. Here, α_i^y is a binary variable that determines which load bus need to have an additional reactive power source. The estimation of power generations and voltage magnitudes at generator buses (operational variables) for satisfying network constraints, are performed by solving OPF (by in-built solvers in MATLAB). Through MABC, objective function (1) is minimized along with satisfaction of constraints (13) – (14). For a particular network topology fixed by MABC, OPF is solved for each network contingency to satisfy the remaining network and line flow constraints. Originally, power flow equations are non-linear in nature and to obtain adequate accuracy of planning, in base case topology, non-linear OPF is solved. However, repeated solutions of non-linear OPFs for each network contingency results in huge computational burden.

Therefore, to reduce the overall problem complexity, linearized OPF is solved in contingency cases. Such mixed form of solution methodology helps in obtaining a proper balance between the computational burden involved, and the accuracy of expansion planning. Linearization of the network constraints are performed by assuming small angle difference between two connected buses, and small deviation of voltage magnitudes from base values. By such assumption, for any two connected buses i and j, it can be approximated that, $\sin\theta_{ij} \approx \theta_{ij}$ and $\cos\theta_{ij} \approx 1$. Here, $\theta_{ij} = \theta_i - \theta_j$. Substitution of these values in the evaluation of non-linear network constraints (3) – (4) and (9) – (12) and neglecting the higher order terms in Taylor's series expansion reduce them to linear constraints [38], which are solved effectively by OPF solver. At the end of OPF solution by the MATLAB solvers, fitness function values are returned to MABC, required for convergence to the optimal solution. The fitness function values are evaluated in the same manner as has been described in ref. [36].

5. Proposed Methodology

Solution of ACTNEP problems become exponentially complex when network contingencies considered. Further, compared to single-year static situation, when a multi-year dynamic TNEP (DTNEP) is considered, computational burden increases to a level, where rigorous single-stage, brute force solution methodologies cannot even be considered for use. As a result, solution to such problems for moderate to large systems require intelligent strategies that can efficiently obtain a good-quality solution.

In this paper, a four-stage algorithm is proposed to quickly reach an acceptable solution for the N-1 security and voltage stability constrained, multi-year ACTNEP problems by the application of several general intelligent strategies developed from base case ACTNEP and contingency constrained DCTNEP results. These stages are described as follows:

Stage 1: *Solve base case DCTNEP.*

This stage is the easiest to solve and requires minimum computational burden, although it provides a logical starting point for the next stage of solving base case ACTNEP. This stage provides information on the number of new lines in each power corridor, the final cost of planning and the real power generation values. These form the inputs to the next stage, where this information is used for faster solution of base case ACTNEP [36].

Stage 2: *Solve base case ACTNEP.*

Starting from the results of previous stage [36], base case ACTNEP is solved. From this solution we know the new lines, the cost of planning, the real and reactive power generation values and the network voltage profile. The cost of planning and the new lines provide vital clues about the effective search space for contingency constrained ACTNEP. This information is used in the fourth stage for effective estimation of new power corridors and new lines.

Stage 3: *Solve contingency constrained DCTNEP.*

Similar to stage 1, solution of this stage provides vital information on contingency constrained AC planning. The investment cost of planning obtained from this stage provides a good starting point and viable estimation of the upper cost bound for the contingency constrained ACTNEP, solved in the next stage.

Stage 4: *Solve contingency constrained ACTNEP.*

Solution of this stage requires the maximum computational burden. Compared to this stage, results of the first three stages are much easier to obtain and provide valuable information for solving this fourth and final stage of N-1 security constrained ACTNEP. For the efficient solution of this stage, several intelligent strategies are formulated from the results of the previous three stages. These developed strategies form the effective input parameters for this stage of the solution process. The strategies are then applied with MABC to solve multi-year contingency constrained ACTNEP with drastically reduced computational burden. These strategies are described as follows:

5.1. Estimate the set of power corridors in which the final solution will always be present

Computational burden in any optimization algorithm is directly proportional to its search space. A small search space reduces the computation burden for finding the optimum solution. In TNEP, all available power corridors of a system represent its search space. However, final contingency constrained ACTNEP solution shows new lines in only a few of all available power corridors. An estimation of these corridors with a very high possibility of having new lines in the final solution, confines the search within this set and provides substantial reduction in computational burden This violation set (PC_{viol}) can be obtained from the N-1 security analysis on base case ACTNEP solution. It provides all the power corridors where there are line power flow limit violations. Set of these power corridors ($PC_{viol} \in \Omega$) which is far lesser in size than the original set Ω, provide a viable search space for the metaheuristic algorithm (MABC) in the fourth stage of the solution process. Therefore, PC_{viol} acts as an input to the final stage that defines the available search space.

5.2. Find the set of power corridors which will definitely have new lines in the final solution

Computational burden can be further reduced if a set of power corridors is precisely estimated which is sure to have new lines in the final security constrained planning. Such an estimation of fixed set (PC_{fix}) of power corridors allows MABC to always direct its search with in this set of power corridors which helps in faster arrival at the final solution. This set can be obtained by finding the common corridors present in set PC_{viol} and in the contingency constrained DCTNEP results (DC_{cont}).

Therefore, $PC_{fix} = PC_{viol} \cap DC_{cont}$.

PC_{fix} acts as a common factor for the new solution strings generated in this stage by MABC. That is, every solution string generated by MABC in all of its bees' phases [35] has new lines for the set of power corridors denoted by PC_{fix}.

5.3. Reduce the number of times AC OPF is solved

The most time-consuming block in security constrained ACTNEP is the block that solves AC OPF. For each combination string generated by MABC, fitness function needs to be evaluated which involves solution of AC OPF. Computational burden can be effectively reduced by reducing the required number OPF solutions. The following strategies are formulated to reduce the number of OPF solutions. Only when a solution string satisfies the criteria of all of the strategies as described below, OPF is solved.

1) Restrict the Number of Power Corridors Within a Specific Bound:

It has been observed from solving ACTNEP for various systems that, in the final solution, the number of power corridors having new lines is almost 90% of the number present in corresponding DCTNEP results. ACTNEP will certainly have some more corridors than DCTNEP. In order to generalize the technique for use with both static and dynamic TNEP, the number of power corridors in solving ACTNEP are bounded within 90-130% of the number obtained in DCTNEP. Only when the number of power corridors with new lines in a combination string of MABC falls within this range, AC OPF is solved. In other cases, a suitable penalty is added to the objective function in order to discard the combination. The selection of the specific bound on the number of power corridors is a parameter for the proposed solution methodology and this requires proper tuning to obtain a good final result. Its value is determined based on several trials of the solution process as is discussed in detail in section 6.2.

2) Check the Worthiness of a Combination:

In the initial phases of solution, most of the combinations generated by a metaheuristic are infeasible, which are gradually removed from the solution process by evaluating their fitness functions through solving OPFs. Hence, this makes the algorithm extremely inefficient as most of the time is spent in evaluating infeasible combinations. However, if only a combination deemed worthy of having a feasible solution is evaluated by solving AC OPF, the number of OPF solutions over the entire solution process reduces drastically. Worthiness of a combination is determined on the basis of its cost, and, OPF is solved only if its cost is below a specific upper limit, (U_{lim}). For other cases, an appropriate penalty is added.

This limit is adaptively set as per the progress of the algorithm. Initially, it is set as twice the cost of new lines of security constrained DCTNEP. As the algorithm progresses, if a feasible combination with a lower investment cost is obtained, this cost is set as U_{lim}. Such a relaxed setting is used to allow MABC with sufficient flexibility of search to reach the final solution. Too tight a criterion to reject a combination may result in very constricted search space and may lead to trapping of the algorithm at a local optimum.

3) Continue to Solve OPFs for Different Network Contingencies Only if Feasible Results are obtained for Base case and all Previous Contingencies:

Final objective of security constrained TNEP is to obtain a planning which is feasible for every network configuration—base case and all network contingencies. For a combination produced by a metaheuristic, if the base case TNEP is not feasible, it is obvious that the contingency cases will also be infeasible. Further, once an infeasibility at any network contingency is obtained, remaining contingencies are not required to be checked for feasibility, as it will eventually produce an infeasible final result. Suitable penalties are added to remove these types of infeasible combinations from the solution process. Therefore, computational burden in solving security constrained ACTNEP is effectively reduced by avoiding unnecessary OPF solutions.

4) AC OPF is solved only for the years which Experience a change in the Base Topology:

In the dynamic planning process, for a combination string generated, instead of solving the OPF block for all the planning years concerned, by this strategy, it is solved only for those years where there is a change in base network topology. Inclusion of this action is quite logical and produces a substantial reduction in the overall computational burden.

5.4. Additional Reactive Sources are set at Values Obtained by solving Sequential ACTNEP

Multi-year sequential ACTNEP involves sequential solving of static ACTNEP for each year concerned, with the planning at the end of a year becoming the base network for the next year. It is relatively much simpler to solve and results are obtained quite fast compared to DTNEP due to successive planning for every year. Also, sequential planning is short-sighted as it does not take into account future network conditions, and final investment cost obtained over the planning horizon is invariably higher than that obtained by dynamic planning. However, the results obtained from such a planning provides a good, sub-optimal starting point and upper bound for dynamic planning. It has

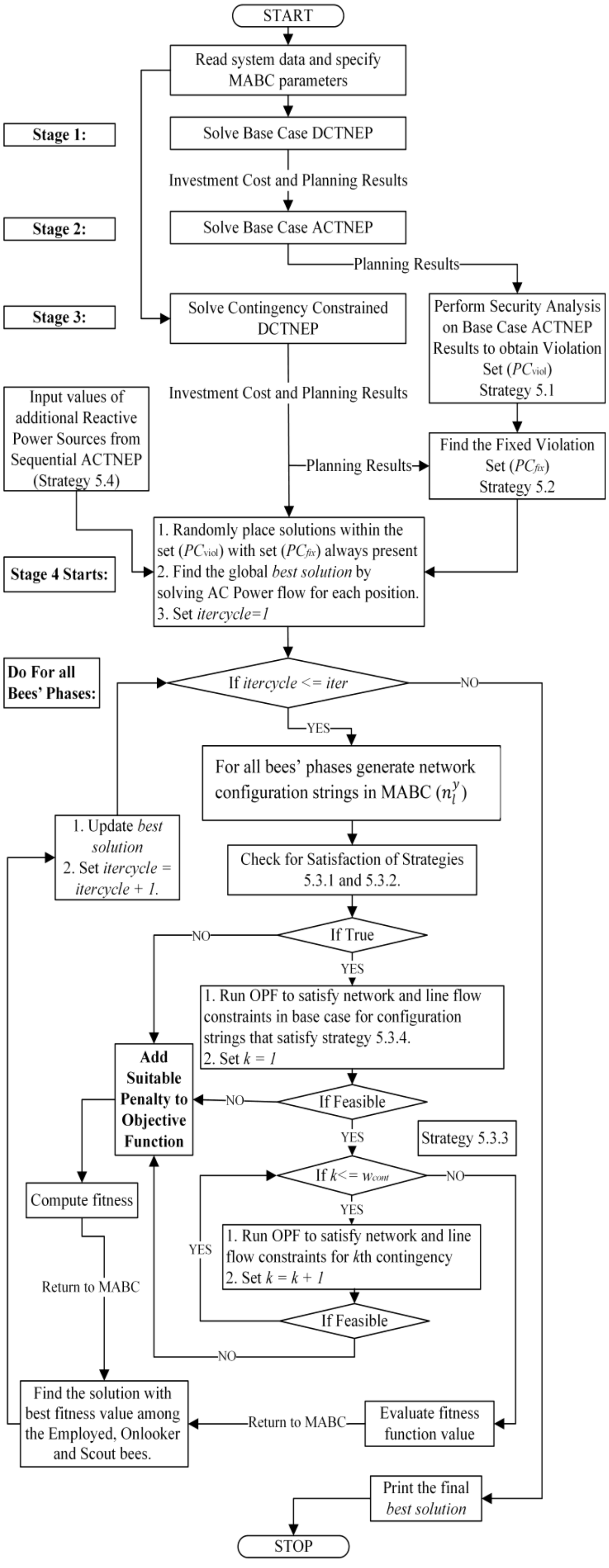

Fig. 1. *Flow Chart of the Proposed Methodology*

been found by several trials of solving sequential and dynamic TNEP that, the values of the additional reactive sources obtained in both planning are very close. Therefore, to reduce the computational burden in solving multi-year AC DTNEP, the values of additional reactive sources are fixed to that obtained in sequential planning.

The proposed four-stage solution methodology although uses several intelligent strategies, it still retains enough flexibility to reach the final solution with drastic reduction of the computational burden. This property of the methodology will be evident in the next section, where detailed discussion on obtained results is done in comparison with single-stage rigorous (also MABC based) method, which does not use any of the proposed intelligent strategies. A detailed flow chart of the proposed solution methodology is depicted in Fig. 1.

6. Results and Discussion

Applicability of the proposed solution methodology is demonstrated by solving security constrained multi-year dynamic ACTNEP for Garver 6 bus [28], IEEE 24 bus [28], South-Brazilian 46 bus [38] and IEEE 118 [39] bus test systems. The systems considered provide an acceptable variation in size to demonstrate the suitability of the proposed methodology toward solving multi-year, security constrained AC TNEP from small to large systems. Sequential ACTNEP is also solved for these systems to demonstrate the benefits of DTNEP over sequential TNEP. As similar results are not available in present literature, comparison of results obtained by the proposed method with any other method is not possible. However, for base case AC DTNEP of 6 bus system, a comparison of results with that obtained by an existing methodology is provided.

Here, for all the test cases considered, all generating units are considered to be completely dispatch-able. In base case, bus voltage magnitudes are constrained within $\pm 5\%$ of their nominal values, whereas, for contingency cases, tolerance limit is $\pm 10\%$. In each of the contingency cases, pv bus voltage magnitudes and generations are modified to reduce line overloads, in accordance with actual practice. Network base case L-index values are constrained within 0.4. Simulations of this work are performed with MATLAB R2015b on a desktop computer with 16 GB RAM, having Intel (R) Core (TM) i5-4590 CPU processor @ 3.30 GHz. 50 trials for each system is performed and the best results are provided for comparison.

In the solution procedure, stage 4 consumes the maximum amount of time and compared to this, time required by the previous stages is considered negligible. Like any other metaheuristic, MABC also requires careful tuning of its parameters for optimum efficiency. Its parameters are tuned according to the criteria in [35], [36], with values for multi-year DTNEP provided in Table 1. Detailed description of the methodology used for tuning these parameters are provided in a subsequent section.

Table 1 Control Parameters of MABC

Method		cs_N	E_h	lim	$iter$	w_g
Proposed	DCTNEP	5	2	6	15	1.5
	ACTNEP	20	2	6	30	1.5
Rigorous	ACTNEP	20	2	6	30	1.5

6.1. *Multi-year Dynamic ACTNEP for Garver 6 Bus System*

This is a small system consisting of 6 buses with 15 power corridors. System data is obtained from [28] and a green-field expansion planning is considered. Total real and reactive power demands are considered to be 760 MW and 152 MVAR respectively for the first year. Dynamic TNEP for the system is carried out considering a planning horizon of three years. System load demands and discount rates are considered in accordance with [28]. Generation limits are considered as per yearly load demands.

A comparison of the planning results for base case DTNEP as obtained by the proposed method and single-stage rigorous method is shown in Table 2. For solving base case TNEP, the strategies which are applicable to obtaining this solution are only applied. That is, strategies 5.3.1, 5.3.2 and 5.4 are only used. It can be observed from Table 2 that, both the rigorous and the proposed method obtains the same line addition costs as that obtained in [28]. However, time reduction achieved by the proposed method to obtain the final solution is 98.87% compared to the rigorous method. This proves the applicability and efficiency of the proposed method.

Table 2 Dynamic AC TNEP results of Garver 6 bus system for base case

	Proposed Method			**Rigorous Method**		
	Year 1	**Year 2**	**Year 3**	**Year 1**	**Year 2**	**Year 3**
New lines Constructed	$n_{1-5} = 1$ $n_{2-3} = 1$ $n_{2-6} = 2$ $n_{3-5} = 2$ $n_{4-6} = 2$		$n_{2-6} = 1$ $n_{3-5} = 1$	$n_{1-5} = 1$ $n_{2-3} = 1$ $n_{2-6} = 2$ $n_{3-5} = 2$ $n_{4-6} = 2$		$n_{2-6} = 1$ $n_{3-5} = 1$
No. of New Lines	8	0	2	8	0	2
v_{lc}^{y} (x 10^3 US$)	**200**	**0**	**50**	**200**	**0**	**50**
v_d (x 10^3 US$)	**223.900**			**223.900**		
L^y	0.2713	0.3217	0.3608	0.2869	0.3214	0.3592
tp	138.59 secs			3.38 hrs		
Reduction in Computational Burden by Proposed Method						**98.87 %**

Planning results for security constrained DTNEP obtained by the proposed and single-stage rigorous methods are shown in Table 3. It can be observed from the table that, similar to the previous case, both methods obtain similar line addition costs. However, the proposed method achieved a reduction in computational burden of 97.81%. This proves the effectiveness of the proposed method to reach the final solution with a drastically reduced computational burden. Also, base case L-index values for all the years are observed to be well within the set limit of 0.4.

6.2. *Parameter Tuning for the proposed Methodology*

In this section, a detailed description on the procedure for an effective parameter tuning is provided. Performance of a metaheuristic algorithm is much dependent on the quality of its population pool. Also, to obtain a good solution, there has to be a sufficient level of variance within the population pool, as it helps in exploring the entire search space in a better way. More the variance, better is the chance of a metaheuristic algorithm to obtain the global optimum solution as shown in [35], [36].

Table 3 Security Constrained Dynamic ACTNEP results obtained with the proposed and rigorous methods for Garver 6 bus system

Proposed Method			
	Year 1	**Year 2**	**Year 3**
New lines Constructed	$n_{1-2} = 1$; $n_{2-6} = 3$; $n_{3-4} = 1$ $n_{3-5} = 4$; $n_{4-6} = 2$	$n_{2-3} = 3$ $n_{4-6} = 1$	$n_{1-2} = 1$
No. of New Lines	11	4	1
v_{lc}^{y} (x 10^3 US$)	**329**	**90**	**40**
v_d (x 10^3 US$)	**413.7300**		
L^y	0.1934	0.1688	0.1797
tp	336.406 secs		
Rigorous Method			
	Year 1	**Year 2**	**Year 3**
New lines Constructed	$n_{1-2} = 1$; $n_{2-6} = 3$; $n_{3-4} = 1$ $n_{3-5} = 4$ $n_{4-6} = 2$	$n_{2-3} = 3$ $n_{4-6} = 1$	$n_{1-2} = 1$
No. of New Lines	11	4	1
v_{lc}^{y} (x 10^3 US$)	**329**	**90**	**40**
v_d (x 10^3 US$)	**413.7300**		
L^y	0.1805	0.1748	0.1712
tp	4.27 hrs		
Reduction in Computational Burden by Proposed Method			**97.81%**

In case the variance of the population pool is low, there remains vary less flexibility for a metaheuristic algorithm to traverse the search space. Therefore, the algorithm is prone to get stuck in a local optimum. This essential feature required in the population of a metaheuristic algorithm is utilized to obtain an appropriate set of values of the different parameters of the proposed solution methodology. For tuning of a parameter, 5 solution trials are conducted with different values of the parameter, while the other parameters are kept fixed at their previous values. The value of the parameter that provides the maximum variance in the population pool compared to other values is considered to be best and used for the final solution of TNEP. The process is repeated for every parameter that needs tuning to obtain the final set of tuned parameters. In the proposed solution methodology, there are two sets of parameters that need to be properly tuned: parameters related to MABC (w_g, cs_N, $iter$, E_h and lim), and parameters related to the intelligent strategies used .

For the MABC parameters, in case of w_g, its value is considered as 1.5 as per [40]. In [41], it is stated that the performance of ABC is not strongly dependent on colony size cs_N. As MABC is developed around the original ABC, it also shows a similar behaviour and the value of cs_N is kept at a conservative 20 for ACTNEP. An even lower value of 5 is used in case of DCTNEP as it is much easier to solve compared to ACTNEP. Also, it has been found that, the final solution is obtained within about 30 iterations in all the test cases. Therefore, value of $iter$ is set at 30 for ACTNEP. For DCTNEP, again a lower value of $iter$ is considered due to the reasons stated previously. Thus, the MABC parameters required to be properly tuned are only E_h and lim. For tuning of these parameters, rigorous solution of security constrained dynamic ACTNEP for Garver 6 bus system is performed. Here, as stated earlier, one variable is kept fixed and the other is gradually changed to find its best value. The results obtained by such changes of the parameters are shown in Tables 4 and 5. Minimum (min), maximum (max) and mean costs obtained at the end of five trial runs along with their standard deviations (std. dev.) are provided in these tables. It can be observed from these tables that, highest amount of variance in the population is obtained only with E_h value of 2 and lim value of 6. Therefore, these values are considered for solving sequential and DTNEP for the various test systems by the proposed method.

After the parameters for MABC are tuned, it is required to tune the parameters related to the intelligent strategies developed. For these strategies, the most important parameter is the bounding of the number of power corridors as a percentage of its number in DCTNEP results. Therefore, this bound needs to be properly tuned. Same procedure as used in the previous tuning procedure is also used for this case.

Table 4 Effect of E_h on security-constrained DTNEP results for Garver 6 bus system (with 5 trials and $lim = 6$)

E_h		1	**2**	3	4	5	6
Variance of population pool	1st trial	2.7901	**5.0989**	5.6138	1.6218	5.7966	3.6890
	2nd trial	3.2992	**4.4356**	2.8771	1.3291	8.1304	4.9047
	3rd trial	1.6127	**15.3464**	14.6887	5.2093	4.3461	6.0627
	4th trial	5.0095	**5.8443**	2.7930	2.2491	4.3506	1.5330
	5th trial	6.0395	**17.2202**	12.9559	5.1182	3.4245	3.8001
Min. cost	(x 10^3 US$)	588.350	**498.900**	444.450	588.350	550.884	583.480
Max. cost		727.320	**659.450**	717.144	713.368	723.350	727.740
Mean cost		662.780	**596.916**	570.510	677.980	665.930	691.336
Std. Dev.		44.498	**57.704**	103.010	46.231	61.150	54.210

Table 5 Effect of lim on security-constrained DTNEP results for Garver 6 bus system (with 5 trials, and $E_h = 2$)

lim		3	5	**6**	10	15	20
Variance of population pool	1st trial	2.4512	3.6583	**5.0989**	6.7881	3.5789	5.6446
	2nd trial	3.4404	4.7171	**4.4356**	1.1205	1.3062	4.1547
	3rd trial	3.9021	2.9659	**15.3464**	8.7556	9.5734	6.5556
	4th trial	5.7037	3.7013	**5.8443**	3.0036	5.5109	5.0880
	5th trial	9.4456	3.0539	**17.2202**	4.6634	3.1733	12.2611
Min. cost	(x 10^3 US$)	564.320	562.450	**498.900**	605.984	588.350	680.580
Max. cost		727.030	686.320	**659.450**	726.848	726.174	726.450
Mean cost		666.526	612.814	**596.916**	651.606	668.100	707.480
Std. Dev.		70.598	41.279	**57.704**	44.197	61.076	18.471

Security constrained DTNEP for Garver 6 bus system is solved by the proposed method for this tuning process. The particular bound which provides the highest variance in the population pool is considered as the best. Results for this tuning process are provided in Table 6. As can be observed, the corridor bound of 90-130% provides the highest variance in the population pool. Hence, this bound is used for solution of sequential and DTNEP of all the test systems.

6.3. Multi-year Dynamic ACTNEP for IEEE 24 Bus System

This 24-bus system has a real and reactive power demand of 8550 MW and 1740 MVAR respectively in the first year. There are 41 power corridors with each corridor having the ability to accommodate a maximum of 3 new lines. System data and installation costs have been obtained from [28]. A three-year planning horizon is considered, with load increment and discount costs similar to the previous case. Due to extreme computational burden experienced in solving multi-year ACTNEP by rigorous method, solution is only obtained by the proposed method.

Table 6 Effect of percentage matching of corridors on security-constrained DTNEP results for Garver 6 bus system (with 5 trials, $E_h = 2$ and $lim = 6$)

Percentage matching of corridors		70-200%	70-150%	80-150%	90-150%	**90-130%**	90-200%
Variance of population pool	1st trial	5.4066	7.7541	21.8641	12.2707	**10.3884**	15.2393
	2nd trial	9.4667	14.5107	4.7658	4.9605	**7.0348**	1.9990
	3rd trial	8.3063	21.8774	15.0616	1.6646	**31.6930**	12.5272
	4th trial	8.0107	13.5674	9.1951	5.8764	**34.7697**	2.6933
	5th trial	9.9602	7.4006	4.5130	10.0106	**5.8265**	10.9062
Min. cost	(x 10^3 US$)	573.160	588.990	529.700	467.870	**680.410**	643.610
Max. cost		685.160	721.840	719.610	722.740	**715.350**	703.594
Mean cost		637.830	657.710	662.920	592.870	**695.900**	685.650
Std. Dev.		45.267	45.662	68.673	86.713	**11.742**	59.480

Detailed solution procedure of obtaining the results for the first-year security constrained sequential ACTNEP by the proposed methodology can be described as follows:

1) *Stage 1: Base case DCTNEP*

Solution of base case DCTNEP is obtained extremely fast (in approx. 9.75 secs) with a planning cost of 78 x10^6 US$. New lines are obtained in corridors 6-10, and 13-14.

2) *Stage 2: Base case ACTNEP*

Starting from stage 1, base case ACTNEP results are obtained according to the procedure described in [36]. The final planning cost obtained is 98 x10^6 US$ with new lines in power corridors 6-10, 7-8 and 11-13, i.e. in corridor numbers 13, 14 and 21. Solution time is just about 100 secs.

3) *Stage 3: Contingency Constrained DCTNEP*

Solution of this stage provides a planning cost of 376 x10^6 US$ with new lines in corridor numbers 3, 8, 10, 13, 14, 19, 21, 28 and, 40. So, $DC_{cont} = \{3, 8, 10, 13, 14, 19, 21, 28, 40\}$, i.e. 9 corridors have new lines, with solution time of approx. 135 secs.

4) *Stage 4: Contingency Constrained ACTNEP*

This stage starts by estimation of the sets PC_{viol} and PC_{fix}. Set PC_{viol} is obtained by performing security analysis on stage 2 results. Represented by corridor numbers, this is,

$$PC_{viol} = \{1, 2, 3, 5, 6, 8, 9, 10, 11, 13, 14, 15, 18, 19, 20, 21, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32, 33, 35, 36, 37, 40, 41\}$$

Therefore, $PC_{fix} = \{3, 8, 10, 13, 14, 19, 21, 28, 40\}$.

Application of strategy 5.1 of Section 5 confines the search within 32 of 41 available corridors, thereby providing a reduction of 21.95% in the search space. Further, strategy 5.2 forces MABC to always include set PC_{fix} in its search. Next, 5.3 reduces the required number of OPF solutions by the application of three strategies 5.3.1, 5.3.2 and 5.3.3. With the application of 5.3.1, OPF is solved only if the number of corridors with new lines in a combination is within 90-130% of 9, i.e. within 8 and 12 corridors. Further, by 5.3.2, OPF is solved only when cost of new lines in a combination is less than U_{lim}. It can be mathematically represented as:

$$\text{Solve AC OPF if, } \forall b \in all\ combinations, y = 1,$$

$$v_{lc_b}^{y} < U_{lim} \ \ \& \ \ 8 \le \sum_{n_{l\,b}^{y} > 0} l_b^{y} \le 12 \qquad (20)$$

By 5.3.3, OPF is not required to be solved for a combination for remaining network configurations once an infeasibility is obtained. Table 7 provides the results for both sequential and dynamic ACTNEP for IEEE 24 bus system. The final result as in Table 7 shows that for first-year sequential TNEP, new lines are confined within 10 power corridors of PC_{viol} as provided by strategy 5.3.1. It can be further observed that by solving dynamic TNEP, it is possible to obtain an investment cost, which is 5.48% lower than that obtained by sequential TNEP. This translates to savings of 44.96 x 10^6 US$, which is a substantial amount, while increase in computational burden in solving dynamic TNEP over sequential is around 38.71%. Base case L-index values are limited within 0.4 as per the system stability constraint used. Further restriction of their values to even lower limits will result in greater system stability at an increased investment cost and vice-versa.

Table 7 Security Constrained Multi-year ACTNEP results obtained with the proposed method for IEEE 24 bus system

Dynamic Planning			
	Year 1	**Year 2**	**Year 3**
New lines Constructed	$n_{1-5} = 1$; $n_{2-4} = 1$ $n_{3-9} = 1$; $n_{4-9} = 1$ $n_{6-10} = 2$; $n_{7-8} = 3$ $n_{10-11} = 1$; $n_{11-13} = 2$ $n_{14-16} = 1$; $n_{20-23} = 1$	$n_{3-9} = 1$; $n_{6-10} = 1$ $n_{9-11} = 1$; $n_{14-16} = 1$ $n_{16-17} = 1$; $n_{19-20} = 1$ $n_{21-22} = 1$	$n_{10-11} = 1$ $n_{15-21} = 1$ $n_{20-23} = 1$
No. of New Lines	**14**	**7**	**3**
v_{lc}^{y} (x 10^6 US$)	**459**	**336**	**148**
v_d (x 10^6 US$)	**774.6880**		
L^y	0.3478	0.3741	0.3968
tp	4788.719 secs		
Sequential Planning			
	Year 1	**Year 2**	**Year 3**
New lines Constructed	$n_{1-5} = 1$; $n_{3-9} = 1$ $n_{4-9} = 1$; $n_{6-10} = 2$ $n_{7-8} = 3$; $n_{10-11} = 1$ $n_{11-13} = 1$; $n_{14-16} = 1$ $n_{14-23} = 1$; $n_{20-23} = 1$	$n_{3-24} = 1$; $n_{6-10} = 1$ $n_{11-13} = 1$; $n_{15-24} = 1$ $n_{16-17} = 1$; $n_{17-22} = 1$	$n_{1-2} = 1$ $n_{1-5} = 1$ $n_{9-11} = 1$ $n_{10-11} = 1$ $n_{15-21} = 1$
No. of New Lines	13	6	5
v_{lc}^{y} (x 10^6 US$)	446	386	193
v_d (x 10^6 US$)	819.6480		
L^y	0.3710	0.3447	0.3264
tp	3452.385 secs		
Reduction in Overall Cost by Dynamic TNEP Compared to Sequential TNEP			**5.48%**

6.4. Multi-year Dynamic ACTNEP for South-Brazilian 46 Bus System

This is a practical South-Brazilian network consisting of 46 buses and 79 power corridors [38]. The real and reactive power demand for the first year is considered to be 6880 MW and 1032 MVAR respectively. Originally, this system has several unconnected buses which present a considerable challenge for an optimization algorithm to solve TNEP. For the solution of multi-year ACTNEP, the planning horizon, load growth and discount factors are considered to be same as in previous test system. The planning methodology ensures that all the generator and load points of the network are always connected. However, any previously unconnected bus which does not have any generator or loads connected to it or does not act as an intermediary bus, is left unconnected in the final planning.

The results of the security constrained multi-year dynamic and sequential ACTNEP for this system as obtained by the proposed methodology are provided in Table 8. Similar to the previous case, here also, the results are only obtained by the proposed methodology as solution by rigorous method will be extremely computationally intensive. Table 8 shows that the dynamic planning investment costs are 3.68% lower than that of the sequential planning at the expense of 56.7% of increased computational burden. However, the investment plan obtained by dynamic ACTNEP results in a saving of 12.5908 x 10^6 US$.

Table 8 Security Constrained Multi-year ACTNEP results obtained with the proposed method for South-Brazilian 46 bus system

Dynamic Planning			
	Year 1	**Year 2**	**Year 3**
New lines Constructed	$n_{2-5} = 1$; $n_{5-6} = 3$ $n_{12-14} = 1$; $n_{19-21} = 1$ $n_{20-21} = 3$; $n_{20-23} = 1$ $n_{24-33} = 1$; $n_{28-31} = 2$ $n_{31-32} = 2$; $n_{32-43} = 1$ $n_{33-34} = 1$; $n_{40-45} = 2$ $n_{42-43} = 2$; $n_{46-6} = 2$	$n_{19-25} = 1$ $n_{24-25} = 2$ $n_{37-40} = 1$ $n_{42-43} = 1$	$n_{12-14} = 1$ $n_{14-22} = 1$ $n_{32-43} = 1$
No. of New Lines	**23**	**5**	**3**
v_{lc}^{y} (x 10^6 US$)	**255.3950**	**70.6710**	**46.7750**
v_d (x 10^6 US$)	**329.2726**		
L^y	0.3996	0.3768	0.3893
tp	2.57 hrs		
Sequential Planning			
	Year 1	**Year 2**	**Year 3**
New lines Constructed	$n_{2-5} = 1$; $n_{5-6} = 3$ $n_{12-14} = 1$; $n_{19-21} = 1$ $n_{20-21} = 3$; $n_{20-23} = 1$ $n_{24-33} = 1$; $n_{28-31} = 2$ $n_{31-32} = 2$; $n_{32-43} = 1$ $n_{33-34} = 1$; $n_{37-40} = 1$ $n_{40-45} = 1$; $n_{42-43} = 2$ $n_{46-6} = 2$	$n_{12-14} = 1$ $n_{19-25} = 1$ $n_{24-25} = 2$ $n_{42-43} = 1$ $n_{42-44} = 2$	$n_{19-32} = 1$ $n_{20-23} = 1$ $n_{32-43} = 1$
No. of New Lines	23	7	3
v_{lc}^{y} (x 10^6 US$)	249.7900	83.2560	65.6480
v_d (x 10^6 US$)	341.8634		
L^y	0.3986	0.3900	0.3902
tp	1.64 hrs		
Reduction in Overall Cost by Dynamic TNEP Compared to Sequential TNEP			**3.68%**

It may be observed that the constraint on the limiting value of network base case L-index (6) has played an important role in determining the final investment plan. In the absence of this limiting constraint, the investment plan may have been economically more attractive, but with a loss of considerable voltage stability margin for the final planned network. Further, from Table 8 it can be observed that the proposed methodology obtained security constrained dynamic planning results in about 2.57 hrs, compared to almost 26 hrs reported for simplistic base case planning in [28] for a similar-sized system. Hence, although not an exact comparison, this shows the effectiveness of the proposed methodology in solving dynamic ACTNEP for a variety of test systems.

6.5. Multi-year Dynamic ACTNEP for IEEE 118 Bus System

This large system consists of 118 buses and 179 physical power corridors [39],[42]. Out of this 179, seven power corridors consist of two different sets of lines, thereby in actual totalling to 186 power corridors to be considered. It consists of 54 generators and 91 loads. Total real and reactive power demands are respectively 3733.07 MW and 1442.98 MVAR. Line capacities are reduced to 60% of their original values to create network congestion. Line construction costs are estimated as in [39]. With a planning horizon of three years, load demands and discount factors for the second and third years are considered to be in accordance with that utilized for the IEEE 24 bus system.

For a large system as this, computational burden in solving ACTNEP by rigorous method is prohibitively large. Therefore, multi-year ACTNEP is only solved by the proposed method. Results obtained are provided in Table 9.

Table 9 Security Constrained Multi-year ACTNEP results obtained with the proposed method for IEEE 118 bus system

Dynamic Planning			
	Year 1	**Year 2**	**Year 3**
New lines Constructed	$n_{8-5} = 1$; $n_{23-32} = 1$ $n_{38-37} = 1$; $n_{38-65} = 1$ $n_{64-65} = 1$; $n_{77-78} = 1$ $n_{94-100} = 1$	$n_{65-68} = 1$ $n_{94-95} = 1$ $n_{94-100} = 1$ $n_{99-100} = 1$	$n_{2-12} = 1$; $n_{17-18} = 1$ $n_{30-17} = 1$; $n_{26-30} = 1$ $n_{34-37} = 1$
No. of New Lines	**7**	**4**	**5**
v_{lc}^{y} (x 10^6 US$)	**66.4665**	**36.4860**	**44.7570**
v_d (x 10^6 US$)	**114.4586**		
L^y	0.0676	0.0827	0.0947
tp	4.02 hrs		
Sequential Planning			
	Year 1	**Year 2**	**Year 3**
New lines Constructed	$n_{8-5} = 1$; $n_{23-32} = 1$ $n_{38-65} = 1$; $n_{64-65} = 1$ $n_{77-78} = 1$	$n_{8-30} = 1$; $n_{34-37} = 1$ $n_{38-37} = 1$; $n_{65-68} = 1$ $n_{80-99} = 1$ $n_{94-100} = 1$	$n_{5-11} = 1$ $n_{2-12} = 1$ $n_{17-18} = 1$ $n_{26-30} = 1$ $n_{94-95} = 1$
No. of New Lines	5	6	5
v_{lc}^{y} (x 10^6 US$)	49.2765	62.8770	55.7460
v_d (x 10^6 US$)	121.7604		
L^y	0.0678	0.0828	0.0945
tp	2.76 hrs		
Reduction in Overall Cost by Dynamic TNEP Compared to Sequential TNEP			**6.00%**

It can be observed from Table 9 that, the proposed method obtained both sequential and DTNEP results within a manageable time frame. Savings of 7.3018 x 10^6 US$ in investment cost is obtained by solving DTNEP over sequential TNEP, with high system stability in both the cases, as depicted by their base case L-index values.

7. Conclusion

This paper proposes a four-stage solution methodology for the efficient solution of non-linear, multi-year network security and voltage stability constrained ACTNEP problems, which has not been attempted in the past. Several intelligent and logical solution strategies are developed from the results of DC base case (stage 1), AC base case (stage 2) and DC security constrained (stage 3) planning. Through the effective application of these strategies, final security constrained ACTNEP (stage 4) results are obtained with substantially reduced computational burden. The developed strategies lead to a significant narrowing down of the overall search space for finding optimum solution in the final stage. It should be noted here that, although there is a reduction in search space in the final AC stage, it does not hamper the algorithm convergence process as the previous stages consider the entire space for obtaining respective results. This is evident from the comparison of results obtained by traditional, rigorous single-stage method and that obtained by the proposed methodology. However, application of the proposed methodology provides near 97% reduction in computational burden compared to the rigorous method.

Proper parameter tuning for the solution methodology is performed to obtain good quality final solutions. The planning topologies also provide a high degree of network voltage stability to the final planned system as is evident from the low L-index values in all case studies. Further, Tables 7, 8 and 9 show that even for medium to large systems, voltage and network security constrained multi-year ACTNEP results are obtained by the proposed method within manageable time-frames and computational burdens.

The strategies developed in this work are derived in accordance with the results obtained in previous stages of solution process. Hence, these are not system or metaheuristic algorithm specific, and general enough to be used in any system, with any solution algorithm. Therefore, by the use of proposed methodology, in future, solution of much complex TNEP problems for larger, near-practical systems may be obtained with tremendous efficiency. In addition, these intelligent strategies have a substantial potential to be utilized for the development of efficient solution methodologies for multi-stage ACTNEP problems involving uncertainty, dynamic stability, etc.

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