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# Transmission Expansion Planning Using A Noval Meta-Heauristic Method

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**Abstract-** Transmission Expansion Planning (TEP) is an optimization study aimed at determining new transmission lines to be added to the transmission network in order to expansion or reinforcement of the network within the scope of different purpose functions in parallel with the increase in demand and generation. In this study, the objective function of the TEP problem is determined as minimizing the investment costs of the lines to be added to the network and the loss of load cost. This article proposes Forensic Based Investigation Optimization (FBIO) which is a new and efficient meta-heuristic method in solving of the TEP problem for the first time. In the literature, there are many studies used individual optimization methods, but comparisons of different methods are lacking. Therefore, this article presents a comprehensive comparative study of recent published 5 different methods. The proposed FBIO method is applied for 4 different scenarios on IEEE 24-bus test system which is one of the most used test system using the DC model. Obtained results are compared with the results which get using 5 different methods in literature. In addition that the reliability of the power network is a substantial issue for utilities since the stronger transmission system means the better social welfare. Hence, Transmission System Operators have to ensure the sustainable energy to consumers at any point of the grid. Accordingly, N-1 criteria of the transmission system which is extremely important for safety should be considered in the expansion planning studies. Therefore, in this study, the N-1 contingency criterion is implemented during optimization process of the TEP problem which means that the obtained results present not only a cost-effective solution, but more robust system.Python programming language is applied in modeling and solving the problem. Panda Power, an open source Python library, is used in modeling the IEEE 24- bus test system and carrying out power flows.

**Keywords**- Transmission expansion planning, meta-heauristic optimization, investment cost, cost of energy not supplied, dc model.

## 1. Introduction

Power systems, which are very complex and large structures covering generation, transmission and distribution systems, basically provide access to electrical energy for end users in the position of consumers [1]. Partial or full unbundling and liberalization in the electricity market in the last 30 years has caused the generation and distribution side to be operated by multiple private companies on a competitive basis according to market conditions. However, most transmission systems continue to be operated by a government-controlled monopoly institution/company.

Unbundling and liberalization in the power systems have led to the separate execution of Generation Expansion Planning (GEP), Transmission Expansion Planning (TEP) and Distribution System Planning (DSP) studies, which are carried out centrally and integratedly by a single authority or institution [2-4]. This separation has brought with it much more uncertainty and problem than the solution [5, 6]. In the new environment, GEP and DSP are carried out in line with the decisions taken by private sector investors within the framework of their own evaluations, while TEP is continued to be made in line with the decisions taken by the state-controlled institution/company [7].

TEP can be expressed as the expansion and/or strengthening of the transmission system with minimum cost in order to meet the electrical energy demand reliably and economically while maintaining the system stability and reliability for future planning periods [8–10]. TEP is the study of determining when, where and how many new transmission lines should be installed [11-14] .

In the new environment created by the competitive market, one of the most important objectives of the TEP is to ensure that the transmission system is open to all electricity market players without discrimination and to increase competition among these players [15]. TEP also has different purposes such as reducing system congestions, minimizing risks, minimizing environmental effects, minimizing costs, maximizing total social welfare [16, 17]. Looking at the objective set of the TEP, it is seen that the TEP is interested in the economic side of the system as well as the technical side.

In the recent years, within the framework of net zero emission targets in the world, the share of renewable energy in the system is increasing significantly. In parallel with the increase in the share of renewable energy in the system, requirement of the planning and establishment of new and larger capacity transmission lines from regions in which generated electricity from intermittent wind and solar energy to consumption regions has increased as well. TEP has been getting more important in the environment of the growing interest to renewable energy particularly intermittent wind and solar energy [19]–[24].

TEP is made by considering the current system status, future load and generation scenarios, capacities of transmission lines and system conditions. Planning studies are carried out for periods of 5-10 years or longer. TEP is classified as static and dynamic according to planning time [25]. Static TEP is concerned with where and how many a new transmission line will be added to the system for only one time slot during the planning period, with minimum cost [26]. Unlike static TEP, in dynamic TEP, the planning period is divided into multiple time intervals and the planning study is carried out for each time interval [27].

In general, AC and DC based power flow models are used in modeling power systems in TEP studies [28]. The AC model deals with the linear and non-convex complexity of the TEP [29]. The DC model, on the other hand, is the linearized and simplified version of the AC model and does not deal with power flow parameters such as line losses, reactive power flow, voltage variation [30]. DC model is widely used in TEP because it offers simpler, easier and faster solutions than AC model [24, 25].

In TEP, due to the large and complex size of the system, its inherently non-convex nature and various uncertainties, it is very difficult to find the most appropriate solution to problems such as when, where and how many new transmission lines will be installed or what the cost will be [33].Therefore, TEP emerges as a non-linear, complex integer optimization problem that aims to find the optimal values of certain objective functions [27-29].

Two basic approaches, mathematical and heuristic algorithms, are used to solve the TEP problem [37]. There is also a third optimization method, also known as the hybrid algorithm, which contains the features of these two approaches. In the mathematical optimization algorithms, the formulas created for the defined TEP problem are solved by operating a deterministic process [38]. Due to the non-linear and non-convex nature of the transmission system, solving problems using mathematical algorithms lead to problems such as memory insufficiency, snagging in the local optimal, and long solution time [39]. However, the accuracy rate of the results obtained with deterministic techniques is high. In general, in the solving of the TEP problems, the mathematical optimization algorithms are used such as Linear Programming (LP) [40], Nonlinear Programming (NLP), Mixed-Integer Linear Programming (MILP) [24, [42], Mixed-Integer Nonlinear Programming (MINLP) [43], Benders Decomposition (BD) [44].

Heuristic algorithms are optimization methods that are not derivative based and are easier to use and implement through step by step search, but take longer time because they are search based [11]. Heuristic algorithms are generally created to solve one type of problem, while meta-heuristic algorithms are designed to reliably obtain optimal solutions from different types of problems [38, 39]. Genetic Algorithm (GA) [40, 41], Simulated Annealing (ST) [49], Game Theory (GT) [50], Particle Swarm Optimization (PSO) [51], Tabu Search (TS) [52], Ant Colony Optimization (ACO) [53], Greedy Randomized Adaptive Search Procedure (GRASP) [54], Grey Wolf Optimizer (GWO) [55], Imperialistic Competitive Algorithm (ICA) [56], Symbiotic Organisms Search (SOS) [57], Gases Brownian Motion Optimization (GMBO) [58], Artificial Bee Colony (ABC) [59], Constructive Heuristic Algorithm (CHA) [60] and Mosquitoes Behavior Based (MOX) [61] are among the meta-heuristic algorithms used in TEP.

When the studies in the literature are examined, it is seen that especially meta-heuristic methods are widely used in the TEP problems, which include different objective functions. In general, the objective function of the TEP problem is designed to determine the most economically viable lines, the system security (N-1 constraint condition) criterion, which has an important place in the planning studies, has been ignored in [39, 41, 43, 55, 56]. In general, the methods used to solve the TEP problems are tested and verified on more than one scenario, the optimization methods used in [57–60] are applied on only one scenario.

The differences and contributions of this study from the studies on TEP in the literature can be listed as follows:

- In the literature, it is seen that meta-heuristic methods are widely used in TEP studies. However, studies comparing the results obtained by applying the same scenario studies on similar test systems are insufficient. In this study, Forensic Based Investigation Optimization (FBIO) [68] technique has been proposed for the first time to solve the TEP problem. The proposed method has been applied for 4 different scenarios on the IEEE 24-bus test system. The obtained results are compared with the results get by applying meta-heuristic methods SOS [57], GMBO [58], ABC [59], CHA [60], MOX [61] used previously in the literature on the same scenarios and test system. It has been determined that FBIO gives better results than the other 5 meta-heuristic methods in terms of the total costs of the new transmission lines to be established for the planning period.

- The FBIO algorithm has been applied on various scenarios with different objective functions.
- The situation that no consumer is affected as a result of 1 of N equipment in the system being out of service is explained as the N-1 rule. The fact that the N-1 criterion, which is frequently used in static system security analyzes in the literature, is not taken into account, causes the network models created within the scope of TEP studies not to show the expected resistance. For this reason, system security (N-1) has been taken into account for the scenarios where we carry out different planning activities within the scope of our study.
- Programs such as Matlab, Cplex, Gams are widely used in modeling and solving the problem determined in TEP studies. In this study, the Python programming language, which is less used in TEP and is thought to be widely used in the future, is used. Panda Power which is an open source Python library is used in modeling the IEEE 24- bus test system and carrying out power flows.

The main motivation behind this study is to provide transmission system planners with the most appropriate solutions in determining the necessary lines for the system in future planning periods. The remaining of this article is organized as follows: In section 2, the mathematical formulation of the TEP problem is presented. Section 3 includes applied algorithm to solve the TEP problem. Section 4 shows analyses results and comparisons. Finally, section 5 presents comments, conclusions and future works.

## 2. Mathematical Model of TEP

In this study, the static TEP problem is solved by using the DC model for the planning period. In the problem, the investment costs of the new transmission lines to be added for the planning period and loss of load (LOL) cost that cannot be provided are formulated as the total cost. In addition, the problem is formulated according to whether the generation plants are resizing or not, and the N-1 security criterion is taken into account for each case.

Notations used in the model:

$C_T$: total cost
$C_I$: investment cost
$C_L$: LOL cost
$C_{ij}$: cost of line added from bus i to bus j
$a_i$: penalty cost at bus i
$r_i$: dummy generation at bus i
f: active power flows through the lines
g: active power generations
$\bar{g}$: maximum generation capacity
r: loss of load
d: loads
$\bar{d}$: maximum loads
$f_{ij}$: active power flow between buses i and j
${f_{ij}}^c$: active power flow between buses i and j in the single outage of line c
$\bar{f}_{ij}$: maximum active power flow between buses i and j
$B_{ij}$: line susceptance ij
$n_{ij}^0$: initial number of lines from bus i to bus j
$n_{ij}$: number of new lines added from bus i to bus j
$\bar{n}_{ij}$: maximum number of new lines which can be added from i to j
$\theta_{ij}$: voltage phase angle difference between bus i and bus j
$\Omega$: set of all candidate lines
$\Omega_{ctl}$: set of congested lines

*2.1. Objective Function*

In general, the objective function in TEP is expressed as minimizing the cost of new transmission lines to be added to the system in order to meet the electrical energy demand for the planning periods.

The mathematical model of the objective function can be formulated as [50-53, 62]:

$$\mathrm{Min}\ C_T = \sum_{ij} C_{ij} n_{ij} \tag{1}$$

Equation (1) expresses the objective function of the problem. The objective is to figure out the best right of ways in order to supply the load of the consumers for the planned time horizon without any violation the constraints including power system necessities.

*2.2. Constraints*

While formulating the TEP problem determined in this study, power balance, power flow, thermal limits of transmission lines, generation limits of generation plants and system security criteria are modeled as constraints.

*2.2.1. Equality Constraints*

Power balance equation for active power is often used to represent one of the equality constraints in TEP problem, ensuring that the load demand is met while compensating for power losses. The other constraint mostly considered in the mathematical model of the TEP is the power flow equation in transmission lines between buses. These equations can be shown as follows [4, 62-67]:

$$f + g + r = d \tag{2}$$

$$f_{ij} - B_{ij}(n_{ij}^0 + n_{ij})\theta_{ij} = 0 \tag{3}$$

The loss of load term in the Eq. (3) is utilized to ensure the power balance with obeying the constraints while implementing the generation resizing aiming to reduce the cost of the expansion planning. However, since the loss of load is also costly for the utility and leads to decreasing the social welfare, it should be removed as much as possible by finding a suitable right of way. Therefore, the loss of load cost is attached to the objective function as a penalty in the constraints handling section.

*2.2.2. Inequality Constraints*

Inequality limits cover the generation limit at each bus (4), loss of load limit for each consumer (5) and right-of-way expansion limit for each branch (6). It also includes power flow thermal limit for each branch both base case (7) and contingency case (8).

$$0 \leq g \leq \bar{g} \tag{4}$$

$$0 \leq r \leq \bar{d} \tag{5}$$

$$0 \leq n_{ij} \leq \bar{n}_{ij} \qquad \forall(i,j) \in \Omega \tag{6}$$

$$|f_{ij}| \leq (n_{ij}^{0} + n_{ij})\bar{f}_{ij} \tag{7}$$

$$|f_{ij}|^{c} \leq (n_{ij}^{0} + n_{ij})\bar{f}_{ij} \quad \forall(i,j) \in \Omega, \forall(c) \in \Omega_{ctl} \tag{8}$$

*2.3. Constraints Handling*

In order to figure out an appropriate solution to the TEP problem, the constraints related to power system necessities should be obeyed. In the equality constraints, the power balance equation includes the loss of load term, which means leading to an extra cost for the utility and reducing social welfare. Hence, the cost of loss of load should be integrated into the objective function so as to acquire a correct solution. Moreover, in the inequality constraints, transmission line thermal limits in both base case and contingency are constraints that need to be addressed in the solution process. The punishment and aggregating approach can be used to handle the constraint compliance problem. Therefore, the objective function of the TEP problem can be reconstituted by attaching the associated constraints to the function as a penalty.

$$\text{Minimize: } P = C_I + C_L + \pi_b + \pi_c \tag{9}$$

$$C_L = \sum_i a_i r_i \tag{10}$$

$$\pi_b = \omega_1 \sum_{i=1}^{\Omega} \max(0, f_{ij} - \bar{f}_{ij}) \tag{11}$$

$$\pi_c = \omega_2 \sum_{c=1}^{\Omega_{ctl}} \sqrt{\frac{\sum_{i=1}^{\Omega} \max(0, {f_{ij}}^{c} - \bar{f}_{ij})^2}{T_c}} \tag{12}$$

Where P is a penalty function to be optimized, $C_L$ symbolizes loss of load cost, $\omega_1$ and $\omega_2$ are constant penalty coefficients, $T_c$ stands for the number of lines overloading in the contingency c, $\pi_b$ and $\pi_c$ represent punishments with regard to the thermal overloading occurred in the base case and contingency, respectively.

## 3. Proposed Algorithm

*3.1. Forensic-based Investigation Algorithm*

In this study, FBI, which is a new meta-heuristic method and used for the first time in TEP studies, is used to solve the static TEP problem. The FBI is a human based meta-heuristic algorithm in order to find global solutions for continuous nonlinear problems with high accuracy and performance developed by Chou and Nguyen in 2020 [68]. Although FBI is designed to apply to continuous problems, the transformation from the continuous to the binary search space is implemented so as to solve the TEP problem by using the transfer function and position updating rule. In general, each meta-heuristic algorithm has its own advantages in terms of robustness, performance and search space. Therefore, it is necessary to investigate which meta-heuristic algorithm is better in effectively solving the TEP problem, which is the main purpose of this research.

FBI optimization is inspired by the forensic process of suspect investigation, location and tracking of the detectives in criminal cases [70]. There are two basic mechanisms for inquiring about the offender, and these processes are conducted by the investigation and pursuit team. The investigation team tries to figure out the most promising area in the search space while the pursuit team aims to obtain the exact location of the offender by using the suspected location received from the investigation team. In the meta-heuristic terminology, it can be mentioned that the exploration phase is performed by the investigation team and the exploitation phase is conducted by the pursuit team. Each team uses two steps, containing their own mathematical expressions, in order to catch a criminal and these investigations are implemented cyclically during iterations. The flowchart of the implementation of FBI to solve TEP problem can be seen in Fig. 1.

The initial step A1 of the investigation team, the interpretation of findings step, can be expressed as follows:

$$X_{A1_{ij}} = X_{A_{ij}} + ((\mathrm{rand} - 0.5) * 2) * \left(X_{A_{ij}} - X_{A_{kj}} + X_{A_{hj}}/2\right), i = 1,2,\ldots,NP; j = 1,2,\ldots,D \tag{1}$$

Where NP is the number of population, D is the dimension of a position, k and h are randomly selected individuals from the population, D is the dimension of a position, NP is the number of the population and rand is a random number in the range [0,1]. We benefitted from Gaussian Distribution while generating random number instead of $((rand - 0.5) * 2)$ term of Eq. (1).

The individuals k, h and i should be different positions of the population. In this step, if the new position achieved with Eq. (1) is better than the current solution, it is assigned as the new current solution ($X_{Ai} = X_{A1i}$), which means that the greedy selection procedure is implemented.

The next step A2 in the investigation team, the direction of the inquiry, is conducted according to the following expression:

$$X_{A2_{ij}} = X_{best} + X_{A_{dj}} + rand * \left(X_{A_{ej}} - X_{A_{fj}}\right), \quad i = 1,2,\ldots,NP; \ j = 1,2,\ldots,D \tag{2}$$

Where $X_{best}$ is the best location obtained from the initial step A1, rand represents the random number in the range [0,1], d, e and f are positions chosen randomly from the population and these individuals and the current position i should be different from each other.

The directions of other probable places have an impact on the updating of a searching location. However, not all directions are modified; to boost the diversity of search areas, randomly selected directions in the updated location are adjusted. Furthermore, a prospective bias is implemented to converge to the promising area by using probability of each position thanks to the next equation:

$$Prob(X_{A_i}) = (p_{worst} - p_{A_i})/(p_{worst} - p_{best}) \quad (3)$$

Where $p_{worst}$ is the worst objective value which means the lowest possibility, $p_{best}$ symbolizes the best objective value (the highest possibility), $p_{A_i}$ represents the objective value of the current position and $Prob(X_{A_i})$ corresponds to the probability of the current position i. Actually, Eq. (3) is known as min-max normalization, which each solution can be shown in range [0,1].

Following the investigation team's report of the best location, all members in the pursuit team must attack the target in a cohesive way to seize the criminal. In the initial step B1 of the pursuit team, each individual seeks the location with the best objective value according to the following equation:

$$X_{B1_{ij}} = rand * X_{B_{ij}} + rand * \left(X_{best} - X_{B_{ij}}\right),$$
$$i = 1,2,\dots,NP;\ j = 1,2,\dots,D \quad (4)$$

Where $X_{best}$ is the best position provided by investigation team and rand is random number in the range [0,1].

The police agents report the possibilities (objective values) of the new locations to headquarters whenever they make a move and the pursuit team is instantly dispatched to that place by headquarters. Agent $B_i$ rushes toward the best location, and he is influenced by the other members of his team. The other member of the population chosen randomly among the entire team is called $B_r$, and its possibility is represented by $p_{B_r}$. If $p_{B_r}$ is better than $p_{B_i}$the new position of agent $B_i$ is updated with regard to Eq. (5); otherwise, it is determined by Eq. (6).

$$X_{B2_{ij}} = X_{B_{rj}} + rand * \left(X_{B_{rj}} - X_{B_{ij}}\right) + rand * \left(X_{best} - X_{B_{rj}}\right), i = 1,2,\dots,NP;\ j = 1,2,\dots,D \quad (5)$$

$$X_{B2_{ij}} = X_{B_{ij}} + rand * \left(X_{B_{ij}} - X_{B_{rj}}\right) + rand * \left(X_{best} - X_{B_{ij}}\right), i = 1,2,\dots,NP;\ j = 1,2,\dots,D \quad (6)$$

Where $X_{best}$ is the best location achieved from Step B1, rand stands for random numbers in the range [0,1], member i and randomly chosen rare two members of the pursuit team.

### *3.2. Binary transformation*

The FBI algorithm is created to solve the problems with continuous decision variables, so some modifications to the original algorithm are required so as to deal with the TEP problem having binary search space. The chance of changing the elements of a position vector from 0 to 1 and vice versa is defined by a transfer function. Particles are required to move in a binary space through transfer function [70]. In this research, the hyperbolic tangent transfer function is used in order to map the process of search in a continuous search space to a binary search space while preserving the original mechanism of the FBI algorithm.

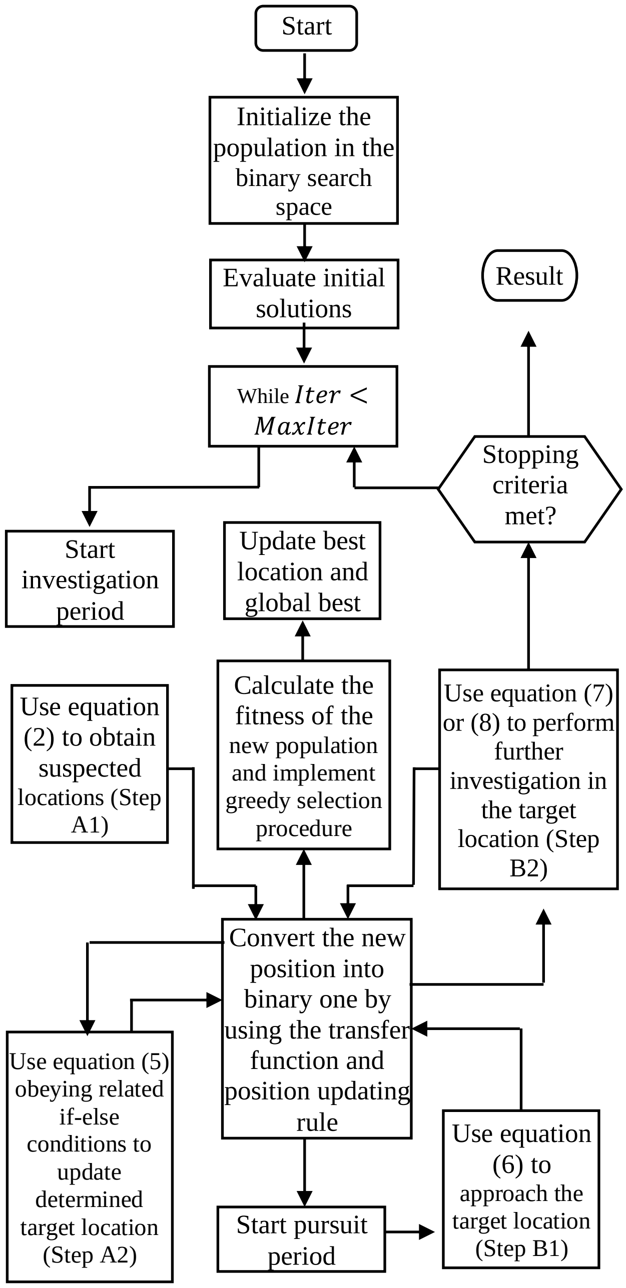



**Fig. 1.** Flow chart of the proposed algorithm.

$$TF(x) = |\tanh(x)| \quad (7)$$

The alteration of an element should be implemented with respect to the comparison between the output of the transfer function and randomly generated number in the range [0,1]. At this point, a position updating rule is conducted according to the following expression:

$$XB_{ij} = \begin{cases} (XB_{ij})^{-1}, & if\ rand < TF(X_{ij}) \\ X_{ij}, & if\ rand \geq TF(X_{ij}) \end{cases}$$

Where $XB_{ij}$ represents the binary position of the element j of the individual i, $X_{ij}$ is the position with continuous variable obtained from FBI algorithm, rand is the random number in the range [0,1] and TF is the transfer function.

When the values of continuous search space are low, this position updating rule encourages agents to stay in their existing locations, whereas when the values are high, it provides agents to switch to their complement positions (0 or 1).

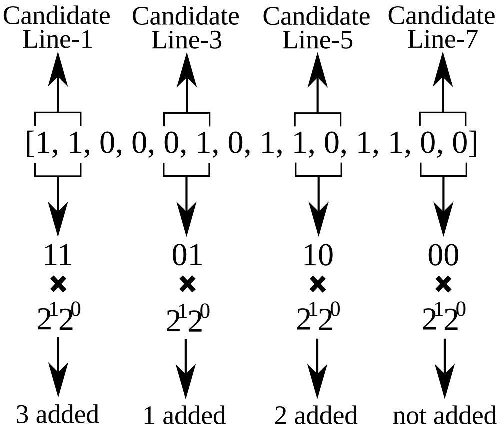



**Fig. 2**. Binary structure of an individual.

Binary code of an individual includes the information of which and how many candidates will be integrated into the grid in order to relieve the transmission system in the future perspective. In this direction, the binary structure of an agent is shown in Fig. 2. In this study, the maximum allowable amount of candidate lines to be added into the network is chosen 3. Each two binary codes of an individual symbolize one candidate line and decimal equivalent of them demonstrate how many related candidate lines will be constructed to the power network. To illustrate, the binary codes of the candidate line-1 are given as "11" and decimal equivalent of this binary codes is "3" $(2^0 * 1 + 2^1 * 1)$, which means that candidate line-1 will be built in three times in the transmission expansion process. The pseudocode of the entire algorithm can be seen in Fig. 3.

*1: **Input**: Objective function, Number of iteration and population size, Upper and Lower Bounds;*
*2: **Initialization**: Create and evaluate the population*
*3: **while** iter < MaxIter **do**;*
*4: **Investigation period:***
*5: **Step A1:***
*5.1: **for** $i = 1$ to Pop Size **do**;*
*5.2: **for** $j = 1$ to Dimension **do**;*
*5.3: Generate new location by using Eq. (2)*
*5.4: **end for;***
*5.5: Convert the location into binary position by using transfer function*
*5.6: **end for;***
*5.7: Determine the fitness of the new population*
*5.8: Implement greedy selection*
*5.9: **if** $p_{best} \neq p_{worst}$ **do**;*
*6: **Step A2:***
*6.1: Calculate probability prob(pop) by using Eq. (3)*
*6.2: **for** $i = 1$ to Pop Size **do**;*
*6.3: **if** rand > prob(pop[i]) **do**;*
*6.4: **for** $j = 1$ to Dimension **do**;*
*6.5: **if** rand > rand **do**;*
*6.6: Generate new location by using Eq. (5)*
*6.7: **end if;***
*6.8: **end for;***
*6.9: **end if;***
*6.10: Convert the location into binary position by using transfer function*
*6.11: **end for;***
*6.12: Determine the fitness of the new population*
*6.13: Implement greedy selection*
*7: **Pursuit period;***
*8: **Step B1;***
*8.1: **for** $i = 1$ to Pop Size **do**;*
*8.2 **for** $j = 1$ to Dimension **do**;*
*8.3: Generate new location by using Eq. (6)*
*8.4: **end for;***
*8.5: Convert the location into binary position by using transfer function*
*8.6: **end for;***
*8.7: Determine the fitness of the new population*
*8.8: Implement greedy selection*
*9: **Step B2;***
*9.1: **for** $i = 1$ to Pop Size **do**;*
*9.2: r = choose randomly an individual from population*
*9.3: **if** fitness of r better than fitness of p[i] **do**;*
*9.4: **for** $j = 1$ to Dimension **do**;*
*9.5: Generate new location by using Eq. (7)*
*9.6: **end for;***
*9.7: **else do;***
*9.8: **for** $j = 1$ to Dimension **do**;*
*9.9: Generate new location by using Eq. (8)*
*9.10: **end for;***
*9.11: Convert the location into binary position by using transfer function*
*7.12: **end for;***
*9.13: Determine the fitness of the new population*
*9.14: Implement greedy selection*
*10: **end while;***

**Fig. 3.** Pseudocode of the proposed method.

## 4. Results and Discussion

This section presents implementation of the FBIO algorithm described in the previous section. TEP problem is solved for four case studies applying FBIO on the IEEE 24-bus test system using DC model. In order to evaluate the effectiveness of the FBIO algorithm, the results obtained with FBIO are compared with the published results with the other five meta-heuristic based algorithms (SOS, GMBO, ABC, CHA, MOX) in the literature. The proposed algorithm is implemented using the Python program. The optimum investment cost results are obtained using the proposed FBIO algorithm with a population of 50 individuals and 500 iterations. FBIO is run 30 times for each case study.

### *4.1. Case Studies*

As test system, the IEEE 24-bus test system is used. On the base topology, the system consists of 24 buses and 38 existing lines. The system is assumed to be expanded with three times generation and load values in the planning period. In parallel with the increasing demand and generation in the system, it is necessary to establish new lines in order to prevent congestions and keep the system in balance. In this study as possible candidate lines, 38 existing lines and 7 new corridors, created 45 rights of way in total. The system data is available [26]. Maximum lines per right of way is three in the system.

The TEP problem is analyzed for four different case studies: Case Study 1A(without generation resizing), Case Study 1B(N-1 constraint condition), Case Study 2A(with generation resizing) and Case Study 2B(N-1 constraint condition).

*Case Study 1A:*

In this case study, TEP is solved without generation resizing consideration. The obtained optimal results by FBIO and the other algorithms are provided in Table 1. As shown Table 1, the proposed FBIO algorithm with cost of 370 M$ is one of the best solution in terms of the total cost.

**Table 1.** Comparison results for without generation resizing

| Added lines | | | | | | | |
|---|---|---|---|---|---|---|---|
| From | To | SOS [50] | GMBO [51] | ABC [52] | CHA [53] | MOX [54] | FBIO |
| 1 | 5 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3 | 24 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | 10 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7 | 8 | 2 | 2 | 2 | 2 | 2 | 2 |
| 14 | 16 | 1 | 1 | 1 | 1 | 1 | 1 |
| 15 | 21 | - | - | - | 1 | - | - |
| 15 | 24 | 1 | 1 | 1 | 1 | 1 | 1 |
| 16 | 17 | 2 | 2 | 2 | 2 | 2 | 2 |
| 16 | 19 | 1 | 1 | 1 | 1 | 1 | 1 |
| 17 | 18 | 1 | 1 | 2 | 1 | 2 | 1 |
| Total added lines | | 11 | 11 | 12 | 12 | 12 | 11 |
| Total cost (M$) | | 370 | 370 | 390 | 438 | 390 | 370 |

*Case Study 1B:*

In this study case, as parallel with case 1a to evaluate the system security, N-1 contingency analysis is performed for all existing and added lines. Table 2 shows the 39 new lines are needed to keep security for the system. Total optimal cost of the results is 1,771 M$. As compared with the case 1a results, consideration of the system security has resulted in more investment cost.

**Table 2.** N-1 contingency results for case study 1b and 2b

| From | To | Case study 1b | Case study 2b | From | To | Case study 1b | Case study 2b |
|---|---|---|---|---|---|---|---|
| 1 | 2 | - | 1 | 15 | 24 | 2 | 2 |
| 1 | 5 | - | 2 | 16 | 17 | 3 | 3 |
| 2 | 4 | 1 | - | 16 | 19 | 2 | 2 |
| 2 | 6 | 1 | 1 | 17 | 18 | 2 | 2 |
| 4 | 9 | - | 1 | 17 | 22 | 2 | 1 |
| 5 | 10 | 1 | - | 18 | 21 | 2 | - |
| 6 | 10 | 3 | 2 | 19 | 20 | 1 | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7 | 8 | 3 | 3 | 20 | 23 | - | 2 |
| 11 | 14 | 2 | 1 | 10 | 11 | 2 | 3 |
| 12 | 13 | 1 | 1 | 9 | 12 | - | 1 |
| 14 | 16 | 2 | 2 | 10 | 12 | 1 | - |
| 15 | 16 | 2 | 1 | 3 | 24 | 2 | 2 |
| 15 | 21 | 2 | 1 | 1 | 8 | 2 | - |
| Total added lines | | Case study 1b | | 39 | Case study 2b | | 34 |
| Total cost (M$) | | | | 1771.00 | | | 1390.01 |

*Case Study 2A:*

In this study case, TEP is solved with generation resizing consideration. In generation resizing, generation values are allowed to change between the maximum and minimum limits of the generators. In order to reduce the number of new lines to be added and the investment costs accordingly, the generation plants located close to the load operated at maximum limit. As shown in Table 3, optimal cost is obtained 152 M$ using the proposed FBIO algorithm. FBIO is one of the best fitted algorithms while comparing with the other algorithms.

**Table 3.** Comparison results for with generation resizing

| Added lines | | Algorithms | | | | | |
|---|---|---|---|---|---|---|---|
| From | To | SOS [50] | GMBO [51] | ABC [52] | CHA [53] | MOX [54] | FBIO |
| 6 | 10 | 1 | 1 | 1 | 1 | - | 1 |
| 7 | 8 | 2 | 2 | 2 | 2 | - | 2 |
| 10 | 12 | 1 | 1 | 1 | 1 | - | 1 |
| 14 | 16 | 1 | 1 | 1 | 1 | - | 1 |
| 16 | 17 | - | - | - | 1 | - | - |
| 20 | 23 | - | - | - | 1 | - | - |
| Total added lines | | 5 | 5 | 5 | 7 | - | 5 |
| Total cost (M$) | | 152 | 152 | 152 | 218 | - | 152 |

*Case Study 2B:*

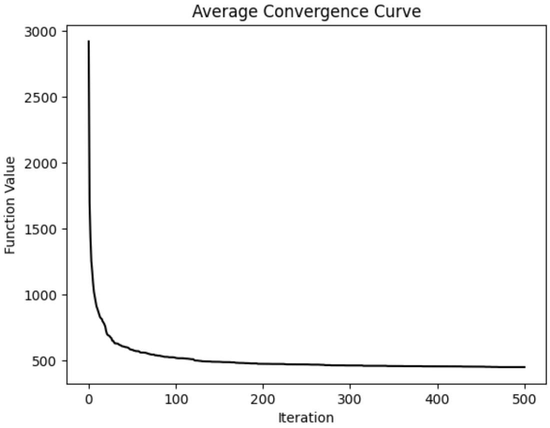
In this case study, in parallel with consideration of the generation resizing case, N-1 security analysis is performed for all existing and added lines. As shown in Table 2, to keep security of the system totally 34 new lines are needed. For new lines, total optimum investment cost is 1,390.01 M$. As compared with the case 1 b results, total investment cost of the case 2b is less because of consideration of the generation resizing. Comparison of obtained statistical results which are standard deviation, variance, mean, maximum and minimum values of the objective function from all case studies can be seen in Table 4.

**Table 4.** Comparison of obtained statistics from all case studies

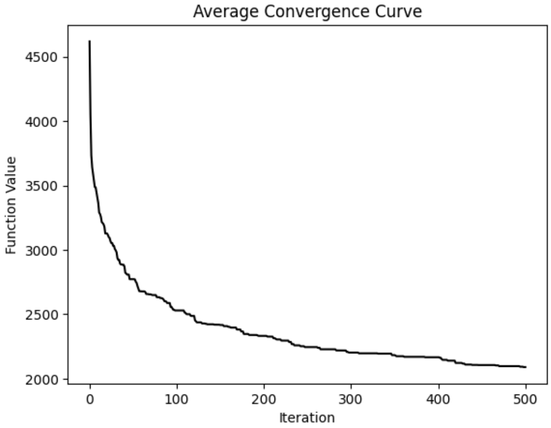
| Statistics | Case study 1a | Case study 1b | Case study 2a | Case study 2b |
|---|---|---|---|---|
| Standard Deviation | 67.51 | 167.46 | 2.91 | 134.18 |
| Variance | 4556.88 | 28043.35 | 8.44 | 18003.63 |
| Mean | 449.21 | 2089.40 | 152.95 | 1701.19 |
| Max | 583.07 | 2404.00 | 164.01 | 2007.69 |
| Min | 370.00 | 1771.00 | 152.00 | 1390.01 |

In order to analysis the performance of FBIO, curves regarding with average convergence, diversity measurement and exploration and exploitation are obtained for all case studies.

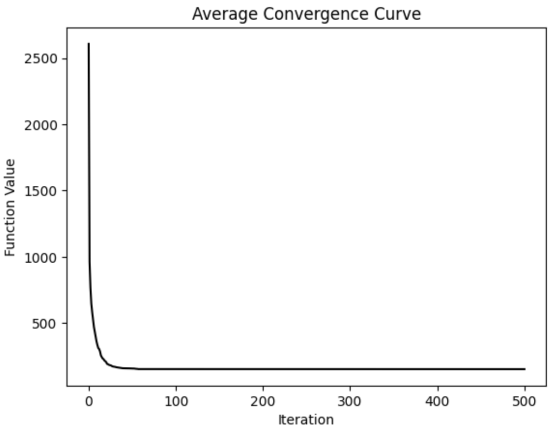
In Figure 4, for all case studies the average convergence curves obtained using FBIO is shown. In this study maximum number of iterations is to 500. Figure 4 shows FBIO has good convergence performance although when applied more complex case study N-1. Generation resizing case studies have needed less iterations to converge to get the optimum value.



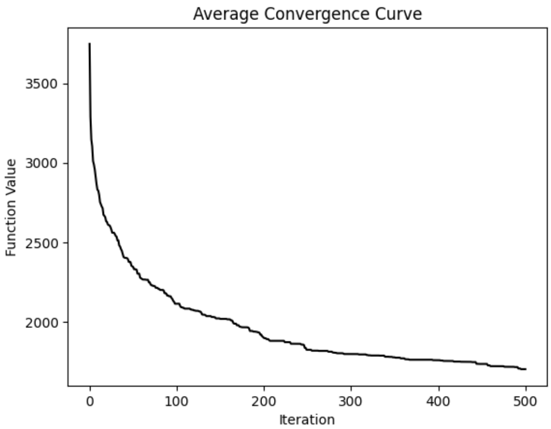

a) Case study 1a




b) Case study 1b



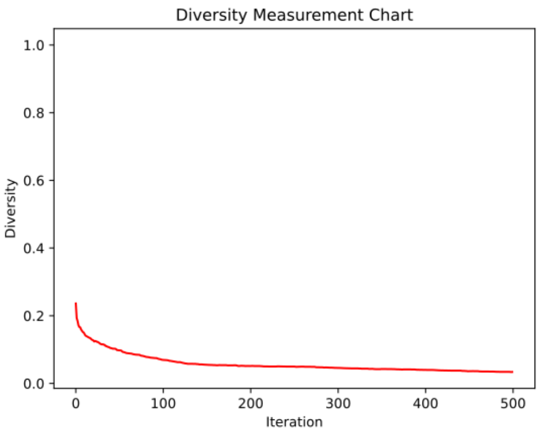

c) Case study 2a



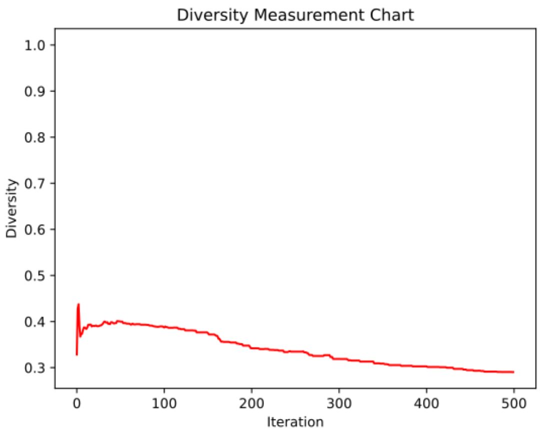

d) Case study 2b

**Fig. 4.** Average convergence curves for all case studies.

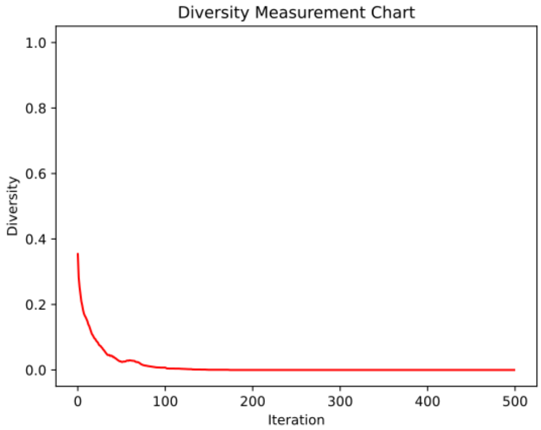
In Figure 5, the population diversity measurement results for all case studies can be seen.



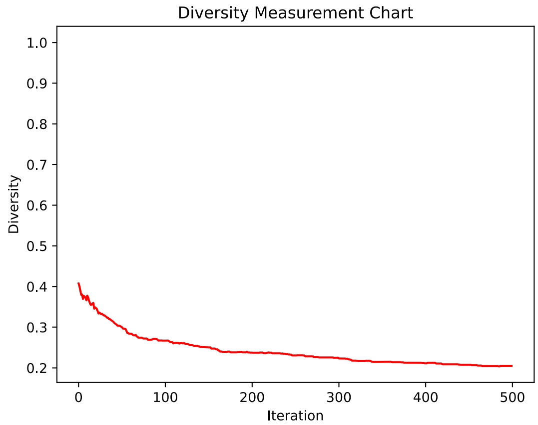

a) Case study 1a




b) Case study 1b

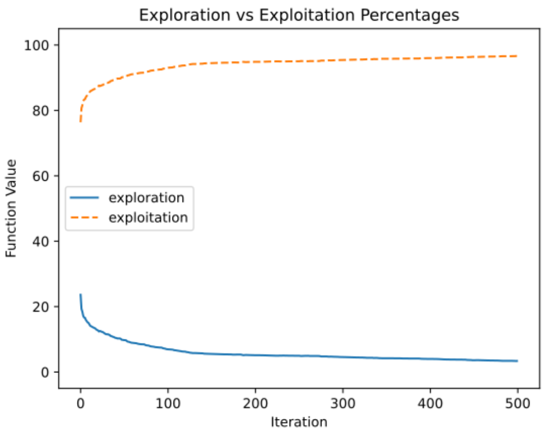



c) Case study 2a

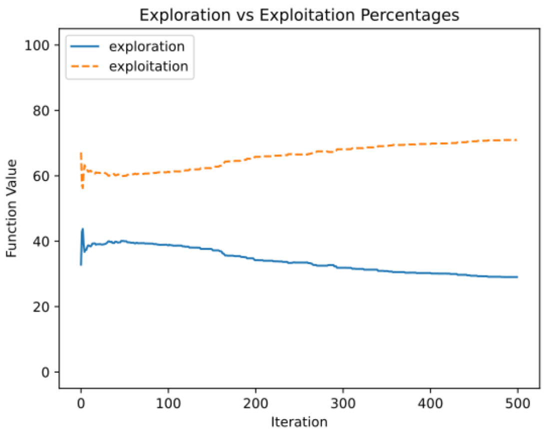



d) Case study 2b

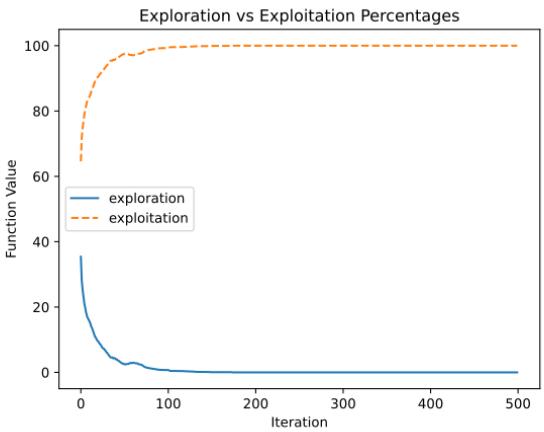
**Fig. 5.** Diversity measurement for all case studies.



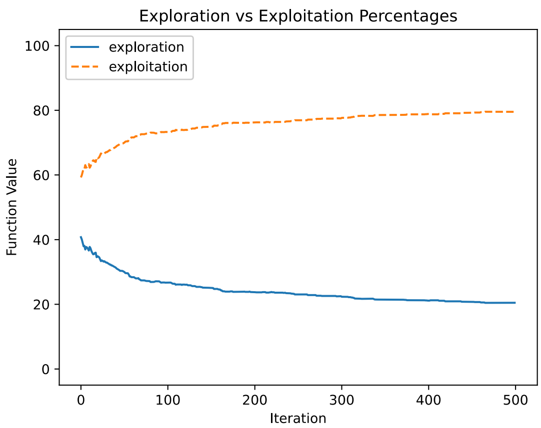

a) Case study 1a




b) Case study 1b




c) Case study 2a




d) Case study 2b

**Fig. 6.** Exploration and Exploitation characteristics for all cases.

It can be seen the exploration and exploitation capability results of the proposed FBIO algorithm for all case studies in Fig. 6. The reader who is unsure about how to depict the diversity, exploration, and exploitation capabilities of a meta-heuristic algorithm should consult the insightful study provided by Hussain et al. [64]. It can be said from these figures that FBIO algorithm is highly exploitative while solving cases without N-1 security, however, when it comes to considering contingency cases, the algorithm maintains more effectively its diversity and construct better balance between exploitation and exploration. This difference occurs because of the difficulty of the problem.

In this direction, the problem without N-1 criteria is easier to solve for FBIO, which leads to obtain promising areas at first iterations and algorithm lost its population diversity. Nonetheless, the consideration of N-1 criteria complicates the problem, which brings about to continue the searching process of promising areas to acquire the optimal solution. Therefore, the algorithm runs both exploration and exploitation phases in order to avoid the loss of diversity. Consequently, it can be inferred from the solutions obtained that FBIO investigates the search space the exploitative way in the most of the iterations.

## 5. Conclusion

In this study, the FBIO algorithm, which is a meta-heuristic optimization method, is proposed to solve a TEP problem aiming to minimize the investment costs and the loss of load cost. This article proposes Forensic Based Investigation Optimization (FBIO) which is a new and efficient meta-heuristic method in solving of the TEP problem for the first time. With the proposed method, optimum new transmission lines to be added to the system for the planning period have been determined. In order to evaluate the efficiency of the proposed method, FBIO has been applied for 4 different case studies on the IEEE 24-bus test system using DC model. Obtained results for with/without generation resizing cases have been compared with the results which obtained using 5 different methods in literature. The results showed that FBIO is one of the meta-heuristic optimization methods that gives the best results in solving the TEP problem. In addition to benchmarking, TEP problem has been solved for 2 case studies with N-1 constraint condition.

In future studies, it is aimed to realize transmission system planning for 5 and 10 year planning periods on the basis of different generation and load scenarios on the Turkish transmission network and/or static equivalent model using FBIO method. In modeling the problem, the intermittent/variable nature of renewable energy sources and the stochastic structure of the transmission network will be included.

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