Binary and Integer Coded Backtracking Search Optimization Algorithm for Transmission Network Expansion Planning

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Abstract: - This paper proposes binary and integer coded of backtracking search (BS) technique for solving the Transmission Network Expansion Planning (TNEP) considering security constraints. TNEP is formulated as a mixed integer, non-linear, non-convex optimization problem. It aims to optimally select of the routs, types, and number of the added circuits to meet economically the expected future load forecasted while the operational and planning constrained are considered. The BS technique has various significant advantages of being simple structure, having single control parameter, and operating with two new tuned mutation and crossover which control the amplitude of the search-direction matrix and search space boundaries. The BS technique is applied to solve the TNEP problem on two Egyptian networks namely West Delta System (WDS) and 500 kV of Extra High Voltage System (EHVS) where the predicted load forecasting up to 2030 is based on the adaptive neuro-fuzzy inference system (ANFIS). The simulation results for the two realistic networks show the capability of the proposed technique to solve efficiently the TNEP problem and their superiority over the heuristic technique, the integer-based particle swarm optimization (IBPSO) technique and multi-verse optimizer (MVO) at acceptable economical and technical benefits.

Key-Words: - Transmission network, expansion planning, backtracking search technique, investment cost, binary coding, integer coding, security.

1 Introduction

The problem of Transmission Network Expansion Planning (TNEP) is one of the serious problems in electrical power networks. Its objective is exploring the optimal selection of the routs, types, and number of the added circuits to face the expected future system with minimum capital investment cost [1-2]. Also, security of the transmission lines in the considered system must be considered in the TNEP. Thus, it is mainly formulated as a mixed integer, non-linear, non-convex optimization problem.

For solving the TNEP problem, some complexities are existed in the search space of the optimization due to the discrete nature of the control variables and the large number of scenarios to be simulated especially the large size of the considered systems [3]. For simulating each scenario, Direct Current (DC) Load Flow represents a fast and effective tool to estimate the power flows through the transmission lines in the power systems. It is dependent on simplifying the nonlinear model of the power system based on some assumptions by neglecting the line resistances, considering flat voltage profile, and diminishing the voltage angle differences. This tool is non-iterative and convergent [4] and [5].

For handling this problem, various meta-heuristic optimization techniques have been proposed for TNEP such as modified tabu search algorithm [6], genetic algorithm [7], greedy randomized adaptive search procedure (GRASP) [8], heuristic technique [9], and particle swarm optimization [10]. In [11], a two-stage procedure has been suggested for the TNEP where the predicted load forecasting has been demonstrated in the first stage and, the Integer Based Particle Swarm Optimization (IBPSO) has been employed for solving the TNEP problem. In [12], an application of harmony search technique has been introduced to solve the TNEP with security constraints. A modified harmony search algorithm has been presented for the TNEP developing the improvisation step by modifying the selection phase of the harmony vector to store the previous best harmonies of the harmony memory [13]. In [14] and [15], various versions of differential evolution algorithm have been applied for planning the reactive power sources in power systems.

Recently, continuous development in the era of optimization is noticed and the application of new search-based optimization algorithm in all of engineering and science fields. In this line, a new technique known as backtracking search (BS) technique used for solving engineering optimization problems was first proposed by Civicoglu in [16]. The BS technique is effective, fast and featured with a simple structure. It has the capability to memorize previous individuals randomly for use in producing the search-direction matrix. Thus, BS technique has the advantage of experiences in creating the offsprings from previous generations. The ability of the BS technique for solving power system optimization problems has been proved such as the power system restoration [17], optimal reactive power dispatch [18] and [19], and load frequency control problem in multi-machine power networks [20].

In view of the BS capabilities, this paper integrates binary and integer versions of BS technique for solving the TNEP with security constraints. The security constraints are preserved via kept the power flow in exit and added routes within the permissible limits. The binary and integer versions are developed and applied to solve the TNEP problem for two realistic transmission Egyptian networks which are West Delta System (WDS) and 500 kV of Extra High Voltage System (EHVS) where the predicted load forecasting up to 2030 is considered based on the adaptive neuro-fuzzy inference system (ANFIS). The simulation results for the two realistic systems show the capability of the proposed technique to solve efficiently the TNEP problem and their superiority over the heuristic technique, the Integer Based Particle Swarm Optimization (IBPSO) technique and Multi-Verse Optimizer (MVO) at acceptable benefits.

2 Problem Formulation

In electrical networks, the objective of the TNEP is mainly to minimize the investment costs of the additional transmission branches that meet the power system requirements for future demand and future generation configuration while various operational limits are satisfied. The solution of this problem involves determining the new circuits must be installed in power systems in order to meet the forecast demand at the lowest cost, while at the same time satisfying prescribed technical, financial and reliability criteria.This is mathematically stated as follows:

$$\text{Min } F = \text{Min } (\sum_{i,j \in N} C_{ij} N_{ij}) \quad (1)$$

Where, F is the total investment costs of the new circuits. C_{ij} and N_{ij} represent the cost of the circuits that can be added to the right-of-way from bus i to bus j, the number of circuit added to the i-j right-of-way, respectively. N refers to the total number of the added transmission lines in the power system. This objective function is subjected to:

$$S.Pf + g = d \quad (2)$$

$$|Pf_{ij}| \le (No_{ij} + N_{ij}) Pf_{max,ij} \quad (3)$$

$$Pf_{ij} = \frac{No_{ij} + N_{ij}}{x_{ij}} (\theta_i - \theta_j) \quad (4)$$

$$lb \le N_{ij} \le ub \quad (5)$$

$$0 \le g \le G \quad (6)$$

Where, S is the branch-node incidence transpose matrix of the power network, Pf is the power flow vector with Pf_{ij} elements, g is the generation vector with g_k elements that represent the generation in k bus, and d is the demand vector. No_{ij}, Pf_{ij}, and $Pf_{max,ij}$ represent the number of the existed circuits in the system, the total power flow passing through the route i − j, and the maximum power flow in each route i - j, respectively. θ_i and θ_j are the phase angle vectors in bus i and j, respectively. x_{ij} is the reactance of the connected line between bus i and j. lb is the existed circuits in the power system, ub is the maximum number of that circuits that can be added to the i - j right-of-way. G is the maximum value of the elements in the generation vector.

3 Backtracking Search Technique for Solving the TNEP Problem

Backtracking search (BS) is a population-based optimization technique designed for handling real-valued optimization problems. It maintains a population of N individual and D-dimensional individuals. In BS technique, three basic operators (selection, mutation, and crossover) have been adopted to generate trial populations. It has a random mutation strategy that uses only one direction individual for each target individual and it possesses a memory in which it stores a population from a randomly chosen previous generation for use to identify the search-direction matrix [18 and 19]. The major phases of the BS technique are described as follow:

3.1 Initialization

Initially, the BS technique constructs randomizing individuals within the considered feasible range:

$$P_{ij} \sim U(low_j, up_j), \quad i = 1,2,...., N, \; j = 1,2,..., D \quad (7)$$

Where, N is the population size; D is the problem dimension; U is the uniform distribution function; P_i is the position of the i^{th} population individual in the solution space; low_j and up_j are lower and upper limits of the solution space, respectively. The TNEP dimension refers to the number of the control variables that are represented by the total number of the possible added routes to the system (N). Each control variable represents the number of circuits added to each route so it is ranging from 0 to the maximum number of the parallel circuits that may be to the route.

3.2 Fitness function evaluation

The considered objective function is minimizing the total investment costs of the new circuits in Eq. 1. In addition, the fitness of any individual that violates any constraint of dependent variable is set to a very high value. So, the infeasible solutions, which violate the constraints, have a little chance to be transferred to the next generation.

3.3 Selection-I

In this stage, BS technique generates the historical population utilized to determine the search direction as follows:

$$P_{old,ij} \sim U(low_j, up_j), \quad i = 1,2,...., N, \; j = 1,2,..., D \tag{8}$$

Where $P_{old,ij}$ is the historical population. BS technique gives a chance to redesign the historical population at the beginning of each iteration using the following rule:

$$P^{old} = \begin{cases} P, & \text{if } \; a < b \\ P^{old}, & \text{if } \; a \geq b \end{cases} \tag{9}$$

Where a and b ~ U(0,1) in order to decide if the historical population is selected from previous generation. Then the shuffling function is applied in order to rearrange the individuals as follows:

$$P^{old} := \text{Permutting}(P^{old}) \tag{10}$$

Where the permuting ( ) function is a random shuffling function.

3.4 Mutation

After that, the mutation process generates mutant vectors (V) at every generation as follows:

$$V = P + F.(P^{old} - P) \tag{11}$$

Where, F is a real number which controls the amplitude of the search direction. BS technique employed historical experiences to determine the search direction by considering the values of the historical population [18].

3.5 Crossover

The crossover operation of the BS technique creates trial population (T) by exchanging the components of the mutant vectors (V) and the target vectors in P [19]. After this process, the individuals may exceed the search space limits. Thus, the movement of the individuals must be restricted by randomly regeneration for the exceeded variables in the feasible search space.

3.6 Selection-II

The selection-II process is carried out in the last stage to compare the fitness of the trial vector and the corresponding target vector and select the parent which will survive in the next generation as follows:

$$P^{next}_{i,j} = \begin{cases} T_{i,j}, & \text{if } f(T_{i,j}) < f(P_{i,j}) \\ P_{i,j}, & \text{otherwise} \end{cases} \tag{12}$$

Where f () is the fitness function. Then, these stages are repeated across generations and stopped whenever maximum number of generations is reached or other stopping criterion is satisfied. Fig. 1 depicts the flowchart of the major phases of the BS technique. Gen is the maximum number of the generation that have been specified to iterate until it is achieved.

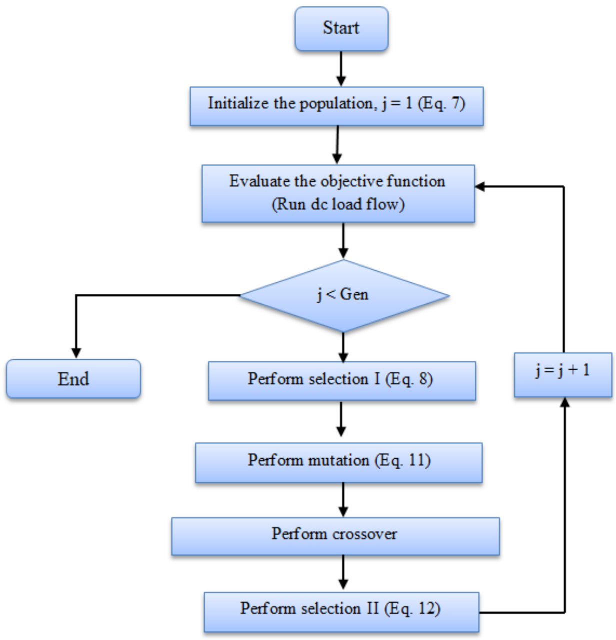

Fig. 1. The phases of the backtracking optimization technique

3.7 Integer and binary coding schemes of the proposed BSA

The control variables may be handled as integer variables or binary variables. The integer coding handles each right of way route and it takes an integer value that translates the number of the parallel circuits in this considered route.

On the other hand, the binary coding handles each single circuit in each right of way route. Therefore, the number of control variables will be increased in the binary coding whilst the considered range for each one is decreased.

4 Load Forecasting Process

The long-term load forecasting process is employed using ANFIS to predict the peak load demand of the Egyptian networks. The ANFIS method gathers the merits of fuzzy logic and artificial neural networks in the same topology [11]. ANFIS structure has the following basic steps:

Step 1. Define historical peak load data for certain years of model.

Step 2. Normalize the historical data.

Step 3. Classify the historical data into two categories, training and test data. Approximate 80% of these data are considered as training data while the rest 20% are specified for test data.

Step 4. Running ANFIS module in the MATLAB environment.

Step 5. Employing the future projection of historical data using autoregressive method for the forecasted period.

Step 6. The predicted peak loads are rescaled by post-processing methods.

Step 7. ANFIS issued to obtain long term forecasting results and the results are compared to mathematical methods to show validity and error levels. In order to show error levels, mean absolute error and mean absolute percentage error.

5 Applications

5.1 Test systems description

In this section, the BS technique has been adopted with integer and binary coding schemes to solve the TNEP problem. For this purpose, two realistic transmission Egyptian networks are utilized which are West Delta System (WDS) [21] and 500 kV of Extra High Voltage System (EHVS) [22]. Figs. 2 and 3 depict the one-line diagram of the real power system for WDS and EHVS, respectively.

The first system is the West Delta System (WDS) is a sub-transmission network of 66-kV. It is a part of the Unified Egyptian Network and consists of existed 52-bus and 8 generation buses. They are connected by 55 double circuits [20] and [21].

To estimate the new economical configuration parameters of WDS, it is planned to meet the predicted peak load of 2195.8 MW load system where a new site generator is proposed at bus 53 and 31 candidate new lines. For the WDS, 31 control variables in each population are considered for integer coding and 62 control variables are considered for binary coding.

The second system is the Extra High Voltage System (EHVS) is a realistic Egyptian network for 500 kV. The predicted load is 13176.90 MW at 2030 and the system is composed of 18 existing buses and 19 existing lines as shown in Fig. 3. The data of the generation dispatch, transmission line parameter, possible routs direction and the predicted load forecasting up to 2030 of both systems are taken from Ref. [11].

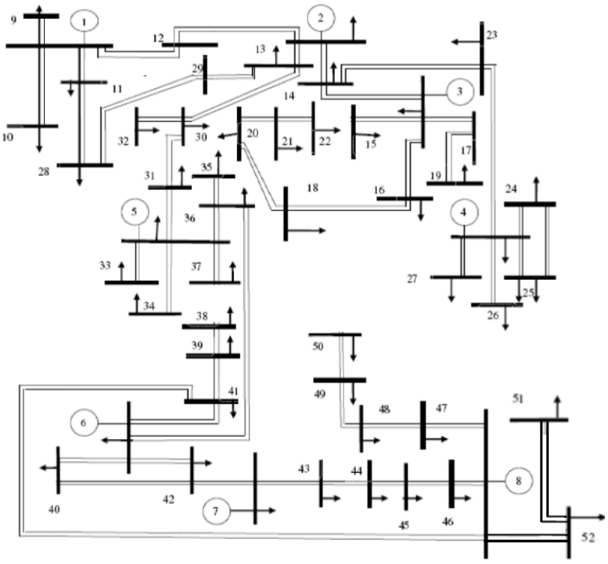

Fig. 2. Line diagram for actual WDS [23]

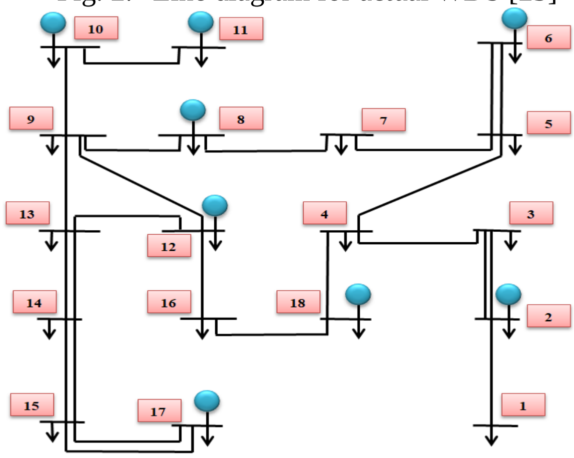

Fig. 3. Line diagram for EHVS

For the EHVS, 19 candidate new lines can be added according to the nature of the tracks of paths [11]. Thus, 19 control variables in each population are considered for integer coding and 33 control variables are considered for binary coding. For simulating each individual, DC Load Flow [24] is applied to estimate the constraints of dependent variables.

5.2 Load forecasting process for the tested networks

Table 1 shows the expected load forecasting for WDS and EHVS in the period 2018-2030 based on historical data reported in [11], [25] and [26]. For the WDS, it is found that the load is increased from 1325 MW in 2017 to around 2195 MW by an increase of 730 MW. It is expected an average increase of 5% yearly. For the EHVS, the expected load is varied from 9240.55 MW in 2017 to around 13176.9 MW.

Table 1: Forecasting loads for WDS and EHVS in Egypt using ANFIS

WDS		EHVS	
Year	Predict loads (MW)	Year	Predict loads (MW)
2017	1325	2017	9240.55
2018	1390.56	2018	9481.86
2030	2195.80	2030	13176.90

5.3 TNEP simulation results for WDS
The BS technique has been applied to solve the TNEP problem for the WDS and the related results are tabulated in Table 2. As shown, the BS technique achieved the minimum investment costs for the added transmission lines by both the integer and binary coding with 18.605 and 18.455 US million $, respectively. Using the same conditions, the obtained results using the proposed BS technique are compared to some other approaches reported by many researches as shown in Table 3. This comparison demonstrates that the proposed BS technique outperforms many techniques used to solve the TNEP problem in minimizing the investment costs for the added transmission lines.

Table 2: Output results of the proposed BS technique for WDS

	Proposed Integer Based BS	Proposed Binary Based BS
Terminals From-to (Line No.)/No. of circuits	6-34(63)/1	5-7(57)/1
	7-32(65)/1	6-34(63)/1
	22-53(77)/1	33-53(80)/1
	33-53(80)/1	5-53(81)/2
	5-53(81)/2	36-53(84)/2
	36-53(84)/2	20-53(85)/2
Length (km)	372.1	369.1
Total costs (Millions $)	18.605	18.455

Table 3: Comparison of the results for WDS

	Length (km)	Total costs (Millions $)
Proposed Binary Based BS	369.1	18.455
Proposed Integer Based BS	372.1	18.605
MVO [27]	412.9	20.645
HT [9]	424.8	21.24
IBPSO [11]	443.8	22.19

Fig. 4 shows the related power flow in the transmission lines for the new configuration of WDS based on the proposed BS technique and the MVO to face the future demand at year 2030. This figure elucidates that all the power flows are within its particular limits.

5.4 TNEP simulation results for EHVS
For this system, the BS technique has been applied to solve the TNEP problem and the corresponding results are put in Table 4. Both coding of the BS technique select three single circuits in the new right of way routes (8-7; 9-12; 13-12). Using the same conditions, the obtained results using the proposed BS technique are compared to MVO [27] and IBPSO [11] as shown in Table 5. The obtained results of the proposed BS technique cost 288 US million $ whereas MVO [27] and IBPSO [11] acquired higher total investment costs of 308 and 295 US million $, respectively.

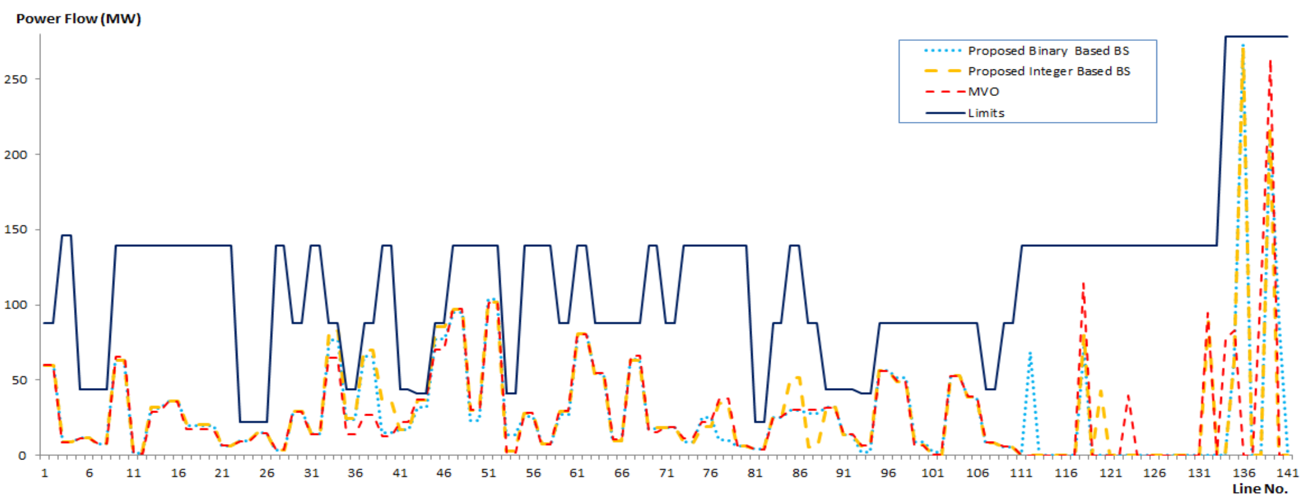

Fig. 4. Power flows in the WDS lines for the new configuration related to the proposed BS and the MVO

Table 4: Output results of the proposed BS technique for EHVS

Terminals	Proposed Integer Based BS	Proposed Binary Based BS
From-to (Line No.)/No. of circuits	8-7(26)/1	8-7(26)/1
	9-12(31)/1	9-12(31)/1
	13-12(32)/1	13-12(32)/1
Total costs (Millions $)	288	288

Table 5: Comparison of the results for EHVS

Method	Total costs (Millions $)
Proposed Binary Based BS	288
Proposed Integer Based BS	288
MVO [27]	295
IBPSO [11]	308

Fig. 5 depicts the related power flow in the transmission lines for the new configuration of EHVS based on the proposed BS technique and the MVO to face the future demand at year 2030. As shown, all the power flows are within its particular limits.

5.5 Convergence characteristics of the proposed backtracking search technique

Figs. 6 and 7 display the convergence characteristics of the proposed integer and binary coded versions of BS technique compared to the solution obtained by MVO [25] for WDS and EHVS, respectively. These figures assure the superiority of the proposed binary- and integer-based BS technique over MVO in finding lower investment costs. In addition to that, MVO is stuck very early in a local minimum. On the other side, the proposed integer-based BS technique maintains good diversity and remains developing towards the minimum investment costs.

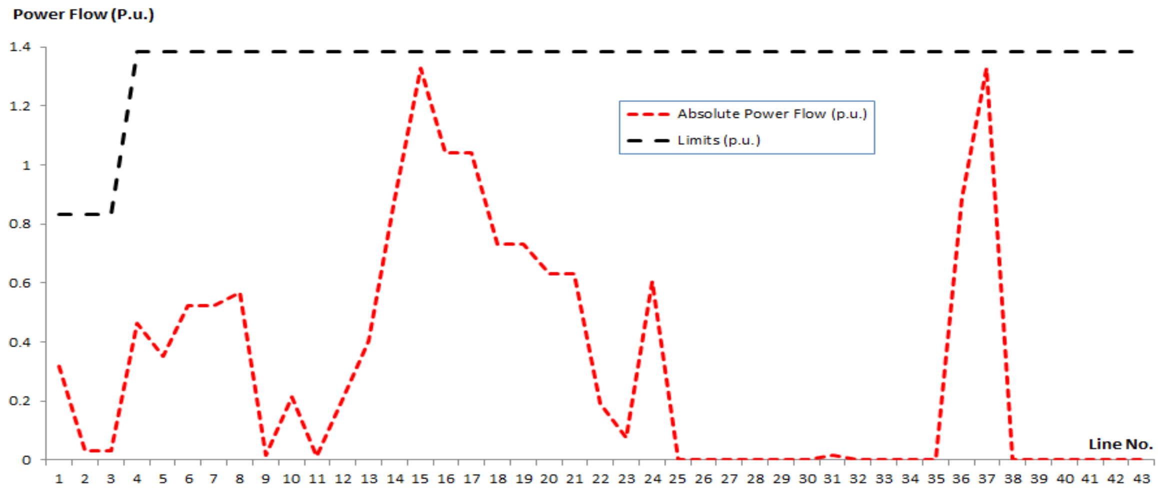

Fig. 5. Power flows in the EHVS lines for the new configuration related to the proposed BS technique

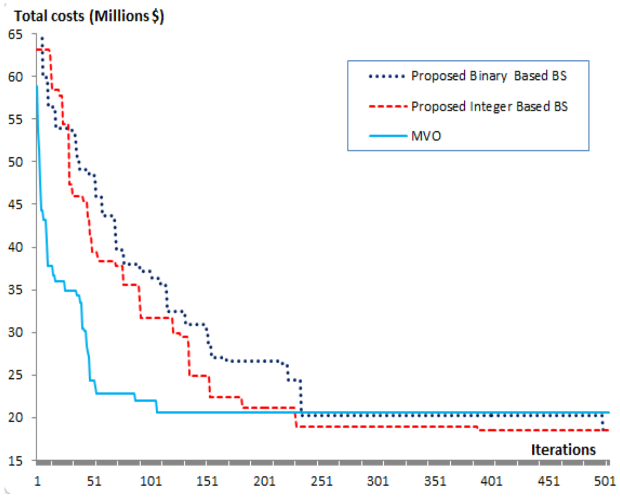

Fig. 6. Convergence charcteristics of the BS technique and MVO for WDS

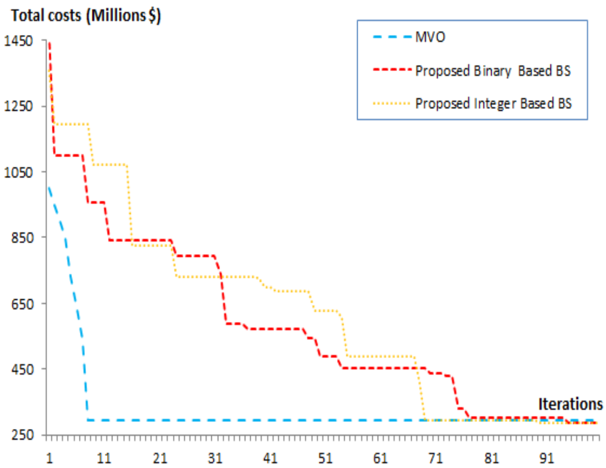

Fig. 7. Convergence charcteristics of the BS technique and MVO for EHVS

6 Conclusions

In this paper, the BS technique has been employed with integer and binary coding to solve the TNEP on two realistic transmission Egyptian networks which are West Delta System (WDS) and 500 kV of Extra High Voltage System (EHVS). The TNEP has been modeled to minimize the total investment costs of the expanded transmission lines while satisfying the security constraints to face the expected future system demand. In addition, the BS results were compared with the other heuristic methods reported in the literature and demonstrated its effectiveness and robustness. Added to that, the quality of the new configuration is appeared via satisfying the security constraints of the transmission line rating. Moreover, the convergence characteristics of the proposed binary and integer versions BS technique demonstrate the capability to avoid local optima stagnation in minimizing the total investment costs of the new circuits.

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