IDCGA Based Evaluation of Network Losses Role in TNEP under Uncertainty in Demand

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Abstract:- Transmission network expansion planning (TNEP) is an important component of power system planning. It determines the characteristic and performance of the future electric power network and influences the power system operation directly. Up till now, various methods have been presented for the solution of static TNEP (STNEP) problem. However, in all of them, STNEP problem has been solved regardless of the network losses role in TNEP under uncertainty in demand. Thus, in this paper, the role of network losses in STNEP problem is being studied under uncertainty in demand using an improved decimal codification genetic algorithm (IDCGA). The effectiveness of the proposed idea is tested on an actual transmission network of the Azerbaijan regional electric company, Iran. The results reveal that, considering the losses even for transmission expansion planning of a multi voltage level network with low load growth is caused that operational costs decreases considerably and the network satisfies the requirement of delivering electric power more safely and reliable to load centers.

Key-Words: - Transmission expansion planning, Uncertainty in demand, Network losses, IDCGA.

1 Introduction

Transmission network expansion planning (TNEP) is an important component of power system planning that its task is to minimize the network construction and operational cost while satisfying the demand increasing, imposed technical and economic conditions. It determines where, when and how many new transmission lines should be added to the network during the planning horizon [1]-[3]. Determination of investment cost for power system expansion is very difficult work because this cost should be determined from grid owners with agreement of customer and considering the various reliability criteria [4]. Transmission expansion planning is a hard and highly non-linear combinatorial optimization problem that generally, can be classified as static or dynamic. Static expansion determines where and how many new transmission lines should be added to the network during the planning horizon. If in the static expansion the planning horizon is separated for several stages we will have dynamic planning [5], [6].

In majority of power systems, generating plants are located far from the load centers. In addition, the planned new projects are still so far from completion. Due to these situations, the investment cost for transmission network is huge. Thus, the STNEP problem acquires a principal role in power system planning and should be evaluated carefully, because any effort to reduce the cost of the transmission system expansion by some fraction of a percent allows saving of a significant amount of capital. After Garver's paper that was published in 1970 [7], much research has been done on the field of TNEP problem until now. Some of this research such as [1]-[3], [6], [8]-[25] is related to problem solution method. Some others, irrespective of solution method, proposed different approach for solution this problem considering various parameters such as uncertainty in demand [5], reliability criteria [4], [26], [27], and economic factors [28]. Also, some of them investigated this problem and generation expansion planning together [29, 30]. Recently, different methods such as GRASP [3], Bender decomposition [6], HIPER [17], branch and bound algorithm [31], sensitivity analysis [15], genetic algorithm [1], [11], [20], simulated annealing [16], [25] and Tabu search [12] have been proposed for solution of the STNEP problem. In all of these methods, the problem has been solved regardless to role of network losses in transmission expansion planning considering uncertainty in demand. In Ref. [8], authors proposed a neural network based method for solution of the TNEP problem with considering both the network losses and construction cost of the lines. But the role of network losses under uncertainty in demand has not been investigated in this study. In Ref. [10], the network expansion costs and transmitted power through the lines have been included in objective function and the goal is optimization of both expansion costs and loading of lines. In addition, the objective function is different from those which are represented in [6], [11], [12], [15]-[17], [20], [31], but the effect of network losses on TNEP considering uncertainty in demand has not been investigated.

In Ref. [32], the voltage level of transmission lines has been considered as a subsidiary factor but its objective function only includes expansion and generation costs and one of the reliability criteria i.e. power not supplied (PNS). In addition, expansion planning has been studied as dynamic type. However, the role of network losses in TNEP under uncertainty in demand has not been considered. Finally, in pervious author's papers [33], [34], the expansion cost of substations with the network losses have been considered for the solution of STNEP problem. The results evaluation in [33] was shown that the network with considering higher voltage level save capital investment in the long-term and become overload later. In [34], it was shown that the total expansion cost of the network was calculated more exactly considering effects of the inflation rate and load growth factor and therefore the network satisfies the requirements of delivering electric power more safely and reliably to load centers. However, role of network losses with considering uncertainty in demand has not been studied.

In this paper, the effect of network losses on static expansion planning of a transmission network with various voltage levels under uncertainty in demand is investigated. For this reason, network losses cost, uncertainty in demand and also the expansion cost of related substations from the voltage level point of view are included in the proposed objective function. The studied voltage levels, in this study are 230 and 400 kV. The results evaluation reveals that considering the role of network losses for solution of the STNEP problem under environments with uncertainty in demand is caused that even for low load growth coefficients, configurations which have higher voltage levels be more economic for network expansion and therefore the total expansion cost of network (expansion and operational costs) decreases considerably.

This paper is organized as follows: Formulation of STNEP problem under uncertainty in demand is given in Sec. 2. Sec. 3 describes completely improved DCGA based method and chromosome structure for solution of the STNEP problem. Method of choosing the fitness function is represented in Sec. 4. The characteristics of case study system and applying of the proposed method are given in Sec. 5. Finally, in Sec. 6 conclusion is represented.

2 Formulation of STNEP Problem under Uncertainty in Demand

The STNEP problem is a mixed-integer nonlinear optimization problem. Due to evaluating effect of the network losses on STNEP problem in a multi voltage level transmission network under uncertainty in demand and subsequent adding expansion cost of substations to expansion costs, the proposed objective function is defined as follows:

$$OF = \sum_{k=1}^{NS}\left(EC_k + LC_k + \alpha \times \sum_{i=1}^{NB} r_i^k \right) \times PR_k \tag{1}$$

$$EC_k = \sum_{i,j\in\Omega} CL_{ij} n_{ij}^k + \sum_{i=1}^{NB}\sum_{c=1}^{ST} m_i^k SC_c \tag{2}$$

$$LC_k = \left(\sum_{t=1}^{NY}\sum_{i=1}^{NC} R_{ij}^k {I_{ij,t}^k}^2 \right) \times K_{loss} \times 8760 \times C_{MWh} \tag{3}$$

where,
OF: Objective function of STNEP.
EC_k: Expansion cost of network in scenario k.
LC_k: Annual losses cost of network in scenario k.
r_i^k : Loss of load for i-th bus in scenario k.
α: A coefficient for converting loss of load to cost ($US/MW).
PR_k: Occurrence probability of scenario k.
CL_{ij}: Construction cost of transmission line in corridor i-j.
n_{ij}^k : Number of new circuits of corridor i-j in scenario k.
SC_c: Cost of c-th type transformer (related costs are given in Appendix A).
m_i^k : Number of transformers that have been predicted for constructing in i-th bus under scenario k.
C_{MWh}: Cost of one MWh ($US/MWh).
R_{ij}^k: Resistance of branch i-j in scenario k.

$I_{ij,t}^k$: Flow of branch *i-j* in t-th year under scenario *k*. This current is varied with respect to annual load growth and therefore depends on the time.
K

K_{loss}: Losses coefficient.
Ω : Set of all network busses.
NY: Number of years after expansion to calculate the network losses. Its rate in all scenarios has been considered 10 years.
NC: Number of expandable corridors of network.
NB: Number of network busses.
ST: Number of types for constructed transformers.
NS: Number of scenarios

The calculation method of K_{loss} has been given in [33]. Several restrictions have to be modeled in a mathematical representation to ensure that the mathematical solutions are in line with the planning requirements. These constraints are as follows (see Refs. [5], [33] for more details):

$$S^k f^k + g^k - d^k = 0 \tag{4}$$

$$f_{ij}^k - \gamma_{ij}^k (n_{ij}^0 + n_{ij}^k)(\theta_i^k - \theta_j^k) = 0 \tag{5}$$

$$\left|f_{ij}\right|^k \le \beta \cdot (n_{ij}^0 + n_{ij}^k)\overline{f_{ij}} \tag{6}$$

$$0 \le n_{ij}^k \le \overline{n_{ij}} \tag{7}$$

Where, $(i,j) \in \Omega$ and:
S^k: Branch-node incidence matrix in scenario *k*.
$f^{\ k}$: Active power matrix for each corridor in scenario *k*.
g^k: Generation vector in scenario *k*.
d^k: Demand vector in scenario *k*.
θ_i^k : Phase angle of each bus in scenario *k*.
γ_{ij}^k : Total susceptance of circuits for corridor *i-j* in scenario *k*.
n_{ij}^k : Number of constructible circuits for corridor *i-j* in scenario *k*.
$\overline{n_{ij}}$: Maximum number of constructible circuits in corridor *i-j*.
$\overline{f_{ij}}$: Maximum of transmissible active power through corridor i-j which will have two different rates according to voltage level of candidate line.
β: A coefficient for providing security margin from loading of lines view point. This coefficient guaranties required adequacy of lines to satisfy the all of network loads at years after expansion.

In this study, the objective function is different from those which are mentioned in [1]-P20], [23]-[28], [30], [31], [33], [34]. The goal of the STNEP problem is to obtain number of lines and their voltage level to expand the transmission network in order to ensure required adequacy of the network along the specific planning horizon. Thus, problem parameters are discrete time type and consequently the optimization problem is an integer programming problem. For solution of this problem, there are various methods such as classic mathematical and heuristic methods [5]-[21]. In this study, an Improved Decimal Codification Genetic Algorithm (IDCGA) is used to solve the STNEP problem due to flexibility and simple implementation. In the proposed method, expansion and completion of objective function (for example, adding the network losses to objective function, extending the studied voltage levels to another levels and etc) would be practicable.

3 IDCGA and Chromosome Structure of the Problem

3.1 Improved DCGA

Standard genetic algorithm is a random search method that can be used to solve non-linear system of equations and optimize complex problems. This algorithm manipulates the binary strings which may be the solutions of the problem. This algorithm can be used to solve many practical problems such as transmission network expansion planning [33]. The genetic algorithm generally includes the three fundamental genetic operators of reproduction, crossover and mutation. These operators conduct the chromosomes toward better fitness. There are three methods for coding the transmission lines based on the genetic algorithm method [33]: 1) Binary codification for each corridor. 2) Binary codification with independent bits for each line. 3) Decimal codification for each corridor. Although binary codification is conventional in genetic algorithm but in here, the third method has been used due to following reasons that were mentioned in [33].

In this method crossover can take place only at the boundary of two integer numbers. Mutation operator selects one of existed integer numbers in chromosome and then changes its value randomly. Reproduction operator, similar to standard form, reproduces each chromosome proportional to value of its objective function. But since the proposed STNEP of this study is a large-scale combinatorial optimization problem, improving performance and convergence speed of DCGA in optimization process, can be very useful. Therefore in order to improve efficiency and convergence speed of DCGA, some schemes are considered as follows:

3.1.1 Elitism strategy

In this strategy, one individual of next generation is replaced randomly by elite individual of previous one. This manner is one of the best solutions to improve the GA performance. Thus, best genetic features of previous generations which have been gathered in elite one are used in next generations. Accordingly, ability of algorithm is enhanced in order to obtain new optimal points. It should be noted that if this manner is not performed, when the genetic operators are applied, elite individual and therefore good features of previous generations may be wasted. Thus, fitness probability of best individual of next generation in comparison with previous one decreases and is caused that the optimization process procedure becomes slow.

3.1.2 Fitness scaling

With increasing gradually the fitness rate of individuals, their fitness variance is decreased. This fact is one of disadvantages of selections which are based on comparison like roulette-wheel one. In other words, with increasing the GA iterations, fitness ratio of best individual to worst one and therefore the competition of individuals for selection is decreased (i.e. selection probability of better individuals is decreased). For solving this problem, a specified value is subtracted from fitness of individuals. In this study, this value is equal to the lowest fitness rate of related generation plus to 1.

3.1.3 Saving fitness of some individuals in program memory

Regarding to this fact that a time is lasted from encoding of an individual to calculation of its fitness, saving fitness of individuals in program memory for some generations in order to increasing the speed of GA running can be useful. Since, if one of these individuals is iterated in next generations, it does not need to calculate their fitness again. Advantage of this manner is more obvious in last iterations, because acceptation probability of new individuals is reduced and therefore iteration of individuals in one generation is increased.

3.2 Selection, crossover and mutation process

This operator selects the chromosome in the population for reproduction [33]. Selection is based on the survival-of-the-fittest strategy, but the key idea is to select the better individuals of the population, as in tournament selection, where the participants compete with each other to remain in the population. The most commonly used strategy to select pairs of individuals that has applied in this paper is the method of roulette-wheel selection. After selection of the pairs of parent strings, the crossover operator is applied to each of these pairs.

The crossover operator involves the swapping of genetic material (bit-values) between the two parent strings. Based on predefined probability, known as crossover probability, an even number of chromosomes are chosen randomly. A random position is then chosen for each pair of the chosen chromosomes. The two chromosomes of each pair swap their genes after that random position. Crossover may be applied at a single position or at multiple positions. In this work, because of choosing smaller population multiple position crossover is used with probability of 0.3.

Each individuals (children) resulting from each crossover operation will now be subjected to the mutation operator in the final step to forming the new generation. The mutation operator enhances the ability of the GA to find a near optimal solution to a given problem [33]. This operator randomly flips or alters one or more bit values usually with very small probability known as a mutation probability (typically between 0.001 and 0.01). In a binary coded GA, it is simply done by changing the gene from 1 to 0 or vice versa. In DCGA, as in this study, the gene value is randomly increased or decreased by 1 providing not to cross its limits. Practical experience has shown that in the transmission expansion planning application the rate of mutation has to be larger than ones reported in the literature for other application of the GA. In this work mutation is used with probability of 0.1 per bit.

After mutation, the production of new generation is completed and it is ready to start the process all over again with fitness evaluation of each chromosome. The process continues and it is terminated by either setting a target value for the fitness function to be achieved, or by setting a definite number of generations to be produced. Due to the stochastic nature of the GA, there is no guarantee that different executions of the program converge to the same solution. Thus, in this study, a more suitable criteria termination has accomplished that is production of 1500 generations after obtaining the best fitness and finding no better solution and iteration (run) of this process for 5 times.

3.3 Chromosome structure of the problem

The selected chromosome considering voltage level and also simplicity in programming was divided into the following parts as shown in Fig. 1 for a network with 6 corridors. In part 1, each gene includes number of existed circuits (both of constructed and new circuits) in each corridor. Genes of part 2 describe voltage levels of existed genes in part 1. It should be noted that the binary digits of 0 and 1 have been used for representing voltage levels of 230 and 400 kV, respectively. If other voltage levels exist in the network, the numbers 2, 3 and etc., can be used for representing them in the genes of part 2. Therefore, the proposed coding structure would be extendable to other voltage levels. In Fig. 1, in the first, second, third corridor and finally sixth corridor, one 400 kV, two 230 kV, three 400 kV and two 230 kV transmission circuits have been predicted, respectively. Fig. 2 shows the flowchart of the proposed IDCGA for the solution of STNEP problem.

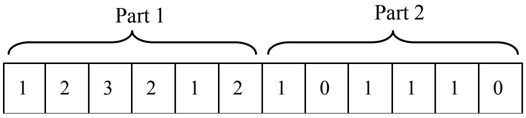

Fig. 1 Typical chromosome structure

4 Fitness Function Choosing

The fitness function is one of the key elements of genetic algorithms (GAs) as it determines whether a given potential solution will contribute its elements to future generation through the selection process or not. Since the objective of GAs is to maximize the fitness, while the objective of transmission planning model is to minimize the objective function (OF) presented by Eq. (1), therefore it is necessary to map the objective function into the fitness function. The fitness function (Fit) adopted in this work is.

$$Fitness = \frac{A}{OF} \qquad (7)$$

where, A is a system-dependent constant that in order to prevent the fitness from obtaining too small values, its value is considered big.

5 Case Study

The transmission network of the Azerbaijan regional electric system is used to test and evaluation of the proposed method. This actual network has been located in northwest of Iran and is shown in Fig. 3. The arrangement of lines, substation information, generation and loads data of the test system are listed in Tables 1-3. Also, characteristics and construction costs of 230 and 400 kV lines are given in Appendix A.

For considering uncertainty in STNEP problem, three different scenarios with equal occurrence probabilities have been predicted for load growth. Also planning horizon is year 2018 (10 years ahead) and network losses is calculated by DC load flow from planning horizon year to 10 years after it (year 2028). Therefore, for feasibility of comparing the scenarios from their effect rate on network load view point, rates of network load at planning horizon with related load growth coefficients for different scenarios are given in Table 4. Value of coefficients α and β, and also C_{MWh} are considered 10^7 \$US/MW), 40% and 33 (\$US/MWh) respectively. The proposed method is applied to the case study system and the results (lines which must be added to the network during the planning horizon year) are given in Tables 5 and 6.

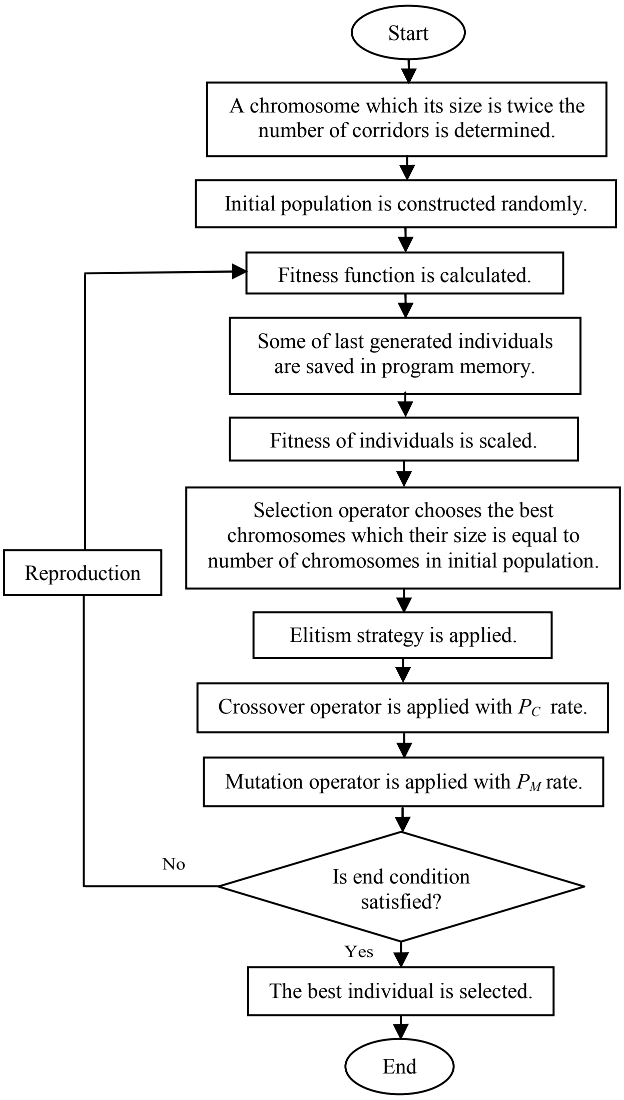

Fig. 2 Flowchart of the proposed method

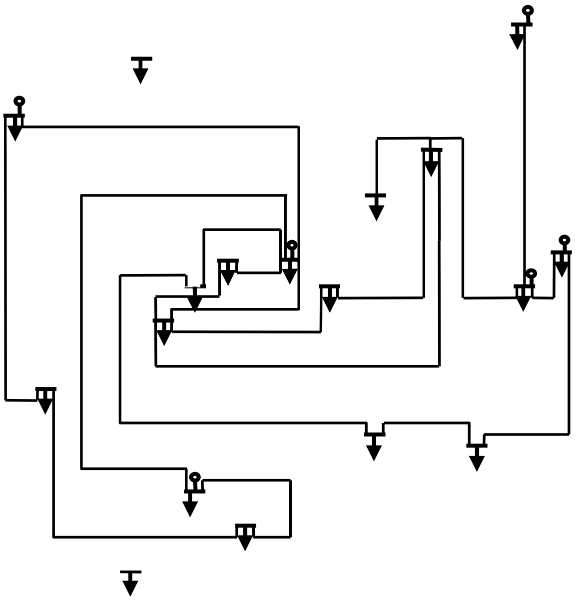

Fig. 3 Transmission network of the Azerbaijan regional electric company

TABLE 1
ARRANGEMENT OF LINES

Corridor	Length of Corridor (km)	Voltage Level (kV)	Number of Circuit
6-1	55	230	1
2-1	14	230	2
9-6	18	230	1
4-2	83	230	1
14-5	110	230	1
11-8	65	230	2
11-10	125	230	2
15-14	139	230	1
12-1	122	400	1
9-5	100	230	1
6-5	103	230	2
13-3	105	400	1
4-3	81	230	1
14-13	44	230	2
12-10	134	230	2
8-1	75	230	2
7-6	33	230	1
7-1	22	230	1
5-16	53	230	2

TABLE 2
ARRANGEMENT OF SUBSTATIONS

Substation	Voltage Level (kV)	Substation	Voltage Level (kV)
1	400/230	10	230/132
2	230/132	11	230/132
3	400/230	12	230/132
4	230/63	13	230/63
5	230/132	14	400/230
6	230/132	15	230/63
7	230/132	16	230/20
8	230/132	17	230/132
9	230/132	18	230/132

TABLE 3
GENERATION AND LOAD ARRANGEMENTS

Bus	Load (MW)	Generation (MW)	Bus	Load (MW)	Generation (MW)
1	378	715	10	134	0
2	202	0	11	125	0
3	42	0	12	256	288
4	53	0	13	78	101
5	45	0	14	46	60
6	64	0	15	45	101
7	88	0	16	11	0
8	49	514	17	14	0
9	70	0	18	79	0

TABLE 4
PROPOSED SCENARIOS FOR CONSIDERING UNCERTAINTY IN DEMAND

Scenario Number	Scenario 1	Scenario 2	Scenario 3
Load Growth (%)	5	7	9
Load (MW)	3427	4139	4981

TABLE 5
FIRST CONFIGURATION FOR ALL SCENARIOS: NEGLECTING THE NETWORK LOSSES

Corridor	Voltage Level (kV)	Number of Circuits
2-5	230	2
2-7	230	1
2-8	230	1
3-11	400	1
3-14	230	2
4-13	230	1
5-16	230	2
5-17	230	1
8-9	230	1
8-18	400	1
6-16	230	1
9-16	230	1
15-16	230	1

The first and second configurations are obtained neglecting and considering the network losses, respectively. It should be noted, the program was run by a Pentium 4 computer with 2.4-GHz processor and memory of 256 megabyte. Time of each run (iteration) for obtaining the first and second configuration is 74 and 220 seconds respectively. By comparing the Tables 5 and 6, ignoring the network losses, a configuration with lower voltage level lines is proposed for expansion of the network. But if the network losses is considered, a configuration with higher voltage level lines is proposed for expansion purpose. Also, for better analyzing of proposed configurations, their expansion costs for different scenarios form load growth point of view are given in Tables 7 and 8.

TABLE 6
SECOND CONFIGURATION FOR ALL SCENARIOS: CONSIDERING THE NETWORK LOSSES

Corridor	Voltage Level (kV)	Number of Circuits
1-5	400	2
1-7	230	1
1-8	230	2
2-5	400	2
2-7	230	2
2-8	230	2
2-17	400	1
3-13	400	1
4-8	400	1
5-6	400	1
5-7	400	2
5-9	400	2
6-9	230	1
6-13	400	2
7-8	400	2
8-9	230	2
8-11	400	2
8-18	230	2
10-11	230	2
11-13	400	2
11-18	230	2
13-14	230	2
13-15	400	2

TABLE 7
EXPANSION COSTS OF THE NETWORK FOR FIRST CONFIGURATION UNDER DIFFERENT SCENARIOS

Scenario Number	Scenario 1	Scenario 2	Scenario 3
Expansion Cost of Lines (million $US)	69.2	69.2	69.2
Expansion Cost of Substations (million $US)	2.2	2.6	2.6
Losses Cost (million $US)	542	1458.8	3922.5
Loss of Load Cost (million $US)	0	0	0
Total Expansion Cost of Network (million $US)	613.4	1530.6	3994.3

TABLE 8
EXPANSION COSTS OF THE NETWORK FOR SECOND CONFIGURATION UNDER DIFFERENT SCENARIOS

Scenario Number	Scenario 1	Scenario 2	Scenario 3
Expansion Cost of Lines (million $US)	236.9	236.9	236.9
Expansion Cost of Substations (million $US)	22.4	26.4	27.4
Losses Cost (million $US)	72.4	194.8	523.7
Loss of Load Cost (million $US)	0	0	0
Total Expansion Cost of Network (million $US)	331.7	458.1	788

Comparison between Tables 7 and 8 shows that if network losses is neglected for solution of STNEP problem, a configuration with respectively lower expansion cost and higher network losses is obtained. But considering the network losses, a plan with respectively higher expansion cost and lower network losses is proposed for network expansion. Moreover, Tables 7 and 8 show that uncertainty in demand has no effect on expansion cost of lines while it effects on losses cost and expansion cost of substations. The reason is that expansion cost of substations from voltage level point of view and losses cost depend on loading of lines and substations. Thus, different load growths can be effect on these costs. Finally, it can be said that proposed configurations by improved DCGA for different scenarios are same and any loss of load is not exist. This fact reveals that proposed method has high efficiency for solution of STNEP problem. Total expansion cost (sum of expansion and losses costs) of expanded network with the two proposed configurations for different scenarios is shown in Figs 4-6.

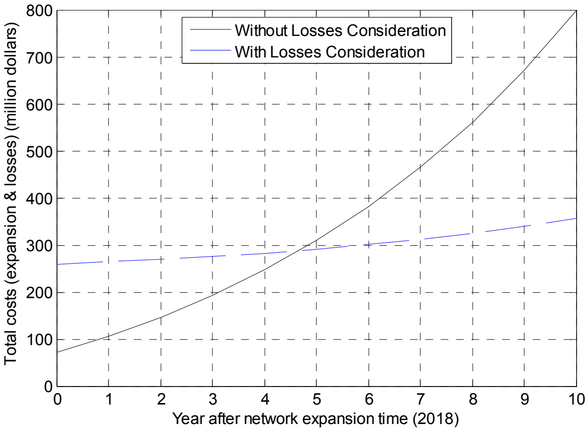

Fig. 4 Sum of expansion costs and annual losses cost of the network with the two proposed configurations for scenario 1

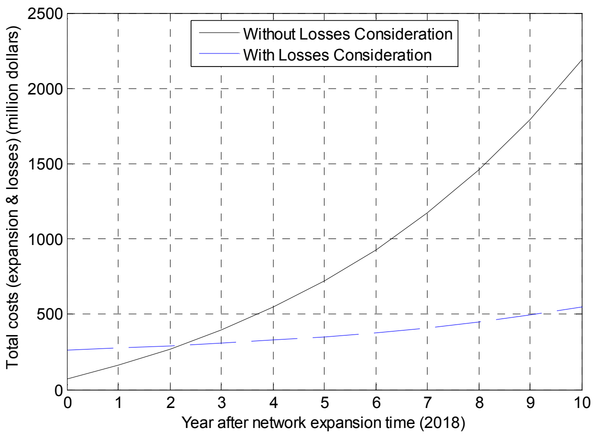

Fig. 5 Sum of expansion costs and annual losses cost of the network with the two proposed configurations for scenario 2

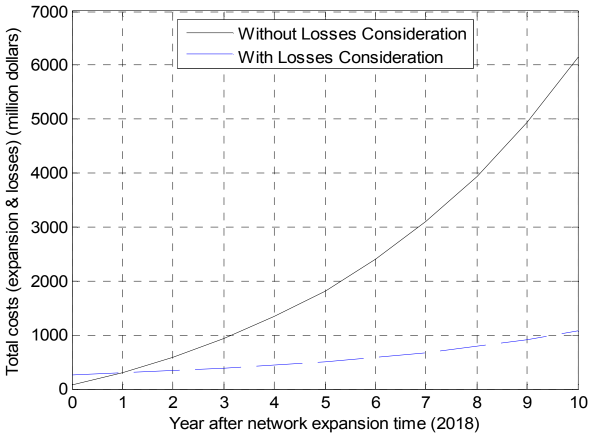

Fig. 6 Sum of expansion costs and annual losses cost of the network with the two proposed configurations for scenario 3

For load growth of 5%, second one has investment return in comparison with first one about 5 years after expansion time. With rising load growth, investment return takes places earlier (for load growths of 7% and 9% this time is about 2 years and 1 year respectively). Accordingly, it can be concluded that the network losses has important role in transmission expansion planning even for low load growths.

6 Conclusion

In this paper, the effect of network losses on STNEP problem under environments with uncertainty in demand is studied using an improved decimal codification genetic algorithm. The results analysis reveals that considering the network losses in transmission expansion planning under different load growths is caused that total expansion costs and losses cost of network is decreased for long-term and mid-term. Also, it can be said that although cost of lines with higher voltage levels are more than other lines (lines with lower voltage levels), constructing this type of lines in transmission network is caused that investment cost is considerably saved and therefore the total expansion cost is calculated more exactly. Consequently, even in networks with low load growth, network losses plays important role in transmission expansion planning and subsequent determination of network arrangement and configuration. In addition, it can be concluded that the proposed algorithm is a respectively fast and efficient method for solution of STNEP problem.

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Appendix

Characteristics and construction costs of case study lines

Tables 9-11 show the characteristics and the construction costs of 230 and 400 kV lines. Also, the cost of different types of transformer with voltage ratio of 400/230 kV is given in Table 12.

TABLE 9
CHARACTERISTICS OF 230 AND 400 KV LINES

Voltage Level (kV)	Maximum Loading (MVA)	Reactance (p.u/Km)	Resistance (p.u/Km)
230	397	3.85e-4	1.22e-4
400	750	1.24e-4	3.5e-5

TABLE 10
CONSTRUCTION COST OF 230 KV LINES

Number of Line Circuits	Fix Cost of Line Construction ($\times 10^3$ dollars)	Variable Cost of Line Construction ($\times 10^3$ dollars)
1	546.5	45.9
2	546.5	63.4

TABLE 11
CONSTRUCTION COST OF 400 KV LINES

Number of Line Circuits	Fix Cost of Line Construction ($\times 10^3$ dollars)	Variable Cost of Line Construction ($\times 10^3$ dollars)
1	1748.6	92.9
2	1748.6	120.2

TABLE 12
COST OF DIFFERENT TYPES OF TRANSFORMERS

Rated Power (MVA)	125	160	200	315
Cost (million $US)	18	22	26	32