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Regular paper

Role of Voltage Level and Network Losses in TNEP Solution

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 operation of the power system directly. Up till now, various methods have been presented for solution of the static transmission network expansion planning (STNEP) problem. However, in all of these methods, STNEP problem has been solved regardless to voltage level of transmission lines and role of voltage level in reducing annual losses of the network. In this paper, STNEP is studied considering voltage level and network losses using decimal codification based genetic algorithm (DCGA). Genetic Algorithms (GAs) have demonstrated the ability to deal with non-convex, nonlinear, mixed-integer optimization problems, like the TNEP problem, better than a number of mathematical methodologies. The proposed method is tested on Garvers 6-bus network and an actual transmission network of the Azerbaijan regional electric company, Iran to illustrate its robust performance. The results show that considering the network losses in a power system with different voltage levels, decreases the operational costs considerably and the network satisfies the requirement of delivering electric power more safely and reliably to load centers.

Keywords: STNEP, Network Losses, Genetic Algorithms, Combinatorial Optimization

1. INTRODUCTION

Transmission network expansion planning (TNEP) is a basic part of power system planning that determines where, when and how many new transmission lines should be added to the network. Its task is to minimize the network construction and operational cost, while meeting imposed technical, economic and reliability constraints. TNEP should be satisfied required adequacy of the lines for delivering safe and reliable electric power to load centers along 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]. Thus, the long–term TNEP is a hard, large-scale combinatorial optimization problem. Generally, transmission network expansion planning can be classified as static or dynamic. Static expansion determines where and how many new transmission lines should be added to the network up to 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, 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

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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], [8-24] is related to problem solution method. Some others, irrespective of solution method, proposed different approaches for solution of this problem considering various parameters such as uncertainty in demand [5], reliability criteria [4, 25-26] and economic factors [27]. Also, some of them investigated this problem and generation expansion planning together [28, 29]. Recently, different methods such as GRASP [3], Bender decomposition [6], HIPER [17] branch and bound algorithm [30], sensitivity analysis [15], genetic algorithm [1, 11, 20, 24], simulated annealing [16] 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 voltage level of transmission lines and role of voltage level in reducing annual losses of the network. In Ref. [8], a neural network based method for solution of the TNEP problem was proposed considering both the network losses and construction cost of the lines. But the role of line voltage level and substations 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, 24, 30], but the voltage level of transmission lines and the network losses have not been investigated. In Ref. [31], 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 energy. In addition, expansion planning has been studied as dynamic type. However, the network losses have not been considered.

In this paper, due to various voltage levels in transmission network which cause different annual losses, STNEP is being studied considering voltage level and network losses using decimal codification genetic algorithm. Thus, the network losses cost of lines and the expansion cost of related substations from the voltage level point of view is included in the objective function. The studied voltage levels in this research are 230 and 400 kV. These voltages are extendable to another voltage levels, too. The proposed method is tested on Garvers 6-bus network and a real transmission network of the Azerbaijan regional electric company in order to demonstrate the effectiveness of the proposed idea. This network has been located in northwest of Iran.

This paper is organized as follows: the mathematical model and objective function is given in Sec. 2. Sec. 3 describes completely chromosome structure and the proposed GA based method for solution of the STNEP problem. The characteristics of case study system and applying of the proposed method are given in Sec. 4, respectively. Finally, in Sec. 5 conclusion is represented.

2. MATHEMATICAL MODEL OF THE STNEP PROBLEM

The STNEP problem is a mixed-integer nonlinear optimization problem. Due to considering voltage level of lines in transmission network expansion planning and subsequent adding expansion cost of substations to expansion costs, the proposed objective function is defined as follows:

$$C_T = \sum_{i,j \in \Omega} CL_{ij} n_{ij} + \sum_{k \in \Psi} CS_k + C_{loss} \tag{1}$$

$$CL_{ij} = CL_1 + CL_2 \tag{2}$$

$$C_{loss} = Loss \times C_{loss_u} \times k_{loss} \times 8760 \tag{3}$$

Where,

C_T : Total expansion cost of network.

CL_1 : Construction cost of 230 kV line in corridor *i-j*.

CL_2 : Construction cost of 400 kV Line in corridor *i-j*.

CS_k : Expansion cost of k^{th} substation.

C_{loss} : Annual losses cost of network.

Loss: Total losses of network.

C_{loss_u} : Cost of unit losses ($\$/Mwh$).

k_{loss}: Losses coefficient.

Ω : Set of all corridors.

Ψ : Set of all substations.

n_{ij} : Number of all new circuits in corridor *i-j*.

The calculation method of k_{loss} and CS_k is given in Appendices A and B, respectively.

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. [5-11] for more details):

$$Sf + g - d = 0 \tag{4}$$

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

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

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

$$Line\_Loading \le LL_{max} \tag{8}$$

Where, $(i, j) \in \Omega$ and:

S: Branch-node incidence matrix.

f: Active power matrix in each corridor.

g: Generation vector.

d: Demand vector.

θ: Phase angle of each bus.

γ_{ij} : Total susceptance of circuits in corridor *i-j*.

n_{ij}^0 : Number of initial circuits in corridor *i-j*.

$\overline{n_{ij}}$: 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.

Line_Loading: Loading of lines at planning horizon year and start of operation time.

LL_{max}: Maximum loading of lines at planning horizon year.

In this study, the objective function is different from those which are mentioned in [1-20, 23-27, 29, 30] and in part of the problem constraints, $\overline{f_{ij}}$ is considered as an addition constraint. In addition to above-mentioned changes, also *Line_Loading* constraint is taken as a new constraint into account in order to ensure adequacy of the network after expansion. It should be noted that LL_{max} is an experimental parameter that is determined according to load growth coefficient and its rate is between 0 and 1. Added lines to the network, network adequacy (increasing of overload duration time) and expansion cost is increased with reducing rate of this parameter. Also, network losses and lines loading is decreased.

3. PROPOSED SOLUTION ALGORITHM

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, the decimal codification genetic algorithm is being used for solution of the STNEP problem due to flexibility, 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.

3.1. Decimal codification genetic algorithm and chromosome structure of the problem

Standard genetic algorithm is a random search method that can be used to solve non-linear system of equations and optimize complex problems. The base of this algorithm is the selection of individuals. It doesn't need a good initial estimation for sake of problem solution, In other words, the solution of a complex problem can be started with weak initial estimations and then be corrected in evolutionary process of fitness. 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. The genetic algorithm generally includes the three fundamental genetic operators of reproduction, crossover and mutation. These operators are used to find better fitness function.

There are three methods for coding the transmission lines based on the genetic algorithm method [11]:

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:

1) Avoiding difficulties which are happened at coding and decoding problem.

2) Preventing the production of completely different offspring from their parents and subsequent occurrence of divergence in mentioned algorithm.

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. Therefore, the chromosomes which have better objective functions will be selected more probable than other chromosomes for the next population (i.e, Elitism strategy). Thus, selected chromosome considering voltage level and also simplicity in programming is divided to following parts as shown in Figure. 1. 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 describing them in the genes of part 2. Therefore, the proposed coding structure will be extendable to other voltage levels. A typical chromosome for a network with 6 corridors is shown in Figure. 1. In the first corridor, one 400 kV transmission circuit, in the second corridor, two 230 kV transmission circuits, in the third corridor, three 230 kV transmission circuit and finally in the sixth corridor, two 230 kV transmission circuit have been predicted. The flowchart of the proposed GA-based method for solution of the STENP problem is shown in Figure. 2.

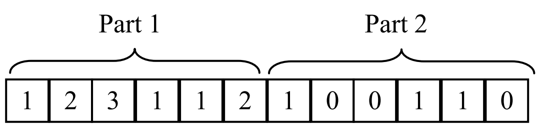

Figure. 1:. Typical chromosome structure

3.2. Selection, crossover and mutation process

This operator selects the chromosome in the population for reproduction. The more fit the chromosome, the higher its probability of being selected for reproduction. Thus, 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, in which every string is assigned a slot in a simulated wheel sized in proportion to the string's relative fitness. This ensures that highly fit strings have a greater probability to be selected to form the next generation through crossover and mutation. 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 1. Each individuals (children) resulting from each crossover operation will now be subjected to the mutation operator in the final step to create the new generation. The mutation operator enhances the ability of the GA to find a near optimal solution to a given problem by maintaining a sufficient level of genetic variety in the population, which is needed to make sure that the entire solution space is used in the search for the best solution. In a sense, it serves as an insurance policy; it helps prevent the loss of genetic material. 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 literatures for other application of the GA. In this work, mutation is used with probability of 0.01 per bit.

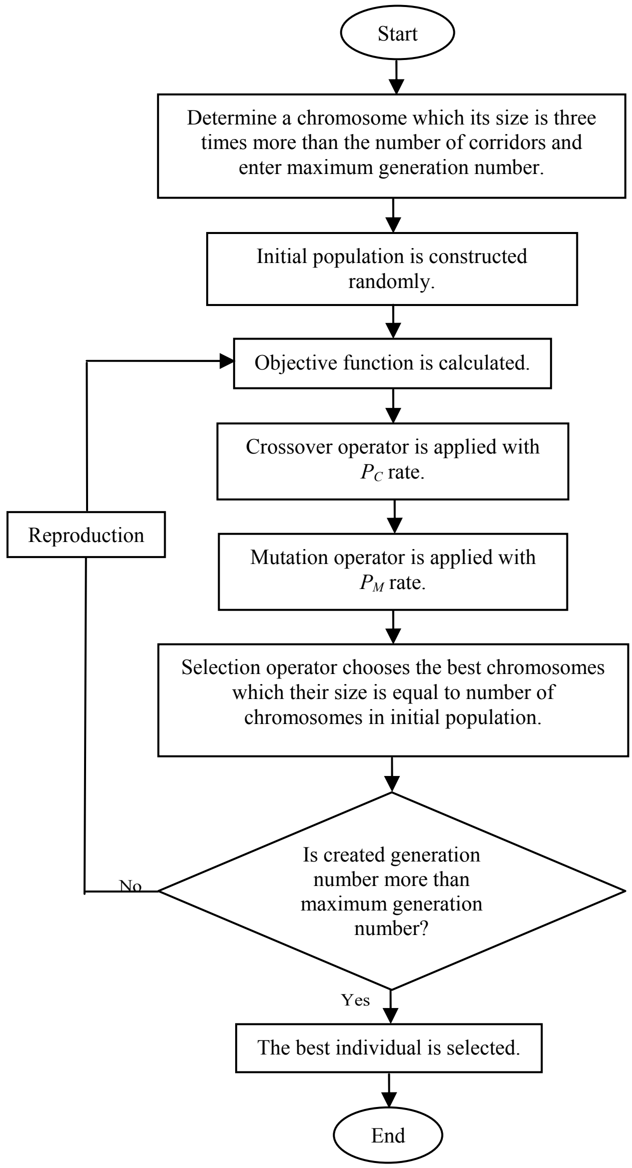

Figure. 2. : Flowchart of the proposed method

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, the program has been executed for four times as continual i.e. after running of the genetic program, obtained results are inserted in initial population of next run and this process is iterated for three times. In addition to this continual run, a more suitable criteria termination has accomplished that is production of predefined generations after obtaining the best fitness and finding no better solution. Here, the maximum number of generations is considered 3500.

4. SIMULATION RESULTS

In this work, two test networks have been studied. First case is Garvers 6-bus network and second case is transmission network of the Azerbaijan regional electric company. In the next sub-sections results of the proposed algorithm on two mentioned networks will be described.

4.1. Garvers 6-bus network

First network that is studied is Garver's network. This network is shown in Figure. 3 and its details are described in [7].

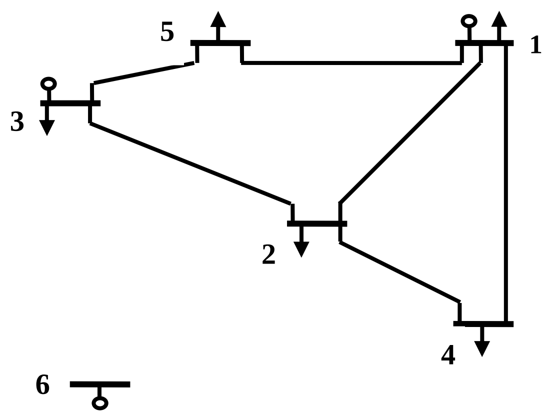

Figure. 3: . Garvers 6-bus network

In order to evaluate the effect of the losses in various networks, the proposed idea is test on this network for two scenarios. The network, in each scenario, has different configurations. In scenario 1, the both substations and lines have two different voltage levels but in scenario 2, all the lines have a same voltage levels (230 kV). The goal of presentation of scenario 2 is investigating construction of lines with higher voltage level in the networks with only one transmission voltage level.

Scenario 1

In this scenario, the network configuration is considered according to Tables 1 and 2.The planning horizon year and the maximum loading is considered 15 (year 2022) and 50% at planning horizon year, respectively:

Table 1. Characteristics of the lines

Corridor	Voltage Level (kV)	Corridor	Voltage Level (kV)
1-2	230	2-3	400
1-4	230	2-4	230

1-5	230	3-5	400

Table 2. Characteristics of substations

Substation	Voltage Level (kV)	Substation	Voltage Level (kV)
1	230/63	4	230/63
2	400/230	5	400/230
3	400/63	6	400/230

The proposed method is applied to the above test network and the results (lines which must be added to the network up to planning horizon year) are given in Tables 3. Also, Table 4 shows the expansion costs. The first and second configurations are obtained neglecting and considering the network losses, respectively.

Table 3. First and second configurations in scenario 1

	First configuration		Second configuration	
Corridor	Voltage Level (kV)	Number of Circuits	Voltage Level (kV)	Number of Circuits
2-6	230	4	400	4
3-5	400	2	400	2
4-6	230	4	230	3
5-6	230	1	-	-

Table 4. Expansion cost of network with the first and second configurations in scenario 1

	First configuration	Second configuration
Expansion Cost of Substations	0	0
Expansion Cost of Lines	96.175 M$	108.415 M$
Total Expansion Cost of Network	96.175 M$	108.415 M$

According to Table 4, expansion cost of substations has obtained zero. The reason is that the voltage level of the proposed lines for network expansion has been existed in their both first and end substations and therefore substations have not required expansion from voltage level point of view. Total expansion cost (sum of expansion and losses costs) of expanded network with the two proposed configurations is shown in Figure. 4.

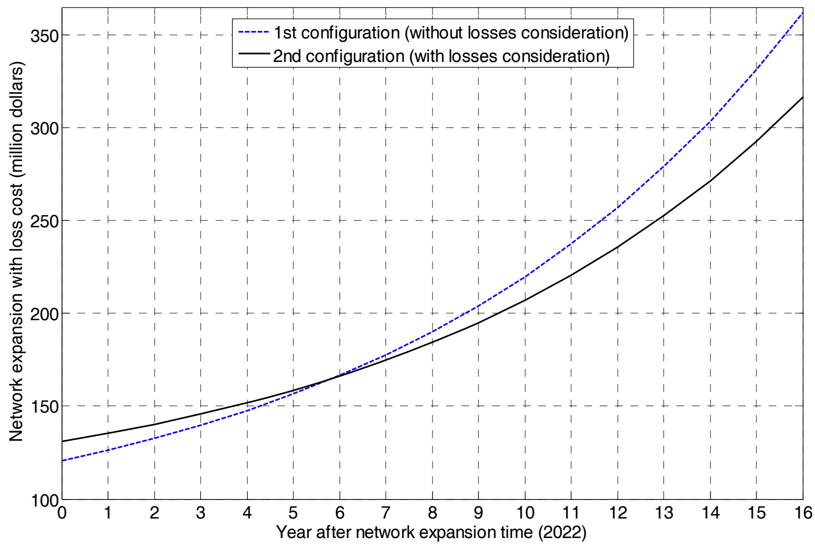

Figure. 4. : Sum of expansion costs and annual losses cost of the network with the two proposed configurations in scenario 1

It can be seen that the start point of second curve is upper than start point of first curve on the vertical axis, but this curve about 6 years after planning horizon (year 2028) cuts the first curve. Although it seems that the first configuration (most of the lines are 230 kV) is more economic but if the network is studied considering the network losses after planning horizon time the second configuration (most of the lines are 400 kV) is more economic. The reason is that the annual network losses cost of first configuration will become considerable in comparison with second configuration about 6 years after planning horizon time and finally it is caused the sum of expansion and network losses costs for both configurations become equal together. In this method, total expansion cost of the first configuration will become more than another one after about 6 years from the planning horizon time and subsequent the second configuration will be more economic after this time. Thus, in second configuration investment cost is returned after the 6th year of the expansion time. Process of investment return for this configuration in comparison with the first one is shown in Fig. 5. In fact, this curve is equal to subtraction of cost curves of two mentioned configurations in Figure. 4. From the transmitted power through the lines point of view, the second configuration is better. Because with the run of DC load flow according to load growth for years after expansion time it seen that this configuration is overloaded 16 years after planning horizon, whereas first configuration is overloaded 14 years after expansion time.

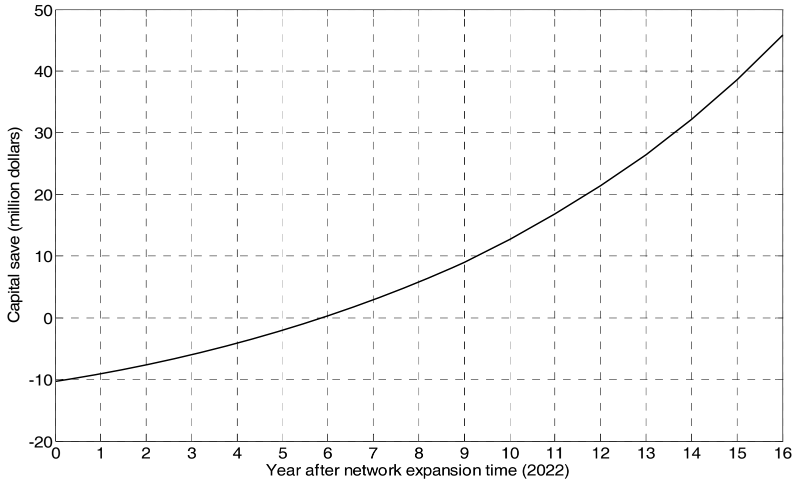

Figure. 5 : Investment return curve by choosing of the second configuration in comparison with the first one

A. Scenario 2

In this scenario planning horizon year and maximum loading of lines and substations are similar to scenario 1 but the network configuration is as follow:

- Voltage level of substations 1 to 5 is 230/63 kV and Voltage level of substation 6 is 400/63 kV.
- Voltage level of lines is 230kv.

Here, the proposed GA-based method is test on the Garver's network and the results are given in Tables 5 and 6.

Table 5. First and second configurations in scenario 2

	First configuration		Second configuration	
Corridor	Voltage Level (kV)	Number of Circuits	Voltage Level (kV)	Number of Circuits
2-6	230	4	400	3
3-5	230	3	230	3
4-6	230	4	230	3
5-6	230	1	230	1

Table 6. Expansion cost of network with the first and second configurations in scenario 2

	First configuration	Second configuration
Expansion Cost of Substations	31.475 M$	31.257 M$
Expansion Cost of Lines	89.18 M$	99.809 M$
Total Expansion Cost of Network	120.655 M$	131.066 M$

Total expansion cost (sum of expansion costs and losses cost) of expanded network with the two proposed configurations by genetic algorithm based method is shown in Figure. 6. Similar to previous scenario with neglecting the network losses, the first configuration (all its lines are 230) is better. But with considering the network losses, after about 6 years from the planning horizon, the second one (most of its lines are 400) is more economic. The reason is that the annual network losses cost of the first configuration will be more than another one about 6 years after planning horizon. Thus, in second configuration investment cost is returned after the 6th year of the expansion horizon. Process of investment return for the second configuration in comparison with the first one is shown in Figure. 7. Similar to scenario 1, this curve is equal to subtraction of two cost curves of Figure. 6. Also, results of DC load flow for years after expansion time show that the second configuration is better, because this configuration is overloaded 2 years later than the first configuration.

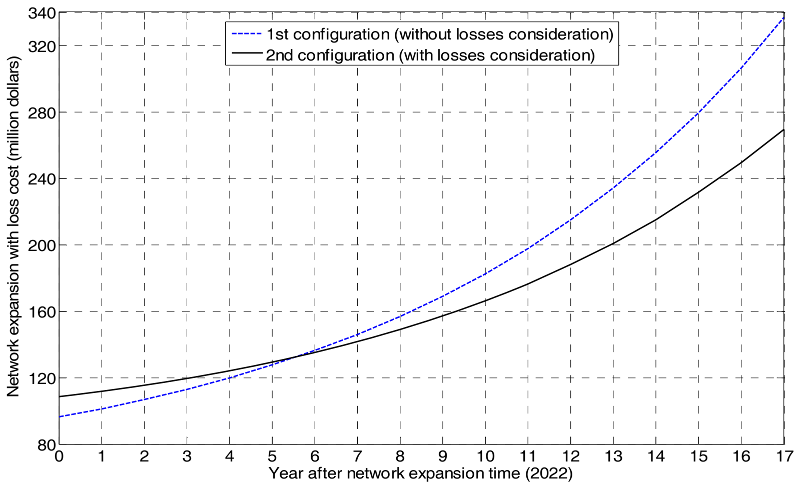

Figure. 6. : Sum of expansion costs and annual losses cost of the network with the two proposed configurations in scenario 2

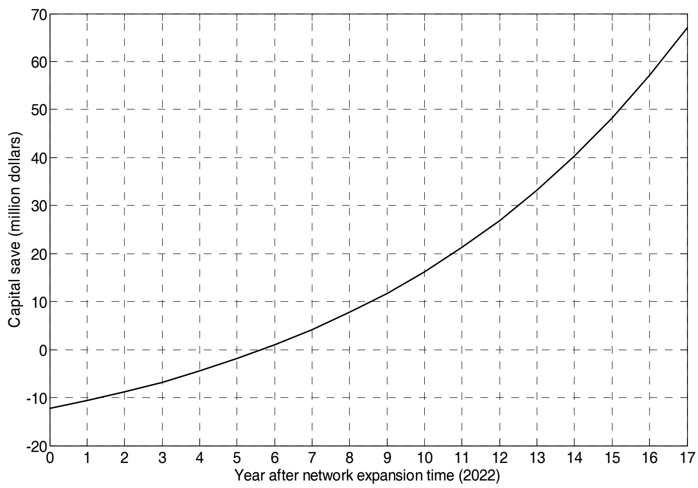

Figure. 7 : Investment return curve by choosing of the second configuration in comparison with the first one

4.2. Transmission network of the Azerbaijan regional electric company

The second studying network is transmission network of the Azerbaijan regional electric company. This actual network has been located in northwest of Iran and is shown in Figure. 8. The network characteristics and required data are given in Appendix C.

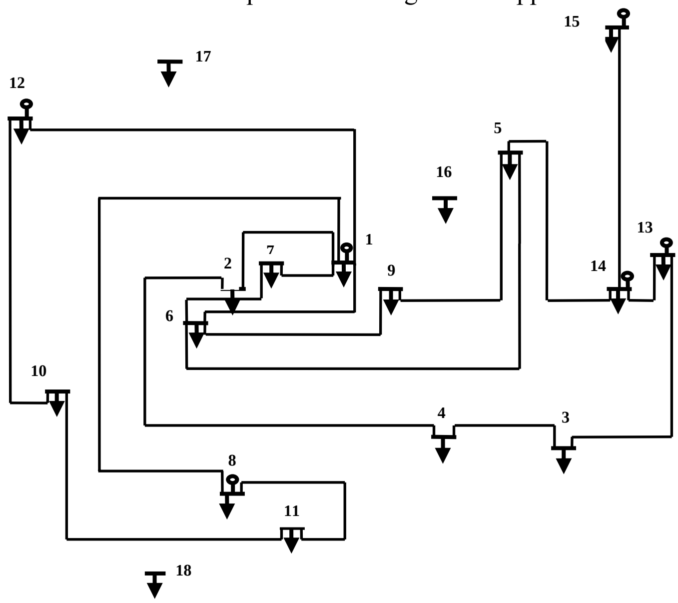

Figure. 8. Transmission network of the Azerbaijan regional electric company

Here, the planning horizon year and the maximum loading have been considered as follows:

- Planning horizon year is 15 (year 2020).
- Maximum loading of lines and substations is 30% at planning horizon year.

The proposed method is applied to this actual network under two different cases. In first case the network losses is not included in the objective function and second case the network losses is included in the objective function. The proposed configurations (added lines to network) are given in Table 7 for two cases. Also, Table 8 shows expansion cost of the network with these configurations. Total expansion cost (sum of expansion and losses costs) of expanded network with the two proposed configurations has been shown in Figure. 9. It can be seen that the start point of second curve is upper than start point of first curve on the vertical axis, but this curve about 8 years after planning horizon cuts the first curve. Although it seems that the first configuration is more economic but if the network is studied considering the network losses after planning horizon time second configuration is more economic. Thus, in second configuration investment cost is returned after the 8th year of the expansion time. Process of investment return for this configuration in comparison with the first one is shown in Figure. 10.

Table 7. First and second configurations

	First configuration		Second configuration	
Corridor	Voltage Level (kV)	Number of Circuits	Voltage Level (kV)	Number of Circuits
1-9	230	2	230	2
2-8	400	2	400	2

4-8	230	2	230	2
6-8	230	2	230	2
7-8	400	1	400	1
8-10	230	2	230	2
5-15	230	1	230	2
1-11	230	1	230	1
1-18	230	1	230	1
10-18	230	1	230	1
11-18	230	2	230	2

Table 8. Expansion cost of network with the first and second configurations

	First configuration	Second configuration
Expansion Cost of Substations	25.6 M$	25.6 M$
Expansion Cost of Lines	72.019 M$	73.679 M$
Total Expansion Cost of Network	97.619 M$	99.279 M$

According to Figure 10, it should be noted that expanded transmission network with second configuration will save capital about 33 million dollars 16 years after expansion time in comparison with first configuration totally. This value according to Table 8 is about 33% of total expansion cost of network that is considerably, while expansion cost of network with this configuration is different with the first configuration a little (less than 3 million dollars). Therefore it is realized that the network losses play important role in determining of network configuration and arrangement.

From voltage level of added lines point of view, expansion of the network by 400 kV lines is not economic and it is rejected by the proposed GA based method. The reason is that the construction of 400 kV lines in corridors which their sending and receiving substations have not voltage level of 400 kV, which would be caused substations are expanded and subsequent total expansion cost of the network is increased.

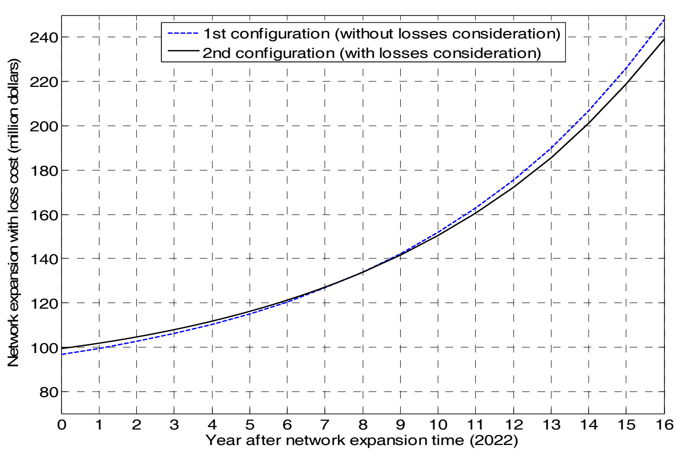

Figure. 9. Sum of expansion costs and annual losses cost of the network with the two proposed configurations

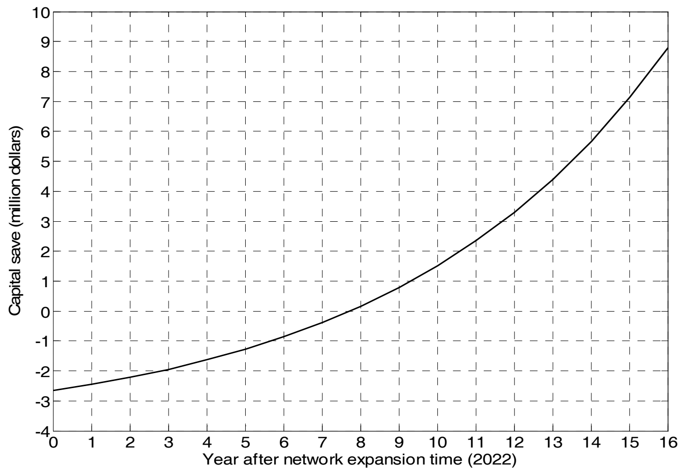

Figure. 10. Investment return curve by choosing of the second configuration in comparison with the first one

5. CONCLUSION

In this paper, the static transmission network expansion planning is studied using the decimal codification genetic algorithm with various voltage levels. According to simulation results, it can be concluded that the network losses and voltage level of transmission lines play important role in determining of network configuration and arrangement. Thus, considering voltage level of lines and subsequent the network losses in expansion planning of a network is caused more 230 kV and 400 kV lines are added to network. Although expansion cost of the network with considering voltage level and subsequent the network losses becomes more, but due to be less of the network losses, total expansion cost of network (the sum of expansion cost of lines and substations and network losses cost) is decreased in mid-term and long-term planning. In addition, networks which are expanded by more 400 kV lines are economic in long-term and from the power flow through the lines point of view is overloaded later. Moreover, results evaluation reveals that expanding of the network by lines with higher voltage levels in transmission networks with only one voltage level decreases the operational costs considerably. Finally, it considers the investment cost in terms minimal of added lines and ohmic power losses considering voltage levels of lines in lines under technical and economical constraints.

References:

[1] A.R. Abdelaziz., Genetic algorithm based power transmission expansion planning, IEEE International Conference on Electronics, Circuits and Systems, Vol. 2, pp. 642 – 645, 2000.

[2] T. Al-Saba and I. El-Amin, The application of artificial intelligent tools to the transmission expansion problem, Electric Power Systems Research, Vol. 62, pp. 117-126, 2002.

[3] S. Binato, G.C. Oliveira and J.L. Araújo, A greedy randomized adaptive search procedure for transmission expansion planning, IEEE Transaction on Power Systems, Vol. 16, No. 2, pp. 247-253, 2001.

[4] S. Binato, M.V.F. Periera and S. Granville, A new benders decomposition approach to solve power transmission network design problems, IEEE Transaction on Power Systems, Vol. 16, No. 2, pp. 235-240, 2001.

[5] R.S. Chanda and P.K. Bhattacharjee, A reliability approach to transmission expansion planning using minimal cut theory, Electric Power Systems Research, Vol. 33, pp. 111-117, 1995.

[6] R.S. Chanda and P.K. Bhattacharjee, A reliability approach to transmission expansion planning using fuzzy fault-tree model, Electric Power Systems Research, Vol. 45, pp. 101-108, 1998.

[7] R. Chaturvedi, K. Bhattacharya and J. Parikh, Transmission planning for Indian power grid: a mixed integer programming approach, International Transaction in Operation Research, Vol. 6, pp.465-482, 1999.
[8] J. Choi, T. Mount and R. Thomas, Transmission system expansion plans in view point of deterministic, probabilistic and security reliability criteria, The 39th Hawaii International Conference on System Sciences, pp. 1-10, 2006.
[9] J. Contreras and F.F. Wu, A kernel-oriented algorithm for transmission expansion planning, IEEE Transaction on Power Systems, Vol. 15, No. 4, pp. 1434-1440, 2000.
[10] R.A. Gallego, A. Monticelli and R. Romero, Transmission system expansion planning by an extended genetic algorithm, IEE Proc. on Generation, Transmission and Distribution, Vol. 145, No. 3, pp. 329-335, 1998.
[11] R. A Gallego, R. Romero and A. J. Monticelli, Tabu search algorithm for network synthesis, IEEE Transaction on Power Systems, Vol. 15, No. 2, pp. 490-495, 2000.
[12] L.L. Garver, Transmission net estimation using linear programming, IEEE Trans. on Power Apparatus and Systems, Vol. 89, No. 7, pp. 1688-1696, 1970.
[13] B. Graeber, Generation and transmission expansion planning in southern Africa, IEEE Transaction on Power Systems, Vol. 14, pp. 983-988, 1999.
[14] M.S. Kandil, S.M. El-Debeiky and N.E. Hasanien, Rule-based system for determining unit locations of a developed generation expansion plan for transmission planning, IEE Proc. on Generation, Transmission and Distribution, Vol. 147, No. 1, pp. 62-68, 2000.
[15] K.J. Kim, Y.M. Park and K.Y. Lee, Optimal long-term transmission expansion planning based on maximum principle, IEEE Transaction on Power Systems, Vol. 3, No. 4, pp. 1494-1501, 1988.
[16] S. Lee, K.L. Hocks and H. Hnyilicza, Transmission expansion of branch and bound integer programming with optimal cost capacity curves, IEEE Transaction on Power Application Systems, Vol. 93, pp. 1390-1400, 1970.
[17] V.A. Levi and M.S. Ćalović, Linear-programming-based decomposition method for optimal planning of transmission network investments, IEE Proc. on Generation, Transmission and Distribution, Vol. 140, No. 6, pp. 516–522, 1993.
[18] G. Liu, H. Sasaki and N. Yorino, Application of network topology to long range composite expansion planning of generation and transmission lines, Electric Power Systems Research, Vol. 57, pp. 157-162, 2001.
[19] M.V.F. Periera and L.M.V.G. Pinto, Application of sensitivity analysis of load supplying capacity to interactive transmission expansion planning, IEEE Transaction on Power Application Systems, Vol. 104, pp. 381-389, 1985.
[20] R. Romero, R. A. Gallego and A. Monticelli, Transmission system expansion planning by simulated annealing, IEEE Transaction Power Systems, Vol. 11, No. 1, pp. 364-369, 1996.
[21] R. Romero and A. Monticelli, A hierarchical decomposition approach for transmission network expansion planning, IEEE Transaction. on Power Systems, Vol. 9, No. 1, pp. 373-380, 1994.
[22] R. Romero and A. Monticelli, A zero-one implicit enumeration method for optimizing investments in transmission expansion planning, IEEE Transaction on Power Systems, Vol. 9, No. 3, pp. 1385-1391, 1994.
[23] H.M.D.R.H Samarakoon., R.M. Shrestha and O. Fujiwara, A mixed integer linear programming model for transmission expansion planning with generation location selection, Electric Power and Energy Systems, Vol. 23, pp. 285- 293, 2001.
[24] E.L. Silva, H. A. Gil and J.M. Areiza, Transmission Network Expansion Planning Under an Improved Genetic Algorithm, IEEE Transaction on Power Systems, Vol. 15, No. 3, pp. 1168-1175, 2000.
[25] I.J. Silva, M.J. Rider, R. Romero and C.A. Murari, Transmission network expansion planning considering uncertainness in demand, IEEE Power Engineering Society General Meeting, pp. 1424-1429, 2005.
[26] A. Silvestr, D. Braga and J.T. Saraiva, A multiyear dynamic approach for transmission expansion planning and long-term marginal costs computation, IEEE Transaction on Power Systems, Vol. 20, No. 3, pp. 1631-1639, 2005.
[27] N.H. Sohtaoglu, The effect of economic parameters on power transmission planning, IEEE Transaction on Power Systems, Vol. 13, pp. 941-945, 1998.

[28] R.C.G. Teive, E.L. Silva and L.G.S Fonseca., A cooperative expert system for transmission expansion planning of electrical power systems, IEEE Transaction on Power Systems, Vol. 13, No. 2, pp. 636-642, 1998.
[29] J. Yen, Y. Yan, J. Contreras, M. Pai-Chun and F.F. Wu, Multi-agent approach to the planning of power transmission expansion, Decision Support Systems, Vol. 28, pp. 279-290, 2000.
[30] K. Yoshimoto, K. Yasuda and R. Yokoyama, Transmission expansion planning using neuro-computing hybridized with genetic algorithm", IEEE Transaction on Power Systems, Vol. 10, pp. 126-131, 1995.
[31] P. Zhiqi, Z. Yao and Z. Fenglie, Application of an improved genetic algorithm in transmission network expansion planning, International Conference on Advances in Power System Control, Operation and Management, Vol. 1, pp. 318-326, 2003.

Appendix:

A. Calculation method for losses Coefficient (k_{loss})

This coefficient that simulates changes of load is equal to square of under the Load Duration Curve (LDC). For a typical network LDC is shown in Figure. 11. Coordinate axis are normalized therefore this coefficient will be between 0 and 1.

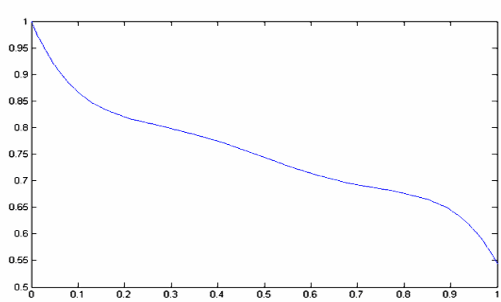

Figure. 11. LDC for a typical network

B. Calculation method for expansion cost of substations (CS_k)

In the transmission network expansion planning it is assumed that power plants and substations do not require expanding and only lines should be expanded. If the voltage levels of related substations (the placed substations on the both of the candidate line) are not equal to voltage level of its candidate line, these substations must be expanded from the voltage level point of view. Therefore the aim of calculating expansion cost of the substations is calculating the expansion cost of substations that their voltage levels are not match to the voltage levels of their related candidate lines. For calculating this cost, DC Load Flow (DCFL) program is run with presence of candidate lines. Then according to transmitted power trough the lines and using KCL law the power of transmission substations is calculated. In accordance with this obtained powers and the other hand, the standard capacities of transformers, number of required transformers is determined. Therefore, total expansion cost of substations can be calculated.

B. Characteristics of Case Study system

Tables 9- 13 shows the configuration of lines, substation information, generation and loads data of the test system as given in Sec. 4.2. The construction costs of 230 and 400 kV lines are listed in Table 14.

Table 9. Arrangement of lines

Corridor	Length of Corridor (km)	Voltage Level (kV)	Number of Circuits
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

Table 10. Characteristics of 230 kV lines

Number of Line Bundles	Maximum Loading (MVA)	Reactance (p.u/Km)	Resistance (p.u/Km)
1	397	3.85e-4	1.22e-4
2	794	2.84e-4	2.44e-4

Table 11. Characteristics of 400 kV lines

Number of Line Bundles	Maximum Loading (MVA)	Reactance (p.u/Km)	Resistance (p.u/Km)
1	750	1.24e-4	3.5e-5
2	1321	9.7e-5	7e-5
3	1982	8.6e-5	1.05e-4

Table 12. 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 13. 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 14. Construction cost of 230 kV and 400 kV lines

Voltage level (kV)	Number of Line Circuits	Fix Cost of Line Construction ($\times 10^3$ dollars)	Variable Cost of Line Construction ($\times 10^3$ dollars)
230	1	546.5	45.9
	2	546.5	63.4
400	1	1748.6	92.9
	2	1748.6	120.2

C. Other required data

Load growth coefficient = 1.08

Inflation coefficient for losses = 1.15

Losses cost in now = 36.1($\$/MWh$)