A Genetic Algorithm for Transmission Network Expansion Planning Considering Line Maintenance

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***Abstract*—This paper proposes a decimal codification genetic algorithm to solve the transmission network expansion planning (TNEP) problem considering the economic impact of line maintenance. The goal is to extend the lifespan of the time-worn lines in order to reduce the investment cost in the expansion of the transmission network and to improve the worth of the transmission system. To assess the economic impact of the maintenance on the deterioration of transmission lines and transformers, the *sum of years* digit method is implemented. The proposed algorithm is evaluated using the IEEE reliability test system, and the assessment of the results shows that by including the effect of line maintenance on the TNEP problem, significant savings can be made in the overall cost of the system.**

Keywords—Decimal codification genetic algorithm, lines' degradation, maintenance, mixed-integer nonlinear programming, transmission network expansion planning.

NOMENCLATURE

(ij)	Line *j* of corridor *i*;
Ω^b	Set of buses;
Ω^{ec}	Set of existing corridors;
Ω^c	Set of existing and candidate corridors;
Ω^{cs}	Set of existing corridors including a substation;
$A_z(k)$	Age of element *z* after maintenance actions until the end of the k^{th} mission;
$B_z(k)$	Age of element *z* at the end of the k^{th} mission (year);
C_T	Total expansion cost of the network ($);
C^L	Cost of the power losses ($/MWh);
C_i^C	Construction cost of a line in corridor *i* ($);
C_i^R	Replacement cost of a line in corridor *i* ($);
C_z^M	Total maintenance cost of element *z* ($);
$\underline{C_z^M}$	Fixed maintenance cost of element *z* ($);
C_i^M	Total maintenance cost of transmission lines in corridor *i* ($);
C_z^r	Repair cost of element *z* ($);
C_i^S	Construction cost of a substation in corridor *i* ($);
D_n	Total demand on bus *n* (MW);
G_n	Total generation on bus *n* (MW);
k^L	Losses coefficient;
$LS_{n,z}$	Load shedding of bus *n* due to the outage of element *z* (MW);
n_i	Number of new circuits in corridor *i*;
n_i^s	Number of new substations in corridor *i*;
$\overline{n}_i$	Maximum number of circuits in corridor *i*;
$\underline{n_i}$	Initial number of circuits in corridor *i*;
n_z^{le}	Life expectancy of element *z* (year);
n_z^u	Usual life of element *z* (year);
n_z^{l0}	Initial operation period of element *z* (year);
P_i	Active power of corridor *i* (MW);
$\overline{P}_i$	Maximum active power of corridor *i* (MW);
P_{nm}	Active power transmitted from bus *n* to *m* (MW);
P^L	Active losses (MW);
T	Planning horizon (year);
r_i	Resistance for one kilometer of corridor *i* (Ω/km);
γ_i	Susceptance for one kilometer of corridor *i* (Ω^{-1}/km);
U_z	Unavailability of element *z*;
k_z	Maintenance cost coefficient of element *z*;
V_i	Voltage level of corridor *i* (kV);
ℓ_i	Length of corridor *i* (km);
$VOLL_n$	Value of lost load (VOLL) for bus *n* ($/MWh);
WTS	Worth of the transmission system ($);
$\Delta\theta_i$	Difference between the phase angles of start and end buses in corridor *i*;
τ_z	Mean time to repair (MTTR) of element *z* (hour);
ϑ_z	Life coefficient of element *z*;
ς_z	Degradation coefficient of element *z*;
δ_z	Salvage value factor of element *z*;
λ_z	Failure rate of element *z* (1/year).

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I. INTRODUCTION

The transmission network expansion planning (TNEP) is a hard, large-scale, and nonlinear programming problem that aims to install new transmission lines in the power system so that the future demand is met [1]. After the year 1970 extensive research has been conducted on the TNEP, which can be categorized as follows: (i) papers that are about the problem's solution method [2], [3]; (ii) papers that have included several characteristics, such as uncertainty [4], network security [5], reliability criteria [6], [7], and bundled lines [8], for solution of the TNEP problem; (iii) works that investigate the integrated transmission and generation expansion planning problem [9].

The aim of this paper is to use a decimal codification genetic algorithm (DCGA) to solve the TNEP problem with a new framework. Thus, only papers that have considered different characteristics in the TNEP are investigated. Table I shows references for the problem classified with different aspects. In [10], the objective function includes investment and operational costs related to the fuel supply requirement of power plants, the investment cost for the construction of transmission lines, and the network's power losses. In [11], the TNEP is formulated as an optimization problem that accounts for three objective functions, including the investment for constructing lines, congestion cost, and the cost of load shedding. In [12], a method based on risk/investment is proposed to solve the TNEP problem taking into account multiple future generation and load scenarios. In [13], the investment cost related to the construction of new lines is minimized considering two probabilistic reliability constraints and the uncertainties related to the forced outage rates of the elements of the network.

TABLE I. CLASSIFICATION OF THE SPECIALIZED LITERATURE

Ref.	Generation	Market	Security	Congestion	Reliability	Uncertainty
[6]	–	–	–	–	✓	–
[7]	–	–	–	✓	✓	–
[10]	✓	–	✓	–	–	–
[11]	–	✓	–	✓	✓	–
[12]	–	–	–	–	–	✓
[13]	–	–	–	–	✓	✓
[14]	–	–	–	–	✓	–
[15]	✓	–	–	✓	✓	–
[16]	✓	–	✓	–	✓	✓
[17]	✓	–	–	–	✓	✓

Later, [14] introduced two probabilistic reliability criteria called loss of load expectation (LOLE) and expected energy not supplied (EENS) for solving the problem of [13]. It was concluded that the LOLE and the EENS provide higher reliability for customers. Also, in [15], the reliability criteria of expected demand not supplied (EDNS) and expected generation not served (EGNS) are accounted for in the objective function of the TNEP problem. It is demonstrated that the capacity of the existing lines should be upgraded besides the traditional approach of constructing new transmission lines in order to achieve more economic and reliable expansion plans. Furthermore, in [16], the investment cost in new transmission lines, the expected operation cost, and the load shedding costs were minimized under load uncertainty and voltage security constraints. Finally, in [17], the Benders decomposition method was used to solve a mixed-integer linear programming (MILP) formulation for the TNEP problem considering generation reliability.

These studies, however, do not consider the economic impact of lines' maintenance on the solution of the TNEP problem. Several transmission system equipment, such as the lines and transformers, have been increasingly getting older. This fact causes the lines to reach the end of their usual lifetime earlier. Maintenance activities can increase the lifetime of the lines so that they satisfy the required level of the system's reliability. Even though an increase in the maintenance budget may cause an increase in the total cost, it can avoid the construction of new lines that can result in a costly expansion of the transmission system. Therefore, it is crucial to include a general age-dependent formulation that explicitly considers the economic influence of maintenance in the TNEP problem.

II. MATHEMATICAL MODEL OF THE PROBLEM

The proposed problem is formulated as shown in (1)–(13).

$$\begin{aligned}\text{Min}\left\{C_T\right\} = \sum_{i\in\Omega^c} C_i^C n_i + \sum_{i\in\Omega^{ec}} C_i^R + \sum_{i\in\Omega^{cs}} C_i^S n_i^s + 8760 k^L C^L P^L \\ + \sum_{i\in\Omega^{ec}} C_i^M + \sum_{n\in\Omega^b} VOLL_n \sum_{i\in\Omega^c} \sum_{j=1}^{n_i+\underline{n}_i} LS_{n,(ij)} U_{(ij)} - WTS\end{aligned} \tag{1}$$

where,

$$P^L = \sum_{i\in\Omega^c} \frac{\ell_i r_i P_i^2}{\left|V_i\right|^2} \tag{2}$$

$$P_i = \ell_i \gamma_i \Delta\theta_i \tag{3}$$

$$C_i^M = \sum_{j=1}^{\underline{n}_i} C_{(ij)}^M \tag{4}$$

$$C_{(ij)}^M = k_{(ij)} \underline{C_{(ij)}^M} \tag{5}$$

$$U_{(ij)} = \frac{\lambda_{(ij)} \tau_{(ij)}}{\lambda_{(ij)} \tau_{(ij)} + 1} \tag{6}$$

$$WTS = \sum_{i\in\Omega^{ec}} \ell_i \sum_{j=1}^{\underline{n}_i} \left[1 - \left(1 - \delta_{(ij)}\right) \varsigma_{(ij)}\right] C_{(ij)}^C \tag{7}$$

$$\varsigma_{(ij)} = \sum_{q=1}^{n_{(ij)}^{l0}+T} \frac{2q}{n_{(ij)}^{le}\left(1 + n_{(ij)}^{le}\right)} \tag{8}$$

subject to:

$$\sum_{n\in\Omega^b} G_n = \sum_{n\in\Omega^b} D_n \tag{9}$$

$$G_n = D_n + \sum_{m\in\Omega^b, m\neq n} P_{nm} - \sum_{i\in\Omega^c} \sum_{j=1}^{n_i+\underline{n}_i} LS_{n,(ij)} \qquad \forall n \in \Omega^b \tag{10}$$

$$\left|P_i\right| \le \overline{P}_i \qquad \forall i \in \Omega^c \tag{11}$$

$$0 \le n_i \le \overline{n_i} - \underline{n_i} \quad \forall i \in \Omega^c \tag{12}$$

$$0 \le LS_{n,(ij)} \le D_n \quad \forall n \in \Omega^b, i \in \Omega^c, j = 1, \ldots, (n_i + \underline{n_i}) \tag{13}$$

The objective function (1) minimizes the total cost of investing in the construction of new transmission lines, the cost of replacing existing lines, the cost of investing in substations, the cost of annual losses, the maintenance cost of transmission lines, and the total load shedding in the system while maximizing the worth of the transmission system.

Constraint (9) specifies that the total generation in the network is equal to the total demand, (10) is the equation of the active power balance, (11) represents the capacity of the power flow for the lines in each corridor, (12) limits the number of lines that can be installed in each corridor, and (13) limits the load shedding at each bus in the system.

A. *Description of the Maintenance Cost Coefficient Effect on the Life Coefficient*

Transmission equipment, such as lines and transformers, have normal lifespans under normal operating conditions if the required maintenance actions are taken. Predefined or variable maintenance costs are required for these acts to be carried out. If the maintenance budget is more or less than that cost, the component age (life expectancy) will be longer or shorter than its usual lifetime [18]. This can be defined analytically using the age factor of element *z* (a_z) as follows [18]:

$$a_z = \frac{A_z(k)}{B_z(k)} = \left(\frac{C_z^M - \underline{C}_z^M}{C_z^r} \right)^{\frac{1}{m_z}} \tag{14}$$

Rewriting (14) for the transmission lines and transformers of the TNEP problem, results in (15).

$$a_{(ij)} = \frac{A_{(ij)}(T)}{B_{(ij)}(T)} = \left(\frac{C_{(ij)}^M - \underline{C}_{(ij)}^M}{C_{(ij)}^r} \right)^{\frac{1}{m_{(ij)}}} \tag{15}$$

Where m_z is a characteristic constant of element *z*. Larger or smaller m_z correspond to the newer or older elements, respectively. The following equations arise from replacing $A_{(ij)}(T) = n_{(ij)}^{le} - n_{(ij)}^{l0} - T$ and $B_{(ij)}(T) = n_{(ij)}^{u} - n_{(ij)}^{l0}$ in (15).

$$\frac{n_{(ij)}^{le} - n_{(ij)}^{l0} - T}{n_{(ij)}^{u} - n_{(ij)}^{l0}} = \left(\frac{C_{(ij)}^M - \underline{C}_{(ij)}^M}{C_{(ij)}^r} \right)^{\frac{1}{m_{(ij)}}} \tag{16}$$

$$\frac{n_{(ij)}^{le}}{n_{(ij)}^{u}} = \left(1 - \frac{n_{(ij)}^{l0}}{n_{(ij)}^{u}} \right) \left(\frac{\underline{C}_{(ij)}^M}{C_{(ij)}^r} \right)^{\frac{1}{m_{(ij)}}} \left(\frac{C_{(ij)}^M}{\underline{C}_{(ij)}^M} - 1 \right)^{\frac{1}{m_{(ij)}}} + \left(\frac{n_{(ij)}^{l0}}{n_{(ij)}^{u}} + \frac{T}{n_{(ij)}^{u}} \right) \tag{17}$$

Equation (18) is obtained by replacing $\vartheta_{(ij)} = n_{(ij)}^{le} / n_{(ij)}^{u}$, $\alpha_{(ij)} = n_{(ij)}^{l0} / n_{(ij)}^{u}$, and $\beta_{(ij)} = \underline{C}_{(ij)}^M / C_{(ij)}^r$ in (17).

$$\vartheta_{(ij)} = \left(1 - \alpha_{(ij)}\right) \left(\beta_{(ij)}\right)^{\frac{1}{m_{(ij)}}} \left(k_{(ij)} - 1\right)^{\frac{1}{m_{(ij)}}} + \left(\alpha_{(ij)} + \frac{T}{n_{(ij)}^{u}} \right) \tag{18}$$

This equation, known as the *life coefficient curve*, indicates the relationship between $\vartheta_{(ij)}$ and $k_{(ij)}$. The curve is illustrated in Fig. 1 for various characteristic constants of $m_{(ij)}$, with $a_{(ij)}=0.6$ ($n^{l0}_{(ij)}=18$ and $n^{u}_{(ij)}=30$), $\beta_{(ij)} = 0.7$, and $T=12$ in comparison with the life coefficient curve for a new transformer.

Fig. 1 indicates that the curve of an 18 years old transmission line for $m_{(ij)}=1.5$ is nearly similar to the one of a new transformer where the slope is reduced by increasing $m_{(ij)}$ (decreasing of initial line age). It shows that if the maintenance efforts increase, the lifetimes of new lines increase less than time-worn lines. However, $a_{(ij)}$ cannot be assumed constant when $m_{(ij)}$ is variable because it depends on the initial lines' age ($n^{l0}_{(ij)}$) too. It should be noted that $m_{(ij)}$ varies in the interval $[1, M_{(ij)}]$ because of $a_{(ij)}$ limitation ($0 \leq a_{(ij)} \leq 1$), where, $M_{(ij)}$ depends on lines' characteristics, such as type, voltage level, etc. So, for new lines: $a_{(ij)}=0$ and $m_{(ij)}= M_{(ij)}$, and for lines which have quite worn: $a_{(ij)}=m_{(ij)}=1$.

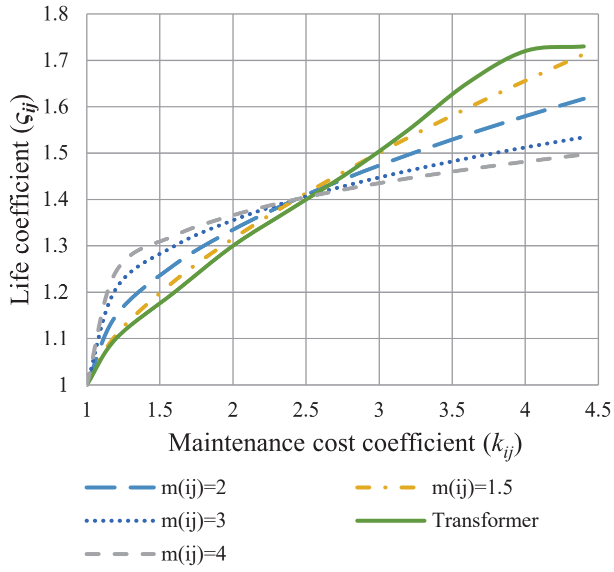

Fig. 1. Life coefficient curves.

Therefore, from Fig. 1, above-mentioned results, and the nonlinear relation between $m_{(ij)}$ and $a_{(ij)}$ (18), the following equation can be defined:

$$m_{(ij)} = M_{(ij)} - \left(M_{(ij)} - 1\right) \alpha_{(ij)}^{\left(\frac{1}{2}\right)} \tag{19}$$

From Fig. 1, it can be seen that the life expectancy of older lines increases more than that of newer ones when maintenance cost increases.

III. SOLUTION METHOD

The purpose of the presented version of the TNEP problem is to determine the number of new lines for network expansion while optimizing the costs of expansion, repair, reliability, and losses. There are several methods to solve this problem, such as classical and heuristic approaches [1]. Thanks to its versatility and simple implementation, the DCGA technique is used in this analysis to solve the TNEP problem. In this method the suggested chromosome codification is as follows:

$$X_i = [N, L] = [n_1, n_2, \ldots, n_{|\Omega^c|}, n_1^s, n_2^s, \ldots, n_{|\Omega^{cs}|}^s, n_1^{le}, \ldots, n_{|\Omega^{cs}|}^{le}] \tag{20}$$

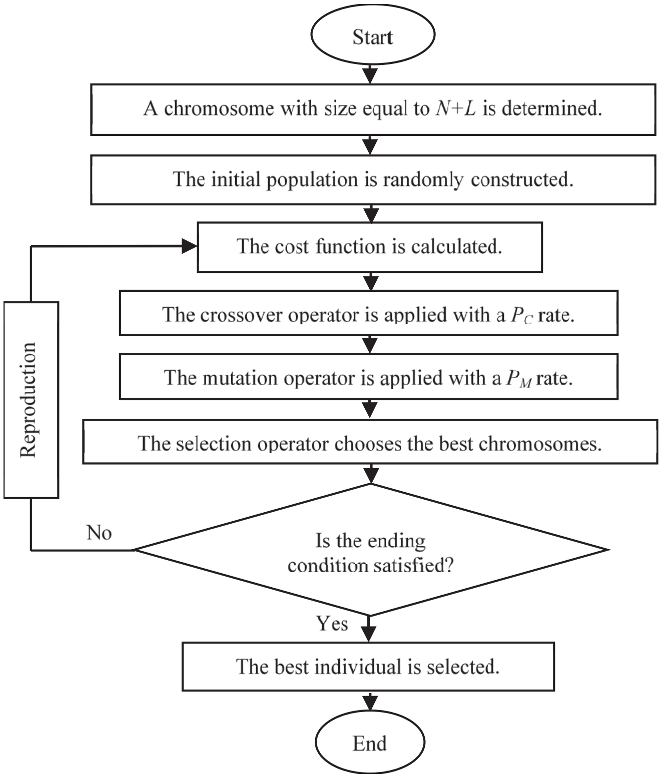

Fig. 2. Flowchart of the proposed method.

$$n_i = \left\{0,1,\dots,\overline{n_i} - \underline{n_i}\right\} \qquad \forall i \in \Omega^c \tag{21}$$

$$n_i^s = \left\{0,1,\dots,\overline{n_i} - \underline{n_i}\right\} \qquad \forall i \in \Omega^{cs} \tag{22}$$

$$n_i^{le} = \left\{n_{(i1)}^{le}, n_{(i2)}^{le},\dots,n_{(i\underline{n_i})}^{le}\right\} \qquad \forall i \in \Omega^{ec} \tag{23}$$

The new lines and substations are represented in vector N (20). This vector's size is equal to the number of candidate corridors. Vector L identifies the life expectancy of the lines on existing corridors. Equation (2) is calculated using a DC power flow, taking into consideration constraints (9) and (10). If (11) is fulfilled, the fifth term of the objective function (1) is solved using MATLAB's *fmincon* function, considering constraints (10) and (11). Next, (4)–(8) are computed, and the objective function (1) is determined accordingly.

The selection operator in the DCGA chooses the chromosomes in the population that are more suitable for reproduction. The reproduction operator reproduces each chromosome in proportion to the value of its cost function (1). Therefore, it is more probable that the chromosomes with better objective functions will be selected for the next population, rather than other chromosomes. After selecting the pairs of parent chromosomes, the crossover operator is applied to each of these pairs. In this method, the crossover can take place at the boundary of two integer numbers (between two variables). An even number of chromosomes is selected at random based on a predefined rate, known as the *crossover probability* (P_C). Random positions (two positions) are chosen for each pair of selected chromosomes, followed by the two chromosomes of each pair swapping their genes (variables). In the final step of forming the new generation, each chromosome resulting from the crossover operation will be subjected to the mutation operator. This operator selects certain existing integer numbers (variables) in the chromosome and then randomly changes their values according to a small probability, defined as the *mutation probability* (P_M).

The creation of the new generation is complete after the mutation operator, and the cycle will start again with the evaluation of objective function (1) for each chromosome. The process continues and is terminated either by setting a target value to be reached for the fitness function or by setting a certain number of generations to be formed. Because of the stochastic nature of the genetic algorithm, in this study, a more suitable termination criterion has been established: the production of a predefined number of generations after obtaining the best fitness and finding no better solution. The flowchart for the proposed method is shown in Fig. 2.

IV. CASE STUDIES AND RESULTS

The proposed DCGA was implemented in MATLAB, and the tests were carried out on a computer with a 3.6 GHz Intel® Core™ i7-7700 processor and 16 GB of RAM. The IEEE reliability test system (IEEE RTS) was used to evaluate the proposed approach. The data for this test system can be found in [19]. It should be mentioned that $\overline{n_i}$ is 2 and n_i^u is 30 years. Also, n_i^{l0} and VOLL of the existing lines are listed in Tables II and III, respectively.

The parameters of the algorithm were: the size of the population equal to five, crossover rate $P_C = 0.9$, mutation rate $P_M = 0.1$, number of generations equal to 10,000.

TABLE II. OPERATION PERIODS OF THE LINES FOR THE IEEE RTS

Corridor	n_i^{l0} (year)	Corridor	n_i^{l0} (year)	Corridor	n_i^{l0} (year)
1-2	10	8-9	14	15-24	18
1-3	18	8-10	18	16-17	18
1-5	18	11-13	14	16-19	18
2-4	18	11-14	18	17-18	14
2-6	18	12-13	18	17-22	18
3-9	14	12-23	18	18-21	18
4-9	18	13-23	18	19-20	18
5-10	18	14-16	18	20-23	18
6-10	10	15-16	18	21-22	18
7-8	18	15-21	14	–	–

TABLE III. VOLL OF BUSES FOR THE IEEE RTS

Bus	$VOLL_n$ (\$/MW)	Bus	$VOLL_n$ (\$/MW)	Bus	$VOLL_n$ (\$/MW)
1	1900	7	2200	15	5550
2	1700	8	3000	16	1750
3	3200	9	3100	18	5850
4	1300	10	3400	19	3250
5	1250	13	4200	20	2250
6	2400	14	3400	–	–

In this section, the proposed approach was tested on the case study system in two scenarios as follows.

A. *Scenario 1*

In this case, the TNEP problem was resolved considering network losses and the reliability of the transmission system. The proposed approach was tested on the case study system mentioned above, in which the proposed plan appears in Fig. 3. Furthermore, the network's expansion and operating costs are listed in Table IV.

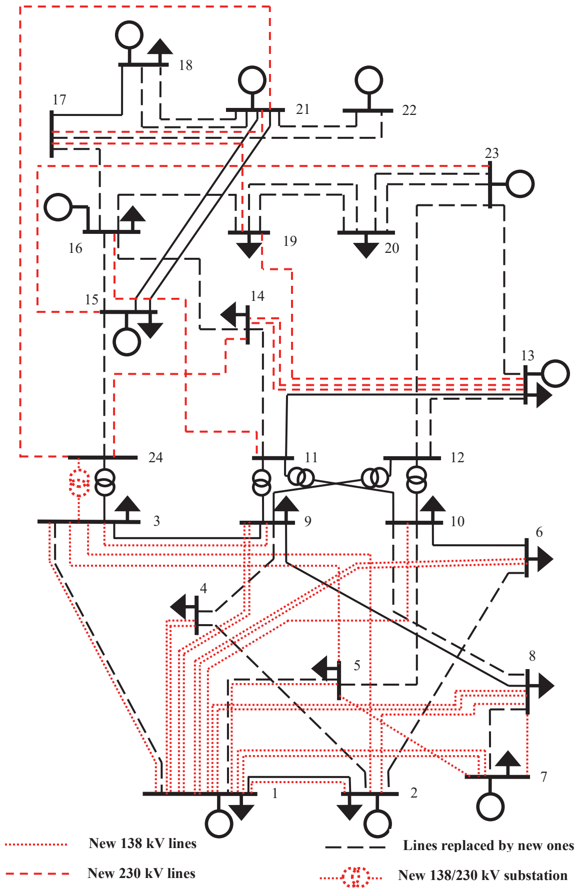

Fig. 3. Proposed expansion plan for the IEEE RTS in Scenario 1.

TABLE IV. COSTS OF THE IEEE RTS IN SCENARIO 1 (MUS$)

Expansion cost of the transmission system (*TC*)	90.16048
Expansion cost of substations	3.5
Active losses cost (*LC*)	13.178
Cost of load shedding (Reliability cost)	1.2293
Total cost of the transmission network (C_T)	108.07

B. *Scenario 2*

In this scenario, consideration is given to the economic effect of the maintenance of lines on the TNEP problem. The results are presented in Fig. 4 and Tables V and VI.

A comparison of Fig. 3 with Fig. 4 shows that proposed configurations are different for both scenarios. In other words, for Scenario 2, two 138 kV and 230 kV lines are installed in corridors 1-10, and 13-19, respectively. Also, the construction of a 230 kV line is not necessary between buses 15 and 23. Hence, the expansion cost of the lines is expected to be higher than in Scenario 1, but it is verified from Tables IV and VI that the expansion cost of the transmission system in Scenario 2 is $31.1 million less than in the other scenario.

TABLE V. NEW LIFETIMES OF THE IEEE RTS

Corridor	n_i^{l0} (year)	Corridor	n_i^{l0} (year)	Corridor	n_i^{l0} (year)
1-2	43	8-9	33	15-24	36
1-3	34	8-10	34	16-17	37
1-5	35	11-13	35	16-19	37
2-4	34	11-14	36	17-18	38
2-6	34	12-13	36	17-22	35
3-9	34	12-23	35	18-21	37
4-9	34	13-23	35	19-20	36
5-10	35	14-16	36	20-23	37
6-10	35	15-16	38	21-22	35
7-8	35	15-21	35	–	–

TABLE VI. COSTS OF THE IEEE RTS IN SCENARIO 2 (MUS$)

Expansion cost of the transmission system (*TC*)	59.058
Expansion cost of substations	3.5
Active losses cost (*LC*)	13.224
Maintenance cost	14.409
Cost of load shedding (Reliability cost)	1.902
Worth of transmission system (*WTS*)	32.813
Total cost of the transmission network (C_T)	59.28

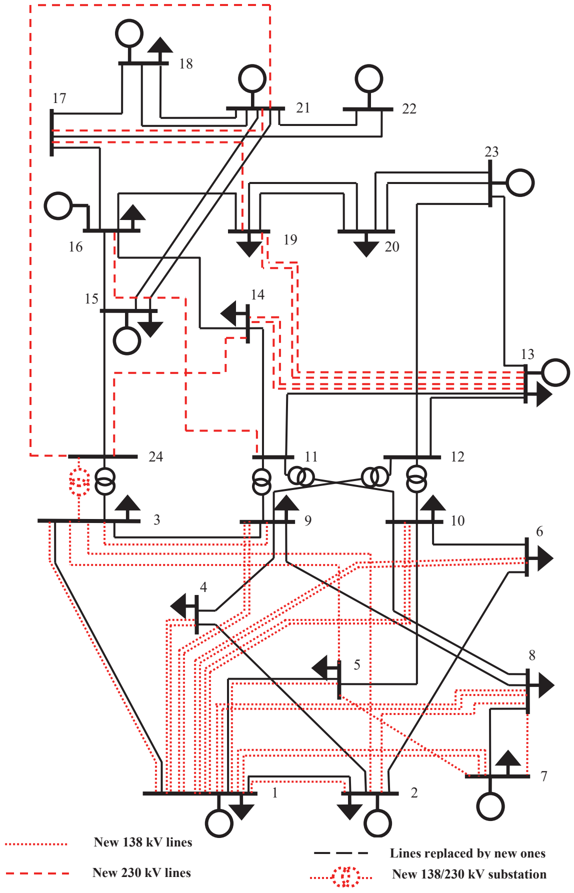

Fig. 4. Proposed expansion plan for the IEEE RTS in Scenario 2.

As seen in Fig. 3, lines of 22 corridors must be replaced by new ones because of their high initial ages (refer to Table V for more details), while the lines' lifetimes of all existing corridors in Scenario 2 are extended. This fact allocated $14.409 million to network maintenance and provides $32.813 million credit (worth) for the transmission system. Despite increasing of 403.8 kW in network losses and 440.46 MW in probable load shedding, and also allocating $14.409 million for lines' maintenance in Scenario 2, the arrangement offered in this scenario is more economic and has $48.79 million investment return for the network in comparison with the one of Scenario 1. Therefore, taking into account the economic effect of lines' maintenance in the TNEP problem leads to a reduction in the total cost.

V. CONCLUSION

This paper proposed a decimal codification genetic algorithm for the TNEP problem, taking into account the mathematical relationship between the cost of maintenance and the lifespan of the lines. Besides, the effect of the lines' lifetimes is modeled through the degradation coefficient which is formulated by the *sum of years* digit method. This coefficient affects the worth of the transmission system and therefore the TNEP problem. Simply put, if the worth of the transmission system increases, the overall transmission network cost will decrease, and vice-versa. An increase in the worth of the transmission system, however, increases the cost of maintenance. On the other hand, the changes in the total cost can affect the network configuration.

The proposed decimal codification genetic algorithm can effectively solve the problem. The evaluation of the simulation results shows that taking into account the effect of line maintenance on the TNEP problem can prevent unnecessary construction of new lines by extending the life of time-worn lines or by prohibiting the nonessential expansion of a worn-out transmission system.

Including the economic effect of the maintenance of lines in the objective function of the TNEP problem also causes the costs of the transmission network to be reduced and higher quality solutions can then be found for the problem. It is concluded that the proposed arrangement with consideration of maintenance effect is more economic and leads to large cost savings for the network.

REFERENCES

[1] R. Hemmati, R. Hooshmand, and A. Khodabakhshian, "Comprehensive review of generation and transmission expansion planning," *IET Gener. Transm. Distrib.*, vol. 7, no. 9, pp. 955–964, Sep. 2013.

[2] E. L. Silva, H. A. Gil, and J. M. Areiza, "Transmission network expansion planning under an improved genetic algorithm," *IEEE Trans. Power Syst.*, vol. 15, no. 3, pp. 1168–1174, Aug. 2000.

[3] N. Gupta, M. Khosravy, N. Patel, and T. Senjyu, "A bi-level evolutionary optimization for coordinated transmission expansion planning," *IEEE Access*, vol. 6, pp. 48455–48477, 2018.

[4] C. Roldán, R. Mínguez, R. García-Bertrand, and J. M. Arroyo, "Robust transmission network expansion planning under correlated uncertainty," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 2071–2082, May 2019.

[5] X. Zhang, K. Tomsovic, and A. Dimitrovski, "Security constrained multistage transmission expansion planning considering a continuously variable series reactor," *IEEE Trans. Power Syst.*, vol. 32, no. 6, pp. 4442–4450, Nov. 2017.

[6] M. Mahdavi, H. Monsef, and R. Romero, "Reliability and economic effects of maintenance on TNEP considering line loading and repair," *IEEE Trans. Power Syst.*, vol. 31, no. 5, pp. 3381–3393, Sep. 2016.

[7] M. Mahdavi, H. Monsef, and R. Romero, "Reliability effects of maintenance on TNEP considering preventive and corrective repairs," *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 3768–3781, Sep. 2017.

[8] M. Esmaili, M. Ghamsari-Yazdel, N. Amjady, and A. J. Conejo, "Short-circuit constrained power system expansion planning considering bundling and voltage levels of lines," *IEEE Trans. Power Syst.*, vol. 35, no. 1, pp. 584–593, Jan. 2020.

[9] B. Alizadeh and S. Jadid, "Reliability constrained coordination of generation and transmission expansion planning in power systems using mixed integer programming," *IET Gener. Transm. Distrib.*, vol. 5, no. 9, pp. 948–960, Sep. 2011.

[10] M. S. Sepasian, H. Seifi, A. A. Foroud, and A. R. Hatami, "A multiyear security constrained hybrid generation-transmission expansion planning algorithm including fuel supply costs," *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1609–1618, Aug. 2009.

[11] A. A. Foroud, A. A. Abdoos, R. Keypour, and M. Amirahmadi, "A multi-objective framework for dynamic transmission expansion planning in competitive electricity market," *Int. J. Electr. Power Energy Syst.*, vol. 32, no. 8, pp. 861–872, Oct. 2010.

[12] M. Rahmani, R. Romero, and M. J. Rider, "Risk/investment-driven transmission expansion planning with multiple scenarios," *IET Gener. Transm. Distrib.*, vol. 7, no. 2, pp. 154–165, Feb. 2013.

[13] J. Choi, T. T. Tran, A. A. El-Keib, R. Thomas, H. S. Oh, and R. Billinton, "A method for transmission system expansion planning considering probabilistic reliability criteria," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1606–1615, Aug. 2005.

[14] J. Choi, T. D. Mount, R. J. Thomas, and R. Billinton, "Probabilistic reliability criterion for planning transmission system expansions," *IET Gener. Transm. Distrib.*, vol. 153, no. 6, pp. 719–727, Nov. 2006.

[15] N. Gupta, R. Shekhar, and P. K. Kalra, "Congestion management based roulette wheel simulation for optimal capacity selection: probabilistic transmission expansion planning," *Int. J. Electr. Power Energy Syst.*, vol. 43, no. 1, pp. 1259–1266, Dec. 2012

[16] T. Akbari, A. Rahimi-Kian, and M. T. Bina, "Security-constrained transmission expansion planning: a stochastic multi-objective approach," *Int. J. Electr. Power Energy Syst.*, vol. 43, no. 1, pp. 444–453, Dec. 2012.

[17] B. Alizadeh and S. Jadid, "A dynamic model for coordination of generation and transmission expansion planning in power systems," *Int. J. Electr. Power Energy Syst.*, vol. 65, pp. 408–418, Feb. 2015.

[18] Y. Liu and H.-Z. Huang, "Optimal selective maintenance strategy for multi-state systems under imperfect maintenance," *IEEE Trans. Reliab.*, vol. 59, no. 2, pp. 356–367, Jun. 2010.

[19] M. Mahdavi, C. Sabillón, M. Ajalli, H. Monsef, and R. Romero, "A real test system for power system planning, operation, and reliability," *J. Control, Autom. Electr. Syst.*, vol. 29, no. 2, pp. 192–208, Apr. 2018.