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MULTI-STAGE TRANSMISSION EXPANSION PLANNING BY SIMULATED ANNEALING ALGORITHM

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Abstract- This study provides a simulated annealing based approach with the aim of solving a multi-stage transmission expansion planning problem in a competitive pool-based electricity market, which is a large-scale non-linear combinatorial problem. We take into account some characteristics in our modeling including a multi-year time horizon, investment and operating costs, a number of scenarios based on the future demand system, the continuous non-linear functions of market-driven generator offers and demand bids. Additionally the optimal expansion plan for maximizing the cumulative social welfare among the multi-year horizon is examined. The suggested simulated annealing-based model is applied to an 8-bus test system and the IEEE 24-bus Reliability Test System.

Keywords: Simulated Annealing, Transmission Expansion Planning, Electricity Market.

I. INTRODUCTION

Today vertical integrated power systems are being slowly reformed to deregulated power systems. Deregulation of the power systems has caused these results: the emergence of new actors (including marketers, brokers, and independent power producers), the decentralization of decision making, and adoption of the social welfare maximization as an alternative to the usual cost minimization for transmission expansion planning (TEP) objective, and increase in the uncertainties. Because of these issues, the transmission expansion planning activity has become more complicated, so that new approaches are required for TEP in the context of deregulated power systems.

Garver is the beginning of the article in 1970 [1], a range of methods have traditionally employed to deal with the TEP problem from the cost minimization viewpoint, including linear planning [1, 2], dynamic planning [3], non-linear planning [4], mixed-integer linear planning [5, 6], Analysis rounded corners [7], genetic algorithm Method [8, 9], simulated annealing planning [10-12], game theory Method [13-15], GRASP [16] and fuzzy logic planning [17]. With the emergence of markets by the pool and bilateral contracts, researchers have considered other perspectives: operating profits [18, 19], LMP variances [20, 21], maximizing community prosperity [22, 23], the flexibility on minimizing risks scheduled [24], multi-objective optimization [25], And a dual approach for minimizing the cost of Investing in network while Ease Power commerce.

The article is structured in the following described. In the beginning section II, the transmission expansion planning Issue is defined. At section III, a SA based approach is provided to solve the above issue. In section IV, as a result of applying the approach proposed onto the IEEE proposed eight-bus power system case study and the IEEE RTS 24-bus system is provided. In the end, the results presented.

II. TEP ISSUE DEFINITION

To define the TEP issue, the time Skyline of the studied is divided N_y years (period); and N_{s_y} Scenarios in each year considered based on predicted load of the year. Actually for every different level of demand scenario is considered independent. Each scenario shows the number of hours in which the demand of the system has reached a certain level (low, medium, high, or very high load). In this article, the network development plan which provide maximum the net social welfare (*NW*) between the years of Studied is investigated. Each plan determines the Time (year) and location of each line must be added on network. Equation (1) gives the net social welfare (*NW*):

$$NW = SW - INV \tag{1}$$

Where, *SW* is the maximum accumulated community prosperity (social welfare) During the Skyline for extend transmission grid and *INV* is the total investment cost for the new line. SW is calculated by Equation (2):

$$SW = \sum_{y=1}^{Ny} \sum_{s_y=1}^{Ns_y} \omega_{s_y} .SW_{s_y} \tag{2}$$

where, ω_{s_y} is the weighting factor of scenario *s* in year *y*th. It would be equivalent to the number of hours in the year *y*th that we have scenario *s*th and SW_{s_y} is the maximum social welfare at scenario *s* in year *y* that is found from Running the program power flow which is the operating model of the competitive pool-based electricity market.

$$\underset{P_G^{s_y}, P_D^{s_y}, \delta}{\text{maximize}} \quad SW_{s_y} = \sum_{j=1}^{Nd} f_{dj}^{s_y}(P_{dj}^{s_y}) - \sum_{i=1}^{Ng} f_{gi}^{s_y}(P_{gi}^{s_y}) \tag{3}$$

subject to:

$$B^{s_y}.\delta = P_G^{s_y} - P_D^{s_y} \tag{4}$$

$$P_{G\min}^{s_y} \le P_G^{s_y} \le P_{G\max}^{s_y} \tag{5}$$

$$P_{D\min}^{s_y} \le P_D^{s_y} \le P_{D\max}^{s_y} \tag{6}$$

$$-P_{l\max}^{s_y} \le H^{s_y}.\delta \le P_{l\max}^{s_y} \tag{7}$$

In all above-mentioned variables and parameters, Index s_y represents scenario *s* in year *y*.

Limitation (4) demonstrator the DC power flow equations. Imparity (5), (6) and (7) indicate of the limits of generators, consumers and the flow capacity of the transmission lines.

The total cost of investment in the new grid during the total time horizon of the planning (*INV*) at base year y_0 is derived by Equation (8).

$$INV = \sum_{y=1}^{Ny} \frac{I_y}{(1+\tau)^{y-y_0}} \tag{8}$$

where, I_y is the investment cost in the new circuits during year y with discount rate τ.

The proposed function for resources and consumers can be linear or non-linear. In this paper, the function of each generator (for example generator *i*) is proposed according to the Equation (9):

$$f_{gi}^{s_y}(P_{gi}^{s_y}) = a + bP_{gi}^{s_y} + c\left(P_{gi}^{s_y}\right)^2 \tag{9}$$

where, *a*, *b* and *c* are constant coefficients. Additionally, the consumer model in this paper is the above equation expressed [24, 25].

III. SA BASED APPROACH TO SOLVE TEP PROBLEM

Target of solution of TEP problem that in the previous section is formulated is finding the best plan transmission network development so that the maximum net social welfare is provided (*NW*). Each plan determines the Time (year) and location of each line needs to be added on grid. In this paper, it has been assumed that one transmission line can be constructed from one or more parallel circuit and there are some existing or new transmission lines so that one or more circuit can be added or subtracted on each path.

The main issue in this problem is the enormous number of expansion plans in a path that to investigate all of them appears impossible. On the other side, Problem search space (expansion plans) is discrete and Target function is non-linear. Thus to solve this Problem used of simulated algorithm to create different structures grid.

This algorithm consists of iterative steps of solution evaluation mostly providing good solutions in a way that they improve a performance index (evaluation function value). The algorithm is begun by evaluating an arbitrary primary solution. Then during each of the next steps a new solution in neighborhood of the solution of the previous step is randomly generated and the performance index is calculated for the new solution.

If the new solution improves the performance index, it will be accepted. However, if the new solution is worse and does not improve the index it can still be acceptable but, depending on a small acceptance probability. So it is avoided to be trapped in a local optimal solution, and a wider search on the solution space is done until a more promising area is located. The acceptance probability of weaker solutions is progressively reduced. The immediate cause is that the search is more chaotic at the beginning but it will be significantly more concentrated in promising area as the algorithm proceeds.

Despite the disadvantage of taking long computational time, it has powerful advantages, such as independence from the initial solution, simple modeling, and certain convergence to the optimal solution, and reasonable computational memory needs. See the detail of steps of the SA algorithm in [25].

To implement the SA algorithm, first of all the solutions (expansion plans) need to be coded. Here we code an expansion plan by a vector. Each member of the vector is a number between zero and N_y (the total time horizon of the study) Related to one of the circuits that can be added on the basic transmission grid. If a member is equal to zero it shows that this path of transmission grid does not include development plan while a greater than zero number for an element indicates the year when the corresponding circuit should be added to the network. It should be noted that if we want to be able to add two circuits to a single line, two elements must be assigned for the line.

We consider the negative of the net social welfare (*NW*) obtained from the transmission expansion among the entire years of the planning period as the performance index of each response (expansion plan) which is minimized by the algorithm. Consequently, the net social welfare is maximized.

At each step of the SA algorithm, a new response in neighborhood of the previous step response must be generated. The method used to generate the new response is the most effective factor to achieve the response with a high degree of optimality and a high speed. In this study many different methods were tested until a high-effective method was found. According to the obtained method in order to generate the response one or more elements of the response vector in previous iteration are changed.

In the first iteration of the algorithm the number of the changed elements are up to ten percent of the total numbers of elements (response vector dimension) but, in the next iterations the numbers of the changed elements are gradually reduced until after passing a number of primary iterations the number is limited to a single element per iteration (i.e. one circuit). Each change can be one of the following four types with a specified probability:

- Adding a circuit: One of the "zero" elements of the previous response vector is chosen randomly and its value is increased to a number greater than zero representing the year when the corresponding circuit should be added to the network.
- Removing a circuit: One of the "non-zero" elements of the previous response vector is randomly chosen and its value is reduced to zero.

- Swapping a circuit with another: One of the existing circuits of the previous response is randomly selected and removed and then a new circuit is randomly added to it.
- Changing the year of an existing circuit: one of the "non-zero" elements of the previous response vector is randomly chosen whose value is randomly increased or decreased by one year.

In a number of the primary iterations (about 75 percent of the total required iterations), the probability of the above four change types are equally set to 0.25 while in the next iterations the probability of changing the year of an existing circuit compared to the other three types of changes is increased. In the "case studies" section it is shown that the above proposed method can quickly (in a small number of iterations) lead the response to a plan with a high degree of optimality.

IV. CASE STUDIES

The proposed methodology has been successfully applied to two case studies. The first case study analyses an 8-bus system [24, 25] and the second one analyses the IEEE RTS 24-bus system [23]. The market structure of the considered systems consists of a number of generating units and a number of loads; both generating units and loads submit offers/bids to the market trying to attain their respective maximum profits. All lines are built by a central entity, the network planner.

The characteristics of the 8-bus and 24-bus systems are given in appendices 1 and 2, respectively. A 10% discount rate is considered to estimate the investment cost in new lines in the upcoming years. The supply offer function of each generator and the demand bid function of any of the consumers are considered as Equation (9) where their constants *a, b* and *c* are given in the tables in the Appendices. The maximum power limits of generators and consumers given in the appendices are at the base year while for the next years five percent growth is assumed. To describe the behavior of the future demand forecasted, four scenarios consisting of low, medium, high, and very high load level are considered per year. The weighting factors of all scenarios in all years are considered equal to $\omega_{s_y} = 0.25\times 365\times 24$. The maximum demand value of every consumer in all years in the low, medium, high, and very high load level scenarios are 55%, 70%, 85% and 100%, respectively. These numbers are calculated based on the yearly maximum demand value of the consumer.

V. SIMULATION RESULTS

A. 8-Bus Sample Test for System Study

The single-line diagram of the original grid has been shown in Figure 1. It contains eight buses and eleven single-circuit lines connecting them.

In this system the considered total time horizon of the study (N_y) is 2 years and we assume that we can add up to one new circuit (similar to its existing one) to any of the existing lines.

Since there are three alternatives relating to add a new circuit to each line (to add it in the first year or second year or not add it at all) and since there are 11 lines, there will be $3^{11} = 177147$ expansion plans. It is noted that for this small system with only two-year time horizon there is a very large number of expansion plans which causes too much time needed to evaluated the whole set.

To study this system, first we obtained the optimal expansion plan (the expansion plan which maximizes the net social welfare gained among the entire years of the planning horizon) by examining all possible expansion plans. The plan is to add a circuit to line 2 in the first year. Then we searched the optimal expansion plan by using the proposed SA based approach.

To do so, we began the algorithm with the original network and then we adjusted the initial temperature in a way that the acceptance probability of the response in the first iteration becomes equal to 0.8. After this iteration, we reduced the temperature of the algorithm to 97% of the previous temperature per iteration. We set the probabilities of all the four change types to 0.25. Optimal expansion plans in different iterations of implementing the SA algorithm are given in Table 1. It is observed that with implementing the proposed SA based approach we have achieved the optimal plan obtained by enumeration method in very few iterations (at the sixth iteration).

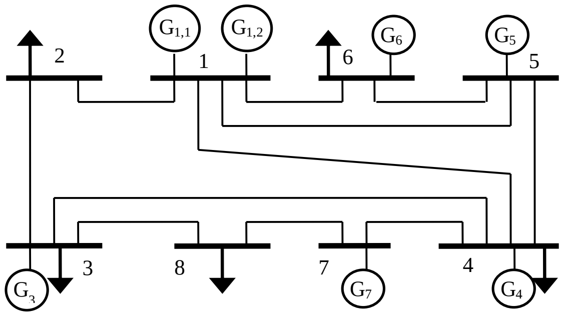


Figure 1. The diagram of the 8-bus system [25]

Table 1. Optimal expansion plans in different iterations of implementing the SA for 8-bus system

Iteration(s)	Optimum plan	*NW* of the optimum plan ($)
1-4	Original network	1887482366
5	Adding one circuit on line 2 in year 2	1889601375
≥6	Adding one circuit on line 2 in year 1	1898904938

B. 24-Bus Sample Test for System Study

The single-line diagram of the original of the system has been shown in Figure 2. It contains 24 buses and 30 single-circuit and 4 double-circuit lines connecting them.

In this system the considered total time horizon of the study (N_y) is 20 years and we assume that we can add up to one new circuit (similar to its existing one) to any of the existing lines. Since there are 21 options relating to add a new circuit to each line (to add it in any of the 20 years or not add it at all) and because there are 34 lines, there will be 21^{34} expansion plans.

To do so we began the algorithm with the original network and then we adjusted the initial temperature in a way that the acceptance probability of the response in the first iteration becomes equal to 0.8. After this iteration, we reduced the temperature of the algorithm to 97% of the previous temperature per iteration. We set the probabilities of all the four change types to 0.25 in first 150 iterations and then in the next iterations we set the probability of changing the year of an existing circuit to 0.7 and the probability of the other three change types to 0.1.

Optimal expansion plans achieved in different iterations of implementing the SA algorithm are given in Table 2. Figure 3 shows the net social welfare (*NW*) for analyzed expansion plans at different iterations of the implementation of our proposed SA based approach. In Table 2, it is observed that the net social welfare of optimal response have been improved during 188 primary iterations and after that it remains fixed which means performing further iterations have not altered the optimal response. So the final expansion plan is that there should be one circuit to be added at line 11 in 9th year.

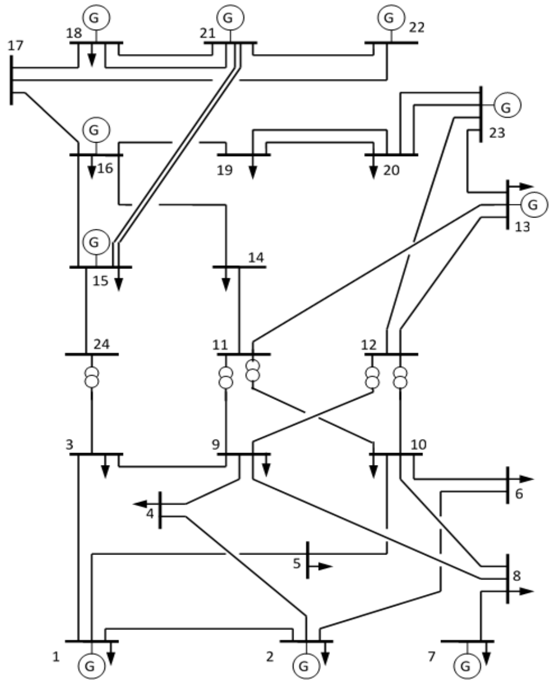
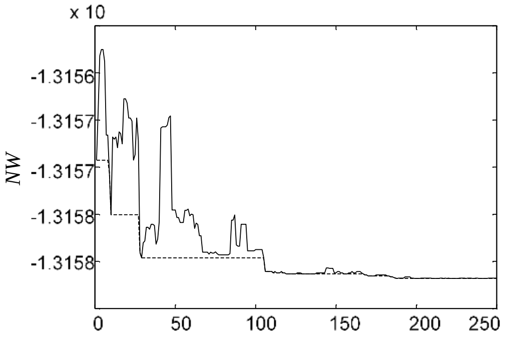


Figure 2. The diagram of the 24-bus Test system (IEEE-RTS) [23]

Table 2. Optimal expansion plans in different iterations of implementing the SA for 24-bus system

Iteration(s)	Optimum plan: circuits to add on (Line number, year)	*NW* of the optimum plan ($)
1-8	Original network	13156925838
9	(11,17), (17,13), (24,1)	13157055586
10-27	(10,1), (11,17)	13157503970
28	(11,1), (15,13), (29,13)	13157904783
29-105	(11,1), (15,13)	13157962716
106-127	(11,1)	13158107548
128-167	(11,3)	13158132792
168-169	(11,4)	13158143720
170-183	(11,5)	13158153655
184-185	(11,6)	13158162687
186	(11,7)	13158170897
187	(11,8)	13158177659
≥188	(11,9)	13158180630



- *NW* of the analyzed plan in each iteration
-- *NW* of the optimum plan in each iteration

Figure 3. The *NW* of studied plans by SA for the 24-bus system

VI. CONCLUSIONS

Multi-stage of transmission expansion scheduling problem in a power market based on The monetary competition which Includes a of perennial long-term planning, Several scenarios based on future demand system, investment and operating costs, the continuous non-linear functions of market-driven generator offers and demand bids is a large-scale non-linear combinatorial problem. The fundamental problem is an extreme increase in the number of alternatives that have to be analyzed even for moderately sized systems. In this study a simulated annealing based approach was proposed to solve the problem. Employing the proposed method in an 8-bus test system and the IEEE 24-bus Reliability Test System showed we could achieve the optimal expansion plan with a high degree of optimality and a high speed.

APPENDICES

Appendix 1. Specifications of 8-Bus Power System Case Studied

Clarify the specifications of the generators, loads and transmission lines of the 8-Bus Power System Case Studied Provide in Tables 3, 4 and 5. Figure 1 illustrates single line diagram of power system studies. Information has been per united on base 1000 MW.

Table 3. Information about the generators in the 8-bus test system [25]

Bus	Max. MW Gen.	*a* ($)	*b* ($/MW)	*c* ($/MW^2)
1	110	135.828	8.4	0.02308802
1	100	132.300	9.0	0.02721088
3	520	1146.600	15.0	0.00872144
4	250	661.500	18.0	0.02176871
5	600	529.200	6.0	0.00302343
6	400	705.600	12.0	0.00907029
7	200	352.800	12.0	0.01814059

Table 4. Information about the loads in the 8-bus test system [25]

Bus	Max. MW Demand	*a* ($)	*b* ($/MW)	*c* ($/MW^2)
2	300	893.02500	30	-0.00907029
3	300	952.56000	32	-0.00967498
4	300	1041.86250	35	-0.01058201
6	250	694.57500	28	-0.01015873
8	250	868.21875	35	-0.01269841

Table 5. Information about the lines in the 8-bus test system [25]

Line Num.	From bus	To Bus	Reactance (pu)	Limit (MW)	Investment Cost ($M)
1	1	2	0.030	280	28
2	1	4	0.030	140	14
3	1	5	0.0065	380	38
4	2	3	0.010	120	12
5	3	4	0.030	230	23
6	4	5	0.030	200	20
7	5	6	0.020	300	30
8	6	1	0.025	250	25
9	7	4	0.015	250	25
10	7	8	0.022	340	34
11	8	3	0.018	240	24

Appendix 2. Specifications of 24-Bus Power System Case Studied

Clarify the specifications of the generators, loads and transmission lines of the 24-bus Power System Case Studied Provide in Tables 6 and 7. The trans $P_D^{s_y}$ mission lines' specifications of the system are the specifications of lines 1 to 34 given in [25]. Figure 2 illustrates single line diagram of power system studies. Information has been per united on base 1000 MW.

Table 6. Information about the generators in the 24-bus test system [23]

Bus	Max. MW Gen.	*a* ($)	*b* ($/MW)	*c* ($/MW^2)
1	344	949.24379	15.6	0.01139433
2	344	839.71566	13.8	0.01007960
7	600	1655.65777	15.6	0.00653275
13	1100	3035.37257	15.6	0.00356332
15	420	1248.11124	16.8	0.01005039
16	290	800.23459	15.6	0.01351604
18	800	1952.82711	13.8	0.00433423
21	700	1857.30839	15.0	0.00538414
22	500	1379.71481	15.6	0.00783930
23	1320	3642.44709	15.6	0.00296943

Table 7. Information about the loads' in the 24-bus test system [23]

Bus	Max. MW Demand	*a* ($)	*b* ($/MW)	*c* ($/MW^2)
1	216	1005.81209	39	-0.01360990
2	194	1019.18471	44	-0.01709602
3	360	1117.56899	26	-0.00544396
4	148	689.16755	39	-0.01986309
5	142	746.00118	44	-0.02335653
6	272	1266.57819	39	-0.01080786
7	250	1313.38236	44	-0.01326651
8	342	1061.69054	26	-0.00573048
9	350	1629.78812	39	-0.00839925
10	390	2048.87649	44	-0.00850417
13	530	2467.96486	39	-0.00554668
14	388	2038.36943	44	-0.00854801
15	634	1968.16317	26	-0.00309121
16	200	931.30749	39	-0.01469869
18	666	3498.85062	44	-0.00497992
19	362	1685.66657	39	-0.00812082
20	256	1344.90354	44	-0.01295558

NOMENCLATURES

$f_{gi}^{s_y}$: The supply offer function of generator *i*

$f_{dj}^{s_y}$: The demand bid function of consumer *j*

$P_{gi}^{s_y}$: Active power of generator *i*

$P_G^{s_y}$: Vector of active power of generators

$P_{dj}^{s_y}$: Active demand of consumer *j*

$P_D^{s_y}$: Vector of active demand of consumers;

$P_{G\min}^{s_y}$, $P_{G\max}^{s_y}$: Vectors of minimum and maximum power limits of generators

$P_{D\min}^{s_y}$, $P_{D\max}^{s_y}$: Vectors of minimum and maximum power limits of consumers

$P_{l\max}^{s_y}$: Vector of maximum line flow limits

B^{s_y} : Linearized Jacobian matrix for DC load flow

H^{s_y} : Matrix of linearized line flows

δ : Vector of voltage angles

N_g : Number of generators

N_d : Number of consumers

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BIOGRAPHIES

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