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**MARKET BASED TRANSMISSION PLANNING UNDER UNCERTAINTY TO
MINIMIZE TOTAL INVESTMENT COST AND LOSSES REDUCTION**

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ABSTRACT

Congestion and load shedding may reduce the competition level of the electricity market and therefore market participants may incur large losses. In this paper, the total expectation of the losses is considered as a part of transmission expansion cost; and an efficient method is utilized to calculate the expectation with enough accuracy. The method is illustrated over the IEEE-RTS power system.

Keywords: Transmission expansion planning, Restructured power systems, congestion.

INTRODUCTION

In restructured power systems, power producers and consumers compete for trading electric power via power electricity markets. Whereas the function of the transmission network is transmitting sold powers from producers (generators) to buyers (consumers), any insufficiency in transmission network capacity can cause congestion. Congestion may cause inability to accomplish the market competitive transactions and so the competition level in the market is reduced. Reduction of the

competition level incurs costs for producers and consumers.

Occurrence of faults in a transmission network are unavoidable. A fault in a transmission line may cause the line to be disconnected. If the adequacy level of a transmission network is not enough, a line disconnection may cause congestion in the other lines of the network or even may cause to be shed load. In any case, congestion or load shedding may result some producers and consumers get losses.

Expansion of transmission network to provide full competitive environment may require large investment cost. On the other hand, inadequate investment for transmission expansion may considerably decrease competition level among the market participants whereupon some of the participants (power producers and consumers) suffered large losses. In this paper, firstly the losses of the producers and consumers are defined and computed. Secondly it is assumed that transmission owner (planner) compensates all the losses. Thirdly transmission expansion is planned so that the total investment cost of the expansion plan and the losses of the power producers and consumers (hereinafter referred to as the customers) are minimized. In restructured power systems, transmission expansion planning (TEP) faces with many uncertainties in future data [1, 2 and 3]. The most important of these uncertainties are loads and bids of the market customers. Because these uncertainties are random, it is necessary to use probabilistic methods. In this paper, uncertainties in load demanded and bids of the producers and consumers are assumed random with certain probability density functions. Uncertainties make different probable conditions for the future conditions of the system; hence the expected values of the producers and consumers losses are computed. Also in this paper, a

method to calculate the expected values are presented that reduces needed computations with respect to Monte-Carlo simulation method.

In recent years, many researches have been performed on TEP in the restructured power systems. In these researches many approaches have been used to solve TEP problem. These approaches are market based approaches, meta-heuristic optimization approaches, mathematical optimization approaches and game theory approach. An overview of TEP in restructured power systems can be found in [1, 3, 4 and 5].

Market based approaches is a widely used method for TEP. Market based planning concept is the integration of financial and engineering analysis that considers the economics as well as the physical laws of generation, load and transmission. For example, four market based transmission planning approaches were proposed by Buygi et al. in [6, 7, 8 and 9].

Meta-heuristic optimization approaches such as GA [10], chance constrained programming (CCP) [11], expert system (ES) [12], fuzzy-set theory [13], Pareto-based solution technique [14], Simulated Annealing [15] and LP-Based Particle Swarm Optimization [16] have been proposed to solve TEP problems.

Mathematical optimization approaches, such as Benders decomposition [17] and “branch

and bound” algorithm [18 and 19] are continuously used for TEP in deregulated environment.

In deregulated market, game theory [20] was also applied as TEP approach. Contreras and Wu [21 and 22] and Yen et al. [23] have presented a cooperative game theory approach to solve TEP problem in a deregulated environment.

Another algorithm was proposed in [24]. Fang and Hill [24] explored a new strategy to respond to changes in power flow patterns. De la Torre et al. [2] have also developed a TEP approach which is able to quantify and hedge risk.

In continuation, in section 2 the definitions needed for the proposed method are presented. Then in section 3, the method of calculating total losses is stated. In section 4, the method of calculating the mathematical expectation of the loss is introduced. In section 5, the method of forming the random structures of the transmission expansion is stated. In section 6, an overview of simulated annealing is presented. In section 7, the proposed method to solve TEP problem by simulated annealing is presented. In section 8, the results of applying the proposed method over a sample power system is studied. Finally, conclusions of the paper are expressed.

I- Definitions

1- Random uncertainties

In this paper, we assume that maximum load demanded, bid of generators, bid of loads and lines availability are uncertain. Because their statistics can be derived from the past observations and they have a known probability distribution, they have been considered as random uncertainties [1]. In this paper, the probability density functions of the maximum load demanded, bid of generators, and bid of loads are assumed normal. In addition, we assume that the probability values of lines availability are known. The probability is obtained using the rate of the fault occurrence and the repair rate of the line.

2- Ideal transmission network

The Ideal state of a transmission network is an assumptive transmission network that does not have any limitation on the corresponding electricity market and does not been affected by any fault. We can assume that the ideal network has only one bus that all generators and consumers have been connected to it. Therefore the ideal transmission network has full competitiveness and adequacy.

3- Real transmission network

The Real transmission network is a network that its lines capacities have been limited. Therefore, the lines of the real transmission network may congest and the LMPs at all buses of the network may not be the same. In addition, the faults may be happened on

the lines of the real network and consequently it may be caused congestion or load shedding.

4- System condition

For each random uncertainty, we define a random variable with known probability density function. Each random variable may have different values, for example, each maximum load demand may have different values, each generator may have different bids, or each consumer may have different bids. If we generate a combination of values that each value of them corresponds to a random variable, we can obtain many different combinations. Because the values of all random variables (the maximum demand, the generator and consumer bids, and available lines) are known in each combination, each combination represents a special condition of the power system, so we define it as a "condition".

5- Set of sample conditions

The set of sample conditions is a set that each element of it is a system condition. Each element of this set is obtained by randomly sampling from all random uncertainties. So to create each condition, we sample from each random uncertainty according to its probability density function. The number of elements of the set relates to the number of created samples.

6- Market customers losses costs

In the ideal transmission network, power transactions are competitively accomplished under market roles. But in the real transmission network, due to congestion (under normal operation) and load shedding (under fault occurrence), market transactions may be uncompetitive. So produced and consumed powers under the two cases, real and ideal networks, may be different. Thus some customers of the market may suffer losses. In this paper with comparing produced and consumed powers in ideal and real transmission networks, the losses of market customers are defined. Because the transmission congestion and/or load shedding is due to the capacity shortage of the transmission lines and transmission network inadequacy, we assume the transmission owner will pay the losses of the market customers to them. Thus, the losses are taken account in transmission network costs. We define the sum of the customer losses, which are due to shortage of transmission network, as the costs of market customers. In the next sections, we express the calculation method of the losses.

7- Customer losses

For a certain condition of a power system, a consumer may be suffered two types of losses:

- Price of electric power for a consumer in the real transmission network case may be greater than the price in the ideal

transmission network case, so the consumer is suffered losses due to increasing the price. The loss is defined as:

$$PIL_i = P_{Di}^{Re} (LMP_i^{Re} - LMP_i^{Id}) \quad (1)$$

Where PIL_i is the loss of the consumer i due to the price rise; P_{Di}^{Re} is supplied active load for the consumer connected to bus i under real transmission network; LMP_i^{Id} is locational marginal price in bus i under ideal transmission network; LMP_i^{Re} is Locational marginal price in bus i under real transmission network.

So the consumer loss due to the price rise is defined as the product of multiplying supplied active load power for the consumer by the locational marginal price rise in corresponding bus to the consumer.

- The supplied active power under the real transmission network may be smaller than the same power in the ideal transmission network case. Thus the consumer suffers the loss which is due to its not supplied energy (due to reduction of buying energy). This loss is defined as:

$$NBL_i = \alpha_i \cdot LMP_i^{Id} \cdot (P_{Di}^{Id} - P_{Di}^{Re}) \quad (2)$$

Where NBL_i is the loss of the consumer i due to its not supplied load; P_{Di}^{Id} is supplied active load for the consumer connected to bus i under ideal transmission network; α is percent of profit that is obtained by the consumer i from buying energy. The other parameters were defined previously.

In fact, the consumer loss due to its not supplied load (NBL) is defined as a percent of cost of the consumer which is reduced due to reduction of supplied load. This percent is the percent of the profit that the consumer will gain if the transmission network is ideal.

Now total loss of a consumer is defined as the sum of the consumer loss due to the price rise and the consumer loss due to its not supplied load.

$$CL_i = PIL_i + NBL_i \quad (3)$$

Where CL_i is the total loss of the consumer i and PIL_i and NBL_i was previously defined.

8- Producer losses

For a certain condition of a power system, a power producer in the real transmission network case respect to the ideal network case may be suffered two types of losses:

- In the real network case respect to the ideal network case, smaller amount of power may be bought from the producer, so the producer suffer the loss due to its not sold energy (due to reduction of its sold energy).

This loss is defined as:

$$NSL_j = \beta \cdot Pr_j^{Id} \cdot (P_{Gj}^{Id} - P_{Gj}^{Re}) \quad (4)$$

Where NSL_j is the loss of the producer j due to its not sold energy; Pr_j^{Id} is price of buying power from the producer i connected to bus j under ideal transmission network; P_{Gj}^{Id} is active power of buying from the

producer connected to bus j under ideal transmission network; P_{Gi}^{Re} is active power of buying from the producer connected to bus j under real transmission network; β is the percent of profit that is obtained by the producer j from selling energy. The other parameters were defined previously.

In fact, the producer loss due to its not sold energy (NSL) is defined as a percent of revenue of the producer which is reduced due to reduction of sold power. This percent is the percent of the profit that the producer will gain, if the transmission network is ideal.

- For example in the nonexclusive auction market (that the same price is paid to all producers), the price paid to a producer under the real transmission network may be greater than the paid price to the producer under the ideal transmission network. In this case, the producer gains some additional profit due to the price increase. The additional profit is defined as:

$$IPP_j = P_{Gj}^{Re} (Pr_j^{Re} - Pr_j^{Id}) \quad (5)$$

Where IPP_j : The profit of the producer j due to the price increase;

Pr_j^{Re} : the paid price to the producer connected to bus j under real transmission network;

The other parameters were previously defined.

Now total loss of a producer is defined as the difference between the loss of the producer due to its not sold energy and the profit of the producer due to price increase.

(6)

Where GL_j is the total loss of the producer j and NSL_j and IPP_j were previously defined. It has to be mentioned that all the parameters defined in the equations (1)-(6) will be valid only if they are positive. If every one of the parameters is negative, its parameter value should be set zero.

9- Total loss of customers

The total loss of the market customers (the producers and the customers) are defined as the sum of the total losses of producers and the total losses of consumers.

$$L = T \cdot \left(\sum_{i=1}^{NL} CL_i + \sum_{j=1}^{NG} GL_j \right) \quad (7)$$

Where L is the total loss expressed in the unit of money per hour, T is the duration that the transmission network will be operated in future, that is expressed per hour, NL is the number of the consumers, NG is the number of the producers. CL_i and GL_j were previously defined.

10- Expected total loss for a set of conditions

In a certain set of sample conditions, the expected total loss is defined as:

$$EL = \frac{\sum_{k=1}^{NC} L_k}{NC} \quad (8)$$

Where EL is the Expected total loss, L_k is the total loss for the condition k and NC is the number of conditions.

II- Total loss calculation method

The total loss for a transmission network plan is calculated using equations (1) to (6) and according to equation (7). According to the equation, active power generations and active loads should be calculated for every system condition under both ideal and real networks. For this propose in continuation, we assume a pool market with nonexclusive auction where the electrical power is sold to all consumers and/or is bought from all producers based on the locational marginal prices (LMPs) of buses. As well as we assume that there are maximum one producer and one consumer for each bus.

Here the condition of system is known; so maximum demanded load in every bus, bid of every producer (generator) and bid of every consumer (load) are known. Now, the pool market is modeled by following optimal power flow (OPF) [9]:

$$\text{Minimize}_{P_G, P_D, \delta} \quad F = C_G^T \cdot P_G - C_D^T \cdot P_D \quad (9)$$

Subject to:

$$B \cdot \delta = P_G - P_D \quad (10)$$

$$P_G^{\min} \leq P_G \leq P_G^{\max} \quad (11)$$

$$P_D^{\min} \leq P_D \leq P_D^{\max} \quad (12)$$

$$-P_l^{\max} \leq H \cdot \delta \leq P_l^{\max} \quad (13)$$

Where P_G is vector of active power of generators; P_D is vector of active power of loads; C_G is vector of bid of generators; C_D is vector of bid of loads; B is Linearized Jacobean matrix; H is matrix of Linearized line flows; δ is vector of voltage angles; P_G^{\min} and P_G^{\max} are vectors of minimum and maximum power generation limits; P_D^{\min} and P_D^{\max} are vectors of minimum and maximum demanded load limits; P_l^{\max} is vector of maximum line flow limits; and losses are ignored.

By solving the above OPF, the generator powers (P_G) and the supplied load of buses (P_D) and LMPs of buses are obtained. The LMPs are the Lagrange multipliers of DC Load Flow constraints expressed in the equation (10).

The above OPF is for the real transmission network case. We can use it for the ideal transmission network, in which, the line flows constraints in equation (13) is eliminated and the DC Load Flow equations (equation 10) is replaced by the below power balance equation:

$$\text{sum}(P_D - P_G) = 0 \quad (14)$$

Where "sum" is a function that calculates the summation of all elements of a vector. In the ideal network case, the LMPs of all buses are the same. The same LMP is the

Lagrange multiplier of the power balance equation.

III-Expected total loss (EL) calculation method

The expected total loss (EL) for a certain plan and a certain set of sample conditions is calculated by equation (8). Each element of the set has been obtained by random sampling. To achieve accurate value of the EL , we should have all possible conditions and their probabilities. But even for a small number of random variables, the number of possible conditions is very large. Since a long time is needed for accurately calculating the expected total loss, the number of samples must be limited as much as possible, i.e. we should estimate the expected total loss by acceptable and limited number of sample conditions. In fact, the EL is a mean value, so we can estimate it by the central limit theorem. To utilize the theorem, we assume that the accurate EL (mean value of the total losses) is μ and accurate variance of power errors is σ^2 . It is assumed that we have a set of conditions containing n elements and we have calculated EL for each condition (elements). We suppose that the expected (mean value) and the variance of total losses for these n samples of the conditions set are \bar{X} and S^2 respectively. In fact μ and σ^2 are mean value and variance of statistical universe, while \bar{X} and S^2 are mean value and variance of sampling

population. According to the central limit theorem with increasing number of samples (n), distribution of random samples (derived from an arbitrary statistical universe) mean value trends to a normal distribution with mean value μ and standard deviation $\frac{\sigma}{\sqrt{n}}$. In other words, \bar{X} oscillates around μ with normal distribution, so we can find a distance around \bar{X} which contains μ with specific probability for example 95%. \bar{X} is an estimation of μ and deviation from its target (μ) is the estimation error. Standard deviation of random variable \bar{X} is called mean value error and denoted as $\sigma_{\bar{X}}$. According to the central limit theorem, we have $\sigma_{\bar{X}} = \frac{\sigma}{\sqrt{n}}$. Also according to the theorem since \bar{X} has normal distribution, it can be demonstrated that μ occurs in the distance $\bar{X} - 1.96\sigma_{\bar{X}} < \mu < \bar{X} + 1.96\sigma_{\bar{X}}$ with probability 95%. The distance is called the 95 percent reliable distance of μ . In other words, $1.96\sigma_{\bar{X}}$ is the error of \bar{X} from μ with probability 95 percent. The 95% reliable distance of μ is shown as $\mu: \bar{X} \pm 1.96\sigma_{\bar{X}}$. Since actual standard deviation of statistical universe (σ) is not known from past, so $\sigma_{\bar{X}} = \frac{\sigma}{\sqrt{n}}$ is not known too. But in statistical theory it has been shown that if the number of sampling is

large (more than 50), the standard deviation of samples (s) will be an estimation of σ with sufficient accuracy [25]. Therefore, we can say the 95% reliable distance of μ is as follows [25]:

$$\mu: \bar{X} \pm 1.96 \frac{S}{\sqrt{n}} \quad (15)$$

Hereon, the expected total loss is estimated so that its 95% reliable distance is less than a specified value (say RD^{\max}). Therefore, firstly, we sample from all random variables many times and attain a system condition for each sampling. We form an ordered conditions set. Now, we select a number of conditions (minimum 50 conditions) from the conditions set and calculate total loss (L) for each of the selected conditions. Then we calculate average of these total losses (\bar{X}) and the 95% reliable distance ($RD = 1.96 \frac{S}{\sqrt{n}}$). If this 95% reliable distance is less than its specified limit ($RD < RD^{\max}$), then the average of total losses is considered as the expected total loss ($EL = \bar{X}$) otherwise we calculate total loss (L) for another next of the sampled conditions. We add this new sample condition to old conditions and then calculate the average total loss (\bar{X}) and the 95% reliable distance (RD) again. We repeat above stages until $RD < RD^{\max}$, in this time the expected total loss has been obtained (i.e. $EL = \bar{X}$).

IV- Random determination of transmission network structure

Whereas in this paper, the cost of low adequacy level of transmission network is taken into account too, so the transmission network structure i.e. transmission line availability is considered as probabilistic. As already was defined, each condition of the system conditions set is a random sample of all random variables. Therefore, one random sample should be also created for transmission network structure. In other words, a random sample from available lines should be known.

For this propose, if we create a two-state (available or unavailable) random sample for every line depending on its failure probability, then we will have the various combinations of the available lines, and accordingly we will have the various structures for the network. In each structure, none or one or more lines may be unavailable. Since the occurrence probability of simultaneous failures in two or more lines is very small, we do not consider these cases; we consider only cases that none or one line is singly faulted. Therefore, if we have N lines in a network, we will have $N+1$ probable structures in the network. In one of these structures, all of the lines are available; this structure with respect to the other structures generally has maximum probability. In the other

structures, only one line is unavailable. Now to create a random sample of the above probable structure, we do the following. According to the reliability theory, to calculate the occurrence probability of a fault in a line, the annual failure rate (λ) and the annual repair time (r) of lines are used. For this purpose, first we obtain unavailability of every line:

$$u_i = \frac{\lambda_i}{\lambda_i + \mu_i} ; \mu_i = \frac{1}{r_i} \quad (16)$$

Where u_i is unavailability of line i ; λ_i is the annual failure rate of line i ; r_i is The annual repair time of line i .

The probability that the only single line i failed ($Prob_i$) is the product of the unavailability of the line i multiplied by the availability of the other lines. Therefore $Prob_i$ is obtained by:

$$Prob_i = u_i \cdot \prod_{\substack{k=1 \\ k \neq i}}^N (1 - u_k) \quad (17)$$

Furthermore, the probability that none of the lines is failed ($Prob_0$) is the product of the availabilities of all lines. Therefore $Prob_0$ is.

$$Prob_0 = \prod_{k=1}^N (1 - u_k) \quad (18)$$

In equations (17) and (18), N is the number of transmission lines; and the term $(1 - u_k)$ is the availability of the line k ; and the other variables were previously defined. Now to generate a random structure

of the transmission network, we allocate a percentage of the distance between zero to one for every feasible structure of the transmission network of the plan. The allocated percentage to each structure is proportional to its probability. Then we generate a random number with uniform distribution in the distance zero to one. This random number stands in one of the allocated distances. So the corresponding structure of the distance is selected as the random structure of this sample.

V-Simulated Annealing - An overview

Simulated annealing is a metaheuristic optimization procedure to solve combinatorial problems. This approach usually provides good solutions in the sense that they improve a performance index, but it is not usually possible to guarantee global optimality. In the simulated annealing procedure, we move away from one solution by sampling another one. The performance index is calculated for the new solution. If the new solution improves the performance index, it will be accepted. If the new solution is worse and does not improve the index; it can still accept, depending on a small acceptance probability. So it is avoided to locate in local optima, and a wider search on the solution space is done until a more promising area is located. The acceptance probability of the worse solution is progressively reduced to avoid oscillation

and to make sure that the search is more chaotic in the beginning and concentrated in a promising area as the algorithm proceeds. The simulated annealing algorithm is summarized below [15]:

1) Select an initial solution x_0 in the solution space X and set the iteration counter ITC at zero.

2) Evaluate x_0 computing the evaluation function $f(x_0)$.

3) Assign x_0 to x^{opt} and $f(x_0)$ to $f(x^{opt})$. The index opt denotes the best solution identified so far.

4) Sample a new solution in the neighborhood of the current solution at iteration ITC, and compute the evaluation function $f(x_{ITC})$.

5) Testing

a) If $f(x) \leq f(x_{ITC})$ then assign x to x_{ITC+1} .

b) If $f(x) \leq f(x^{opt})$, then assign x to x^{opt} and $f(x_0)$ to $f(x^{opt})$.

c) Else, get a random number rp in $[0.0,1.0]$; and compute the probability of accepting worse solutions at iteration ITC by (19):

$$rp(ITC) = \exp\left(\frac{f(x_{ITC}) - f(x)}{KT}\right) \quad (19)$$

Where KT is the control parameter that is called system temperature in

analogy with the original application of annealing.

d) if $rp \leq rp(ITC)$, assign x to x_{ITC+1} .

6) End if a stopping rule is reached; otherwise, let $ITC = ITC + 1$ and go back to step 4).

Along the algorithm, the temperature (KT) is lowered in a slow pace. Usually, the temperature evolves by levels, meaning that each one is used during a fixed number of iterations. After that, the temperature is lowered by a coefficient α , which is inferior but usually close to 1.0.

VI- Solving of the TEP problem by simulated annealing

Here, the TEP problem is defined, in which, we assume that each transmission line of every expansion plan is included a number of similar circuits that every circuit has a known specification. We want to determine the expansion plan, which has minimum total cost. The total cost of each plan is defined as the sum of the investment cost and the expected total loss of the plan:

$$Cost_j = INV_j + EL_j \quad (20)$$

Where $Cost_j$ is total cost of plan j; INV_j is investment cost of plan j; EL_j is expected total loss of plan j.

To calculate the expected total loss of each expansion plan, we sample from all random uncertainties so many iterations. A random system condition is formed for each of iteration of sampling, and then an ordered

condition set is generated. For each of the random condition, the random structure of the transmission network is also determined with the method that has been described in section 5. As we stated before, the total loss is caused by insufficiency in transmission network capacity and low adequacy level of the network, therefore we assume that the transmission network owner is obligated to compensate the losses of the customers. For this reason, in equation (20), the expected total loss is considered as a part of the transmission network costs. Because it needs huge computations and time to search the target plan among a large number of plans, the simulated annealing is utilized as searching algorithm. To implement the simulated annealing, the following remarks are implemented:

a) To solve the problem by the simulated annealing, we must code each solution (expansion plan); hence we denote each solution by X . X is a vector of integers. Each element of the vector X corresponds to a right-of-way (line) of the transmission network, where new circuits can be constructed in or added to. Each element of the vector represents the number of new circuits that can be added to the corresponded line.

b) To generate the initial solution, a number of new circuits are randomly selected for each line, so that the number of

circuits of each line does not become greater than the maximum acceptable number of the circuits of the line.

c) In each stage of the simulated annealing algorithm, a new solution in the neighborhood of the old solution must be generated. To generate the new solution, first an integer number is randomly selected between 1 to $nchange$. $nchange$ is a number which is almost equal to 10 percent of the total number of lines (the total elements of the vector X). Then $nchange$ elements of vector X are randomly selected and the number of circuits of each element is randomly reduced or increased by one circuit if any or not changed.

d) To use the simulated annealing algorithm for solving the TEP problem, an evaluation function should be defined. Therefore, we define the evaluation function as follows:

$$f(X) = Cost(X) \quad (21)$$

Where $f(X)$ is the evaluation function of plan X . The plan X will be better, if the corresponding function value is smaller. $Cost(X)$ is the total cost of the plan X .

e) Whereas in each iteration of this algorithm, for example the iteration i , the optimal plan X_i^{opt} is plan that has minimum total cost until the iteration i ; so definitely none of the plans that have investment cost more than the total cost of the optimal plan

X_i^{opt} can be optimum. Therefore in the fourth stage of the simulated annealing (section 6), for each generated new solution X_i , before computing the expected total loss ($EL(X_i)$), first the investment cost of the generated solution is compared with the evaluation function (total cost) of the optimal plan (X_i^{opt}). If the investment cost of the new expansion plan (X_i) is more than the evaluation function of the optimal plan (X_i^{opt}), the new plan will be discarded and the other new plan will be generated until its investment cost becomes smaller than the evaluation function of the optimal plan (X_i^{opt}). Implementing of this remark causes that in each iteration, the space of solutions is limited to the solutions that their investment cost is smaller than the evaluation function of the optimal plan of the iteration. Therefore, the speed of achieving the final optimal solution becomes very high.

VII- Application of the proposed method to a test power system

The proposed method is applied to the 24-bus test system (IEEE-RTS [24, 26]), which is shown in figure 1. This figure shows only existing transmission lines. Table 1 shows the system lines data. In this table, the lines 1 to 34 have one or two existing circuits, and the lines 35 to 41 are new right-of-ways [24] that can be constructed. The annual failure

rate (λ) and the annual repair time of all lines of the system are also given in **Table 1**.

Table 1: Line data of the studied transmission network (IEEE-RTS)

Line Num	From-To	Cap.	Reactance (p.u.)	Investment Cost (10000\$)	Number of circuits	Failure Per Year	Repair time
1	1-2	175	0.0139	3	1	0.24	16
2	1-3	175	0.2112	55	1	0.51	10
3	1-5	175	0.0845	22	1	0.33	10
4	2-4	175	0.1267	33	1	0.39	10
5	2-6	175	0.1920	50	1	0.48	10
6	3-9	175	0.1190	31	1	0.38	10
7	3-24	400	0.0839	50	1	0.02	768
8	4-9	175	0.1037	27	1	0.36	10
9	5-10	175	0.0883	23	1	0.34	10
10	6-10	175	0.0605	16	1	0.33	35
11	7-8	175	0.0614	16	1	0.30	10
12	8-9	175	0.1651	43	1	0.44	10
13	8-10	175	0.1651	43	1	0.44	10
14	9-11	400	0.0839	50	1	0.02	768
15	9-12	400	0.0839	50	1	0.02	768
16	10-11	400	0.0839	50	1	0.02	768
17	10-12	400	0.0839	50	1	0.02	768
18	11-13	500	0.0476	66	1	0.40	11
19	11-14	500	0.0418	58	1	0.39	11
20	12-13	500	0.0476	66	1	0.40	11
21	12-23	500	0.0966	134	1	0.52	11
22	13-23	500	0.0865	120	1	0.49	11
23	14-16	500	0.0389	54	1	0.38	11
24	15-16	500	0.0173	24	1	0.33	11
25	15-21	500	0.0490	68	2	0.41	11
26	15-24	500	0.0519	72	1	0.41	11
27	16-17	500	0.0259	36	1	0.35	11
28	16-19	500	0.0231	32	1	0.34	11
29	17-18	500	0.0144	20	1	0.32	11
30	17-22	500	0.1053	146	1	0.54	11
31	18-21	500	0.0259	36	2	0.35	11
32	19-20	500	0.0396	55	2	0.38	11
33	20-23	500	0.0216	30	2	0.34	11
34	21-22	500	0.0678	94	1	0.45	11
35	1-8	175	0.1344	35	0	0.40	10
36	2-8	175	0.1267	33	0	0.39	10
37	6-7	175	0.1920	50	0	0.48	10
38	13-14	500	0.0447	62	0	0.30	11
39	14-23	500	0.0620	86	0	0.50	11
40	16-23	500	0.0822	114	0	0.02	768
41	19-23	500	0.0606	84	0	0.52	11

We consider below assumptions for this system:

a) We assume that every line (right-of-ways) can be expanded up to three similar circuits. Therefore, the total combinations (plans) that can be generated from

expanding the lines become more than 1.5 billions (1.5099×10^9). It is seen that for this comparatively small power system, the number of the expansion plans is extremely large so that the analysis of all the plans is impractical. Therefore, application of the Simulated Annealing algorithm is necessary to find the optimal plan.

b) We assume that each bus has at most one producer and one consumer.

c) The maximum load demanded in each bus is assumed as random variable with the normal distribution. The present load of each bus is given in **Table 2**. We assume the future mean load of each bus is equal to its present value multiplied by 1.1. It is also assumed the standard deviation of each load is equal to 10 percent of its mean value.

Table 2: The mean load demanded of the IEEE-RTS system (Mw)

Bus	Load	Bus	Load	Bus	Load
1	108	7	125	15	317
2	97	8	171	16	100
3	180	9	175	18	333
4	74	10	195	19	181
5	71	13	265	20	128
6	136	14	194		

d) Bid of every producer (generator) is assumed as random variable with the normal distribution. The capacity and the future mean bid of the generators are given in **Table 3**. We assume that the standard deviation of each producer (generator) is equal to 10 percent of its mean value.

Table 3: Generator's data of the IEEE-RTS system

Bus	1	2	7	13	15	16	18	21	22	23
Maximum generation capacity	172	172	300	550	210	145	400	350	250	660

Mean bid of generators	15	14	16	17	15	18	20	22	16	24
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e) We assume that the bids of all loads are equal to the maximum bid of generators so that the maximum demanded load at each bus is always supplied so far as possible. In fact, we assume consumers (loads) do not bid any price; in other words, all consumers agree to buy the power with the maximum bid of generators, i.e. we have one sided pool market.

f) To calculate the evaluation function of each solution, 10000 times was sampled from all random variables (maximum load demanded of each bus, bids of generators and the structure of the transmission network); after that the set of conditions which has 10000 elements was formed. Then to compute the expected total loss (EL) in accordance with section 4, we consider $\alpha = 10\%$ for all consumers and $\beta = 10\%$ for all producers; and the 95% reliable distance (RD^{\max}) is assumed 5000\$; and the duration of the future operation (T) is assumed 5 years.

The simulated annealing algorithm was performed; and the optimal plan was obtained after 90 iterations. The optimal plan has only one new circuit in the line 11. The investment cost of the plan is 160000\$, and its expected total loss is 18409\$.

VIII-CONCLUSION

The main results of this paper are as follows:

- It was shown that the congestion in lines or load shedding, caused by insufficient transmission network capacity and scanty adequacy level of the transmission network, might reduce the level of competition in the electricity market. Thus, some of the market participants (producers and consumers) incurred large losses. In this paper the losses of the producers and consumers were defined and it was assumed that the owners of the transmission network obligate to compensate these losses. With this assumption, the losses are considered as a part of the transmission network expansion cost. Then the expansion plan that minimizes the sum of the losses and the investment cost of the transmission expansion was searched. Therefore, in this paper, the real worth of the expansion plan for a restructured power system was considered.

- In this paper, the bids of the producers and consumers were considered uncertain and so they were assumed as random variables. In addition, the occurrences of faults over the transmission lines of an expansion plan were considered as probabilistic, and hence the transmission network structure of each plan was modeled as random.

- Because there were random variables, the expectation of the loss was evaluated.

- By using the central limit theorem, we could calculate the expected total loss with a specified maximum error by a small number of samples.

- Due to extent of the problem solution space, the simulated annealing algorithm was successfully used to determine the optimal plan.

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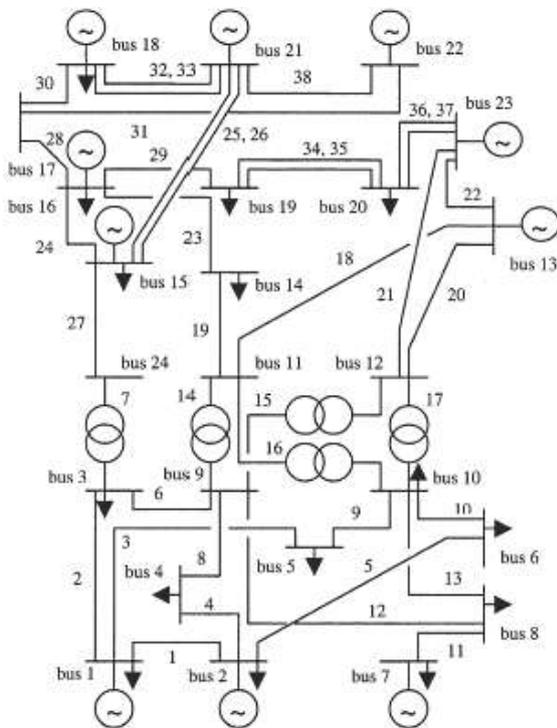


Figure 1: 24-bus Test system (IEEE-RTS)