Transmission and Generation Expansion Planning Considering Loadability Limit Using Game Theory & ANN

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Abstract— **Transmission and generation expansion planning (TEP and GEP) considering loadability limit of power system is studied in this paper. Artificial neural network (ANN) technique is used to evaluate loadability limit of the power system because of its sensitivity characteristic. Power system restructuring and separation of decision-making organizations of transmission and generation expansion, make coordination between generation and transmission companies more crucial. On the other hand, voltage stability is one of the indicators of power system security level. In this paper, first the load pattern of a six-bus power system is improved and then the best bus for load increment is determined using sensitivity characteristic of ANN. Afterwards the strategic interaction between transmission company (TransCo) and generation company (GenCo) for TEP and GEP in a competitive electricity market is proposed using Game Theory (GT). The proposed algorithm comprises three optimization levels to determine Nash equilibrium such that the most profitable strategy for both sides of the game can be found out in an expansion planning game.**

Keywords- Generation expansion planning , Transmission expansion planning , Game Theory, Loadability Limit and ANN.

I. INTRODUCTION

Power systems restructuring and deregulation introduces new challenges to power system planning. In a monopoly power market, decision maker is just one entity who may decide both for Generation Expansion Planning (GEP) and Transmission Expansion Planning (TEP). Due to emergence of competition in power markets, the decision makers for GEP and TEP should be separated such that the transmission company (TransCo) decides for TEP and the generation company (GenCo) decides for GEP. In such an environment, the coordination between these two entities becomes more crucial as each capacity expansion may influence the other one and as a consequence the profit of each company might be affected dependently. In a competitive power market with open access to the transmission system, the generation company is expected to supply the load without any congestion in the transmission lines. Transmission companies are obliged to provide a congestion-free, reliable and non-discriminative path from the generation companies to the consumers of electricity. Therefore, the transmission networks must be regulated so that optimal operation is performed. In a restructured power market, the Genco decides on generation capacities, places and time of construction of new power plants at its own discretion. Under such environment, generation capacity expansion strategies taken by GenCos involve network conditions that may impose uncertainties and challenges to TEP and vice versa. On the other hand, there is no guarantee that transmission network can provide sufficient capacity for the new generation capacity constructed by the GenCo [1-5]. This interaction between Genco and TranCo leads to a new scheme of GEP & TEP that considers both entities' profit. In such an environment, Game Theory (GT) seems to be a useful method to handle a combinatorial strategy for Gencos and TransCos for generation expansion capacity and transmission expansion capacity while evaluates the power market equilibrium [6-10]. TEP and GEP have been studied separately in many researches but the interaction between two in a deregulated environment is studied in a few papers. In order to study the relationship between generation and transmission investment, a three-stage model is presented in [11]. A study in [12] shows that in a deregulated power markets, the degree of competition between different generators is dependent on the capacity of transmission lines. The interaction between transmission and generation expansion planning using Game Theory is done using a basic three-bus system in [13]. To study the strategic interaction between GenCo and TransCo, a single-stage deterministic model is proposed to in [14]. The expansion behaviors of both GenCo and TransCo can be simulated using Cournot model. The equilibrium in the power market in [14] is obtained using a Mixed Complementarity Problem (MCP) approach and the proposed model is applied to a basic three-bus system as well as an IEEE 14-bus system. On the other hand, power system security which is the ability of a power system to withstand disturbances against any violation in system operation conditions should be considered in the new method of capacity expansion, while the aforementioned studies haven't considered power system security. In this paper, first the load pattern in a six-bus power system is improved where the best bus for load increment is determined using sensitivity characteristic of ANN. Then a strategic interaction between GEP and TEP in a competitive electricity

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market environment is proposed using Game Theory. It should be noted that a manageable load is assumed which can be increased or decreased using reward or penalty in a flexible manner. The paper is organized as follows: In section II, the loadability limit as a security index is introduced. The neural network used for the improvement of load pattern is presented in section III. Application of Cournot model of duopoly for TEP and GEP is discussed in section IV. Section V proposes Game Theory for solving TEP and GEP problem. A case study is presented in section VI, while conclusions are presented in section VII.

II. LOADABILITY LIMIT AS A SECURITY INDEX

In order to study the static voltage stability of the power system, loadability limit of system is proposed as voltage stability index for system security evaluation. Loadability limit of a power system is defined as the maximum load, which can be imposed on the system buses without the loss of voltage stability. In order to achieve the most appropriate load pattern to maintain power system security, the sensitivity characteristic of neural network is utilized [15-16]. The input data for training the neural network are obtained from solving the load flow.

III. BACK PROPAGATION NEURAL NETWORK

In this paper, the back propagation neural network is used for sensitivity analysis. Back propagation networks are multi-layer networks with nonlinear transfer functions. Back propagation networks are used for function estimations, finding the relations between input and output and approximation of inputs. Back propagation networks usually have one or more hidden layers of neurons with a sigmoid transfer function and the output layer is mainly linear. Fig. 1 shows the two-layer Tansig/Purelin network architecture which includes a hidden layer and an output layer with back propagation structure. This network can be used to approximate any function with a limited number of discontinuities [17].

A. Sensitivity analysis

In order to evaluate the loadability limit of the power system, sensitivity analysis is performed between the system loadability limit index and load increment pattern coefficients at each bus using the information stored in the weighting factors of the trained neural network layers. In this network, load increment pattern coefficients are considered as the inputs and loadability limit is considered as the output. The algorithm used in the proposed approach for the sensitivity analysis is shown in Fig. 2.

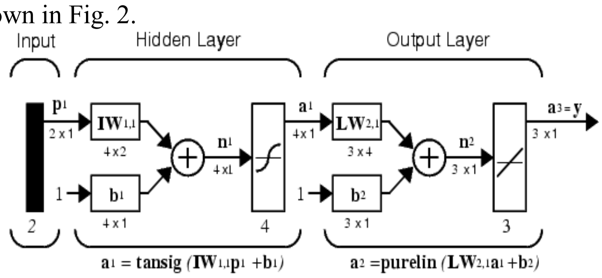

Fig.1. The back propagation network structure

The sensitivity relationship between inputs and outputs of the neural network is expressed in (1) and the evaluation process of the loadability limit of power system by neural network is presented in Fig. 3. In order to analyze the sensitivity of the neural network outputs to the inputs, (1) is used.

$$\frac{dP_{\max}^k}{d\beta}=\frac{dP_{\max}^k}{d\sigma_k}\sum_{h=1}^{NH}W_{2hk}\frac{\partial\Psi_h}{\partial\phi_h}W_{1hj} \qquad (1)$$

Where: $\sigma_k, P_{\max}^k$ are input and output of the K^{th} output neuron; Ψ_h, φ_h are input and output of the h^{th} neuron of hidden layer; W_{2kh} is the information stored in the weighting factor connecting k^{th} output neuron to the h^{th} neuron of hidden layer; W_{1hj} is the information stored in the weighting factor connecting the h^{th} neuron of hidden layer to the j^{th} input neuron and NH is the number of neurons of hidden layer.

B. Calculation of $\frac{dP_{\max}^k}{d\sigma_k}, \frac{\partial\Psi_h}{\partial\phi_h}$

Neural network used to evaluate the loadability limit has a hidden layer and an output layer. The activation function used in the hidden layer is Sigmoid and the derivative of this function is obtained from (2):

$$f'(x)=f(x)\left(1-f(x)\right) \qquad (2)$$

Where: $f(x)=\frac{1}{1+\exp(-x)}$

Therefore:

$$\frac{\partial\Psi_h}{\partial\phi_h}=f(x_i)\left(1-f(x_i)\right) \qquad (3)$$

$$x_i=\sum_{i=1}^{n}\left(\beta_i W_{ij}+b_{0i}\right) \qquad (4)$$

Where: β_i is the matrix of the neural network inputs; W_{ij} are the weighting factors from the input layer to the hidden layer of neural network and b_{0i} are the bias values of hidden layer neurons. Activation function used in the output layer is Purelin and as the derivative of this function is equal to one, therefore $\frac{dP_{\max}^k}{d\sigma_k}$ is also constantly equal to one.

C. Preparing training patterns of neural network

In order to train the neural network, 150 training patterns are used, 100 patterns as training patterns and 50 patterns for testing the neural network. The load increment pattern coefficients are considered as inputs regardless of the load increment at the slack bus. For each load increment pattern coefficient, loadability limit is considered as the output of the neural network. Specifications of the used neural network are shown in Table I. The number of hidden neurons is determined experimentally. After deciding on the structure of ANN, it is trained by the Levenberg- Marquardt training algorithm for 62 epochs. The final error is 0.0001 in term of mean square error. Then ANN is examined by 50 unseen testing patterns with error of 0.005. After the completion of training and testing procedure, ANN is applied and used in the proposed approach. Once the neural network finds the most suitable bus for load increment and the security of the power system is ensured, Carnot model makes a competition between Transco and Genco to supply the load.

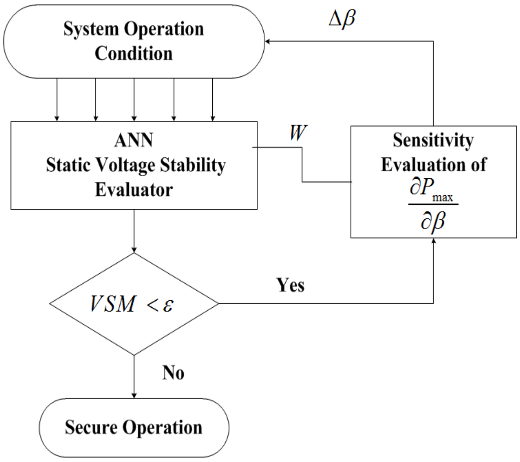

Fig. 2. Structure of the proposed approach.

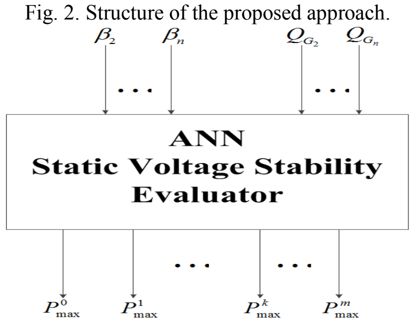

Fig. 3. Input/output pattern structure of ANN

TABLE I. SPECIFICATIONS OF THE PROPOSED ANN

Layers	*Input Layer*	*Hidden layer*	*Output layer*
Number of neurons	5	10	1
Activation function	-	Sigmoid	Purelin

IV. APPLICATION OF COURNOT DUOPOLY MODEL TO TEP/GEP PROBLEM

In the Cournot duopoly model, two companies produce a homogenous product and without knowing the decision of the other one, they must decide how much product they should produce to obtain the maximum profit [18]. As the Cournot model is somehow similar to the TEP and GEP behaviors, it can be applied to the problem of TEP and GEP in the restructured power market. The first similarity between the cournot model and TEP and GEP problem is the expansion capacity of TEP and GEP, which is quantity in Cournot model. The second similarity is that in a pool market the product of each generation unit is a homogenous product which is offered by the GenCo at each supply bid. The Cournot model maximizes the profit of each company and defines the amount of their outputs. In terms of mathematical formulas, the optimal quantity pair (q_1^*, q_2^*) is the Coumot equilibrium, if for firm 1, q_1^* solves (5).

$$\max \pi_1(q_1, q_2^*) \qquad (5)$$

Where: π_i is the profit for firm i; i=1, 2; q_i are the quantities produced by firm i and q_i^* are the optimal quantities produced by firm i.

The profit function for firm 1 can be represented by (6):

$$\pi_1(q_1, q_2) = p(q_1 + q_2)q_1 - c_1(q_1) \qquad (6)$$

Where: $p(.)$ is the market price for aggregate quantity; $C_i(.)$ is the cost function for firm i.

V. APPLYING GAME THEORY TO TEP/GEP PROBLEM

A. Assumptions

In order to formulate the strategic interaction between GenCo and TransCo in the expansion planning game, some assumptions are considered.

- The TransCo is the owner of all transmission lines.
- The power market structure is poolco-type in which GenCo offers the price and quantity bids to the Independent System Operator (ISO). Then, the ISO dispatches the cheapest power considering oprational constraints like transfer capacity limitations and energy balance constraints.
- The demand is considered as a constant load.
- The expansion strategies of TransCo and Genco are discrete. It means that the TransCo can either expand its line capacity or maintain the initial transfer capacity of the lines.
- The expansion behaviors of TransCo and GenCo are based on Cournot model.

B. Problem Formulation

As profit maximization is the main purpose of each side of the game theory and profit is the difference between revenues and costs, the revenue of the TransCo for each line is given by a congestion charge of that line [19] which is the difference between local marginal prices (LMPs) [20-21]. The sum of congestion charges of each line is the TransCo total revenue.

In order to make the problem more simple, Transco total cost isn't considered. So, the TransCo profit can be expressed as (7):

$$\pi_T = \sum_{i \neq j} (\lambda_j - \lambda_i) P_{ij} \qquad (7)$$

Where: π_T is profit of Transco in \$/hr; λ_i is LMP at node i in \$/MWhr; λ_j is LMP at node j in \$/MWhr and P_{ij} is active power flow from node i to node j in MW.

As GEP is performed at node i, The GenCo profit from GEP is obtained using (8):

$$\pi_G = \lambda_i P_G - c(P_G) - i(G) \qquad (8)$$

Where: π_G is profit of GenCo in \$/hr; λ_i is LMP at node i in \$/MWhr; P_G is active power generation in MW; $c(P_G)$ is a quadratic cost function of active power generation in \$/hr and $i(G)$ is investment cost in terms of generation expansion capacity in \$/hr.

C. Solution Methodology

The following notations are used in the solution methodology. S_T^i is ith expansion strategy of TEP; i= 1,2,...,n; S_G^j is jth expansion strategy of GEP; j=1,2,…..,n; T is transmission expansion capacity (TEC) in MW; G is generation expansion capacity (GEC) in MW; T^0 is initial TEC in MW; G^0 is initial GEC in MW; ΔT is increment in TEC in MW; ΔG is increment in GEC in MW; $\overline{T}$ is maximum TEC in MW; $\overline{G}$ is maximum GEC in MW. The algorithm of finding the Nash equilibrium among all possible combinations of expansion strategies is shown in flowchart of Fig. 4 and the Cournot equilibrium is found by using an iterative search procedure [22] as shown in Fig. 5.

VI. CASE STUDY

The proposed algorithm is applied to a six-bus system shown in Fig. 6. The Data of the six-bus system is given in Tables II to IV. In the proposed method, first the load pattern is improved and then the most appropriate bus for load increment is selected using sensitivity characteristic of neural network. Afterwards, in order to supply the incremented load in the selected bus, Game Theory is used to study the strategic interaction between the TEP and GEP.

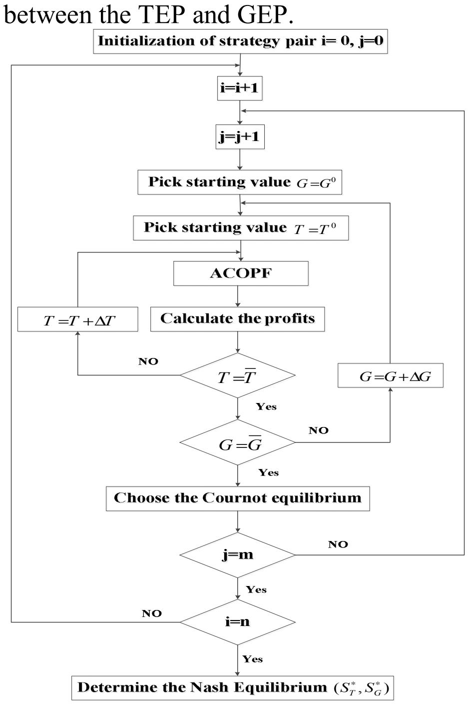

Fig. 4. Strategic interaction between Transco and GenCo.

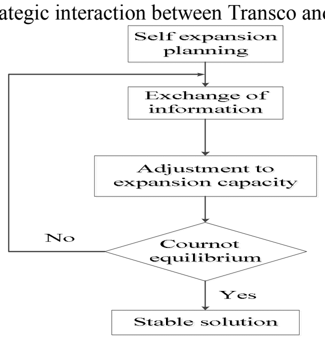

Fig. 5. Flowchart of the Cournot solution algorithm.

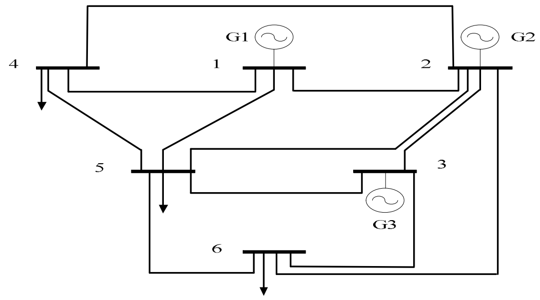

Fig. 6. Six-bus system.

TABLE II. GENERATOR DATA

Generator	*P_{min} (MW)*	*P_{max} (MW)*
G1	50	200
G2	37.5	68
G3	45	73

TABLE III. BUS DATA

Bus No.	*Bus Type*	*V (pu)*	*P_{gen} (pu)*	*P_{load} (pu)*	*λ($/MWhr)*
1	Swing	1.05	-	-	12.492
2	Gen.	1.05	0.5	0	11.565
3	Gen.	1.07	0.6	0	11.877
4	Load	-	0	70	15.674
5	Load	-	0	70	12.939
6	Load	-	0	70	12.206

TABLE IV. LINE DATA

From Bus	*To Bus*	*R (pu)*	*X (pu)*	*Transmission Capacity (MW)*
1	2	0.1	0.2	15.28
1	4	0.05	0.2	40.32
1	5	0.08	0.3	30.63
2	3	0.05	0.25	20.2
2	4	0.05	0.1	42.6
2	5	0.1	0.3	31.42
2	6	0.07	0.2	24.6
3	5	0.12	0.26	28
3	6	0.02	0.1	50.4
4	5	0.2	0.4	18.1
5	6	0.1	0.3	21.6

A. Selection of the best bus for load increment

The initial load increment pattern is considered arbitrary. In this condition, the loadability limit ($P_{\max}$) and the minimum eigenvalue of Jacobean matrix ($\lambda_{\min}$) of power flow equations is as (9):

$$P_{\max} = 210MW \quad and \quad \lambda_{\min} = 0.05 \qquad (9)$$

To obtain the best loadability limit and the most appropriate bus for load increment, sensitivity characteristic of neural network is used. The results show the optimized pattern of load increment in steps of 15MW after 20 iterations. The deviation process of load pattern increment coefficients is shown in Fig. 7. The initial and final patterns of load increment are shown in Fig. 8, which implies that bus 2 is the best bus for load

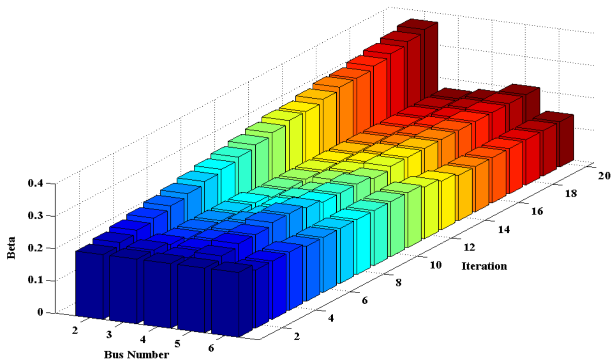

Fig.7. The deviation process of load pattern increment.

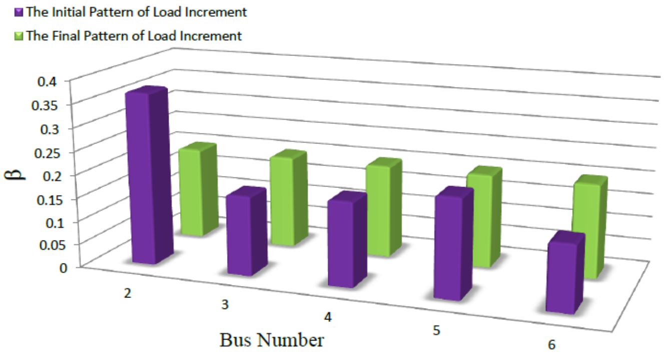

Fig.8. The initial and final patterns of load increment.

increment. The final loadability limit ($P_{\max}$) and minimum eigenvalue of Jacobean matrix ($\lambda_{\min}$) of power flow equations is presented in (10):

$$P_{\max} = 250MW \quad and \quad \lambda_{\min} = 0.03 \qquad (10)$$

B. Transmission and Generation Expansion Planning

After selection of the best bus for load increment, in order to supply the load, Game Theory studies the strategic interaction between transmission expansion planning (TEP) and generation expansion planning (GEP). Under normal operation condition, generator 1 output is 76.5 MW and generator 2 and 3 generate their maximum allowable output power. Supposing the 40 MW load (250-210=40 MW) installed at bus 2 and as the capacity of line1-2 is 15.28MW, a line congestion occurs. Therefore, in order to supply this load, transmission capacity expansion between buses 1 and 2 or generation capacity expansion of generator at bus 2 is required. As a consequence, a competition occurs between TransCo for the capacity expansion of line 1-2 and GenCo for the generation expansion capacity of generator at bus 2. Table V shows the expansions strategies of the two players (TransCo & GenCo) in this case. Equation (7) represents the profit of Transco due to congestion in transmission lines, and (8) represents the profit of GenCo due to expansion of generator capacity at bus 2 and $c(P_{G2})$ for generator 2 is presented in (11).

$$c(P_G) = \alpha P_G^2 + \beta P_G + \gamma \qquad (11)$$

$$\alpha = 0.00889,\ \beta = 10.333,\ \gamma = 200 \ \text{ and } \ i(G) = 200\$/hr$$

In the next step, each of these strategies is applied to the system and at each step, the maximum profit of each company is obtained. Finally, the most profitable strategy for both player using Game Theory and Nash equilibrium is obtained.

TABLE V. EXPANSION STRATEGIES OF TRANSCO AND GENCO

Symbol	*Expansion Strategy*
S_T^1	TransCo will not expand line 1-2
S_T^2	TransCo will expand line 1-2
S_G^1	GenCo will not expand line 1-2
S_G^2	GenCo will expand line 1-2

1) 1st Expansion scenario (S_T^1, S_G^1)

In this scenario, neither TransCo nor GenCo expands its capacity, so there is no revenue or cost for the GenCo and the TransCo gains profit from the congestion charges. The profits of the two players in this strategy are given in Table VI.

TABLE VI. PROFITS OF TWO PLAYERS IN THE 1ST EXPANSION SCENARIO

Line 1-2 capacity (MW)	*Total profit of TransCo ($/hr)*	*GEC in bus 2 (MW)*	*Profit of GenCo ($/hr)*
15.28	14.3	0	0

2) 2nd Expansion scenario (S_T^2, S_G^1)

TransCo will expand line 1-2 capacity from 15.28 MW to 55.28 MW in steps of 5 MW. The TEC with maximum profit for the TransCo is 50.28 MW with profit of 31.03 $/hr. Once again there is no profit for the GenCo in this scenario. The profits of TransCo and GenCo in this scenario are given in Table VII.

TABLE VII. PROFITS OF TWO PLAYERS IN THE 2ND EXPANSION SCENARIO

Line 1-2 TEC (MW)	*Total profit of TransCo ($/hr)*	*GEC in bus 2 (MW)*	*Profit of GenCo ($/hr)*
20.28	5.64	0	0
25.28	8.719	0	0
30.28	11.5	0	0
35.28	15.4	0	0
40.28	20.02	0	0
45.28	25.186	0	0
50.28	**31.03**	**0**	**0**
55.28	20.5	0	0

3) 3rd Expansion scenario (S_T^1, S_G^2)

GenCo will perform GEP in bus 2 and the GEC range is from 68 MW to 108 MW in steps of 5 MW. The GEC with maximum profit for the GenCo is 30 MW with profit of 290.44 $/hr. In this scenario, the TransCo gains profit from congestion charges. The profits of TransCo and GenCo in this scenario are given in Table VIII.

TABLE VIII. PROFITS OF TWO PLAYERS IN THE 3RD EXPANSION SCENARIO

Line 1-2 Capacity (MW)	*Total profit of TransCo ($/hr)*	*GEC in bus 2 (MW)*	*GenCo Profit ($/hr)*
15.28	13.2	5	289.4
15.28	11.84	10	279.3
15.28	10.46	15	269.7
15.28	9.1	20	260.536
15.28	7.7	25	272.33
15.28	**6.39**	**30**	**290.44**
15.28	5.03	35	275.3
15.28	3.67	40	262.1

4) 4^{th} Expansion scenario (S_T^2, S_G^2)

Both TransCo and GenCo will perform TEC and GEC. The most profitable expansion capacity is 37 MW for TEP with profit of 32.03 $/hr and 32 MW for GEP with profit of 291.43 $/hr. So the Cournot capacity pair with maximum profit is (32 MW, 37 MW) among all other Cournot capacity pairs. The profits of TransCo and GenCo are given in Table IX.

TABLE IX. PROFITS OF TWO PLAYERS IN THE 4TH EXPANSION SCENARIO

Line 1-2 TEC (MW)	*Total profit of TransCo ($/hr)*	*GEC in bus 2 (MW)*	*GenCo Profit ($/hr)*
32	31.05	28	261.78
35	30.02	30	288.52
37	**32.03**	**32**	**291.43**

By considering all of the mentioned scenarios, a payoff matrix that comprises the payoffs of TransCo and GenCo is constructed which is shown in Table X. In Table X, the first entry in the box is the profit of TransCo and the second entry is the profit of the GenCo. In this case, the dominant strategy which is characterized as the Nash equilibrium is the pair of strategies (S_T^2, S_G^2) which implies that the most profitable strategy for both TransCo and GenCo is to perform TEP and GEP. In this strategy, the profit of TransCo is 32.03 $/hr while the GenCo profit is 291.43 $/hr.

TABLE X. PAYOFF MATRIX OF THE GAME THEORETIC TEC AND GEC

		GenCo Strategy	
TransCo Strategy	Nash eq.	S_G^1	S_G^2
	S_T^1	(14.3,0)	(6.39,290.44)
	S_T^2	(31.03,0)	**(32.03,291.43)**

VII. CONCLUSIONS

The strategic interaction between TransCo and GenCo in the expansion planning game with various expansion strategies considering the loadability limit of a six-bus system is proposed. The loadability limit is gained using the sensitivity characteristic of ANN. Afterwards the most appropriate bus for load increment which maintains the static voltage stability of the system, is chosen. As the transmission line capacity is not sufficient for the load increment, a congestion in the transmission line occurs which can be an incentive for GenCo and TransCo to gain the maximum profit from supplying this load. Considering multiple scenarios, the Cournot model defines the most profitable TEC and GEC in each scenario. After constituting the payoff matrix which comprises all of the possible strategies combination, the Nash equilibrium is obtained. The results show that the most profitable scenario for both Genco and TransCo is to perform generation expansion and transmission expansion.

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