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Transmission Loss Allocation in the Deregulated Electricity Market based on the Cooperative Game Theory

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ABSTRACT:

Changing the structure of electrical energy markets from traditional to the restructured state, considering the loss allocation has been unavoidable. The importance of this matter is because the amount of loss consist significant part of total electrical energy. Loss in power system is a nonlinear function of power so using linear methods could not be efficient. On the other hand, applied function must consider both network characterizes and participation rate in power supplying and power consumption. The purpose of this paper is to present an applicable and modern solution based on the cooperative game theory for loss allocation of transmission lines in both pool and bilateral markets. This method has been tested on a 4 bus systems and a 14 bus IEEE.

Keywords: Game Theory, Coalitions, Players, Loss allocation, Shapley Value

1. INTRODUCTION

Changing prevalent rules in power system and transmission policy with wide availability would make the calculation of loads and generators participation rate more visible in active and reactive power loss in network. [1] In monopoly markets, generation and transmission is under supervision of a system, so expenses of transmission loss cost could be a part of generation expenses and therefore there is no need to allocate cost to loads and generators and find the share of each in total cost. But, in deregulated market the problem is that who pays the expenses of this cost? The rate of this loss is significant as it includes 4-8 percent of total generation. For example the transmission amount of loss cost is 0.5 billion dollars in Brazil only. [1] The fairest kind of loss allocation in which cost is both allocated to loads and generators. [2] Recently, due to the importance of this case, so many researches had been performed base on four following principles:

1. Methods based on the circuit laws such as z-bus model [11], modified z-bus model [3], and graph method [4] and etc.
2. Methods based on pro rata: It is clear that this method is totally reliant on the power injections at buses and independent of the network topology. Losses are distributed across all buses, according to their level of generation or consumption only. Two loads in different locations but with identical demands will be allocated the same level of loss, irrespective of their comparative Proximity to system generation [10].
3. Methods based on proportional sharing: The problem with this approach, however, is that the distribution of power flows is built on the proportional sharing principle, which lacks physical and economical justification. This departure from electrical behavior of the network may mean that proposed strategies to reduce losses may not be technically satisfactory [16].
4. Methods based on coefficient of transmission expense incensement: the main limitation of this method is that losses are highly dependent on the incremental steps taken. It is expected then that a loss allocation would be non-unique. Furthermore, the method is also highly dependent on the choice of slack bus [16].

Surveying different models of electrical energy market, the retail competition has proved to be the most competitive model in market in which producers could sell the power to retailers in transmission level and retailer, then, sells it to consumersin distribution level. Every retailer is free to buy power from any generator he wants and then sell the power in distribution level to any consumer.

MATPOWER software has been used to find the loss and the game theory method has been used to find the share of each player. Although the Game theory does not have a long history of use in the electricity market, but is has been put into practice in different branches due to its high capability. Application of the Game theory can be studied in two completely separate phases. First is the anticipation and the other is square division and finding share for every single player in the Game. First application of the Game theory is to specify the market price and suggested generators price [13, 14, and 15] and second application is used for transmission cost allocation [7, 8]. The basis of Game theory usage can be found in the reference [16] in which the Shapley Value method is used to trace the consumed power. In order to use the Game theory method, it must be to specify the players primarily. So, every equivalent bilateral exchange can be defined as a player according to type of the electricity market which is a bidirectional type.

Signs:

p_i: Real power of bus i

q_i: Reactive power of bus i

v_i: Voltage of bus i

y_{ij} : Admittance line between bus i, j

M: total bus of the system

p_{ij} : Active power transmitted from bus i to bus j

q_{ij} : Reactive power transmitted from bus i to bus j

Δp_{ij} : Active loss of the line between buss i, j

Δq_{ij} : Reactive loss of the line between bus i, j

S: Desired coalition

N: Players' total number

V(s): Loss in coalition s

V(s-{i}): Loss in coalition s without player i

x_i: Loss allocated to player i

2. LOSS CLCULATION

AC load flow has been used for finding the loss and Newton-Raphson Method has been used for solving its [5]. Load flow or power flow problem means presenting a solution to find voltages, power flow in lines, generators reactive power, line losses and etc. These computations would be performed in Steady state. To solve the load flow problem following equation must be used:

$$p_i - jq_i = v_i^* \sum_{j=1}^{n} y_{ij} \ v_j \qquad (1)$$

Solving the load flow problem, the bus voltages could be founded. Then, using following relations the losses will be founded:

$$p_{ij} + jq_{ij} = v_i \left[\frac{v_i - v_j}{z_k} + \frac{1}{2} y_k v_j\right]^* \qquad (2)$$

$$p_{ji} + jq_{ji} = v_j \left[\frac{v_j - v_i}{z_k} + \frac{1}{2} y_k v_i\right]^* \qquad (3)$$

$$\Delta p_{ij} = \Delta p_{ji} = \left|p_{ij} + p_{ji}\right| \qquad (4)$$

$$\Delta q_{ij} = \Delta q_{ji} = |q_{ij} + q_{ji}| \quad (5)$$

To find losses in coalitions, first the flowing power of lines must be calculated for every player and according to any coalition; the answer provided for every line must be summed together.

3. USING COOPERATIVE GAME THEORY

Cooperative game theory is a method in which each player's share could be obtained from total factor. [7] Game theory in power system has been also applied to transmission cost allocation [7, 8]. The game theory has different branches and methods, however; Shapley Value method, a method for cooperative games, has been used in this study. In this method, first the players are introduced, since the market is a bilateral market, so any equivalent bilateral exchanges ought to be considered as a player. After characterizing the players, variety of coalitions should be formed. Coalition stands for states in which players could participate in the market together. After finding the cost in variety of coalitions, share of each equivalent bilateral exchange (players) from total loss could be found using following relation [7, 8].

$$x_i = \sum_{\forall s \ | i \notin s} p_n(s)[v\ (s \cup \{i\} - v(s)\ ] \quad (6)$$

$$p_n(s) = (|s|!\,(n - |s| - 1)!)/n! \quad (7)$$

Then, two 4-bus studying systems with 4 equivalents and a 14-bus with 6 equivalent shave been used testing the above mentioned method.

4. CASE STUDY

In this section we use two illustrative examples of loss allocation using cooperative game theory where the players are modeled as bilateral contract.

4-1. 4-bus test system

Information and data of this network has been shown in reference [9]. Network characteristics shown in table 1 and diagram are presented in FIG 1. This system has 5 lines, 2 generators and 2 loads. Every generator has two bilateral contracts in which the load on the first one is 3 and the other one is 4. The total load for the system equals to 400 MW.

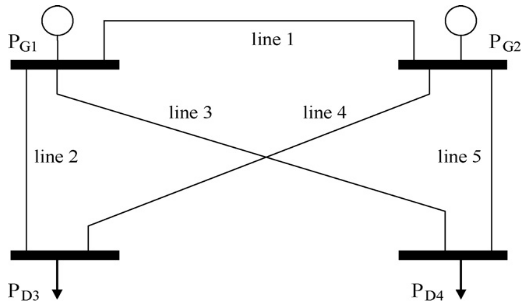

FIG.1. *A 4-bus system*

Characteristics of a 4-bus network: Considering network inductance and resistance rate, can be understood that the network applied in this study is a symmetrical network.

Table 1. Particulars of a 4-bus network

Line	Form bus	To bus	r	x
1	1	2	0.04	**0.01**
2	1	3	0.01	**0.05**
3	1	4	0.01	**0.05**
4	2	3	0.01	**0.05**
5	2	4	0.01	**0.05**

First, different contracts should be characterized. Title and serial number for any bilateral is defined as EBE. For example EBE1 is through the generator 1 and load 3 and EBE3 is through the generator 2 and load of 3 to level of theses bilateral of 110 MW. The levels of contract are the same, but the topologies are not due to demonstration of network topology effects on loss allocation to the bilateral. Bilateral contracts are identical in distance and features caused by the polarity in network, but with presence of different powers to reveal effect of power level on losses. Table 2 showed the all contracts in the system.

Table 2. bilateral contracts in the system

Name	Contract BTW	Generation	Demand
EBE1	G1,D3	110	110
EBE2	G1,D4	140	140
EBE3	G2,D3	110	110
EBE4	G2,D4	140	140

4-2. Loss allocation using Shapley Value method

Loss should be obtained for different coalitions. To do so; every coalition should be considered separately according to following table then the loss would be found.

Table 3. Loss in coalitions

	S: coalitions	V(s)
1	0	0
2	1	1.97
3	2	3.22
4	3	1.88
5	4	3.03
6	1و2	8.899
7	1و3	1.22
8	1و4	1.695
9	2,3	1.717
10	2,4	1.991
11	3,4	7.979
12	1,2,3	5.794
13	1,2,4	6.139
14	1,3,4	5.450
15	2,3,4	5.850
16	1,2,3,4	6.542

Considering the numbers in the table, the effect of nonlinear loss can be understood because the loss in coalitions is not equal to total loss of the players present in coalition stating the concept of being core. For example, the loss in coalition 6 is equal to 8.899 while total loss for two present players is lower than this amount stating that the above coalition is not core.

Now, using following equations:

$$x_i = \sum_{\forall s \; | i \notin s} p_n(s)[v\,(s \cup \{i\} - v(s)\,] \qquad (8)$$

$$p_n(s) = (|s|!\,(n - |s| - 1)!)/n! \qquad (9)$$

The share of each player (contract) would be found from total loss so, results of following table would be obtained.

Table 4. Loss allocation of each player (contract)

EBE	loss	G	G loss	D	D loss
1	1.447	1	0.723	3	0.723
2	2.129	1	1.065	4	1.064
3	1.171	2	0.585	3	0.585
4	1.794	2	0.897	4	0.897
tot	6.542		3.271		3.271

Studying the results, we can see the serious dependency of allocated loss corresponding to contract power rate. For example, contract rate 3 is 110 MW and loss allocated for it, is1.171, and in contract 2 the power rate is 140 MW and the loss allocated for it, is 2.129. Half of the loss allocated to each contract is for the generators and another half to load. Loss allocated for each load and generator of this system. Finding the costs for every generator and load, we should sum up the loss allocated to it in different equivalents which has been done in the following table.

Table 5. Loss allocated to each user

Name	Loss
G1	1.780
G2	1.480
D3	1.308
D4	1.962

Comparing obtained results with results from previous methods

The table 6 compares the results obtained from the recent method with results from previous methods.We also consider the network effects.

Table 6. Loss allocated to each user by different methods

Name	NSV	SV	Z-BUS	ITL	PS	Pro-rata
G1	1.78	1.63	1.33	1.64	1.67	1.66
G2	1.48	1.63	1.24	1.62	1.59	1.62
D3	1.31	1.24	1.35	1.24	1.24	1.42
D4	1.96	2.02	2.60	2.02	2.02	1.81
Total	6.54	6.52	6.52	6.52	6.52	6.52

NSV is a new method applied in this study and it is a method resulted from characteristic equation obtained in this study. Consequently, the new method is more efficient due to involving total loss. The method applied in this study involves both active and reactive loss while previous methods only involved the active power. The SV method uses the following equation to calculate the amount of losses.

$$v_k(c) = -R_k(\Sigma_{L\epsilon C} P_{LK})^2 \qquad (10)$$

To find losses in coalitions, first the flowing power of lines must be calculated for every player and according to any coalition; the answer provided for every line must be summed together.

In order to find losses in every line, the relation should be extended.

For instance to discover the coalition between 1 and 2 players we have:

$$v_k(1) = -R_k\left(P_{f1k}^2\right) \tag{11}$$

$$v_k(2) = -R_k(P_{f2k}^2) \tag{12}$$

$$v_k(2) = -R_k(P_{f1k} + P_{f2k})^2 \tag{13}$$

The major problem with this method is that it is only useful for the DC losses and cannot be used to determine the losses on AC. To solve the mentioned problem the programming capability in MATPOWER environment has been used to organize the coalitions and discover the loss for every coalition by AC load distribution.

Noticing that the production of two generators is at same level, it is expected at first that the allocated loss for the generators to be the same, but with a closer observation we will understand that the first generator deploys the 110 Mega Watts equivalent bilateral exchange with closer load (EBE1) and the 140 Mega Watts equivalent bilateral exchange with the further load (EBE2), but in the second generator, it deploys the 110 Mega Watts equivalent bilateral exchange with the further load (EBE3) and the 140 Mega Watts equivalent bilateral exchange with the closer load (EBE4); So it is expected that the loss allocation for the generator No. 1 to be more that generator No. 2, thus according SV method results, this method not only does not show any effect ,also would consider the loss allocation for two generators equal in which the NSV method would show this effect and so does the more losses on the generator No. 1 rather that the generator No. 2.

4-3. 14-bus Case studies in IEEE

The 14-bus system has been shown in figure 3 and presented in Ref.[15]. Showing the suggested method ability on larger systems, the IEEE 14-bus system has been used.

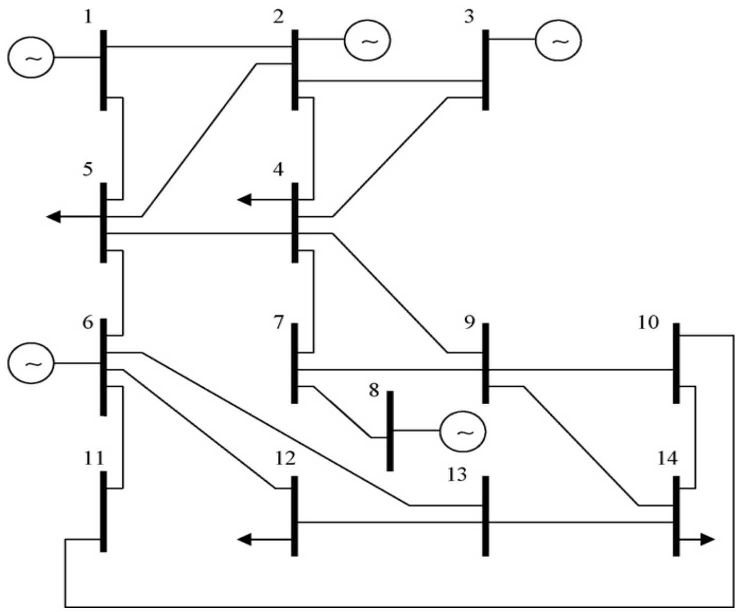

FIG. 3.*IEEE 14-bus system*

The equivalents are selected so that some of equivalents would be between nearer loads and generators (EBE2) and some between distanced loads and generators (EBE6) in order to investigate the network effect on the above method. Also some equivalent bilateral exchanges between generators and load of networks have been identical in order to analyze the effect of load on loss allocation level. So, we define the equivalents as following:

Table 8. Equivalents' table

Name	Contract between	Generation
EBE1	G2,D4	42
EBE2	G1,D4	8
EBE3	G3,D5	50
EBE4	G6,D12	50
EBE5	G8,D14	42
EBE6	G1,D14	8

Obtained results using Shapley method:

Table 9. Loss for each equivalent

	Loss	G	G Loss	D	D Loss
EBE1	1.138	2	0.569	4	0.569
EBE2	0.152	1	0.076	4	0.076
EBE3	1.235	3	0.617	5	0.617
EBE4	2.257	6	1.128	12	1.128
EBE5	1.724	8	0.862	14	0.862

EBE6	0.707	1	0.350	14	0.350
tot	7.210	****	3.605	***	3.605

Half of the loss allocated to each equivalent is for the generators and another half to load. Loss allocated to each load and generator of this system:

Table 10. Loss allocated to each player

Name	Loss
G1	0.429
G2	0.569
G3	0.617
G6	1.128
G8	0.862
D4	0.645
D5	0.617
D12	1.128
D14	1.2185
Total	7.214

Regarding the dependence of the amount of losses allocated, to the two factors including the amount of power and the distance between production and consumption, examining the obtained results of various contracts, we conclude the influence of these two factors in the above method. For example, reviewing the contracts 1 and 2, both of which have the same generator, we encounter with the same amount, but different space between loads and generators. Load 4 is close to the generator 1 (contract 1) and load 14 (contract 2) is far from it; so it is expected that losses allocated to the contract 2 is more than contract 1, which is also clear in the obtained results. For studying the effects of power of the contract and its effects on the amount of losses allocated, we consider contracts 2 and 3, wherein contract 2 counts 8 MW and contract 3 counts 50 MW; in terms of style the two contracts are almost identical. Therefore, it is expected that losses allocated to the contract 3 would be more than contract 2; which in the obtained results it is evident, too.

5. CONCLUSION

Restructuring electrical energy markets, the share determination for each load and generator from total loss has been unavoidable. It should be performed honestly and all loads and generators should participate. In this article a new method has been introduced based on Games theory. In order to analyze the performance of this method, two systems of 4 and 14 bus have been used. By comparing the results of this method to other methods, the following consequences are achieved. The method applied in this theory includes the total loss could be used for active and reactive power loss allocation. Loss would be allocated both to loads and generators. It although considers the players positive effects in loss decrement. Another point to be mentioned is that no matter which method would be used in loss computing, but after computing, the loss allocation should be done using the Game Theory Method. To accelerate performing the calculations, another method can be put into practice to find out the losses such as those that mentioned in reference [9]; but it must be considered that the specified equation must calculate both types of losses in AC and DC.

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