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Cost Allocation for Transmission Investment Using Agent-based Game Theory

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Abstract— Due to electrical power restructuring, a dramatic change has been made to the generation and transmission sectors of the power industry. Rules and legislation are continuously changing. To promote more competition, transmission has to be expanded or upgraded to remove congestion and market power. The cost allocation of new investment in transmission has to be recalculated. The socialization methods of the past have been shown to be unfair to some market and network participants. The decentralization of cost allocation must be considered. The proposed paper provides a comparison between traditional cost allocation methods and a new cost allocation method based on agent-based game theory. A multi-generator/bus system will be used to compare the cost allocation methods.

Index Terms - Game theory, multi-agent, transmission investment, power system deregulation

I. INTRODUCTION

Transmission plays a crucial role in electricity markets since transmission links all generators and loads together.

Transmission is the electricity super highway and responsible for increases in competition in the generator sector and interruption in the growth of load sector. This approach is based on the idea that both the consumer and the generation sector will benefit from the cost reduction and increases in sales. Therefore, the consumer and generation sectors should share the cost of any new line investment. The costs of the new line must be less than the costs of the benefits (congestion saving cost). Future growth of the load must also be considered.

The Department of Energy (DOE) and the Federal Energy Regulatory Commission (FERC) have recently indicated support for the principle of cost allocation, stating that the costs of the transmission upgrade or expansion should be defined by customers who need or benefit from the upgrade or expansion. Before deregulation of the power industry, all transmission projects costs were shared by participants in the load sector. The change of cost allocation structure requires the abandonment of the old cost allocation methods within the new market structure. The new paradigm for cost allocation suggests that parties who have the need and/or benefit from the new transmission investment should pay the costs. The new investment should not be socialized across all customers.

Socialization of costs harms customers who do not benefit. New projects providing economic benefits must recover some cost from those who receive the benefits. The use of a benefit-driven methodology, however, has some drawbacks. It may possibly slow investment and decrease reliability.

The North American Electric Reliability Council (NERC) stated "The gap between the transmission expansion need and the proposed construction of transmission is widening. To support the reliability of the bulk power system, proper incentives must be developed to encourage transmission construction" [24]. The statistical data shows that plans for additional transmission lines decreased from 1994 to 1999, but started to increase from 1999 to the present [24].

Congestion cost is often the primary indicator for utilities in deciding whether to build a new transmission line. The new line will relieve constraints and gain access to lower cost generation between each end of the line. The cost of the new line will not be socialized to all users. A new line with multiple beneficiaries might negotiate joint support among users who will get benefit from the line [3, 7].

In a decentralized market, all users realize that if there is no expansion of the new line to relieve the current congestion, the price of electricity will rise. Therefore, the increase in price results in a monopoly of the transmission business. The monopoly allows transmission companies to earn additional revenue, decreasing their financial interests for expanding the network. Since some transmission has recently been deregulated, the methods used in this paper will assume that customers and generators are allowed to build a new transmission line to relieve congestion and gain access to lower-priced electricity [1, 25].

II. NETWORK EXPANSION

An illustrated example of the limits of transmission lines and power generation is provided in Figure 1 and described later in section V. There are several techniques that can be used to rank possible locations for adding new lines to an existing system. A heuristic approach suggested by [9, 13] is used to identify if a solution is feasible under the domain of a quadratic linear programming problem. The formula is expressed as:

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$$\min \frac{1}{2} \sum_{j=1}^M c_j p_j^2 \quad (1)$$

Subject to

$$B\Theta + K' P_D = P \quad (2)$$

$$|B_L A \Theta| \leq \bar{P}_L \quad (3)$$

where c_j is the cost of adding a line j to the network, P_D is the flow vector for the possible line, M is the number of possible new lines, p_j is the active power (in p.u.) flowing through the added line j , i.e., the j^{th} element of P_D , B is the matrix whose elements are the imaginary parts of the nodal admittance matrix of the existing network, Θ is the phase angle vector, K' is the transpose of the nodal phase connection matrix, P is the nodal injection power for the overall network, B_L is a diagonal matrix whose elements are branch admittance, \bar{P}_L is the branch active power vector, and A is the network incidence matrix. The objective function in Eq. (1) indicates the effect of power transmission costs. A candidate line with the largest power flow is the most effective in the expanded network. Eq. (2) expresses the total nodal injection power as a function of both the existing and potential networks (after adding a new line). Eq. (3) reflects the thermal limits of existing network lines.

The concept of economic use of the transmission network may be divided into two groups [19]:

- 1) **Capacity usage.** The argument is that lines are dimensioned for peaking conditions, so that capacity usage must be the guide to allocate payment among users.
- 2) **Energy usage.** The argument is that lines are dimensioned within a network that must respond to a load curve. Therefore, it is the energy usage by agents that must be the guide to allocate payments among users.

III. MULTI-AGENT AND GAME THEORY

By definition, an agent is an entity that makes decisions according to his/her own interests, as well as the actions of other agents. A system with many decision-makers (agents) is called a multi-agent system [5, 6, 15, 22]. In a power transmission network, several entities can be represented by agents, such as generators, loads, and transmission line owners, each making a decision about the expansion of the network. Typically, it is difficult to determine which agents are going to pay for the new transmission line investment. Thus, we propose a multi-agent approach to cost allocation of a new investment that takes into account the benefits of each player in the system from the addition of the new line.

Each player or agent can act individually in cooperation with other agents to form a coalition. It is assumed that all agents act rationally [12]. This means they prefer to reduce their electricity price in the case of loads, or earn more money in case of generators [8]. There are no restrictions to form coalitions among the agents. The agents create coalitions that minimize their cost participation for a new transmission line. The joint cost is lower than the sum of individual costs [5].

Cooperative game theory is a branch of game theory that relates to games in which there are three or more players who are free to negotiate binding and enforceable agreements about the formation of coalitions and the divisions of the payoffs that result from their coordinated actions [10, 11, 12]. The payoff result is used to determine the percentage cost allocation of a new line to agent i . A cost allocation cooperative game is given by (NA, C) , where NA is the set of the N agents and C is the cost function. N agents group in m mutually exclusive and excluding coalitions. The value S represents the coalition configurations, such that:

$$\delta = \{S_1, S_2, \dots, S_m\} \quad (4)$$

where δ is a partition of NA fulfilling two conditions

$$S_j \neq \Phi; j = 1, 2, \dots, m$$

$$S_i \cap S_j = \Phi$$

where Φ is the empty set

Each agent belongs to one and only one of the m coalitions and the members of a certain coalition are related to each other but not with other agents that belong to other coalitions. The cost assigned to each agent is the result of the game corresponding to the payments $x = \{x_1, x_2, \dots, x_n\}$, where x_i is the agent i payoff. Any agent or coalition of agents should not have to pay more when compared with the stand-alone cost.

The Shapley Value (SV) has been used to solve similar types of problems [2, 12, 22]. The SV calculates a value based on an individual's contributions among all members in a coalition. It is a concept from the n -person corporate game. SV is a weighted average of marginal contributions of a member to all the possible contribution coalitions that a member participates. It is assumed that a grand coalition is formed. The formula for the Shapley Value is given by:

$$\phi_i = \sum_{S, i \in S \subseteq N} \frac{(|S|-1)!(n-|S|)!}{n!} [v(S) - v(S - \{i\})] \quad (5)$$

where i is i^{th} player, S is a coalition of players, $|S|$ is a number of players in coalition S , n is the total number of players, N is the set of all players, and $v(S)$ is the characteristic function associated with coalition S .

In order to reduce the complexity of the Shapley value, Ketchpel introduced the Bilateral Shapley Value (BSV) [23].

Let $CS \subseteq P(A)$ be a coalition structure on a given set of agents $A = \{a_1, \dots, a_m\}$, where $C_i \cup C_j \subseteq A$ is a (bilateral) coalition of disjoint (n -agent) coalitions C_i and C_j ($n \geq 0$). The Bilateral Shapley Value for some coalition C_i in a bilateral coalition C is defined as:

$$BSV_{\{C_i, C_j\}}(C_i) = 0.5v(C_i) + 0.5(v(C) - v(C_j)) \quad (6)$$

Both coalitions C_i and C_j are called founders of C , and $v(c)$ denotes the self-value of coalition C .

The process to form a coalition among agents is based on the approach of [18].

A. Self Value Calculation: Each generator or load is represented by one agent. Each agent uses all available information to calculate its initial self-value. This value is calculated by the maximum value that the agent can get from the new line. If the agent doesn't want to invest in the new line, this value will be zero.

B. Communication and Security Check: All agents send their self-value and the coalitions to independent coordinators (ISO, RTO). The ISO or RTO will check the security of the coalitions and publish to all agents and each coalition. After founder agents receive a message back from the coordinator, each agent proceeds to calculate a new payoff to rank the order, form coalition with other agents, and find the optimal benefit for each agent in the network.

C. Rank Payoff for Each Agent: After receiving messages from the RTO, each agent proceeds to rank the order to form a coalition with other agents. The assumption was made that the transmission line life is 10 years. The interest rate is fixed.

D. Negotiation: Every agent begins to negotiate with other agents to get the optimum benefit for each agent.

IV. APPLICATION IN TRANSMISSION PLANNING

The multi-agent system based on cooperative game theory is used to form a coalition. The Locational Marginal Price (LMP) method [17] is utilized to judge the benefit of each player. The assumption used in the LMP method is that the overall benefit of each player must be increased after the new line is added to the network. If the overall benefit decreases, the new line will be rejected.

By using the LMP method with the system that socializes all customers in the system, the postage stamp method [4] does not produce efficient price signals. The reason is because the customers who do not benefit from the new line must often pay for the line cost. In contrast, the LMP method has proven to provide efficient price signals. The LMP method [17] is essential in achieving market efficiency when the price is the most efficient signal.

Determining the LMP is done most efficiently through a voluntary, bid-based market. Loads submit bids to the system operator to purchase power at a particular node for a maximum acceptable purchase price – that is, they inform the market what they are willing to pay for electricity as transmitted. Generators, on the other hand, submit to the system operator offers to sell electricity – at the sale price at the point of injection into the grid, but prior to transmission. The system operator then purchases and dispatches the generation in the order of offered price, lowest to highest, based on the selling price at the nodes on the bid and offer prices received.

When congestion occurs, least-cost generation must often be passed over for purposes of system security. The system operator acts as a clearing agent and manager of system security. The difference between LMP at two nodes is the cost of transmission between the two nodes [19].

The LMP method is the dollar per MWh cost of supplying the next incremental load to a specific location in the transmission grid. It is the basis for calculating the amount for which power producers will get paid and the amount that customers are charged for their loads. It is also a very important indicator of market conditions. For example, areas that have numerous amounts of inexpensive generation, but with few loads, will have lower energy prices than the locations that have high-cost of generation and high load. Due to congestion, the loads on the congested locations will have higher prices than those in less congested areas. If there is no congestion, the LMP is the same at all nodes. Therefore, each LMP is equal to the Market Clearing Price (MCP), since none of the transmission constraints is binding [14].

V. ILLUSTRATION

From our previous work on load forecasting, loads have seasonal and time effects. The Monte Carlo simulation is used to generate the future load demand for the next 10 years of our 5-bus system, as shown in Figure 1. The demand growth is assumed to be a 2% incremental increase every two years. The Net Present Value (NPV) [20] is used to judge the new transmission investment project. The interest rate is assumed constant at 5% a year. There is no new generator into the market during this period. The benefit is judged based on cost savings from an LMP basis.

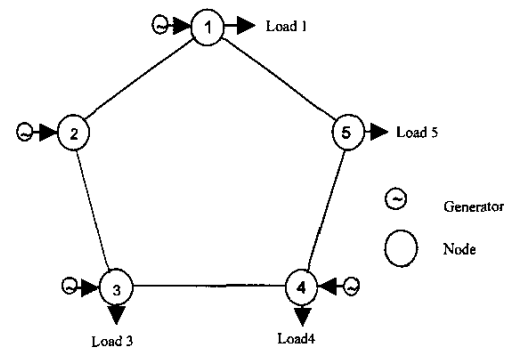


Figure 1: Five-bus testing system (before adding the new investment)

The system consists of four loads and four generators. The generator details are shown in Table 1. The average price of each generator is different to make it more competitive in the current market design. The model assumes that no changes in the system, generation, and transmission over the planning period. All transmission lines have reactance 0.1, resistance 0.01 and rating at 800.

GENERATION OFFERS		
Unit	Generation	Average Price
1	2500	\$15.00
2	500	\$35.00
3	800	\$20.00
4	1000	\$25.00
Total	4800	

Table 1: Detail of generators

Monte Carlo simulation is used to create the demand curve on an hourly basis. This demand curve has seasonal and time of use effects to make it more realistic. We use this data to calculate the average hourly load each year. Again, the growth rate is assumed to increase 2% every two years. The mean average load demand in hourly basis is shown in Table 2. This data is used to calculate the LMP at each node.

	Load 1	Load 3	Load 4	Load 5
Year 0	960.8462	952.8296	564.1727	571.028
Year 1	980.0632	971.8862	575.4561	582.4485
Year 2	980.0632	971.8862	575.4561	582.4485
Year 3	999.6644	991.3239	586.9653	594.0975
Year 4	999.6644	991.3239	586.9653	594.0975
Year 5	1019.658	1011.15	598.7046	605.9795
Year 6	1019.658	1011.15	598.7046	605.9795
Year 7	1040.051	1031.373	610.6787	618.099
Year 8	1040.051	1031.373	610.6787	618.099
Year 9	1060.852	1052.001	622.8922	630.461
Year 10	1060.852	1052.001	622.8922	630.461

Table 2: Load demand detail

	Node 1	Node 2	Node 3	Node 4	Node 5
Year 0	15	35	55.85	41.19	29.84
Year 1	15	35	56.26	41.55	30.05
Year 2	15	35	56.26	41.55	30.05
Year 3	15	35	56.72	41.95	30.29
Year 4	15	35	56.72	41.95	30.29
Year 5	15	35	57.19	42.35	30.53
Year 6	15	35	57.19	42.35	30.53
Year 7	15	35	57.65	42.74	30.77
Year 8	15	35	57.65	42.74	30.77
Year 9	15	35	58.16	43.17	31.03
Year 10	15	35	58.16	43.17	31.03

Table 3: LMP (avg) at each node before the new line is build

Figure 2 illustrates the system after a new investment takes place. The new investment is the transmission line between node 1 and node 3. This line will remove some congestion and increase system reliability. After the line is complete, each node LMP will be changed. The benefit of the new investment is calculated from the cost savings of each node from the change in LMP. LMP is based on hourly basis and converted to a yearly expense. The Net Present Value method with an interest of 5% is used to calculate benefit value of each load.

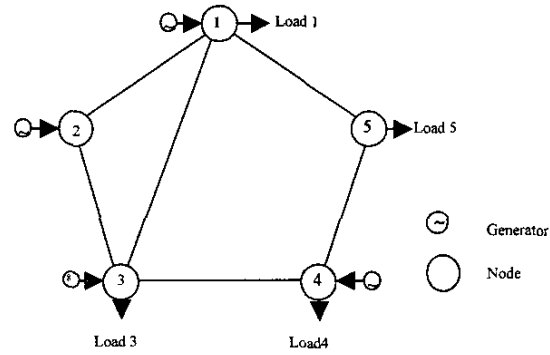


Figure 2: Five-bus testing system after new investment.

	Node 1	Node 2	Node 3	Node 4	Node 5
Year 0	18.13	19.05	20	21.75	21.09
Year 1	18.19	19.08	20	21.83	21.18
Year 2	18.19	19.08	20	21.83	21.18
Year 3	18.25	19.11	20	21.91	21.29
Year 4	18.25	19.11	20	21.91	21.29
Year 5	20.93	21.90	22.90	25	24.38
Year 6	20.93	21.90	22.90	25	24.38
Year 7	21.06	22.03	23.02	25	24.48
Year 8	21.06	22.03	23.02	25	24.48
Year 9	21.20	22.17	23.15	25	24.59
Year 10	21.20	22.17	23.15	25	24.59

Table 4: LMP (avg) at each node after that new line is build

From the NPV analysis, the overall cost saving of the system will be 490M for the next 10 year. This means if the cost of new investment is less than 490M, this line should be build. Customers will save future electricity cost. The next step is to use the Shapley Value to allocate the cost of this investment and then compare it to the social cost and marginal loads.

The LMP calculator program from PA consultant is used to find the LMP at each node. The benefit of each agent is calculated from cost saving before and after the new investment takes place. This criterion is used to form a coalition as shown in Table 5. For example, coalition 1 represents that only load 1 invests in the new transmission. The coalition {1,3,4} represents that load 1, load 3 and load 4 are to invest in the new transmission.

Coalition	Benefit	Coalition	Benefit
0	0	34	\$471,071,712.10
1	-\$31,405,479.72	35	\$406,383,618.08
3	\$356,566,928.37	45	\$164,321,473.44
4	\$114,504,783.73	134	\$439,666,232.38
5	\$49,816,689.71	135	\$18,411,209.98
13	\$325,161,448.65	145	\$132,915,993.72
14	\$83,099,304.01	345	\$520,888,401.81
15	\$18,411,209.98	1345	\$489,482,922.09

Table 5: Benefit of each coalition

Comparisons between each method, along with the results, are shown in Table 4. Each method gives different results due to the different perspectives being considered. This is a win-win situation for each agent. None of them receives a worse payoff from coalition {1,3,4,5}. The agent {3}, {4}, {5} have to pay some to cover the lost of agent {1}. This situation will motivate new investment to take place faster.

Starting from the grand coalition {1,3,4,5}, we split the cost of 490M. Let $BSV_{i,j}(i)$ be the value allocated to agent i using the Bilateral Shapley Value:

$$BSV_{\{3,4,5\}}(3) = 1/2V(345) + 1/2[V(1345) - V(1)] \quad (7)$$

$$BSV_{\{3,4,5\}}(4) = 1/2V(4) + 1/2[V(1345) - V(345)] \quad (8)$$

$$BSV_{\{4,5,3\}}(3) = 1/2V(3) + 1/2[BSV_{\{4,5,3\}}(345) - V(45)] \quad (9)$$

$$BSV_{\{4,5,3\}}(45) = 1/2V(345) + 1/2[BSV_{\{4,5,3\}}(345) - V(3)] \quad (10)$$

The process is continued until the values of individual agents are found: (-32, 357, 115, 50).

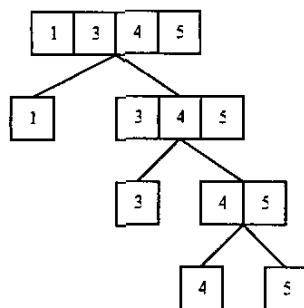


Figure 3: BSV cost allocation process

Method	1	3	4	5
Shapley Value	-6.32%	72.86%	23.47%	10.2%
Social Welfare	25%	25%	25%	25%
Load Proportional	31.56%	31.16%	18.54%	18.74%

Table 6: Cost allocation result of each method

VI. CONCLUSIONS

The multi-agent system has a potential to help decision makers form a coalition between agents, such as load and generation entities. The coalition facilitates the cost allocation of each agent for upgrade or transmission line expansion in the new environment of power deregulation. Competition in the new environment forces all participants in the network to produce additional profit and/or reduce their costs. The system will significantly improve the method for finding the best solution in cost preparation of the new line to those agents who will benefit the most. The coalition will be formed based on the benefits gained by each agent. From the results, the game theory based method is better in the sense of fairness. The agents that will not get benefit from the new investment have been treated fairly. The agents who received benefit from this investment have to pay more. Future work will develop the price model that deals with uncertain in supply and demand to make the cost allocation model more realistic.

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VIII. APPENDIX

The *Social welfare method* is a method that forced every load in the network to share all cost of the new investment in the network. It can be written as

$$C_i = \frac{1}{N} \quad (11)$$

N is number of player

C_i is a cost allocation of player i

Load proportional method

Letting θ_i be the amount of load for player i , we can then write

$$C_i = \frac{\theta_i}{\sum_{j=1}^n \theta_j} \quad (12)$$

C_i is a cost allocation of player i

IX. BIOGRAPHIES

Jakapun Mepokee has a B.S. in Electrical Engineering from Thammasat University, Bangkok, Thailand. He has a M.S. in Engineering Management from University of Missouri – Rolla (UMR). He is currently a Ph.D. student and a Research Assistant in the Department of Engineering Management at UMR. His area of interest is price forecasting using neural networks.

David Enke has a B.S. in Electrical Engineering and a M.S. and Ph.D. in Engineering Management, all from the University of Missouri – Rolla (UMR). His research and teaching interests are in the areas of electric load and price forecasting, financial engineering and financial risk analysis, engineering economics, and investment. Dr. Enke has previously worked with electric utilities developing neural network and expert system-based load and price forecasting models, as well as researching the effects of electricity deregulation in the United States and Europe.

Badrul H. Chowdhury (M'1983, SM'1993) obtained his M.S. and Ph.D. degrees in Electrical Engineering from Virginia Tech, Blacksburg, VA in 1983 and 1987 respectively. He is currently a Professor in the Electrical & Computer Engineering department of the University of Missouri-Rolla. From 1987 to 1998 he was with the University of Wyoming's Electrical Engineering department where he reached the rank of Professor. Dr. Chowdhury's research interests are in power system modeling, analysis and control. He teaches courses in power systems, power quality and power electronics.