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Transmission Cost Allocation using Power flow Tracing

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Abstract: In the present open access deregulated power system market, it is necessary to develop an appropriate pricing scheme that can provide the useful economic information to market participants, such as generation, transmission companies and customers. However, accurately estimating and allocating the transmission cost in the transmission pricing scheme is a challenging task although many methods have been proposed. The objective of this thesis is to introduce a simple transmission pricing scheme using a power flow tracing method, in which transmission service cost, congestion cost and loss cost are considered. Numerical example using a test power system is presented to illustrate the effectiveness of the studied method. Electricity tracing can assess the particular impact of a generator or demand on the power system [1]. For each generator, the technique can determine the demands they supply, and likewise, for each demand, the technique can determine the generators who provide physical supply. In addition, the proportion of the total electricity flow in each individual transmission asset can be attributed to either the generators or demands that use the asset. A tracing algorithm has been developed and applied to historic market load flow solutions for each half–hour during the ten year time period, 1999–2008. Results are presented illustrating flow patterns from generators to demand and patterns of transmission asset usage. Continuing trend towards deregulation and unbundling of transmission services has resulted in the need to assess what the impact of a particular generator or load is on the power system. Anew method of tracing the flow of electricity in meshed electrical networks is proposed which may be applied to both real and reactive power flow. The method allows assessment of how much of the real and reactive power output of a particular station goes to a particular load. It also allows the assessment of the contribution of individual generators to individual line flows. The method can be useful in providing additional insight into power system operation and can be used to modify existing tariffs of charging for transmission loss, reactive power and transmission services.

Keywords: Proportional sharing, LMPs, service cost, congestion cost, loss cost.

I. INTRODUCTION

The traditional vertically integrated power industry is undergoing significant changes. Functions and ownerships of generation, transmission and distribution are unbundled and separated from the traditional power system structure. The competition among generations is allowed to supply the economical energy and customers have more options to choose their suppliers. Pursuing the economical goal in order to increase the revenue or reduce the cost becomes the new objective for all market participants. The transmission system under this environment should provide services through non-discriminatory open access to all generations and customers.

The transmission system is an essential facility that every participant has to use it. It is composed of the integrated transmission network that was owned and controlled by traditional utilities before. Now it can be considered as an independent transmission company and provides open access to all participants. Power suppliers and customers should be charged a price for the recovery cost of the transmission service. Utilities need to know such cost to make correct economic and engineering decisions on upgrading and expanding the generation, transmission and distribution facilities. Any pricing scheme should compensate transmission companies fairly for providing transmission services, estimate costs due to congestion problems, determine the loss cost and allocate entire transmission costs reasonably among all transmission users, both native load and third party. There is significant on-going research into the calculation and allocation of the transmission cost. In [2] some usage-based allocation methods were reviewed and compared. However, these references have focused only on the calculation and allocation of the transmission service cost. Reference [4] made some improvements and estimated the service cost and congestion cost separately.

This section presents a transmission pricing scheme using a power flow tracing method to determine the transmission service, congestion and loss cost. The goal is to trace the actual contributions of generators (loads) to each line flow and loss using tracing method, and then the transmission cost can be calculated and allocated based on these contributions. This method can also be applied to estimate the locational marginal price (LMP) used for the congestion cost calculation instead of the Generation Shift Factor method [4, 9].

The following paper discusses the different components of transmission cost. Cost calculation using the power flow

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tracing method is also presented. An IEEE standard system has been taken as an example and the results cited.

II. OVERVIEW AND SOME BASIC TERMS

The key concept of using the Tracing method is the calculation of the usage of a branch in the system. The contributions by generators and loads are determined by tracing the power which flows through this branch up to the generators and down to the loads which consume it.

The basic assumption used by tracing methods is the proportional sharing principle [5-6]. It means that the nodal inflows will be shared proportionally between the nodal outflows. The proportion of the inflow through a particular node allocated to particular generators is the same as the proportion of the outflow allocated to the same generators. It is illustrated in Fig. 1.

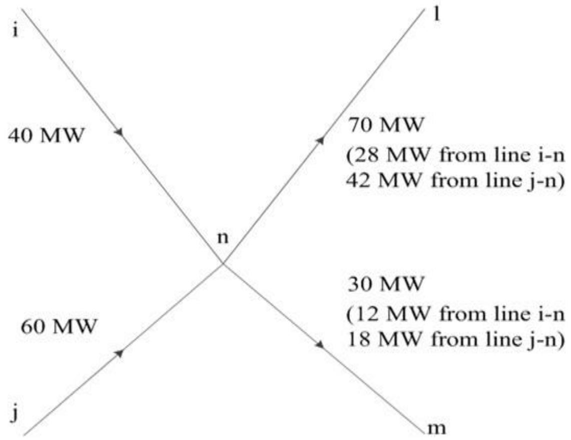

Fig: 1 Proportional sharing principle

The line m-i power inflow through node i is Pi = 60MW, of which 60% is assumed to be supplied by generator 1 and 40% by generator 2. Hence the 20MW outflow of line i-n is allocated to generator 1 as 20x60%=12MW and to generator 2 as 20x40%=8MW. Similarly the 40MW outflow of line i-o consists of the contribution 1 40x60%=24MW from generator 1 and the contribution 2 40x40%=16MW from generator 2. Some important concepts, such as domains, commons, links and state graph, are used. The domain of a particular generator is defined as the set of buses supplied by that generator. The concept of commons is the set of adjacent buses supplied by the same set of generators. In addition, links are branches connecting commons. The power system can be simplified to an acyclic state graph with directed flows between commons. Taking a 6-bus system as an example, the system includes three commons and three links. Fig. 2 shows the generations/loads in commons and flows on links. The recursive calculation procedure for tracing the contribution of generators to commons, links and loads is applied in this method is given by the following equations:

$$F_{ijk} = C_{ij} F_{jk} \quad (1)$$

$$I_k = \sum_j F_{jk} \quad (2)$$

$$C_{jk} = \frac{F_{ijk}}{I_k} \quad (3)$$

C_{jk} = contribution of generator i to the load and the outflow of common k
F_{jk} = flow on the link between commons j and k
F_{ijk} = flow on the link between commons j and k due to generator i
I_k = inflow of common k

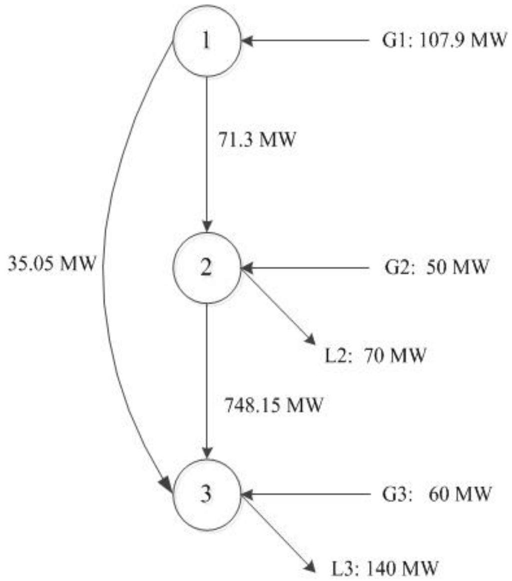

Fig: 2 Acyclic state graph example

III.OVERVIEW AND SOME BASIC TERMS

The study presented in this paper considers three types of costs: transmission service cost, transmission congestion cost and transmission loss cost. Only service cost and congestion cost were mentioned in most references [3-4]. However, the pricing scheme should include loss cost since it can accurately reflect all related transmission costs. A simple 2-bus power system is used to illustrate the different components of the transmission cost.

A. Transmission service cost

Transmission service cost is defined as the fixed transmission cost or embedded cost that covers the transmission revenue requirement of transmission owners. It is the direct cost of providing transmission services for the recovery of past capital transmission networks investment [3, 8].

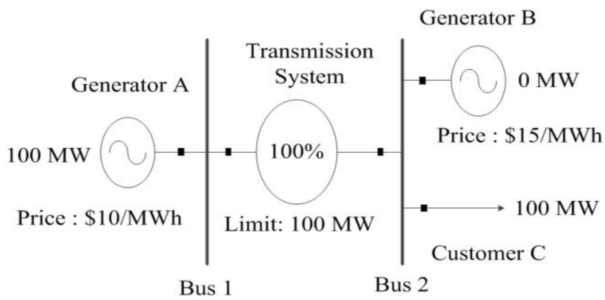

Fig. 3 Illustration for transmission service cost

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Fig. 3 shows that generator A and customer C will be charged as the transmission service cost for 100 MW electricity delivered from A to C. For this operating scenario, generator B does not have to pay.

B. Transmission Congestion Cost

The congestion cost reflects the charge for the incremental electrical power delivery through the constrained transmission networks. It includes operating cost for generation dispatch and transmission transaction rescheduling, reinforcement cost for capital costs of new transmission facilities and opportunity cost for benefits caused by antecedent transaction planning of utilities due to operational constraints [3, 4, 8].

As shown in Fig. 4, when the demand of customer C is increased to 120MW, congestion occurs since the capacity of the transmission line is 100 MW. The more expensive generator B has to be brought into the market to supply extra energy to customer C. The congestion also causes the difference in locational marginal prices (LMPs) of two buses. Therefore, all participants, including generator A, B and customer C will pay the congestion cost to transmission system owner for the dispatching operational cost and extra transaction cost due to the difference in LMPs. Assuming the LMPs of bus 1 and 2 are 10 and 15 $/MWh respectively, the congestion cost is equal to 100 MW x (15-10) = 500 $/hr. and this cost will be allocated to generator A, B and Customer C.

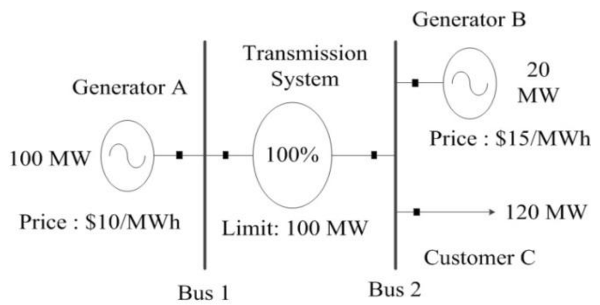

Fig. 4 Illustration for transmission congestion

C. Transmission Loss Cost

The loss cost reflects the recovery cost of electricity transmission losses due to transmission line resistances. Fig. 5 shows that the power flow from generation A to customer C loses 2 MW to loss in the transmission line. Thus, generator A should be compensated and customer C should be charged for the energy loss.

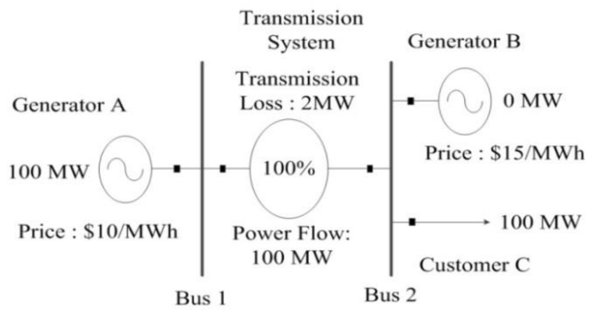

Fig. 5 Illustration for transmission loss cost

Some references claimed that loss cost should not be considered as the component of the transmission cost and it is unfair for those participants being charged. Nevertheless, more and more utilities pay more attention to this topic since the loss has great influence for the efficiency and competition of the company. Hence, the loss cost should be considered in the pricing scheme.

As a result, the total transmission cost in the pricing scheme is given by:

$$TC_t = C_t^S + C_t^C + C_t^L \quad (4)$$

where

TC_t = Total transmission cost of the transaction t
C_t^S = Total service cost of the transaction t
C_t^C = Transmission congestion cost of the transaction t
C_t^L = Transmission loss cost of the transaction t

For generation companies, C_t^S and C_t^C are charges paid to transmission companies and C_t^L is the revenue from customers as the compensation. For transmission companies, C_t^S and C_t^C are revenues while C_t^L is equal to zero since they are not related to loss costs. For customers, all components of the cost are payments. C_t^S and C_t^C are paid to transmission companies and C_t^L is paid to generation companies.

IV. POWER FLOW TRACING METHOD BASED COST CALCULATION

The Tracing methods, including the upstream and downstream looking algorithms, described in the previous chapters, did not consider the calculation of the loss cost. In this section, the calculations of all three components of the transmission cost are presented. In addition, the estimation of the LMPs using tracing method is also given.

A. Calculation of Transmission Service Cost

Using the Tracing Methods, the contribution of each generator (load) on each line flow can be determined. Then the transmission service cost will be allocated to each participant based on the contribution.

Let f_{m-n,G_i} (f_{m-n,D_i}) refer to the contribution of each generator (load) at bus i to each line flow f_{m-n}. D_{m-n} is the length of line m-n in miles, and R_{m-n} represents the required transmission service cost per unit length of line m-n ($/mile hr.), the service cost for line m-n corresponding to generator (load) G_i (D_i) is given by:

$$C_{m-n,G_i}^s = \frac{f_{m-n,G_i} D_{m-n} R_{m-n}}{f_{m-n}} \quad (5)$$

$$C_{m-n,D_i}^s = \frac{f_{m-n,D_i} D_{m-n} R_{m-n}}{f_{m-n}} \quad (6)$$

If Z_{m-n} is the required transmission service cost of line m-n in $/hr and is equal to $Z_{m-n} = D_{m-n} R_{m-n}$, the payment of $G_i(D_i)$ for the service cost of all lines is as follows:

$$C_{G_i}^S = \sum_{all\ lines} C_{m-n,G_i} = \sum_{all\ lines} \frac{f_{m-n,G_i} D_{m-n} R_{m-n}}{f_{m-n}} \quad (7)$$

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$$= \sum_{all\ lines} \frac{f_{m-n,G_i} Z_{m-n}}{f_{m-n}}$$

$$C_{D_i}^S = \sum_{all\ lines} C_{m-n,D_i} \quad (8)$$

$$= \sum_{all\ lines} \frac{f_{m-n,D_i} D_{m-n}\ R_{m-n}}{f_{m-n}}$$

$$= \sum_{all\ lines} \frac{f_{m-n,D_i} Z_{m-n}}{f_{m-n}}$$

The total payment by all participating generators (loads) for transmission service cost is

$$C_{Gt}^S = \sum_{j\in S_G} \sum_{all\ lines} \frac{f_{m-n,G_i} Z_{m-n}}{f_{m-n}} \quad (9)$$

$$C_{Dt}^S = \sum_{j\in S_G} \sum_{all\ lines} \frac{f_{m-n,D_i} Z_{m-n}}{f_{m-n}} \quad (10)$$

B. Calculation of Transmission Congestion Cost

The transmission congestion cost is mainly based on the actual power flow through the congested transmission line and the difference in locational marginal prices (LMPs) between the source buses and sink buses [4, 9]. The key is to determine contributions of generations or loads to each line flow and the LMP value of each bus. Tracing method is considered to calculate these contributions and LMPs.

Let f_{m-n,G_i} (f_{m-n,D_i}) be the contribution of a generator (G_i) or load (D_i) at bus I to a line flow between bus m and a. The congestion costs that are allocated to the generator (load) are presented below:

$$C_{G_j}^C = \sum_{j\in S_G} f_{m-n,G_i} X\ (LMP_n - LMP_m) \quad (11)$$

$$C_{D_i}^C = \sum_{j\in S_G} f_{m-n,D_i} X\ (LMP_n - LMP_m) \quad (12)$$

Contributions of generators using Tracing method can also be used to determine locational marginal prices (LMPs). In reference [13, 17], generation shift factors that predict the effect of generation changes on transmission line flows were applied to determine the LMP value. Since the power flow in generations, the LMP of each bus can be determined based on the contributions of generators on power flows and generator marginal prices.

The first step is to determine all marginal generators that supply the incremental power demand on each bus. For the buses connecting marginal generators in a power system, the LMP value of a particular bus is equal to the marginal price of the particular generator connected to the bus. For other buses without marginal generators, the LMP of a particular bus depends on the contributions of marginal generators to line power flows corresponding to the bus.

Let ${f_{m-n,i}}^{G_j}$ refer to the contribution of each marginal generator j to each line flow $f_{m-n,i}$ corresponding to bus I, and W_{G1} represents the generator marginal price of generator G_j ($/MWh) the LMP at bus i is given by

$$LMP_i = \sum_{all\ generators} W_{G_j} \frac{\sum {f_{m-n,i}}^{G_j}}{\sum f_{m-n,i}} \quad (13)$$

C. Calculation of Transmission Loss Cost

The principle and procedure of loss cost calculation and allocation are similar to the calculation of the service cost. It is also based on the contribution of each generator (load) on each line flow using tracing method.

Let L_{m-n,G_i} (L_{m-n,D_i}) refers to the contribution of each generator (load) at bus I to each line lossL_{m-n}, and W_{G_I} represents the generator marginal cost unit of generator G_i ($/MWh). The loss cost for line m-n corresponding to generator G_i is given by:

$$C_{m-n,G_i}^L = \sum_{all\ lines} L_{m-n,G_I} W_{G_i} \quad (14)$$

Since generators and load should equally share the loss cost and loads will pay these costs to generations, the payment of D_i for the loss cost of the line m-n is as follows:

$$C_{m-n,G_i}^L = \frac{1}{2} C_{m-n,G_i} \frac{L_{m-n,D_i}}{L_{m-n}} \quad (15)$$

The payment of D_i for the loss cost of all lines is given by:

$$C_{D_i}^L = \sum_{all\ lines} C_{m-n,D_i} \quad (16)$$

$$= \sum_{all\ lines} \frac{1}{2} C_{m-n,G_i} \frac{L_{m-n,D_i}}{L_{m-n}}$$

The total payment by all participating customers for transmission cost is:

$$C_{Dt}^L = \sum_{j\in S_G} \sum_{all\ lines} \frac{1}{2} C_{m-n,G_i} \frac{L_{m-n,D_i}}{L_{m-n}} \quad (17)$$

The outline of the proposed transmission pricing scheme is as follows:

Step 1: Determine power flows based on the initial transaction schedule.

Step 2: Calculate contributions of generators (Loads) to line flows and losses using the tracing method.

Step 3: Determine LMPs based on the contributions of generators to the power flow in the lines.

Step 4: Allocate transmission service cost, congestion cost and loss charges to each participant.

V. RESULTS AND CALCULATIONS

In the study of this thesis, the standard IEEE 14 bus system is used to demonstrate the results. The results of the Newton Rhapson Load Flow analysis are shown in Table 2 and 3 respectively.

After applying the Upstream looking algorithm we may obtain the load flow in line 1-2 due to generation in bus1, generation in bus 2 and so on. Similarly the power flows in other lines due to different generations may also be calculated. It also provides us with the proportion of power supplied to the different loads by different generations.

The results obtained for the given 14 bus system in two of the lines due to generations in bus 1 and 2 is shown in Table 1 below.

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Table 1: Line flows due to different generations.

Load Flow in line	Generation in bus 1	Generation in bus 2
1-2	127.31	0
2-3	11.08	3.2

Table 2: Newton Rhapson Load flow analysis

Bus no	V (pu)	Angle (degree)	Injection (MW)	Injection (MVAr)	Generation (MW)	Generation (MVAr)	Load (MW)	Load (MVAr)
1	1.0600	0.0000	188.862	-9.902	188.862	-9.902	0.000	0.000
2	1.0450	-4.0505	18.300	21.934	40.000	34.634	21.700	12.700
3	1.0100	-11.174	-94.200	4.904	0.000	23.904	94.200	19.000
4	1.0202	-8.2376	-47.800	3.900	-0.000	-0.000	47.800	-3.900
5	1.232	-6.9145	-7.600	-1.600	0.000	0.000	7.600	1.600
6	1.0700	-10.326	8.800	8.338	20.000	15.838	11.200	7.500
7	1.0528	-9.3976	-0.000	-0.000	-0.000	-0.000	0.000	0.000
8	1.0900	-7.6384	20.000	23.311	20.000	23.311	0.000	0.000
9	1.0356	-11.169	-29.500	-16.600	0.000	0.000	29.500	16.600
10	1.0341	-11.302	-9.000	-5.800	0.000	0.000	9.000	5.800
11	1.0482	-10.935	-3.500	-1.800	-0.000	-0.000	3.500	1.800
12	1.0537	-11.204	-6.100	-1.600	-0.000	-0.000	6.100	1.600
13	1.0473	11.2762	-13.500	-5.800	0.000	-0.000	13.500	5.800
14	1.0225	-12.238	-14.900	-5.000	-0.000	-0.000	14.900	5.000
Total			9.862	14.285	268.862	87.785	259.00	73.500

Table 3: Line Flow and Losses

From bus	To bus	P (MW)	Q (MVar)	From Bus	To bus	P(MW)	Q(MVar)	Line Loss (MW)	Line Loss (MVar)
1	2	128.756	-10.62	2	1	-125.877	19.413	2.879	8.790
1	5	60.107	6.452	5	1	-58.349	0.802	1.757	7.254
2	3	67.659	6.530	3	2	-65.671	1.846	1.988	8.376
2	4	44.671	1.589	4	2	-43.608	1.637	1.063	3.226
2	5	31.847	3.421	5	2	-31.312	-1.788	0.535	1.634
3	4	-28.529	5.945	4	3	29.087	-4.521	0.558	1.424
4	5	-53.936	10.422	5	4	53.323	-9.202	0.387	1.221
4	7	10.632	-16.17	7	4	-10.632	16.901	0.000	0.736
4	9	10.025	-2.663	9	4	-10.025	3.220	0.000	0.557
5	6	27.738	-19.55	6	5	-27.738	22.132	0.000	2.583
6	11	9.458	7.259	11	6	-9.340	-7.013	0.118	0.247
6	12	8.170	2.942	12	6	-8.089	-2.773	0.081	0.168
6	13	18.911	9.150	13	6	-18.656	-8.648	0.255	0.502
7	8	-20.00	-21.91	8	7	20.000	23.311	0.000	1.399
7	9	30.632	16.935	9	7	-30.632	-15.719	0.000	1.216
9	10	3.209	0.703	10	9	-3.206	-0.695	0.003	0.009
10	11	-5.794	-5.105	11	10	5.840	5.213	0.046	0.107
12	13	1.989	1.173	13	12	-1.978	-1.164	0.011	0.010
13	14	7.134	4.012	14	13	-7.029	-3.799	0.104	0.213

Table 4: Contribution of selected Generators to selected Line flows

Line	Pij (MW)	Flow Allocation to Generator 1	Flow Allocation to Generator 2
1 – 2	128	127.32	0
2 – 3	67.65	11.08	3.2
2 – 4	44.67	7.34	2.12
2 – 5	31.84	5.25	1.52

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4 – 3	29.1	0.42	0.05
4 – 7	10.63	0.15	0.02
4 – 9	10.02	0.15	0.02
5 – 4	54.32	11.1	0.26
5 – 6	27.74	5.7	0.13

Based on the concept of the 'commons' and the tracing method, selected line power flows have been allocated to individual generators or as shown in Table 4. It gives us the contributions of selected generators to selected line flows.

The locational marginal price of each bus should be estimated in order to calculate the congestion costs. Table 5 and 6 present the LMPs results based on the contributions of generators to line flows (buses linked with bus 2) and the assumed generator marginal prices. Based on equation (13), the LMP of bus 2 is given by:

LMP_2 = 28.04 x (127.32 + 11.08 + 7.34 + 5.25) / (67.65 + 44.67 + 31.84 + 128) + 27.44 x (3.2 + 2.12 +1.52) / (67.65 + 44.67 + 31.84 + 128)

Table 5: Locational Marginal Prices (LMP) of selected buses

Bus No.	LMP ($/MWh)
2	16.25
3	4.3
4	4.1
5	5.9

Table 6: Assumed Selected Generator Marginal Prices

Generators	Assumed Marginal Price ($/MWh)
G1	28.04
G2	27.44

Table 7: Assumed required Transmission Service Costs (TSC)

Lines	TSC ($/hr.)
2 – 3	150
2 – 4	200
2 – 5	180

Table 8: Transmission Costs Allocated to selected Generators

Generator	Transmission Service Cost ($/hr)	Transmission Congestion Cost ($/hr)	Total Cost ($/hr)
G1	87.11	275.92	363.03
G2	25.18	79.73	104.91

VI. CONCLUSION

As shown in table 8, generator G1 is allocated the highest transmission cost since it is the larger energy supplier among the two selected generators. It demonstrates that the more power electricity suppliers deliver through the transmission networks, the more money they have to pay for the service. In addition, transmission service and congestion cost values of generators are positive because they are charges paid to transmission owners from generations. In contrast, the loss costs of generations are negative since the loss cost is a kind of "revenue compensations" of energy losses from loads. However, all transmission costs values of loads are positive and they are payments from loads. Service and congestion costs will be paid to transmission network owners and loss costs will be considered as compensations paid to generation companies.

This study illustrates that the proposed transmission pricing scheme can provide economic signals to each market participant about energy transactions.

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