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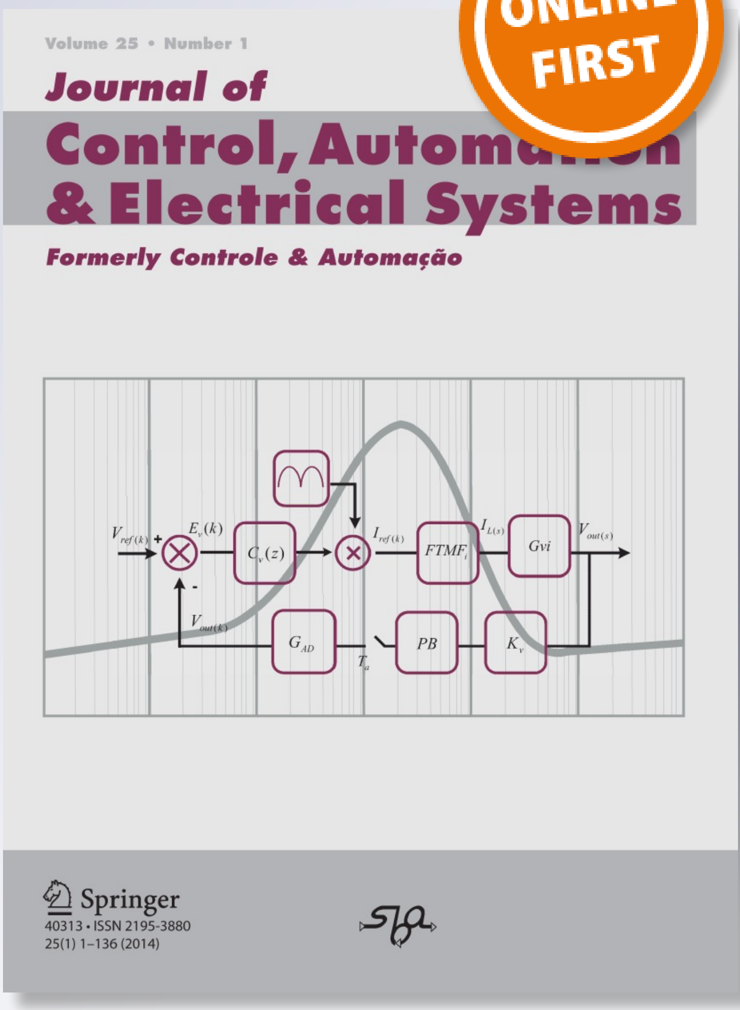
Journal of Control, Automation and Electrical Systems
formerly CONTROLE & AUTOMAÇÃO

ISSN 2195-3880

J Control Autom Electr Syst
DOI 10.1007/s40313-014-0106-x

ONLINE FIRST



Springer

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Security-Based Tariff for Wheeling Contracts Considering Fair Congestion Cost Allocation

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Received: 11 September 2013 / Revised: 3 December 2013 / Accepted: 31 December 2013

Abstract Transmission pricing is an important issue for transmission cost allocation. Because of the importance of this issue in the restructured power systems, several methods have been presented in recent years. Also, fairness of methods is a vital issue from the viewpoint of market designers and policy makers. This paper proposes a novel fair method to specify transmission tariffs, especially for wheeling contracts during peak and off-peak periods. In comparison to other recent studies, this approach has the advantage of considering congestion and security cost, when the wheeling contract leads to deviation from the optimum operation of wheeler network. Moreover, the security cost which is usually ignored in the transmission pricing will be allocated to market participants fairly. This method is applicable to implement in combined pool and bilateral electricity markets. In order to make a fair competition among market users, the congestion cost is allocated to all users in proportion to their contribution in network congestion. Compared with the current methods, the proposed approach take into consideration the congestion and security cost to strike the right balance between profit and cost related with fair market-based mechanisms. At the end, numerical examples on nine-bus test power system are utilized to demonstrate the effectiveness of the proposed approach.

Keywords Congestion cost · Security cost · Transmission tariff · Wheeling contract

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List of Symbols

Variables

F_{l-k}	Total transmission flow between buses l and k
F^0_{l-k}	Transmission flow between buses l and k obtained in previous iteration
$D_{l-k,r}$	D factor related to line connecting buses l and k caused by generation variation in reference bus
G_i	Total generation in bus i
$A_{l-k,i}$	Generation shift distribution factors (GSDF or A factors) related to line connecting buses l and k caused by generation changes in bus i
$C_{l-k,j}$	D factor related to line connecting buses l and k caused by generation variation in reference bus
$C_{l-k,r}$	GLDF related to the line between buses l and k caused by demand in bus r
L_j	Total demand in bus j
TTC	Total transmission cost
TC_t	The allocated cost to contract
TP	Wheeling tariff for the contract
TC	Transmission capacity cost
CC	Congestion cost allocated to contract

Published online: 31 January 2014

L_k	Length of line k (mile)
C_k	Cost per MW due to line unit length
$\mathrm{CC_B}$	Congestion cost allocated to Buyer
$\mathrm{CC_S}$	Congestion cost allocated to seller
$C_{N_{ij}}$	Normalized C factor related to buyer
$D_{N_{ij}}$	Normalized D factor related to seller
$\mathrm{TP_B}$	Wheeling tariff for buyer
$\mathrm{TP_S}$	Wheeling tariff for seller
C^k	Interruption cost for case k
B_I	The interruption cost in each buses
SC	System security cost
SC_{AC}	Security cost after applying wheeling contract to the network
SC_{BC}	Security cost before applying wheeling contract to the network
SP	Security tariff for wheeling contract

Set

T	Set of contracts
K	Set of transmission lines

Constant

P_D	Active power demand
P_G	Active power generation
$P_i\,j$	Power transferred by transmission lines
P	The amount of transmitted power
π^k	Probability that contingency k occur
k	Line number
P_L^0	Load in buses before line k outage
P_L^k	Load in buses after line k outage
Δf_l	Change in megawatt power flow on line l
ΔP_i	Change in injection or demand at bus i

1 Introduction

Power systems in many countries of the world have experienced restructuring during the last decades. The aim is increasing the efficiency in power generation and offering better services to electric power consumers (Bashian et al. 2011). In a monopoly electricity industry, the embedded cost approach is the basis for pricing. The purpose of this approach is to determine the transmission service cost and to allocate it among network users. This is one of the most commonly used methods; therefore, the return of the total transmission costs is guaranteed (Olmos and Arriaga 2009). After restructuring of power systems, transmission lines have been subjected to more efficiently operate to maximize their profit. As a result, bilateral contracts have received more consideration. In this environment, determination of contract tariff has become more important than before.

Nodal pricing method is the most popular method of transmission pricing, which is based on the difference between marginal cost prices at nodes in transmission systems. The main drawback of this method is that it is not able to produce enough revenue to recover the total transmission network costs (Ghayeni and Ghazi 2011).

Wheeling has been defined as the usage of a utility's transmission facilities to transmit power for other buyers and sellers (Panyakaew and Damrongkulkamjorn 2008. Therefore, the wheeling contract refers to a right for a buyer and a seller to use a utility's transmission network for energy transfer. Pricing of transmission services plays a crucial role in determining whether providing transmission crucial role in determining whether providing transmission services is economically beneficial to both the wheeling utility and the wheeling customers (Murali et al. 2011).

At least, three parties are involved in a wheeling transaction: a buyer, a seller, and one or more utilities which transmit the power from the seller to the buyer. The third party is paid for the usage of its network. The wheeler may not necessarily be the owner of transmission network, but it is generally known as the operator of the power system. Until now, several methods have been proposed for determination of wheeling cost. Wheeling cost models mainly have been based on two principles: the amount of the used transmission capacity for the transaction and the cost for transmission capacity (Majidi et al. 2008).

A wheeling transaction is defined as an injection into one or more nodes of the network and simultaneous retrieval from one or more nodes of the network. It can be classified as the following three categories (Liu et al. 2004):

1. Point to point wheeling transaction: both injection and retrieval are located in the same network. In the case of injection, this is an independent power producer (IPP).
2. Interconnected system-point: in this case, the retrieval of electrical energy is released in distribution network and injection is located outside of this network.
3. Point-inter connected system: in this case, the retrieval of electrical energy is located outside of network and injection is located inside of network.

Wheeling contracts have several impacts on wheeler network such as increasing losses, transmission congestion, and deviation from optimal power generation (Wang and Li 2004). Transmission security is one of the most important issues of transmission expansion planning and operation. Considering the network security, transmission lines are not fully loaded, and so considering the security cost in the transmission tariff seems to be reasonable. On the other words, when a wheeling contract is concluded, with respect to the presence of congestion in the wheeler network, the system security may be reduced or even deteriorated if the operation plans are not well coordinated. The security cost is ignored in all of the methods of transmission pricing approximately.

A wheeler tries to keep the power generation in its optimal pattern (Gnanadass and Padhy 2005). For each wheeling contract, the forced losses due to the contract must be recovered by sellers and buyers.

In this paper, the transmission cost is divided into three parts: capacity cost, congestion cost, and security cost. In order to make the fair transmission cost allocation mechanism, the proposed method utilizes power transfer distribution factors (Shahidehpour et al. 2000). Firstly, transmission capacity cost is calculated using distribution factors and MW-mile method. Then with implementation of wheeling contract to the network, congestion costs and security cost related to wheeling contracts are allocated to the contract parties, fairly.

This paper is organized as following: in Sect. 2, the existing different methods for transmission cost allocation are briefly explained. In Sect. 3, the distribution factors method is described. In Sect. 4, the novel proposed method of this paper for specifying fair hourly tariff of wheeling contracts has been described. Finally, in Sect. 5, the proposed method has been implemented on a nine-bus IEEE test power system. Using simulation results in Sect. 5, the validity of the method is evaluated.

2 Overview of Transmission Pricing Methods

From the network owner's viewpoint, transmission pricing should recover the total costs for transmission services. On the other hand, network users tend to have a reasonable pricing scheme for usage of power system. Different methods for transmission pricing have been proposed. Based on the recent studies, the wheeling prices mainly utilize one of the two basic methods as:

1. Marginal cost methods.
2. Embedded cost methods (Shahidehpour et al. 2000).

A complete wheeling charge method has to fulfill the following items (Hassan 2000):

1. Conciseness and transparency.
2. Recovery of invested cost.
3. Efficient operation of electric network.
4. Fairness and acceptability for wheeling service users.

Marginal cost methods do not necessarily satisfy the first and the second items mentioned above. Therefore, embedded cost methods are more acceptable. On the other hand, the embedded cost methods have remarkable features (Hamada et al. 2009). Embedded cost methods are advantageous, because these methods not only allocate total costs to transmission network users according to their usage of system, but also these methods can recover the investment cost (Abdullah et al. 2008). In embedded cost methods, network owner cannot make illegal profit by exercising the market power. However, the total cost for transmission usage is recovered in these methods; it is more acceptable for network users (Su and Liaw 2001). On the other hand, the embedded cost method may be disadvantageous, because this method, in its general form, does not determine high or low usage of network. The main deficiency for both of the above mentioned methods is that they do not consider the costs for congestion and losses (Happ 1994).

Embedded cost methods include post stamp, contract path and MW-mile methods. In the first two methods load flow calculation is not performed. On the other hand, the MW-Mile method is based on load flow calculation. In MW-mile method, transmission embedded cost is allocated to transactions in proportion to the ratio of flow magnitude contributed by each particular transaction. In order to consider the reactive power transactions and active power in transmission facilities simultaneously, MW-mile method may be expanded as MVA-mile method. In this way, both active and reactive power changes are considered (Yousefi and Seifi 2004). In Hamada et al. (2009), wheeling charges are calculated based on identification of transactions paths. Utilizing this method, some of disadvantages of conventional MW-mile method may be resolved.

In this paper, a fair method for specifying transmission tariffs, especially for wheeling contracts, during peak and off-peak periods is proposed. In this method, the congestion cost is allocated to all users whose their transactions contribute in congestion occurrence. Moreover, the security cost which is usually ignored in the transmission pricing methods is allocated to market users fairly. The congestion and security cost are allocated to market users in proportion to their contribution in network congestion and network security reduction, respectively. The proposed approach can ensure fairness among market participants and guarantee power system security during wheeling contract.

3 Distribution Factor Method

Distribution factors are calculated using linear load flow. By using these factors, the effect of each generator and load on transmission flow can be evaluated properly (Shahidehpour et al. 2000).These factors show the approximate change in line flows for changes in generation on the network configuration and are derived from the DC load flow. These factors can be derived in a variety of ways and basically come down to two types:

- Generalized generation distribution factors (GGDF).
- Generalized load distribution factors (GLDF).

In this paper, the mentioned linear sensitivity factors are used in order to evaluate the power system security. This sensitivity factors are described in the next parts.

4 Generalized Generation Distribution Factors (GGDF or D Factors)

These factors specify the amount of change in real power of a transmission line caused by variation in generation level of a certain generator. The type of cost allocation depends on the structure and regulations of the market. Usually in case of negative GGDF, system operator allocates no cost to the participants.

D factors are defined as follows:

$$\begin{aligned} &F_{l-k} = \sum_{i=1}^{N} D_{l-k,i} G_i \\ &D_{l-k,i} = D_{l-k,r} + A_{l-k,i} \\ &D_{l-k,r} = \left\{ F^{\circ}_{l-k} - \sum_{i=1}^{N} A_{l-k,i} G_i \right\} \sum_{i=1}^{N} G_i . \end{aligned} \tag{1}$$

GGDF factors determine the total usage of transmission network related to injections in the network.

4.1 Generalized Load Distribution Factors (GLDF or C Factors)

These factors determine the contribution of each load in transmission line flow. C factors are defined as follows (Shahidehpour et al. 2000):

$$C_{l-k\cdot r} = \left\{ F^{\circ}_{l-k} + \sum_{\substack{j=1 \\ j\neq}}^{N} A_{i-k,j} L_j \right\} / \sum_{j=1}^{N} L_j \tag{2}$$

$$C_{l-k\cdot j} = C_{l-k,r} - A_{l-k,j} \tag{3}$$

$$C_{l-k\cdot r} = \left\{ F^{\circ}_{l-k} + \sum_{\substack{j=1 \\ j\neq}}^{N} A_{i-k,j} L_j \right\} / \sum_{j=1}^{N} L_j . \tag{4}$$

Note that these factors are obtained from reactance matrix and DC load flow relaxation.

5 Proposed Method Formulation

In this paper, the transmission cost is divided into three parts: capacity cost, congestion cost, and security cost. The congestion cost is allocated to all users whose transactions contribute in congestion occurrence. Distribution factors are used to allocate this cost to different buses. Capacity cost is calculated using distribution factors and utilizing the MW-mile method. Then, by applying wheeling contracts to the network, the congestion cost related to the contract is allocated fairly to contract parties. Also the security cost related to the wheeling contract is allocated to its parties in proportion to their contribution in network security reduction.

In the proposed method, the Pool–Bilateral model is assumed for the electricity market. After setting the amount of power for the wheeling contract including wheeler generation and load data, an optimal power flow (OPF) will be performed in the network. Therefore, the generation and consumption of buses, power transmitted in each line, transmission losses, bus voltage and the locational marginal pricing (LMP) in network buses is calculated. The OPF problem in restructured power system is formulated as follows:

$$\text{Min} \sum C_{G_i}(P_{G_i}) \tag{5}$$

$$s.t: g(\delta, V, Q_{\text{G}}, P_{\text{G}}, P_{\text{D}}) = 0 \tag{6}$$

$$0 \le P_{\text{G}} \le P_{\text{G}\max} \tag{7}$$

$$0 \le P_{\text{D}} \le P_{\text{D}\max} \tag{8}$$

$$\left| P_{ij}(\delta \cdot V) \right| \le P_{ij\max} \tag{9}$$

$$Q_{\text{G}\min} \le Q_{\text{G}} \le Q_{\text{G}\max} \tag{10}$$

$$V_{\min} \le V \le V_{\max}, \tag{11}$$

where the Eq. 6 represent load flow equations for power network. This nonlinear optimization is solved based on Lagrange method. The Lagrange factor is involved with an economic concept. It can show the locational marginal price in each bus in the power network.

6 Capacity Cost

In this paper, transmission capacity cost is calculated using the method in Bashian et al. (2011):

$$TC_t = TC \cdot \frac{\sum_{k\in K} C_k L_k MW_{t,k}}{\sum_{t\in T} \sum_{k\in K} C_k L_k MW_{t,k}}. \tag{12}$$

TC refers to as the transmission cost which includes the investment and operation costs. TC is calculated for each line of the network using the information which is determined by the network manager (Shahidehpour et al. 2000).

According to the above formulation, each user of the network should pay a kind of cost as the transmission cost in proportion to its contribution in transmission lines flows which can be calculated by using distribution factor method.

7 Congestion Cost

By applying the wheeling contracts, due to network congestion and losses, the wheeler network deviates from its optimal generation pattern. So wheeler should receive additional costs imposed by contract parties. For this reason, OPF is executed for the network until injections and deviations of generations from the optimal pattern are calculated. This cost will be added to transmission cost. Therefore, if congestion occurs in some weak lines, the congestion cost must be allocated only to contract parties. After calculation the contribution of each user in congested lines, according to distribution factors, the congestion cost for buyer and seller will be calculated and added to transmission tariff as followings:

$$CC_{\mathrm{S}} = D_{N_{ij}} \cdot CC \tag{13}$$

$$CC_{\mathrm{B}} = C_{N_{ij}} \cdot CC \tag{14}$$

In off-peak hours, the congestion cost is not allocated to contract parties, because the transmission lines do not exceed their thermal limit. This can be important for transmission cost allocation.

The wheeling tariff can be written as below:

$$TP = \frac{TC + CC}{P} \tag{15}$$

The transmission tariff for contract parties can be written as below:

$$TP_{\mathrm{B}} = \frac{TC/2 + CC_{\mathrm{B}}}{P} \tag{16}$$

$$TP_{\mathrm{S}} = \frac{TC/2 + CC_{\mathrm{S}}}{P} \tag{17}$$

8 Security Cost

In this paper, in addition to considering the capacity cost and congestion cost, the system security cost is considered. The security cost approach can strike the right balance between power system security and cost which is compatible with market mechanisms. The security cost of wheeling charge has not been considered in the previous methods. In this method, N-1 contingency is assumed for security cost calculation. Firstly, the security cost will be considered in the network without wheeling contract. Then, applying wheeling contracts to the network, security cost is calculated. The difference between two costs is considered as the cost of security reduction related to the wheeling contract.

In this method, random line outage is taken into account as the N-1 examination of lines to evaluate the power system security. Therefore, the load interruption cost is calculated associated with random line outage.

The load interruption cost minimization is the objective function in this method:

$$Min\{\sum_{k=1}^{k} \pi^k C^k\} \tag{18}$$

Where $C^k$is defined as below:

$$C^k = B_I[P_L^0 - P_{\mathrm{L}}^k]. \tag{19}$$

For minimizing the C^{k}, the A factors must be calculated firstly. These factors show the effect of injections and demands on the transmission line flows. These factor can be written as below:

$$A_{\mathrm{l_i}} = \frac{\Delta f_{\mathrm{l}}}{\Delta P_{\mathrm{i}}} \tag{20}$$

where ΔP represent the change in injection or demand at bus i as one unit and Δf is represent the change in active power flow on line l when a change in generation ΔP_{i} occurs at bus i. The A factor may be positive or negative.

Considering the random line outage in the transmission network, A factors are calculated and the congested lines will be determined. Now, some loads must be interrupted for congestion relieving. For interruption cost minimization, two important point are assumed:

1. Choice of a load that has the most effect on the congested line respect of A factors ($A_{\max}$).
2. Interruption cost in each bus per MW (B_{I}).

Therefore in each case, A factors are sorted and divided to buses interruption cost:

$$\mu_{\mathrm{L}} = \frac{A_{\max}}{B_I}. \tag{21}$$

Therefore, a load with lower interruption cost is determined. The interruption cost due to load interruption is calculated as below:

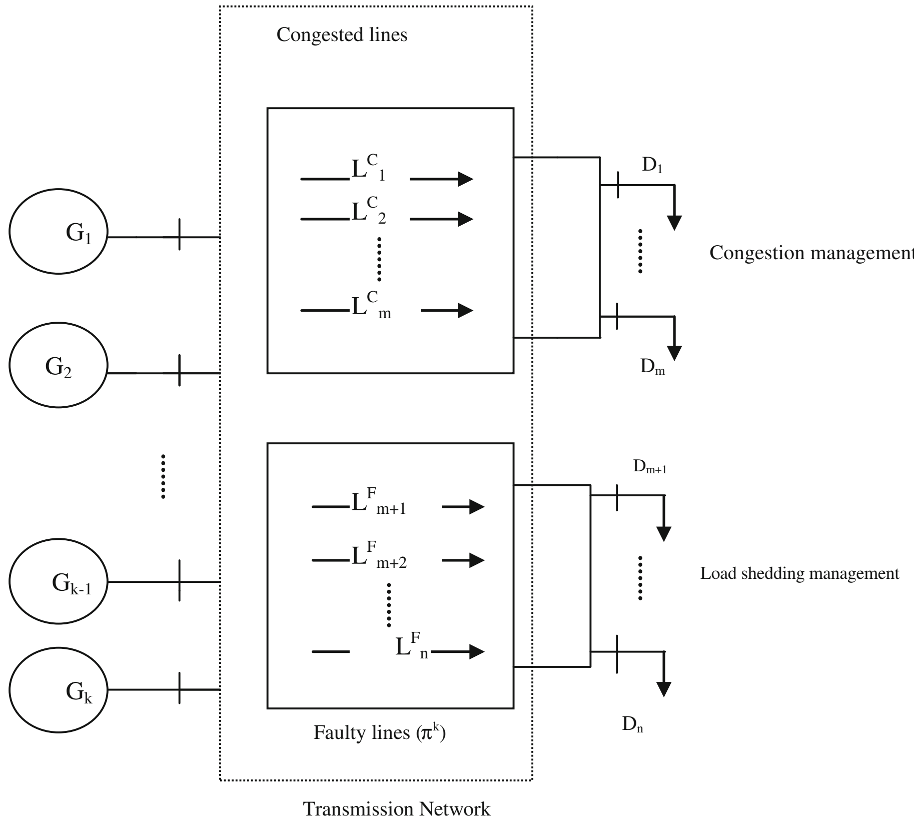
$$C^k = B_I[P_{\mathrm{L}}^0 - P_{\mathrm{L}}^k]. \tag{22}$$

There are some technical limitations on the load magnitude we can drop when a random line outage occurs in weak transmission lines. This amount is given by $P_{\mathrm{Li,min}}$. If the amount of load for interrupting be more than the predefined load limit, second priority will be taken for load interruption.

Now, with considering line outage probability π^k and calculation of C^k in each case, the security cost can be written as below:

$$SC = \sum_{k=1}^{k} \pi^k C^k. \tag{23}$$

Fig. 1 The schematic plan of transmission network in proposed approach



Therefore the security tariff for wheeling contract can be written as follow:

$$SP = \frac{SC_{AC} - SC_{BC}}{P}. \tag{24}$$

Figure 1 shows the schematic plan of congested lines (because of congestion occurrence) and faulty lines (because of executing the N-1 examination of lines) in transmission network.

9 Wheeling Tariff

After calculation of capacity, congestion, and security cost for wheeling contract, we can obtain the wheeling tariff. By applying the wheeling contract during the peak loads, the congestion probability will be increased and the congestion cost should be paid by contract parties; therefore, this method leads to a significant increase in transmission price in peak periods. Moreover, the security cost will be increased by reason of approaching the lines to the thermal limit. Therefore, the proposed method causes wheeling tariff to increase in peak periods, without assuming the excess tariff in these hours. It can send a good signal for system users for load shifting from peak hours to off peak hours. Respect to Eqs. 16, 17, and 24, wheeling tariff for seller and buyer can be written as below:

$$TP_B = \frac{(TC + SC)/2 + CC_B}{P} \tag{25}$$

$$TP_S = \frac{(TC + SC)/2 + CC_S}{P} \tag{26}$$

The proposed approach can be summarized as the following steps.

- Step 1 Run OPF in normal condition of power system without wheeling contract.
- Step 2 Calculate security cost.
- Step 3 Apply wheeling contract to the network.
- Step 4 Run OPF in new condition with applying wheeling contract.
- Step 5 Calculate distribution factors and A factors.
- Step 6 Calculate security cost with applying wheeling contract.
- Step 7 Check the congestion occurrence in all transmission lines. If the congestion occurred in a line go to step 8, otherwise go to step 9.
- Step 8 Calculate distribution factors and wheeling parties' portion of congested lines.
- Step 9 Determine security, congestion and capacity cost according to step 5, 6 and 8.
- Step10 Calculate wheeling tariff for buyer and buyer.

The process is summarized in flowchart of figure 2.

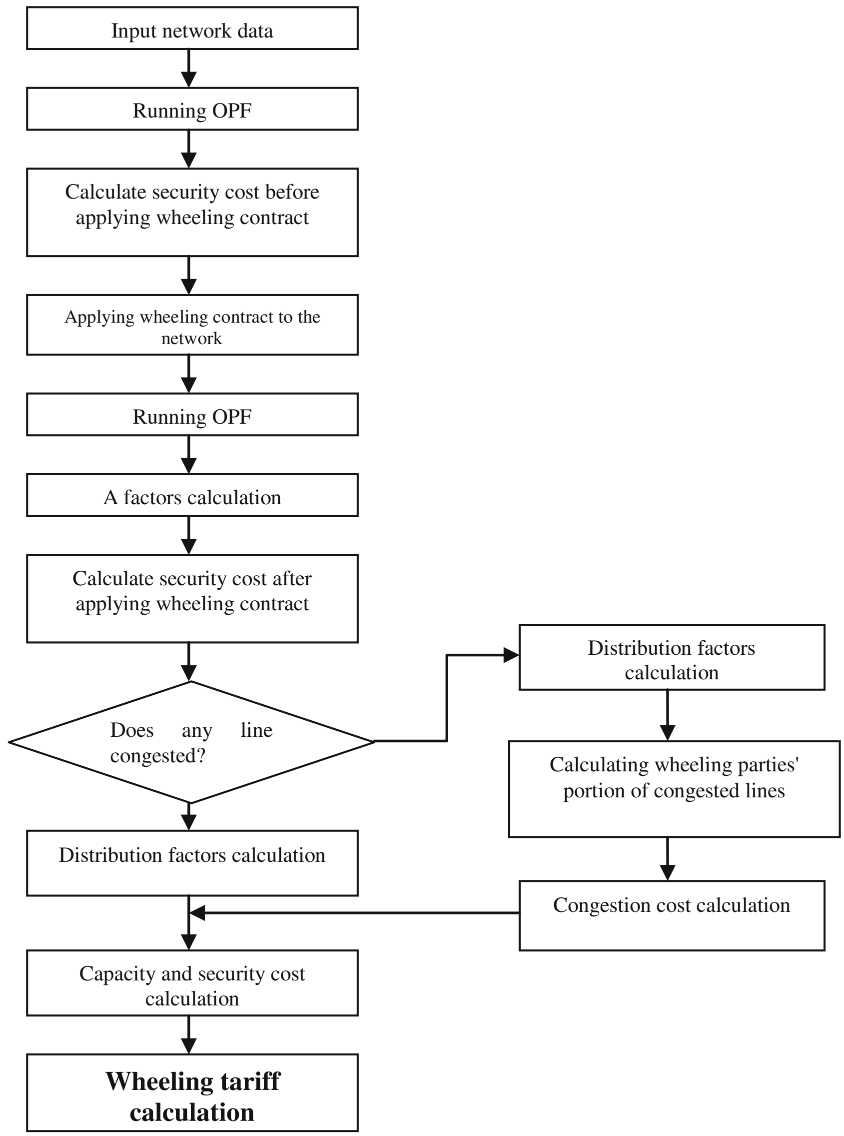


Fig. 2 The flowchart of proposed wheeling tariff approach

10 Case Study and Discussion of the Results

To investigate the proposed method, it has been applied to the 9-bus test power system shown in Fig. 3, (Yousefi and Seifi 2004). The network data are given in the Tables 1, 2, and 3. It is also assumed that there is a wheeling transaction between buses 6 and 8. In this contract, the seller and the buyer are located in buses 8 and 6 respectively.

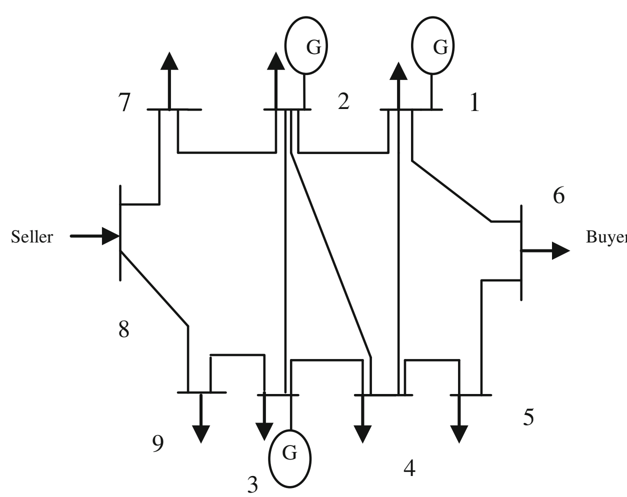


Fig. 3 The nine-bus test power system

11 Calculation of Transmission Cost During Peak Period

Assume a contract for exchanging power between contract parties at buses 6 and 8 with the amount of 60 MW are available. Considering network topology, distribution factors including C and D for these buses can be calculated as Table 4.

Table 1 Wheeler buses load

Condition	load	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 7	Bus 9
Peak	Active (MW)	80	80	80	120	120	70	70
	Reactive (MW)	30	30	30	50	50	20	20
Off peak	Active (MW)	50	50	50	50	50	40	40
	Reactive (MW)	20	20	20	20	20	20	20

Table 2 Test system data

Line no.	Start and	$R(p \cdot u)$	$X(p \cdot u)$	$Y(p \cdot u)$
1	1–2	0.042	0.0168	0.041
2	1–4	0.031	0.121	0.031
3	1–6	0.053	0.21	0.051
4	2–3	0.031	0.126	0.031
5	2–4	0.084	0.336	0.082
6	2–7	0.053	0.21	0.051
7	3–4	0.053	0.21	0.051
8	3–9	0.053	0.126	0.051
9	4–5	0.03	0.126	0.031
10	5–6	0.031	0.126	0.031
11	7–8	0.03	0.126	0.031
12	8–9	0.015	0.0513	0.015

Table 3 Wheeler generators data

Generator	$C(P_g) = A \cdot P_g^2 + B \cdot P_g + C$ (\$/h)			$Q_{g\max}$	$Q_{g\min}$	$P_{g\max}$	V
	A	B	C	(MVar)	(MVar)	(MW)	$(p \cdot u)$
1	0.00156	7.92	561	561	800	−800	1.06
2	0.00194	7.85	310	100	−90	400	1.045
3	0.00482	7.97	78	100	−90	400	1.01

Considering values in Table 1 and D factors for the three generators, the contribution of injection buses in the network from the transmitted power will be as those shown in Table 5.

12 Calculation of Capacity Cost During Peak Period

Now, using Eq. (12) with considering values in Table 5, the transmission capacity cost due to the contract are calculated as below:

$$TC_t = TC \cdot \frac{\sum_{k \in K} C_k L_k MW_{t,k}}{\sum_{t \in T} \sum_{k \in K} C_k L_k MW_{t,k}} \quad (27)$$

$$= 5280 \times \frac{50812}{50812 + 88963 + 221566 + 140363}$$

$$= 534.76 \frac{\$}{h}.$$

TC stands for the transmission cost which is expressed in second column of the Table 5. Therefore, the transmission capacity cost that should be paid by contract parties can be calculated as mentioned above.

Table 4 Distribution factor due to wheeling transaction

Line	Cij,6	Dij,8
1–2	0.364595	−0.06408
1–4	0.029261	0.063964
1–6	0.59453	0.007066
2–3	−0.00768	0.205655
2–4	0.170499	0.005038
2–7	−0.00318	0.397659
3–4	0.280049	−0.10669
3–9	0.000999	0.609874
4–5	0.442296	−0.01657
5–6	−0.43124	0.011689
7–8	0.002026	−0.39153
8–9	−0.00168	−0.60149

Table 5 Transmission usage allocation applying distribution factor

Line	Line cost	Pij^{G8}	Pij^{G1}	Pij^{G2}	Pij^{G3}
1–2	200	−3.84	−34.93	100.38	34.42
1–4	840	3.84	37.20	12.27	−10.27
1–6	1,000	0.42	21.57	37.64	16.61
2–3	760	12.34	12.34	88.56	−69.94
2–4	300	0.30	−2.19	51.53	12.19
2–7	400	23.86	11.00	42.54	−3.08
3–4	320	−6.40	−10.49	34.17	57.63
3–9	120	36.59	6.58	5.92	29.91
4–5	600	−0.99	9.09	47.21	30.21
5–6	80	0.70	−8.15	−1.13	3.42
7–8	280	−23.49	4.27	−0.24	26.06
8–9	380	−36.09	8.63	35.88	−6.51
Total	5,280	–	–	–	–

13 Calculation of Congestion Cost During Peak Period

In the test system, if the wheeling contract is not considered, the generation cost will be equal to 5638.13\$/h. On the other hand, considering the wheeling transaction for the network, the heavy congestion will be occurred in line 1–4. This is mainly because of the fact that the transfer capacity is only

60 MW. After generation re-dispatch in the network, the generation cost deviates from the optimum value and increases to 5923.47 \$/h.

Considering the Sect. 7, the excess cost related to network congestion occurrence must be compensated by transaction parties. Table 4 shows the distribution factor for both buyer and seller. As it can be observed, they are equal to 0.029261 and 0.063964, respectively. This means that the seller and buyer must pay 68.7 and 31.3 % of the congestion cost, respectively.

$$CC_{\text{S}} = D_{N_{ij}} \cdot CC = 285.34 \times 0.687 = 196.02\$/h, \quad (28)$$

$$CC_{\text{B}} = C_{N_{ij}} \cdot CC = 285.34 \times 0.313 = 89.31\$/h. \quad (29)$$

Therefore, the transmission cost due to the capacity and congestion cost is equal to:

$$TTC = TC + CC = 534.76 + 285.34 = 820.1\$/h. \quad (30)$$

In (28), TTC is the total transmission cost. According to (15), wheeling tariff for mentioned transaction is equal to:

$$TP = \frac{TC + CC}{P} = \frac{820.1}{60} = 13.66\,\frac{\$}{MWh}. \quad (31)$$

Wheeler receives the tariff calculated in (31) from transaction parties. It should be noted that this cost must be compensated by transaction parties in proportion to their contribution in transmission capacity and the congestion occurrence. Transmission capacity cost for both seller and the buyer is paid equally. However, according to (16) and (17), the congestion cost will be allocated between both contributors according to their portion in congestion according to Table 6.

14 Calculation of Security Cost During Peak Period with Wheeling Contract

For calculating the network security cost, some network data are needed. In this network, the load limit in each bus for the maximum interruption are shown in Table 7.

Table 6 Wheeling tariff

Wheeling tariff for contract parties (\$/MWh)		
Tarrif	Seller	Buyer
Capacity	4.456	4.456
Congestion	3.267	1.488
Total	7.723	5.944

Table 7 Minimum load in network buses

Bus no.	1	2 3	4	5	6	7	9
Minimum load	20	20	20	30	30	20	20

Running OPF in the network, the LMP, loads and B_I (bus interruption cost) at all buses of network are listed in Table 8. In this paper, we assume that the B_I value in each bus is double the amount of LMP.

Applying wheeling contract to the network, the interrupted load related to each line outage is calculated. For example, with outage of line 1–2, the μ_{L} factors respect to Eq. (21) are listed in Table 9.

In the network of test system, the maximum transferred power limit for each line is equal to 90 MW. According to load flow result, with outage of line 1–2, the flow of line 1–4 and 1–6 are equal to 115.4 and 102 MW, respectively. Therefore, for congestion relieving, according to Table 9, demands in buses 2 and 5 have the most effect on congestion occurrence in lines 1–2 and 1–6, respectively. For this reason, load shedding management must be done for buses 2 and 5 according to Table 10.

If the probability of line 1–2 outage be equal $0.02(\pi^1 = 0.02)$:

$$\begin{aligned} C^1 &= B_1[P_{\text{L}}^0 - P_{\text{L}}^1] \\ &= 25.88 \times (80 - 49.66) + 25.054 \times (120 - 101) \\ &= 1261.2\$/h. \end{aligned} \quad (32)$$

Therefore, security cost due to line 1–2 outage is equal to:

$$SC = \pi^1 \times C^1 = 0.02 \times 1261.2 = 25.224\$/h. \quad (33)$$

Finally, the amounts of interrupted loads due to line outage are listed in Table 11. Note that, if the maximum value of loud interruption does not lead to a complete congestion relieving, the second priority of load will be chosen for interruption.

According to Table 11, the total decreased load is equal to:

$$\sum_{k=1}^{12} [P_{\text{L}}^0 - P_{\text{L}}^k] = 812.76\,\text{MW}. \quad (34)$$

If the probability of line outage is supposed to be 0.02 (π^k= 0.02) for all transmission lines, the system security cost after applying wheeling contract is calculated as following:

$$SC = \sum_{k=1}^{k} \pi^k C^k = \sum_{k=1}^{k} \pi^k B_I (P_{\text{L}}^0 - P_{\text{L}}^k) = 395.4\$/h \quad (35)$$

Now, for comparing the security cost with and without wheeling contract, the security cost without wheeling contract will be considered in the next part.

Table 8 LMP and load in wheeler network

Bus no.	Before contract			After contract		
	Demand (MW)	LMP ($/MWh)	BI ($/MWh)	Demand (MW)	LMP ($/MWh)	BI ($/MWh)
1	80	8.761	17.522	80	8.302	16.604
2	80	8.82	17.64	80	9.16	18.32
3	80	9.093	18.186	80	9.763	19.526
4	120	9.366	18.732	120	12.94	25.88
5	120	9.736	19.472	120	12.527	25.054
6	0	9.341	18.682	0	11.193	22.386
7	70	9.585	19.17	70	9.808	19.616
8	0	9.648	19.296	0	9.801	19.602
9	70	9.675	19.35	70	9.957	19.914

Table 9 μ_L factor due to the lines and load with line 1–2 interrupting

	2	3	4	5	6	7	8	9
1–4	0.83173	0.806728	0.640385	0.523012	0.202203	0.825503	0.813005	0.815826
1–6	0.206059	0.200201	0.167931	0.37633	0.339939	0.204657	0.201641	0.202375
2–3	0	0.272906	0.001638	0.002524	0.000988	0	0.025167	0.098696
2–4	0	0	0	0	0	0	0	0
2–7	0	0.061775	0.000371	0.000571	0.000224	0.582109	0.362791	0.275515
3–4	0	0	0.000654	0.00101	0.000394	0	0	0
3–9	0.103127	0	0	0	0	0.463052	0.663101	0.751692
4–5	0	0	0	0.477023	0.184333	0	0	0
5–6	0.191472	0.185983	0.154764	0.345061	0	0.190151	0.187338	0.188015
7–8	0.102677	0	0	0	0	0.458255	0	0
8–9	0	0.060754	0.000365	0.000562	0.00022	0	0	0.270222

Table 10 Bus demand before and after line 1–2 outage

Bus no.	After contingency	Before contingency
1	80	80
2	49.6	80
3	80	80
4	120	120
5	101	120
7	70	70
9	60	60

15 Calculation of Security Cost During Peak Period Without Wheeling Contract

Now, without wheeling contract in the network, the security cost will be calculated.

In this case, the amounts of interrupted load due to outage of each line are listed in Table 12.

According to Table 12, the total decreased load is equal to:

$$\sum_{k=1}^{12} [P_{\mathrm{L}}^{0} - P_{\mathrm{L}}^{k}] = 614.6\,\mathrm{MW}. \tag{36}$$

Table 11 Demand in buses due to lines outage

Line outage	1	2	3	4	5	6	7	8	9	10	11	12
Bus. 1	80	80	80	80	80	80	80	80	80	80	80	80
Bus. 2	49.7	80	79	80	80	80	80	80	80	80	80	80
Bus. 3	80	80	80	20	80	80	80	80	80	80	80	80
Bus. 4	120	97.9	120	119.2	48.7	112.8	44.7	82.5	120	120	83	74.8
Bus. 5	101	47.3	120	94	83.5	95.2	80.7	99	118.7	30.1	99.2	96.1
Bus. 7	70	70	70	70	70	20	70	70	70	70	70	70
Bus. 9	60	60	60	60	60	60	60	60	60	60	60	60

Table 12 Demand in buses due to lines outage

Line outage	1	2	3	4	5	6	7	8	9	10	11	12
Bus. 1	80	80	80	80	80	80	80	80	80	80	80	80
Bus. 2	80	80	80	80	80	80	80	80	80	80	80	80
Bus. 3	80	80	80	20	80	80	80	80	80	80	80	80
Bus. 4	120	78.6	30.8	120	56.5	120	61.6	111.9	120	31.2	82.7	82.7
Bus. 5	120	120	88.7	120	120	120	120	120	120	88.7	120	120
Bus. 7	40.2	70	70	70	70	33.3	70	70	70	70	70	70
Bus. 9	60	60	60	59.2	60	60	60	59	60	60	60	60

Table 13 Wheeling tariff in peak period

Wheeling tariff for contract parties($/MWh)		
Tarrif	Seller	Buyer
Capacity	4.456	4.456
Congestion	3.267	1.488
Security	1.365	1.365
Total	9.088	7.309

If the probability of line outage is supposed to be 0.02 ($\pi^k = 0.02$) for all transmission lines, the system security cost after applying wheeling contract is calculated as following:

$$SC = \sum_{k=1}^{k} \pi^k C^k = \sum_{k=1}^{k} \pi^k B_I (P_L^0 - P_L^k) = 231.2\$/h \tag{37}$$

After calculation of security cost before and after applying wheeling contract to the network, the difference value allocated to the contract parties:

$$SC_{AC} - SC_{BC} = 395.4 - 231.2 = 164.2\$/h \tag{38}$$

where SC_{AC} and SC_{BC} represent the security cost after and before applying wheeling contract to the network, respectively. This cost for both seller and the buyer is paid equally. Therefore according to Eq. (24), the security tariff per MW in peak hours is as below:

$$SP = \frac{SC}{P} = \frac{164.2}{60} = 2.73 \frac{\$}{\text{MWh}}. \tag{39}$$

Therefore, the seller and the buyer will pay 1.365 $/MWh for security cost individually. Finally, total transmission tariff for wheeling contract in peak hours is shown in Table 13.

16 Calculation of Transmission Cost During Off Peak Period

The network data for off peak period is given in Table 1. In this case, line 1–4 is loaded less than 60 MW and therefore, it will not be congested. Data for line flow and D factors are listed in Table 14.

Table 14 D factors in off peak period

Line	Flow (MW)	Dij,8	Dij^{G1}	Dij^{G2}	Dij^{G3}
1–2	9.69	−0.21683	−0.28088	0.328652	0.214912
1–4	52.99	0.179851	0.333093	0.033962	−0.06753
1–6	62.78	0.044929	0.2301	0.15213	0.125591
2–3	25.53	0.237307	0.086643	0.2499	−0.38779
2–4	24.64	−0.03665	−0.0105	0.171102	0.078407
2–7	18.1	0.400995	0.056855	0.094474	−0.05246
3–4	24.52	−0.19727	−0.067	0.1297	0.349497
3–9	1.79	0.589746	0.004768	−0.0325	0.113073
4–5	50.29	−0.04896	0.103597	0.180239	0.206319
5–6	0.58	0.046873	0.046212	−0.02917	−0.05483
7–8	22.16	−0.40008	0.063166	0.025606	0.172318
8–9	37.67	−0.59306	0.115324	0.152903	0.006117

The transmission capacity cost in this case is equal to:

$$TC_t = TC \cdot \frac{\sum_{k \in K} C_k L_k MW_{t,k}}{\sum_{t \in T} \sum_{k \in K} C_k L_k MW_{t,k}} = 489.61 \frac{\$}{h.} \tag{40}$$

Considering (6), the wheeling tariff for this contract will be equal to:

$$TP = \frac{TC}{P} = \frac{489.61}{60} = 8.16 \frac{\$}{\text{MWh}}. \tag{41}$$

Transmission capacity cost is allocated to the seller and the buyer equally. Therefore, the seller and the buyer will pay 4.08 $/MWh individually. It can be seen that, during off peak periods, the transmission cost is less than the peak periods. The main reason is the presence of congestion in all transmission lines.

In off peak periods, respect to the amount of load, the security cost in the network is zero. But, by applying wheeling contract to the network, this cost will be increased. The amounts of interrupted loads due to outage of each line are listed in Table 15.

Table 15 Demand in buses due to lines outage

Line outage	1	2	3	4	5	6	7	8	9	10	11	12
Bus. 1	50	50	50	50	50	50	50	50	50	50	50	50
Bus. 2	50	50	50	50	50	50	50	50	50	50	50	50
Bus. 3	50	50	50	50	50	50	50	50	50	50	50	50
Bus. 4	50	50	42	50	50	50	50	50	50	50	50	50
Bus. 5	50	50	30	50	50	50	50	50	30	50	50	50
Bus. 7	40	40	40	40	40	40	40	40	40	40	40	40
Bus. 9	40	40	40	40	40	40	40	40	40	40	40	40

Table 16 Wheeling tariff in off peak period

Wheeling tariff for contract parties ($/MWh)		
Tarrif	Seller	Buyer
Capacity	4.08	4.08
Congestion	0	0
Security	0.15	0.15
Total	4.23	4.23

According to Table 15, the total decreased load is equal to:

$$\sum_{k=1}^{12} [P_L^0 - P_L^k] = 48.01\,\text{MW}. \qquad (42)$$

The system security cost after applying the wheeling contract to the network is as below:

$$SC = \sum_{k=1}^{k} \pi^k C^k = \sum_{k=1}^{k} \pi^k B_I (P_L^0 - P_L^k) = 18.575\$/h. \qquad (43)$$

After calculation of security cost before and after applying wheeling contract to the network, the difference value allocated to the contract parties:

$$SC_{AF} - SC_{BF} = 18.575 - 0 = 18.575\$/h. \qquad (44)$$

Therefore, the security tariff per MW in peak hours is as below:

$$SP = \frac{SC}{P} = \frac{18.575}{60} = 0.3\frac{\$}{\text{MWh}}. \qquad (45)$$

Therefore, the seller and the buyer will pay 1.365 $/MWh for security cost individually. Finally, total transmission tariff for wheeling contract in off peak hours is shown is Table 16.

Comparison between Tables 13 and 16, we can see that during off peak periods, the transmission cost is less than the peak period. The main reason is the decrease of congestion and security cost in off peak hours. This is an important issue in transmission pricing. This method can send proper signals to transmission users for load shifting to off peak hours. In Fig. 4, we can see the wheeling tariff comparison between peak and off peak periods.

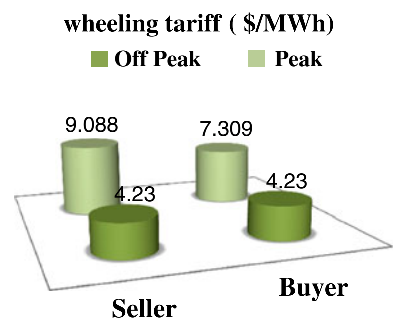


Fig. 4 Wheeling tariff comparison in *peak* and *off-peak* periods

17 Conclusion

In this paper, a new security-based framework for wheeling contract is proposed in order to make a perfect market and maximize the power system security, emphasizing the risk associated with random line outage. Proper transmission pricing can promote the efficient operation of power system and encourage investment in production and transmission. The marginal cost method may not cover all of the investment and operation costs. Therefore, the embedded cost methods are more acceptable.

In this paper, the transmission pricing method is evaluated. Then, the wheeling tariff has been modified to allocate the congestion cost to all users in proportion to their contribution in network congestion. Also, the wheeling tariffs during peak and off peak periods are compared to show the applicability of proposed method. The market equations are characterized by the locational marginal pricing (LMP) and can be obtained by optimal power flow (OPF) scheme based on power market structure. In addition, when the impact of applying the wheeling contract on power system security is investigated, the random line outages were also taken into account with N-1 examination of lines. Congestion management is considered in the proposed approach to guarantee the power system security. This paper provides a new framework for wheeling tariff in competitive markets and a lot of realistic problem to be solved are still remained. To overcome the limitations of this paper, inclusion of wide spread transmission network constraints and analysis on the impact of market requirement on the solution should be further investigated. Based on the results of this paper, one can investigate to obtain more precise presentations as well as more efficient wheeling contract procedure in the future.

References

Abdullah, M.P., Hassan, M.Y., & Hussin F. (2008). Congestion cost allocation in a pool-based electricity market. *International Conference on Power and Energy IEEE*, pp. 1033–1037. doi:10.1109/PECON.2008.4762617.

Bashian, A., Sharifian, T., Javidi, M. H., & Hojat, M. (2011). Determination of tariff for wheeling contracts considering fairness congestion cost allocation. *European Conference on Power and Energy Systems IASTED*. doi:10.2316/P.2011.714-084.

Ghayeni, M., & Ghazi, R. (2011). Transmission network cost allocation with nodal pricing approach based on Ramsey pricing concept. IET Journals & Magazines 384–392. doi:10.1049/iet-gtd.2010.0169.

Gnanadass, R., & Padhy, N. P. (2005). A new approach for transmission embedded cost allocation in restructured power market. *Journal of Energy & Environment*, *4*, 37–47.

Hamada, H., Tanaka, H., & Yokoyama, R. (2009). Wheeling charge based on identification of transaction paths in deregulated power markets. *InternationalUniversities Power Engineering Conference UPEC*, pp. 1–5.

Happ, H. (1994). Cost of wheeling methodologies. *IEEE Transactions on Power, System, 9*, 147–156. doi:10.1109/59.317547.

Hassan, M. (2000). *MW-mile charging methodology for wheeling transaction*. PhD thesis, University of Strathclyde.

Liu, B., Liu, Y., & Inabam, T. (2004). A new wheeling price calculation method considering transmission line congestion and loss costs. *IEEE International Conference on Power System Technology*, *2*, 1201–1206. doi:10.1109/ICPST.2004.1460184.

Majidi, M., Ghazizadeh, M.S., Afsharnia, S. (2008). A novel approach to allocate transmission embedded cost based on mw-mile method under deregulated environment. *IEEE Electrical Power & Energy Conference*, pp. 1–6. doi:10.1109/EPC.2008.4763344.

Murali, M., Kumari, M.S., & Sydulu, M. (2011). A comparison of embedded cost based transmission pricing methods. *IEEE International Conference on Energy, Automation, and Signal (ICEAS)*, 1–6. doi:10.1109/ICEAS.2011.6147073.

Olmos, L., & Arriaga, I. J. P. (2009). A comprehensive approach for computation and implementation of efficient electricity transmission network charges'. *Energy Policy*, *37*(12), 5285–5295.

Panyakaew, P., & Damrongkulkamjorn, P. (2008). Optimal loss allocation of multiple wheeling transactions in a deregulated power system. *International Conference on Electrical and Computer Engineering ICECE*, pp. 343–348. doi:10.1109/ICECE.2008.4769229.

Shahidehpour, M., Yamin, H., & Li, Z. (2000). *Market operation in electric power systems: Forecasting, scheduling, and risk management* (1st ed.). New York: Wiley-IEEE Press.

Su, C., & Liaw, J. (2001). Power wheeling pricing using power tracing and MVA-KM method, Vo. 1. *IEEE Power Tech Proceedings*, Porto. doi:10.1109/PTC.2001.964570.

Wang, J., & Li, F. (2004). Optimal economic environmental dispatch considering wheeling charge. *IEEE International Universities Power Engineering Conference*, *1*, 398–401.

Yousefi, G. R., & Seifi, H. (2004). Wheeling charges with consideration of consumer load modeling. *Power Systems Conference and Exposition IEEE*, *1*, 168–173. doi:10.1109/PSCE.2004.1397521.