Assessment of MW-mile method for pricing transmission services: a negative flow-sharing approach

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Abstract: A negative flow-sharing approach to allocate transmission transaction charges among users of transmission services is proposed. The approach uses the properties of the MW-mile method but takes into account the economic benefits of both trading parties by analysing their shares in negative power flow or counterflow. This approach is incorporated with the justified distribution factor for power flow tracing purposes. Two case studies based on a 5-bus system and an IEEE 14-bus system are used to illustrate the proposed approach. The results show that the proposed approach has merit over the traditional MW-mile approaches in the context of revenue reconciliation of transmission services, regardless of transaction arrangements and locations. The profit-sharing concept introduced here provides a better economic signal in allocating charges for counterflows, which could benefit trading parties.

1 Introduction

The electric utility industry in many countries has been deregulated to further increase its competitiveness and efficiency and to reduce the cost of power generation, transmission and distribution. With deregulation, generation, transmission and distribution would be in different companies and their interactions would be based on purely commercial bases. As a result, a transmission company plays a major role in determining the charges for wheeling transactions. In the past, wheeling transactions have accounted for a small portion of the overall transmission network capacity usage. However, recent trends towards unbundling of electric services have resulted in renewed interest in pricing of transmission services, particularly as it relates to wheeling transactions [1].

Many methods have been used or proposed to evaluate the costs of transmission transactions or the so-called wheeling transactions. Most methods attempt at least two basic measurements: the amount of transmission capacity used and the per-unit cost of transmission capacity [2]. These methods can be classified into one of these categories: embedded cost and incremental or marginal cost. These categories have been discussed by some authors [2–5] and show their ability to provide reasonable economic costs. Among these methods, the embedded cost methods are used commonly throughout the utility industry. They offer several benefits, that is, practicality and fairness to all parties and ease of measuring electricity loss and protecting stockholders from free riders. However, it also has some drawbacks, that is, it does not reflect the degree to which these facilities are over-utilised or under-utilised and does not provide efficient means to allocate resources to relieve constrained transmission capacity.

There are four types of embedded cost methods extensively used to allocate the transmission transaction cost, namely, postage stamp method, contract path method, distance-based MW-mile method and power-flow-based MW-mile method [5–7].

In the postage stamp method, the transmission charges are allocated on the basis of an average embedded cost and the magnitude of transacted power. This method is popular because of its simplicity; however, it ignores the actual system power flows. The contract path method, in contrast, is based on the assumption that the transaction is confined to flow along a specified, continuous current path throughout the wheeling company's transmission system. The embedded capital costs are correspondingly limited to those facilities that lie along this assumed path. A drawback of the method is that the actual path taken by the transaction does not flow only along the specified contract path, but also involves the use of other transmission paths outside the contracted one. As a result, it affects the cost of transmission outside the contracted path. Meanwhile, the distance-based MW-mile method allocates the charges based on the magnitude of transacted power and the airline distance between the point of delivery and receipt. This method could also give an incorrect economic figure to the wheeling participant. The airline distance does not indicate the actual transmission facilities involved in the transaction.

The power-flow-based MW-mile method is more widely used because it has been shown to be more reflective of actual usage of the transmission system in allocating the transmission cost [1]. This method allocates the charges for each wheeling participant based on the extent of use of transmission facilities. These allocated charges are then added up over all transmission facilities to evaluate the total price. Unlike the contract path and postage stamp methods, this method considers the changes in MW flows because of the wheeling in all the transmission lines of the wheeling companies and the line length in miles. Two power flows executed successively, with and without the

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wheeling, yield the changes in MW flows in all transmission lines.

There are three different MW-mile approaches that can be used to determine the wheeling charges for a particular transaction, and these are classified as net, absolute and positive-only approaches. Among these approaches, MW-mile absolute approach is the most popular as there is some certainty that it will provide sufficient revenue to the transmission owner. However, this approach has some drawbacks in that it ignores the contribution of users for negative power flow or counterflow. In contrast, the other two approaches may not be easy for the transmission owner to accept, who may be unable to recover appropriate revenue return if the transactions coincidently create many counterflows across the transmission network. The drawbacks of these approaches can be overcome if the benefit from the counterflow is shared between the transmission owner and the users, which is the motivation of this article.

2 MW-mile methodology

The MW-mile methodology is a technique to allocate the use of the electric power transmission system among the various beneficiaries. It may be regarded as the first pricing strategy proposed for the recovery of fixed transmission costs based on the actual use of transmission network [1, 8]. Many economists prefer this concept because it encourages the efficient use of the transmission facility and, further, the expansion of the system. The development of this method is explained in [9], which can be mathematically expressed as

$$\mathrm{WC}_t = A_i \cdot \sum_i C_i \cdot \frac{\sum_i l_i \Delta P_{i,t}}{\sum_i l_i \overline{P_{i,t}}} \tag{1}$$

where WC_t is the wheeling charge for transaction t, i the transmission lines, A_i the annual fixed charge rate in per-unit or percent, C_i the annual embedded cost of transmission line in pounds, l the length of transmission lines in miles, ΔP the impact in line flow because of transaction t in MW, $\bar{P}$ the transmission line (circuit) capacity in MW.

ΔP represents either positive or negative flow impacts. Negative ΔP occurs when the loading of lines decreases because of the wheeling transaction, whereas positive ΔP occurs when the loading of lines increases. Depending on the sign of ΔP, three cases can be distinguished.

(a) Absolute impact: the absolute value of positive and negative ΔP is added

$$\sum_i |\pm \Delta P_i| \tag{2}$$

(b) Only positive impact: only positive value of ΔP is added

$$\sum_i + \Delta P_i \tag{3}$$

(c) Net impact: the negative value of ΔP is subtracted from positive value of ΔP

$$\sum_i \pm \Delta P_i \tag{4}$$

A variation of this method is obtained by referring the costs of the changes because of the wheeling transaction to the total actual power flows in the transmission lines, as shown in (5)

$$\mathrm{WC}_t = A_i \cdot \sum_i C_i \cdot \frac{\sum_i l_i \Delta P_{i,t}}{\sum_i l_i |P_{i,t}|} \tag{5}$$

Also, depending on the sign of ΔP, three cases can be distinguished as in (2)–(4) to determine the wheeling charges based on the sum of absolute actual power flows.

In our proposed approach, the negative value of ΔP is shared between the transmission owner and users to reconcile the transmission owner's revenue as well as an incentive to the users.

3 Proposed approach

This section describes the concept and formulation of the proposed approach: a negative flow-sharing approach to allocate the wheeling charges among the users of transmission services. It also includes the description of the allocation method, and a justified distribution factor (JDF) is used to estimate the contributions of the transmission users in the line flows.

3.1 *Justified distribution factor*

JDF was originally used to solve the congestion curtailment in bilateral trading. This factor, which is derived in [10], has advantages over the original distribution factor [11], whereby the elements in the distribution matrix do not vary with the reference bus position. This could reduce the computational time in generating a new set of distribution factors when transmission users request the use of a different reference node to accommodate their transaction. However, the power flows obtained from both distribution factor matrices are the same under the DC power flow assumption. In the proposed approach, this factor is used to trace the power flows in transmission lines for the base case and be transaction-related flows. For example, the power flow in line i for both cases can be traced using (6)

$$P_i = \sum_j^m \mathrm{JDF}_i^j \cdot P_j \tag{6}$$

where JDF_i^j is the factor for line i with respect to bus j, P_j the net injection power at bus j and m the number of buses.

The power flow determined from (6) is then compared with P_i max to ensure that the capacity of this line is not violated. The power flow for the rest of the lines in the network is determined in the same manner using the JDFs of the associated lines.

3.2 *Negative flow-sharing approach*

Counterflow or negative flow is the flow component of a particular transaction that goes in the opposite direction of the net flow. In the original MW-mile formulation as well as some usage-based allocation pricing rules, the impact of each transaction on the flows is measured by the magnitude so that all transmission users irrespective of the flow directions are required to pay for the use of paths providing the service. However, in view of the contributions of counterflows in relieving the congested transmission lines, the proposals of giving a negative charge or credit to the users producing counterflows may not be easily accepted by the transmission service providers [12].

In the proposed approach, the transmission owner and the users will share the benefits of the counterflow using the profit-sharing approach. The concept and formulation of the proposed approach can be explained as follows.

First, we determine the power flow impact in all the lines of the transmission system when a new wheeling transaction is to take place in the system.

This net power flow impact is determined using an incremental absolute approach as shown in (7), which considers the difference in magnitude, irrespective of the flow direction

$$\Delta P_i = |\pm P_{t,i}| - |\pm P_{b,i}| \tag{7}$$

where ΔP_i is the power flow impact in line i, $P_{t,i}$ the power flow in line i during transaction in MW and $P_{b,i}$ the power flow in line i for base case in MW.

ΔP is the negative power flow impact if $|\pm P_t| < |\pm P_b|$.

Furthermore, the power flow impact calculated in all the lines is summed using the proposed approach, which uses the same method as the traditional MW-mile approaches to sum any positive power flow impact in the lines. The total positive power flow impact for n lines can be written as

$$\sum_i^n \Delta P_i = \Delta P_{\text{pos}} \quad \text{for all } \Delta P_i > 0 \tag{8}$$

The summation of the negative power flow impact incurred in the lines, which was formerly negative, is taken as an absolute value and then by using the profit-sharing factor, r, the share proportion of this value for the transmission owner can be calculated. For n lines, it can be written as

$$\frac{1}{r}\sum_i^n |\Delta P_i| = \frac{\Delta P_{\text{neg}}}{r} \quad \text{for all } \Delta P_i < 0 \tag{9}$$

where r is the profit-sharing factor used to determine sharing of the profit arising from the negative power flow between the transmission network owner and users.

The profit-sharing factor is determined according to the willingness of the transmission network owner to share counterflow benefits with the users. For example, if this factor is set to 2, the transmission owner and the transmission users will each receive 50% of the benefits of the counterflow, respectively. If the factor is set to 5, the transmission owner will receive 20% of the benefits and the remaining 80% is awarded to the transmission users. It would appear that a value of $r = 2$ is most reasonable, as both the transmission network owner and users will share equally the benefits. In practice, the setting of the factor would be likely to involve the regulatory authority and could well be determined through negotiation, and the regulator authority might impose certain conditions on the transmission network owner, such as additional network reinforcement.

Combining (8) and (9), the new total power flow impact can be obtained as shown in (10)

$$\Delta P_{\text{ps}} = \Delta P_{\text{pos}} + \frac{\Delta P_{\text{neg}}}{r} \tag{10}$$

To illustrate how the wheeling charges can be determined with the proposed approach, consider a single line circuit as shown in Fig. 1.

Fig. 1 *Single line circuit*

Let WC_{i-k} be the charge of the new power transacted by a generator for line $i-k$, which can be written as

$$\text{WC}_{i-k} = A_{i-k}\frac{C_{i-k}}{\overline{P_{i-k}}} \cdot \Delta P_{i-k} \tag{11}$$

where A_{i-k} is the fixed charge rate for line $i-k$ in per-unit, C_{i-k} the embedded cost of line $i-k$ in pounds, $\overline{P_{i-k}}$ the circuit capacity in MW and $\Delta P_{i-k} = P_t - P_b$ the positive or negative power flow impacts.

For simplicity, we assume A_{i-k}, C_{i-k} and $\overline{P_{i-k}}$ are equal to 1 p.u., thus

$$\text{WC}_{i-k} = \Delta P_{i-k} \tag{12}$$

If the calculation of the wheeling charge is based on the absolute approach, the following two equations are used

$$\text{WC}_{i-k} = \Delta P_{i-k} \quad \text{for } \Delta P_{i-k} > 0 \tag{13}$$

$$\text{WC}_{i-k} = |-\Delta P_{i-k}| = \Delta P_{i-k} \quad \text{for } \Delta P_{i-k} < 0 \tag{14}$$

If the calculation of the wheeling charge is based on the positive-only approach, the following two equations are used

$$\text{WC}_{i-k} = \Delta P_{i-k} \quad \text{for } \Delta P_{i-k} > 0 \tag{15}$$

$$\text{WC}_{i-k} = 0 \quad \text{for } \Delta P_{i-k} < 0 \tag{16}$$

If the calculation of the wheeling charge is based on the net approach, the following two equations are used

$$\text{WC}_{i-k} = \Delta P_{i-k} \quad \text{for } \Delta P_{i-k} > 0 \tag{17}$$

$$\text{WC}_{i-k} = -\Delta P_{i-k} \quad \text{for } \Delta P_{i-k} < 0 \tag{18}$$

The wheeling charge resulting from (14) shows that there is no benefit given to the transmission user for their contribution to counterflow.

In contrast, the wheeling charge resulting from (16) shows that the transmission service seems to be provided free of cost to the user as no charge is collected during the transaction. Meanwhile, the wheeling charge resulting from (18) is not acceptable as the transmission owner has to pay for the service that is provided to the users.

The drawbacks of the traditional approaches in dealing with counterflow transaction can be rectified if the transaction cost is shared between the user and the owner of the transmission system. This can be done by distributing the proportion of wheeling charge when $\Delta P_{i-k} < 0$ by using the profit-sharing factor r.

Therefore (14), (16) and (18) are replaced by the newly developed wheeling charge equation and can be written as follow

$$\text{WC}_{i-k} = \frac{|\Delta P_{i-k}|}{r} \quad \text{for } \Delta P_{i-k} < 0 \tag{19}$$

Based on (13), (15), (17) and (19), a new wheeling charge rule for line i–k can be written as

$$\mathrm{WC}_{i-k} = \Delta P_{i-k} = \mathrm{WC}_{i-k,\mathrm{pos}} \quad \text{for } \Delta P_{i-k} > 0 \tag{20}$$

$$\mathrm{WC}_{i-k} = \frac{|\Delta P_{i-k}|}{r} = \frac{\mathrm{WC}_{i-k,\mathrm{neg}}}{r} \quad \text{for } \Delta P_{i-k} < 0 \tag{21}$$

For n lines, the proposed wheeling charge can be written as

$$\mathrm{WC}_{\mathrm{ps}} = \sum_{i}^{n} \mathrm{WC}_{i,\mathrm{pos}} + \frac{1}{r}\sum_{i}^{n} \mathrm{WC}_{i,\mathrm{neg}} \tag{22}$$

or

$$\mathrm{WC}_{\mathrm{ps}} = \mathrm{WC}_{\mathrm{pos}} + \frac{\mathrm{WC}_{\mathrm{neg}}}{r} \tag{23}$$

where, $\mathrm{WC}_{\mathrm{pos}}$ is the wheeling charge calculated for positive power flow impact (positive charge) and $\mathrm{WC}_{\mathrm{neg}}$ the wheeling charge calculated for negative power flow impact (negative charge).

In the event of simultaneous transactions, the proposed approach allocates the negative charges as an incentive to the transmission users according to the proportion of their contribution to the counterflow. This proportion can be obtained by evaluating the sensitivity of the power flow on the lines with respect to each transaction in two different cases: when the associated transaction is introduced in the base case system and when it has been removed from the simultaneous transaction case system.

Using this concept, the proportion of incentive charge for each transaction is now calculated as follows

$$\mathrm{WIC}_{\mathrm{Ti}} = \frac{\Delta P_{\mathrm{neg,Ti}}}{\sum_{i}^{k} \Delta P_{\mathrm{neg,Ti}}} \cdot \frac{\mathrm{WC}_{\mathrm{neg}}}{r} \tag{24}$$

where $\mathrm{WIC}_{\mathrm{Ti}}$ is the wheeling incentive charge for transaction user i, $\Delta P_{\mathrm{neg,Ti}}$ is the negative power flow impact produced by transaction user i and k the number of simultaneous transaction users.

The wheeling charge for transaction user i can be calculated by considering the following equation

$$\mathrm{WC}_{\mathrm{abs}} = \mathrm{WC}_{\mathrm{ps}} + \mathrm{WIC} \tag{25}$$

where $\mathrm{WC}_{\mathrm{abs}}$ is the wheeling charge based on the absolute approach, $\mathrm{WC}_{\mathrm{ps}}$ the wheeling charge based on the proposed approach and WIC the incentive charges rewarded to simultaneous users.

Rearranging (25) yields

$$\mathrm{WC}_{\mathrm{ps}} = \mathrm{WC}_{\mathrm{abs}} - \mathrm{WIC} \tag{26}$$

Table 1: Base case flows and transaction-related flows for T1 and T2

Line	Base case power Flow, MW	T1 case power flow, MW	T2 case power flow, MW
1-2	57.0001	60.9287	57.8572
1-3	32.9999	34.0713	32.1427
2-3	24.9998	25.1188	23.5712
2-4	27.9998	28.3173	26.1905
2-5	34.0000	37.4921	33.0952
3-4	18.0001	19.1906	15.7144
4-5	−3.9998	−2.4919	−3.0951

Based on (26), the wheeling charge for transaction user i with respect to the k simultaneous transaction users can be calculated as

$$\mathrm{WC}_{\mathrm{ps_{Ti}}} = \frac{\mathrm{WC}_{\mathrm{abs}}}{k} - \mathrm{WIC}_{\mathrm{Ti}} \tag{27}$$

The profit-sharing factor, r, shown in (23) behaves as an incentive to transmission users. Depending on the value of r that is set by the transmission owner, users would receive the proportion of negative charge ($\mathrm{WC}_{\mathrm{neg}}$) for their contribution in enhancing transmission capacity. At the same time, it also behaves as a security or compensatory factor for the transmission owner who will also receive a proportion of the negative charge. This ensures that the transmission owner does not receive a lower revenue when involved in the counterflow transaction. Unlike the traditional MW-mile approaches, the proposed approach treats the negative charge, which was formerly credited to transmission users for their contribution to counterflow, as a ‘balancing charge’ to both transmission owner and users. Users are credited for their contribution to decreasing the flow on the lines, thereby increasing the available transfer capacity. The transmission owner who provides transmission facilities should also share the proportion of the charge.

4 Case studies

The proposed approach has been tested on a 5-bus system and an IEEE14-bus system using Matlab simulation programs. The transmission network data and the transmission cost of services used for both test systems are referred to in [7]. These case studies are based on DC power flow and losses are neglected. The wheeling transaction is assumed to involve only real power and the contributions of reactive power flows are also neglected. For simplicity, it is assumed that generators have to pay 100% of the transmission cost of services to the transmission owner. In practice the cost would be shared between the generator and the consumer in a certain ratio, which would be determined by the regulatory authority. The profit sharing during counterflow is assumed to be equally shared, which means that $r = 2$ is used.

4.1 Case 1: 5-bus system

Two wheeling transactions are involved in the bilateral trading and are listed as follows:

T1: injection of 5 MW at bus 1 and removal at bus 5,

T2: injection of 5 MW at bus 4 and removal at bus 2.

The Matlab program is simulated and the JDFs are used to determine base case power flows. These factors are obtained on the basis of the DC linear power flow approximations. The transaction-related flows, with the power injection of 5 MW for T1 and T2, respectively, are then simulated to determine the power flow impact for each transaction.

Table 1 depicts the transaction-related flows for T1 and T2. It can be seen that the transaction T1 causes power flow increases in most of the lines as a result of the positive flow transaction. In contrast, transaction T2 causes power flow decreases in most of the lines because of the counterflow. The wheeling charge can be obtained by first determining the total power flow impact ΔP_i for related transactions using (2)–(4) and (10), respectively. Table 2 summarises the total power flow impacts and wheeling charges resulting from different approaches.

Table 2: Total power flow impact and wheeling charges

Transactions		Absolute	Net	Positive only	Proposed
T1	$\sum$ MW-mile impact	11.6270	8.6111	10.1191	10.8731
	wheeling charges (£)	16518	12233	14375	15447
T2	$\sum$ MW-mile impact	9.0476	−7.3333	0.8571	4.9523
	wheeling charges (£)	12853	−10418	1218	7035

Table 3: Transaction-related flows and base case flows for three non-simultaneous bilateral transactions for the IEEE 14-bus system

Line	Capacity	Base case	T1	T2	T3
1-2	200	147.8164	160.0268	143.9188	132.8872
1-5	100	71.1486	78.9361	75.0421	66.0794
2-3	100	70.0100	72.0716	73.1727	59.3700
2-4	100	55.1424	59.4569	61.7613	52.2752
2-5	100	40.9623	46.7974	47.2839	39.5411
3-4	100	−24.1897	−22.1281	−21.0270	−14.8297
4-5	100	−61.7437	−55.7189	−63.3587	−55.6105
4-7	100	28.3506	28.5724	35.5472	28.5777
4-9	100	16.5459	16.6754	20.7460	16.6784
5-6	100	42.7685	42.4150	51.3678	42.4105
6-11	100	6.7177	6.5049	7.3716	6.5020
6-12	100	7.6068	7.5756	9.3734	7.571
6-13	100	17.2492	17.1401	23.4287	17.1383
7-8	100	0.000	0.000	0.0000	0.0000
7-9	100	28.3510	28.5728	35.5477	28.5781
9-10	100	5.7576	5.9690	5.1010	5.9744
9-14	100	9.6414	9.7816	21.6950	9.7842
10-11	100	−3.2315	−3.0195	−3.8869	−3.0152
12-13	100	1.5067	1.4755	3.2732	1.4750
13-14	100	5.2586	5.1184	13.2049	5.1158

In Table 2, the values of total power flow impact for T1 for the different approaches are close to each other because of the effect of positive flow transaction. However, big differences are observed in the case of T2 because it is associated with counterflow transaction. As the wheeling charge is directly proportional to the power flow impact, the transmission owner could lose some revenue in this transaction when net and positive-only approaches are used, because the benefits of counterflow are credited solely to the transmission users, which is illustrated in the table. The net flow approach produces a negative charge, which means that the transaction actually relieves congestion and hence the user should pay no charge or in theory the user could seek a refund. The positive-only approach produces a charge which is only $\simeq$10% of the sum produced by the absolute approach. It is clear from the table that the charge produced by the absolute approach is excessive. However, through the profit-sharing concept introduced in this article, transmission charge would be more reasonable to both the owner and the user.

Table 4: Wheeling charges (£) based on circuit capacity

Approach transaction	Absolute	Net	Positive only	Proposed
T1	52927.98	37115.80	45021.89	48974.94
T2	177676.54	162284.17	169980.35	173828.45
T3	66807.75	−63089.55	1859.10	34333.42

Table 5: Wheeling charges (£) based on the sum of absolute actual power flow

Approach transaction	Absolute	Net	Positive only	Proposed
T1	203421.98	142649.87	173035.93	188228.95
T2	605529.19	553071.33	579300.26	582414.72
T3	286015.33	−270097.09	7959.12	146987.23

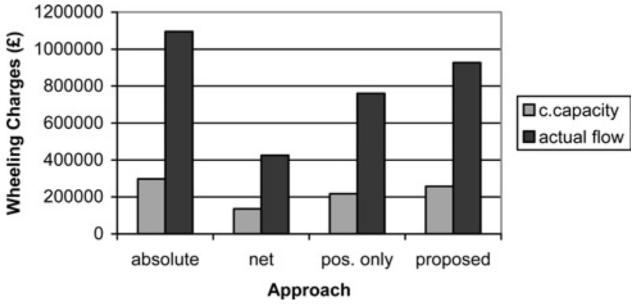

Fig. 2 *Total wheeling charges based on network capacity and sum of absolute actual power flow*

4.2 Case 2: IEEE 14-bus system

The proposed approach has also been tested on an IEEE 14-bus system to show its ability to provide appropriate revenue to the transmission owner. Altogether, three wheeling transactions have been considered, which involve different transaction locations. In the analysis, the transactions are considered first separately and then simultaneously. These locations can be categorised as close, distant and counterflow. The details of the transactions are as follows

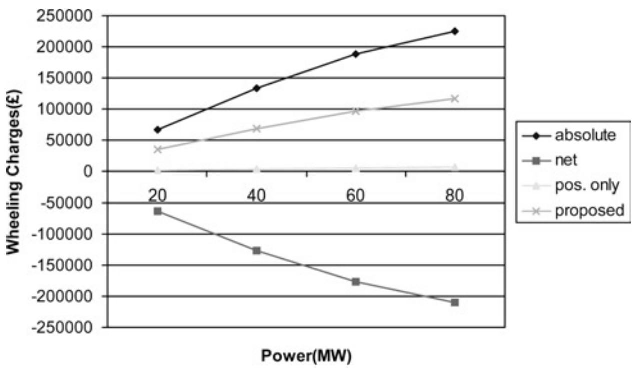

Fig. 3 *Wheeling charges with incremental power for transaction T3*

Table 6: Wheeling charges (£) for simultaneous transaction

Approach transactions	Absolute	Net	Positive only	Proposed
T1 + T2 + T3	218 600	136 310	177 450	198 030

T1: injection of 20 MW at bus 1 and removal at bus 5;
T2: injection of 20 MW at bus 2 and removal at bus 14;
T3: injection of 20 MW at bus 3 and removal at bus 1;
T1 + T2 + T3: simultaneous transactions with T1, T2 and T3.

The wheeling charge is calculated using two methods: network capacity and sum of absolute actual power flows, respectively.

Table 3 shows the power flow pattern for the IEEE 14-bus system for the base case and also the transaction-related flows. It can be observed that the power flows in all lines differ among the transactions, because they are influenced by the transaction arrangements and locations. However, none of them exceeds the circuit capacity.

Table 4 shows the wheeling charges determined on the basis of the circuit capacity. In this charging method, the transmission users will be charged only for the actual capacity they use but not for the unused capacity. It can be seen that the wheeling charges for transactions T1 and T2 are very similar among the approaches as both produce positive flows. However, for transaction T3, the wheeling charges obtained are different because they are associated with counterflows. It is clearly observed that the transmission owner either receives a low return or no return (negative charge) when the contribution of counterflows is taken into account. As a result, it seems difficult for the transmission owner to recover the transmission costs.

Conversely, the wheeling charge based on the sum of absolute actual power flows as shown in Table 5 is much higher when compared with the one that is based on circuit capacity. This charging method assumes inherently that all transmission users have to pay both for the actual capacity used and for the unused transmission capacity. The charges for unused capacity may be payment for system reliability, stability and security.

The absolute actual power flow method could help the transmission owner to receive sufficient revenue and thus ensure the full recovery of transmission costs. However, once again the revenue received depends on the approach used. In the case of counterflow transaction, the transmission owner could lose more revenue because of the increase in the negative charges. Meanwhile, with the proposed approach, which has been applied for both cases, these losses can be minimised. Fig. 2 shows the total wheeling charges obtained as a result of the three single wheeling transactions, which are based on network capacity and sum of absolute actual power flow. It can be observed that the revenue increases slightly with the use of the proposed approach when compared with the other two approaches. This is advantageous as it helps the transmission owner towards revenue reconciliation. Furthermore, as the approach also considers the benefit of the users, there is a significant reduction in wheeling charges when compared with these determined by the absolute approach. Thus, it is a good alternative to replace the absolute approach, which totally ignores the contribution the transmission user made in the counterflow.

The proposed approach has also been tested with the incremental power at the transaction locations. Transaction T3 has been chosen to show the capability of the proposed approach in providing appropriate revenue, although associated with counterflow transaction. Fig. 3 shows the variation of wheeling charge with respect to incremental power. It can be seen that the wheeling charge determined using the absolute approach increases positively as it does not consider the counterflow. In contrast, the charge either increases slowly or decreases negatively when it is determined using the positive-only approach and net approach, respectively.

Table 7: Power flows sensitivity due to transaction T1

BUS *i-j*	Base case	T1 in	ΔP_{neg}	T1 + T2 + T3	T1 out	ΔP_{neg}
1-2	147.8164	160.0268		141.2000	128.9896	
1-5	71.1486	78.9361		77.7605	69.9730	
2-3	70.0100	72.0716		64.5944	62.5328	
2-4	55.1424	59.4569		63.2087	58.8942	
2-5	40.9623	46.7974		51.6960	45.8618	
3-4	−24.1897	−22.1281	−2.0616	−9.6053	−11.6669	−2.0616
4-5	−61.7437	−55.7189	−6.0248	−51.2006	−57.2255	−6.0248
4-7	28.3506	28.5724		35.9962	35.7743	
4-9	16.5459	16.6754		21.0080	20.8785	
5-6	42.7685	42.4150	−0.3534	50.6564	51.0098	−0.3534
6-11	6.7177	6.5049	−0.2128	6.9432	7.1559	−0.2128
6-12	7.6068	7.5756	−0.0312	9.3105	9.3417	−0.0312
6-13	17.2492	17.1401	−0.1091	23.2086	23.3177	−0.1091
7-8	0.000	0.000		0.0000	0.0000	
7-9	28.3510	28.5728		35.9967	35.7748	
9-10	5.7576	5.9690		5.5291	5.3178	
9-14	9.6414	9.7816		21.9780	21.8378	
10-11	−3.2315	−3.0195	−0.2120	−3.4587	−3.6707	−0.2120
12-13	1.5067	1.4755	−0.0312	3.2103	3.2415	−0.0312
13-14	5.2586	5.1184	−0.1402	12.9220	13.0622	−0.1402

Table 8: Power flows sensitivity due to transaction T2

BUS *i-j*	Base case	T2 in	ΔP_{neg}	T1 + T2 + T3	T2 out	ΔP_{neg}
1-2	147.8164	143.9188	−3.8976	141.2000	145.0976	−3.8976
1-5	71.1486	75.0421		77.7605	73.8669	
2-3	70.0100	73.1727		64.5944	61.4317	
2-4	55.1424	61.7613		63.2087	56.5898	
2-5	40.9623	47.2839		51.6960	45.3753	
3-4	−24.1897	−21.0270	−3.1627	−9.6053	−12.7680	−3.1627
4-5	−61.7437	−63.3587		−51.2006	−49.5857	
4-7	28.3506	35.5472		35.9962	28.7996	
4-9	16.5459	20.7460		21.0080	16.8079	
5-6	42.7685	51.3678		50.6564	42.0570	
6-11	6.7177	7.3716		6.9432	6.2893	
6-12	7.6068	9.3734		9.3105	7.5439	
6-13	17.2492	23.4287		23.2086	17.0291	
7-8	0.000	0.0000		0.0000	0.0000	
7-9	28.3510	35.5477		35.9967	28.8000	
9-10	5.7576	5.1010	−0.6566	5.5291	6.1857	−0.6566
9-14	9.6414	21.6950		21.9780	9.9244	
10-11	−3.2315	−3.8869		−3.4587	−2.8032	
12-13	1.5067	3.2732		3.2103	1.4438	
13-14	5.2586	13.2049		12.9220	4.9756	

It can be observed that the wheeling charge determined by the proposed approach increases positively and is shared through the profit-sharing factor, *r*. This advantage over the other approaches could encourage the transmission owner to continue providing services for future transaction without worrying too much about counterflows because of the amount of power demand and locations.

The proposed approach is further tested on simultaneous transaction. In this test, power is injected at different injection points simultaneously. Again, the wheeling charge determined by the proposed approach is better when compared with that obtained by the other two approaches when the counterflow effect is taken into account, as depicted in Table 6.

Meanwhile, the negative charge (WC_{neg}) that is allocated as an incentive for the transmission users should be distributed according to the proportion of their contribution in counterflow. Tables 7–9 depict the power flow sensitivity

Table 9: Power flows sensitivity due to transaction T3

BUS *i-j*	Base case	T3 in	ΔP_{neg}	T1 + T2 + T3	T3 out	ΔP_{neg}
1-2	147.8164	132.8872	−14.9292	141.2000	156.1292	−14.9292
1-5	71.1486	66.0794	−5.0692	77.7605	82.8297	−5.0692
2-3	70.0100	59.3700	−10.640	64.5944	75.2343	−10.640
2-4	55.1424	52.2752	−2.8672	63.2087	66.0759	−2.8672
2-5	40.9632	39.5411	−1.4221	51.6960	53.1181	−1.4221
3-4	−24.1897	−14.8297	−9.3600	−9.6053	−18.9653	−9.3600
4-5	−61.7437	−55.6105	−6.1332	−51.2006	−57.3339	−6.1332
4-7	28.3506	28.5777		35.9962	35.7691	
4-9	16.5459	16.6784		21.0080	20.8755	
5-6	42.7685	42.4105	−0.3580	50.6564	51.0144	−0.3580
6-11	6.7177	6.5020	−0.2157	6.9432	7.1588	−0.2157
6-12	7.6068	7.5751	−0.0317	9.3105	9.3422	−0.0317
6-13	17.2492	17.1383	−0.1109	23.2086	23.3196	−0.1109
7-8	0.000	0.0000		0.0000	0.0000	
7-9	28.3510	28.5781		35.9967	35.7696	
9-10	5.7576	5.9744		5.5291	5.3123	
9-14	9.6414	9.7842		21.9780	21.8352	
10-11	−3.2315	−3.0152	−0.2163	−3.4587	−3.6749	−0.2163
12-13	1.5067	1.4750	−0.0317	3.2103	3.2420	−0.0317
13-14	5.2586	5.1158	−0.1428	12.9220	13.0648	−0.1428

ΔP_{neg}, negative power flow impact

Table 10: Proportion of participant's negative charge due to their contribution in counterflow

	T1	T2	T3
Negative MW-mile impact	84.96	82.7	697.94
Negative charge (£)	2019.96	1966.23	16593.81
Wheeling charge (£)	70850.04	70903.77	56276.19

with respect to each transaction which is based on two different cases as proposed for simultaneous transaction. It can be observed that the lines which are involved in the counterflow and the amount of negative power flow impact produced for both cases are the same.

It can be seen that for both cases, transaction T3 resulted in the reduction of line flows in 14 lines of the transmission system, whereas transactions T1 and T2 resulted eight and three lines, respectively. Having these figures, the proportion of the negative charge for each participant in the simultaneous transaction can be determined. Table 10 shows the proportion of negative charge distributed to the participants because of their contribution in counterflow. It can be observed that the wheeling charges for transaction T3 are lower than the other two transactions as a result of its contribution in counterflow.

5 Conclusions

This article proposes a negative flow-sharing approach to allocate transmission charges among users in transmission services. This approach successfully overcomes the shortcomings of traditional MW-mile approaches in the context of revenue reconciliation of transmission services regardless of transaction arrangements and locations. The introduction of a profit-sharing factor r in the proposed approach provides an intuitive way to allocate the charge for the counterflow, which could benefit both parties in the trading. Further, the use of this approach could encourage the generators to be built at the place that can create counterflow and this could mitigate the congested state of transmission lines. However, the transmission owner could delay further investment for upgrading transmission capacity.

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