Improving the MW-Mile Method Using the Power Factor-Based Approach for Pricing the Transmission Services

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***Abstract*—The MW-Mile method is an embedded cost pricing method, which is widely used to determine transmission pricing. The method is formulated based on the distance and active power flow in each line of the transmission network. This method may be considered as the first pricing strategy proposed for recovering the fixed transmission cost, based on the actual use of the transmission network. However, this method suffers from the provision of unfair charges to the users, since it ignores the quality of the load in allocating the transmission cost. This paper proposes an improved MW-Mile method by considering not only the changes in MW flows but also the quality of the load, i.e., the power factor. In this study, the IEEE 14-bus system was used to illustrate the contribution of the proposed method in allocating transmission cost to the user in a fair manner.**

***Index Terms*—MW-Mile method, power factor, transmission pricing.**

I. Introduction

THE electric supply industry has been changing rapidly throughout the world as a consequence of the implementation of deregulation. Under deregulation, the user subscribing the interconnection network has to pay the cost of the transmission service, and this cost is determined based on the utilization of the transmission line. Many methods have been used and proposed to evaluate the cost of transmission services. These methods are categorized into three types of cost: embedded cost, incremental cost and marginal cost [1].

The embedded cost method is commonly used throughout the utility industry. This method offers several benefits, e.g., it is practical and fair to all parties, easy to measure and provides an adequate remuneration of transmission systems. There are four types of embedded cost methods extensively used to allocate the transmission transaction cost namely; postage stamp, contract path, distance-based MW-Mile and the power flow-based MW-Mile method [2].

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The MW-mile method is more widely used since it has been shown to be more reflective of the actual usage of the transmission system in allocating the transmission cost. However, this method often fails to consider the power factor of the load, though it is one of the factors associated with the transmission transfer capability. In general, the power factor does not change the active power, but can affect the power quality [3].

Poor power factor will cause a decrease in electrical power delivery capability because it can lead to the increase of current injection and voltage drop in the lines. One of the factors that contribute to the decrease in the quality of the power factors is the use of reactive loads, such as induction motors and lamp typed high intensity discharge (HID), which are widely used in the industry. As reported in [4], most electricity companies in the USA charge a penalty (additional cost) to users who have a low power factor, below the standard (< 0.95). In [5], Taiwan Power Company provides a promotion of the rules, which is based on a power factor of 0.8.

The State Electricity Company (PLN) in Indonesia has also established a reference for a power factor of 0.9. An additional fee will be charged to users who have a power factor less than the reference power factor [6]. National Electricity Market Management Company (NEMCO) of Australia dictates that generators should provide a power factor in range of 0.9 lagging to 0.93 leading. Meanwhile, Norway, Sweden and Denmark provide a power factor range of 0.92 lagging to 0.98 leading [7].

Some study papers have tried to consider the power factor by using reactive power parameters [7]–[9]. For instance, an MVA+MVAr Miles charging methodology is proposed through a separating of the network cost due to the real and reactive power flows for each user [8].

In [10], the authors proposed a strategy to determine the transmission cost through the use of proportionality-based real power tracing to find out the network usage for each constituent, whereas [11] and, [12] proposed a point-to- point method. The authors in [13] proposed an approach based on monetary flow methods, and [14] proposed transmission pricing based on electricity tracing and long run average incremental cost. As far as we are concerned, there is still no work proposed in the literature about transmission cost methodology that includes the load power factor in pricing the transmission services, thus this is the main motivation of this paper.

This paper is organized as follows: Section II describes the problem structure of the MW-Mile method. Section III presents the formulation of the proposed method based on the load power factor. Application of the proposed method on the IEEE 14-bus system and the results are presented in Section IV. Finally, Section V concludes the paper.

II. Problem Description

As described in the previous section, the MW-Mile method is widely used by utilities for pricing transmission services since it has been shown to be more reflective of the actual usage of the transmission system [15]–[17]. Although it considers the real usage of the transmission line, however, the power factor of the load, which receives the power through a transmission line, is often not considered.

Several papers in the literature have reported attempts to use a power factor and reactive power (MVAr or MVA power)-based approach in pricing the transmission user [8], [9], [18], [19]. However, these methods did not consider the reference power factor set by the regulator. For instance, in [8], the transmission charge was determined by separating the active (MW) and reactive power (MVAr) without considering the reference load power factor. In this method, the user only being charges when the load power factor below the reference power factor set by the utilities (e.g., penalty charge for load power factor less than 0.9) without consider the change of active power (MW) of the system. No incentive will be given for the load power factor more than the reference power factor. In the deregulated power system, it is essential to implement a method that is fair to all parties (especially for the load and transmission owners) in determining the cost of transmission usage.

Based on these arguments, this paper introduces a power factor coefficient (C_{LF}) in calculating the cost for the transmission services based on reference power factors incorporated with the MW-Mile method.

The MW-Mile method is the first pricing scheme to consider the actual system conditions using power flow analysis. This method allocates the cost for each transmission facility to transmission transactions based on the extent of use of that facility by these transactions. The allocated costs are then added up over all transmission facilities to evaluate the total cost for the use of the transmission system [1]. This method is complicated because every change in transmission lines requires a recalculation of flows in all lines. However, many economists prefer this method because it directly encourages the efficient use of the transmission facility and the expansion of the system [20]. In general, the transmission cost based on the MW-Mile method can be calculated as follows [21]:

$$C_k = \left[\sum_{i=1}^{N} \frac{T_c \cdot L_i \cdot P_i^k}{P_i}\right] \tag{1}$$

where

C_k	transmission cost to user k (k\$);
T_C	pre-determined unit cost of line (k\$/mile);
L_i	length of transmission line i (mile);
P_i^k	power flow in line i by user k (MW);
$\overline{P}_i$	power flow (capacity) in line-i (MW).
N	number of line.

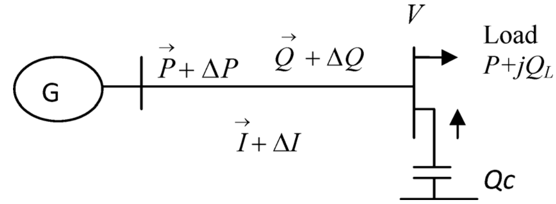

Fig. 1. Load with the capacitor bank installation.

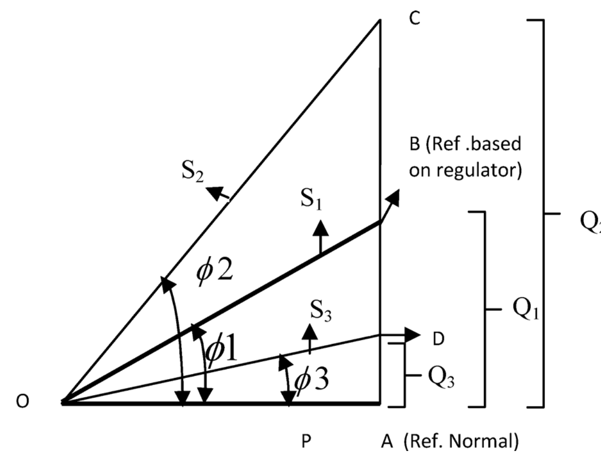

Fig. 2. Load characteristic.

According to (1), the transmission cost for the load is calculated based on the actual power (P) flow in each transmission line. The reactive power supplied to the load is ignored. If the load power factor is equal to the reference power factor, the transmission owner will pay the transmission cost based on the normal cost as calculated using the aforementioned equation.

Meanwhile, when the load is added with a reactive power of (Q_L), the transmission owner will not have to pay any additional utilization fees because the active power (P) in the load is constant. In this situation, the transmission capability is decreased due to the increase of the losses. Conversely, if the load improves its power factor, for example, with the installation of capacitor banks Q_c [Fig. 1], the user will not have to pay a transmission cost reduction, since the active power demand does not change In this situation, the transmission owner gets the benefit because the capacitor banks increases the transmission capability. In addition, it also helps to reduce the generation capacity.

According to the IEEE std. 1459-2000 [22], the reactive power, active power and apparent power can be expressed as follows [22]:

$$S = P + jQ. \tag{2}$$

Therefore, a load with reactive power Q_1, can be expressed as

$$\cos\phi_1 = \frac{P}{S_1} = \frac{P}{P + jQ_1}. \tag{3}$$

Equation (3) shows the load power factor under initial conditions and is taken as the reference power factor. ($\cos\phi_1 = \cos\phi_{ref}$), where $\mathrm{Q}_1 = \text{length of AB}$ (Fig. 2), and ΔQ is the reactive power consumed by the line.

Based on (2) and (3), a new load power factor is obtained when adding the reactive power Q_L to the existing load, which can be expressed as

$$\cos\phi_2 = \frac{P}{P + jQ_2} \tag{4}$$

where $jQ_2 = jQ_1 + jQ_L$ (length of AC), and $\Delta Q'$ is the reactive power change in line due to Q_L.

The line current due to a load with reactive power Q_2 is formulated as

$$I' = \frac{P + jQ_2}{V} \tag{5}$$

where

$$I' = I + \Delta I'. \tag{6}$$

Similarly, the apparent power with the installation of capacitor bank, Q_c can be expressed as

$$I'' = \frac{P + jQ_3}{V} \tag{7}$$

where

$$I'' = I + \Delta I''. \tag{8}$$

The smaller the line current, I, the smaller the line loss will be. Thus, the transmission line carrying capacity can be optimized.

III. Proposed Method

A power factor or $\cos\phi$ is defined as a ratio of the active power to the apparent power of the load [22]. The active power of the load can be expressed as

$$P = VI \times \cos\phi. \tag{9}$$

This equation can also be written as

$$P = VI \times \cos\phi_1 = VI' \times \cos\phi_2 = VI'' \times \cos\phi_3 \tag{10}$$

and hence

$$\frac{P}{V} = I\cos\phi_1 = I'\cos\phi_2 = I''\cos\phi_3. \tag{11}$$

For simplicity, voltage V in (11), is assumed as a constant, and $\cos\phi_1 = \cos\phi_{ref}$ where ΔI is the current changes due to the change of power factor, thus the relationship is obtained as follows:

$$I\cos\phi_{ref} = I'\cos\phi_2. \tag{12}$$

By substituting (6) into (12), the equation can be further written as follows:

$$I\cos\phi_{ref} = (I + \Delta I')\cos\phi_2. \tag{13}$$

Therefore

$$I\cos\phi_{ref} = I\cos\phi_2 + \Delta I'\cos\phi_2 \tag{14}$$

then, can rewrite as

$$I\cos\phi_{ref} - I\cos\phi_2 = \Delta I'\cos\phi_2. \tag{15}$$

If the resistance of the transmission line is constant, the power flow change ($\Delta P'$) is equivalent with current flow change in line. Therefore, (15) can be expressed approximately as follows:

$$\frac{\Delta I'}{I} = \frac{\cos\phi_{ref} - \cos\phi_2}{\cos\phi_2} \approx \frac{\Delta P'}{P} = \frac{\cos\phi_{ref} - \cos\phi_2}{\cos\phi_2} \tag{16}$$

and

$$\Delta P' = P\left[\frac{\cos\phi_{ref} - \cos\phi_2}{\cos\phi_2}\right] \tag{17}$$

where $\Delta P'$ is an additional power flow due to $\text{load power factor} < \text{reference power factor}$.

Similarly, the calculation for $\text{load power factor} > \text{reference power factor}$ is expressed as

$$\frac{\Delta I''}{I} = \frac{\cos\phi_{ref} - \cos\phi_3}{\cos\phi} \approx \frac{\Delta P''}{P} = \frac{\cos\phi_{ref} - \cos\phi_3}{\cos\phi_3} \tag{18}$$

and

$$\Delta P'' = P\left[\frac{\cos\phi_{ref} - \cos\phi_3}{\cos\phi_3}\right] \tag{19}$$

where P is the power flow of the line.

Let we define P_i as power flow in line-i due transaction-k, Therefore, by substituting (17) into (1), the transmission charge for load power factor ($\cos\phi_2$) can be written as follows:

$$C_k = \left[\sum_{i=1}^{N} \frac{T_c \cdot L_i(P_i^k + \Delta P')}{\overline{P}_i}\right]. \tag{20}$$

by substituting (17) in (20), we obtain

$$C_k = \left[\sum_{i=1}^{N} \frac{T_c \cdot L_i \cdot \left[P_i^k + P_i^k\left(\frac{\cos\phi_{ref} - \cos\phi_2}{\cos\phi_2}\right)\right]}{\overline{P}_i}\right]. \tag{21}$$

Similarly, for the power factor improvement, the general equation for the transmission charge can be expressed as

$$C_k = \left[\sum_{i=1}^{N} \frac{T_c \cdot L_i(P_i^k + \Delta P)}{\overline{P}_i}\right] \tag{22}$$

where ΔP is the power flow change due to load power factor variation which are

$$\Delta P = P_i^k\left[\frac{\cos\phi_{ref} - \cos\phi_{act}}{\cos\phi_{act}}\right]. \tag{23}$$

Therefore, (22) can be rewritten as

$$C_k = \left[\sum_{i=1}^{N} \frac{T_c \cdot L_i \cdot \left(P_i^k\left[1 + \frac{(\cos\phi_{ref} - \cos\phi_{act})}{\cos\phi_{act}}\right]\right)}{\overline{P}_i}\right] \tag{24}$$

and (24) can also be written as

$$C_k = \left[\sum_{i=1}^{N} \frac{T_c \cdot L_i \cdot \left(P_i^k \cdot C_{LF} \right)}{\overline{P}_i} \right]. \tag{25}$$

C_{LF} is the power factor correction coefficient and can be expressed as follows:

$$C_{LF} = 1 + \frac{(\cos\phi_{ref} - \cos\phi_{act})}{\cos\phi_{act}}. \tag{26}$$

There are three load power factor conditions that can be derived from (26), which are as follows:

A. $\cos\phi_{act} = \cos\phi_{ref}$

For the actual power factor equal to the reference power factor, the user (load) only pays a usage fee according to the amount of MW used, since

$$C_{LF} = 1 + \frac{(\cos\phi_{ref} - \cos\phi_{act})}{\cos\phi_{act}} = 1. \tag{27}$$

B. $\cos\phi_{act} < \cos\phi_{ref}$

For an actual power factor less than the reference power factor, then the user has to pay an additional fee, since

$$C_{LF} = 1 + \frac{(\cos\phi_{ref} - \cos\phi_{act})}{\cos\phi_{act}} > 1. \tag{28}$$

C. $\cos\phi_{act} > \cos\phi_{ref}$

Conversely, if the actual power factor is more than the reference power factor, then the user pays fewer fees, since

$$C_{LF} = 1 + \frac{(\cos\phi_{ref} - \cos\phi_{act})}{\cos\phi_{act}} < 1. \tag{29}$$

In fact, the power factor varies randomly all the time, therefore, in order to charge the transmission to users , C_{LF} in (25) can be formulated as

$$C_{LF} = 1 + \frac{(\cos\phi_{ref} - \cos\phi_{av})}{\cos\phi_{av}} \tag{30}$$

where $\cos\phi_{av}$ defines the average power factor for each time period [23], according to the transmission charge service agreement in the electricity market.

Therefore, based on the (1), a new MW-Mile method equation can be expressed mathematically as follows:

$$C_k = C_{LF} \left[\sum_{i=1}^{N} \frac{T_C \cdot L_i \cdot P_i^k}{\overline{P}_i} \right] \tag{31}$$

where C_{LF} is the power factor correction coefficient.

For application in the transmission cost for user k, according to the deregulated power system that separate the transmission owner, (24) can be formulated as

$$C_k = \left[\sum_{i=1}^{N} \frac{T_c \cdot L_i \cdot \left(P_i^k \left[1 + \frac{(\cos\phi_{ref} - \cos\phi_{av,k})}{\cos\phi_{av,k}} \right] \right)}{\overline{P}_i} \right] \tag{32}$$

where $\cos\phi_{ref}$, $\cos\phi_{av,k}$ are defined as the power load reference in the contract and the average of load power factor at each user-k for a billing period based on the power purchase agreement.

1) Example 1: Load L2 has an average load power factor of 0.85, ($\cos\phi_{av} = 0.85$), based on the billing period for transmission charge. Transmission owner or regulator set by the reference power factor is 0.9. Therefore, according to (30):

$$C_{LF} = 1 + \frac{(0.9 - 0.8.5)}{0.9} = 1.05882.$$

Then using (31), we obtain the transmission charge for L2:

$$C_k = 1.05882x(5.985) = 6.299 \text{ k\$ (Table II)}.$$

2) Example 2: Conversely, if the load L2 has a average load power factor of 0.95 (power factor improved), therefore: $C_{LF} = 0.94736$ and $C_k = 5.699$ k\$. Both these examples show that the differences in the transmission charge of the load depend on the average power factor (Tables II and III).

Equation (32) shows the variation of the cost of the transmission line utilization. It can also be defined as a price parameter due to the difference between the average power factor and the reference power factor set by a regulator.

Table I shows that if the C_{LF} value is one, the load will have a power factor equal to the reference. The greater the difference between the reference of the average power factor of the load, the greater the value of the C_{LF}. The C_{LF} values are in the range of 0.95 to 1.3 for a reference power factor of 0.9 and an average load power factor of 1 to 0.7. Meanwhile, when the reference power factor is 0.95 and the average power factor is reduced to 0.7, the loads should pay transmission costs of 1.357 times than the normal one.

IV. Case Study

The proposed method was tested on an IEEE 14-bus system. The case study based on DC power flow and losses were neglected. The transaction was assumed to involve only real power and the contributions of reactive power flows were also neglected. The proposed method was compared with the original widely used MW-Mile method for transmission utilities as described in Section II, to investigate its ability to provide a better economic signal to transmission system users. In this case study, the proposed method was tested on the IEEE 14-bus system as shown in Fig. 3. The transmission network data and the transmission cost of services used for the IEEE 14-bus system were referred from [2]. This system included two generators on Buses 1 and 2, while 11 loads were located at buses 2, 3, 4, 5, 6, 9, 10, 11, 12, 13, and 14. The generators served a total system load of 259 MW. The reference power factors used in this case study were 0.8 and 0.9, respectively. The generalized generation distribution factors (GGDF) and generalized load distribution factors (GLDF) were used to determine the contribution of generation and load to the line flows, respectively [24].

The GLDF method was used to determine the load contribution to line flows. It was observed that this method was also able to identify the effect of counter flow in the network. Table II tabulates the transmission cost allocated to the load using the MW-Mile method and the proposed method based on a reference power factor of 0.8.

TABLE I
COEFFICIENT C_{LF} BASED ON THE AVERAGE POWER FACTOR

Average power factor	Coefficient C_{LF} -based reference power factor			Average power factor	Coefficient C_{LF} -based reference power factor		
	0.8	0.9	0.95		0.8	0.9	0.95
1	0.8	0,9	0.95	**0.84**	0.95238	1.07143	1.13095
0.99	0.80808	0.90909	0.95959	**0.83**	0.96385	1.08433	1.14457
0.98	0.81632	0.91836	0.96938	**0.82**	0.97561	1.09756	1.15853
0.97	0.82474	0.92783	0.97938	**0.81**	0.98765	1.11111	1.17284
0.96	0.83333	0.9375	0.98958	**0.80**	1	1.125	1.1875
0.95	0.84210	0.94736	1	**0.79**	1.01265	1.13924	1.20253
0.94	0.85106	0.95744	1.01063	**0.78**	1.02564	1.15384	1.21794
0.93	0.86021	0.96774	1.02150	**0.77**	1.03896	1.16883	1.23376
0.92	0.86956	0.97826	1.03260	**0.76**	1.05263	1.18421	1.25
0.91	0.87912	0.98901	1.04395	**0.75**	1.06666	1.2	1.26666
0.90	0.88888	1	1.05555	**0.74**	1.08108	1.21621	1.28378
0.89	0.89887	1.01123	1.06741	**0.73**	1.09589	1.23287	1.30137
0.88	0.90909	1.02272	1.07954	**0.72**	1.11111	1.25	1.31944
0.87	0.9195	1.03448	1.09195	**0.71**	1.12676	1.26760	1.33802
0.86	0.93023	1.04651	1.10465	**0.70**	1.14285	1.28571	1.35714
0.85	0.94117	1.05882	1.11764	**0.69**	1.15942	1.30434	1.37681

TABLE II
TRANSMISSION COST BASED ON MW-MILE METHOD AND PROPOSED METHOD (REFERENCE $\cos\Phi = 0.8$)

Bus No.	MW-Mile method	Cos Φ reference =0.8 lagging Proposed (k$)			
	k$	Cos Φav= 0.8	Cos Φav = 0.85	cos Φav = 0.9	cos Φav = 0.95
L2	5.985	5.985	5.699	5.440	5.204
L3	58.623	58.623	55.827	53.288	50.973
L4	28.216	28.216	26.870	25.648	24.533
L5	3.836	3.836	3.653	3.487	3.335
L6	11.109	11.109	10.579	10.098	9.660
L9	31.792	31.792	30.275	28.899	27.643
L10	10.864	10.864	10.346	9.875	9.446
L11	7.807	7.807	7.435	7.097	6.788
L12	7.807	7.807	7.435	7.097	6.788
L13	16.154	16.154	15.383	14.684	14.046
L14	17.803	17.803	16.954	16.183	15.480

TABLE III
TRANSMISSION COST BASED ON MW-MILE METHOD AND PROPOSED METHOD (REFERENCE $\cos\Phi = 0.9$)

Bus No.	MW-Mile method	Cos Φ reference =0.9 lagging Proposed (k$)			
	k$	cos Φav = 0.8	cos Φav = 0.85	cos Φav = 0.9	cos Φav = 0.95
L2	5.985	6.643	6.299	5.985	5.699
L3	58.623	65.071	61.706	58.623	55.827
L4	28.216	31.319	29.700	28.216	26.870
L5	3.836	4.258	4.038	3.836	3.653
L6	11.109	12.332	11.694	11.109	10.579
L9	31.792	35.289	33.464	31.792	30.275
L10	10.864	12.059	11.436	10.864	10.346
L11	7.807	8.666	8.218	7.807	7.435
L12	7.807	8.666	8.218	7.807	7.435
L13	16.154	17.931	17.003	16.154	15.383
L14	17.803	19.762	18.740	17.803	16.954

In Table II, it can be observed that the load 2 will pay k$ 5.985 for the transmission pricing services when using the oiginal MW-Mile method. While, with the proposed method the cost would be reduced accordance to variation of load power factor. For instance, when using the proposed method by a power factor of 0.85, the load only paid k$ 5.699 which resulted of k$ 0.286 transmission cost reduction. It also can be observed from the table that the transmission cost will reduce as the user's power factor is improved. Also, the production cost will decrease as a result of power factor improvement reduction as the user's power factor is improved. Also, the production cost will decrease as a result of power factor improvement.

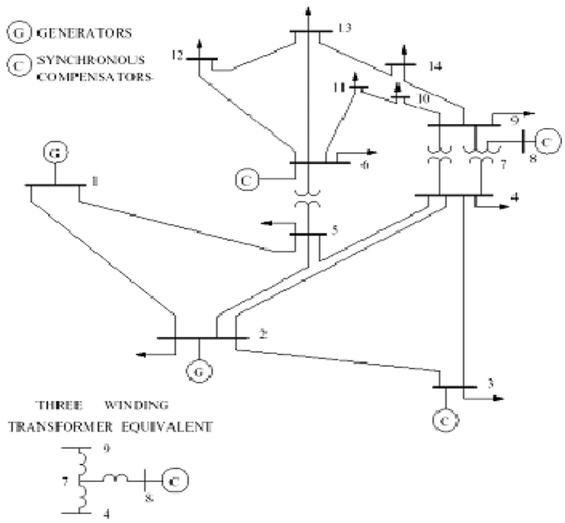

Fig. 3. IEEE 14-bus system.

Similarly, in Table III shows the transmission pricing services to the load based on the MW-Mile method and the proposed method with a reference power factor of 0.9 while the load power factor was varied from 0.8 to 0.95. It was estimated that by using the original MW-mile method, the load 2 would have to pay the same amount of transmission costs, although the reference power factor would be different because it would not consider the reference power factor. Meanwhile, by using the proposed method, the transmission cost for the load would increase if the load power factor was below the reference power factor. From Tables II and III, it can also be observed that the cost of using the transmission on each line differs, e.g., line L3 is higher for a reference power factor 0.9 compared to the reference power factor 0.8. For instance, the load with an average power factor of 0.85, 0.9, and 0.95 and a reference power factor of 0.8, will receive a transmission cost reduction of 4.7%, 9.1%, and 13.05%, respectively.

Conversely, if the reference power factor is 0.9, and the load has with a power factor 0.8, the load will have to pay 11% additional transmission costs and 5.26% for a power factor of 0.85. Meanwhile, if the power factor is 0.95, the load will receive an incentive of a 4.7% reduction. It can be seen that the user's charges depend on the relative difference between the average load power factor and the reference power factor.

V. Conclusion

This paper proposes an improved MW-Mile method to allocate a more accurate transmission cost to the load user. The proposed method, which applies a power factor-based approach, has shown significant results in allocating the transmission cost in a fair manner. The results, tested on the IEEE 14-bus system, indicated that there were differences in the cost of transmission utilization, which in reality, depends on how good the power factor of the load user is. The advantage of the proposed method over the MW-Mile method lies in the incentive given to the user due to power factor improvement. This proposed method can be further extended by considering transmission losses allocation and carbon emissions.

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