Harmonic Distortion Contribution for the Transmission Loss Allocation in Deregulated Energy Market: A New Scheme for Industry Consumer

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Abstract – The industry has rapidly growth and energy supply technology advanced are become main factor which to contribute of the harmonic losses. This problem is one aspect that may affect the capability of the transmission line and also to the efficiency of electricity. This paper proposes a new scheme to allocate the cost pertaining to transmission loss due to harmonics. The proposed method, called as Generalized Harmonic Distribution Factor, uses the principle of proportional sharing method to allocate the losses among the transmission users especially for industry consumers. The IEEE 14- and 30 bus test system is used to compare the proposed method with existing method. The results showed that the proposed method provided a scheme better in allocating the cost of transmission loss, which could encourage the users to minimize the losses.

Keywords: Transmission losses, Harmonic distortion, Industry consumer, Deregulated energy market.

1. Introduction

Recently, the issue of harmonic losses is always disputable in the deregulated power system. The industry rapidly growth and energy supply technology advanced are main contribute for the harmonic distortion [1]. Many industry consumers that use electronic devices, including the use of reactive power compensation devices such as static compensator variables and UPS, are the main factors on the emergence of harmonic pollution on the distribution network [2]. For instance, Korean will be development of the infrastructure battery charging for electric vehicles which can be to contribute of the harmonic distortion [3]. The utility companies usually install the mitigation equipment to maintain the quality of power supplied. Once this equipment is installed, its cost must be recovered from the consumers who have caused the power quality (PQ) problem, i.e. harmonic distortion [4]. The consumer will pay according to the amount of stress (usage) that their equipment causes onto the mitigation equipment [5].

The IEEE Standard 519-1992 [6] has become a standard of PQ associated with the harmonic distortion caused by the source or load. This standard establishes a maximum limit of 5% of the Total Harmonic Distortion (*THD*) factor for the current and voltage [7]. The *THD* indicates the amount of content of the harmonic components either in current or voltage waveform.

Many approximate models and algorithms have been introduced in the literature that tried as accurate as possible to identify and allocate the cost of losses to each participant in the transmission network. In several papers have been exploited of the harmonic focused on the loss allocation due to the harmonic distortion. Power quality problem is one aspect that may affect the ability of the facility within the power system and also the efficiency of electricity distribution from generation sources to the consumer [8].

The development of loss allocate scheme for harmonic distortion is to determine what harmonic loss should be accurate in PCC for all ICs. The system operator concentrates on solving the technical problems of finding proper incentive signals for transmission owner, while the load effort to encourage harmonic reduction.

This paper proposes a new method to determine of the harmonic contribute for transmission losses allocate. After the introduction in section I, the problem description an overview of transmission loss allocation in presented in section II. Section III explains and formulates the proposed method. A test case based on the 14-bus system is provided in Section IV. Results and discussions are provided in Section V. Section VI presents concluding remarks.
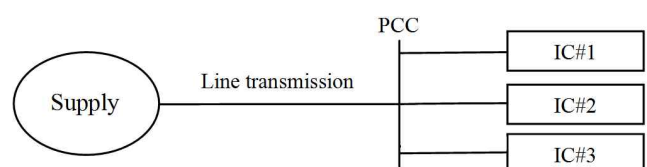
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Fig. 1. Single line diagram with several industry consumers (IC) connected to point of common coupling (PCC).

2. Problem Description

Total Harmonic Distortion (THD) is an index that commonly used to determine the level of wave distortion. This parameter is power quality level on an equipment or system. The index of THD, which is shown in Eqs. (5-6), is the ratio of the number of rms value of each individual harmonic waves and fundamental wave, and is used to indicate the level of harmonic generation. There are two types of THD is namely; voltage and current THD. Basically, the electric power supply must provide good power quality like constant voltage magnitude and frequency. Meanwhile, by using electronic devices and non-linear load non-sinusoidal, which can result in poor power quality. It can cause of electrical disturbances like transients, sags, swells, harmonics, and even disruption in power supply [4]. And also, can be to increase of losses in line due harmonic component for line flow.

Generally, transmission losses commonly contribute between 3-5% of the total power losses in network [9]. Therefore, it is a major problem in the efficiency of generation cost. Several methods have been developed and introduced in the literature to identify the losses caused by each component in the electricity market. In the context of loss, the determination of transmission loss allocate (*TLA*) should be as accurate as possible to all users. A widely used approach in *TLA* is the proportional method Pro-rata method is a technique to solve the problem of the *TLA* [10], which uses the principle of proportional sharing (*PSP*) [11]. The approach is based on the concept of the exact power that has been developed through the analysis of the circuit [12]. While, based on the load flow analysis, the method proposed based on Z-bus matrix of the network [13]. Then, to obtain accurately, the author in [14] proposed an approach using neural networks and other methods using the modified nodal equations to identify the actual power loss allocation for the generator and the load [15]. Meanwhile, [16] proposed a loss allocation method based on circuit theory. A new method was verified by [17] for allocating the user's loss contribution in each branch, called as Equivalent Bilateral Exchange (EBE). The EBE method assumes that the users of the network have their own contribution on the system based on the contribution of currents power.

Finally, a satisfactory *TLA* scheme should have the following features; charging the user for the actual usage of the grid; providing to new scheme for consumer and power plants about scheme best that can relieve transmission congestion and losses; predictable; simple and easy to implement and can ensure recovery of the total transmission revenue [18].

3. Proposed Method

In the proposed method, the system loss was calculated by using load flow analysis. By defining the line impedance of system as:

$$Z_{ij} = R_{ij} + jX_{ij} \tag{1}$$

and the power equation:

$$P_i = \sum_{n=1}^{N} |Y_{in}V_iV_n| \cos(\theta_{in} + \delta_n - \theta_i)$$
$$Q_i = -\sum_{n=1}^{N} |Y_{in}V_iV_n| \sin(\theta_{in} + \delta_n - \theta_i) \tag{2}$$

thus, the transmission losses from bus-i to bus-j can be expressed as:

$$MW_{lossij} = S_{ij} + S_{ji} \tag{3}$$

where:

$$S_{ij} = V_i . I_{ij}^* \tag{4}$$

and,

$$S_{ji} = V_j . I_{ji}^* \tag{5}$$

Where:

S_{ij}= Power flow from bus i to bus j
S_{ji}= Power flow from bus j to bus i

Basically, the level of power quality due to harmonic load can be divided into two types; load without distortion, where the load does not contain distortions, and the load with distortion. The utility total harmonic distortion factor for current (THDI$_U$) is defined as:

$$THDI_U = \sqrt{\frac{\sum_{h=N_A}^{\infty} I_h^2}{I_1^2}} \tag{6}$$

The utility total harmonic distortion factor for voltage (THDV$_U$) is defined as:

$$THDV_U = \sqrt{\frac{\sum_{h=N_A}^{\infty} V_h^2}{V_1^2}} \tag{7}$$

Meanwhile, the total transmission losses with harmonic component can be written as:

$$MW_{loss}^h = MW_{loss}(\sqrt{1+THD^2}) \tag{8}$$

By defined the contribution of harmonic for each load j at Demand (D) as $MW^*_{loss,D}$, therefore we obtain:

$$MW_{loss,D}^h = \sum_{j=1}^N C_j^h . MW_{loss,Dj} \qquad (9)$$

Where;

$$\sum_{j=1}^N C_j^h = C_1^h + C_2^h + C_3^h + ... + C_n^h = 1 \qquad (10)$$

And,

$$C_j^h = \frac{THD_{Dj}}{\sum THD_{Dj}} \qquad (11)$$

Where:

C_j^h = harmonic share load-j of the total harmonic in load.

Let be the harmonic factor for each Demand (D) as follows;

$$\sum_{j=1}^N f_{THD,Dj} = f_{THD,D1} + f_{THD,D2} + ...f_{THD,DN} \qquad (12)$$

Let, we define $f_{THD,DN}$ as harmonic component due load-N, can be expressed as follows :

$$MW_{loss,D}^h = P_{loss} - F_{THD,D}.P_{loss} = P_{loss}(1 - F_{THD,D}) \qquad (13)$$

We defined the total harmonic loss component as ;

$$MW_{loss,D}^h = P_{loss} - \left[\frac{1}{\sum_{j=1}^N f_{THD,Dj}}\right] P_{loss} \qquad (14)$$

Can be re-writing as:

$$f_{THD,DN} = \left(\sqrt{1 + THD_{DN}^2}\right) \qquad (15)$$

and

$$MW_{loss,D}^h = F_{THD,D}.P_{loss} \qquad (16)$$

Therefore, the general formulation of transmission loss allocation with consideration of total harmonic distortion *(THD)* factor for the users can be written as:

$$L_{Dj}^h = [f_{TLA}] + C_j^h . MW_{loss,D}^h \quad j \in NB; \qquad (17)$$

Where:

L_{Dj}^h as transmission loss allocate with harmonic contain for each load j. And $C_j^h MW_{loss,D}^h$ as the harmonic loss contribute due load –j or demand-D.

While, f_{TLA} is transmission loss based on TLA methods, for example:

1. Pro-rata [17]:

$$f_{TLA} = \frac{L}{2}.\left[\frac{P_{Dj}}{P_D}\right] \qquad (18)$$

Therefore, using Eqs. (17) and (18), we obtained:

$$L_{Dj} = \frac{L_R}{2}\left[\frac{P_{Dj}}{P_D}\right] + \left[\frac{THD_{Dj}}{\sum_{j=1}^N THD_{Dj}}.(MW_{loss,D}^h)\right] \qquad (19)$$

2. Incremental Transmission Losses (ITL)

$$f_{TLA} = P_{Dj}.\frac{\partial L}{\partial_{Dj}} \qquad (20)$$

3. Z-Bus Method [14]:

Similarly, using Eq. (17) for Z bus method, we obtained:

$$f_{TLA} = \Re\left\{I_k^*\left(\sum_{j=1}^N R_{kj}.I_j\right)\right\} \qquad (21)$$

The component of function in (17) is called as "Generalized Harmonic Distribution Factor (*GHDF*)" where f_{TLA} = function of the Transmission Loss Allocation method caused by line parameter R, and $C_j^h MW_{loss,D}^h$ is the contribution of losses for each load due harmonic [21].

According to *IEEE std 1459-2000*, the established maximum limit of *THD* would be 5% [6]. This means that each load should pay an additional charge if *THD* in load more than 5% (for instance: industry consumer).

$$TLA_{load} = TLA_{THD:5\%} \qquad (22)$$

where:

TLA_{load} = Transmission loss allocated to load.
$TLA_{THD5\%}$ = Transmission loss allocated to demand with *THD* load is 5%.

then:

$$MW_{loss}^h = MW_{loss}\left[\sqrt{(1 + THD_{5\%}^2)}\right] \qquad (23)$$

By setting the THD5% as *THD_{ref}* which is based on *IEEE std 1459-2000*, then the net total harmonic distortion for the load with 5% THD will be equal to zero or can be written mathematically as:

$$\Delta THD = THD_{ref} - THD_{5\%} = 0 \qquad (24)$$

Therefore Eq. (24) substitute to (8), the total transmission losses with harmonic component in Eq. (8) can be obtain as follows:

$$MW_{loss}^h = MW_{loss} \qquad (25)$$

Meanwhile, if the *THD* load is not equal to THD_{ref} then the total harmonic distortion THD can be written as:

$$\Delta THD = THD_{ref} - THD_{load} \qquad (26)$$

Hence,

$$MW_{loss,Dj}^h = MW_{loss,Dj} \left[\sqrt{(1 + \Delta THD^2)} \right] \qquad (27)$$

4. Case Study and Discussion

The proposed method was tested on the IEEE14-bus system. The proposed method was compared with the original Z method with and without harmonic by transmission utilities as described in Section 4, 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 systems and the IEEE 30-bus systems as shown in Figs. 2 and 3.

By using three methods: each Pro-average method, ITL method and Z method bus then Z method gives better results. The third method results are shown in Table 1. For example on bus 1, two methods of pro rata and ITL provides value 0 while the bus Z method losses are by 7 MW. Similarly, on the bus 8. Then based on Table 2, the
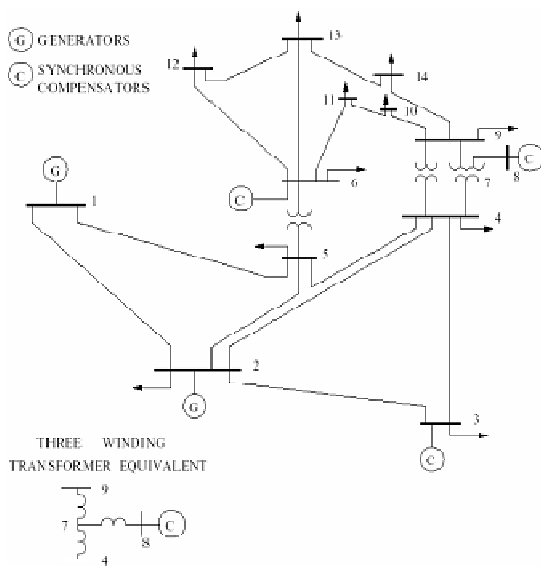

Fig. 2. The IEEE 14 bus test system

Table 1. Compare of transmission loss allocation without harmonic distortion using the IEEE-14 bus systems.

No. bus	Demand		Loss Allocation (MW)		
	MW	MVAr	Pro rata	ITL	Z bus
1	0.00	0.00	0.000	0.000	7.094
2	21.70	12.70	1.123	0.510	0.090
3	94.20	19.00	4.874	5.520	3.087
4	47.80	-3.90	2.473	2.490	1.003
5	7.60	1.60	0.393	0.290	0.101
6	11.20	7.50	0.580	0.440	0.158
7	0.00	0.00	0.000	0.000	0.000
8	0.00	0.00	0.000	0.002	0.010
9	29.50	16.50	1.526	1.520	0.610
10	9.00	5.80	0.466	0.510	0.205
11	3.50	1.80	0.181	0.150	0.069
12	6.10	1.60	0.316	0.270	0.132
13	13.50	5.80	0.699	0.690	0.339
14	14.90	5.00	0.771	1.010	0.505
Total	259.00	73.40	13.402	13.402	13.403

Table 2. Compare of transmission loss allocation with harmonic distortion of each load using the IEEE-14 bus systems

No. Bus	Transmission loss allocation (MW)			
	Losses without harmonic	Proposed with net harmonic distortion		
		ΔTHD =2.5%	ΔTHD =5%	ΔTHD =10%
1	7.094	7.182	7.269	7.440
2	0.090	0.091	0.092	0.094
3	3.087	3.125	3.163	3.238
4	1.003	1.015	1.028	1.052
5	0.101	0.102	0.103	0.106
6	0.158	0.160	0.162	0.166
7	0.000	0.000	0.000	0.000
8	0.010	0.010	0.010	0.010
9	0.610	0.618	0.625	0.640
10	0.205	0.208	0.210	0.215
11	0.069	0.070	0.071	0.072
12	0.132	0.134	0.135	0.138
13	0.339	0.343	0.347	0.356
14	0.505	0.511	0.517	0.530
Total	13.403	13.570	13.734	14.057

method considered more accurate Z bus, hence become to consider used for compare the proposed method.

In Table 2, can be seen that the transmission cost allocation is conditional, where:

Case-1 : Assume there are three loads of industry costumer with *THD* L3, L4 and L9 equal to 5% (according to *IEEE std*). Based on pro-rata method, the obtained *TLA* should be equal. This means that transmission owner will be charged according to pro-rata method original.

Case-2 : Assume there are three loads of industry costumer with *THD* is L3 5%, L4 (7.5%) and L9(10%). Therefore, based on pro-rata method, the owner of the transmission line will pay more according to THD rate. This means that transmission users will be charged due to the additional cost.

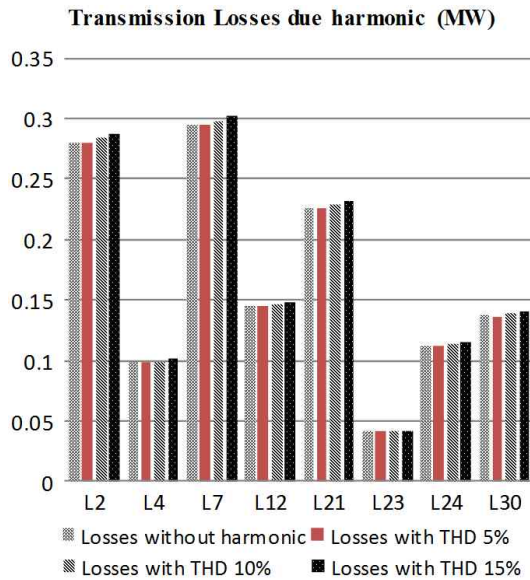*Case-3* : L3, L4 and L9 have THD of 7.5%,10% and

Transmission Losses due harmonic (MW)

Fig. 3. Transmission losses allocation due to harmonic content, estimated using the IEEE-30 bus systems.

15% according to *IEEE std*. Based on pro-rata method, the users will pay more for the *TLA* compared to the payment in case-2. In this case, L3, L4 and L9 have higher *THD* content, therefore they will get *TLA* more than for the load in Case-1 and Case-2.

By using Eq. (25) above, that when the *THD* 5%, then we obtain that:

$$MW_{loss,Dj}^{h} = MW_{loss,Dj} \qquad (28)$$

By the above equation in (28), then power losses are calculated according to the method used *TLA*. This proposal was then tested on the *IEEE 30 bus system* as shown in Fig 3. Based on the proposed method, at 10% THD for example in L2 load will has resulted losses of 0.284 MW and increase it if the *THD* load becomes 15% so on. The result will give a value significantly when the *THD* levels greater will increase in load. While for *THD* 5%, transmission losses is equal between existing methods with propose.

Based on the above, it will cause an increase in harmonic content losses on the transmission line. As a result, there is an increase in power flow in line caused by harmonics on the user. This condition causes a loss in the generation and transmission owners. For that, in order that the industry and gain the satisfaction and power providers are fair, then the harmonic components can be included in the calculation of the cost of transmission.

With reference to the *IEEE std.1459-2000* that defines 5% for *THD* of current, then the user can be charged additional costs due to harmonic, when has *THD* greater than 5%.

Further, the estimation results from the use of different IEEE bus systems can be a reference for transmission

owners in charging penalties to users who have the load quality below of standard. They can also provide information for determining the transmission charge scheme with considered harmonic content by each user, so that both economic aspect and technical aspects in power systems can be covered.

This proposal can provide a good economic signal to all parties in the deregulated of electricity industry supply in the future, especially for transmission owners. Besides, the industry consumer will be encouraged to improve load quality and energy efficiency.

5. Conclusion

This paper presents a new method to allocate the cost of transmission loss due to harmonics. The proposed method has shown differences in contribution costs in terms of conditions of harmonics in the use of transmission network. Through this method, the customer who uses electricity with higher *THD* will pay a higher transmission cost than other users. Meanwhile, the user who has *THD* content according to *IEEE std. 1459-2000* (until maximum limit is 5%) does not have to pay an additional charge to transmission owner.

This method also provides an alternative solution in the scheme for the determination of transmission charges for customers with varying load characteristic. Another benefit of this proposed method is that it provides economic signals for electricity industry supply, especially transmission and distribution company. The proposed method is suitable for the pool market in deregulated power system.

Acknowledgements

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