Investigation of Power Losses in Light Loaded Power Networks

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Abstract

In electricity markets, participants utilize the network differently to maximize their profits, which means their effects on the system, such as losses, can also be different. The development of a fair power loss allocation scheme is significant to avoid cross subsidies and to have correct charges for all participants. This paper investigates power losses in bilateral electricity markets operating under light load conditions in which excess reactive power needs to be absorbed to avoid unacceptable high voltage rises. The basic idea of the method used in the paper assumes that transactions have their own effects on the system and their interactive effects with each other. Each transaction share of the network losses depends on its contribution to the system current flows. The method determines these currents contributions using the so-called current adjustment factors. It can easily allocate both real and reactive losses simultaneously. The method is verified on IEEE-14-bus system.

1. Introduction

In electricity markets, the system operator assures security of the network whether it is a pool based market or a Bilateral based market. Power system must be balanced at every second which means that generation equals loads plus losses all the time. Energy trading of participants does not take into consideration system loss and the system operator is the entity who is in charge of securing the system by providing the required real and reactive power [1]. Since the power network is not lossless, entities providing the network with the required losses must be compensated for their contribution, normally at the pool marginal price in a pool based market, or at their marginal cost in bilateral markets [2]. The purpose of loss allocation is to assign each user of the network, whether a generator or a load, its share of the cost of transmission losses based on how much losses the user causes.

Network losses cost millions of dollars every year as they can account for five to ten percent of the total generation in the system [2]. So, fair allocation of the network losses has very important impact on all users. This is so because unfair allocation causes cross subsidies and it gives wrong indicative signals to network operator and users. A user who causes more network losses must be charged more while a user who helps to reduce the losses, due to counter flow, must be rewarded. Loss allocation methods that have been proposed so far fall into five categories: pro rata, marginal loss, proportional sharing, circuit based, and different approaches for bilateral contracts [1]-[3]. A short description of the first four categories is given here. Pro rata method is one of the most common techniques. It is based on generators injections or load real power level rather than on their relative locations in the network. In other words, loads close to the "centre of gravity" of the generation subsidise remote loads and generators close to "centre of gravity" of the loads subsidise remote generators. Marginal losses method is based on incremental transmission loss (ITL) coefficients. This method depends on the location of the slack bus. It needs normalization since the direct application of its coefficients results in over recovery [1]. The ITL coefficients can be positive or negative. Distributed slack bus is proposed in [3]. Proportional sharing technique [4]-[7] provides efficient computational method for loss allocation starting from the output of a solved load flow. However, it only uses Kirrchoff's first law and it is based on the proportionality sharing assumption which is neither provable nor disprovable. Further more, the technique traces power flow from generators to loads in which neither loads nor generators have control on the price they would be charged since they do not have any control on how their power reaches its destination and where that destination is.

Circuit-based loss allocation is proposed in [2]. The authors use the network Z-bus matrix without any simplifying assumptions. This method is based on a solved power flow and all its computations are based on the admittance matrix. Similar to marginal loss method, Z-bus technique can yield negative allocation to "reward" those participants who contribute to reduce network losses due to their strategically well positioned locations within the system. The negative ITL coefficients are being interpreted as cross subsidies in [1] and [2]. Unsubsidized ITL (U-ITL) method has been proposed to avoid negative allocated losses. It was emphasized in [1] that U-ITL method is to allocate non negative losses costs and not to explain physical facts. In [2], it is stated that Z-Bus method is similar to ITL method in which both methods can yield negative loss allocations. It is stated also that negative loss allocation using Z-Bus method is to "reward" generators or loads that are strategically well positioned in the network. The cross subsidy term means that a participant or a group of participants are charged more than they should be while others are either not charged or rewarded. So, the reward of the second group comes actually from the charges of the former group. For example, case study conducted in [1] using ITL method results in generators being allocated 146 % of losses and demands -46%.

The current adjustment factor method was proposed by the author in [8] to allocate real and reactive power losses in heavy loaded bilateral markets. It allocates each contract its share of both real and reactive power losses using the so-called current adjustment factors based the effects of the contract on system currents flows. There is excess reactive power in the network when it is lightly loaded that needs to be absorbed by generators and compensators. On the other hand, all participants use the network by which some currents flow and cause real and reactive power losses.

2. Problem Formulation

In a deregulated energy system, users should be responsible for the system losses that they cause. In light loaded networks, there is excess reactive power in the network that needs to be absorbed by generators and compensators. All participants use the network by which some currents flow and cause real and reactive power losses. Participants should be responsible for the losses they cause. On the other hand, entities that participate in releasing the network from the excess reactive power and participate in easing the high voltage rise problem should be rewarded. This paper extends and verifies the application of the current adjustment factors for allocating real and reactive power losses in light loaded power systems.

For any system, real and reactive power allocations including losses to all transactions present in the system can be determined through the following procedure:

1. From a solved load flow (base case) where all transactions deliver their shares of the market, i.e. each generator injects its contracted real power and each counterpart load consumes it, calculate all currents in all branches of the network

$$\bar{I}_k = I_{kx} + j\ I_{ky}\ ,\quad k = 1, 2, \ldots, NB \tag{1}$$

where NB = total number of branches

I_{kx} = real part of the complex current

I_{ky} = imaginary part of the complex current

2. With the transaction of interest T^i inactivated, run power flow program again and calculate resulted currents in all branches

$$\bar{I}_k^{Ti} = I_{kx}^{Ti} + j\ I_{ky}^{Ti}\ ,\ k = 1, 2\ldots NB,\ i = 1, 2\ldots NT \tag{2}$$

Where NT = total number of transactions. In this step, generator *i* (or groups of generators under the same entity *i*) is kept active with zero real power output. This ensures convergent solution, especially for the Must-Run generators.

3. The contribution of each transaction T^i in a branch is equal to the corresponding current flow difference between the base case and that when T^i is inactive;

$$\bar{I}_{k,cont}^{Ti} = \bar{I}_k - \bar{I}_k^{Ti} \tag{3}$$

4. The nonlinearity of the network due to the interaction between loads and generators when they are run at the same time makes the sum of currents obtained in step 3 does not match that obtained in step 1, i.e.

$$\bar{I}_k \neq \sum_{i=1}^{NT} \bar{I}_{k,cont}^{Ti} \tag{4}$$

So, the current adjustment factors are used to adjust the obtained currents in step 3 as follows

$$\bar{I}_k = CAF_k \sum_{i=1}^{NT} \bar{I}_{k,cont}^{Ti} \tag{5}$$

where CAF = c*urrent adjustment factor, which is* generally a complex matrix which is expected since the nonlinearity of the system is due to real and imaginary factors interactions.

5. Calculate the new adjusted currents

$$\bar{I}_{k,Adj}^{Ti} = CAF_k \times \bar{I}_{k,cont}^{Ti} \tag{6}$$

6. Calculate the real and reactive power losses allocations for each transaction, P_{Losses}^{Ti} and Q_{Losses}^{Ti} respectively as follow

$$P_{losses}^{Ti} = \sum_{k=1}^{NB} \{[(I_{kx,adj}^{Ti})^2 + (I_{ky,adj}^{Ti})^2 + C_k^{\mathrm{Re}} \times \frac{(I_{kx,adj}^{Ti})^2}{I_k^{\mathrm{Re},sum}} + C_k^{\mathrm{Im}} \times \frac{(I_{ky,adj}^{Ti})^2}{I_k^{\mathrm{Im},sum}}] \times R_k\}$$

$$Q_{losses}^{Ti} = \sum_{k=1}^{NB} \{[(I_{kx,adj}^{Ti})^2 + (I_{ky,adj}^{Ti})^2 + C_k^{\mathrm{Re}} \times \frac{(I_{kx,adj}^{Ti})^2}{I_k^{\mathrm{Re},sum}} + C_k^{\mathrm{Im}} \times \frac{(I_{ky,adj}^{Ti})^2}{I_k^{\mathrm{Im},sum}}] \times X_k\} \tag{7}$$

where

$$I_k^{\mathrm{Re},sum} = \sum_{i=1}^{NT} (I_{kx,adj}^{Ti})^2,\quad I_k^{\mathrm{Im},sum} = \sum_{i=1}^{NT} (I_{ky,adj}^{Ti})^2$$

$$C_k^{\mathrm{Re}} = \sum_{i=1}^{NT} \sum_{\substack{j=1 \\ i \neq j}}^{NT} I_{kx,adj}^{Ti} \times I_{kx,adj}^{Tj},\quad C_k^{\mathrm{Im}} = \sum_{i=1}^{NT} \sum_{\substack{j=1 \\ i \neq j}}^{NT} I_{ky,adj}^{Ti} \times I_{ky,adj}^{Tj}$$

R_k = the resistance of branch k, X_k = the reactance of branch k

$I_{kx,adj}^{Ti}$ = the real part of $\bar{I}_{k,adj}^{Ti}$, and $I_{ky,adj}^{Ti}$ = the imaginary part of $\bar{I}_{k,adj}^{Ti}$

3. Application Case Studies

3.1. A simple 3-bus system

This system is illustrated in Figure 1. There are two transactions: transaction one is between generator 1 and load 3a and transaction two is between generator 2 and load 3b. Three scenarios have been studied:

Scenario 1: Since the slack bus location affects system losses generally, a rotating slack bus is used between buses 1 and 2. Then the average is calculated. With unity power factor loads, traded power of transaction 2 increases from 0.1 MW to 20 MW in steps of 0.1 MW while keeping transaction one's at 10 MW. Fig. 2(a) and Fig.2(b) show that as transaction 2 increases, its allocated losses increase while the allocated losses of transaction 1 have slightly increased. The little increase of loss allocated to transaction 1 is due to the interaction between transactions when they are applied simultaneously as shown in (7).

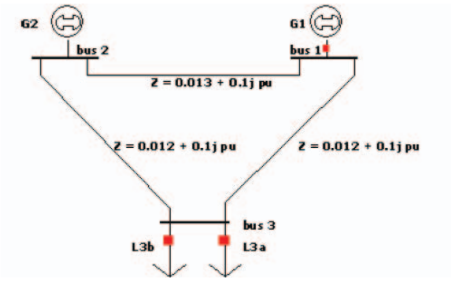

Fig. 1. Simple 3-bus system

It is worth noting that real and reactive power loss allocations shown in Fig. 2 have the same pattern except that the y-axis values are different. This is expected since the method is based on branches currents which are the same for real and reactive power loss allocations (7). They are different only according to line resistance and reactance and this is actually the strength of the method. Since the electric distance for both transactions is the same, the loss allocations must be the same when both transactions traded powers are 10 MW which can be seen from the results above.

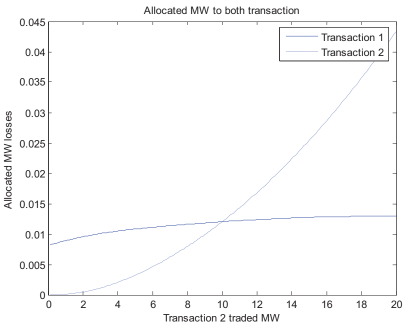

Fig. 2(a). Real power loss allocation to both transactions (scenario 1)

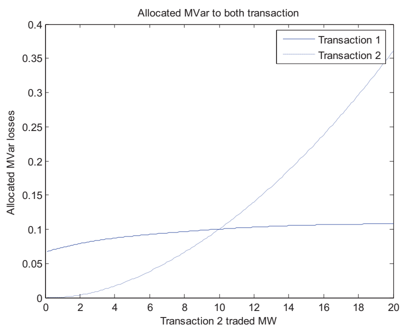

Fig. 2(b). Reactive power loss allocation to both transactions (scenario 1)

Scenario 2: In this case, the traded power of transaction 2 has a fixed non unity power factor (0.89 lagging). This means that this transaction burdens the system more than it does in the previous case. The results shown in Fig. 3 are consistent with expectation as transaction 2 is now allocated more losses compared to the previous case for the same MW output.

Scenario 3: If generator 2 is far away from the load centre, the shipping of its energy burdens the system much more than that of transaction 1. To study this, the impedance of the branch connecting generator 2 to bus 3 is increased to z = 0.03 + j0.2 pu. It is expected that transaction 2 will be allocated the same losses as that of transaction 1 when generator 2 has a lower output than that of generator 1. In other words, for 10 MW from both generators, transaction 2 will be allocated more losses than generator 1 due to its larger electric distance. This is shown in Fig. 4.

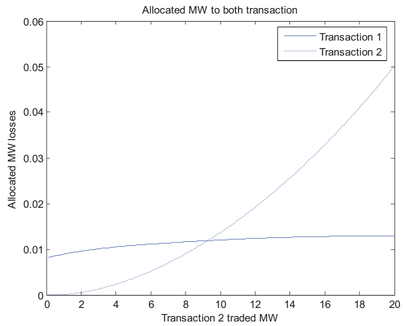

Fig. 3(a). Real power loss allocation to both transactions when transaction 2 has 0.89 lagging power factor (scenario 2)

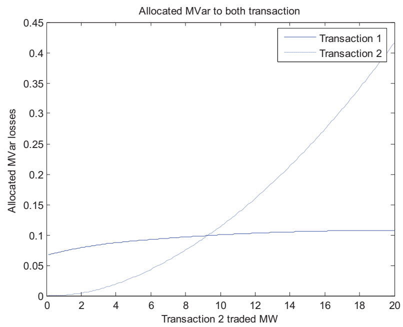

Fig. 3(b). Reactive power loss allocation to both transactions when transaction 2 has 0.89 lagging power factor (scenario 2)

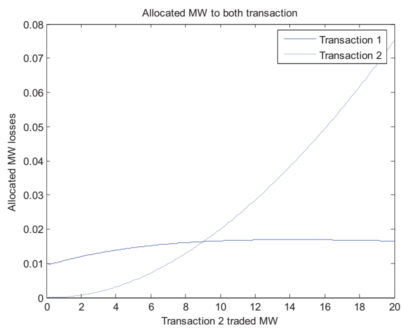

Fig. (4). Real power loss allocation to both transactions when transaction 2 has longer electrical distance (scenario 3)

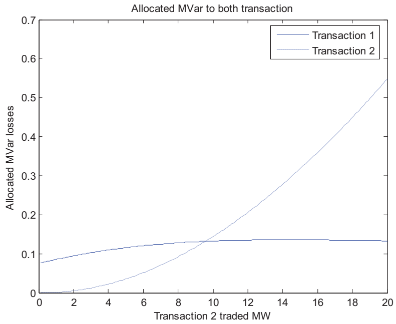

Fig. 4(b). Reactive power loss allocation to both transactions when transaction 2 has longer electrical distance (scenario 3)

3.1. IEEE-14 bus system

The one line diagram of the system is shown in Fig. 5 and transactions data is given in Table 1. Two different case studies have been conducted to test the characteristic performance of the method under light loading conditions. The simulation results of these scenarios are shown in Table 2.

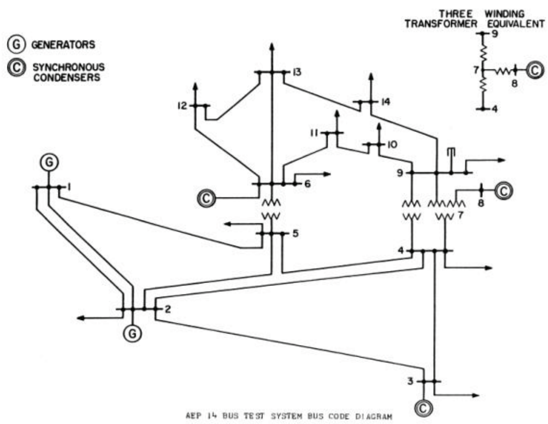

Fig. 5. One line diagram of IEEE-14-bus system

Case Study (a):

This scenario simulates the base case of the system where all generators and loads are dispatched according to the data given in Table 1 in which there are two transactions:

Transaction 1 Generator 1 has a transaction with the loads at buses 2 and 3.

Transaction 2 Generator 2 has a transaction with the loads at buses 5, 6, 7, 9, 10, 11, 12, 13 and 14.

Case Study (b):

This scenario simulation studies the system when the reactive power source at bus 8 is disconnected. The total system losses increase as reactive power needs to travel longer electrical distance than it does in scenario 1. The results show that the losses increase is allocated to transaction 2. This is expected as it reflects the fact that all the contracts of generator 2 are with demands in load center in which they are affected more by losing the reactive source at bus 8.

Table 1. Bilateral contracts between generators and loads of the IEEE-14-bus system

Bus #	Transactions quantities in MVA	
	Generator 1	Generator 2
1	0	0
2	$1.05 + j0.635$	0
3	$4.7+j0.95$	0
4	0	$2.35 - j\,0.195$
5	0	$0.5 + j0.08$
6	0	$0.75+j0.375$
7	0	0
8	0	0
9	0	$1.5+j0.83$
10	0	$0.45+j0.29$
11	0	$0.75+j0.09$
12	0	$1.75+j0.08$
13	0	$1.5+j0.29$
14	0	$1+j0.25$
Total	5:75 + j1:585	$10{:}55 + j2{:}09$

Table 2. Results of case studies (3.1)

Case #	Generator	Load		Allocated losses	
		P (MW)	Q(Mvar)	P (MW)	Q (MVar)
a	G1	5.75	1.585	0.4	0.14
	G2	10.55	2.09	0.16	2.16
b	G1	5.75	1.585	0.4	0.14
	G2	10.55	2.09	0.23	2.27

6. Conclusions

This paper investigates electric power losses in the power system operating under light load conditions in which excess reactive power needs to be absorbed in order to avoid unacceptable high voltage at certain buses in the network. The basic idea of the method assumes that transactions have their own effects on the system as well as their interactive effects with each other. The real use of the system mainly depends on two factors; the nature of the individual contracts and the relative locations of parties involved in the contract. This paper contributes towards a competitive reactive power market by extending and verifying the application of the current adjustment factorsfor allocating real and reactive power losses in light loaded power systems. The paper also contributes to the current real power markets, where real power is still the main traded commodity, by applying the method presented in the paper to both heavy as well as light loaded systems. The method has shown consistency with intuitive expectation through many test systems where only a few of these cases are presented in this paper due to space limitation. The cases included a simple three bus system and IEEE-14 bus system.

7. References

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