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Real and reactive power loss allocation in pool-based electricity markets

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ABSTRACT

Although real power is the main traded commodity in electricity markets, reactive power plays crucial roles in power systems reliability and security. Market participants utilize the network differently to maximize their profits. It means that their effects on the system, such as losses, can also be different. The development of a fair and accurate loss allocation scheme for real and reactive power is significant to avoid cross subsidies and to have the correct charge for each participant. This paper introduces a new method to allocate real and reactive losses in pool-based markets. The basic idea assumes that network users have their own effects on the system as well as their interactive effects which are based on their contributions to currents flows. The proposed method determines these contributions and adjusts them, due to system nonlinearity, according to Current Adjustment Factors (CAFs). Unlike other approaches, the proposed method can easily and effectively allocate real and reactive losses simultaneously without any additional calculation except the substitution of line reactance instead of resistance. The proposed method is illustrated on a simple system and tested on the standard IEEE-14-bus and IEEE-30-bus systems. Results have shown validity and consistency of the proposed method.

1. Introduction

In electricity markets, the system operator assures security of the network whether it is a pool market or a bilateral market. Power system must be balanced at every second which means that generation equals loads plus losses at all times. In electricity markets, power dispatch does not take into consideration system losses and the system operator (SO) is the entity responsible for system security by providing the required real and reactive power [1]. Since the power network is not lossless, entities providing the network 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 5–10% of the total generation in the system [2]. The development of a fair and accurate loss allocation scheme for real and reactive power is significant to avoid cross subsidies and to have the correct charge for each participant. 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.

Many loss allocation methods have been proposed. They fall into five main categories: pro-rata, marginal loss, proportional sharing, circuit-based, and different approaches for bilateral contracts [1–5]. A short description of the first four categories is given here.

Pro-rata method is one of the most common techniques [1,6]. It is based on generators injections or load real power levels rather than on their relative locations in the network. In other words, generators/loads close to "center of gravity" of loads/generators subsidies remote generators/loads.

Marginal loss allocation method is based on incremental transmission loss (ITL) coefficients [1,6,7]. 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. The latter might be interpreted as cross subsidy (for example, a case study conducted in [1] using ITL method results in generators being allocated 146% of losses and demands −46%.). A distributed slack bus approach is proposed in [3].

Proportional sharing technique [8–13] provides efficient computational method for loss allocation starting from the output of a converged power flow calculations. However, it only uses Kirrchoff's first law and it is based on the proportionality sharing assumption which is, as stated by the original authors [8], neither provable nor disprovable. Furthermore, neither loads nor

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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 allocation method, Z-bus technique can yield negative allocation which might be interpreted as cross subsidy.

The negative ITL coefficients are being interpreted as cross subsidies in [1,2]. 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. Similar to ITL, U-ITL needs normalization.

Since transmission losses are nonlinear function of line flows, it is impossible to divide system losses to unique separate parts; i.e. each part is uniquely assigned to a generator or a load. So, any loss allocation approach has a certain degree of arbitrariness. Nonetheless, there are characteristics that a loss allocation scheme must have to be equitable, or at least accepted as a reasonable approach. The scheme should have most of the following characteristics: (1) Reflects the amount produced or consumed by a user. (2) Takes into consideration the relative location of a user within the network. (3) The sum of all loss allocated terms is consistent with the results of the power flow. (4) Avoids volatility. (5) Easy to understand and implement.

The new proposed method in this paper satisfies all the characteristics suggested above as well as it introduces six more characteristics: (a) It does not yield negative allocations that might be interpreted as cross subsidy. (b) It can allocate both real and reactive power losses simultaneously in which calculating real allocations and those of reactive allocations is the same except the substitution of line reactance instead of resistance. (c) It has the ability to allocate real and reactive power losses on each branch to each network participant. (d) It takes into consideration counterflow effect by allocating those participants that cause counterflow less allocations. (e) It allocates losses to generators and loads depending on their utilization of the network without a need for arbitrary sharing percentage. (f) It creates incentives or disincentives to participants with respect to their relative locations within the network.

2. Proposed Current Adjustment Factors (CAFs) method

In a deregulated energy system, every user should be responsible for the system losses that he or she caused. Every user contributes differently to system loss. The interaction between different users losses causes allocation difficulty. To illustrate this difficulty, consider the following branch that carries two power flows; P_A and P_B as shown in Fig. 1.

Real power losses can be easily calculated as follows:

$$P_{Loss} = |\bar{I}_t|^2 \times R = |\bar{I}_A + \bar{I}_B|^2 \times R = |\bar{I}_A^2 + \bar{I}_B^2 + 2 \times \bar{I}_A \times \bar{I}_B| \times R \quad (1)$$

where $\bar{I}_t$ is the current vector, $|\bar{I}|$ is magnitude of $\bar{I}$ and R is the line resistance. But if the power losses of these flows are calculated individually, then

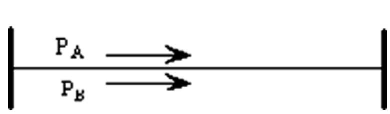

Fig. 1. A branch that carries two traded real power flows.

$$P_{Loss,A} = |\bar{I}_A^2| \times R \quad (2)$$

$$P_{Loss,B} = |\bar{I}_B^2| \times R \quad (3)$$

The summation illustrates that

$$P_{Loss} \neq P_{Loss,A} + P_{Loss,B} \quad (4)$$

There is a cross term difference $(2 \times \bar{I}_A \times \bar{I}_B \times R)$ inside the absolute term. If one traces $\bar{I}$'s of A transaction and those of B transaction. Then

$$P_{Loss} = |(I_{Ax} + I_{Bx}) + j(I_{Ay} + I_{By})|^2 \times R \quad (5)$$

where I_x and I_y are the real and imaginary parts of $\bar{I}$, respectively. But the squared absolute term of a vector is equal to the dot product of that vector, so,

$$\begin{aligned} P_{Loss} &= \left[(I_{Ax} + I_{Bx})^2 + (I_{Ay} + I_{By})^2)\right] \times R \\ &= \left[I_{Ax}^2 + I_{Ay}^2 + 2 \times I_{Ax} \times I_{Bx} + 2 \times I_{Ay} \times I_{By} + I_{Bx}^2 + I_{By}^2\right] \times R \end{aligned} \quad (6)$$

Then it is fair enough to assign each contributor its share of the losses as follows:

$$\begin{aligned} P_{Loss,A} = \Bigg[& I_{Ax}^2 + I_{Ay}^2 + 2 \times I_{Ax} \times I_{Bx} \times \frac{I_{Ax}^2}{I_{Ax}^2 + I_{Bx}^2} \\ & + 2 \times I_{Ay} \times I_{By} \times \frac{I_{Ay}^2}{I_{Ay}^2 + I_{By}^2} \Bigg] \times R \end{aligned} \quad (7)$$

$$\begin{aligned} P_{Loss,B} = \Bigg[& I_{Bx}^2 + I_{By}^2 + 2 \times I_{Ax} \times I_{Bx} \times \frac{I_{Bx}^2}{I_{Ax}^2 + I_{Bx}^2} \\ & + 2 \times I_{Ay} \times I_{By} \times \frac{I_{By}^2}{I_{Ay}^2 + I_{By}^2} \Bigg] \times R \end{aligned} \quad (8)$$

In Eqs. (7) and (8), all terms are separated except the cross terms which are assigned to each user according to the separated terms ratio on the same transmission line (not based on sharing on other lines).

Define M_A and M_B as follows:

$$M_A = \left[I_{Ax}^2 + I_{Ay}^2 + 2 \times I_{Ax} \times I_{Bx} \times \frac{I_{Ax}^2}{I_{Ax}^2 + I_{Bx}^2} + 2 \times I_{Ay} \times I_{By} \times \frac{I_{Ay}^2}{I_{Ay}^2 + I_{By}^2}\right] \quad (9)$$

$$M_B = \left[I_{Bx}^2 + I_{By}^2 + 2 \times I_{Ax} \times I_{Bx} \times \frac{I_{Bx}^2}{I_{Ax}^2 + I_{Bx}^2} + 2 \times I_{Ay} \times I_{By} \times \frac{I_{By}^2}{I_{Ay}^2 + I_{By}^2}\right] \quad (10)$$

The squared values of currents in fractions in Eqs. (9) and (10) are used instead of the normal values as the transmission loss is proportional to the current squared and the separable terms of the expressions are already squared. So, when assigning each contributor its share of the cross term, it is logical to use the other squared terms in the expression rather than their normal values. In addition, using normal values instead of squared values of currents has been conducted on many test networks. The results may yield negative allocations which may be interpreted as cross subsidy.

Then reactive loss allocations can be obtained straightforwardly as follows:

$$Q_{Loss,A} = M_A \times X, \quad (11)$$

$$Q_{Loss,B} = M_B \times X, \quad (12)$$

where X is the line reactance.