A novel loss allocation in pool markets using weight-based sharing and voltage sensitivity analysis

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1. Introduction

Nowadays, generation, transmission and distribution companies have been derived from traditional vertically integrated systems. The main objective of the deregulation of power markets is to provide a reduction of customer electricity prices [1]. The responsibility of paying for the part of system losses is assigned to individual participants through the transmission loss allocation [2]. Despite the fact that generation levels or power flows are not affected by the transmission loss allocation, it is a major factor in locational spot pricing [3,18]. Therefore, the distribution of revenues and payments among participants is affected by such allocation.

In the literatures, several loss allocation methods have been presented. They can be classified into four categories: (a) pro rata, (b) proportional sharing, (c) incremental transmission loss (ITL) and (d) loss formula or circuit-theory.

System losses are allocated considering the active generation or load of each participant in the pro rata method. The method is very common due to simple implementation. However, such method cannot consider the location of loads/generators in the network.

The applications of such method can be found in England, Spain, and Brazil [4–7].

Proportional sharing methods based on flow tracing technique are developed where allocated losses are based on the results of a converged power flow used along with a linear proportional sharing procedure [8–12]. An assumption that inflows are proportionally shared among outflows at each network node is the main principle of the procedure whose validity “can neither proved nor disproved” [13].

ITL methods use the sensitivities of losses in relation to bus injections or transactions. In Ref. [14], the authors have presented an integral method which uses a distributed slack bus. Practical implementation of a marginal allocation method in the Norwegian electric system has been presented in Ref. [15]. A sharing of transmission losses among generators and loads based on a predefined proportion has been provided using the concept of “center of losses” [16,17]. A path-integral method has been presented by integrating the partial differential of system losses along a path [18].

In the recent years, loss formula or circuit theory methods have been proposed. System losses as the sum of the squares of power injections and crossed terms have been expressed using a dc network model [19]. In Refs. [20,21], a quadratic function of the bilateral transactions has been proposed to express the system losses similarly. Another quadratic expression for transmission losses in power systems has been expressed in Ref. [22]. In Ref. [23], the authors have proposed the main circuit theory based
method which expresses the total system loss as a function of Z-bus matrix and bus current injections. Ref. [24] presented a new method based on graph theory for transmission loss allocation in hybrid markets. Chen and Dhole have presented analytical closed-form expressions that uncover the contributions of nodal active- and reactive-power injections to the active- and reactive-power flows on transmission lines in an AC electrical network [25]. The paper has claimed that the method is very useful for loss allocation.

Loss allocation in distribution networks considering distributed generations is another subject which have been studied recently [26,27]. The methods try to explicitly exploit the characteristics of such networks to develop a suitable loss allocation method.

As discussed earlier, the main problem of loss allocation is uncertain due to the nonlinear nature of transmission losses. This paper tries to deal with this problem and presents a fair, certain and transparent method. Transmission losses are divided into two components including direct component (DCM) and indirect component (IDCM) which simplifies each component and also makes the allocation of such components easy. Two different methods are used to allocate DCM and IDCM. DCM is much greater than IDCM and is naturally separated in terms of power injections so that it can be allocated certainly which implies that the main part of losses is allocated via a fair, certain and transparent method. However, former studies cannot deliver such fairness and certainty especially [25], the most important work which has been done in this field recently. The minor part (IDCM) which its certainty is not clear is allocated based on its characteristics using a novel voltage sensitivity analysis which is accurate and can present the same transparency for the allocation of the DCM.

This paper is organized as follows: problem formulations are presented in Section “Problem formulations”. In Section “Loss classification”, loss classification is introduced. The proposed loss allocation methods for DCM and IDCM are introduced in Sections “Proposed loss allocation method for DCM” and “Proposed loss allocation method for IDCM”, respectively. Test results and comparisons with previous methods are given in Section “Test results”. The conclusion is given at the end.

2. Problem formulations

AC power-flow methods can determine total transmission losses in power systems. In Ref. [28], transmission losses in terms of power injections have been expressed as:

\[ P_{\text{loss}} = \Re \left\{ \sum_{i=1}^{n} \sum_{j=1}^{n} R_{ij} \left( P_i P_j Q_j - j Q_i Q_j - P_i Q_j - Q_i P_j \right) / |V_i||V_j| \right\} \]

(1)

where \( P_i \) and \( Q_i \) are the active and reactive power injections at bus \( i \), respectively. \( |V_i| \) and \( \delta_i \) are the magnitude and angle of the voltage of bus \( i \). \( R_{ij} \) is the real part of the \( i \)-th row and \( j \)-th column of the impedance matrix.

Based on (1), a loss matrix can easily be constructed as follows:

\[ P_{\text{loss}} = \sum \begin{bmatrix} P_{i11} & P_{i12} & \cdots & P_{i1n} \\ P_{i21} & P_{i22} & \cdots & P_{i2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{in1} & P_{in2} & \cdots & P_{inn} \end{bmatrix} \]

(2)

where

\[ P_{lii} = \frac{R_{ii}}{|V_i|^2} \left[ P_i^2 + Q_i^2 \right] \]

(3)

To allocate this loss matrix to loads and generators, (4) has been divided into four smaller components in Ref. [28] where each component has two participants and can be allocated to such participants using weight-based sharing method for example the first component of (4) is allocated to \( P_i \) and \( P_j \) as:

\[ L_{pi} = \frac{R_{ij}}{|V_i||V_j|} P_i \cos \delta_i - \frac{1}{|P_i| + |P_j|} P_i^2 \]

(5)

\[ L_{pj} = \frac{R_{ij}}{|V_i||V_j|} P_j \cos \delta_j - \frac{1}{|P_i| + |P_j|} P_j^2 \]

(6)

This method has suggested a good idea to separate transmission losses in terms of power injections especially for diagonal elements which are naturally separated as can be seen in (3) and must be allocated to their participants certainly. However, the method ignores the effect of loads on voltage drops and angle changes. It is clear that voltage drops and angle changes contribute to some parts of (3) and (4). Indeed, each of power injections can cause some part of voltage drops and angle changes and if such indirect effects are extracted from the loss matrix, then matrix elements are simplified and can be shared transparently. Therefore, in the next section, the loss matrix is classified to the direct and indirect effects of power injections and each component is allocated through a different, fair, transparent method.

3. Loss classification

In power systems, consuming active and reactive powers by each load lead to the voltage drop of the load bus and also other buses. These voltage variations (magnitude and angle changes) involve in the construction of each element of the loss matrix and can be derived as follows entitled ‘indirect component of power injections’.

3.1. DCM of power injections

The DCM is obtained if voltage drops and angle changes in (3) and (4) are ignored. In other words, when there are no such variations, the only variables in such equations (3) are load/generator power injections. Hence, the DCM can be obtained from (3) and (4) as:

\[ P_{lii}^{\text{IDCM}} = \frac{R_{ii}}{|V_i|^2} \left[ P_i^2 + Q_i^2 \right] \]

(7)

\[ P_{lij}^{\text{IDCM}} = \frac{R_{ij}}{|V_i||V_j|} \left[ P_i P_j \cos \delta_i + Q_i Q_j \cos \delta_j \sin \delta_i + P_j P_i \sin \delta_i \right] \]

(4)

where \( V_i \) is the voltage of the slack bus.

3.2. IDCM of power injections

The IDCM as can be seen in (4) complicates the loss components and it can be separated from the loss matrix as:

\[ P_{lij}^{\text{IDCM}} = P_{lij} - P_{lij}^{\text{IDCM}} \]

(9)

\[ P_{lij}^{\text{IDCM}} = P_{lij} - P_{lij}^{\text{IDCM}} \]

(10)
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