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Optimal compensation of transmission losses in a multiple-transaction framework

Qifeng Ding [a,*], Ali Abur [b]

[a] Centerpoint Energy, Houston, TX, United States
[b] Department of Electrical and Computer Engineering, Northeastern University, Boston, MA, United States

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Abstract

This paper presents an optimal power flow formulation in which the generation is dispatched in order to compensate for losses allocated to different transactions. Since the loss allocation itself depends on the solution, the two problems are combined and solved together. Loss allocation scheme developed by the authors earlier [Ding Q, Abur A. Transmission loss allocation in a multiple-transaction framework, IEEE Trans Power Syst 2004;19(1):214–20] is used in this formulation. It is assumed that each transaction is entitled to select its own designated generators to compensate for its allocated losses. The case where some transactions prefer instead to let the independent system operator (ISO) to provide the loss compensation service is also considered. An optimization procedure, which yields the least-cost compensation from participating generators, is developed for this purpose by using an OPF model. Several numerical examples are included to demonstrate the proposed procedures.

Keywords: Power flow analysis; Transmission loss allocation; Optimization

1. Introduction

Electric power industry is going through important changes as a result of restructuring. In the newly created electricity markets, sellers and buyers of electricity engage in bilateral power transactions, which take place over the transmission system and create losses. Since transmission losses are not negligible, their allocation among the participating transactions has been an issue under investigation from the very beginning.

Among the schemes proposed so far for the allocation of losses [1–10], there are different approaches ranging from allocating losses to generators/loads in a pool market to allocating then to individual transactions in a bi-lateral contract market. A single slack bus is often used to compensate for all the losses incurred by transactions, but it is possible to have each transaction assign its own chosen buses for the loss compensation. Such a choice will however yield a different power flow solution, necessitating further discussion of loss allocation along with loss compensation. Power flow solution algorithm should then incorporate the chosen loss allocation strategy so that the solution will yield a system state and generation dispatch consistent with this loss allocation strategy. One possible solution which uses distributed slack buses is described in [11] where losses are compensated for bilateral transactions. In [12], the same problem is formulated for the multiple-transaction case where transactions get to designate generator buses for compensation of losses allocated to them or they may opt for purchasing loss compensation service from the ISO. While very comprehensive, this approach may lead to possible inaccuracies as shown in [7] due to its use of the DC power flow approximation and the LP optimization model.

This paper presents an alternative solution to the above problem. First, the multi-transaction framework definition is extended to include loss compensation entities for

* Corresponding author.
E-mail address: kevin.ding@CenterPointEnergy.com (Q. Ding).

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transactions so that each individual transaction is able to freely choose any generators instead of the system slack bus for loss compensation. Unlike some previous papers, the transactions are allowed to select a single generator or multiple generators for loss compensation and do not necessarily designate the system slack or their own generators for loss compensation. Next, the conventional power flow analysis is combined with the transaction loss allocation and transaction designated loss compensation methods which are developed by the authors in [1]. These methods allow a natural separation of losses among individual transactions in a multiple-transaction setting. This combined formulation leads to a systematic solution procedure in order to adjust generation while simultaneously allocating losses to the generators designated by individual transactions. However, if some transactions choose not to designate any specific loss compensation generators, then this will provide an opportunity for the ISO to implement a least-cost loss compensation solution. An OPF model is then utilized to optimize the loss compensation for those transactions electing to purchase the loss service from the ISO and accordingly the incurred losses are fairly allocated back to individual transactions. Consequently, all transactions will be able to either choose self-compensation or ISO-compensation for their allocated losses.

The paper is organized in such a way that, the proposed formulation is presented first, followed by its implementation algorithm. Numerical examples are included at the end to illustrate the application of the proposed method to typical power systems.

2. Transaction framework formulation

We extend the multi-transaction framework definition in [1] and [7] for the system with n buses and M transactions. For $m = 1, 2, \ldots, M$, the transaction $T^{(m)}$ involving the set of selling entities $S^{(m)}$, the set of buying entities $B^{(m)}$, the set of loss compensating entities $C^{(m)}$, the loss compensation portion $l^{(m)}$ and the MW amount $t^{(m)}$ is defined by the quintuplet

$$T^{(m)} = \{t^{(m)}, S^{(m)}, B^{(m)}, C^{(m)}, l^{(m)}\} \tag{1}$$

where

$$S^{(m)} = \{(s_i^{(m)}, \alpha_i^{(m)}), i = 1, 2, \ldots, N_s^{(m)}\}$$
$$B^{(m)} = \{(b_i^{(m)}, \beta_i^{(m)}), i = 1, 2, \ldots, N_b^{(m)}\}$$
$$C^{(m)} = \{(c_i^{(m)}, \gamma_i^{(m)}), i = 1, 2, \ldots, N_c^{(m)}\}$$

For each transaction m, the selling bus $s_i^{(m)}$ provides the fraction $\alpha_i^{(m)}$ of the total MW amount $t^{(m)}$ while the buying bus $b_i^{(m)}$ receives the fraction $\beta_i^{(m)}$. The loss compensation bus $c_i^{(m)}$ ($c_i^{(m)}$ is not necessarily among the selling buses of the transaction) supplies the fraction $\gamma_i^{(m)}$ of the transaction allocated loss. The fraction $l^{(m)}$ of the transaction MW amount $t^{(m)}$ is the portion of the system losses allocated to that transaction. Since $l^{(m)}$ will not be known before the loss allocation solution is reached, it must be computed iteratively.

Since the nodal power injections can be written as a sum of individual transactions, eventually we can express the amount of the power injection at any bus as follows:

$$P_h = \sum_{m=1}^{M} \delta_h^{(m)} t^{(m)} \tag{2}$$

where the components of the vector $\delta_h^{(m)}$ are

$$\delta_h^{(m)} = \begin{cases} \alpha_i^{(m)} & \text{if } s_i^{(m)} = h, \quad i = 1, 2, \ldots, N_s^{(m)} \\ \alpha_i^{(m)} + \gamma_k^{(m)} l^{(m)} & \text{if } s_i^{(m)} = c_k^{(m)} = h, \quad i = 1, 2, \ldots, N_s^{(m)}, \\ & \quad k = 1, 2, \ldots, N_c^{(m)} \\ -\beta_j^{(m)} & \text{if } b_j^{(m)} = h, \quad j = 1, 2, \ldots, N_b^{(m)} \\ \gamma_k^{(m)} l^{(m)} - \beta_j^{(m)} & \text{if } b_j^{(m)} = c_k^{(m)} = h, \quad j = 1, 2, \ldots, N_b^{(m)}, \\ & \quad k = 1, 2, \ldots, N_c^{(m)} \\ \alpha_i^{(m)} - \beta_j^{(m)} & \text{if } s_i^{(m)} = b_j^{(m)} = h, \quad i = 1, 2, \ldots, N_s^{(m)}, \\ & \quad j = 1, 2, \ldots, N_b^{(m)} \\ \alpha_i^{(m)} - \beta_j^{(m)} + \gamma_k^{(m)} l^{(m)} & \text{if } s_i^{(m)} = b_j^{(m)} = c_k^{(m)} = h, \\ & \quad i = 1, 2, \ldots, N_s^{(m)}, \; j = 1, 2, \ldots, N_b^{(m)}, \\ & \quad k = 1, 2, \cdots, N_c^{(m)} \\ \gamma_k^{(m)} l^{(m)} & \text{if } c_k^{(m)} = h, \quad k = 1, 2, \cdots, N_c^{(m)} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

3. Mathematical formulation

3.1. Loss allocation scheme

A loss allocation method in a multiple-transaction framework is described in [1]. The approach presented in [1] is based on a symmetric transaction-loss matrix TL which can be constructed as follows:

$$\mathrm{TL} = \begin{array}{c} \\ 1 \\ 2 \\ \vdots \\ \vdots \\ M \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & \cdots & \cdots & M \end{array} \\ \begin{bmatrix} P_L^{(1,1)} & P_L^{(1,2)} & \cdots & \cdots & P_L^{(1,m)} \\ P_L^{(2,1)} & P_L^{(2,2)} & \cdots & \cdots & P_L^{(2,m)} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ P_L^{(m,1)} & P_L^{(m,2)} & \cdots & \cdots & P_L^{(m,m)} \end{bmatrix} \end{array} \tag{4}$$

where $P_L^{(m,m)}$ and $P_L^{(m,k)}$ can be calculated by transactions $t^{(m)}$, line impedance, and bus voltages (V_i, θ_i) as:

$$P_L^{(m,m)} = \frac{t^{(m)}}{\sum_{i=1}^{M} t^{(i)}} P_{LQQ} + \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{R_{ij}}{V_i V_j} \cos\theta_{ij} \cdot \delta_i^{(m)} \delta_j^{(m)} t^{(m)} t^{(m)} + \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{R_{ij}}{V_i V_j} \sin\theta_{ij} (-\delta_i^{(m)} Q_j + Q_i \delta_j^{(m)}) \cdot t^{(m)} \tag{5}$$

$$P_L^{(m,k)} = \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{R_{ij}}{V_i V_j} \cos\theta_{ij} \cdot \delta_i^{(m)} \delta_j^{(k)} t^{(m)} t^{(k)} + \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{R_{ij}}{V_i V_j} \cos\theta_{ij} \cdot \delta_i^{(k)} \delta_j^{(m)} t^{(m)} t^{(k)} \quad k \neq m \tag{6}$$

The self-induced loss term $P_L^{(m,m)}$ is solely due to the individual transaction m, and the cross term $P_L^{(m,k)}$, which should