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Identification of wheeling paths by an extended sensitivity analysis

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ABSTRACT

This paper proposes a practical method for identifying wheeling paths in deregulated electricity markets based on an extended sensitivity analysis. Using this method, it becomes possible to decide the proper and fair wheeling rate according to the degree of burden on transmission lines by each power flow transaction. Moreover, a wheeling rate based on the real power flow burden is also an important signal to new power suppliers in the markets. In order to show the validity of the proposed method, a series of simulations on the IEEE 30-bus test system were conducted.

1. Introduction

There is a trend toward competitive markets in the electric power industry all over the world [1–3]. In Japan, although the deregulation of electricity is being implemented mainly in the wholesale power market, partial retail wheeling is allowed. In other words, any party (player) who is in the business of supplying electricity to the market can supply it to its customers, not only from its own generators but also from the market, selling both inside and outside their regions. High voltage customers can purchase power from either existing regional utility companies, or new power suppliers. Since the pricing for these purchases is not regulated, bilateral contracts between suppliers and customers may be negotiated and arranged. However, if electricity based on the bilateral transactions uses the grid owned by the regional utility company, the wheeling rate must be paid to the grid owner. Under such circumstances, appropriate setting of the wheeling rate is one of the critical issues for both suppliers and grid owners in deregulated electricity markets [4,5].

Several methodologies to determine wheeling rates, such as postage stamp, contract path, distance based *MW*-mile, and power flow based *MW*-mile have been proposed and deeply investigated [6–8]. However, since in the aforementioned methods, the use of transmission lines and time variable load flows is not modeled sufficiently, a wheeling rate reflecting the transmission line condition (change by time and a day of week) is preferable in order to obtain a fair rate.

In this paper, we propose an efficient method for identifying wheeling paths based on an extended sensitivity analysis. Using this method, it becomes possible to fix the proper and fair wheeling rate according to the degree of burden on transmission lines by each power flow transaction. The proposed method has four advantages compared with the existing transmission routes identification techniques. (i) The proposed approach incorporates the concept of generation distribution factor [9–11] into the sensitivity analysis, which can take the consideration of not only variable loads but also generator characteristics (generation capacity, speed regulation, and dispatching strategies) and load characteristics (voltage and frequency elasticity, constant power features) under various conditions. (ii) Comparing with most of the techniques which target to identify wheeling path from single generator to single customer [12–14], the proposed method can identify multiple wheeling paths accurately, i.e., any combination among the generators and the customers, such as single to single, plurality to single, single to plurality and plurality to plurality. This approach is applicable to the situation where new power suppliers have more than two generators and there are many customers in the market. (iii) The computational complexity of the proposed method is approximately equivalent to one iteration of power flow calculation, and is computationally efficient. (iv) There is no special assumption, and also no additional theoretical error except numerical error.

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The paper is organized as follows. In the next section, the sensitivity and generation distribution factor is described. In Section 3, in order to identify the wheeling paths of any combination among generators and customers, the sensitivity factor concept introduced in Section 2 is expanded. Then, wheeling paths identification technique and the algorithm that uses the extended sensitivity method are described. Moreover, we explain the outline of applications of the proposed method to the actual power market. In Section 4, in order to show the validity of the proposed method, several simulations on the IEEE 30-bus test system are conducted and numerical results are described. Section 5 concludes the paper.

2. Sensitivity in power system operation

2.1. Sensitivity analysis in power systems

To determine the sensitivity factor, firstly, is necessary to develop the sensitivity matrix of power flow [15]. The power flow of the general N-node T-branch power system is described by a set of N simultaneous complex equations

$$P_k + jQ_k = C_k + jD_k + E_k \sum_{\alpha}^{N} (Y_{k\alpha} E_\alpha)^* \tag{1}$$

where P_k and Q_k represent active and reactive power generations of the node-k, respectively. In addition, C_k and D_k represent active and reactive power demands of the node-k, respectively. Let the voltage vector $\mathbf{E_k}$ at node-k be expressed in polar form and the admittance $\mathbf{Y_{k\alpha}}$ in rectangular form. The following 2N equations ($G_{2k-1} = 0$ and $G_{2k} = 0 (k = 1, 2, \cdots, N)$) are obtained dividing (1) in the real part and the imaginary part

$$G_{2k-1} = C_k - P_k + E_k \sum_{\alpha} E_\alpha \{G_{k\alpha} \cos(\theta_k - \theta_\alpha) + B_{k\alpha} \sin(\theta_k - \theta_\alpha)\} \tag{2}$$

$$G_{2k} = D_k - Q_k + E_k \sum_{\alpha} E_\alpha \{G_{k\alpha} \sin(\theta_k - \theta_\alpha) - B_{k\alpha} \cos(\theta_k - \theta_\alpha)\} \tag{3}$$

For simplicity, the variables and parameters involved in (2) and (3) are defined with two vectors:

(i) Dependent variable vector $\mathbf{X}$ (2N-dimensional vector). Here, vector $\mathbf{X}$ comprises unknown variables in a usual power flow calculation.
(ii) Controllable variable vector $\mathbf{U}$ (M dimensional vector). This is a M-dimensional vector comprising the operating (manipulated) variables in system analysis and control.

Using the two vectors $\mathbf{X}$ and $\mathbf{U}$ defined above, (2) and (3) can be rewritten as the simple vector

$$\mathbf{G}(\mathbf{X}, \mathbf{U}) = 0 \tag{4}$$

where $\mathbf{G}$ is a 2N-dimensional column vector function with $\mathbf{G}_{2k\text{-}1}$ and G_{2k} $(k = 1, 2, \cdots, N)$. Suppose that in a N-node power system, the operating condition is such that $\mathbf{X} = \mathbf{X}_0$ for a specified control vector $\mathbf{U} = \mathbf{U_0}$. Since the pair of vectors $\mathbf{X_0}$ and $\mathbf{U_0}$ satisfies the power flow (4), then

$$\mathbf{G}(\mathbf{X_0}, \mathbf{U_0}) = 0 \tag{5}$$

Let us assume that by changing the operating condition of regulating devices (in what follows, simply called the regulating devices), the controllable variable vector $\mathbf{U}$ changes of a $\Delta\mathbf{U}$ from $\mathbf{U_0}$. If dependent variable vector $\mathbf{X}$ changes from $\mathbf{X_0}$ to $\mathbf{X_0} + \Delta\mathbf{X}$ in accordance with the change $\Delta\mathbf{U}$, then

$$\mathbf{G}(\mathbf{X_0} + \Delta\mathbf{X}, \mathbf{U_0} + \Delta\mathbf{U}) = 0 \tag{6}$$

If $\Delta\mathbf{U}$ is taken to be very small, then the variance $\Delta\mathbf{X}$ is generally small. By applying Taylor's series expansion [16] to (6) with $(\mathbf{X_0}, \mathbf{U_0})$ as the reference state and neglecting higher order terms in $\Delta\mathbf{X}$ and $\Delta\mathbf{U}$, we have

$$\mathbf{G}(\mathbf{X_0}, \mathbf{U_0}) + \mathbf{G_X}(\mathbf{X_0}, \mathbf{U_0})\Delta\mathbf{X} + \mathbf{G_U}(\mathbf{X_0}, \mathbf{U_0})\Delta\mathbf{U} = 0 \tag{7}$$

where $\mathbf{G_X}$, $\mathbf{G_U}$ are the Jacobian matrix of $\mathbf{G}$ with respect to dependent variable vector $\mathbf{X}$ and controllable variable $\mathbf{U}$. From (5), as the first term of (7) is zero

$$\Delta\mathbf{X} = -\mathbf{G_X^{-1}} \cdot \mathbf{G_U} \cdot \Delta\mathbf{U} \tag{8}$$

Let

$$\mathbf{S} \equiv -\mathbf{G_X^{-1}} \cdot \mathbf{G_U} \tag{9}$$

(8) can be rewritten in the form

$$\Delta\mathbf{X} = \mathbf{S} \cdot \Delta\mathbf{U} \tag{10}$$

or more concretely in the form

$$\begin{pmatrix} \Delta X_1 \\ \Delta X_2 \\ \vdots \\ \Delta X_{2N} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & \cdots & S_{1M} \\ S_{21} & S_{22} & \cdots & S_{2M} \\ \cdots & \cdots & \cdots & \cdots \\ S_{2N1} & S_{2N2} & \cdots & S_{2NM} \end{pmatrix} \begin{pmatrix} \Delta U_1 \\ \Delta U_2 \\ \vdots \\ \Delta U_M \end{pmatrix} \tag{11}$$

The $2N \times M$ coefficient matrix $\mathbf{S}$ in (11) is called the sensitivity matrix of power flow with respect to the controllable variable vector $\mathbf{U}$.

Next, we derive the sensitivity matrix of power flow. By the use of the two vectors $\mathbf{X}$ and $\mathbf{U}$, the line flows or line currents are conveniently expressed by the simple function vector $\mathbf{F}(\mathbf{X}, \mathbf{U})$, where $\mathbf{F}$ is a T-dimensional column vector function. Let us assume that when the state of the system is changed from an initial state $(\mathbf{X_0}, \mathbf{U_0})$ to a state $(\mathbf{X_0} + \Delta\mathbf{X}, \mathbf{U_0} + \Delta\mathbf{U})$ by the operation of some regulating devices, line flows are also changed by $\Delta\mathbf{F}(\mathbf{X_0}, \mathbf{U_0})$

$$\Delta\mathbf{F}(\mathbf{X_0}, \mathbf{U_0}) = \mathbf{F}(\mathbf{X_0} + \Delta\mathbf{X}, \mathbf{U_0} + \Delta\mathbf{U}) - \mathbf{F}(\mathbf{X_0}, \mathbf{U_0}) \tag{12}$$

Like (7), the Taylor series expansion of (12) with $(\mathbf{X_0}, \mathbf{U_0})$ as the reference state and neglecting higher order terms in $\Delta\mathbf{X}$ and $\Delta\mathbf{U}$ yields

$$\begin{aligned} \Delta\mathbf{F}(\mathbf{X_0}, \mathbf{U_0}) &= \mathbf{F}(\mathbf{X_0}, \mathbf{U_0}) + \mathbf{F_X}(\mathbf{X_0}, \mathbf{U_0})\Delta\mathbf{X} + \mathbf{F_U}(\mathbf{X_0}, \mathbf{U_0})\Delta\mathbf{U} - \mathbf{F}(\mathbf{X_0}, \mathbf{U_0}) \\ &= \mathbf{F_X}(\mathbf{X_0}, \mathbf{U_0})\Delta\mathbf{X} + \mathbf{F_U}(\mathbf{X_0}, \mathbf{U_0})\Delta\mathbf{U} \end{aligned} \tag{13}$$

The sensitivity $\mathbf{S_F}$ expresses the change $\Delta\mathbf{F}(\mathbf{X_0}, \mathbf{U_0})$ of the power flow, which corresponds to the change $\Delta\mathbf{U}$ of the controllable variable vector $\mathbf{U}$. Hence, from (13), following relation is obtained

$$\mathbf{S_F} = \frac{\Delta\mathbf{F}(\mathbf{X_0}, \mathbf{U_0})}{\Delta\mathbf{U}} = \mathbf{F_X}(\mathbf{X_0}, \mathbf{U_0}) \cdot \frac{\partial\mathbf{X}}{\partial\mathbf{U}} + \mathbf{F_U} \cdot (\mathbf{X_0}, \mathbf{U_0}) \tag{14}$$

Let $\mathbf{F}$ be the line power flow from node-k to node-m. When the line power flow from node-k to node-m is assumed to be $P_{km} + jQ_{km}$, the line power flow is given by

$$P_{km} + jQ_{km} = \mathbf{E_k}(\mathbf{E_k} - \mathbf{E_m})^*(-\mathbf{Y_{km}})^* \tag{15}$$

Thus, $\mathbf{F}(\mathbf{X}, \mathbf{U})$ is given by following general form:

$$\mathbf{F}(\mathbf{X}, \mathbf{U}) \equiv \mathbf{F}(E_k, E_m, \theta_k, \theta_m, \mathbf{U}) \tag{16}$$

Partial derivatives, $\mathbf{F_X}$ and $\mathbf{F_U}$ are obtained quite easily by simple calculation. $(\partial\mathbf{X}/\partial\mathbf{U})$, i.e., $\partial E_k/\partial\mathbf{U}$, $\partial E_m/\partial\mathbf{U}$, $\partial\theta_k/\partial\mathbf{U}$ and $\partial\theta_m/\partial\mathbf{U}$ are the sensitivities of E_k, E_m, θ_k and θ_m to the unit amount of change in a regulating device, which is already known as the elements of the sensitivity matrix $\mathbf{S}$. Thus the sensitivity constants for line power flows and line currents can be calculated from (14).

2.2. Generation distribution factor

Next, we describe generation distribution factor, which plays an important role in identifying wheeling paths for the cases with two or more wheeling contracts. The possibility to identify wheeling