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Power Tracing Method for Transmission Usage Allocation Considering Reactive Power

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Abstract - In many countries, the electric power industry is undergoing significant changes known as deregulation and restructuring. These alterations introduce competition in generation and retail and require open access to the transmission network. The competition of the electric power industry causes many issues to surface. Among them, unbundling of the transmission service is probably the most complicated as it is a single and integrated sector and the transmission revenue requirement must be allocated to market participants in a fair way. In these situations, it is valuable to research the methodologies to allocate transmission usage. The power tracing method offers useful information such as which generators supply a particular load or how much each generator (load) uses a particular transmission line. With this information, we can allocate required transmission revenue to market participants. Recently, several algorithms were proposed for tracing power flow but there is no dominant power tracing method. This paper proposes a power tracing method based on graph theory and complex-current distribution. For practicability, the proposed method for transmission usage allocation is applied to IEEE 30 buses and compared with the method proposed by Felix F.Wu.

Keywords: deregulation, graph theorem, power tracing method, proportional sharing principle

1. Introduction

In many countries, the electric power industry is undergoing transformations known as deregulation and restructuring. They introduce competition in generation and retail and require open access to the transmission network. Competition in the electric power industry causes many issues to surface. Among them, unbundling of the transmission service is probably the most complicated as it is a single and integrated sector and the transmission revenue requirement must be allocated to market participants in a fair way. If we know how much each generator (load) uses a particular transmission line, we can allocate required transmission revenue to market participants by their transmission usage. The power tracing method can provide this information. In Korea, a portion of the costs related to transmission facilities are allocated to market participants according to the usage of each line that is calculated by the power tracing method [6]. Due to nonlinearity of the power system, there is no dominant power tracing method.

Recently, several algorithms were proposed for tracing power flow. Methods based on dc load flow can represent the impact of a certain load/generation to the flows on the network but they can't determine how much of a certain load is provided by a particular generator [1]. Some methods trace the flow of power using the graph theorem, which is suitable for large-scale power systems [2, 3]. Another method introduces "fictitious line nodes" but it requires an inverse matrix calculation that is time-consuming for large power systems [4].

Many of the tracing methods accept the proportional sharing principle, which insists that the inflow of real power is proportional to the outflow in a node. This principle thinks that the buses are perfect mixers of the inflows. Although it seems to agree with common sense, the principle can't be proved. The power tracing method using the proportional sharing principle traces the real power and the reactive power respectively from the result of the power flow calculation. However the method can't consider the two powers simultaneously, so a new tracing method considering the two powers concurrently is necessary.

This paper proposes a power tracing method considering reactive power. It is based on the graph theorem and uses the complex-current distribution instead of the proportional sharing principle for real power. It traces flows of complex power as well as real power. And for practicability, the proposed method for transmission usage allocation is applied to the IEEE 30-bus system and compared with Felix F.Wu's method, which is adopted by KEPCO [6].

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2. Weakness of Proportional Sharing Principle for Real Power

Many of the tracing methods accept proportional sharing principle for real power. This principle insists that the inflow is proportional to the outflow in a node. It can't be proved but seems to be highly rational.

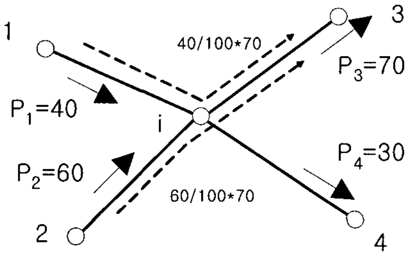

Fig. 1 Example of proportional sharing principle

Fig. 1 demonstrates the proportional sharing principle. In Fig. 1, there are two inflows and two outflows at bus *i*. If we apply the principle to the example, we can calculate

$$P_{3-1} = \frac{P_1}{P_1+P_2} \times P_3 = \frac{40}{100} \times 70 \tag{1}$$

$$P_{3-2} = \frac{P_2}{P_1+P_2} \times P_3 = \frac{60}{100} \times 70 \tag{2}$$

$$P_{j-i} = \frac{P_i}{\text{total passing power}} P_j \tag{3}$$

where in P_{j-i}, j indicates at which outgoing point the power flows out, and i indicates at which injection point the power comes from.

The power tracing method using the proportional sharing principle traces the real power and the reactive power respectively from the result of power flow calculation. The weakness of this principle is that it can't consider the two powers simultaneously.

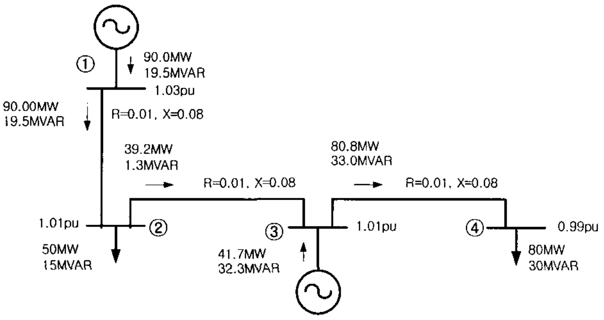

Fig. 2 Example of the weakness of the proportional sharing principle for real power

In Fig. 2, generators 1 and 3 make use of line 3-4 by about 50:50 respectively but the reactive power of load 4 is supplied by generator 3. It is reasonable that generator 3 makes more use of line 3-4 than generator 1.

3. Distribution of Complex-currents

To trace power flow considering reactive power, complex-currents distribution at a node is proposed. It is similar to the proportional sharing principle except that it uses complex-current rather than real power.

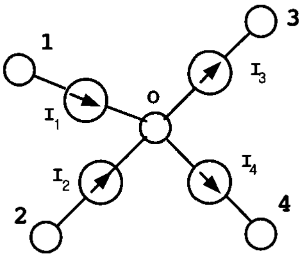

Fig. 3 Example of complex-currents distribution

Fig. 3 demonstrates the example of complex-currents distribution. We assume that the direction of the complex-current is the same as the direction of real-power. If we apply the complex-currents distribution to the example in Fig. 3, we can calculate

$$I_{3-1} = I_1 \frac{1/Z_3}{1/Z_3 + 1/Z_4} = I_1 \frac{V_0/Z_3}{V_0/Z_3 + V_0/Z_4} = \frac{I_1}{I_1+I_2} I_3 \tag{4}$$

$$I_{3-2} = I_2 \frac{1/Z_3}{1/Z_3 + 1/Z_4} = I_2 \frac{V_0/Z_3}{V_0/Z_3 + V_0/Z_4} = \frac{I_2}{I_1+I_2} I_3 \tag{5}$$

$$I_{j-i} = \frac{I_i}{\text{total passing current}} I_j \tag{6}$$

where in I_{j-i}, j indicates at which outgoing point the current flows out, and i indicates at which injection point the current comes from. Z_i is not the transmission line impedance but the impedance calculated from the transmission line current and the node voltage. Because we use the impedance quantity, the complex-currents distribution has greater physical meaning than the proportional sharing principle for real power.

Under normal operating conditions, the magnitude of bus voltages are maintained close to 1 pu. and the angle difference of close buses is reasonably small. Therefore we can trace the power flow using complex-current information.

4. Proposed Methodology

In this paper, the graph theorem that is introduced in Felix F.Wu's paper is used and the distribution rule in the graph theorem is complex-currents distribution at a node as stated above. Detailed application of the graph theorem is explained in Felix F.Wu's paper [3]. Here, we will discuss basic application of power tracing for transmission usage allocation of a simple 4-bus power system [see Fig. 4].

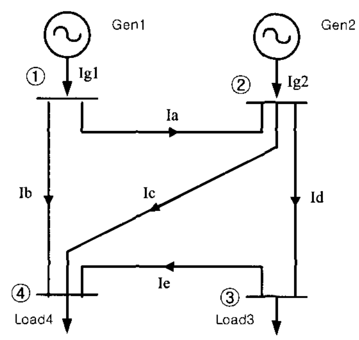

Fig. 4 Simple 4-bus power system

For simplicity, we assume that line shunt components belong to the closest bus. Consequently, transmission lines have series components only. We first need two matrices: an extraction factor matrix (A_{line}) of lines and contribution factor matrix (B) of generators.

$$(A_{line})_{line\ j,bus\ i} = \frac{line\ j's\ complex\text{-}current}{bus\ i's\ total\ passing\ complex\text{-}current} \tag{7}$$

$$(B)_{bus\ i,bus\ k} = \begin{cases} 1(k = i, k \in net\ gen\ buses) \\ 0(k = i,.k \notin net\ gen\ buses) \\ 0(k > i), 0(k < i, k \notin net\ gen\ buses) \\ \sum\limits_{Line_j \in i} A_{Linej,m} \cdot B_{m,k} (k < i, k \in net\ gen\ buses) \end{cases} \tag{8}$$

A_{line} and B for a simple 4-bus power system shown in Fig. 4 can be composed as follows.

$$A_{line} = \begin{array}{c|cccc|} & \mathrm{I_{t1}} & \mathrm{I_{t2}} & \mathrm{I_{t3}} & \mathrm{I_{t4}} \\ a & I_a / I_{t1} & 0 & 0 & 0 \\ b & I_b / I_{t1} & 0 & 0 & 0 \\ c & 0 & I_c / I_{t2} & 0 & 0 \\ d & 0 & I_d / I_{t2} & 0 & 0 \\ e & 0 & 0 & I_e / I_{t3} & 0 \end{array} \tag{9}$$

$$B = \begin{array}{c|cccc|} & \mathrm{I_{g1}} & \mathrm{I_{g2}} & \mathrm{I_{g3}} & \mathrm{I_{g4}} \\ I_{t1} & 1 & 0 & 0 & 0 \\ I_{t2} & I_a / I_{t1} & 1 & 0 & 0 \\ I_{t3} & I_d / I_{t2} \cdot I_a / I_{t1} & I_d / I_{t2} & 0 & 0 \\ I_{t4} & \frac{I_b}{I_{t1}} + \frac{I_c}{I_{t2}} \frac{I_a}{I_{t1}} + \frac{I_e}{I_{t3}} \frac{I_d}{I_{t2}} \frac{I_a}{I_{t1}} & \frac{I_c}{I_{t2}} + \frac{I_e}{I_{t3}} \frac{I_d}{I_{t2}} & 0 & 0 \end{array} \tag{10}$$

where, I_{ti} is total passing current on bus i and I_k is transmission line current on series component of line k.

We can calculate transmission usage allocation to the generators by multiplying A_{line} and B. The line currents are allocated to each generator and finally we can determine the allocated complex power to each generator by the product of the allocated current and injected bus voltage as shown below.

$$S_{line,gen} = V_{line} \times conj(A_{line} B I_g) \tag{11}$$

where V_{line} is a diagonal matrix. Its diagonal components indicate bus voltage and its non-diagonal components are zeros.

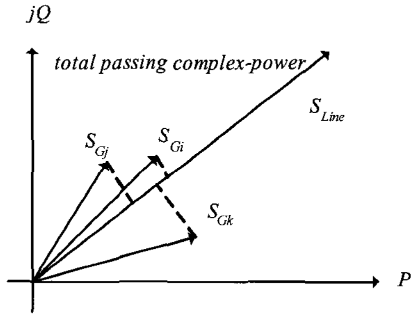

Fig. 5 Example of transmission usage percentage on a transmission line

Transmission usage percentage is calculated by the inner product of each generator's allocated complex power and the unit vector of the line's total passing complex-power. In Fig. 5, we can calculate transmission usage percentage to generator i on a transmission line as in the following.

$$f_{line}^{Gi} = \frac{|S'_{Gi}|}{|S'_{Gi}| + |S'_{Gj}| + |S'_{Gk}|} \times 100[\%] \tag{12}$$

where f_{line}^{Gi} signifies transmission usage percentage to generator i on a transmission line and $|S'_{Gi}|$ is the inner product of generator i's allocated complex-power and the unit vector of the line's total passing complex-power.

Through similar ways, transmission usage can be allocated to each load.

If transmission usage percentage for all transmission lines can be calculated as stated above, we can evaluate total cost allocated to generators or loads as follows.

$$TC^u = \sum_{k=1}^{n} C_k \cdot f_k^u \tag{13}$$

where TC^u is total cost allocated to generator (load) u; C_k is the cost related to transmission line k; and f_k^u is transmission usage percentage of line k to generator (load) u.

5. Comparison of Transmission Usage Results on IEEE 30-Bus System

In order to test the feasibility and the accuracy of the algorithm proposed above, a computer software has been developed and tested on the IEEE 30-bus and 118-bus power system. To be concise, we deal with the results on the IEEE 30-bus power system [see Fig. 6].

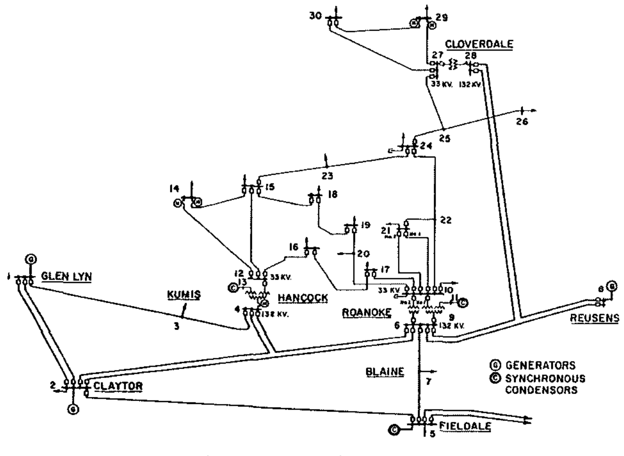

Fig. 6 The IEEE 30-bus power system

The proposed method for transmission usage allocation is applied to the IEEE 30-bus system and compared with Felix F.Wu's method, which is adopted by KEPCO.

Most of the results are similar between the proposed method and Felix F.Wu's method because the two methods trace the flow of power using the same graph theorem. However, different results occur on some transmission lines due to reactive power distribution. For example, generator 8 produces relatively more reactive power than generators 1 and 2, so in the result of the proposed method, generator 8 has further transmission usage percentage than Felix F.Wu's [see Fig. 7]. Complete results of transmission usage to generators on the IEEE 30-bus system are described in Table 2 of the Appendix.

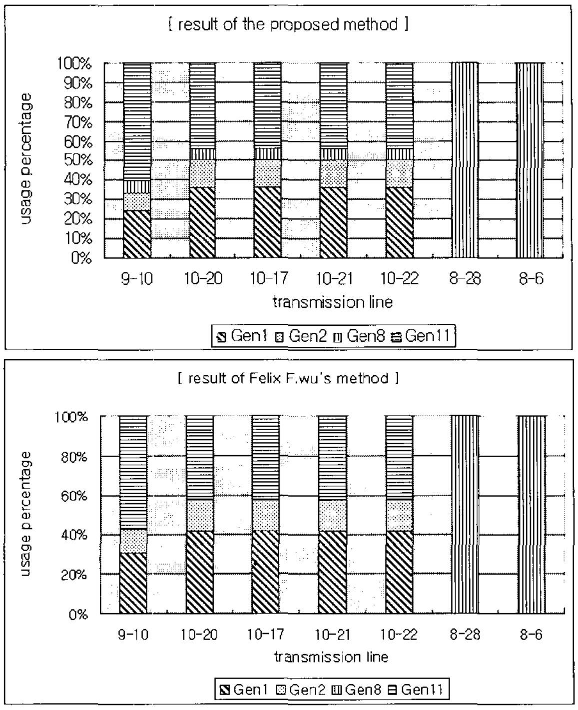

Fig. 7 Transmission usage percentage to generators on the IEEE 30-bus power system

There are varying results of transmission usage to loads due to the same reason. In Fig. 8, relatively larger reactive power than real power is supplied to load 24 through line 25-27, so in the result of our method, load 24 has greater transmission usage of line 25-27 than Felix F.Wu's.

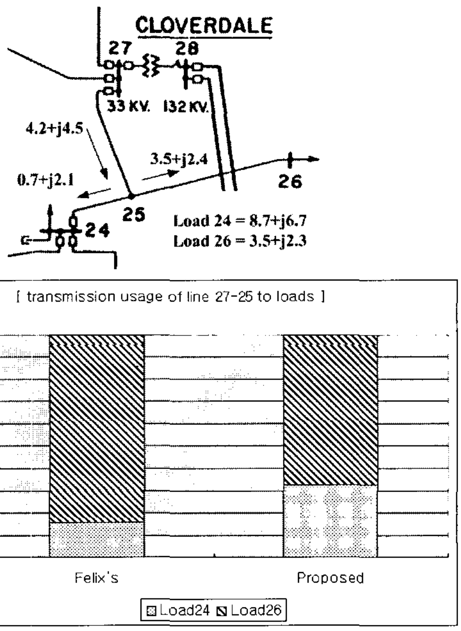

Fig. 8 Transmission usage percentage to loads on line 27-25

6. Conclusion

Deregulation and restructuring introduce competition in generation and retail and require open access to the transmission network. Competition in the electric power industry causes many issues to arise. Among them, unbundling of the transmission service is probably the most complicated as it is a single and integrated sector and the transmission revenue requirement must be allocated to market participants in a fair way.

The information regarding how much each generator (load) uses a particular transmission has been significant since we can allocate required transmission revenue to market participants with this information. The power tracing methods can provide this information.

In this paper, we point out the weakness of the proportional sharing principle for real power, which is accepted by many of the power tracing methods. We suggest a power tracing method based on the graph theorem and the complex-currents distribution. For practicability, the proposed method for transmission usage allocation is applied to the IEEE 30-bus power system and compared with the method of Felix F.Wu. The result of the proposed method is mostly similar to the result of Felix F.Wu's method. The only differences occur at a part of the system in which great disparity exists between real power and reactive power.

Appendix

Table 1 Generation data on IEEE 30-bus system

Bus#	Type	Load(P) (MW)	Load(Q) (MVAR)	Gen(P) (MW)	Gen(Q) (MVAR)
1	slack	0	0	138.63	3.13
2	gen	21.7	12.7	57.56	13.75
8	gen	30	30	35	48.89
11	gen	0	0	17.93	7.53
13	gen	0	0	16.91	14.65

Table 2 Result of transmission usage allocation on IEEE 30-bus system (method A: proposed method, B: Felix F.Wu's method)

Line	Method	Gen1 (%)	Gen2 (%)	Gen8 (%)	Gen11 (%)	Gen13 (%)
1-2 1-3 3-4	A	100	0	0	0	0
	B	100	0	0	0	0
2-4 2-5 2-6	A	61	39	0	0	0
	B	61	39	0	0	0
4-6 4-12	A	85	15	0	0	0
	B	85	15	0	0	0
7-5 6-7 6-9 6-10 6-28	A	73	27	1	0	0
	B	72	27	1	0	0
8-6 8-28	A	0	0	100	0	0
	B	0	0	100	0	0
11-9	A	0	0	0	100	0
	B	0	0	0	100	0
9-10	A	24	9	7	60	0
	B	31	12	0	57	0
13-12	A	0	0	0	0	100
	B	0	0	0	0	100
12-14 12-15 12-16 14-15 16-17 15-18 18-19	A	55	10	0	0	35
	B	53	10	0	0	37
20-19 10-20 10-17 10-21 10-22 22-21 22-24	A	36	14	6	44	0
	B	42	16	1	42	0
15-23 23-24	A	55	10	0	0	35
	B	53	10	0	0	37
25-24 25-26 27-25 28-27 27-29 27-30 29-30	A	52	20	28	0	0
	B	55	21	25	0	0

References

[1] ebastian P.Rosado, Khatib Abdel-Rahman, Nouredine HadjSaid, "Tracing the path of electric power flow – a study for deregulated power systems", IEEE Power Engineering Society Winter Meeting, Volume: 3 , pp. 1479-1484, 28 Jan.-1 Feb. 2001.

[2] Daniel Kirschen, Ron Allan, Goran Strbac, "Contributions of Individual Generators to Loads and Flows", IEEE Trans. On Power Systems, Vol. 12, No 1, pp. 52-60, February. 1997.

[3] Felix F. Wu, Yixin Ni, Ping Wei, "Power Transfer Allocation for Open Access Using Graph Theory-Fundamentals and Applications in Systems Without Loop flow", IEEE Trans. on Power Systems, Vol. 15, No. 3, pp. 923-929, August 2000.

[4] J. Bialek, D. B. Tam, "Tracing the Generators' Output", IEE conference publication No. 419, pp. 133-136, 1996.

[5] R. Reta, A. Vargas, "Electricity tracing and loss allocation methods based on electric concepts," IEE Proc-Gener. Transm. Distrib. Vol. 148. No. 6, pp. 518-522, 2001.

[6] J. Choi, H. Kim, S. H. Rim, "Power Allocation of Individual Generators to Loads Using Graph Theory", KIEE summer conference publication, No 10-12, pp. 422-424, 2002.

[7] Kyoung-Soo Ro, "Introduction of Power Flow Tracing Method for Determination of Power Transmission Network Charge and Verification of Its Effectiveness", KIEE Trans, Vol. 51A, No. 2, pp. 53-58, February. 2002.

[8] H. Sun, David C. Yu, "AC Power Flow Tracing in Transmission Networks", IEEE Trans. On Power Systems, pp. 1715-1720, 2001.

[9] Fubin Liu, Yang Li, Guoqing Tang, "A Quick & Practicable Power Flow Tracing Method On Electric Energy Market", IEEE Trans. On Power Systems, pp. 1244-1249, 2001.

[10] C. Han, S. Lee, J. Park, "Power trancing method based on complex-currents distribution", KIEE spring conference publication, pp. 182-185, May. 2003.

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