Complex Power Flow and Loss Calculation for Transmission System

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Abstract— This proposed method to allocate the power flow and loss for deregulated systems. This method is developed based on the basic circuit theories, equivalent current injection and equivalent impedance. In this method four step are used for tracing the voltage, current, power flows and losses contributed by each generator sequentially .In this method can be calculated real and reactive power on each transmission lines and their sources and Destinations. This method can also obtain the loss allocation of each line, which is produced by each generator. This test results show that the method satisfy the power balance equation, the power flow and basic circuit theories.

Keywords: Deregulation; Power flow and loss allocation; KCL; KVL

I. INTRODUCTION

The electric power industry today is under restructuring in response to changes in the law, technology, markets, and competitive pressures. Once the primary domain of large, vertically integrated utilities was to provide power at regulated rates, the industry now includes companies selling "unbundled" power at rates set by competition markets. In this environment more competition will mean lower rates for customers [1].

The proportional sharing method has been introduced by a simple method for computing the contribution of each generator to a given load or the flow in a line has been described and demonstrated. This method could be used to resolve some of the difficult pricing and costing issues which arise from the introduction of competition in the electricity supply industry and to ensure fairness and transparency in the operation of the transmission system. [2].

The loss allocation based on incremental transmission loss coefficients was proposed by Schweppes et al.[3].the method based on the ITL that can be used to handle large changes in operating condition was proposed. An integral-based incremental procedure is proposed, which integrates the differential equations of exact loss allocation of infinitesimal transactions to yield the loss allocation of any size. In [4], the concept of "center of losses" is applied to provide a sharing of transmission losses among generators and loads based on a predefined proportion Recently, a complex power flow tracing method is proposed in [5].These methods topologically determine the contribution of generators and loads to power flows and losses at transmission lines based on the proportional sharing assumption. Proposed a physical flow-based approach to allocate transmission loss [6].Quadratic loss approximation formulas and some assumption, such as bus voltage magnitude and bus voltage angle, are required for the loss allocation. In [7] the Z-bus allocation method is proposed, where the total system loss is expression as a function of the Z-bus matrix and the bus current injections. This method is based on power flow tracing and relies on the assumption that a network node is a perfect mixer of incoming flows. For each node, every out coming active power flow is proportionally composed of the incoming flows. For each line, the losses are proportionally allocated to the incoming flows into this line.ITL methodologies use the sensitivities of losses to bus injections to allocate the losses to generators and loads.

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From those methods, the admittance or impedance matrix based method have recently received great attention, since those method can integrated the network characteristics and circuit theories into flow and loss allocation. However, due to the almost singular characteristic of full admittance matrix, the methods based on the admittance or impedance matrices are difficult to allocate the flow and loss generated by swing bus directly. Additional flow and loss allocation formulas may be necessary. The basic circuit theories can be used to solve the problem directly and loss generated by the swing bus can be easily calculated. Four steps proposed in this paper are used to trace the voltages, current, power on each transmission lines and their sources and destinations can be calculated. The loss allocation of each line, which is produced by each generator, can also be obtained. The result demonstrates the main contributions of the proposed method.[9]

II. BASIC CONCEPTS OF THE PROPOSED ALGORITHM

The proposed method is developed based on the converged load flow or state estimator solution. After the solution of the converged power flow or state estimator was obtained, the system status including power injections, bus voltage angles, bus magnitudes, and power flows at both ends of a line can be calculated. For a transmission system with N buses, we assume the system has N_G generator buses (including swing bus) and N_L load buses. It is clear that N is equal to the sum of N_G and N_L Once the solution was obtained, a generator of a power system can be treated as an equivalent current injection that injects its current into the power system can be treated as equivalent impedance, which absorbs current from the power system. For example the converged power injection of a generator bus n can be expressed as

$$S_{n,G} = (P_{n,G} + jQ_{n,G}) \qquad (1)$$

And its corresponding equivalent current injection($I_{n,G}$) is

$$I_{n,G} = \left(\frac{P_{n,G} + jQ_{n,G}}{V_{n,G}}\right)^* \qquad (2)$$

Where $V_{n,G}$ is the voltage of generator bus n obtained from the converged power flow solution. That is voltage change of generator buses will be represented in the power flow solution and then the corresponding equivalent current injection will also be changed accordingly.

Then for a load bus *i*, the corresponding equivalent impedance $(Z_{i,L})$ can be derived as

$$Z_{i,L} = \frac{\mathbf{V_{i,L}}}{\mathbf{I_{i,L}}} = \frac{|\mathbf{V_{i,L}}|^2}{\mathbf{P_{i,L} - jQ_{i,L}}} \qquad (3)$$

Where $V_{i,L}$,$I_{i,L}$, and $S_{i,L} = (P_{i,L} - jQ_{i,L})$ are the voltage ,current and power of load bus I obtained from the converged load flow solution, respectively.

After the equivalent impedance was integrated into the admittance matrix the relationship between bus current injections can be expressed as

$$V_{Bus} = Z_{Matrix} I_G \quad (4)$$

WhereV_{Bus},I_G, and Z_{Matrix} are the bus voltage vector, current vector and impedance matrix including the effects of the equivalent impedance ,respectively. Note that the effects of swing bus are also including in The equivalent impedance is shut impedance; the integration of the equivalent impedance into the admittance matrix can avoid the possible numerical problem in the impedance matrix building process. Besides, the relationship between the power injection and transmission networks are non-linear; thus, tracing the power flows and losses will be seen that the relationship between the current injection and transmission networks are linear; thus the circuit theories, including Kirchhoff's current law(KCL),Kirchhoff's voltage law(KVL), and superposition law can be used and the proposed method can be derived.

III. POWER FLOW AND LOSS ALLOCATION

The proposed method develops four steps to trace the flows and losses for deregulated power systems are following.

- Trace the voltage,
- Trace the current,
- Trace the power flow,
- Trace the losses.

In this section, the derivation will be described in details.

$$\begin{bmatrix} \Delta v_1^n \\ \vdots \\ \Delta v_n^n \\ \vdots \\ \Delta v_N^n \end{bmatrix} = \begin{bmatrix} z_{11} & \cdots & z_{11} & \cdots & z_{11} \\ \vdots & \ddots & \cdots & \cdots & \vdots \\ z_{n1} & \cdots & z_{nn} & \cdots & z_{nN} \\ \vdots & \cdots & \cdots & \ddots & \vdots \\ z_{N1} & \cdots & \cdots & \cdots & z_{NN} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ I_{n,G} \\ \vdots \\ 0 \end{bmatrix} (5)$$

Eq. (5) shown that the voltage at bus *i* contributed by generator bus $n\Delta v_i^n$ can be written as

$$\Delta v_i^n = z_{in} * I_{n,G} \qquad (6)$$

And the voltage of bus *i* contributed by all generator buses will be

$$V_i = \sum_{n=1}^{N_G} \Delta v_i^n \qquad (7)$$

It is clear the voltage contribution of each generator to each bus can be calculated easily by (6) and (7). That information is very important for flow and loss allocation.

Using fig-1 as an example, the line current between bus *i* and j corresponding to the voltage contribution of generator bus n can be expressed as

$$\Delta i_{ij}^n = (\Delta v_i^n - \Delta v_j^n)(g_{ij} + jb_{ij}) + (jc/2)(\Delta v_i^n)(8)$$

$$\Delta i_{ji}^n = (\Delta v_j^n - \Delta v_i^n)(g_{ij} + jb_{ij}) + (jc/2)(\Delta v_j^n)(9)$$

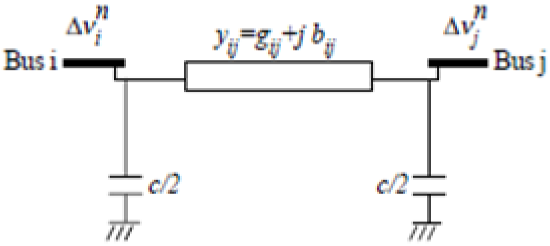

Fig. 1: A Transmission line section model

Where $\boldsymbol{y_{ij=}}_{(\boldsymbol{g_{ij}}+\boldsymbol{jb_{ij}})}$ is the line admittance from bus i to j and c/2 is the charging susceptance. Δi_{ij}^n and Δi_{ji}^n are the line currents, produced by generator bus n, from bus *i* to bus j and bus j to bus *i*, respectively. And the total line current from bus *i* to bus j will be

$$I_{ij} = \sum_{n=1}^{N_G} \Delta i_{ij}^n \qquad (10)$$

Since the voltages and line current contributed by each generator can be traced, the power flow from bus *i* to bus j can be expressed as

$$S_{ij} = V_i (I_{ij})^* = \left(\sum_{n=1}^{N_G} \Delta v_i^n\right)\left(\sum_{n=1}^{N_G} \Delta i_{ij}^n\right)^* \qquad (11)$$
$$= \left(\Delta v_i^1 + \Delta v_i^2 + \cdots + \Delta v_i^{N_G-1} + \Delta v_i^{N_G}\right) *$$
$$\left(\Delta i_{ij}^1 + \Delta i_{ij}^2 + \cdots + \Delta i_{ij}^{N_G-1} + \Delta i_{ij}^{N_G}\right)^*$$

Eq. can be rewritten as

$$S_{ij} = \sum_{m=1}^{N_G} \sum_{n=1}^{N_G} PF_{mn} \qquad (12)$$

Where

$$PF = \begin{bmatrix} \Delta v_i^1 (\Delta i_{ij}^1)^* & \cdots & \Delta v_i^1 (\Delta i_{ij}^n)^* & \cdots & \Delta v_i^1 (\Delta i_{ij}^{N_G})^* \\ \vdots & \ddots & \cdots & \cdots & \vdots \\ \Delta v_i^n (\Delta i_{ij}^1)^* & \cdots & \Delta v_i^n (\Delta i_{ij}^n)^* & \cdots & \Delta v_i^n (\Delta i_{ij}^{N_G})^* \\ \vdots & \cdots & \cdots & \ddots & \vdots \\ \Delta v_i^{N_G} (\Delta i_{ij}^1)^* & \cdots & \Delta v_i^{N_G} (\Delta i_{ij}^n)^* & \cdots & \Delta v_i^{N_G} (\Delta i_{ij}^{N_G})^* \end{bmatrix}$$

From Equation (11), it can be seen that the power flow of a line has to be calculated by the voltage and current contributed by each generator; therefore, it is very difficult to allocate the powers contributed

Proportional sharing assumption is the by a single generator. For example, the

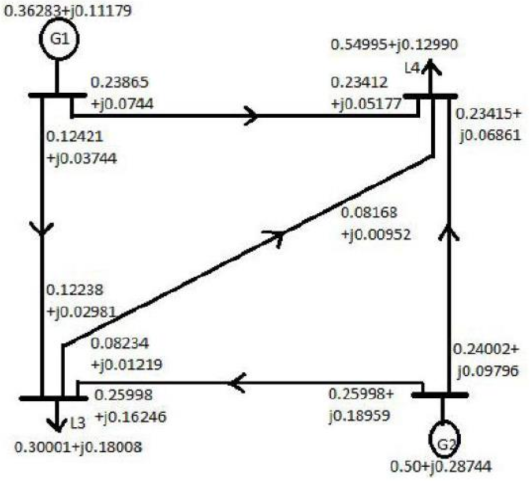

Fig. 2: The power flow solution of the 4-bus system

Prerequisite assumption for the flow and loss allocation proposed if the assumption or approximations are made proper, the power equations, power balance equations and electric circuit theories including Kirchhoff's current law (KCL) Kirchhoff's voltage law (KVL) and superposition

Law should all be satisfied. Therefore by using the voltage contributed by all generators to push the line current contributed by the generator bus n, the power flow contributed by the generator bus can be calculated. That is

$$\Delta s_{ij}^{n} = \left(\Delta v_i^1 + \Delta v_i^2 + \cdots + \Delta v_i^n + \cdots \Delta v_i^{N_G}\right)\left(\Delta i_{ij}^{n}\right)^* = V_i\left(\Delta i_{ij}^{n}\right)^* \qquad (13)$$

Where Δs_{ij}^{n} the line power flow is produced by generator bus n from bus *i* to bus *j*. And the total power flow can be written as

$$= \sum_{n=1}^{N_G} \Delta s_{ij}^{n} \qquad (14)$$

The power from a generator to a load can be also calculated by the same procedure, that is

$$\Delta i_{i,L}^{n} = \frac{\Delta v_i^{n}}{z_{iL}} \qquad (15)$$

Table. 1: The system data of the 4-bus system

Bus no.	P(p.u.)	Q(p.u.)	V(p.u.)	Θ (rad)	Bus type
1	0.36287	0.11188	1.05	0.000	swing
2	-0.54995	-0.12990	1.00707	-0.08475	PQ
3	-0.30001	-0.18008	1.01945	-0.05385	PQ
4	0.50000	0.28755	1.070	0.01771	PV

Table. 2: Line parameter data

Line No.	from	To	R(p.u.)	X(p.u.)
1	1	2	0.08	0.4
2	1	3	0.12	0.5
3	3	2	0.10	0.4
4	2	4	0.10	0.5
5	4	3	0.0	0.3

Where Δi_{iL}^{n} is the current injection of load bus *i* contributed by generator bus n. The total current injection of load bus *i* will be

$$I_{i,L} = \sum_{n=1}^{N_G} \Delta i_{i,L}^{n} \qquad (16)$$

Therefore, the power of load bus I contributed by generator bus n can be written as

$$\Delta s_{i,L}^{n} = V_i\left(\Delta i_{i,L}^{n}\right)^* \qquad (17)$$

And the total power of load bus *i* can be expressed as

$$S_{i,L} = \sum_{n=1}^{N_G} \Delta s_{i,L}^{n} \qquad (18)$$

The line loss contributed by generator bus n can be calculated by

$$P_{ij,Loss} = Re\left(\Delta s_{ij}^{n}\right) + \mathrm{Re}\left(\Delta s_{ji}^{n}\right) \qquad (19)$$

The total line losses can be expressed as

$$P_{ij,Loss} = \sum_{n=1}^{N_G} \Delta p_{ij,Loss}^{n}$$

The proposed method uses four steps to trace the voltage, current, power, and loss contributed by a generator.

A. Voltage Tracing Result

Table. 3: Voltage tracing in pu

Bus No.	Contributed by gen. of bus 1	Contributed by gen. of bus 4
1	0.4483+j0.0919	0.60173-j0.09195
2	0.4091+j0.0169	0.59436-j0.10223
3	0.4065+j0.0245	0.6115-j0.07936
4	0.4078+j0.0219	0.66204-j0.00289

B. Current Tracing Result

Table. 4: Current tracing in pu

Line no.	From	To	Corresponding to the voltage contribution of gen.bus 1	Corresponding to the voltage contribution of gen.bus 4
1	1	2	0.1990-j0.05814	0.02824-j0.0128
2	1	3	0.14654-j0.0485	-0.0285+j0.0128
3	3	2	-0.0163+j0.0269	-0.0639+j0.0269
4	2	4	-0.0089-j0.00437	-0.21705+j0.0919
5	4	3	0.0089+j0.0044	-0.2548+j0.1685

Table. 5: Power tracing in pu

Line no.	From	To	Contributed by gen. of bus 1	Contributed by gen. of bus 4
1	1	2	0.2090+j0.0612	0.0297+j0.0135
2	1	3	0.1539+j0.0509	-0.02966-j0.0135
3	3	2	-0.0153+j0.0119	-0.0665-j0.0216
4	2	4	-0.0088-j0.0052	-0.2257-j0.0738
5	4	3	0.0088-j0.0049	-0.2687-j0.1576

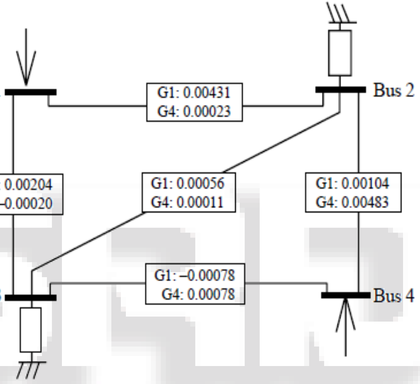

Fig. 3: loss tracing result of the 4-bus system

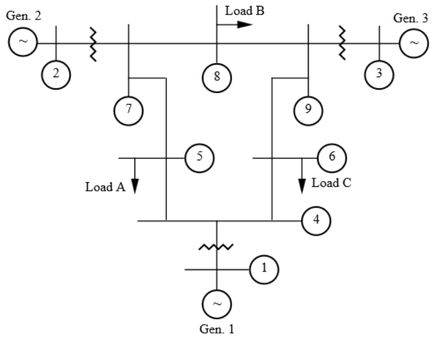

Fig. 4: 9-bus system network

Table. 6: converged 9-bus system

Bus no.	P(p.u.)	Q(p.u.)	V(p.u.)	Bus type
1	-	-	1.04	Swing
2	1.63	0.000	1.025	PV
3	0.85	0.000	1.025	PV
4	0.00	0.00	2.326	PQ
5	1.25	0.5	3.009	PQ
6	0.9	0.3	2.212	PQ
7	0.00	0.000	-1.416	PQ
8	1.00	0.350	-3.361	PQ

9	0.000	0.000	-3.264	PQ

Table. 7: Line parameter data

Line No.	from	To	R(p.u.)	X(p.u.)
1	1	4	0.0	0.0576
2	4	5	0.01	0.085
3	5	7	0.032	0.161
4	4	6	0.017	0.092
5	6	9	0.039	0.170
6	7	2	0.0	0.0625
7	7	8	0.0085	0.072
8	8	9	0.0119	0.1008
9	9	3	0.0	0.0586

C. Voltage Tracing Result

Table 8: Voltage tracing in pu

Bus No.	Contributed by gen. of bus 1	Contributed by gen. of bus 2	Contributed by gen. of bus 3
1	0.6258-j0.1477	-1.6634+j1.3006	2.2482-j1.3798
2	0.3219-j0.3586	2.9496+ j 0.5837	-1.6242+j2.8865
3	0.2481-j0.3834	1.6049- j 0.1503	0.7159 - j1.5161
4	0.2475-j0.3879	1.6159- j 0.1616	-0.9750 + j1.3793
5	-0.3418+j0.3235	1.6387- j 0.2715	-0.9834 + j1.3647
6	-0.3036+ j 0.3396	-1.6048- j 0.0994	0.0458 + j0.0222
7	-0.3148+ j 0.3329	-0.0204- j 0.1601	-0.2757 - j0.0852
8	0.2872- j 0.3488	0.0041+ j 0.0488	-0.1458 - j0.0520
9	-0.3470+ j 0.3235	-0.0646- j 0.2698	-0.2570 - j0.0877

D. Current Tracing Result

Table. 9: Current tracing in pu

Line no.	From	to	Corresponding to the voltage contribution of gen.bus 1	Corresponding to the voltage contribution of gen.bus 2	Corresponding to the voltage contribution of gen.bus 3
1	1	4	1.1064 + j1.0187	-1.1901 +j 4.7521	-4.7546 - j2.1577
2	2	7	1.2063 +j 1.0154	-0.2038 +j 2.8489	2.4375 +j 1.6602
3	3	9	0.4170 - j0.6568	2.5384 + j5.6932	-4.7902 - j5.5959
4	5	4	-0.7450 - j0.7810	0.1245 + j0.0415	0.0181 - j0.0077
5	5	7	-0.6576 - j0.7206	0.5602 - j3.3973	1.2282 + j1.3366
6	6	4	-0.0088 + j0.0150	0.1305 - j1.0046	0.7823 + j0.5951
7	6	9	0.8364 + j0.9349	-0.2901 - j0.0001	-0.0665 + j0.1725
8	7	8	0.0146 - j0.0221	-0.1023 + j0.8826	0.1002 - j0.1551
9	9	8	-0.5845 - 0.6981i	0.3196 - 0.0304i	0.0478 - 0.1047i

E. Power Tracing Result

Table. 10: Power tracing in pu

Line no.	From	to	Contributed by gen. of bus 1	Contributed by gen. of bus 2	Contributed by gen. of bus 3
1	1	4	1.1082 - j1.4844	1.2826 - j1.1531	-0.7791 + j1.5289
2	2	7	1.2300 -j 1.5031	0.8529 -j 0.5327	0.2858 - j0.9261
3	3	9	0.6539 +j 0.7005	2.1896 - j0.1480	-0.0835 + j2.4194
4	5	4	-0.7246 + j1.1146	0.0334 + j0.0319	0.0062 – j0.0017
5	5	7	-0.6326 + j1.0216	-0.9648 + j0.7339	0.0415 - j0.5951
6	6	4	-0.0141 - j0.0162	-0.2911 + j0.2061	0.0790 - j0.3132
7	6	9	0.8004 - j1.3216	-0.0478 - j0.0903	-0.0524 - j0.0307
8	7	8	0.0227 +j0.0235	0.2578 - j0.1772	0.0575 + j0.0193
9	9	8	-0.5492 + j0.9778	0.0432 + j0.104	0.0337 + j0.0171

IV. NUMERICAL EXAMPLE AND DISCUSSIONS

A load flow program is used to obtain the system status. The convergence tolerance of the load flow program is 0.001p.u. For power mismatches. Many power systems have been tested to verify the validity of the proposed method; however, only the results of a 4-bus system and a 9-bus system were shown. The sizes of the test systems are not large, however; it is good enough to illustrate the correctness of the proposed method. Table 1 is the line parameters and the converged bus solution of the 4-bus system. The bus types of swing, PV, and PQ as shown in Table 1 are the swing bus, generator bus, and load bus, respectively. Fig. 2 shows the network topology of the 4-bus system. There are two generators at bus 1 and 4 and two loads at bus 2 and 3 for this system. The system status including the power injections and power flows at both ends of each line are also shown in Fig. 2. All numerical values shown in Fig. 2 are in p.u. It can be seen that the line loss is equal to the absolute value of the difference between the line flows of both ends. From Table. 3, it can also be seen that the sum of the bus voltages contributed by each generator is equal to the converged bus voltages. Table. 4 and 5 show the line currents and powers contributed by each generator, respectively. it can be seen that the KCL of each bus and the KVL of each loop are satisfied. The fulfilment of KCL and KVL are both for each individual generator and the full system. Fig. 3 shows the losses contributed by each generator. It can be seen that the total line losses produced by generator buses 1 and 4 are 0.00716 and 0.00674, respectively. The sum of line losses produced by each generator is the same as the line losses calculated by load flow program

Fig. 4 show the network topology of the 9-bus system. From fig it can be seen that the 9-bus system has three generators, three load and nine transmission lines. The converged solutions of the 9-bus system including bus voltage magnitudes, bus voltage angles, loss of each generator, line flows and line losses are shown in Table 8,9 and 10. Show the voltage, line currents and powers contributed by each generator, respectively.

This paper proposes a systematic solution procedure to allocate the flow and loss in deregulated environments. Using the equivalent current injection and equivalent impedance transformed from the generation and load respectively, the bus voltage and current generated by each generator can be traced. The information is very useful for and loss allocation. Test results show that the proposed method can provide a reasonable and accurate solution for power and loss allocation.

V. CONCLUSION

In this paper proposed a method to trace four steps. The proposed method to trace the voltage, current, power flow and loss for deregulated transmission systems based on the electric circuit theories, equivalent current injection, and equivalent impedance. The method can determined the amount of the real and reactive power output from a particular generator goes to a particular load. The loss allocation of each line, which is produced by each generator, can also be obtained.

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