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Tracing real and reactive power in open access network

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ABSTRACT

The main objective of this paper is to present a simple and general methodology for tracing the power output of each generator to the line flows and loads through out the electrical power network. The tracing algorithm is based on basic circuit theories including superposition law, equivalent current injection and equivalent impedance. After power flow solution is obtained, the contributions of individual generators are determined through the voltages, currents, power flows and losses tracing sequentially. The veracity and accuracy of the method is demonstrated by numerical examples. Comparisons of the result with previous methods are also given.

INTRODUCTION

In transmission open access, new tools are needed for control and operation. Among others, it is interesting to know the contribution of particular generator to a particular load and overall system. It is necessary to find the capacity usage of different transactions happening at the same time so that a fair use-of-transmission-system charge can be given to the individual customer separately. Then, the transparency in the operation of deregulated power system can be achieved [1].

It has been demonstrated recently regarding the algorithms to trace real and reactive power in deregulation systems. Ref [2-3] proposed the nodal generation distribution factors (NGDF-s) to trace the power flow in the system. This method is based on search algorithm for determining the share of every generator in the particular line flow. For reactive power tracing, this method introduces virtual bus for the case where the power flow is negative value or it is assuming that a line is not supplied from none of its ends points.

Topological Generation/Load Distribution factors (TGDF-s and TLDF-s) were proposed in Ref [4-7]. This method is based on proportional sharing assumption. Even though the approach is conceptually simple, it requires inverting a sparse matrix of the rank equal to number of network nodes. In addition, to trace the reactive power, fictitious nodes in the middle of network branch are introduced.

This makes the system becomes larger and lead to more complex calculation that requires longer computational time.

Ref [8] proposed a modified TGDF/TLDF in power tracing algorithms. One of the modifications is by introducing of decoupled power flow of line instead of additional fictitious node. However, the size of the matrices is still large if applied to the large systems. A generalized methodology to trace reactive power flow is presented in [9]. This method introduces a dominion concept that is creation of directed graph consisting one source, sinks and branches. It also described about transmission element classification, which is, appoint the equations that related to the types of transmission element.

Ref [10] reported the power tracing scheme using nominal-T model. This method proposed to change the nominal π model to T-model and power flows are traced by using the combination of graph and proportional sharing methods. However, this approach only can handle the system without loop flow. The method that incorporated Artificial Neural Network (ANN) to the reactive power tracing has been proposed in [11]. Initially, the reactive power is traced by implementation of the modified Y-bus matrix and then almost all reactive power tracing results are used as input to the neuron of ANN. This approach uses a powerful tool of ANN to adapt the reactive power flow tracing problem and manage to predict the power flow allocation within certain period of time without running the base load flow. Ref [12] uses the same convention with [11] that incorporated ANN to the power tracing problem. However, in [12] they use graph method as a teacher to train the neural network.

Abhyankar et al. [13-15] proposed an optimization approach to real power tracing. They propose a tracing compliant modified postage stamp allocation method that computes a traceable solution that minimizes overall deviation from the postage stamp allocation. Ref [16-17] uses proportional tree method to determine the transmission cost allocation. Basically, this method uses proportional sharing principle and searching scheme to trace the generators' contribution to the system. This convention is quite identical with the method that proposed in [2-3]. The difference is [16-17] propose a tree model for each test system before the power can be traced.

In term of transmission loss allocation, Ref [18] proposed three methods to allocating the loss viz., by using proportional, quadratic and geometric allocation. However, it is end up without proofing which one is the correct method.

This paper is emphasized on the method that has been proposed in Ref [1]. Based on [1], the equations are reviewed and reduced to meet the requirement of power tracing algorithm. An equation is improved by introducing the effect of injected MVAR that will be presented later.

METHODOLOGY

Basic Concept

The method is developed based on basic circuit theories. After power flow solution is obtained, we can identify voltage magnitudes, angles, total real power and reactive power for each bus network. This method assumes that the generator bus can be treated as equivalent current injection and load bus as equivalent impedance. The apparent power of generator bus n and its corresponding equivalent current injection can be expressed as:

$$S_{n,G} = \left(P_{n,G} + jQ_{n,G}\right) \tag{1}$$

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

where n is the number of generator, Vn,G is the generator bus voltage, Pn,G is the real power and Qn,G is the reactive power for the generator bus. These elements are obtained from power flow solution study. For load bus i, the corresponding equivalent impedance can be derived as:

$$Z_{i,L} = \frac{V_{i,L}}{I_{i,L}} = \frac{\left|V_{i,L}\right|^2}{P_{i,L} - j(Q_{i,L} - Q_c)} \tag{3}$$

where Vi,L, Ii,L and Si,L=[Pi,L – j(Qi,L-Qc)] are the voltage, current apparent power of load bus i including effect of injected MVAR respectively. It can be seen that the effect of injected MVAR, Qc is included in this equation. This is due to the facts that in power system, generators and loads are not the only sources and/or sinks of complex power. Thus, this additional element is included into the corresponding equivalent impedance that derived from Ref [1]. After equation (3) is integrated into the admittance matrix, the relation between bus voltages and bus current injections become:

$$V_{BUS} = Z_{MATRIX} I_G \tag{4}$$

where VBUS, ZMATRIX and IG are the bus voltage vector, impedance matrix including the effects of the equivalent impedance and current injection vector respectively.

Trace the Voltage at Bus from Each Generator

To trace the voltage, superposition law is applied as a foundation of this method's development. Using this law, only one generator is connected to the system and at the same time the other generators in the system are open circuit. The voltage contributed by generator bus n can be expressed as:

$$\begin{bmatrix} \Delta v_1^n \\ \vdots \\ \Delta v_n^n \\ \vdots \\ \Delta v_N^n \end{bmatrix} = \begin{bmatrix} z_{11} & \cdots & z_{1n} & \cdots & z_{1N} \\ \vdots & \ddots & \vdots & \cdots & \vdots \\ z_{n1} & \cdots & z_{nn} & \cdots & z_{nN} \\ \vdots & \cdots & \vdots & \ddots & \vdots \\ z_{N1} & \cdots & \cdots & \cdots & z_{NN} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ I_{n,G} \\ \vdots \\ 0 \end{bmatrix} \tag{5}$$

From expression (5), voltage at bus i contributed by generator bus n and the voltage of bus i contributed by all generator buses can be written as:

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

$$V_i = \sum_{n=1}^{N_G} \Delta v_i^n \tag{7}$$

From these equations, it is clear that the voltage contributions of each generator to each bus can be calculated easily.

Trace Current through Each Line

Base on the circuit theory concept and referring to figure 1, the current flow at each line in deregulated network can be determined as:

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

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

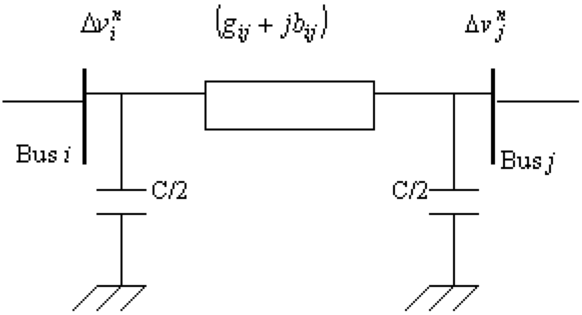


Figure 1. A Transmission line section model.

where yij = (gij + jbij) is the line admittance from bus i to j and C/2 is the line charging susceptance. Δinij and Δinji are the line currents, produced by generator bus n, from bus i to bus j and bus j to bus i, respectively.

Power Flow and Loss Allocation

Since the voltage and current at the bus has been identified, the power flow at every line in the system can be calculated. The power flow from bus i to bus j and the losses produced by generator n can be expressed as:

$$\Delta s_{ij}^{n} = V_i \left(\Delta i_{ij}^{n}\right)^* \tag{10}$$

$$P_{ij,Loss}^{n} = \mathrm{Re}\left(\Delta s_{in}^{n}\right) + \mathrm{Re}\left(\Delta s_{ji}^{n}\right) \tag{11}$$

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

$$\Delta i_{i,L}^{n} = \frac{\Delta v_i^n}{Z_{i,L}} \tag{12}$$

where Δini,L is the current injection of load bus contributed by generator bus n. Therefore the power of load bus i contributed by generator bus n can be written as:

$$\Delta s_{i,L}^{n} = V_i \left(\Delta i_{i,L}^{n}\right)^{*} \tag{13}$$

The correctness of this method can be verified by comparing the results obtained by the derivations above with the converged power solution.

NUMERICAL EXAMPLES AND DISCUSSIONS

A number of simulations have been carried out to demonstrate the veracity of the method. The method was implemented using Matlab programming language. A load flow program that developed by Ref [19] is used to obtain the system status. For purpose of this paper, 4-bus and IEEE 30 bus test systems are chosen. Even though the system is small, it is adequate to show the veracity of the proposed method. The 4-bus system is made up of 4 nodes, 5 lines, 2 generators and 2 loads [4, 9]. Table 1, 2 and 3 show the converged bus data, line parameter data and power flow solution of the 4-bus test system respectively.

Figure 2 shows the equivalent current injection of bus 1 and 2 obtained using (2) and the equivalent impedance obtained using (3). From this figure also shows the voltage contribution by each generator using (5) and (6). It can be seen that the sum of the voltages contributed by each generator is equal to the converged bus voltages using (7).

Table 1. Bus Data Of 4-Bus Test System

		Voltage		**Load**		**Generation**	
Bus No.	**Bus Type**	**Mag (p.u)**	**Ang (deg)**	**P (MW)**	**Q (Mvar)**	**P (MW)**	**Q (Mvar)**
1	PV	1.04348	5.75610	0.0000	0.0000	400.0000	124.8761
2	Slack	1.00000	0.00000	0.0000	0.0000	114.2890	26.5020
3	PQ	0.90339	-11.60027	300.0000	100.0000	0.0000	0.0000
4	PQ	0.95155	-5.79091	200.0000	80.0000	0.0000	0.0000
Total				500.0000	180.0000	514.2890	151.3781

Table 2. Line Parameter Data

Line No.	From	To	R (p.u)	X (p.u)	B (Total)
1	1	2	0.024100	0.183400	0.454940
2	1	3	0.011340	0.131400	0.370300
3	1	4	0.022120	0.181500	0.446476
4	2	4	0.006616	0.058220	0.190440
5	4	3	0.010870	0.109600	0.306820

Table 3. Power Flow Solution of 4-Bus Test System

Line	From	To	From Bus Injection		To Bus Injection		Loss	
No.	Bus	Bus	P (MW)	Q (Mvar)	P (MW)	Q (Mvar)	P (MW)	Q (Mvar)
1	1	2	59.6613	-5.0006	-58.7870	-35.8609	0.8743	-40.8615
2	1	3	224.7577	104.3576	-217.8818	-59.9558	6.8758	44.4019
3	1	4	115.5811	25.5313	-112.3626	-43.6432	3.2185	-18.1119
4	2	4	173.0785	62.3700	-170.7546	-60.0641	2.3238	2.3059
5	4	3	83.1172	23.7072	-82.1182	-40.0442	0.9991	-16.3370
Total Loss							14.2915	-28.6027

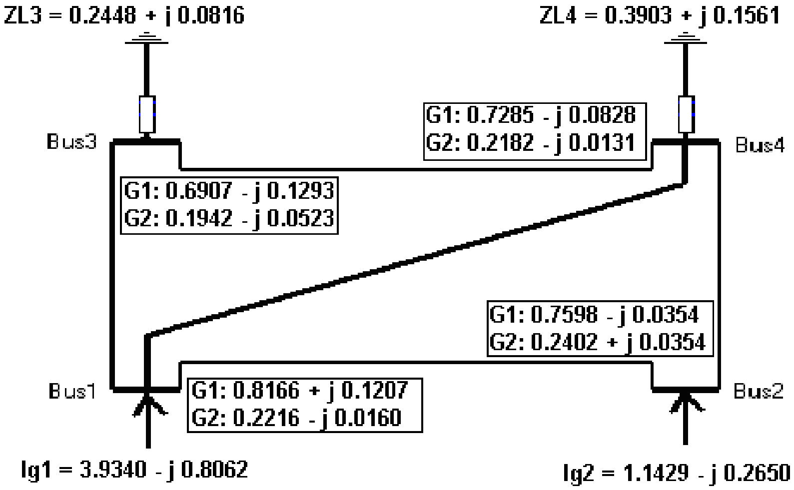


Figure 2. Voltage tracing result, equivalent current injection and equivalent impedance.

Figure 3 and 4 show the line currents and powers contributed by each generator respectively. These results obtained by applying (8), (9) and (10). Note that only the values indicated by arrows are shown. In figure 4, it can be seen that the summation of the power tracing results is equal to sending end power that obtained by load flow study in Table 3.

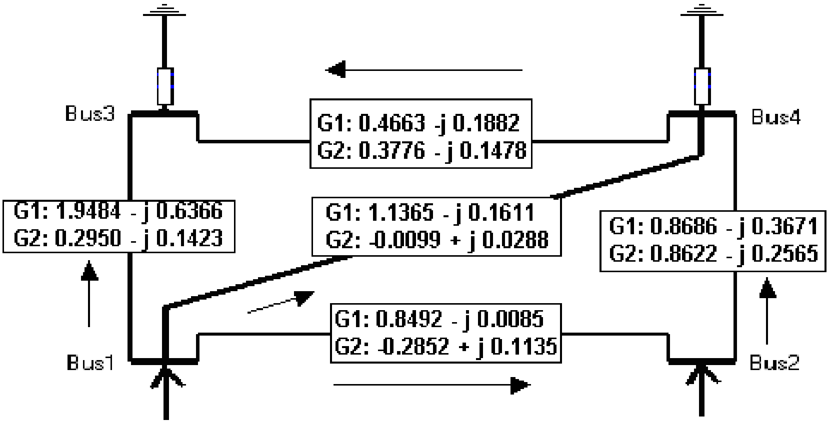


Figure 3. Current tracing results.

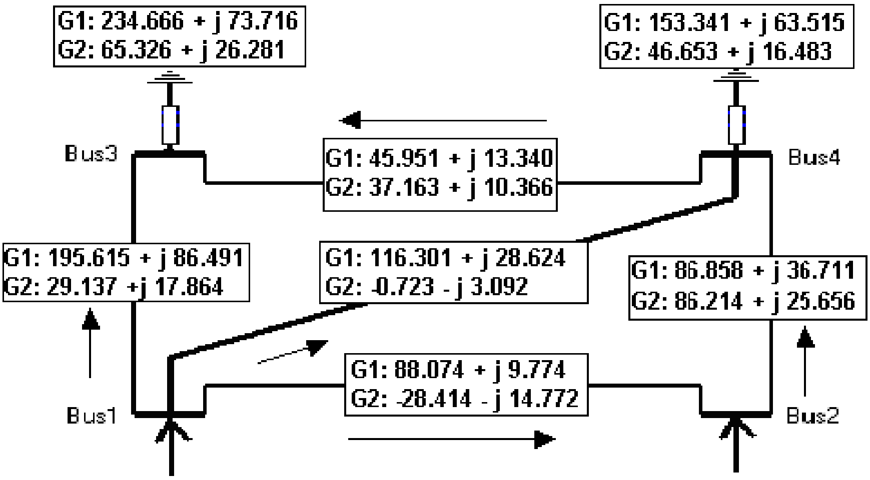


Figure 4. Power tracing results.

Figure 5 shows the loss tracing result that obtained using (11). It can be seen that the losses in each line can be traced and appointed to the each generator in the system. Table 4 shows the comparison of proposed method with NGDF and Bialek's method. It is obvious that each method gives the difference results. For example, at line 1-2, the proposed method gives the result that contributed from both generator buses 1 and 2 while for NGDF and Bialek's method, the line flow is just contributed by generator bus 1 only. In addition, for NGDF method, the result of reactive power for this line is equal to zero due to introduction of virtual bus that said that this line is not contributed by any generators in the system.

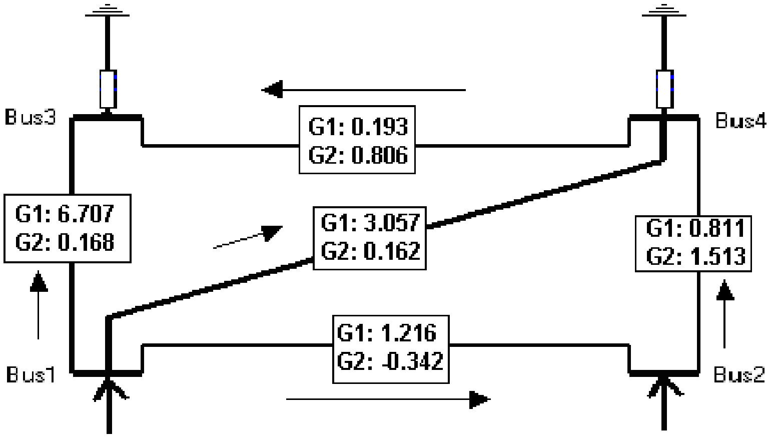


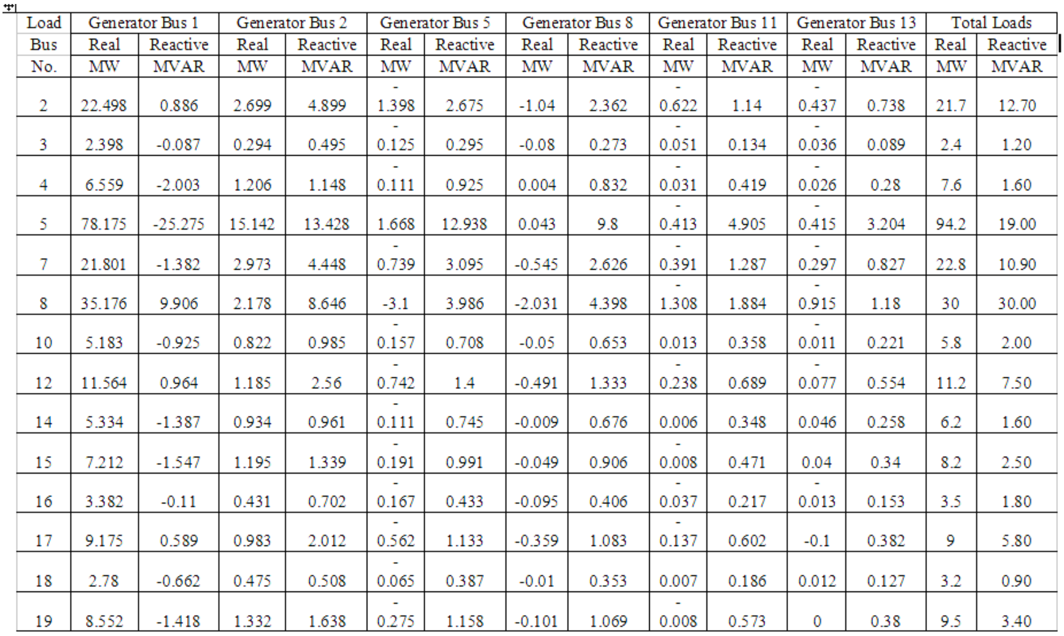
Figure 5. Loss tracing results.

Table 4. Power Contribution from Individual Genarators to Line Flows

			Generator Bus 1					**Generator Bus 1**				
Line	**From**	**To**	**Proposed Method**		**NGDF**		**Bialek's Method**	**Proposed Method**		**NGDF**		**Bialek's Method**
No.	**Bus**	**Bus**	**P (MW)**	**Q (Mvar)**	**P (MW)**	**Q (Mvar)**	**P (MW)**	**P (MW)**	**Q (Mvar)**	**P (MW)**	**Q (Mvar)**	**P (MW)**
1	1	2	88.074	9.773	59.661	0.000	59.661	28.414	14.722	0.000	0.000	0.000
2	1	3	195.615	86.491	224.758	104.358	224.758	29.137	17.864	0.000	0.000	0.000
3	1	4	116.301	28.624	115.581	25.531	115.581	-0.723	-3.092	0.000	0.000	0.000
4	2	4	86.858	36.711	58.788	0.000	0.000	86.214	62.370	114.291	26.505	173.078
5	4	3	45.951	13.340	50.014	9.977	51.448	37.163	10.366	33.150	13.730	33.553

To show the veracity of this method to the power flow at loads, IEEE 30-bus system is used. IEEE 30-bus system consists of two generators and four synchronous condensers. The proposed method will treat the condensers as generators. Thus the contribution from each generators and condensers to the loads can be identified using the equations (12) and (13) that have been derived above. Table 5 shows the results of power flow allocation for each generator to the loads. It can be seen that the total contributions of each generators are equal to the load demand. The power flow solution for IEEE 30-bus system can be obtained in Ref [19].

Table 5. Power Contribution From Individual Genarators To Loads For Ieee 30-Bus System



Load	Generator Bus 1		Generator Bus 2		Generator Bus 5		Generator Bus 8		Generator Bus 11		Generator Bus 13		Total Loads	
Bus	Real	Reactive	Real	Reactive	Real	Reactive	Real	Reactive	Real	Reactive	Real	Reactive	Real	Reactive
No.	MW	MVAR	MW	MVAR	MW	MVAR	MW	MVAR	MW	MVAR	MW	MVAR	MW	MVAR
2	22.498	0.886	2.699	4.899	-1.398	2.675	-1.04	2.362	-0.622	1.14	-0.437	0.738	21.7	12.70
3	2.398	-0.087	0.294	0.495	-0.125	0.295	-0.08	0.273	-0.051	0.134	-0.036	0.089	2.4	1.20
4	6.559	-2.003	1.206	1.148	-0.111	0.925	0.004	0.832	-0.031	0.419	-0.026	0.28	7.6	1.60
5	78.175	-25.275	15.142	13.428	1.668	12.938	0.043	9.8	-0.413	4.905	-0.415	3.204	94.2	19.00
7	21.801	-1.382	2.973	4.448	-0.739	3.095	-0.545	2.626	-0.391	1.287	-0.297	0.827	22.8	10.90
8	35.176	9.906	2.178	8.646	-3.1	3.986	-2.031	4.398	-1.308	1.884	-0.915	1.18	30	30.00
10	5.183	-0.925	0.822	0.985	-0.157	0.708	-0.05	0.653	0.013	0.358	-0.011	0.221	5.8	2.00
12	11.564	0.964	1.185	2.56	-0.742	1.4	-0.491	1.333	-0.238	0.689	-0.077	0.554	11.2	7.50
14	5.334	-1.387	0.934	0.961	-0.111	0.745	-0.009	0.676	0.006	0.348	0.046	0.258	6.2	1.60
15	7.212	-1.547	1.195	1.339	-0.191	0.991	-0.049	0.906	-0.008	0.471	0.04	0.34	8.2	2.50
16	3.382	-0.11	0.431	0.702	-0.167	0.433	-0.095	0.406	-0.037	0.217	-0.013	0.153	3.5	1.80
17	9.175	0.589	0.983	2.012	-0.562	1.133	-0.359	1.083	-0.137	0.602	-0.1	0.382	9	5.80
18	2.78	-0.662	0.475	0.508	-0.065	0.387	-0.01	0.353	0.007	0.186	0.012	0.127	3.2	0.90
19	8.552	-1.418	1.332	1.638	-0.275	1.158	-0.101	1.069	-0.008	0.573	0	0.38	9.5	3.40

CONCLUSION

This paper proposes a method for calculating real and reactive power from individual generators to line flows, loads and transmission losses. This method uses basic circuit theories to trace the voltages, currents, power flows and losses contributed by each generator sequentially. The algorithm is simple and accurate. The 4-bus and IEEE 30-bus systems were chosen as the test cases to show the simplicity and veracity of the method. The integration of the proposed method into the charging of transmission usage can be proposed in future work.

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