An Alternative Power Tracing Method for Transmission Open Access

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ABSTRACT

This paper suggests a method for tracing the current and complex power from individual power sources to system loads. Based on solved load flow, the method converts power injections and line flows into real and imaginary current injections and current flows. These currents are then represented independently as real and imaginary current networks. Since current networks are acyclic lossless networks, proportional sharing principle and graph theory is used to trace the relationship between current sources and current sinks. The contributions from each current source are finally translated into power contributions to each load. IEEE 14-bus test system is used to illustrate the effectiveness of the method. Comparison of the results with previous methods is also given.

1. INTRODUCTION

The competitive environment of electricity markets necessitates wide access to transmission networks that connect dispersed customers and suppliers. Regardless of market structure, it is important to know whether or not, and to what extent, each power system user contributes to the usage of a particular system component. This information facilitates the restructured power system to operate economically and efficiently. Moreover it brings fair pricing and open access to all system users.

Due to non linear nature of power flow, it is difficult to determine transmission usage accurately. Therefore it required to use approximate models, tracing algorithms or sensitivity indices for usage allocation. The tracing methods are based on the actual power flows in the network and the proportional sharing principle. To date several tracing algorithms have been proposed in the literature [1-11].

A novel tracing method is presented in [1-3]. But, even though the approach is conceptually very simple, it requires inverting a sparse matrix of the rank equal to the number of network nodes. In [4] graph theory is applied to trace active power and it is limited to systems without loop flows. Reference [5] is based on the concept of generator 'domains', 'commons' and 'links'. The disadvantage of this method is that the share of each generator in each 'common' (i.e., the set of buses supplied from the same set of generators) is assumed to be same. Furthermore, the 'commons' concept can lead to problems, since the topology of a 'common' could radically change even in the case of slight change in power flows. Line utility factor is introduced in [6] to identify the impact of each generator to each line which is only applicable to active power tracing.

In general all the above mentioned methods are most appropriate for active power flow tracing rather than reactive power tracing.

Nodal generation distribution factor (NGDF) [7] for active and reactive power allocation is based on time consuming search algorithm. AC power flow tracing algorithms [8], [9] use a complicated line representation to account for the losses and line charging, Detecting and solving the loop flows is a pre requisite to these methods.

In order to overcome the difficulties arise in reactive power tracing due to interaction cause by losses, [10] traces active and reactive power using real and imaginary currents respectively. This technique automatically becomes lossless real and imaginary current networks and does not require to model line losses but the method still involves the disadvantages of the concept of 'domains' and 'commons'. Reference [11], proved that real and imaginary current networks are acyclic directed graphs. Then authors attempt to show the share of the generators to the loads, ignoring line charging elements.

The above mentioned disadvantages have been the reason for developing a new method to know how much, and to what extent, each generator supplies to each load. The algorithm uses the advantages of real and imaginary current networks along with the basic concept of graph theory. Starting from load flow solutions, it first decomposes line complex currents based on the proportion of generator and network injected currents. The amount of current attributed to each current source in the lines and to each current sink is then used to allocate the contribution from each active and reactive generator to system loads. Shunt elements are handled by introducing additional fictitious nodes.

2. APPROACH

Reference [4] reports a power flow tracing algorithm using graph theory which can only apply to systems without losses and loop flows. Moreover, the paper quotes that evaluating loop flows were not easy especially when loops have complicated paths and therefore the issue needs to be further investigated. To avoid these limitations, this paper suggests a new approach to handle loop flows and form lossless network. Finally a new and improved algorithm is proposed that can trace active and reactive power supplied from each physical power source to each physical system load.

In the previous section the paper has unveiled that real and imaginary current networks are lossless networks without loops [10-11]. Therefore these current network properties makes it [4] very suitable to trace the contribution of current sources (current sinks) to line flows and to current sinks (current sources). Necessary modifications are made to the method by introducing fictitious lines and treated as network current sources or sinks at additional nodes. Moreover, generators and loads are considered independently instead of a net generator or a net load bus as in the original algorithm [4].

2.1. Current Flow Diagrams and Proportionality Principle

Starting from AC power flow solution one can convert the complex power injections and line flows into complex current equivalents. Injected currents, line currents and currents due to shunt elements can be represented respectively as

$$I_{inj} = \left(\frac{S_i}{V_i}\right)^* \tag{1}$$

$$I_{ij} = y_{ij}(V_i - V_j) \tag{2}$$

$$I_{i\_sh} = y_{i\_sh}(V_i) \tag{3}$$

where $I_{inj}, S_i, V_i, y_{i\_sh}$ and I_{i_sh} are the injected current, injected power, voltage, equivalent shunt admittance and current flow through y_{i_sh} of bus *i* respectively. I_{ij} is the line current from bus *i* to bus *j*. The term y_{ij} is the admittance of the line l_{ij} between buses *i* and *j*. Voltage at bus *j* is V_j.

The complex current flow diagram obtained from (1)-(3) can be further decoupled into real and imaginary current diagrams. These diagrams can then be used to estimate the relationship between the current sources and the current sinks using proportional sharing principle [1]. Details of current source and current sinks are found on [10].

2.2. Handling network Elements

In a power system, generator and loads are not the only sources and/or sinks of complex power. Static Var Compensators (SVCs), transformers, shunt capacitors/reactors and line charging capacitances play a vital role in transferring power between suppliers and consumers. In order to assess possible contributions from these network elements, it is necessary to consider the amount of current injected or absorbed by equivalent shunt impedance seen at each bus. These shunt currents can be handled by introducing fictitious lines and treated as network current sources or sinks at additional nodes as shown in Figure 1.

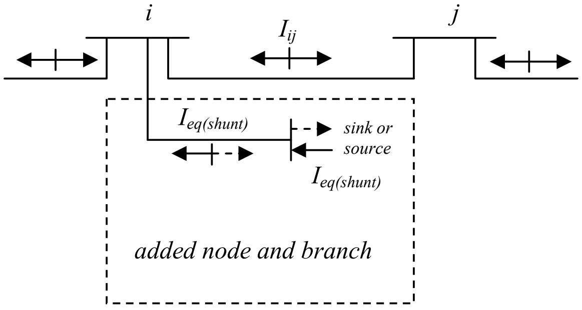

Figure 1: Representation of equivalent network element at node *i* using a fictitious node and branch.

2.3. Graph Method in Short

The method assumes that a generator has the priority to provide power to the load on the same bus and is based on the following lemmas of graph theory.

Lemma 1: A lossless, finite-nodes power system without loop flow has at least one pure source, i.e. a generator bus with all incident lines carrying outflows.

Lemma 2: A lossless, finite-nodes power system without loop flow has at least one pure sink, i.e. a load bus with all incident lines carrying inflows.

Based on these two lemmas downstream tracing sequence briefly describes the method. The downstream tracing (DSTR) is used for calculating the contribution factors of individual generators to line flows and loads. This process initially requires the formation of intermediate matrices called extraction factor matrix of lines , A_l and loads A_L from total passing power of their upstream buses i.e. $P_l = A_l.P$ and $P_L = A_L.P$ respectively. Where P_l is a vector of line power. P is a vector of bus total passing power in the bus sequence of down stream tracing. Then the nonzero elements in A_l and A_L are calculated with the following equations.

$$(A_l)_{line\ j, bus\ i} = \frac{line\ j's\ power\ flow}{bus\ i's\ total\ pass\ power\ P_i} \tag{4}$$

$$A_{L_{ii}} = \begin{cases} 0 & i \notin net\ load\ buses \\ \dfrac{net\ load\ power\ on\ bus\ i}{P_i} & i \in net\ load\ buses \end{cases} \tag{5}$$

The next step involves the calculation of contribution factor matrix (B) of generators to bus total passing power. Mathematically this can be expressed as $P = B.P_G$. The elements of B are calculated using the equation given below

$$B=\overset{B_{bus-i,bus-k}}{\begin{cases} 1 & (k=i, k \in net\ gen.\ buses) \\ 0 & (k=i, k \notin net\ gen.\ buses) \\ 0 & (k>i) \\ 0 & (k<i, k \notin net\ gen.\ buses) \\ \sum\limits_{l_j \in i} \left(A_{lj-m} \cdot B_{m-k}\right) & (k<i, k \in net\ gen.\ buses) \end{cases}} \qquad (6)$$

where $k< i$ means k is an upstream bus of bus i, and $k> i$ means k is a downstream bus of bus i . The last expression is for the lower triangular nonzero elements. The term $l_{j\in i}$ means line j is an inflow line of bus i. $A_{l_{j-m}}$ is the unique nonzero element corresponding to line j in matrix A_l with bus m as its upstream terminal. B_{m-k} is the element in matrix B already calculated which represents the contribution of generator k to the total injection power of bus .

By substituting $P = B.P_G$ in $P_l = A_l.P$ and $P_L = A_L.P$ contribution of each generator to line flows and loads can be calculated. Exact derivation can be found on [4].

3. DECOUPLING LOAD POWER

The output of tracing procedure apportions real and reactive current sources to line currents and to each current sink within their respective real and imaginary current diagrams. Then the complex current contribution by each current source k to each load i is simply

$$I_i^k = \left(I_i^{k\_r} + jI_i^{k\_im}\right) \qquad (7)$$

where I_i^k is the complex current of source k attributed to load i. $I_i^{k\_r}$ and $I_i^{k\_im}$ are real and imaginary component of I_i^k respectively.

Finally complex power share of each current source to each load can be represented as

$$S_i^k = V_i\left(I_i^k\right)^* \qquad (8)$$

from (8) the total load complex power

$$S_i = \sum_{k=1}^{inj} V_i\left(I_i^k\right)^* \qquad (9)$$

where S_i and S_i^k are the complex power of load at bus i and contribution from current source k to S_i respectively. The term $\left(I_i^k\right)^*$ means the conjugate of I_i^k . Superscript inj represents the total number of current sources.

3.1. CONTRIBUTION OF ACTUAL POWER SOURCES

Equation (9) shows the implicit contribution of all current sources to loads. The next step consists of evaluating how much each real and reactive power source contributes to each system load. For this purpose the following derivations are used.

3.1.1. REAL POWER ALLOCATION

Starting from equation (9), one can obtain total real power of load at bus i from equation (10).

$$P_i = \mathrm{Re}\sum_{k=1}^{inj} V_i\left(I_i^k\right)^* \qquad (10)$$

where P_i is the real power component of S_i .

Splitting (10) into number of generators, ng and remaining current sources defined as network sources, ns

$$P_i = \mathrm{Re}\sum_{g=1}^{ng} V_i\left(I_i^g\right)^* + \mathrm{Re}\sum_{m=1}^{ns} V_i\left(I_i^m\right)^* \qquad (11)$$

$$P_i = \sum_{g=1}^{ng} P_i^g + \sum_{m=1}^{ns} P_i^m \qquad (12)$$

$$P_i = P_{i\_gen} + P_{i\_net} \qquad (13)$$

where I_i^g , P_i^g and P_{i_gen} are the complex current share of generator g ,component of P_i due to I_i^g and sum of real power contribution from generators to load at bus i respectively. Similarly I_i^m , P_i^m and P_{i_net} represents the complex current share of network source m, component of P_i due to I_i^m and sum of real power contribution from network sources to load at bus i respectively.

In the equation (13) P_{i_net} , does not show exhibit explicit dependence on generator contributions. Therefore P_{i_net} term may be divided among actual generators proportionally to their respective exchanged real power. With this assumption the P_{i_net} term can be assigned to generators as

$$P_{i\_net} = \sum_{g=1}^{ng} \frac{P_i^g}{\sum\limits_{g=1}^{ng} P_i^g} \times P_{i\_net} \qquad (14)$$

3.1.2. REACTIVE POWER ALLOCATION

Similarly from (9), it is possible to derive related equations for reactive power as follows

$$Q_i = \mathrm{Im}\sum_{k=1}^{inj} V_i\left(I_i^k\right)^* \qquad (15)$$

Splitting (15) into generators and network terms

$$Q_i = \operatorname{Im}\sum_{g=1}^{ng} V_i \left(I_i^g\right)^* + \operatorname{Im}\sum_{m=1}^{ns} V_i \left(I_i^m\right)^* \tag{16}$$

$$Q_i = \sum_{g=1}^{ng} Q_i^g + \sum_{m=1}^{ns} Q_i^m \tag{17}$$

$$Q_i = Q_{i\_gen} + Q_{i\_net} \tag{18}$$

where Q_i is the reactive power of load *i* supplied by all current sources, Q_{i_gen} means the reactive power contribution from generators to load *i*. Q_{i_net} means the reactive power contribution from network sources to load *i* including reactive power sources attributing negative share.

Q_{i_net} term in (18) cannot be further allocated to physical reactive power sources. This consideration is reasonable because unlike real power, the network not only absorbs reactive power but it can also cater reactive power to the system.

4. RESULTS AND ANALYSIS

A number of simulations have been carried out to demonstrate the validity of the method. The result of IEEE 14-bus test system is presented. Load flow data of IEEE 14-bus test case is given in Appendix

4.1. ACTIVE POWER TRACING

The active power flow tracing results are shown in Tables 1-3. The implicit result obtained from (10) is shown in Table1. Since SVCs and shunt elements are not actual real power generators the interaction term assigned to them are combined as equivalent network term and are listed in Table 2.

Table 1: Active Power Trace to Loads Due to All Current Sources in Megawatt (MW)

Supplied by	Load bus number										
	2	3	4	5	6	9	10	11	12	13	14
Gen1	16.56	70.01	39.50	6.46	7.85	19.69	6.01	2.55	4.76	9.99	10.73
Gen2	4.93	16.92	5.78	0.60	0.57	2.82	0.66	0.18	0.34	0.72	1.23
SVC3	0.00	5.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SVC6	0.00	0.00	0.00	0.05	0.67	0.00	0.17	0.18	0.22	0.64	0.23
SVC8	0.00	0.06	0.35	0.03	0.00	1.11	0.26	0.00	0.00	0.00	0.29
shunt1	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
shunt2	0.21	0.44	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
shunt3	0.00	0.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
shunt4	0.00	0.43	0.92	0.00	0.00	0.46	0.07	0.00	0.00	0.00	0.15
shunt5	0.00	0.41	0.88	0.26	0.31	0.44	0.18	0.10	0.19	0.40	0.31
shunt6	0.00	0.00	0.00	0.13	1.80	0.00	0.47	0.49	0.59	1.74	0.62
shunt7	0.00	0.04	0.25	0.02	0.00	0.79	0.19	0.00	0.00	0.00	0.21
shunt9	0.00	0.02	0.09	0.01	0.00	4.20	0.98	0.00	0.00	0.00	1.12
Total:	21.70	94.20	47.80	7.60	11.20	29.50	9.00	3.50	6.10	13.50	14.90

The final allocation of active power to loads is presented in Table 3 along with the result obtained through the procedure proposed by Bialek, [1]. Note that the result obtained by the proposed method in this paper is compared well with the results of [1]. Table 3 also shows the loss shared by individual generators and the balance of system power.

Table 2: Active Power Allocation in Terms of Generators and Equivalent Network Term in Megawatt (MW

Supplied by	Load bus number										
	2	3	4	5	6	9	10	11	12	13	14
Gen1	16.56	70.01	39.50	6.46	7.85	19.69	6.01	2.55	4.76	9.99	10.73
Gen2	4.93	16.92	5.78	0.60	0.57	2.82	0.66	0.18	0.34	0.72	1.23
net	0.21	7.28	2.52	0.54	2.77	7.00	2.33	0.77	1.00	2.78	2.93
Total:	21.70	94.20	47.80	7.60	11.20	29.50	9.00	3.50	6.10	13.50	14.90

Table 3: Active Power Contribution of Individual Generators to Loads in Megawatt (MW)

Bus number	Load (MW)	Proposed method		Bialek's method	
		Supply generator bus		Supply generator bus	
		1	2	1	2
1	0.00	0.00	0.00	0.00	0.00
2	21.70	16.72	4.97	17.19	4.51
3	94.20	75.87	18.34	76.28	17.92
4	47.80	41.69	6.11	41.24	6.56
5	7.60	6.95	0.65	7.03	0.57
6	11.20	10.44	0.76	10.37	0.83
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00
9	29.50	25.81	3.69	25.45	4.05
10	9.00	8.11	0.89	8.00	1.00
11	3.50	3.27	0.24	3.24	0.26
12	6.10	5.69	0.41	5.65	0.45
13	13.50	12.59	0.91	12.50	1.00
14	14.90	13.37	1.54	13.21	1.69
Loss:	13.38	11.88	1.50	12.23	1.16
Total:	272.39	232.39	40.00	232.39	40.00

4.2. REACTIVE POWER TRACING

The numerical result for IEEE 14-bus test case is obtained by adopting (15). In particular, Table 4 gives interactions of reactive power to loads due to real and imaginary current sources. As can be seen, some of the terms attributed to the injections are negative. This implies that those sources act as a reactive power burden in providing real and reactive power to the loads. Therefore they do not contribute any reactive power support to the load. For example, reactive power attributed to generator at bus 1 are all with negative values indicating that it requires reactive support from the network to deliver its real power to the loads and it is considered as a negative contribution from the network.

Table 4: Reactive Power Trace to Loads Due to All Current Sources in Megavar (MVAr)

Supplied by	Load bus number										
	2	3	4	5	6	9	10	11	12	13	14
Gen1	-1.44	-15.80	-7.19	-1.00	-1.99	-5.26	-1.62	-0.67	-1.28	-2.71	-3.09
Gen2	11.73	6.44	-0.29	0.81	-0.14	-0.75	-0.18	-0.05	-0.09	-0.20	-0.35
SVC3	0.00	22.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SVC6	0.00	0.00	0.00	0.31	2.62	0.00	0.64	0.68	0.82	2.37	0.80
SVC8	0.00	0.28	1.91	0.19	0.00	4.14	0.96	0.00	0.00	0.00	1.03
shunt1	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
shunt2	2.42	1.95	0.15	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
shunt3	0.00	3.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
shunt4	0.00	-0.10	-0.17	0.00	0.00	-0.12	-0.02	0.00	0.00	0.00	-0.04
shunt5	0.00	-0.09	-0.16	-0.04	-0.08	-0.12	-0.05	-0.03	-0.05	-0.11	-0.09
shunt6	0.00	0.00	0.00	0.84	7.09	0.00	1.74	1.86	2.20	6.44	2.15
shunt7	0.00	0.20	1.37	0.14	0.00	2.97	0.69	0.00	0.00	0.00	0.74
shunt9	0.00	0.07	0.48	0.05	0.00	15.73	3.64	0.00	0.00	0.00	3.88
Total:	12.70	19.01	-3.89	1.61	7.51	16.59	5.80	1.80	1.59	5.80	5.02

Unlike the real power sources there are many reactive power sources such as generators, SVCs, synchronous condensers, shunt capacitor etc. For the purpose of identifying the share of each actual reactive power sources (in this case generators and SVCs) to loads, (18) is utilized. The results of final allocation are shown in Table 5. As illustrated, the proposed method is fair and reasonable since higher share goes to local sources than distant sources. The result coincides with reactive power transfer theory.

Table 5 also shows the result obtained from the Bialek's method [1]. As can be seen, the result is quite different from that obtained by proposed method. The main difference of the method [1] may be due to negligence of active power flows and shunt elements when tracing reactive power. On the other hand the proposed method calculates the active and reactive power contributions simultaneously. It takes the actual current flows in the lines and the effect of shunt elements.

Table 5: Contribution of Reactive Power Sources to Loads in Megavar (MVAr)

Bus number	Load (MVAr)	Proposed method					Bialek's method				
		Supplied by					Supplied by				
		Gen2	SVC3	SVC6	SVC8	net	Gen2	SVC3	SVC6	SVC8	net
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	12.70	11.73	0.00	0.00	0.00	0.97	12.05	0.10	0.00	0.32	0.23
3	19.00	6.44	22.26	0.00	0.28	-9.97	0.00	19.00	0.00	0.00	0.00
4	-3.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	1.60	0.81	0.00	0.31	0.19	0.30	0.07	0.21	0.00	0.72	0.60
6	7.50	0.00	0.00	2.62	0.00	4.88	0.13	0.41	4.45	1.38	1.14
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	16.60	0.00	0.00	0.00	4.14	12.45	0.00	0.00	0.00	3.16	13.44
10	5.80	0.00	0.00	0.64	0.96	4.20	0.03	0.08	0.91	1.09	3.69
11	1.80	0.00	0.00	0.68	0.00	1.11	0.03	0.10	1.07	0.33	0.27
12	1.60	0.00	0.00	0.82	0.00	0.78	0.03	0.09	0.95	0.29	0.24
13	5.80	0.00	0.00	2.37	0.00	3.43	0.10	0.32	3.44	1.06	0.88
14	5.00	0.00	0.00	0.80	1.03	3.19	0.03	0.09	0.94	0.94	3.01

5. CONCLUSIONS

This paper proposes a method for calculating the contribution from each active and reactive power source to each system load. Instead of power tracing, the algorithm traces real and imaginary currents to handle the problem of system losses and loop flows. The traces from current sources to current sinks are then converted to power contributions. The algorithm is simple and accurate. Accordingly, a small, illustrative network was selected as the test case to show simplicity and veracity of the method.

The method could be used to resolve some of the difficult pricing and costing issues which arise from the introduction of competition in the power industry and to ensure fairness and transparency.

6. APPENDIX

Table 6: Bus Data of the IEEE 14-Bus System

	Voltage		Generation		Load	
Bus no.	Mag(pu)	Ang(deg)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
1	1.06	0	232.39	-16.89	0	0
2	1.05	-4.98	40	42.40	21.70	12.70
3	1.01	-12.72	0	23.39	94.20	19.00
4	1.02	-10.32	0	0	47.80	-3.90
5	1.02	-8.78	0	0	7.60	1.60
6	1.07	-14.22	0	12.24	11.20	7.50
7	1.06	-13.37	0	0	0	0
8	1.09	-13.37	0	17.36	0	0
9	1.06	-14.95	0	0	29.50	16.60
10	1.05	-15.10	0	0	9.00	5.80
11	1.06	-14.80	0	0	3.50	1.80
12	1.06	-15.08	0	0	6.10	1.60
13	1.05	-15.16	0	0	13.50	5.80
14	1.04	-16.04	0	0	14.90	5.00
			272.39	87.50	259.00	73.50

7. ACKNOWLEDGEMENTS

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