An Improved Usage Allocation Method for Deregulated Transmission Systems

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***Abstract*--This paper suggests an improved method for usage allocation to individual generators in a deregulated power system. Based on solved load flow, the method converts power injections and line flows into real and imaginary current injections and 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, line flows and losses. IEEE 14-bus test system is used to illustrate the effectiveness of the method. Comparison of the results with previous methods is also given.**

***Index Terms*--Directed graphs, energy management, load flow analysis, losses, power pools.**

I. 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 and line flows. Besides, the method is suitable in allocating transmission losses to individual generators. 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 from each current source in the lines is then used to identify the usage allocation. Shunt elements are handled by introducing additional fictitious nodes.

II. 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

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new approach to handle loop flows and form lossless network. Finally a new and improved algorithm is proposed that can trace active power usage by the system generators.

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].

A. 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. Theses 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 reference [10].

B. 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 Fig. 1.

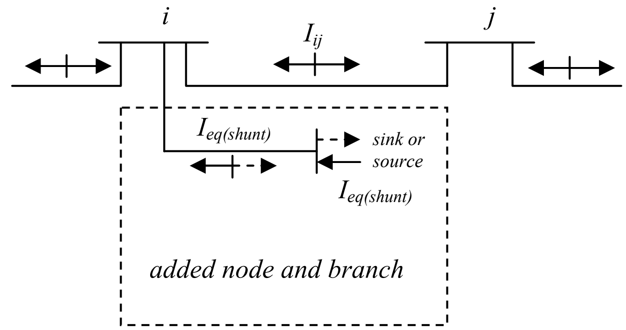

Fig. 1. Representation of equivalent network element at node *i* using a fictitious node and branch.

C. 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.

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

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 reference [4].

III. Decoupling Line and 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 line between nodes i and j is simply

$$I_{ij}^{k} = \left(I_{ij}^{k-r} + jI_{ij}^{k-im}\right) \tag{7}$$

where I_{ij}^{k} is the complex current of source k attributed to l_{ij}. I_{ij}^{k-r} and I_{ij}^{k-im} are real and imaginary component of I_{ij}^{k} respectively.

Assuming that the receiving end of l_{ij} is j, one can obtain the complex power share of each current source to l_{ij} as

$$S_{ij\_r}^{k} = V_j\left(I_{ij}^{k}\right)^* \tag{8}$$

from (8) the total line complex power at the receiving end of l_{ij}, due to all current sources will be

$$S_{ij\_r} = \sum_{k=1}^{inj} V_j\left(I_{ij}^{k}\right)^* \tag{9}$$

where S_{ij_r} and $S_{ij\_r}^{k}$ are the complex power at the receiving end of line l_{ij} and contribution from current source k to S_{ij_r} respectively. The term $\left(I_{ij}^{k}\right)^*$ means the conjugate of I_{ij}^{k}. Superscript inj represents the total number of current sources.

Equation (9) shows the implicit contribution of all current sources to a line. The next step consists of evaluating how much each real power source contributes to each line of the transmission network. For this purpose the following derivations are used.

Starting from (9), total real power at the receiving end of l_{ij} can be obtained from the following equation.

$$P_{ij\_r} = \mathrm{Re}\sum_{k=1}^{inj} V_j\left(I_{ij}^{k}\right)^* \tag{10}$$

where P_{ij_r} is the real power component of S_{ij_r}.

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

$$P_{ij\_r} = \mathrm{Re}\sum_{g=1}^{ng} V_j\left(I_{ij}^{g}\right)^* + \mathrm{Re}\sum_{m=1}^{ns} V_j\left(I_{ij}^{m}\right)^* \tag{11}$$

$$P_{ij\_r} = \sum_{g=1}^{ng} P_{ij\_r}^{g} + \sum_{m=1}^{ns} P_{ij\_r}^{m} \tag{12}$$

$$P_{ij\_r} = P_{ij\_gen} + P_{ij\_net} \tag{13}$$

where I_{ij}^{g}, $P_{ij\_r}^{g}$ and P_{ij_gen} are the complex current share of generator g ,component of P_{ij_r} due to I_{ij}^{g} and sum of real power contribution from generators to l_{ij} respectively. Similarly I_{ij}^{m}, $P_{ij\_r}^{m}$ and P_{ij_net} represents the complex current share of network source m, component of P_{ij_r} due to I_{ij}^{m} and sum of real power contribution from network sources to l_{ij} respectively.

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

$$P_{ij\_net} = \sum_{g=1}^{ng} \frac{P_{ij\_r}^{g}}{\sum_{g=1}^{ng} P_{ij\_r}^{g}} \times P_{ij\_net} \tag{14}$$

Once the contribution P_{ij_net} term is assigned to generators, line power P_{ij_r} can be expressed as

$$P_{ij\_r} = P_{ij\_r}^{1} + P_{ij\_r}^{2} + \ldots + P_{ij\_r}^{ng-1} + P_{ij\_r}^{ng} \tag{15}$$

where the superscripts denote the supply generator.

By following the same procedure, it is also possible to obtain the decomposed sending end line power P_{ij_s} as

$$P_{ij\_s} = \sum_{g=1}^{ng} P_{ij\_s}^{g} \tag{16}$$

$$P_{ij\_s} = P^{1}_{ij\_s} + P^{2}_{ij\_s} + \ldots + P^{ng\text{-}1}_{ij\_s} + P^{ng}_{ij\_s} \tag{17}$$

where $P^{g}_{ij\_s}$ is the amount of real power contributed by the generator g to sending end of line l_{ij}.

The result of (15) and (17) provides important information that can be used to determine the share of real power produced by generator g that is consumed by the load at bus j. Mathematically this can be expressed as

$$Load^{g}_{j} = \begin{cases} \sum\limits_{i \in \alpha_j} P^{g}_{ij\_r} - \sum\limits_{k \in \delta_j} P^{g}_{jk\_s} & g \notin bus\ j \\ P^{g}_{j} - \sum\limits_{k \in \delta_j} P^{g}_{jk\_s} & g \in bus\ j \end{cases} \tag{18}$$

where $i \in \alpha_j$ the set of lines supplying directly to bus j, $k \in \delta_j$ is the set of outflow lines from bus j, $P^{g}_{jk\_s}$ means power component of generator g at the sending end of line l_{jk} and P^{g}_{j} is the power injection at load bus j.

IV. Application to Power Loss

The unbundled real power components can be used to allocate line power loss to individual generators. The line power loss, $Loss_{P_{ij}}$ can be written as

$$Loss_{P_{ij}} = P_{ij\_s} - P_{ij\_r} \tag{19}$$

$$Loss_{P_{ij}} = \sum_{g=1}^{ng} \left(P^{g}_{ij\_s} - P^{g}_{ij\_r} \right) \tag{20}$$

where the term $\left(P^{g}_{ij\_s} - P^{g}_{ij\_r} \right)$ represents the line losses allocated to generator g.

Finally the contribution from generator g to system loss is obtained as

$$Loss_{g} = \sum_{l_{ij}=1}^{nl} \left(Loss^{g}_{l_{ij}} \right) \tag{21}$$

where

$$Loss^{g}_{l_{ij}} = \left(P^{g}_{ij\_s} - P^{g}_{ij\_r} \right) \tag{22}$$

and nl is the number of lines in the system.

V. 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 analysis including bus data and line power flows for IEEE 14-bus test case is given in Appendix.

The active power flow tracing results are shown in Tables 1-2. The implicit result obtained from (10) is shown in Table 1. Due to lack of space, result for one half of the system lines is shown in Table 1. Note that the contributions from the equivalent shunt elements and loads. This result is expected because loads generally act as the sources of imaginary current and equivalent shunt elements may become either sources or sinks of real and/or imaginary current. Since loads, SVCs and shunt elements are not actual real power generators their interaction terms are distributed among the actual generators using (14) and are listed in Table 2. Table 2 also shows the loss shared by individual generators and the balance of line powers and losses.

TABLE I
Active Power Components of Line Flows Due to All Current Sources

Supplied by	Line power flow in Megawatt (MW)									
	line 1-2	line 1-5	line 2-3	line 2-4	line 2-5	line 4-3	line 5-4	line 4-7	line 4-9	line 5-6
Gen 1	152.946	71.872	55.317	43.483	32.163	19.502	55.876	26.754	14.321	42.534
Gen 2	0.000	0.000	12.939	10.171	7.524	2.790	4.041	3.834	2.048	3.076
shunt 4	0.000	0.000	0.000	0.447	0.000	0.456	0.000	-1.432	-0.180	0.000
shunt 5	-0.367	0.835	0.000	0.159	0.841	0.435	1.386	-0.138	0.134	-1.250
load 3	0.000	0.000	2.615	0.024	0.000	0.149	0.000	-0.108	-0.027	0.000
load 4	0.000	0.000	0.000	0.163	0.000	0.000	0.000	-0.751	-0.188	0.000
load 5	-0.037	0.086	0.000	0.016	0.086	0.000	-0.084	-0.074	-0.019	-0.297
load 9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
load 10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
load 11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
load 12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
load 13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
load 14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total:	152.543	72.792	70.871	54.463	40.614	23.331	61.219	28.085	16.089	44.063

TABLE II
Active Power Contribution from Individual Generators to Line Flows and Losses in Megawatt(MW)

Line ID	Line power supplied by		Total flow	Line loss caused by		Total loss
	generator 1	generator 2		generator 1	generator 2	
line 1-2	152.54	0.00	152.54	4.30	0.00	4.30
line 1-5	72.79	0.00	72.79	2.76	0.00	2.76
line 2-3	57.44	13.43	70.87	1.88	0.44	2.32
line 2-4	44.14	10.32	54.46	1.36	0.32	1.68
line 2-5	32.91	7.70	40.61	0.73	0.17	0.90
line 4-3	20.41	2.92	23.33	0.32	0.05	0.37
line 5-4	57.09	4.13	61.22	0.48	0.04	0.52
line 4-7	24.57	3.52	28.09	0.00	0.00	0.00
line 4-9	14.08	2.01	16.09	0.00	0.00	0.00
line 5-6	41.09	2.97	44.06	0.00	0.00	0.00
line 6-11	6.79	0.49	7.28	0.05	0.00	0.06
line 6-12	7.19	0.52	7.71	0.07	0.01	0.07
line 6-13	16.34	1.18	17.52	0.20	0.01	0.21
line 7-8	0.00	0.00	0.00	0.00	0.00	0.00
line 7-9	24.57	3.51	28.08	0.00	0.00	0.00
line 9-10	4.57	0.65	5.22	0.01	0.00	0.01
line 9-14	8.16	1.17	9.33	0.10	0.02	0.12
line 10-11	3.52	0.25	3.77	0.01	0.00	0.01
line 12-13	1.50	0.10	1.60	0.01	0.00	0.01
line 13-14	5.20	0.38	5.58	0.05	0.00	0.05

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. The loss share of each generator in Table 3 is obtained by using (21).

TABLE III
ACTIVE POWER CONTRIBUTION FROM 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	14.08	7.62	17.19	4.51
3	94.20	77.85	16.35	76.28	17.92
4	47.80	41.86	5.95	41.24	6.56
5	7.60	7.04	0.56	7.03	0.57
6	11.20	10.45	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	3.68	25.45	4.05
10	9.00	8.09	0.90	8.00	1.00
11	3.50	3.26	0.24	3.24	0.26
12	6.10	5.68	0.42	5.65	0.45
13	13.50	12.59	0.90	12.50	1.00
14	14.90	13.36	1.55	13.21	1.69
Loss:	13.38	12.32	1.07	12.23	1.16
Total:	272.39	232.39	39.99	232.39	40.00

VI. CONCLUSION

This paper proposes a method for calculating the contribution from individual generators to line flows, loads and transmission losses. 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.

VII. APPENDIX

TABLE VI
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

TABLE V
LINE DATA OF THE IEEE 14-BUS SYSTEM

Line number	From Bus	To Bus	From Bus Injection		To Bus Injection		Loss	
			P(MW)	Q(MVAr)	P(MW)	Q(MVAr)	P(MW)	Q(MVAr)
1	1	2	156.83	-20.39	-152.54	27.66	4.30	13.11
2	1	5	75.55	3.5	-72.79	2.58	2.76	11.41
3	2	3	73.19	3.57	-70.87	1.58	2.32	9.77
4	2	4	56.14	-2.29	-54.46	3.39	1.68	5.09
5	2	5	41.51	0.76	-40.61	-1.63	0.90	2.75
6	3	4	-23.33	2.81	23.7	-5.42	0.37	0.95
7	4	5	-61.22	15.67	61.74	-15.37	0.52	1.63
8	4	7	28.09	-9.42	-28.09	11.11	0.00	1.69
9	4	9	16.09	-0.32	-16.09	1.62	0.00	1.3
10	5	6	44.06	12.82	-44.06	-8.39	0.00	4.43
11	6	11	7.34	3.47	-7.29	-3.36	0.06	0.11
12	6	12	7.78	2.49	-7.71	-2.34	0.07	0.15
13	6	13	17.74	7.17	-17.53	-6.75	0.21	0.42
14	7	8	0	-16.91	0	17.36	0.00	0.45
15	7	9	28.09	5.8	-28.09	-4.99	0.00	0.8
16	9	10	5.24	4.31	-5.23	-4.27	0.01	0.03
17	9	14	9.44	3.67	-9.32	-3.42	0.12	0.25
18	10	11	-3.77	-1.53	3.79	1.56	0.01	0.03
19	12	13	1.61	0.74	-1.6	-0.74	0.01	0.01
20	13	14	5.63	1.69	-5.58	-1.58	0.05	0.11

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