Manuscript received Aug. 14, 2007; revised Oct. 20, 2007

Modified Method of Computing Generator Participation Factors by Electricity Tracing with Consideration of Load Flow Changes

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Abstract: - Open access is an essential feature in the deregulated power system. It permits all the generators to transmit power into the system. Depending upon the transmission network parameters, generator responses to the variation in loads differ from each other. To know these responses is important from various aspects such as for determination of nodal prices which will be needed in charging differential tariffs and also in congestion management. By considering the load flow changes due to change in load at a bus, electricity tracing is applied to compute the generator participation factors. A new algorithm of proportional sharing principle is developed. A sensitivity analysis is proposed to determine these changes in power flows due to changed load. This new approach for determination of generators participation could be more appropriate when compared with the other method based on proportional sharing principle of electricity tracing

Key-Words: - Deregulation, Generator Participation Factors, Electricity Tracing, Proportional Sharing Principle, Sensitivity Analysis

1 Introduction

In a deregulated power system, unbundling of the generation, transmission and distribution systems has invited various problems as regards to the planning and operation of a transmission infrastructure. While providing the open access to the market participants, the generation companies can transmit the power as per the changes in load demands. Since the generator cost functions are not same, the issues related to differential power tariffs may become more complex. Also due to free trading, some of the lines may get overloaded thereby causing network congestion. The congestion management model considering demand elasticity is proposed in [1].

The pricing issues and congestion management could have been effectively met if the participations of every generator in sharing the changes in load were known. Although tracing the participation of generators in loads is not possible, the relationships between the change in load and generator power changes can be established.

The contribution of generators to the loads and line flow is described in [2]. A technique is proposed with the help of which it could be possible to trace the power produced by the generator. In this technique, the buses which are reached by the power produced from each generator are first identified and then the set of buses supplied by same generators are determined. A proportionality principle was assumed to determine the sharing of generators.

A systematic approach has been proposed in [3]. Using proportional sharing principle, the line flows are traced and the contribution of each generator in loads is determined. Simultaneously, sharing of loads in each generator is also determined. Upstream looking and downstream looking algorithms are proposed to trace the electricity.

Application of power tracing has been used to compute the energy and connection costs [4]. In [5], proportional sharing principle of tracing power flows has been rationalized. It is shown that Shapley value solution concept satisfies the principle of proportional sharing. Similar research is found to be in [6]. A new power flow tracing and loss allocation method based on loop analysis is proposed in [7].

In all these researches, so as to know the participation of generators or loads, the load flow solution must be known. The research is very much suitable to the standstill condition of a power system. When the system load is changed, the changes in system losses are allocated not only to the changed load but to the other loads also. This approach of proportional sharing of changed load will not be accurate from the point of view of charging the prices for loss allocation when the load is changed. Since the power system behaviour is dynamic in nature, a modified approach is needed to determine the participations of generators. In this paper, a sensitivity analysis approach with proportional sharing principle is proposed. It can compute the changes in power shared by generators for the changes in loads. Also the changes in losses due to changed load are allocated to the changing load only. Main objective of this paper is to prove that proportional sharing principle as proposed by Bialek [3], can also be applied with consideration of only changes in line flows, especially for continuously changing load conditions. A simple approach of sensitivity analysis can be applied to determine these changes. Algorithms of proportional sharing principle with normal and changed load flow conditions have been developed and implemented in MATLAB.

2 Proportional Sharing Principle

In a meshed structure, electrical power can flow from source to sink through number of optional paths. The electricity tracing method is very much identical to a general transportation problem. The tracing of power from individual generator to individual load is highly impossible. But the physical paths linking the generators and loads can be established. Two different approaches are explained in [5]. These are downstream and upstream looking algorithms. The study in this paper is restricted to upstream looking algorithm only.

Consider the four branches are connected through node k, as shown in Fig.1. Let p_1, p_2, p_3 and p_4 be the real power flows through i-k, j-k, k-m and k-n respectively.

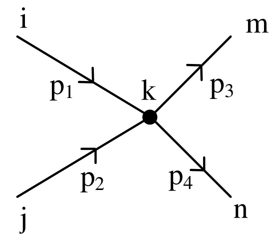

Fig.1. Power Flow through Branches

While applying the proportional sharing principle, it is assumed that the node, to which different branches are connected (here it is node k), is a perfect mixer. The incoming power is proportionally distributed through the branches with outgoing powers. Obviously $p_1 + p_2 = p_3 + p_4$, thereby satisfying Kirchoff's current law. p_3 is the sum of shares of p_1 and p_2. Share of p_1 in p_3 will be $\frac{p_1}{p_1+p_2}p_3$ and that of p_2 will be, $\frac{p_2}{p_1+p_2}p_3$. Total power p_3 can be,

$$p_3 = \frac{p_1}{p_1+p_2}p_3 + \frac{p_2}{p_1+p_2}p_3 \tag{1}$$

Similarly, p_4 will be,

$$p_4 = \frac{p_1}{p_1+p_2}p_4 + \frac{p_2}{p_1+p_2}p_4 \tag{2}$$

Proportional sharing principle can be extended to entire network to trace the contribution of incoming flows in the outgoing flows. An upstream looking algorithm with the consideration of gross powers is explained below.

2.1 Upstream looking algorithm with gross power flows

In this approach nodal balance of inflows is considered. It can compute the sharing of generations in the loads and the loss allocation to the loads as well.

Defining the following terms-

$P_i^{(gross)}$, $P_j^{(gross)}$ -Total power flow through node i and j respectively which satisfies KCL and which would flow through network when the network is fed with actual generation without any power loss.

$P_{i-j}^{(gross)}$, $P_{j-i}^{(gross)}$ -Gross power flows in line i-j nodes i and j respectively which would flow under lossless condition. It gives,

$$\left|P_{i-j}^{(gross)}\right| = \left|P_{j-i}^{(gross)}\right|$$

P_i, P_j - Actual power flow through node i and j respectively, considering losses
P_{i-j}, P_{j-i} - Actual power flows through line i-j from nodes i and j respectively, considering losses
P_{Gi} - Total generation at node i
P_{Li} - Total demand at node i
α_i -The set of nodes supplying directly node i (i.e. the set of nodes from which the power flows towards i)
β_i -The set of nodes supplying directly from node i (i.e. the set of nodes towards which the power flows from i)
The gross nodal flow when looking at the inflows can be expressed as,

$$P_i^{(gross)} = \sum_{j\in\alpha_i} \left|P_{i-j}^{(gross)}\right| + P_{Gi} \tag{3}$$

where,
i=1,2,3….n
Since $\left|P_{i-j}^{(gross)}\right| = \left|P_{j-i}^{(gross)}\right|$ and rearranging, (3) can be rewritten as,

$$P_i^{(gross)} = \sum_{j\in\alpha_i} \frac{\left|P_{j-i}^{(gross)}\right|}{P_j^{(gross)}} P_j^{(gross)} + P_{Gi} \tag{4}$$

Since the transmission line losses are small, the ratio of gross power flow over the line j-i to the total power flow, can be approximated as,

$$\frac{\left|P_{j-i}^{(gross)}\right|}{P_j^{(gross)}} \simeq \frac{\left|P_{j-i}\right|}{P_j}$$

Thus (4) can be written as,

$$P_{Gi} = P_i^{(gross)} - \sum_{j\in\alpha_i} \frac{\left|P_{j-i}\right|}{P_j} P_j^{(gross)} \tag{5}$$

If P^{gross} is the vector of gross nodal flows, A is the upstream distribution matrix of order nxn and P_G is the vector of generating powers, then (5), in matrix form will be,

$$P_G = A.P^{gross} \tag{6}$$

The elements of A can be obtained as,

$$[A]_{ij} = \begin{cases} 1 & \text{for i = j} \\ -\left|P_{j-i}\right| \big/ P_j & \text{for j} \in \alpha_i \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

If A^{-1} exists,

$$P^{gross} = A^{-1} . P_G \tag{8}$$

i^{th} element of P^{gross} will be,

$$P_i^{(gross)} = \sum_{k=1}^{n} \left[A^{-1}\right]_{ik} P_{Gk} \tag{9}$$

Contribution of the k^{th} generator into i^{th} nodal power is $\left[A^{-1}\right]_{ik} P_{Gk}$. Once the gross nodal flows are determined as given by (9), gross line flows and gross demands can be found using proportional sharing principle. The gross flow in line i-l ($l \in \beta_i$) will be

$$\left|P_{i-l}^{(gross)}\right| = \frac{\left|P_{i-l}^{(gross)}\right|}{P_i^{(gross)}} P_i^{(gross)} \simeq \frac{\left|P_{i-l}\right|}{P_i} P_i^{(gross)}$$

or $$\left|P_{i-l}^{(gross)}\right| \simeq \frac{\left|P_{i-l}\right|}{P_i} \sum_{k=1}^{n} \left[A^{-1}\right]_{ik} P_{Gk} \tag{10}$$

Obviously, contribution of the k^{th} generator into (i-l)th element will be $\frac{\left|P_{i-l}\right|}{P_i} . \left[A^{-1}\right]_{ik} . P_{Gk}$

Gross demand at node i will be,

$$P_{Li}^{(gross)} \simeq \frac{P_{Li}}{P_i} \sum_{k=1}^{n} \left[A^{-1}\right]_{ik} P_{Gk} \tag{11}$$

and contribution of k^{th} generator into load connected at i^{th} node will be $\frac{P_{Li}}{P_i} . \left[A^{-1}\right]_{ik} . P_{Gk}$. Further, gross losses, allocated to load at i^{th} bus can be obtained as,

$$P_{loss} = P_{Li}^{(gross)} - P_{Li} \tag{12}$$

To analyze the dynamic behaviour of the system, changes in the generation and load flows are required to be determined. After applying proportional sharing principle as explained above, participation of changes of generator powers in the changes at loads can be determined. However for determination of only changes in line flows, a sensitivity analysis approach would be more suitable.

3 Proportional Sharing Principle Applied to Changes in Line Flows

Sensitivity analysis has been used in many of the power system applications. Sensitivity studies are used for determining different customer outage cost functions in sub-transmission systems [8].

When load at bus is changed, power flows over the lines, change according to network behaviour. These changes can be directly obtained by power flow sensitivity analysis [9]. Thus for a change in power (ΔP_k) at a load bus, corresponding changes in generator powers and load bus voltages and angles can be obtained using,

$$\left[\Delta P_g, \Delta Q_g, \Delta V_l, \Delta \theta_l\right] = [\mathbf{S}]\left[\Delta V_g, \Delta \theta_g, \Delta P_l, \Delta Q_l\right] \quad (13)$$

where,

$\Delta P_g, \Delta Q_g$ -Change in Active and Reactive power at generator buses

$\Delta P_l, \Delta Q_l$ - Change in Active and Reactive power at load buses

$\Delta V_g, \Delta \theta_g$ -Change in Voltage and Angle at generator buses

$\Delta V_l, \Delta \theta_l$ -Change in Voltage and Angle at load buses

S- Sensitivity matrix

Similarly changes in line currents can be given by,

$$[\Delta \mathbf{I}] = [\mathbf{R}]\left[\Delta V_g, \Delta V_l, \Delta \theta_g, \Delta \theta_l\right] \quad (14)$$

where,

$\Delta \mathbf{I}$ -Changes in Currents of various lines

$\mathbf{R}$ -Current Sensitivity Matrix

The corresponding change in power flow ΔP_{ij}, over the line i-j can be determined thereafter.

Now consider that, proportional sharing principle is to be applied to the changes in line flows instead of line flows, These changes can be obtained directly by sensitivity analysis as above.

Directly from (11), change in the gross demand will be given as,

$$\Delta P_{Li}^{(gross)} \simeq \frac{\Delta P_{Li}}{\Delta P_i} \sum_{k=1}^{n} \left[A_d^{-1}\right]_{ik} \Delta P_{Gk} \quad (15)$$

where,

ΔP_{Li} -Change in actual demand at node i

$\Delta P_i, \Delta P_j$ -Change actual power flow through node i and j respectively by considering losses

ΔP_{Gk} -Change in total generation at node k

ΔP_{i-j}, ΔP_{j-i} - Change in actual power flows through line i-j from nodes i and j respectively by considering losses.

The elements of matrix A_d can be obtained as,

$$\left[A_d\right]_{ij} = \begin{cases} 1 & \text{for i = j} \\ -\left|\Delta P_{j-i}\right| / \Delta P_j & \text{for } j \in \alpha_i \\ 0 & \text{otherwise} \end{cases} \quad (16)$$

Contribution of change in the generation of k^{th} generator into change in load connected at i^{th} node will be,

$$\Delta P_{Gki} = \frac{\Delta P_{Li}}{\Delta P_i} \cdot \left[A_d^{-1}\right]_{ik} \Delta P_{Gk} \quad (17)$$

Further, change in gross losses, allocated to change in load at i^{th} bus can be obtained as,

$$\Delta P_{loss} = \Delta P_{Li}^{(gross)} - \Delta P_{Li} \quad (18)$$

Thus sharing of changes at all the generators for the specific changes in loads can be obtained by (28). For such determination changes in line flows is the only requirement which can be determined by sensitivity analysis as proposed in section III.

4 Case Study

6-bus system as shown in Fig. 2 is discussed in detailed to compute the generator sharing. Buses 1, 2 and 3 are the generator buses where as buses 4, 5, and 6 are the load buses. It is desired to obtain the sharing of changes in loads by the generators.

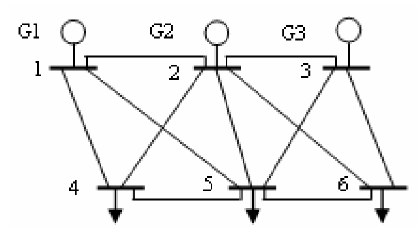

Fig.2. A 6- Bus System

5 Results

Sharing the generators by loads, total generator participations and losses allocation for the change in load at a bus can be obtained by applying proportional sharing principle with i) Conventional approach (taking the difference of load sharing before and after applying the change in load) and ii) Sensitivity analysis (by applying the proportional sharing principle directly to the changes in line flows).

5.1 Sharing Obtained by Conventional Approach

In this approach proportional sharing principle is applied at two different load conditions. For a specific load condition, a load flow is obtained by Newton-Raphson method. For this load flow, proportional sharing principle is applied as explained in section-I. The sharing of loads by generators is mentioned in Table-I. Further, load at bus 4 is changed by an amount of 10MW. Again the sharing is obtained as earlier. The sharing of changed load by generators is given in Table-II. Differences of the sharing given in Table-I and Table-II, are mentioned in Table-III. These values represent the sharing of changes in load at 4 by the generators. Last row of the columns G1, G2 and G3 of this table represents the generator participations for the specified change in load at bus 4. Last column represents the losses allocated to the various loads. Implementation of algorithm is made in

MATLAB. Program BSHARE computes the sharing of loads in generators.

Table-I
Sharing at Base Load Flow (Load Flow Obtained by NR method)

Loads	Sharing Loads by			Total Allocation to loads (MW)	Losses Allocated to Loads (MW)
	G1	G2	G3		
L4	0	0	0	0	0
L5	42.634	30.55	29.907	103.09	3.0912
L6	2.0572	16.335	32.412	50.804	0.80441
Total	44.691	46.885	62.32	153.9	3.8956

Table-II
Sharing at Changed Load (Load Flow Obtained by NR method)

Loads	Sharing Loads by			Total Allocation to loads (MW)	Losses Allocated to Loads (MW)
	G1	G2	G3		
L4	5.6986	4.3491	0.03303	10.081	0.08072
L5	40.575	32.129	30.385	103.09	3.0884
L6	1.843	16.552	32.404	50.8	0.79956
Total	48.116	53.03	62.823	163.97	3.9686

Table-III
Sharing at Changed Load (Load Flow Obtained by NR method)

Loads	Sharing Loads by			Total Allocation to loads (MW)	Losses Allocated to Loads (MW)
	G1	G2	G3		
L4	5.6986	4.3491	0.033	10.0807	0.0807
L5	-2.059	1.5784	0.478	-0.0028	-0.0028
L6	-0.214	0.2174	-0.008	-0.0048	-0.0048
Total	3.4251	6.1449	0.503	10.073	0.073

5.2 Sharing Obtained by Applying Proportional Sharing Principle to the Changes in Line Flows

In this approach, proportional sharing principle is applied to the changes in load flow as obtained by sensitivity analysis. For the given system, at the initial load condition load flow is obtained. After applying the same amount of 10MW change in load at bus 4, changes in line flows are determined by sensitivity analysis. Proportional sharing principle with modified algorithm is applied to theses changes to determine the sharing of changes in load at bus 4, by generators. These values are given in Table-IV. Last row of the columns G1, G2 and G3 of the table represents the generator participation for corresponding change in the load. Last column represents the losses allocated to the loads. The algorithm is implemented in MATLAB and results are obtained by the program SENSSHARE, developed by the authors.

Table-IV
Sharing of Change in Load of 10 MW at bus 4 (Proportional Sharing Principle applied to Load Flow Changes, obtained by Sensitivity Analysis)

Loads	Sharing Loads by			Total Allocation to loads (MW)	Losses Allocated to Loads (MW)
	G1	G2	G3		
L4	3.4163	6.1187	0.50159	10.037	0.036654
L5	0	0	0	0	0
L6	0	0	0	0	0
Total	3.4201	6.1287	0.50146	10.037	0.036654

The load flow values required to obtain the sharing by generators can also be obtained using Power World Simulator 8.0. They are very similar to that of mentioned in tables I to IV. The participations by the generators for change in loads are considered as of main importance. They are presented graphically in Fig. 3 to 5. These figures show a comparison of generator participations as obtained by sharing principle along with NR Load Flow (Program BSHARE), Sensitivity Analysis (Program SENSSHARE) and Power World Simulator 8.0.

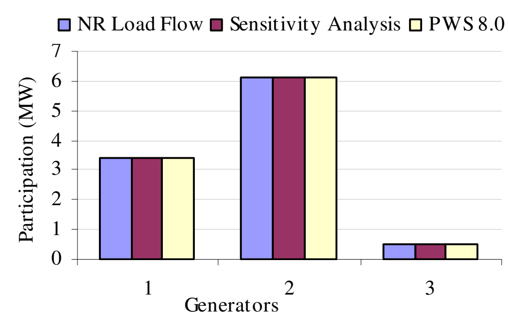

Fig.3 Generator Participations by Various Methods (10 MW change at bus 4)

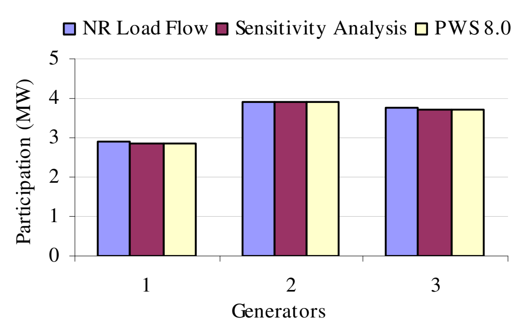

Fig.4 Generator Participations by Various Methods (10 MW change at bus 5)

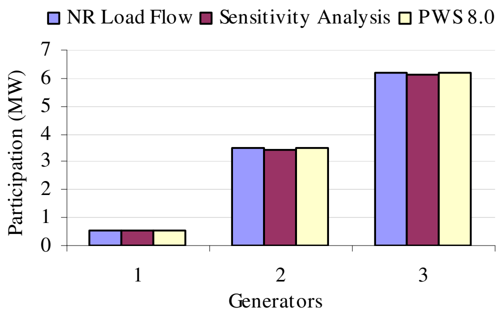

Fig. 5 Generator Participations by Various Methods (10 MW change at bus 6)

6 Conclusion

Proportional sharing with upstream looking algorithm and gross power flows is applied to IEEE 6-bus system. The conventional algorithm is modified by considering only the changes at a load. The system is simulated by both of these algorithms to determine the sharing of generators in the loads, generator participations and allocation of losses to the loads, for the specified changes in loads. Using the conventional algorithm, from table III, it is seen that, the changed load is proportionally shared by the generators. But changes in losses are allocated to other loads also, although the percentage is less. Proportional sharing principle with modified approach can determine the sharing of generators in the changed load. It is seen from the table IV that changes in generator power correspond to the respective loads only. Similarly the losses due to changed load are allocated to the corresponding load bus only. This modified approach of computing generator participations is found to be more accurate and should be applied for continuously changing loads. It is seen from the figures 4 to 6 that the total generator participations for the changes in loads are almost same when obtained by conventional (NR Load Flow), the modified algorithms (Sensitivity Analysis) and the Power World Simulator 8.0. While considering the pricing issues, to compute the allocation of losses for the load changes, modified algorithm is more appropriate. In the deregulated environment, the new proposed method could be applicable to modify the transfer capability by controlling the generator participation factors. It would further assist in managing the network congestion.

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