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Allocation of Transmission Cost Using Power Flow Tracing Methods

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ABSTRACT

In the open access restructured power system market, it is necessary to develop an appropriate pricing scheme that can provide the useful economic information to market participants, such as generation, transmission companies and customers. Though many methods have already been proposed, but accurately estimating and allocating the transmission cost in the transmission pricing scheme is still a challenging task. This work addresses the problem of allocating the cost of the transmission network to generators and demands. In this work four methods using DC Power flow and AC power flow have been attempted. They are MW-Mile Method, MVA-Mile Method, GGDF method and Bialek Tracing method.MVA-Mile method and Bialek Tracing method applies AC power flow and considers apparent power flows. The purpose of the present work is to allocate the cost pertaining to the transmission lines of the network to all the generators and demands. A load flow solution is run and, the proposed method determines how line flows depend on nodal currents. This result is then used to allocate network costs to generators and demands. The technique presented in this work is related to the allocation of the cost to GENCO's TRANSCO's and DISCO's. A technique for tracing the flow of electricity of lines among generators with GGDF and Bialek upstream looking algorithm is proposed. With these methods correct economic signals are generated for all players. All these methods are tested on IEEE 14 bus system.

I. INTRODUCTION

De regulation of the electricity industry has been taking place in many countries. It will bring about significant changes in generation and transmission patterns. The pricing of wheeling services is an unresolved issue. The cost of power wheeling includes fixed and variant costs. The fixed cost means that it does not increase or decrease with the change of wheeling power. On **the** contrary, the variant cost means that it changes with the variation of wheeling services. This research will focus on variant cost only.

In Eighties, almost all electric power utilities throughout the world were operated with an organizational model in which one controlling authority—the utility—operated the generation, transmission, and distribution systems located in a fixed geographic area and it refers to as vertically integrated electric utilities(VIEU). With the example of the economic benefits to society resulting from the deregulation of other industries such as telecommunications and airlines, electric utilities are also introducing privatization in their sectors to improve efficiency. The aim of deregulation is to introduce an element of competition into electrical energy delivery and thereby allow market forces to price energy at low rates for the customer and higher efficiency for the suppliersIn a Deregulated Power Structure, Power producers and customers share a common Transmission network for wheeling power from the point of generation to the point of consumption

II. TRANSMISSION PRICING METHODS

An efficient transmission pricing mechanism should recover transmission costs by allocating the costs to transmission network users in a proper way. The study objectives and structures are main factors for choosing algorithms in the evaluation of transmission pricing. Regardless of the market structure, it is important to accurately determine transmission usage in order to implement usage-based cost allocation methods. To determining an accurate transmission usage could be difficult due to the nonlinear nature of power flow. This fact necessitates using approximate models, sensitivity indices, or tracing algorithms to determine the contribution to the network flows from individual users or transactions.

III. PERFORMANCE OF MW-MILE METHOD

The MW-Mile method is an embedded cost method that is also known as a line-by-line method because it considers, in its calculations, changes in MW-Transmission flow and transmission line lengths in Miles. The method calculates charges associated with each wheeling transaction based on the transmission capacity use as a function of the magnitude of transaction power, the path followed by transacted power, and the distance traveled by transacted power.

The MW-Mile method is also used in identifying transmission paths for a power transaction. As such, this method requires dc-power flow calculation. The MW-Mile method is the first pricing strategy proposed for the recovery of fixed transmission costs based on the actual use of transmission network. The method guarantees the full recovery of fixed transmission costs and reasonably reflects the actual usage of transmission systems.

a) Algorithm for MW Mile method

Step1: Run the DC load flow for base case data.
Step2: Evaluate the line flows of each line and slack bus power in the given power system.
Step3: Read the line lengths in miles of the system.
Step4: Fix the unit rate i.e.,$/MW/Mile
Step5: Evaluate the transmission charges of each line by multiplying the line flows with unit rate and line lengths.
Step6: Evaluate total cost of each generator.
Step7: Evaluate the transaction cost for each generator.

$$\textit{transaction cost}\,(\$) = \frac{\text{total transmision cost of each generator}}{\text{total transmission cost of all generators}}$$

***total line cost**

Step8: Calculate cost ($/MW) for each generator.

$$\textit{per unit cost}\,(\$/Mw) = \frac{\text{each transaction cost}}{\text{power generation of generator}}$$

IV. PERFORMANCE OF MVA-MILE METHOD

In all the above methods reactive power changes in the transmission facilities caused by transaction party are not considered. MVA-Mile method can take into consideration both active and reactive power loading of the transmission network caused by the transaction and hence allocates embedded cost of transmission accordingly. Hence a transaction causing more reactive power loading will be allocated more cost than other transactions. Generally, the MW-Mile and MVA-Mile methods are known as distance based methodologies.

a) Algorithm for MVA Mile method

Step1: Run the AC load flow i.e., Newton Raphson load flow for base case data.
Step2: Evaluate the line flows of each line and slack bus power in the given power system.
Step3: Read the line lengths in miles of the system.
Step4: Fix the unit rate i.e.,$/MVA/Mile
Step5: Evaluate the transmission charges of each line by multiplying the line flows with unit rate and line lengths.
Step6: Evaluate total cost of each generator.
Step7: Evaluate the transaction cost for each generator.

$$\textit{transactioncost}\,(\$) = \frac{\text{totaltransmisioncostofeachgenerator}}{\text{totaltransmissioncostofallgenerators}}$$

***total line cost**

Step8: Calculate cost ($/MVA) for each generator.

$$\textit{perunitcost}(\$/MW) = \frac{\text{eachtransactioncost}}{\text{powergenerationofgenerator}}$$

V. PERFORMANCE OF GGDF

Distribution factors are calculated based on linear load flows. In general, generation distribution factors have been used mainly in security and contingency analyses. They have been used to approximately determine the impact of generation and load on transmission flows. In recent years, these factors are suggested as a mechanism to allocate transmission payments in restructured power systems, as these factors can efficiently evaluate transmission usage. To recover the total fixed transmission costs, distribution factors can be used to allocate transmission payments to different users. By using these factors, allocation can be attributed to transaction-related net power injections, to generators, or to loads. The distribution factors are given as follows:

a) Generation Shift Distribution Factors (GSDFs or *A* factors)

GSDFs or *A* factors provide line flow changes due to a change in generation. These factors can be used in determining maximum transaction flows for bounded generation and load injections.

GSDFs or *A* factors are defined as

$$\Delta F_{l-k} = A_{l-k,i}\Delta G_i$$

$$\Delta G_r = -\Delta G_i$$

Where

ΔF_{l-k} = Change in active power flow between buses l and k

$A_{l-k,i}$ =*A* factor (GSDF) of a line joining buses l and k corresponding to change in generator at bus i

ΔG_i =change in generation at bus *i*, with the reference bus excluded

ΔG_r =change in generation at the reference bus (generator) r

$A_{l-k,i}$ is calculated using the definition of a reactance matrix and the dc load flow approximation. The *A* factor measures the incremental use of transmission network by generators and loads (consumers). We also notice that GSDFs are dependent on the selection of reference (marginal) bus and independent of operational conditions of the system.

b) Generalized Generation Distribution Factors (GGDFs or *D* factors)

They determine the impact of each generator on active power flows; thus they can be negative as well. Since GGDFs are based on the dc model, they can only be used for active power flows. GGDFs or*D*factors are defined as

$$F_{l-k} = \sum_{i=1}^{N} D_{l-k,i} G_i$$

Where

$$D_{l-k,i} = D_{l-k,r} + A_{l-k,i}$$

$$D_{l-k,r} = (F^0_{l-k} - \sum_{\substack{i=1 \\ i \neq r}}^{N} A_{l-k,i} G_i) / \sum_{i=1}^{N} G_i$$

F_{l-k} = total active power flow between buses land k

F^0_{l-k} =power flow between buses land k from the previous iteration

$D_{l-k,i}$ = *D* factor (GGDF) of a line between buses land k corresponding to generator at bus 'i'

$D_{l-k,r}$ = GGDF of a line between buses *l* and *k* due to the generation at reference bus 'r'

G_i =total generation at bus 'i'

c) Algorithm for transmission cost allocation using dc load flow

Step1: Run the DC load flow for base case data.
Step2: Evaluate the line flows of each line and slack bus power in the given power system.
Step3: Read the line lengths in miles of the system.
Step4: Fix the unit rate i.e.,$/MW/Mile
Step5: Calculate A factors.
Step6: Calculate D factors using A factors.
Step7: Evaluate the tracing of line flow of each line.
Step8: Evaluate total cost of each generator.
Step9: Evaluate the transaction cost for each generator.

$$\textit{transactioncost}\ (\$) = \frac{\text{total transmision cost of each generator}}{\text{total transmission cost of all generators}}$$

*total line cost
Step10: Calculate cost ($/MW) for each generator.

$$\textit{perunitcost}(\$/Mw) = \frac{\text{each transaction cost}}{\text{power generation of generator}}$$

VI. BIALEK TRACING METHOD

Tracing methods determine the contribution of transmission users to transmission usage tracing methods may be used for transmission pricing and recovering fixed transmission costs. In this section, we will discuss Bialek' stracing method. And it is generally based on the proportional sharing principle.

a) Proportional Sharing Principle Method (PSP-Method)

Proportional Sharing Principle method determines the contribution of transmission users to transmission usage. This method may be used for transmission pricing and recovering fixed transmission costs.

In this method, it is assumed that nodal inflows are shared proportionally among nodal outflows. This method uses a topological approach to determine the contribution of individual generators or loads to every line flow based on the calculation of topological distribution factors. This method can deal with both dc-power flow and ac power flows; that is, it can be used to find contributions of both active and reactive power flows. Proportional Sharing Principle method considers:

- Two flows in each line, one entering the line and the other exiting the line.
- Generation and load at each bus.

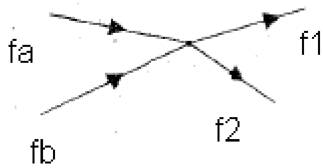

Figure 1. Illustration of Proportional Sharing

The main principle used to trace the power flow will be that proportional sharing. This principle follows the Kirchhoff current law as shown in Fig.1. The figure shows four lines connected to a node. The outflows *(f_1 and f_2)* can be represented in terms of the inflows *(f_a and f_b)*; in other words, we can determine how much of f1 comes from f_a and how much of $f_1$comes from f_b,

$$f_1 = f_1 \frac{f_a}{f_a + f_b} + f_1 \frac{f_b}{f_a + f_b} \quad (1)$$

$$f_2 = f_2 \frac{f_a}{f_a + f_b} + f_2 \frac{f_b}{f_a + f_b} \quad (2)$$

a) Performance of Bialek's Tracing Method

In Bialek's tracing method, it is assumed that nodal inflows are shared proportionally among nodal outflows. This method uses a topological approach to determine the contribution of individual generators or loads to every line flow based on the calculation of topological distribution factors. This method can deal with both dc power flow and ac power flows; that is, it can be used to find contributions of both active and reactive power flows.

In this method algorithm works, we define the *gross demand* as the sum of a particular load and its allocated part of the total transmission loss. The total gross demand in a system is equal to the total actual generation. Topological distribution factors are given by the following equation in which $D_{ij,k}^{g}$ refers to the k^{th} generator's contribution to line *i–j* flow.

$$p_{ij}^{g} = \frac{p_{ij}^{g}}{p_{i}^{g}} \sum_{k=1}^{n} [A_u^{-1}]_{ik}\, p_{Gk} = \sum_{k=1}^{n} D_{ij,k}^{g}\, p_{Gk;}\, j \in \alpha_i^d \qquad +$$

Where

$$p_i^g = \sum_{j \in \alpha_i^u} \left| p_{ij}^g \right| + p_{Gi;} \qquad i=1,2\ldots..,n$$

$$[\boldsymbol{A_u}]_{ij} = \begin{cases} 1 & i=j \\ -\dfrac{|p_{ji}|}{p_j} & j \in \alpha_i^u \\ 0 & \text{otherwise} \end{cases}$$

And

p_{ij}^{g} = An unknown gross line flow in line i-j

p_{i}^{g} = an unknown gross nodal power flow through node i

A_u = upstream distribution matrix

p_{Gk} = generation in node k

α_i^d = set of nodes supplied directly from node i

α_i^u = set of busses supplying directly bus i

$D_{ij,k}^{g}$ = Topological distribution factors

The gross power at any node is equal to the generated power at the node plus the imported power flows from neighboring nodes. The total usage of the network by the *k*th generator (*UGK*) is calculated by summing up the individual contributions (multiplied by line weights) of that generator to line flows. This is given by:

$$U_{Gk} = \sum_{i=1}^{n} \sum_{j \in \alpha_i^d} w_{ij}^g D_{ij,k}^g\, p_{Gk} = p_{Gk} \sum_{i=1}^{n} \left\{ \frac{[A_u^{-1}]_{ik}}{p_i^g} \sum_{j \in \alpha_i^d} C_{ij} \right\}$$

Where

C_{ij} = total supplement charge for the use of line i–j

w_{ij}^{g} = charge per MW of each line i–j

The method can be summarized as follows:

1. Solve power flow (either ac or dc) and define line flows (inflows and outflows).
2. If losses exist, allocate each line's loss as additional loads to both ends of the line.
3. Find matrix $\boldsymbol{A_u}$.
4. Define generation vector $\boldsymbol{P_G}$
5. Invert matrix $\boldsymbol{A_u}$(i.e., A_u^{-1})
6. Find gross power $\boldsymbol{P_g}$ using $\boldsymbol{P_g}$= A_u^{-1} ***PG***. The gross power at node *i* is given as

$$p_i^g = \sum_{k=1}^{n} [A_u^{-1}]_{ik}\, p_{Gk}$$

7. The gross outflow of line *i–j*, using the proportional sharing principle, is given as

$$p_{ij}^{g} = \frac{p_{ij}^{g}}{p_{i}^{g}} p_i^g = \frac{p_{ij}^{g}}{p_{i}^{g}} \sum_{k=1}^{n} [A_u^{-1}]_{ik}\, p_{Gk} = \sum_{k=1}^{n} D_{ij,k}^{g}\, p_{Gk;}$$

Where

$$D_{ij,k}^{g} = \frac{p_{ij}^{g}[A_u^{-1}]_{ik}}{p_i^g} \cong \frac{p_{ij}[A_u^{-1}]_{ik}}{p_i}$$

and *j*is the set of nodes supplied directly from node *i*.

The *downstream-looking* method that allocates usage charges to individual loads would use the same methodology. Allocation of generators to branch flows as, (Up Stream)

$$P_{mk} = \frac{P_{ij}}{P_i} \sum_{k=1}^{n} [A_{u(i,k)}]^{-1} P_{Gk} \quad \text{for} \quad j \in \alpha_i^d$$

Where,

α_i^d = set of nodes supplied directly from node i

m = Branches

k = Buses (Generator Bus)

P_i = Nodal power

P_{Gk} = Generating power at bus k

P_{ij} = Branch power flow (i∈ upstream, j∈ downstream)

b) Algorithm for bialek method

Step1: Run the AC load flow for base case data.
Step2: Evaluate the line flows of each line and slack bus power in the given power system.
Step3: Read the line lengths in miles of the system.
Step4: Fix the unit rate i.e.,$/MVA/Mile
Step6: Evaluate the tracing of line flow of each line with Bialek method.
Step8: Evaluate total cost of each generator.

Step9: Evaluate the transaction cost for each generator.

$$transactioncost\ (\$) = \frac{totaltransmisioncostofeachgenerator}{totaltransmissioncostofallgenerators}$$

*total line cost

Step10: Calculate cost ($/MW) for each generator.

$$perunitcost(\$/MW) = \frac{eachtransactioncost}{powergenerationofgenerator}$$

VII. RESULTS

6.1Transmission cost allocation for MW-Mile method (14 bus system)

Line k	Line cost $C_kL_k(\$)$	**MW-Mile method**	
		$C_kL_kMW_{1,k}$	$C_kL_kMW_{2,k}$
1	59.17	4375.0468	4375.0468
2	223.04	7931.2383	7931.2383
3	197.97	6933.9228	6933.9228
4	176.32	4868.756	4868.756
5	173.88	3556.1915	3556.1915
6	171.03	2065.1668	2065.1668
7	42.11	1312.5645	1312.5645
8	0	0	0
9	0	0	0
10	0	0	0
11	198.9	627.0084	627.0084
12	255.81	965.0617	965.0617
13	130.27	1109.4895	1109.4895
14	0	0	0
15	0	0	0
16	84.5	261.7488	261.7488
17	270.38	1341.242	1341.242
18	192.07	269.355	269.355
19	199.88	144.4277	144.4277
20	348.02	866.3673	866.3673
Total	2723.35	36627.587916	36627.587916
Total cost (\$)		73255.175833	
Each transaction cost (\$)		1361.675	1361.675
Cost(\$/MW)		6.2177	34.0419

6.2 Transmission cost allocation for MVA-Mile method (14 bus system)

Line k	Line cost $C_kL_k(\$)$	**MVA-Mile method**	
		$C_kL_kMVA_{1,k}$	$C_kL_kMVA_{2,k}$
1	59.17	4680.9	4680.9
2	223.04	8431.0044	8431.0044
3	197.97	7260.6853	7260.6853
4	176.32	4948.772	4948.772
5	173.88	3611.3018	3611.3018
6	171.03	2014.3851	2014.3851
7	42.11	1321.508	1321.508
8	0	0	0
9	0	0	0
10	0	0	0
11	198.9	815.321	815.321
12	255.81	1046.638	1046.638
13	130.27	1248.831	1248.831
14	0	0	0
15	0	0	0
16	84.5	282.21	282.21
17	270.38	1362.2593	1362.2593
18	192.07	397.638	397.638
19	199.88	178.554	178.554
20	348.02	1030.715	1030.715
Total	2723.35	38630.728925	38630.728925
Total cost (\$)		77261.457849	
Each transaction cost (\$)		1361.675	1361.675
Cost(\$/MW)		5.8593	34.0419

6.3 Transmission cost allocation for Bialek Tracing method (14 bus system)

Line k	Line cost $C_kL_k(\$)$	**Bialek Tracing method**	
		$C_kL_kMVA_{1,k}$	$C_kL_kMVA_{2,k}$
1	59.17	9306.54768091456	0
2	223.04	16788.6561615581	0
3	197.97	11817.2175822764	3005.30245292671
4	176.32	8033.77367195513	2043.11374944945
5	173.88	5927.92280275337	1507.56308038148
6	171.03	3629.63732400833	567.394706472539
7	42.11	2440.35939619643	193.466298802699
8	0	0	0
9	0	0	0
10	0	0	0
11	198.9	1564.28924124857	124.013393368590
12	255.81	1982.86004427152	157.196761430663
13	130.27	2292.03191693644	181.707224107434
14	0	0	0
15	0	0	0
16	84.5	345.759053929850	54.0499888562143
17	270.38	2137.75762839521	334.180044394415
18	192.07	852.085166181602	67.5514285407198
19	199.88	359.889894521164	28.5312753433056
20	348.02	2149.11201861689	170.376850476306
Total	2723.35	69627.8995837636	8434.44725455052
Total cost (\$)		78062.3468383141	
Each transaction cost (\$)		2429.09863732631	294.251362673690
Cost(\$/MW)		10.4452	7.3563

6.4 Transmission cost allocation for GGDF method (14 bus system)

line k	Line cost $C_kL_k(\$)$	**GGDF method**	
		$C_kL_kMW_{1,k}$	$C_kL_kMW_{2,k}$
1	59.17	9075.84556415045	325.751962449720
2	223.04	14634.5618484348	1227.91478291001
3	197.97	11543.0067402592	2324.83902489429
4	176.32	7892.39033335323	1845.12176505375
5	173.88	5558.71628428438	1553.66674535973
6	171.03	3334.27218782363	796.061478922856
7	42.11	2105.73341084674	519.395657916138
8	0	0	0
9	0	0	0
10	0	0	0
11	198.9	1078.76529548173	175.251619319012
12	255.81	1635.51420945752	294.609281474690
13	130.27	1882.47743819539	336.501595082820
14	0	0	0
15	0	0	0
16	84.5	434.823605131986	88.6741108023431
17	270.38	2251.65953424213	430.824621053253
18	192.07	437.725420656629	100.984978165783
19	199.88	246.963228737876	41.8923136081303
20	348.02	1486.42212899937	246.312590706619
Total	2723.35	63598.8772300551	10307.8025277191
Total cost (\$)		73906.6797577742	
Each transaction cost (\$)		2343.52297887190	379.827021128102
Cost(\$/MW)		10.7010	9.4957

VIII. CONCLUSION

In this paper embedded cost based methods of transmission pricing have been discussed. Different cost components incurred by the transmission transaction were explained. Case studies of MW-Mile method, MVA-Mile method, Distribution factors method and Bialek tracing method for 6bus, IEEE14bus are presented. Bialek tracing method is the best way of transmission pricing, among all embedded cost based methods. It is observed that combination of incremental and embedded cost based methods could result in the recovery of true transmission system costs.

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