Comparison of Flow Based Methods of Transmission Embedded Cost Allocation Under Deregulated Power System Condition

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Abstract— a common feature to all restructuring efforts is to provide non-discriminatory transmission access to producers and consumers. Transmission access rules must be neutral, economically efficient, assure optimal utilization of the transmission network, and allow for full recovery of stranded costs. So transmission pricing is a very important part in electricity market design. Accurately estimating and allocating the transmission cost in the transmission pricing scheme still remains challenging task. This paper gives an overview of different cost incurred in transmission pricing using Bialek Tracing method & Distribution factor method (GGDFs).It mainly focused on determining the embedded transmission cost through Generator side by various methods and compared the result for 12-Bus system.

Key words: Power flow tracing, Usage allocation, Transmission pricing, Proportional sharing principle.

I. INTRODUCTION

Generation, transmission and distribution are three basic components of electrical power industry. Transmission system provides vital link between generation and distribution. Power industry is passing through era of drastic change in its structure and operation. Earlier vertically integrated power system is now converted to deregulated industry in which generation, transmission and distribution are now separate entities [1]. In deregulated power system energy trading take place through pool market or bilateral contracts or power exchange. While the former vertically integrated utility charged one price for power delivery, today every single service has to be priced separately.

Transmission system should provide equal access to all generators and loads without any discrimination to promote fair competition. Due to high capital cost and certain security issues, transmission is natural monopoly industry. The objective of transmission pricing is to recover all or part of existing and new cost of transmission system. Open access customers use electrical 'highway' hence they should pay toll in form of transmission price. The electricity tracing method would make it possible to charge the generators or consumers on the basis of actual transmission facility used.

Electricity is different from other commodities because it cannot be stored in bulk, hence demand and supply must match on real time basis [2]. Electrical power cannot be routed through desired path, it obeys lows of Physics. Due to nonlinear nature of power flow equations, it is very difficult to decompose the network flows into components associated with individual customer. Change of voltage/flow at one node lead to change in voltage/flow at all other nodes. Because of heavy investment required in transmission facility transmission owner cannot recover its revenue with only marginal pricing [3].

Transmission pricing consists of following components [5]:

A. Embedded (Rolled in) Cost

1) Investment cost(returns and depreciation of capital equipment) ,
2) Administrative and general cost including scheduling and coordination services, billing and accounting staff and salaries
3) Investment for operation and maintenance
4) Cost of voltage control and reactive power support.

B. Incremental (Marginal) Cost

Cost of supplying an additional 1 MW of power in a transaction. It includes

1) Operating Cost: Cost due to generation rescheduling and redispatches to minimise system losses, relieve congested transmission line and enhance the system voltage profile.
2) Opportunity Cost: Benefits of all transactions that the utility forgoes due to operating constraints like congestion.
3) Reinforcement cost: Capital cost of new transmission facilities needed to accommodate the transaction.

Transmission pricing should possess following desirable characteristics:

1) Promote the efficient day to day market of the bulk power market.
2) Indicate locational advantages for investment in generation and demand
3) Indicate need for investment in the transmission system
4) Compensate the owner for existing transmission assets
5) Be simple and transparent
6) Be politically implementable

II. TRANSMISSION PRICING METHODS

Mainly three types of pricing paradigms are considered: Rolled in, Marginal and Composite.

Methods in rolled in pricing paradigms are [7]:

1) Postage stamp method
2) Incremental postage stamp method
3) Contract path method
4) Distance based MW-mile method
5) MVA mile method
6) Counter flow method
7) Distribution factor method
8) Point of connection tariff

A. Postage stamp method [8]:

Postage-stamp rate method is traditionally used by electric utilities to allocate the fixed transmission cost among the users of firm transmission service. In postage stamp method cost is proportional to MW only. Same price per MW is applied irrespective of distance in the same control area. This method does not require power flow calculations and is independent of the transmission distance and network configuration. The magnitude of the transacted power for a particular transmission transaction is usually measured at the time of system peak load condition. The main purpose of using this methodology is the entire system is considered as a centrally operated integrated system. This method is simpler. Since this method ignores the actual system operation, it is likely to send incorrect economic signal to transmission customers. If transaction crosses a control area, postage stamp of both areas should be paid. This effect is called pancaking.

B. Incremental postage stamp method [9]:

It is introduced to reduce effect of pancaking, when more control areas are involved. A region is divided into smaller zones and each sub zone has stamp of its own. So that physically nearby nodes have to pay lesser cost compared to far apart nodes.

C. Contract Path Method:

In this method charging is done on the basis of predefined contract path. Contract path is formed by the shortest route formed by series of transmission lines between contracting nodes. Contract path is not necessarily a physical power flow path hence this method gives doubtful economic signals.

D. Distance based MW-mile method:

It is load flow based method. It calculates charges associated with each wheeling transaction based on the transmission capacity use. It takes into account following factors:

1) Magnitude of transacted power
2) Path followed by transacted power
3) Distance travelled by transacted power

Charges are calculated as follows:

$$TC_t = TC * \frac{\sum_{k\in K} C_k L_k MW_{t,k}}{\sum_{t\in T}\sum_{k\in K} C_k L_k MW_{t,k}}$$

Where

TC_t = Cost alloted to transaction t

TC=Total cost of all lines in Rs.

L_k = Length of line k in mile

C_k = Cost per MW per unit length of line k

$MW_{t,k}$ = Flow in Line k due to transaction t

T=Set of Transactions

K=Set of Lines

E. MVA mile method:

It includes charges for reactive power flow in addition to charges for real power flow. It is better approach to measure use of transmission resources.

F. Counter Flow Method:

In this method transmission users are charged or credited on whether their transaction cause flows or counter flows with regard to direction of net flows.

G. Distribution Factor Method [10]:

It determines effect of generation and loads on transmission flows. Generation shift distribution factor (GSDF or A factor) decides the line flow changes due to a change in generation. Generalized generation distribution factor (GGDF or D factors) decides impact of each generator on active power flow in a line. Generalized load distribution factor (GLDF or C factors) determine contribution of each load to line flows.

H. Point of Connection Tariff:

Here pricing mechanism is such that generator/load pays a single price per MW, depending on their point of connection. The price is decided on the basis of average participation or marginal participation method. It enables competition. Tariffs of different networks are coordinated and losses are also included in the cost. The tariff paid at any connection point gives access to the national interconnected system and a subsystem including distribution systems.

III. POWER TRACING

Power tracing is a tool applied on power flow snapshot that provides complete power audit information like:

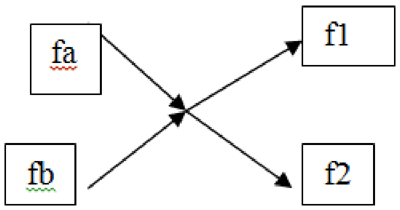
1) Share of loads in generation
2) Generators' contribution in loads
3) Decomposition of transmission line flows into generators and load components
4) Loss allocation to generators and loads

The usage allocation calculated by power tracing is always positive and payment is to be unidirectional [11]. The prerequisites for power flow tracing are state estimation solution or power flows over lines, injections at generators and load buses, network topology. There are two versions of power tracing: upstream looking algorithm and downward looking algorithm. In upstream looking algorithm the transmission usage charge is allocated to individual generators and losses are apportioned to loads.

There are two types of tracing approach. Simultaneous Equation Approach requires matrix inversion and easy to code. It converges in presence of circular flows also. Bialek's tracing and Kirschen's method are using this approach. In Graph Theoretic Approach matrix inversion is not required but it fails in the presence of loop flows.

IV. PROPORTIONATE SHARING PRINCIPLE

Proportionate sharing principle is based on Kirchhoff's current low and it is topological in nature [11]. It is the main principle used for power tracing. It assumes that network node is perfect 'mixture' of incoming flows so that it is impossible to tell which particular electron goes into which particular outgoing line. Figure 1 show four lines connected to a node, two incoming flows fa, fb and two outgoing flows f1, f2



$$f1 = f1\frac{fa}{fa+fb} + f1\frac{fb}{fa+fb}$$

$$f2 = f2\frac{fa}{fa+fb} + f2\frac{fb}{fa+fb}$$

V. USAGE ALLOCATION BASED PRICING

Real power flow on all network lines are calculated using load flow algorithm. Using Bialek's tracing method transmission line usage by each generator is found out. The magnitude of MW flow found using Bialek's tracing method on every line contributed by different generator is multiplied by its length and predefined weighing factor reflecting the cost per unit capacity of line. Finally, the cost allocated to each generator for a particular line is calculated using the following equations [1].

$$P_{ij}^{g} = \frac{P_{ij}^{g}}{P_i^g}\sum_{k=1}^{n}[Au^{-1}]_{ik}P_{Gk} = \sum_{k=1}^{n} D_{ij}{}^{g}{}_{k} P_{Gk}; j \in \alpha_i^d$$

Where,

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

$$[Au]_{ij} = 1; i = j$$

$$[Au]_{ij} = -\frac{|P_{ji}|}{P_j}; j \in \alpha_i^u$$

$$[Au]_{ij} = 0; otherwise$$

P_{ij}^g = an unknown gross line flow in line i-j

Pi^g = an unknown gross nodal flow power through node i

Au = 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 buses supplied directly bus i

$D_{ij}{}^{g}{}_{k}$ = Topological Distribution Factors,kth generators contribution to line i-j flow

The gross power at any node is equal to the generated power at the nodes plus the imported power flows from neighbouring nodes. The total usage of the network by k[th] generator U_{Gk} is calculated by summing up the individual contributions (multiplied by line weights) of that generators to line flows. This is given by:

$$U_{Gk} = \sum_{i=1}^{n}\sum_{j\in\alpha_i^d} w_{ij}{}^{g} D_{ij}{}^{g}{}_{k} P_{Gk}$$

Where, Wij^g =charge per MW of each line i-j

Above equation can be implemented using following steps:

1) Solve power flow and define line flows
2) If losses exist, allocate each line's loss as additional loads to both ends of line
3) Find upstream distribution matrix Au
4) Define generation vector P_G
5) Invert matrix Au (i.e. Au^{-1})
6) Find gross power Pg using $Pg=Au^{-1} P_G$
7) Find the gross outflow of line i-j, using proportional sharing principle.
8) Total usage of the network by the k[th] generator (U_{Gk}) is calculated by summing up the individual contributions of that generator to line flows.

The flow chart for transmission price algorithm is presented in figure 2.

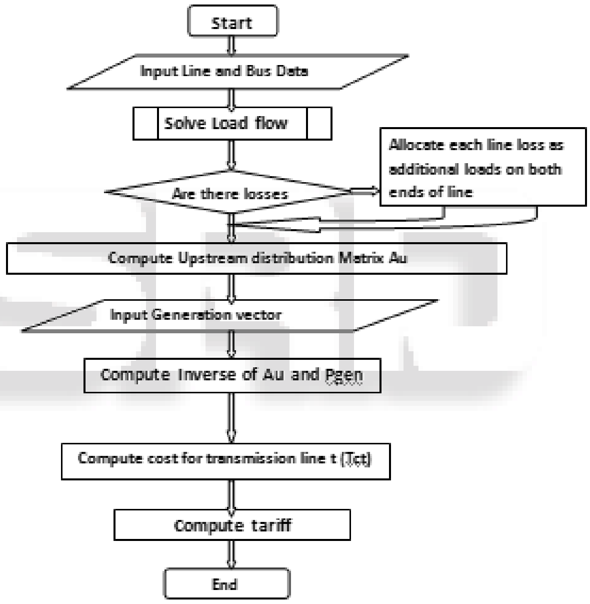


Fig. 2: Transmission pricing flowchart

A. *Generation Shift factors (A factors)*

Which provide line flow changes due to a change in generation (without changing of overall of system power balance). They depend on the selection of reference bus, but are independent of the system.

$$\begin{cases} \Delta P_{\ell,jk} = A_{jk,i} \cdot \Delta P_{gi} \\ \Delta P_{ge} + \Delta P_{gi} = 0 \end{cases} \qquad (1)$$

Where, $\Delta P_{l,jk}$ = Change in active power through network element jk.

$A_{jk,i}$ = Generation Shift Factors through network element jk corresponding to generation at bus i.

ΔP_{gi} = Change in generation at bus i,

ΔP_{ge} = Change in generation at slack bus.

The A factors are determined by DC power flow (which means the neglecting of longitudinal resistance, transversal susceptances and conductance's of network elements, neglecting reactive power flow and considering all voltages equal to unity).

$$P = -B * \delta \quad \text{.......... (2)}$$

Where, ***P*** – vector of injected power in system buses;

δ – Vector of nodal voltage angles,

B – Nodal susceptances matrix.

The voltage angle result:

$$\delta = B^{-1} * P \quad \text{................ (3)}$$

This means

$$\delta_j = -\sum_{i \in N}(b_{ji}^{-1} * P_i),\ j \epsilon N \quad \text{........... (4)}$$

With the same condition, the relation (2) becomes:

$$P_l = -B_l * \delta_l \quad \text{.................. (5)}$$

Where,

P_l= vector of active power through network elements,

δ_l= vector of difference of voltage angles from ends of network element jk,

B_l= diagonal matrix of longitudinal susceptances of network element *jk*.

Writing in Extended variant the relation (5) lead to:

$$P_{ljk} = -B_{ljk} * (\delta_j - \delta_k),\ jk \epsilon R \quad \text{........... (6)}$$

Using the relation (4), relation (6) becomes:

$$P_{ljk} = B_{ljk} * [\sum_{i \in N}(b_{ji}^{-1} * P_i) - \sum_{i \in N}(b_{ki}^{-1} * P_i)]$$

$$= B_{ljk} * \sum_{i \in N}[(b_{ji}^{-1} - b_{ki}^{-1}) * P_i],\ jk \epsilon R$$

.... (7)

Relation (7) is linear and modification of power through network element, $\Delta P_{lj,k}$ due to injected power in bus *i*, ΔP_i can be expressed:

$$\Delta P_{ljk} = B_{ljk} * (b_{ji}^{-1} - b_{ki}^{-1}) * \Delta P_i \quad \text{............. (8)}$$

Comparing the relations (8) and (1), the expression of A factors for network element *jk*, corresponding to the change of generated power in bus *i*:

$$\boldsymbol{A_{jk,i}} = \boldsymbol{B_{ljk}} * (\boldsymbol{b_{ji}^{-1}} - \boldsymbol{b_{ki}^{-1}}),\ jk \epsilon R,\ i \epsilon N \quad \text{....................... (9)}$$

B. Generalized Generation Distribution Factors (D factors)

determine the impact of each generator on active power flow through network elements.

$$P_{l,jk} = \sum_{i \in N}(D_{jk,i} * P_{gi}),\ jk \epsilon R \quad \text{.................. (10)}$$

Where,

$P_{l,jk}$ = active power flow through network element *jk*,

P_{gi} = generated power in bus *i*,

$D_{jk,i}$ = D factor of the network element *jk*, corresponding to the generated power

$$D_{jk,i} = D_{jk,e} + A_{jk,i}$$

$$= \frac{P_{jk}^{0} - \sum_{i \in N}(A_{jk,i} * P_{gi})}{\sum_{i \in N} P_{gi}} + A_{jk,i} \quad \text{……..... (11)}$$

Where,

P_{jk}^{O} = power flow through network element *jk* from the previous iteration,

e = the Slack bus.

D factors reflect the utilization rate of electricity transmission capacity depending on generated power (unlike the A factors, which indicated the incremental rate of use). They depend on network elements and operating regime and not on the choice of reference bus.

VI. RESULTS AND DISCUSSION

The test system with 12-buses is shown in figure. Bus1 is the slack bus. The network elements parameters are presented in table1. Table 2 contains initial data of buses and the result is shown in Table 3.

Line No.	Bus i	Bus j	R (p.u)	X (p.u)	B (p.u)	L (K.M)
1	1	2	0.00415	0.025	0.04	30
2	1	6	0.00969	0.05838	0.0949	70
3	1	7	0.0166	0.1	0.1613	120
4	2	8	0.00415	0.025	0.04	30
5	3	7	0.00526	0.03169	0.0511	38
6	8	3	0.00623	0.03752	0.06	45
7	5	4	0.0083	0.05	0.08	60
8	7	4	0.00387	0.02335	0.0376	28
9	11	4	0.0083	0.005	0.08	60
10	6	5	0.00554	0.03335	0.5379	40
11	6	9	0.00415	0.025	0.04	30
12	6	11	0.00692	0.0417	0.06725	50
13	10	7	0.00554	0.03335	0.05379	40
14	9	10	0.00277	0.01667	0.0269	20

15	10	11	0.00692	0.0417	0.06725	50
16	10	12	0.00484	0.02912	0.047	34
17	11	12	0.00346	0.0208	0.0336	25

Table. 1: Line data

Bus	Bus Type	Voltage	Δ	P_G	Q_G	P_L	Q_L
1	1	1.05	0	490.52	285.79	-	-
2	2	1	0	340.49	-122.86	300	35
3	2	1	0	350	13.32	-	-
4	2	1	0	293.72	41.82	-	-
5	2	1	0	600	-15.85	350	25
6	2	1	0	200	126.55	230	60
7	3	0.989	0	-	-	350	38
8	3	0.988	0	-	-	300	25
9	3	0.979	0	-	-	208	30
10	3	0.977	0	-	-	170	20
11	3	0.979	0	-	-	210	23
12	3	0.974	0	-	-	130	15

Table. 2: Bus data

Here,

1 – Slack Bus

2 – PV Bus

3 – PQ Bus

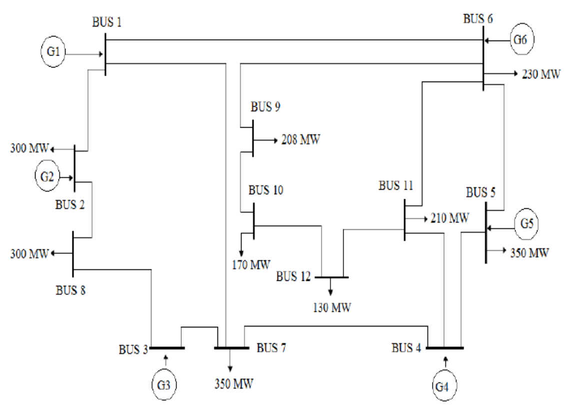


Fig. 3: 12Bus system

			INJECTION		GENERATION		LOAD	
Bus	Voltage (P.U)	Angle	MW	MVAR	MW	MVAR	MW	MVAR
1	1.05	0	489.694	162.467	489.694	162.467	0	0
2	1.03	-1.9237	40.49	-14.636	340.49	20.364	300	35
3	1.01	-2.1594	350	6.709	350	6.709	0	0
4	0.99	-4.1455	293.72	-56.459	293.72	-56.459	0	0
5	1.01	-2.6951	250	52.366	600	77.366	350	25
6	0.99	-6.2981	-30	-49.82	200	10.18	230	60
7	0.9884	-6.4595	-350	-38	0	0	350	38
8	1.0115	-4.492	-300	-25	0	0	300	25
9	0.9732	-9.9763	-208	-30	0	0	208	30
10	0.9732	-9.9086	-170	-20	0	0	107	20
11	0.974	-9.5396	-210	-23	0	0	210	23
12	0.966	-10.641	-130	-15	0	0	130	15
Total			25.904	-50.372	2273.904	220.628	2248	271

Table. 3: Newton Raphson Network Analysis

Line i-j	Line Cost $	GGDFs Method					
		$C_kL_kMW_{1'k}$	$C_kL_kMW_{2'k}$	$C_kL_kMW_{3'k}$	$C_kL_kMW_{4'k}$	$C_kL_kMW_{5'k}$	$C_kL_kMW_{6'k}$
1-2	60	10871	-9817	-2243	2058	5759	2265
1-6	140	26953	15041	5951	-2129	-12301	-5868
1-7	240	26499	12554	-2186	-5385	-3588	452
2-8	60	6995	7917	-5014	-267	1009	682
3-7	76	3950	6614	16740	-3283	-4738	-1142
8-3	90	-4678	-7832	11676	3888	5611	1352
5-4	120	-2600	-2690	-5032	-8899	24398	1591
7-4	56	-2173	-2208	-4062	7957	8678	1208
11-4	120	2058	2042	3671	9297	5802	-998
6-5	80	-4297	-2400	-955	2316	24347	-3523
6-9	60	3104	1529	-46	193	5845	3161
6-11	100	3754	1752	-406	-1918	5836	4114
10-7	80	3856	3799	6780	2499	-1175	-1788
9-10	40	278	-226	-1312	-946	1702	1375
10-11	100	-374	-450	-951	1165	1705	418
10-12	68	1006	807	1107	-186	3	86
11-12	50	660	380	186	976	1713	508
Total	1540	104106	78058	68318	53362	114210	30531
$\Sigma C_kL_k MW_{t'k}$		448585					
$T_{c,t}$		357.397	267.974	234.536	183.192	392.084	104.8

	7	4	8	7	9	134
Cost($/MW)	0.7298	0.7870	0.6701	0.6237	0.6535	0.5241

Table. 4: Allocation of Transmission Charges using GGDFs Method for 12-Bus System

Table 4 shows GGDFs method using AC power flow and Power transfer distribution factor for pricing and traces the actual power flow of each line flow by each participant from generator side.

Line i-j	Line Cost $	$C_k L_k MW_{1'k}$	$C_k L_k MW_{2'k}$	$C_k L_k MW_{3'k}$	$C_k L_k MW_{4'k}$	$C_k L_k MW_{5'k}$	$C_k L_k MW_{6'k}$
1-2	60	9317.46	0	0	0	0	0
1-6	140	29296.82	0	0	0	0	0
1-7	240	30033.6	0	0	0	0	0
2-8	60	3652.986	8009.514	0	0	0	0
3-7	76	1349.665	2959.267	14115.75	0	0	0
8-3	90	3011.846	6603.754	0	0	0	0
5-4	120	831.3567	0	0	0	5081.006	0
7-4	56	3963.445	663.8785	3166.71	0	0	1459.462
11-4	120	11049.78	0	0	0	0	10560.66
6-5	80	7853.783	0	0	0	0	7506.137
6-9	60	7142.501	0	0	0	0	6826.339
6-11	100	6850.621	0	0	0	0	6547.379
10-7	80	7165.183	0	0	0	0	6848.017
9-10	40	459.551	0	0	0	0	439.209
10-11	100	743.5567	0	0	0	0	710.6433
10-12	68	1465.918	0	0	0	0	1401.03
11-12	50	2255.316	0	0	0	0	2155.484
Total	1540	126443.4	18236.41	17282.46	0	5081.006	44454.36
$\Sigma C_k L_k MW_{t'k}$		211497.6272					
$T_{c,t}$		920.6856	132.7867	125.8406	0	36.9968	323.6902
Cost ($/MW)		1.88	0.39	0.36	0	0.06166	1.6184

Table. 5: Allocation of Transmission Charges using Bialek's Methods.

Table 5 shows the result using Bialek tracing method. This method, when applied to the real power flow result in two different algorithms applicable for two different purposes. The upstream-looking algorithm determines the gross power flow which shows how power output from each of the generators would be distributed between the loads if the network was lossless. . The downstream-looking algorithm shows how the actual demand of each of the loads would be distributed between individuals generators if the network was lossless.

		G1	G2	G3	G4	G5	G6
Bialek Tracing method: Total cost = 211497.6272							
Each Transaction Cost ($)	$T_{c,t}$	920.6856	132.7867	125.8406	0	36.9968	323.6902
Cost($/MW)	Cost ($/MW)	1.88	0.39	0.36	0	0.06166	1.6184
GGDF method : Total cost = 448585							
Each Transaction Cost ($)	$T_{c,t}$	357.3977	267.9744	234.5368	183.1927	392.0849	104.8134
Cost($/MW)	Cost($/MW)	0.7298	0.7870	0.6701	0.6237	0.6535	0.5241

Table. 6: Comparison of Bialek & GGDFs Method for 12-Bus system.

VII. CONCLUSION

In a restructured power environment, the transmission network is the key mechanism for generators to compete, supplying large users and distribution companies. One of the main objectives in electric industry's restructuring is to bring fairness and open access to the transmission network. For 12-Bus test system, the cost comparison Table 6 shows that overall transmission cost of the system is less in Bialek's method compared to GGDFs method but per unit MW cost is less in GGDFs method.

Bialek's tracing method creates only positive contributions to the line flows, thus the same charges occur under all MW-Mile approaches for counter-flows. Bialek's method can produce zero charges for some users. Where the Distribution Factors tracing method charges all users of the system, since all users utilize all transmission lines no matter how far they are located. However, it is very sensitive to system operating conditions and can produce relative different results for different operating points.

Bialek tracing method is the best way of transmission pricing among all Pricing methods.

Different results were derived because each tracing method is based on different principle. Moreover, it is not always clear which pricing method suits better a transmission network; it depends mostly on the generation and load location as well as the network topology itself. However, these pricing methods are able to full fill transmission pricing objectives: economic efficiency, non-discrimination, transparency and cost coverage and can be also applied to large power systems.

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