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Design and Allocation of Transmission Price in Electricity Markets

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ABSTRACT: This paper reports a novel design for Transmission Service Charge (TSC) and its allocation in electricity markets. The transmission sector of a multi-agent market is vulnerable to congestion, loss, voltage instability etc. In our design TSC penalizes such abuse and has a versatile and intuitive role in negotiation and coalition formation. We present an innovative method to elasticize TSC with respect to demand. It is one of the two instruments introduced to organize efficient trades in the market, modelled in a Cooperative Game Theory environment. We propose algorithms for construction and execution of the TSC via the elastic curve in compliance with the multi-objective functions of a coalition value. Illustration is on a five bus power system.

Keywords— Cooperative Game Theory (CGT), Electricity Markets, Transmission Price

I. INTRODUCTION

A separate transmission price became necessary when the integrated power system got restructured into electricity markets [1]. Despite present concerns on the economics of transmission pricing and equity in its allocation in power markets [2], differential prices as coalition values in a CGT milieu offers an attractive solution for related issues. We present a novel design for TSC, an innovative method to elasticize it with respect to demand, a new CGT model for negotiation and coalition formation and introduce two instruments to coordinate efficient trades in a complex sector. The proposal expects to trigger thoughts on power markets based on synergies of cooperation among Discos and competition between Gencos for overall efficiency and reduction of electricity prices.

Decentralized systems suffer from coordination losses if they rely only on prices and incentives, since not all constraints and scarce resources can be properly priced. In literature it is addressed via diverse pricing and allocation methodologies. Transmission price relates to the past (embedded), present (opportunity & operating) and future (reliability and planning) costs of transmission service. The assessment equitable allocation of TSC [3-14] has multifaceted research inputs and interesting features. Yet, none of the proposals address the special provisions that fulfil the idealized concepts of a market.

Transmission commerce is not linked with grid operation in the models surveyed because they consider only one issue at a time. Even so, an allocation is an imposition. Also, the sense of freedom and accountability inherent in a conscious coalitional choice is missing. Further, when Gencos who set energy prices also compete and share the payment of TSC, as seen in literature, it is not conducive to fair play or competition. Transmission pricing is a complicated issue in restructuring because power flow respects no contractual borders but those of Kirchhoff's laws and power balance equations. Gencos reach their customers through the same network and actions of any end-user affect all others significantly. Hence it is difficult to investigate the cost each participant is responsible for. The TSC design proposed here gives due consideration to such limitations and attempts to fulfil a set of general and market specific objectives.

II. DESIGN OF TRANSMISSION SERVICE CHARGE

In general, transmission pricing objectives are economic efficiency, network sufficiency and regulation. Market specific aims are that prices promote efficient day-to-day operation and signal location advantages for investment in generation, demand and in transmission. Other aims are non-discrimination, equity and cost coverage, price transparency, considerations for price variations and local specifics etc. in the evaluation of TSC:

A. Functional requirements of TSC

Some analysis is made here as a prelude to synthesizing desirable functions into TSC and prior to delivering it as a financial instrument suitable for a CGT environment.

- Power flow in lines is central to all issues [2] of transmission sector restructuring. We view technical issues like line loss, congestion, loop-flows etc., and real and long time analytic and planning needs- as consequences of multi-agent interactions on lines. Hence TSC based on line flows is proposed to differentiate between agent
- In India line loss is worse than congestion and accounts for over 30% of generation capacity. When such bulk and enduring loss occurs the reputation of engineering and economic side of power sector is at stake.

Recovered loss makes up for the power deficit especially when government funds are low for generation. The pricing tactic proposed releases reliable signals to locate Gencos, motivating more market entrants in apt locations.

- If TSC is designed as an objective function to minimize loss, it can relieve congestion also and ensures security of operation. If the objective is stated as incentives and penalties it can be imbibed into TSC and delivered to markets. Here Transmission Provider (TP) is given the authority for instituting a tariff penalizing abuse of network of common use. This is as per market engineering principle of design of protocols to realize a central goal. So TSC functions as a financial instrument in the custody of TP that exercises control over line flows.
- In market engineering, a protocol exists for any agent to summon all powers and innovations at his disposal to turn tables in his favour. Here, we recommend formation of coalitions that cause counter-flows in vulnerable lines to reduce the impact of TSC. Coalitions formed on the basis of a sharing pattern of TSC, thus counter punitive measures. This is the process of deriving a pay-off vector, another financial instrument. Such a role for TSC empowers Discos to negotiate re-allocations of trades, based on 'willingness to pay' generated.

We infer that a differential and elastic TSC with respect to demand is most appropriate as a coalition value in the CGT model for electricity trades. The TSC design gives an efficient objective function appropriate for minimization. Hence, the criteria of design of the price function were chosen and a proposal to complement current methodologies for a design of TSC as per market engineering principles is presented.

B. Design Criteria And Data Generation

The bases for penalizing some impacts on lines are.

1. Sensitivity analysis to shift of trades by Discos: Fig.2 shows the simulation results of rescheduling of Gencos via reallocation of trades on the 5 bus power system (Fig.1). Four searches are made for least loss in lines. In each case slack bus is made to share 165 MW from full to zero load with the 2nd generator situated on bus 2 to 5. We choose to penalize the worst impact on lines i.e. loss, squared, with a fixed weight as a component of TSC.

2. Sensitivity Analysis to total power flow in lines: A similar analysis shows the need to reduce voltage drop on lines and thus reduce voltage instability, by a TSC component for total power shuttling over all lines. .

3. Congestion is also chosen as a factor in the design of TSC. Load Flow Analysis (LFA) gives the data for the price model. In this case study, guidelines of Central Electricity Regulatory Commission (CERC), India, are used to select the weights.

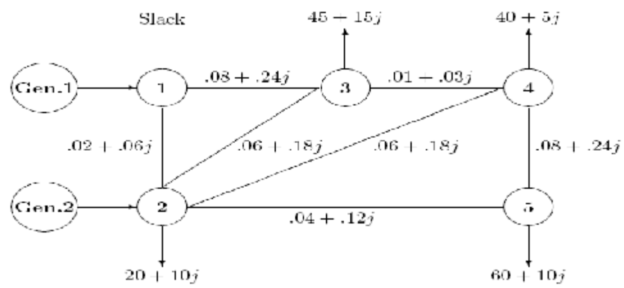

Fig. 1. Five Bus Power System.

C. The Price Model

There are two stages in TSC design. First, weights are judiciously selected and a price model is formulated based on the above objectives and analysis criteria. Weights are given in the construct of TSC ($P(q)$) to penalize loss, congestion and quantum of power shuttling over lines, or all identified undesirable impacts on transmission lines. For a network with n nodes, flow through L lines $\mathbf{z}$, and loss q, if weights for disciplining loss, total power flow in all lines and flow in congested lines are a (Rs. /MW^{2}h), b and d (Rs./MWh) respectively and embedded cost is c in (Rs./hr.), then the price function $P(q)$ in Rs./hr.

$$P(q) = aq^2 + b\sum_{L} z + d\sum_{congested} z + c \qquad (1)$$

In the next stage, TSC is elasticized with respect to demand to incorporate market mechanisms. Elasticity curves are obtained by inter-relating trade demands with price function. Least transmission price and demand plus loss corresponding to such optimal trades are fixed. Any deviation is categorized as bad or worse trades, using the imparted elasticity of the elastic curve as is done next.

III. ELASTICIZING TSC WITH RESPECT TO DEMAND

TSC can function as a negotiable financial instrument to coordinate optimal trades if some elasticity of demand exists. Differential pricing combined with elasticity makes TSC an ideal coalition value in a CGT milieu.

A. Pareto pricing methodology

The TP can set optimal prices by maximizing its profit. In market engineering, TP can try to take advantage of the selfish, profit motive of end-users. This is possible by discriminating between demands resulting in least loss, and trades that deviate from such a formulation; larger the deviation, steeper is the price set. In short TP extracts the elasticity curve as shown in Fig. 3 based on the optimality condition or by the Inverse Elasticity Rule given below.

$$(P(q) - c)/P(q) = 1/\varepsilon(q) \qquad (2)$$

Optimal monopoly price is given by the above rule.

Allocation of TSC based on it has Pareto efficiency, since there is no other feasible allocation making some agents better off and none worse off. Using this elasticity factor, TP allocates prices to coalitions, differentiating them, based on their quantity of impact on the network. The algorithm to derive the elastic curve is next

B. Elastic curves in transmission pricing

The elastic curves lessen conflicts arising from digression from transactions agreed to, in real time, if ramifications on TSC share are notified in advance. It serves as a data base for dispensing information on TSC, for a band of trades and extricated by the TP as per the algorithm.

1. For a given injection vector, TP iterates the trades to least impact on lines, via LFA and computes TSC.

2. The vertical axis is calibrated for demand plus line loss in MW and horizontal axis for TSC in Rs. /hr

3. The reference point for least TSC corresponds to a demand based on optimal trades and allied least loss.

4. Thereafter reallocation of trade of each Disco is taken and summed together. Then the difference in loss for the corresponding injection vector is also added to this sum to get the total deviation in demand. This deviation is plotted against the related TSC for a few cases. The curve joining all these points is the elasticity curve.

C. TSC as a coalition value in a CGT milieu

Built-in differential pricing and elasticity makes TSC a powerful coalition value in the procedural algorithm in the three phases of CGT interactions as follows:

1. *Local Information & Computation Phase*: In this phase Discos collect trade related information. They are not swayed by lucrative offers from Gencos if tariff for TSC is public. Discos compute TSC for initial trade intents, compare it with energy charges (EC) and negotiate to reduce TSC allocation once central data are released.

2. *Central Computation & Least loss iteration phase*: TP iterates the injection vector to least impact on lines and broadcast the least allocable TSC to Discos. Using the elastic curves Discos negotiate for a lower share of TSC.

3. *Negotiation & Common Information Derivation Phase*: Discos optimize the total EC and TSC that they pay by cooperating with other Discos. Least TSC data helps Discos to negotiate and form coalitions wherein the combined TSC share is reduced due to counter-flows. At each merger, more common data is generated and actual trades to be contracted or re-allocation of loads to Gencos is known at each stage. Also, modalities can be worked out for desired deviations from least impact formulation, while considering a merger.

D. TSC and elastic curve in the CGT model

T Next is given, the algorithm using TSC in 3 stages of CGT.

1. 1. The system operator/IP selects criteria and weights for the construct of the price function iteratively, extracts the elastic curve and announces grid data (configuration, impedances, line limits etc) and tariff policies,
2. 2. Discos arrange trades, do LFA, submit demands and compute possible TSC shares.
3. 3. TP collects all demands of Discos to be transacted, performs LFA on this injection vector and iterates trades to get scheduling for least impact on lines, computes TSC using Eq. 1 and other data and publishes them for Discos to negotiate and form coalition, They also release allocable TSC with the total TSC marked up using the elasticity curve. (Update of the elasticity curve by TP, gives a data base for real time retractions.)
4. 4. Discos now find mutually beneficial trades with low share of TSC or pay-off-vector and stable coalitions are formed. Reliability is as per the strategy of the TP and more trades are shopped. Final transactions are intimated.
5. 5. Final demand is scheduled. TP is obligated to implement this agreement honouring charges already communicated and centrally allocated to all coalitions by marking -up the price using elasticity factors.
6. 6. Anomalies from the committed schedules can be compensated by the TP if practicable.The second financial instrument is the tentative pay-off vector derived during the negotiation phase, given next.

IV. NEGOTIATION & COALITION FORMATION

The essence of differential pricing in Ramsey pricing rule is applied in the CGT model for negotiation with prospective partners with the objective of deriving a pay-off vector during coalition formation. Benefits must be split based on the economic advantage the grid offers to each of the negotiating agents in comparison with its intended grid usage. Then the optimization problem for setting socially optimal prices *Pc* and *Pr* for quantity of purchases ***x*** of coalitions designated *c* & *r*, subject to a profit constraint is

$$\max \int_{0}^{x_c(P_c)} (P_c(x) - c)dx + \int_{0}^{x_r(\mathrm{Pr})} (P_r(x) - c)dx$$
$$s.t.$$
$$x_c(P_c)(P_c - c) + x_r(P_r)(P_r - c) = W \qquad (3)$$

A. Optimal Monopoly Price

Performance of a market is measured by its social welfare, the difference between utility and cost. In power markets it is a combination of the cost and benefit of energy to society as measured by its ‘willingness to pay’ for it.

Supply-demand balance will set the market price and quantities at an equilibrium point where social welfare is optimal, subject to constraints. Maximum social welfare is achieved in a perfect market. But real markets are often constrained to operate at sub-optimal levels. In power industry, welfare economics applied to provide maximum social welfare are directed towards pricing policies that maximize benefits in transacting energy efficiently and effectively and in sending signals for desirable reallocation in society. Optimal monopoly price is proposed here to get a compromise operating point between agents in a coalition. Reallocation is thus obtained via elasticity curves given by inverse elasticity rule. At negotiating stage accountability is fixed by treating the trades as separable and distinguishing between Discos using the inverse elasticity rule. Here *i* represent each Disco and ε_i, elasticity of demand with respect to Disco considering merger.

$$\frac{P_i - c}{P_i} = \frac{\frac{\lambda}{\lambda + 1}}{\lambda_i} \quad \text{...... Marked up price} \quad \text{....... (4)}$$

B. Ramsey Pricing Applied To Transmission Sector

Two prospective partners gain common information, swap trade contracts for a better financial bargain and derive other benefits. A coalition requires a common reference point and financial repercussions on deviations from this point. Elastic curves give the price penalties associated with pursuing trades of self-interest only, by one of the parties considering a merger. The rallying point, beyond which there is mark up for allocated TSC, is given by Eq. 4. Elastic curves for coalition formation are treated differently from the previous section because at a negotiation stage, Discos are willing to divulge information in order to further their own cause. The threat looms large of a coalition which excludes one and has to be weighed diligently against the promises of a coalition which includes one. This most interesting feature of CGT is evaluated to arrive at a water-tight pact such that the coalition stands the test of further incentives to deviate.

C. Formation of Coalitions and Elasticity Curves

Elastic curve, with TSC versus demands of coalition of Discos at bus 2 and 3, used to consider their merger, in the five bus case is shown in Fig. 3. The reference point is the least TSC point or when the merger makes minimum impact on lines. An illustration on how the elasticity curve helps to divide the TSC is also shown based on this coalition. This example highlights the mark-up agreed upon, when a higher 'willingness to pay' is exhibited by one partner to move away from the optimal operating point. Any higher 'willingness to pay' arises when EC payable plus the marked up TSC are more lucrative when compared to a shift in trade and the consequential total incremental cost. In this case, say Disco 2 prefers to buy its entire demand from Genco 1 while Disco 3 prefers the trade corresponding to the best operating point. The deviation of Disco 2, takes it to a point on the curve with elasticity equal to ε_2 =1.837kWh/Rs. Disco 3 stays at the best point with ε_3=9.294kWh/Rs. Such a 'wayward' trade results in a line loss of .245MW and impacts giving a total payable TSC of Rs. 26,030/hr. In comparison the ideal coalition condition has a least loss of only 0.231MW, incurring a TSC of Rs. 21400/ hr. shared by the two parties in proportion to their demands, 20 and 45 MW. Thus minimum cost ***c*** for Disco at bus 2 is Rs. 6585/ hr. and for Disco 3 is Rs. 14815/ hr. if they abide by the trades leading to least loss. The consequent mark up equations obtained from Eq.3 and Eq.4 are: $20(P_2-6585) + 45(P_3 - 14815) = 26{,}030$ and

$$\frac{P_2 - 6585}{P_2} x\, 1.837 = \frac{P_3 - 6585}{P_2} x\, 9.294$$

Solving the equations the mark up price for Disco 2 is P_2 = Rs. 7990/ hr. for a transaction of 20MW marked up from Rs. 6585/ hr. by Rs.1415/ hr. and that for Disco 3 is P_3= Rs. 14770/ hr. for 45MW marked lower from Rs. 14815/ hr. by Rs.45/ hr. Thus, digression from optimal point can be penalized in the pay-off allocation also, by making use of the elastic curve for differential pricing.

The algorithm is applied to a five bus power system .

V. CASE STUDY ON A FIVE BUS POWER SYSTEM

In order to apply the algorithms to a 5 bus system, first initial trades are extracted by allocating demand via graph theory [15] to Gencos 1&2 (Table 1). Next, by assigning Genco1 full 100% to 0% of 165MW load and the rest to Genco 2, least loss iteration is done. Then lateral search is similarly made by relocating the 2nd Genco from bus 2 to 3,4 &5 as given in last column of Table 2. To compute TSC, LFA data for above trades and weights for Eq.1 are needed.

TABLE I. ALLOCATION OF INITIAL & OPTIMAL TRADES ON THE FIVE BUS POWER SYSTEM.

	Initial Trades		Optimal Trades	
:o on buses	co 1	co 2	co 1	co 4
(Demand)	d MW	d MW	d MW	d MW
2 (20MW)	13.623	6.376	13.846	6.154
3 (45MW)	39.544	5.456	5.002	39.996
4 (40MW)	30.463	9.536	0	40
5 (60MW)	41.374	18.628	23.654	36.546
Total loading	129.74	40	44.102	122.696
Line loss	4.77MW		1.6MW	
Sum of flow	262.6 MW		163.7MW	

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Table 2. Least impact Iteration on a 5 bus system for 2nd Genco located on buses 2, 3,4 & 5 respectively

	MW load on Gencos, congested lines, sum of power flow in lines and line loss TSC& demand									
CASE 1	Genc	150.	10	10	88.	43.	28.	23.	3.1	26.
	Genc	20	60	65	80	12	14	14	16	14
	Line	42.7	36.	35.	33.	29.	27	26.	19.	23.
	Line	6.86	5.7	5.5	5.1	4.4	4	3.8	2.7	3.3
	Σ z	275	23	23	21	19	17	17	17	15
	q	5.49	4.1	3.9	3.6	3.2	3.0	3.0	3.1	3.0
	TSC	3.94	2.4	2.3	2.0	1.6	1.5	1.5	1.5	1.4
	trade	47.7	85.	91	10	13	14	51.	14	16
CASE 2	Genc	143.	10	82.	61.	61.	41.	22.	2.3	43.
	Genc	45	65	85	10	10	12	14	16	12
	Line	29.1	21.	14.	6.8	6.8	.57	8	15.	.00
	Line	12.5	14.	17.	19.	19.	21.	24	26.	21.
	Σ z	241	21	20	18	18	18	19	20	18
	q	3.67	2.8	2.2	1.9	1.9	1.8	1.9	2.3	1.8
	TSC	2.16	1.5	1.1	.97	.97	.91	1.0	1.2	.90
	trade	87.8	10	12	14	14	16	14	12	16
CASE 3	Genc	128.	10	82.	66.	61.	46.	21.	2.1	43.
	Genc	40	65	85	10	10	12	14	16	12
	Line	32.7	26.	17.	13	11.	6.4	1.7	8.3	5.5
	Line	13.5	16.	20.	22.	23.	25.	29.	32.	26.
	Σ z	211	19	16	16	16	16	16	18	16
	q	3.77	2.8	2.0	1.7	1.7	1.6	1.7	2.1	1.6
	TSC	2.18	1.5	1.0	.89	.87	.82	.88	1.1	.82
	trade	82.8	10	12	14	14	16	14	12	16
CASE 4	Genc	167.	86.	66.	61.	46.	41.	22.	3.4	64
	Genc	60	80	10	10	12	12	14	16	10
	Line	33	28.	24.	23.	20.	19.	14.	10.	23.
	Line	10.6	16.	22.	24.	28.	30.	36.	42.	23.
	Σ z	175.	14	14	14	14	14	15	17	14
	q	2.56	1.9	1.7	1.7	1.8	1.9	2.5	3.4	1.7
	TSC	1.31	.99	.90	.91	.97	1.0	1.2	1.8	.91
	trade	123.	14	16	16	15	14	12	10	16

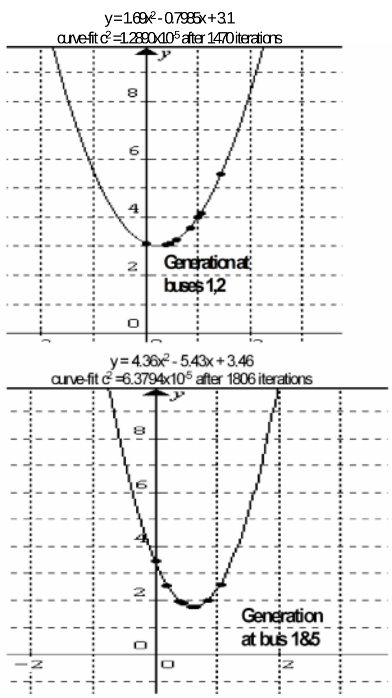

Fig. 2. Least loss iteration for 0-165 MW on Genco 2,3,4 &5.

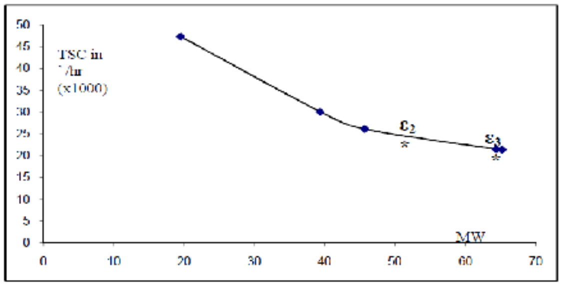

Fig. 3. Negotiation by Ramsey Pricing by Disco 2 & 3.

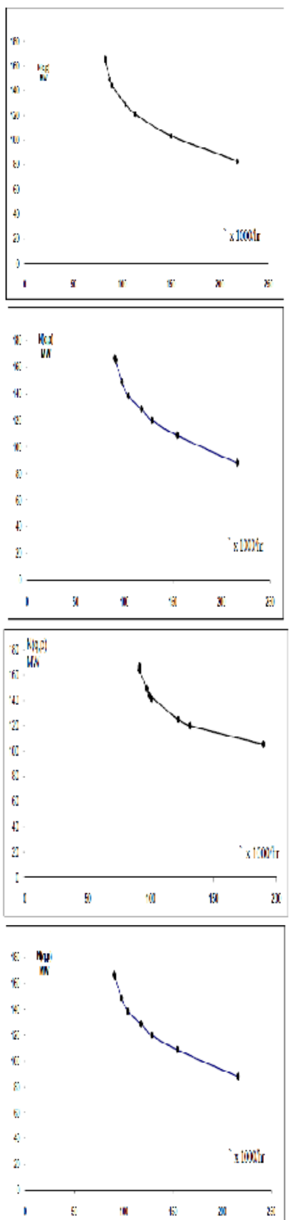

Fig.4. Elastic curve derivation for a 5 bus system for 4 cases.

So elasticizing demand against TSC, can arguably, force an optimal operating point. The design to derive TSC for 5 bus system fulfilled the role of a coalition value very well with per unit TSC dropping from Rs. 1.88 to Rs.0.50, the current wheeling charge. Sensitivity of elastic curves or elasticity indicates the 'willingness to pay' of Discos. For the four cases given (Fig. 4) overall elasticity is 0. 547 kWh/Rs., 0.966 kWh/Rs., 0.619 kWh/Rs. and 0.623 kWh/Rs. respectively or 'willingness to pay'- Rs.1828/MWh, Rs.1035/-, Rs.1616/-, and Rs.1606/- per MWh respectively."

VI. CONCLUSION

Electricity sector is considered to be non-elastic. Elasticity has been introduced into transmission sector which makes it sensitive to desirable trends in the grid. This price model opens room for negotiation, and is projected as a financial instrument to coordinate optimal trades. TSC share evolves as a choice and is more effectively realized than an imposed tariff and reduces economic issues. The combine of differential pricing and elastic demand with respect to price, makes TSC an ideal coalition value. Such a design and implementation of TSC makes feasible the concept that a price is neither set nor taken but evolves in a market as required for perfect competition. It is a good method for computing wheeling charges or for water metering. Such a versatile role for transmission price is a novelty. A multi-agent society, with several functional units and private objectives becomes conflict free, if a mechanism exists to find suitable partners, done in an extension to this work.

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