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ON TRANSMISSION CONGESTION AND FINANCIAL RIGHTS

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ABSTRACT

To optimally price, a congested net- work in restructured electric power systems, the concept of locational marginal prices (LMP), shadow prices are used. Congestion segregates the power market, weakens the competition mechanism and invalidates the optimization of the generator sources in the network. Congestion increases the generating costs and makes the power market less efficient. Market makers in restructured power systems offer point-to-point financial transmission rights (FTRs), whose value is defined as the difference in LMP at any two points in the network, for the market participants to hedge against volatile congestion costs. In this paper, the congestion is studied through the revenues collected as the merchandising surplus which is owned by the ISO, is explained by a simple eight bus example. Here it is revealed that the congestion surplus or the merchandising surplus involves the maximum power that can be transferred between two locations while the short fall of revenue pertains to a specific transaction. The shortfall of revenue is able to cover the shortfall of contracts up to the maximum power transfer between the two markets. Instead of being from point to point, FTRs can be attached to a branch or flowgate in the network. They are called flow gate rights (FGRs) is also studied through the same example.

KEYWORDS: Congestion, FGRs, FTRs, Merchandising surplus, LMP, Shadow Prices.

INTRODUCTION

For defining transmission rights in the restructured electricity market which is done through financial instruments that enable energy traders to hedge congestion risks. The quantities for such instru- ments are either Locational Marginal Prices (LMP) or shadow prices on transmission flow gates which are determined as a part of an Optimal Power Flow (OPF) [1] calculation.

FTRs which is defined as point to point financial transmission rights [2] was first introduced within a general framework of contract networks by Hogan (1992) [3] and has widely adapted in the U.S as the main part of the nodal market designs and worked by the various independent system opera- tors (ISOs). FGRs was first introduced by Chao and Peek in 1996 [4]. FGRs and complements to FTRs were discussed by Chao and Peek in 1996, Chao (2000), Ruff (2001) O'Neil (2002) [5]. FGRs are rarely used in today's markets since energy traders prefer FTRs that are suitable for hedging congestion risk [6].

If there is a bilateral energy transaction of P MW from node A to node B, the network exposed to congestion risk between the two locations is liable for a congestion charge that is equal to the difference of LMPs between the two nodes. A trader can offset the congestion charge [7] by holding an

FTR from node A to B for P MW which entitles him to the nodal price between node B and node A times P. Hence the FTRs pay off exactly equal the congestion charge

PRELIMINARY OF LMPs, SPs, PTDFs

Optimal power flow (OPF) calculates the outputs of generators that are distributed over a transmission network so as to minimize total cost of serving spsecified loads or maximize the social welfare if loads are characterized by price sensitive while accounting for losses and without violating transmission flow constraints. Flows must satisfy thermal and voltage limits. We approximate this by ignoring losses and assuming DC approximation of Kirchoff's laws.

A flow pattern in a network can be found in terms of a matrix of Power Transfer Distribution Factors (PTDF) [8] whose 'ij' element specifies the incremental flow induced on each transmission link 'j' by injecting 1 MW at node 'i' and withdrawing it at reference node. For clarity we denote the transmission links by pairs of indices representing the adjacent from/to nodes so that 'hk' represents the directional link from node 'h' to node 'k'. The PTDF matrix can be easily computed through simulation or directly from the susceptances of the transmission lines. For instance a flow on the line 1 to 6 resulting from injecting 1 MW at node 3 and withdrawing it at node 5 is given by $PTDF_{1-6,3} - PTDF_{1-6,5}$

In the context of optimal power flow or optimal dispatch, the quantities for financial transmission rights, Locational marginal prices (LMPs) or line shadow prices (SP) are meaningful [9]. If no transmission constraint is binding, then the marginal cost of serving one incremental unit of energy at any node is identical and there is at least one marginal generator unit that can be moved to produce such an incremental unit at that cost. If one transmission line is congested and the system is to be dispatched optimally, to supply an incremental unit of energy at any node without violating the binding constraint can be achieved by adjusting the output of up to two generating units, so called marginal generators which can be moved up or down. If there are 'm' binding constraints, then supplying an incremental unit of energy at a specific node without violating the constraints may be required to change in output levels of up to (m+1) marginal generators. Locational marginal prices (LMP) is the least cost of providing an incremental unit of energy at a node under optimal dispatch, without violating the binding transmission constraints. Line shadow price (SP) is the maximum dispatch cost saving under optimal dispatch that can be achieved due to an incremental unit increase in the lines' flow capacity constraint without violating any of the binding transmission constraints [10].

MERCHANDISING SUR- PLUS

If energy is bought and sold at nodal marginal prices, for one hour of operation at constant loads, the consumer payments at all the buses and the sum of the generator revenues at all the buses do not match. More money is collected from the consumers than is paid to the generators. The difference is the merchandising surplus. The surplus is caused by the congestion in the network. One may predict that further increasing the line capacity should result in lower prices as the system is less constrained, but this is not necessarily the case.

MARKET POWER

Nodal markets are perfectly competitive [11]. The nodal price is equal to the marginal cost when energy is produced by local generators. If there is a transmission congestion on a specific branch, a generator which does not produce, desperately wants to produce some power, since it may be a cogeneration plant. If the generator is to run, the owner bids at lower the current nodal marginal price. This lower bid at this cogeneration plant increases the nodal price at other buses. This lower bid of the cogeneration plant has the counter intuitive consequence of being very profitable for the other bus. It may happen that more higher bidding of the other bus can make the nodal price of the cogeneration plant negative. Consumers connected to the cogenerative bus would be paid to consume and generators would have to pay for the privilege of producing energy. The life becoming miserable for cogenerative plant, the other generator makes a profit by raising bids though its output decreases.

Congestion in the network can transform a reason- ably competitive global market into a collection of smaller local energy market [14], [16]-[17].

MANAGING TRANSMISSION RISKS

The security considerations limit the amount of power that can be transmitted across the network and create locational price differences. The effect congestion has the feasibility of these contracts and new contractual tools are needed to manage the risks associated with this congestion. Producers and consumers inject or extract power into the network according to the instructions of the sys- tem operator. They receive or pay the centrally determined price in effect at the location where they are connected. Market players enter into bilateral financial contracts to protect against the differences of the nodal prices [18]-[19]. Two market participent enter into simple contract for difference. Contract for difference cover only the delivery of energy that does not work when the system is congested. Players protect themselves against price variations by contracting for energy production or consumption and the ability of the transmission system. Suppose a consumer and a producer settles with a contract for difference in the presence of congestion. A sign convention is adapted for surplus as positive and for deficit as negative. Let the contract for difference is π_C for an amount F.

Consumers expect to pay=$-F*\pi_C$

Consumers pay at nodal price $\pi_S = -F*\pi_S$

So, consumers expect to pay or receive to settle the contract for difference=$-F*\pi_S -(- F*\pi_C)$

$C_T = F*(\pi_C - \pi_S)$

Producers expect to receive=$F*\pi_C$

Producers sells and receive at nodal price $\pi_B = F*\pi_B$

So, producers expect to pay or receive to settle the contract for difference=$F*\pi_B - F*\pi_C$

$P_T = F*(\pi_B - \pi_C)$

If there is no congestion $\pi_S = \pi_B$, the contract can be settled as $(C_T + P_T) = 0$

If $\pi_S = \pi_B$, both consumer and producer have a total shortfall given by $(C_T + P_T) = F*(\pi_B - \pi_S)$

The congestion surplus involves the maximum power that can be transferred between the two loacations while the shortfall indicates a specific transaction. The congestion surplus should be able to cover the shortfalls for contracts up to the maximum power transfer between the two markets. The contracts for differences can be solved if the parties acquire FTRs.

FGRs operate like FTRs and the value of these rights is associated with the Lagrange multiplier or shadow cost of the maximum capacity of the floegate. The only FGRs produce revenue that are associated with congested branches. FGRs provide the same perfect hedge as FTRs.

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A To calculate the generator dispatches.

Min $\sum_{i=1}^{n} C(P_i)$

s.t. $\sum_{i=1}^{n} P_i = \sum_{j=1}^{q} P_{dj}$
where n= no. of generators,
& q=no. of load demands denoted by 'd'.
$L_f \leq$ Line flow limits.
where L_f are the line flows,
& m=no. of transmission lines.
f=1,2,3....m
$P_i \leq$ Generator capacity Limits
where P_i are the generator dispatches.
i=1,2,3....n

B To calculate the PTDF matrix.
(i) Formulate the Y_{BUS} matrix.
(ii) Formulate the sensitivity matrix **X** by appending with zeroes to the $\mathbf{p^{th}}$ row and column and inverting the rest of the matrix where **p** is the reference bus and i=1,2...s,...p,...r,...n are the generators.
(iii) $\mathbf{PTDF_{(s-r)n}}=1/x_{sr} * (X_{sn} - X_{rn})$ where x_{sr} is the line reactance connecting bus 's' and bus 'r' and there are 'b' no. of buses from 1...s,...p,...r,...n,...b.

C To calculate the LMPs and SPs.
(i) If LMP at node 'p' is to be calculated, it is required to calculate the incremental outputs of

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(c+1) marginal generators where 'c' is the number of constrained lines, so as to deliver 1 MWh at node 'p' without increasing the flow of the congested line.

$LMP_p = \sum^{(c+1)}$(Marginal cost of the marginal generators× Output of the marginal generators.)

(ii) To calculate the shadow price of the congested line connecting nodes say 's' and 'p', it is to perturb the outputs of the marginal generators by incremental amounts so as to increase the flow on the congested line by 1 MW between nodes 's' and 'p' while maintaining the energy balance.

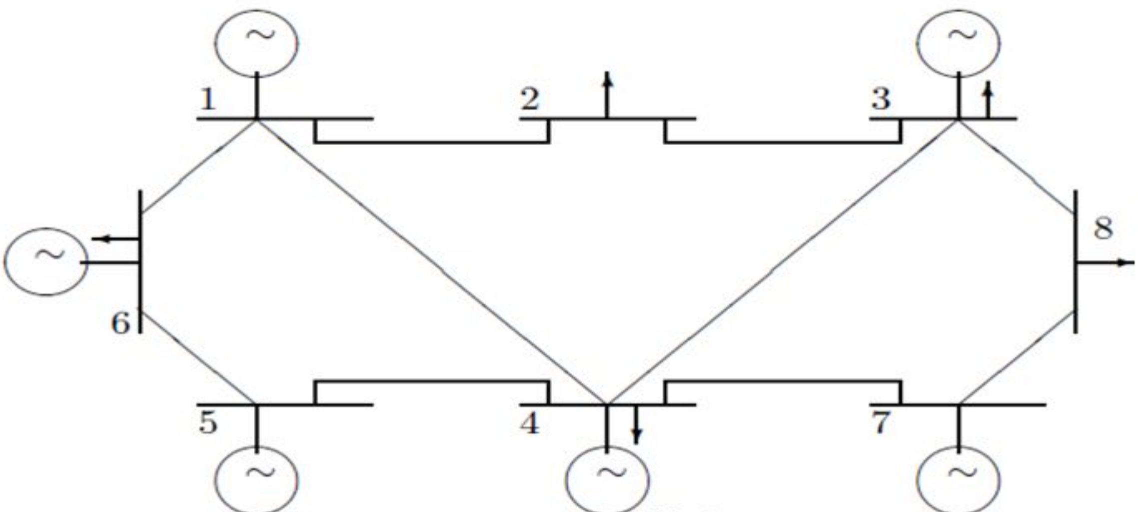
$SP_{s-p} = \sum^{(c+1)}$(Marginal cost of the marginal generators× Output of the marginal generators.)

Clearly there is a close relationship between LMPs and SPs both of which is calculated from the same data

$$LMP_i\text{-}LMP_{ref} = (\sum_{flowgate\ (h-k)} SP_{h-k}) \times (PTDF_{h-k\ i} - PTDF_{h-k\ ref})$$

AN EIGHT BUS EXAMPLE OF ILLUSTARATE THE CENTRALIZED TRADING

Bus 1 is the reference bus, the $P_{min,}$ P_{max} are the range of generated powers.



$Fig1$

Table-I: Generating Units Information & load

Bus	c	b	a	P_{min}	P_{max}	L
1	0.0060	18	100	5	20	-
2	-	-	-	-	-	53.4
3	0.0041	17.02	145	5	70	71.2
4	0.0039	12	112	10	70	62.3
5	0.0040	10.1	110	10	90	-
6	0.0040	30	180	10	70	186.9
7	0.0035	9.3	100	20	200	-
8	-	-	-	-	-	84.55

where the units of c, b, a are $\$/MWh^2$, $/MWh & $/h respectively & **L** denotes load in MW.

Table-II: Line Parameters Information

Line	From	To	X p.u	Limit (MW)
L_1	1	2	0.03	200
L_2	1	4	0.03	200
L_3	2	3	0.011	200
L_4	3	4	0.03	60
L_5	4	5	0.008	22
L_6	5	6	0.02	110
L_7	6	1	0.02	75
L_8	7	4	0.015	200
L_9	7	8	0.022	200
L_{10}	8	3	0.018	200

A ECONOMIC DISPATCH-ED

If the constraints of the network that may impose are ignored and the total load is dispatched solely on the bids of the generator in a way that minimizes the total cost [12].

The generator dispatch, load in MW & cost in $/h are-

Load	Cost	P_1	P_3	P_4	P_5	P_6	P_7
458.35	5858.7	18.35	70	70	90	10	200

The line flows in MW are-

L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}
5	46	48	34	28	118	59	99	101	16

L_5 & L_6 gets overloaded. LMP at all buses is calculated for an extra 1 MW load at any bus which will be borne only by P_1 marginal generator.

The extra cost borne i.e, LMP is $18.4524/MWh is common for all buses.

B SECURITY CONSTRAINED ECONOMIC DISPATCH-SCED

While the economic dispatch minimizes the total production cost, this solution is not viable as it does not satisfy the security criteria. We must determine the output of the generators at least cost so as to remove the line overload [13], [15]- [16].

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The new generator dispatch, load in MW & cost in $/h are-

Load	Cost	P_1	P_3	P_4	P_5	P_6	P_7
458.35	6038	20	54	70	90	24.6	200

The line flows in MW are shown below-

L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}
11.5	44	42	40	20	110	52	96	104	19

The cost for making the system secure is $ 179.6/h. Generators at bus 3 & 6 become marginal, whose marginal costs are 17.02+(2*0.004*P_3) & 30+(2*0.004*P_6). When the security constrained economic dispatch is maintained, the nodal prices or LMPs of each bus in $/MWh are calculated.

LMPs

1	2	3	4	5	6	7	8
22.6	18.8	17.5	14.8	37.8	30.2	15.7	16.7

The tables III, IV below show the payments made by the consumers and the revenues collected by generators, if energy is bought & sold at nodal marginal prices. The quantities are calculated for 1 h of operation at constant loads. More money is collected from the consumers than is paid to the generators.

Table-III

Bus	1	2	3	4
C(MW)	0	53.4	71.2	62.3
P(MW)	20	0	53.7	70
LMPs	22.6	18.8	17.5	14.8
C(pay)	0	1004	1246	922
P(rev)	452	0	940.5	1036

Table-IV

Bus	5	6	7	8
C(MW)	0	186.9	0	84.55
P(MW)	90	24.6	200	0
LMPs	37.8	30.2	15.7	16.7
C(pay)	0	5644	0	1412
P(rev)	3402	743	3140	0

where C(MW), P(MW), C(pay), P(rev) stands for consumption in MW, production in MW, consumer payments, & generator revenues respectively.
So the congestion surplus or merchandising surplus is 10228-9713.5=$ 514.5/h.
Each branch's flow contribution for the congestion surplus in $/h are shown in the tables V, VI below.

Table-V

Flow 1-2	Flow 2-3	Flow 4-3	Flow 4-1	Flow 4-5
-43.7	54.6	108	341	460

Table-VI

Flow 5-6	Flow 1-6	Flow 7-4	Flow 7-8	Flow 8-3
-836	397.4	-86.4	103.9	15.5

Again the total surplus due to congestion in the lines comes out to be $ 514.3/h.

Effect of the maximum flow on branch L_5 connecting between buses '4' & '5' in the operation of the eight bus system is shown in the table VII given below.

Table-VII

F_{12}^{max} (MW)	P_1	P_3	P_4	P_5	P_6	P_7	Surplus($/h)
01	20	15.3	70	90	63.1	200	17.4
10	20	33.5	70	90	44.9	200	272
15	20	43.6	70	90	34.7	200	382
20	20	53.7	70	90	24.6	200	514.5
25	20	53.7	70	90	24.6	200	514.5

It is to be noticed that as the line congestion is relaxed, slowly from 1 MW to 20 MW in the line L5 , the congestion surplus does not decrease rather it increases substainally and it becomes constant from 20 MW onwards.

The table VIII below shows combinations of FTRs with three transactions at a time that meet the simultaneous feasibility condition for the system

Table-VIII

COMBINATION 'A'

From Bus	To Bus	Power(MW)	Rev($/h)
7	6	115.4	1673
7	2	84.6	262.3
5	3	70	-1421

COMBINATION 'B'

From Bus	To Bus	Power(MW)	Rev($/h)
7	6	17.2	249.4
7	3	102.8	185
7	8	80	80

With the specified transaction loads at buses '6', '2' and '3' in combination 'A' & at buses '6', '3' and '8' in combination 'B' the security level is maintained. The total transaction cost is $ 514.41/h & $ 514.44/h for combination 'A' and 'B' respectively which is same as merchandising surplus i.e. $ 514.5 and the generators generate for a total load of 489.55 MW &
489.95 MW which are within the maximum generating capacity for both the combinations 'A' and 'B' respectively as shown in the table IX given below

Table-IX

P_1	P_3	P_4	P_5	P_6	P_7
20	70	70	90	39.55	200
20	70	70	90	39.95	200

FTR holders collect based on their nodal prices is equal to their merchandising surplus that was collected by the market operator. FTRs may have a negative value to balance account book. FTRs may be treated not as option but may be also as an obligation. FGRs for transaction in combination 'A' from bus'7' to '6', '7' to '2' & '5' to '3' and in combination 'B' from '7' to '6', '7' to '3' & '7' to '8' are shown in the table X given below

Table-X

Buses	7-6	7-2	5-3	Net FGR_A
FGR_A	64.93	10.36	-55.14	20.15

Buses	7-6	7-3	7-8	Net FGR_B
FGR_B	9.67	7.08	3.03	19.78

The calculated value of the shadow price for the congested line L5 between the buses 4-5 is $ 25.51/ MWh. The flow on the congested line L5 due to the injection at bus '7' and withdrawal at bus '6' $(PTDF_{4-5,7} - PTDF_{4-5,6})$*115.4=64.93. So, the consumers will collect 20.15MW × 25.51/MWh=$514.03/h which is equal to the merchandising surplus. FGRs provide the same hedge as FTRs. Market participants buy FGRs on at most a few branches of the transmission network that are congested. This approach leaves participants only partially hedged against the risk of congestion as it is difficult to predict the branches that will turn out to be congested.

CONCLUSION

FTRs have possible more combinations due to point to point rights than FGRs which operate solely on the congestion of the branches. Due to trading on a fixed set of flowgates (congested lines) other branches may get congested. Then it reveals that more FGR combinations are possible. Still FTR combinations are more viable than FGR combinations as in a real system only twenty percent of the total lines are congested. Due to changes of the configuration of the network combinations of FTRs are difficult to determine as the generator and branch capacity are constant. FGRs are simpler in the sense as they are on a few congested lines and as another branch becomes congested, the nodal prices also change. Market participants must be aware of the PTDF matrix. The buyers and sellers set their transactions on the fluctuations of the nodal prices not by the configuration of the network. In our eight bus system it has been vividly shown that FTRs and FGRs are equivalent on a perfect competitive market and hedge the congestion surplus.

IX. APPENDIX-CALCULATED SENSITIVITY MATRIX

$$X=10^{-3}*\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 18.6 & 14.4 & 7 & 5.9 & 2.9 & 9 & 12 \\ 0 & 14.4 & 19.7 & 9.6 & 8 & 4 & 12.3 & 16.4 \\ 0 & 7 & 9.6 & 14.1 & 11.8 & 5.9 & 12.9 & 11.1 \\ 0 & 5.9 & 8 & 11.8 & 16.5 & 8.2 & 10.8 & 9.2 \\ 0 & 2.9 & 4 & 5.9 & 8.2 & 14.1 & 5.4 & 4.6 \\ 0 & 9 & 12.3 & 12.9 & 10.8 & 5.4 & 23.7 & 17.4 \\ 0 & 12 & 16.4 & 11.1 & 9.2 & 4.6 & 17.4 & 26.8 \end{bmatrix}$$

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