Electricity Nodal Prices using AC-DC Optimal Power Flow

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Abstract- Over the last decade, electric markets have been significantly restructured throughout the world. Under it, electricity nodal pricing has emerged a powerful and efficient tool of transmission pricing. It also emerged as one of the key elements of a competitive electricity market.

The enactment of the Electricity Act 2003 has opened the door for wholesale electricity market in the Indian electricity sector. The success of Transmission Open Access (TOA) regulation in India needs to reconfirm the required infrastructure and appropriate pricing policy to promote competition in this sector. This paper aims at (1) the transmission pricing issues in general and nodal pricing in particular, (2) optimal nodal price formulation, (3) its' implementation over IEEE-30 Bus and real transmission network of Maharashtra State Electricity Transmission Company Limited (MSETCL) and (4) to assess the impact of generation and transmission investment on the nodal prices. Paper concludes that nodal pricing is easy to implement over real network and effective in achieving transmission pricing objectives.

Index Terms – Electricity market, Transmission, Optimal power flow, Nodal pricing.

I. INTRODUCTION

Over the last decade, electric markets have been significantly restructured throughout the world especially in market structure and regulatory policies [11]. Under competitive electricity market, transmission has economies of scale, making this sector a natural monopoly that has to be regulated. Today in developing countries, the trend of electricity market is heading towards *Transmission Open Access (TOA)* whereby transmission providers will be required to offer the basic transmission service (i.e. operational and/or ancillary services) and transmission pricing [8]. In a restructured electricity market, nodal pricing has emerged a powerful and efficient tool of transmission pricing, both in theory and more recently also in practice. It also emerged as one of the key elements of a competitive electricity market. The main purpose to develop a nodal price theory was to bring efficient use of the transmission grid and generation resources by providing correct economic signals [11].

The enactment of the Electricity Act (EA) 2003 has paved the way for undertaking comprehensive market reforms in the Indian electricity sector. The recently notified TOA, National Tariff Policy by Ministry of Power, Government of India seeks to achieve the

objectives (1) to ensure optimal development of the transmission network, (2) to promote efficient utilization of generation and transmission assets in the country, and (3) to attract the required investments in the transmission sector and to provide adequate returns. The states in India are to follow the policy laid down by the central sector. The Maharashtra state of India is also exercising the restructuring process by allowing TOA as per Maharashtra Electricity Regulatory Commission (MERC) (Transmission Open Access) Regulations, 2005. MERC at present is looking after the feasibility of market based intra-state pricing in the State.

After this introduction, section II provides an overview of Indian electricity market including the electricity restructuring status in Maharashtra state. Section III highlighted the issues and objectives of transmission pricing under competitive electricity markets. Section IV briefs the nodal pricing methodology includes problem formulation and calculation of nodal prices. In section V, nodal price is computed over IEEE-30 Bus and real network of MSETCL. The impact of generation and transmission investment on nodal prices is also evaluated for network under study. Finally, we give several general remarks to conclude this paper.

II: INDIAN ELECTRICITY MARKET OVERVIEW

India's electric power sector has grown substantially since independence, from 1,362 MW in 1947 to 158,218 MW in 2007 with a compound annual growth rate of 8-9%. Despite this growth, India's per capita electricity consumption remains low, about 631 kWh, compared to the world average (CEA, 2007). The power sector has been characterized by shortage of supply vis-à-vis demand. The peak shortage has been hovering between 11 to 13% and energy shortage between 7 to 8.5%. In its quest for increasing availability of electricity, the country has adopted a blend of thermal, hydel and nuclear sources. Even with ample share of the outlay of the national economic plan (about 13-18%), many State Electricity Boards (SEBs) in India have been striving under resource crunches and operating at huge commercial losses resulted into widen demand-supply gap, low capacity expansion, inadequate modernization, poor electricity services to the consumers and failed to address social and environmental dimensions of power sector.

Today Indian economy is growing as one of the fastest economies in the world with a huge demand for energy particularly of electricity. The enacted EA 2003 and other initiatives in Generation (G), Transmission (T) and Distribution (D) by Government of India has outlined the

counters of a suitable enabling framework for the overall development of wholesale electricity market by introducing competition at various sectors. This Act provides electricity market for private investments for increasing generation capacity and efficient network use by encouraging captive generation, TOA to T, D system and delicensing generation. The newly launched National Electricity and Tariff Policy in Indian power sector are gearing up to function in a strong, stable and competitive business environment.

On the electricity transmission front, the Indian grid is divided into five sub grids called regional grids (Northern, Western, Southern, Eastern and North-eastern). Each regional grid has number of constituent sub grids formed by state and private utility networks. All these sub grids and networks are connected to form 400 kV national grids. The constituent systems have their own generation in additional to generation by central government undertakings like NTPC, NHPC, NPC which have thermal, hydro and nuclear stations in different parts of the country and which feed power in the grid at different locations. The Central Transmission Utility (CTU) is responsible for the national and regional transmission system planning and development and is also providing Open Access on its inter-state transmission system. The State Transmission Utility (STU) is responsible for planning and development of the intra-state transmission systems. The Power Grid Corporation of India Limited (PGCIL) was set up for establishment and operation of regional and national power grids to facilitate transfer of power within and across the regions with reliability, security and economy, on sound commercial principles. To increase efficiency and competition in the sector, Central Electricity Regulatory Commission (CERC) allowed open access to power generating and distributing companies. The recent formation of the *National Grid* along with development of inter-regional electricity transmission linkages has opened new business vistas. The advent of hybrid systems comprising HVDC back-to back/bipolar links, ultra high voltage AC lines (765 kV), extra high voltage AC lines (400 kV) combined with applications such as FACTS etc present huge opportunities for equipment suppliers. The present challenges in T and D sector which might impact on competition are: transmission capacity i.e. it's availability & pricing, financial viability of distribution licensees, availability & pricing of fuels, rationalization of tariffs, ensure level playing field in the market, development of a strong regulatory oversight, and to enhance institutional capacity of ERCs.

An Overview of Electricity Sector restructuring in state of Maharashtra

Maharashtra State Electricity Board (MSEB) established in 1961. It provides electricity throughout the State of Maharashtra except for Mumbai city which is serving by three utilities, viz., Bombay Electricity Supply and Transport (BEST), Reliance Energy Ltd (REL), and Tata Power Company (TPC). It has the largest installed capacity of 15,580 MW. The state accounts for about 11 to 12% of India's total installed capacity in power sector. The restructuring exercise in the state started in the early 1990s. In the past decade, the state enjoyed a pride of place amongst the highly industrialized state in India due to sufficient power availability in the state. Later on with the drying of government funds, this sector started suffering adversely in terms of stagnated generation

capacity in the last 5-6 years resulting in huge demand-supply gap (about 4500 MW) which led to large power cuts, high T &D losses (above 39%), free/subsidized power weakening the commercial viability of the sector, accumulated financial losses, low metered sales, increasing dependence on power purchase and multifold increments in consumer tariffs. In August 1999, MERC was established under the ERC Act 1998. In 2005, in accordance with the EA Act 2003, MSEB was unbundled into MSEB Holding Company, Maharashtra State Power Generation Company Ltd (MSPGCL), Maharashtra State Electricity Transmission Company Ltd (MSETCL) which is also a State Transmission Utility (STU) and Maharashtra State Electricity Distribution Company Ltd (MSEDCL).

Due to lack of investment, transmission sector is also feeling the strain with a loading ratio of 76%. The current transformation capacity of 22,168 MVA is proposed to be enhanced to 68,182 MVA to bring the loading to 60% with an investment of over Rs. 200 Billion. Considering this huge required investment for transmission alone, it is proposed to offer most of the new evacuation lines and sub-stations to private sectors on the basis of tariff based bidding. MSETCL's present infrastructure consists of 500 KV HVDC, 400 KV, 220 KV, 132 KV, 110 KV, 100KV, 66 KV with total transformation capacity of 57713 MVA, 486 EHV sub-stations, and 35626 ckt-km lines. The TOA is allowed as per MERC (Transmission Open Access) Regulations, 2005 [15].

III. TRANSMISSION PRICING: AN INTRODUCTION

In a competitive electricity market introduction of appropriate rule of transmission network utilization and transmission pricing, reflected, a cost and value of the network which are necessary in order to maintain economic operation and fair competition in the electric power market. The transmission pricing is in fact the recovery of transmission costs, i.e. the embedded investment, the running costs incurred on a continuing basis, and the ongoing investment for future expansion or reinforcement. Generators, loads and electric transport companies are likely to be interested to find out what they are really paying for. Therefore, transparency in the operation is an essential ingredient in establishing this confidence. The efficient pricing system must motivate market participants, promote competition, investment in new generation and transmission capacity and accommodate new loads.

In the competitive electricity market, transmission pricing scheme fulfill several objectives and meet various criteria like,

- Promote the efficient day-to-day operation of the bulk power market by ensuring demand supply balance at all times and to signal economic efficiency by performing an economic dispatch to meet the demand at the lowest cost possible [8].
- Signal locational advantages for investment in generation and demand by locating power stations and other electricity intensive industries closer together which will ensure lowering the cost of transmission [12].
- Signal the need for investment in the transmission sector through planned investment into the transmission network which could reduce losses, encourage competition, accommodate new loads and hence be able to generate adequate revenues [2].
- Compensate the owners of existing transmission assets through efficient recovery of the existing transmission assets (return on investment). This will encourage investors to invest in the transmission sector in future.

- It should be easy to implement, transparent and conducive to electricity trading by sending correct economic signals to the market participants [8].
- It must be delivered on fully competitive market prices and the government policy on the Electricity Supply Industry (ESI) reforms, maintain the reliability of transmission grid, also social considerations and potential impacts of such price application have to be taken into account.

IV. NODAL PRICE FORMULATION

A. Introduction

Nodal pricing is a method of determining market clearing prices for a number of locations on the transmission grid called nodes. Each node represents a physical location on the transmission system including generators and loads. The price at each node reflects the locational value of energy, which includes the cost of the energy and the cost of delivering it (i.e. losses and congestion). Nodal prices are determined by calculating the incremental cost of serving one additional MW of load at each respective location subject to system constraints (e.g. transmission limits, maximal generation capacity). Differences of prices between nodes reflect the costs of transmission.

These location-specific prices are made up of three components: energy, congestion and losses. The energy component (or marginal cost) is defined as the cost to serve the next increment of demand at the specific location that can be produced from the least expensive generator in the system that still has available capacity. However, if the transmission network is congested, the next increment of energy cannot be delivered from the least expensive generator on the system. The congestion component is calculated at a node as the difference between the energy component of the price and the cost of providing the additional, more expensive, energy that can be delivered at that location.

Nodal prices are one of several important considerations in analyzing where to site additional generation, transmission and load. The implementation of efficient congestion management methods on the basis of nodal pricing is crucial to cope with scarce transmission capacities and to ensure security of supply. In the short-term, it improves the efficiency of the wholesale electricity market by ensuring that the cost of congestion is reflected in electricity prices and ensures that the least-cost supply of electricity is delivered while respecting the physical limitation of the transmission network. In the long-term, it helps relieve congestion by promoting efficient investment decisions. Because it creates price signals that reflect the locational value of electricity, participants can readily determine areas of congestion and will see the value of investing in generation, transmission and demand response programs.

B. Problem Formulation:

The Optimal Power Flow (OPF) problem is widely used to determine the optimal dispatch of generators by minimizing the total operation cost without violating various system security constraints [1], [13].

Mathematically, an OPF can be formulated as a non-linear programming problem to minimize a scalar objective function for 'n' bus system i.e.

$$\text{Minimize F} = \sum_{i \varepsilon NG} F_i(P_{Gi}) \tag{1}$$

Where, the cost characteristic of the ith generator is represented by F_i and P_{Gi} is its real power output. N_G is representing the generation buses.

The generator, in this formulation is considered to have cost characteristics represented by,

$$F = \sum_{i=1}^{NG} a_i PG_i^2 + b_i PG_i + c_i \tag{2}$$

Where a_i, b_i, c_i is representing the cost coefficient of the ith generator.

The various constraints that need to be satisfied during optimization are as follows,

(1) An equality constraint such as power flow balance (i.e. Kirchoff's laws) is represented as:

$$P_D - P_G + P_L = 0 \tag{3}$$
$$Q_D - Q_G + Q_L = 0 \quad (P \varepsilon L_B)$$

Where D represents the demand, G represents the generation and L represents the transmission loss.

(2) The capacity or in-equality constraints i.e. all variables limits and function limits, such as upper and lower bounds of transmission lines, generation outputs, stability and security limits may be given as follows,

(i) The maximum and minimum real and reactive power outputs of the generating sources are given by,

$$PG_i^{\min} \leq PG_i \leq PG_i^{\max} \quad (i \varepsilon G_B) \tag{4}$$

$$QG_i^{\min} \leq QG_i \leq QG_i^{\max} \quad (i \varepsilon G_B) \tag{5}$$

Where $PG_i^{\min}, PG_i^{\max}$ are the minimum and maximum real power outputs of the generating sources and $QG_i^{\min}, QG_i^{\max}$ are the minimum and maximum reactive power outputs.

(ii) Voltage limits (Minimum and Maximum) signals the system bus voltages to remain within a narrow range. These limits may be expressed by the following constraints,

$$\left| V_i^{\min} \right| \leq \left| V_i \right| \leq \left| V_i^{\max} \right| \quad (i = 1, \ldots, N_B) \tag{6}$$

Where N_B represents number of buses.

(iii) Power flow limits refer to the transmission line's thermal or stability limits capable of transmitting maximum power represented in terms of maximum MVA flow through the lines and it is expressed by the following constraints,

$$P_f^{\min} \leq P_f \leq P_f^{\max} \quad (f = 1, \ldots, NOELE) \tag{7}$$

Where NOELE represents number of transmission lines connected to grid.

(iv) Power angle limits of the bus admittance matrix and may be expressed by,

$$\theta_i^{\min} \leq \theta_i \leq \theta_i^{\max} \quad (i = 1, \ldots, N_B) \tag{8}$$

C. Nodal Price:

This OPF uses the bids and offers submitted by the participants and sets the nodal prices (that are obtained as the Lagrangian multipliers), which are in turn used to charge for the power consumption at every node. The prices of real and reactive powers at bus 'i' are the Lagrangian multiplier value of the equality constraints, that is, the real and reactive power flow equation of bus i. The Lagrangian multiplier values are calculated by solving the first order condition of the Lagrangian, partial derivatives of the Lagrangian with respect

to every variables concerned. Therefore the Lagrangian function (or system cost) of equation (1) - (8) defined as,

$$L = F + \sum_{i\varepsilon LB} \lambda p_i(P_{Di}-P_{Gi}+P_{Li}) + \sum_{i\varepsilon LB} \lambda q_i(Q_{Di}-Q_{Gi}+Q_{Li})$$
$$+ \sum_{i\varepsilon GB} \rho p_{li}(PG_i^{min} - PG_i) + \sum_{i\varepsilon GB} \rho p_{ui}(PG_i - PG_i^{max})$$
$$+ \sum_{i\varepsilon LB} \rho q_{li}(QG_i^{min} - QG_i) + \sum_{i\varepsilon GB} \rho q_{vi}(QG_i - QG_i^{max})$$
$$+ \sum_{i=1}^{NB} \rho V_{li}(|V_i^{min}| - |V_i|) + \sum_{i=1}^{NB} \rho V_{ui}(|V_i| - |V_i^{max}|)$$
$$+ \sum_{i=1}^{NB} \rho \theta_{li}(\theta_i^{min} - \theta_i) + \sum_{i=1}^{NB} \rho \theta_{ui}(\theta_i - \theta_i^{max})$$
$$+ \sum_{i=1}^{Noele} \rho F_{li}(P_{fi}^{min} - P_{fi}) + \sum_{i=1}^{Noele} \rho F_{ui}(P_{fi} - P_{fi}^{max}) \quad (9)$$

Where, 'l' and 'u' is the lower and upper limits. Therefore,

$$L= \sum_{i=1}^{NG} a_i PG_i^2 + b_i PG_i + c_i + \sum_{i\varepsilon LB} \lambda p_i(P_{Di}-P_{Gi} + P_{Li})$$
$$+ \sum_{i\varepsilon LB} \lambda q_i(Q_{Di}-Q_{Gi} + Q_{Li}) + \sum_{i\varepsilon GB} \rho p_{li}(PG_i^{min} - PG_i)$$
$$+ \sum_{i\varepsilon GB} \rho p_{ui}(PG_i - PG_i^{max}) + \sum_{i\varepsilon LB} \rho q_{li}(QG_i^{min} - QG_i)$$
$$+ \sum_{i\varepsilon GB} \rho q_{vi}(QG_i - QG_i^{max}) + \sum_{i=1}^{NB} \rho V_{li}(|V_i^{min}| - |V_i|)$$
$$+ \sum_{i=1}^{NB} \rho V_{ui}(|V_i| - |V_i^{max}|)$$
$$+ \sum_{i=1}^{NB} \rho \theta_{li}(\theta_i^{min} - \theta_i) + \sum_{i=1}^{NB} \rho \theta_{ui}(\theta_i - \theta_i^{max})$$
$$+ \sum_{i=1}^{Noele} \rho F_{li}(P_{fi}^{min} - P_{fi}) + \sum_{i=1}^{Noele} \rho F_{ui}(P_{fi} - P_{fi}^{max}) \quad (10)$$

Where $\lambda = (\lambda_1, \ldots, \lambda_n)$ is the vector of Lagrange multipliers concerning the power balance constraints, and $\rho = (\rho_1, \ldots, \rho_n)$ are the Lagrange multiplier value (or dual variables) related to equation (3) to (5) respectively. μ and l are the vectors of multipliers concerning the bus voltages, line power flows and generation constraints respectively. In the solution point the vector λ comprises the system nodal prices. Then at an optimal solution (V, λ, ρ) and for a set of given (P, Q), the nodal price of real and reactive power for each bus are expressed below (for i= 1,……,n),

$$\Pi_{P,i} = \frac{\partial L(V,\lambda,\rho,P,Q)}{\partial P_K} = \frac{\partial F}{\partial P_K} + \lambda \frac{\partial G}{\partial P_K} + \rho \frac{\partial H}{\partial P_K} \quad (11)$$

$$\Pi_{Q,i} = \frac{\partial L(V,\lambda,\rho,P,Q)}{\partial Q_K} = \frac{\partial F}{\partial Q_K} + \lambda \frac{\partial G}{\partial Q_K} + \rho \frac{\partial H}{\partial Q_K} \quad (12)$$

Here the eqn.(11) represents the nodal price of real power at bus 'i' can be viewed as the system marginal cost (the sum of a marginal generation cost plus a set of premiums corresponding to their respective constraints) created by an increment of real power load at bus-i. The same explanation is also applicable to the nodal price of reactive power as shown in eqn.(12).

V. PROBLEM AND EXAMPLES

A: Test Example1: IEEE 30 Bus System:

A IEEE 30-bus test system with 6 generating units and 41-transmission lines is shown in Fig. 1. The upper and lower bounds (real power) for generators G1, G2, G5, G8, G11 and G13 are shown in table 1. Also the upper and lower bounds (reactive power) for all generators i.e. G1, G2, G5, G8, G11 and G13 are $-0.7 \leq q_{Gi} \leq 0.7$. The voltage values for all buses are bounded between 0.95 and 1.05. The fuel cost function for generators is expressed as $(f_i = a_i p_{Gi}^2 + b_i p_{Gi} + c_k)$ in (\$/hour) is shown in table 1. The loads at various buses are shown in table 2. All of the values are indicated by p.u. By applying the nodal pricing methodology, the nodal prices of real power at various power flow constraints are given in the table 3. The impact of Generation on nodal prices are Shown in Fig.2 for the following cases: Case-1: G5 with capacity of 1.5 p.u.; Case-2: All generators are of equal capacity 1.0 p.u.; Case-3: G5 and G13 are reduces to capacity to 0.5; Case-4: G5 and G13 are reduces to capacity to 0.15.
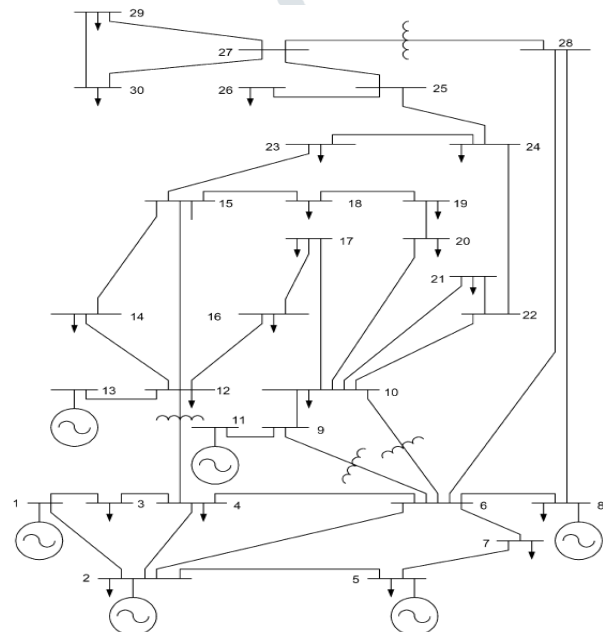

Fig. 1: IEEE 30-bus standard test system

Table 1: Real Power and Fuel cost of generator

Bus No. (Generator)	Lower Limit	Upper Limit	Generation cost		
			a_i	b_i	c_i
1	0.1	1.5	0.14	20.4	5.0
2	0.1	1.0	0.20	19.3	5.0
5	0.1	1.5	0.10	15.0	5.0
8	0.1	1.0	0.20	19.3	5.0
11	0.1	1.0	0.14	20.4	5.0
13	0.2	1.5	0.10	15.0	5.0

Table 2: Demand (p_i+jq_k) for IEEE 30-Bus System

Bus	Demand	Bus	Demand	Bus	Demand
1	0.00+j0.00	11	0.00-j0.177	21	0.175+j0.112
2	-0.217+j0.13	12	0.112+j0.00	22	-0.00+j0.00
3	0.024+j0.012	13	0.00-j0.155	23	0.032+j0.016
4	0.076+j0.016	14	0.062+j0.016	24	0.087+j0.067
5	0.942+j0.019	15	0.082+j0.025	25	0.00+j0.00
6	0.00+j0.00	16	0.035+j0.018	26	0.035+j0.023
7	0.228+j0.109	17	0.090+j0.058	27	0.00-j0.10
8	0.30-j0.30	18	0.032-j0.009	28	0.00+j0.00
9	0.00+j0.00	19	0.095+j0.034	29	0.024+j0.009
10	0.058+j0.00	20	0.022+j0.007	30	0.106+j0.00

Table 3: Nodal Price: IEEE 30-Bus Standard Test System

Bus No.	Volts	Ang (Rad)	P_G (PU)	Q_G (PU)	Nodal Price
1	105.00	-0.05	0.10	0.08	15.61
2	105.00	0.05	0.10	0.09	15.63
3	104.94	0.04	0.00	0.00	15.70
4	104.88	0.04	0.00	0.00	15.71
5	105.00	0.08	1.49	-0.08	15.30
6	104.56	0.03	0.00	0.00	15.85
7	103.84	0.04	0.00	0.00	15.76
8	104.77	0.02	0.10	-0.21	15.91
9	103.50	0.01	0.00	0.00	16.08
10	103.04	-0.01	0.00	0.00	16.22
11	105.00	0.03	0.10	-0.10	16.08
12	104.06	0.08	0.00	0.00	15.24
13	105.00	0.21	1.00	-0.02	15.20
14	102.67	0.06	0.00	0.00	15.60
15	101.84	0.04	0.00	0.00	15.95
16	102.67	0.04	0.00	0.00	15.78
17	102.32	0.00	0.00	0.00	16.17
18	101.22	0.01	0.00	0.00	16.29
19	100.97	0.00	0.00	0.00	16.43
20	101.39	-0.01	0.00	0.00	16.39
21	101.63	-0.02	0.00	0.00	16.50
22	101.64	-0.02	0.00	0.00	16.53
23	100.47	-0.04	0.00	0.00	16.59
24	099.71	-0.04	0.00	0.00	17.31
25	098.05	-0.11	0.00	0.00	19.16
26	095.00	-0.13	0.00	0.00	19.99
27	098.85	-0.14	0.00	0.00	19.93
28	104.75	0.03	0.00	0.00	15.86
29	097.13	-0.16	0.00	0.00	20.58
30	096.31	-0.18	0.00	0.00	21.02

Fig: 2: Impact of Generation on Nodal Prices

B. Example 2: 400KV MSETCL Network.

A real network at peak load condition is selected (shown in fig.3). The peak load condition is computed by analyzing maximum load served at various buses during 24 hours. The upper and lower bounds for generators are allocated as shown in Table 4. The voltage values for all buses are bounded between 0.96 and 1.04. The fuel cost function for intra-state generation and inter-state power purchase from generators expressed as ($f_i = a_i p^2_{Gi} + b_i p_{Gi} + ck$) in (Rs. /KWh) is shown in Table 5. The real power loads on network at various buses are shown in Table 6. The active power flow constraints of intra-state transmission line lies between -0.5 and 0.5, and that for inter-state lines is -1.0 and 1.0. All the values are indicated in p.u. For this system there are total 282 constraints. By applying the nodal pricing methodology, the nodal prices for real power are given in Table 7.
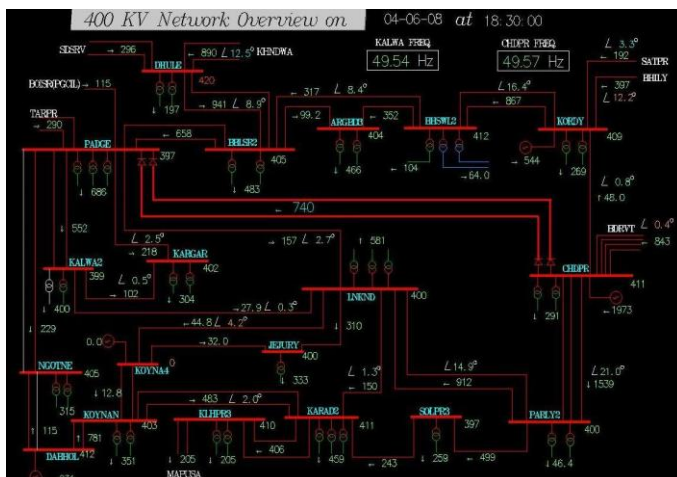

Fig 3: 400 KV Network, MSETCL

Table 4: Generation Data (MW)

Generator	Intra-state Generation Real Power		Generator	Inter-state Power Purchase Real Power	
	Max	Min		Max	Min
C'PUR (G1)	2300	200	BHILY	0600	100
KORADY (G2)	1060	200	KHANDWA	0700	200
DABHOL (G3)	0610	200	SDSRV	0500	010
KOYNA-4 (G4)	2300	100	BOISR	0200	010
			BDRVT	1900	200
			TARAPUR	0400	010
			SATPUR	0110	010

Table 5: Fuel Costs of Generators (Rs./KWh)

Generator	Generation cost			Generator	Purchase cost		
	a_i	b_i	c_i		a_i	b_i	c_i
C'PUR	0.0	1.0	0.0	BHILY	0.0	1.81	0.0
KORADY	0.0	1.1	0.0	KHANDWA	0.0	1.81	0.0
DABHOL	0.0	3.5	0.0	SDSRV	0.0	4.18	0.0
KOYNA	0.0	1.0	0.0	BOISR	0.0	2.73	0.0
				BDRVT	0.0	1.15	0.0
				TARAPUR	0.0	2.87	0.0
				SATPUR	0.0	2.73	0.0

Table 6: The Real Power Peak Demand

Bus No.	Load (MW)	Bus No.	Load (MW)	Bus No.	Load (MW)
1	360	8	589	14	000
2	421	9	252	15	243
3	451	10	746	16	352
4	448	11	292	17	355
5	480	12	000	18	346
6	418	13	318	19	389
7	701				

Table 7: Electricity Nodal Price (Without HVDC Link)

Bus No	Bus Name	Volt. (V)	Angle (Rad)	P_G (pu)	Nodal Price
1	C'PUR	380.00	-2.35	1.44	1.03
2	KORDY	414.73	-2.36	0.54	2.02
3	BHSWL2	420.00	-2.68	0.00	3.93
4	ARGBD4	419.29	-2.78	0.00	4.54
5	BBLSR2	419.30	-2.79	0.00	5.17
6	DHULE	420.00	-2.63	0.00	5.08
7	PADGE	413.92	-2.90	0.00	6.11
8	KALWA	413.60	-2.91	0.00	6.20
9	KARGAR	413.65	-2.91	0.00	6.19
10	LONKD	408.68	-2.90	0.00	7.35
11	N'TNE	400.16	-2.88	0.00	4.60
12	DABHOL	380.00	-2.81	1.44	2.64
13	KOY-N	390.35	-2.88	0.00	12.58
14	KOY-4	390.94	-2.88	0.19	12.21
15	KLHPR3	408.72	-2.97	0.00	13.53
16	JEJURY	400.11	-2.92	0.00	9.76
17	KARAD2	400.21	-2.92	0.00	13.50
18	SOLPR3	398.80	-2.85	0.00	23.03
19	PARLY2	397.77	-2.68	0.00	0.91

Interstate Power Purchase (MW) : BHILY: 600MW; KHANDWA: 890MW; SDSRV: 300 MW; BOISR: 120MW; BDRVT: 100 MW; TARAPUR: 490MW; SATPUR: 90MW

Table 7: Electricity Nodal Price (With HVDC Link)

Bus No	Bus Name	Volt. (V)	Angle (Rad)	P_G (pu)	Nodal Price
1	C'PUR	380.00	-2.51	-1.72	1.03
2	KORDY	420.00	-2.54	0.54	1.32
3	BHSWL2	420.00	-2.80	0.00	1.91
4	ARGBD4	415.08	-2.89	0.00	2.10
5	BBLSR2	410.38	-2.88	0.00	2.28
6	DHULE	417.11	-2.73	0.00	2.23
7	PADGE	392.47	-2.97	0.00	2.58
8	KALWA	392.50	-2.99	0.00	2.58

9	KARGAR	392.44	-2.99	0.00	2.58
10	LONKD	393.27	-3.01	0.00	2.58
11	N'TNE	388.86	-2.99	0.00	2.81
12	DABHOL	380.00	-2.96	1.10	3.07
13	KOY-N	383.77	-3.02	0.00	3.22
14	KOY-4	383.10	-3.02	0.00	3.18
15	KLHPR3	400.24	-3.11	0.00	3.61
16	JEJURY	388.41	-3.05	0.00	2.89
17	KARAD2	391.99	-3.06	0.00	3.60
18	SOLPR3	391.99	-2.98	0.00	6.03
19	PARLY2	392.83	-2.82	0.00	0.52
Interstate Power Purchase (MW) : BHILY: 400MW; KHANDWA: 890MW; SDSRV: 270 MW; BOISR: 120MW; BDRVT: 840 MW; TARAPUR: 290MW; SATPUR: 10MW					

In light of the national power shortages (about 70,000MW), the state of Maharashtra is also facing severe power shortages (about 4500MW) at peak hours. Power utility in the state of Maharashtra is making all efforts to procure extra power and through effective load management. In peak load condition, nodal prices at all buses except at Kordy and C'pur are high. This is due to huge active power deficit, congestion of the transmission lines due to less investment in the transmission sector and rising power demand. For efficient power trading and to make wholesale electricity market more competitive, need is to pour large value of active power at the intra-state level. Since several years no such new generation is added except the IPP like Dabol irrespective of rising demand in Maharashtra. Similarly new investment in transmission segment is also needed at C'Pur-Kordy (S/C), Kordy-Bhswl2 (D/C), Bhswl2-ARGBD3 (S/C), Parly2-Solpr3 (S/C) and Chdpr-Parly2 (D/C) transmission lines where the nodal prices is high. In open access, MSETCL need to confront these issues so as to make wholesale electricity market more competitive and to achieve the market leadership in Maharashtra.

C. Impact of Electricity Generation on Nodal Prices:
The impact of hydro generation (Koyna) on nodal prices with existing transmission capacity is shown in fig. 4. The prices vary at each node. So at peak condition, hydro generation plays an important role to reduce the prices at various nodes.

Fig 4. Impact of Hydro Generation on Nodal Prices

D. Impact of Transmission Expansion on Nodal Prices:
The Nodal prices at peak load condition are high for the existing network under study. Also with the pace of rising demand in Maharashtra, existing transport network will not be able to accommodate the new demand in future, and hence will not promote the required competition. So, present Intra-state transmission capacity needs to be increased i.e. to be doubled with an expected investment in reference to lines mentioned in table 8. The return on new added investment for years can be computed by calculating simple payback period is as follows:

Simple Payback Period (SPP) Calculation: It considered the initial investment costs and the resulting annual cash inflow to evaluate the viability of investment. The payback period is the length of time needed before an investment makes enough to recoup the initial investment. It is calculated as,

$$PaybackPeriod\ (in\ years) = \frac{Initial\ Investment}{AnnualSavings(Cash\ Flow)}$$

For evaluating the investment made to incorporate new transmission lines in the existing network, the annual savings can derived in terms of accommodating peak and new loads by offering marginal pricing at that node, collection of transmission use charges and promoting uniform competitions over the network. In this case, assuming annual cash inflow of Rs. 200 Million, the respective added transmission line single circuit(S/C) or doubled Circuit (D/C) SPP is given in Table 8.

Table 8: Transmission Line Capacity Expansion and Expected Investment

Name of Line	Existing Capacity (MVA)	Added Capacity (MVA)	Investment (USD Million)	SPP (Years)
C'Pur-Kordy (S/C)	500	500	10.30	2.02
Kordy-Bhswl2 (D/C)	500	500	87.28	17.15
Bhswl-ARGBD(S/C)	500	500	14.12	2.78
Parly2-Solpr3 (S/C)	500	500	19.47	3.83
Chdpr-Parly2 (D/C)	500	500	134.73	26.48

By assuming the availability of needed investment with reference to Table 8, the nodal prices obtained and inter-sate power purchases are shown in Table 9.

Table 9: Nodal Electricity Price (Rs./KWh)

Bus No	Bus Name	Voltage (Volt)	Angle (Rad)	P_G (PU)	Nodal Price
1	C'PUR	420.00	0.55	2.30	1.65
2	KORDY	420.00	0.46	1.00	1.68
3	BHSWL2	409.68	-0.01	0.00	1.84
4	ARGBD4	413.28	-0.12	0.00	1.88
5	BBLSR2	418.27	-0.14	0.00	1.88
6	DHULE	420.00	-0.11	0.00	1.87
7	PADGE	412.41	-0.16	0.00	1.89
8	KALWA	412.04	-0.17	0.00	1.89
9	KARGAR	412.16	-0.18	0.00	1.89
10	LONKD	407.80	-0.16	0.00	1.89
11	N'TNE	405.95	-0.17	0.00	1.89
12	DABHOL	393.30	-0.14	0.20	1.88
13	KOY-N	392.22	-0.14	0.00	1.88
14	KOY-4	389.76	-0.13	1.00	1.88
15	KLHPR3	412.24	-0.19	0.00	1.89
16	JEJURY	398.95	-0.18	0.00	1.89
17	KARAD2	402.77	-0.16	0.00	1.89
18	SOLPR3	401.67	-0.08	0.00	1.86
19	PARLY2	403.81	0.11	0.00	1.80
Power Purchase (MW): BHILY: 100MW; KHANDWA: 520MW; SDSRV: 100MW; BOISR: 100MW; BDRVT: 1900MW; TARAPUR: 100MW; SATPUR: 100MW					

The obtained nodal prices at various buses are comparably low and almost uniform at all buses. Also the line flow congestion is reduced considerably and now it is possible to accommodate the new loads in future. This will also promote the required competition uniformly distributed at all nodes. With the maximum availability of Intra-state generation, the new transmission investment scheme reduces the dependability of the costly inter-state power purchases at peak condition. In this way MSETCL may achieve economic advantages.

E. Impact of Electricity Generation and Transmission Expansion on Nodal Prices:
The combine effect of added maximum generation (hydropower) with new transmission capacity as mentioned in

table 9 has resulted to lowest and uniform nodal prices at buses as shown in table 10. Such move can further reduce inter-state power purchases. At a whole this can promote competition in the wholesale electricity market from strategically located lower-cost units and demand response will benefit much of MSETCL, as the transmission grid is utilized more efficiently. Ultimately, increased competition may result in a more efficient wholesale energy market with lower costs. In this way MSETCL can gain economic advantages.

VI. CONCLUSION

With the pace of restructuring electric industry worldwide, transmission remains acts as a regulated monopoly. It also acts as a vital link between sellers and buyers and has long been a focus of academia and industry. Recently transmission pricing is playing an important role in motivating investors and the utility and to develop power market.

This paper presented basics of transmission pricing under power system restructuring in general and optimal nodal pricing in particular. The purpose was:

- To formulate optimal Nodal pricing methodology most suitable to real transmission network situation in India.
- To contribute and suggest the simplicity of implementation of Nodal pricing to system operator, regulatory commissions and utility with reference to Maharashtra state.
- To suggest the economic advantages of generation and transmission investment for wholesale electricity markets like India.

Finally the proposed optimal nodal pricing can ensure economic advantages, system security and reliability for the MSETCL and help in achieving transmission tariff objectives.

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