OPTIMAL ELECTRICITY NODAL PRICE BEHAVIOUR: A STUDY IN INDIAN ELECTRICITY MARKET

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ABSTRACT

In the past decades, electricity markets have significantly restructured in developing countries. The electricity nodal pricing has emerged as an efficient tool under it. Recently, the incorporation of High Voltage Direct Current (HVDC) link in AC network brought significant techno-commercial changes in the electricity markets in developing countries. This paper aims at (1) the motivation and need to study electricity nodal pricing, (2) optimal nodal price formulation with incorporation of HVDC link in a AC transmission system, (3) testing of the methodology on IEEE 30-bus system and computation of nodal prices for real transmission network of India and (4) to assess the combined impact of transmission investment, incorporation of DC link, generation addition on electricity nodal prices. Paper concludes that the nodal prices are reduced with the incorporation of DC link and generation addition is one of the requirements to encourage competition in the wholesale electricity market.

Keywords – *Electricity Market, AC-DC Optimal Power Flow, Nodal Prices*

1. INTRODUCTION

In the past decades, electricity markets have significantly restructured throughout the world with a process of breaking up vertically integrated electricity utilities, introduction of regulations and commercial interfaces between the functions of generation, transmission, distribution of electrical energy. The electric power industry has now entered in an increasingly competitive environment under which it becomes more realistic to improve economics and reliability of power systems by enlisting market forces [1]. Also in developing countries, the trend of electricity market is heading towards *Transmission Open Access* whereby transmission providers will be required to offer the basic transmission service (i.e. operational and/or ancillary services) and pricing [3]. Optimal nodal pricing in this context is one of the effective pricing schemes for providing a higher profit to both the utility and the customers. [1]-[7]. Nodal prices contain valuable information useful for *Poolco* operation and, hence the scheme is to accurately determine them, continue to be an active area of research [1]-[7]. The purpose to develop nodal price theory is to bring efficient use of transmission grid and generation resources by providing correct economic signals.

In the coming years, power consumption in developing and transition countries is expected to more than double, whereas in developed countries, it will increase only for about 35-40%. Also many developing and transition countries are facing the problems of infrastructure investment especially in transmission and distribution segment due to inadequate investments incurred in the past. To reduce the gap between transmission capacity and power demand, trend is to adopt HVDC transmission system in the existing AC networks to gain techno-economical advantages of the investment. Under such scenario, it is obvious to address this trend in designing optimal nodal pricing scheme.

In India, the Electricity Act (EA) 2003 has implemented to undertake comprehensive market reforms in the electricity sector. *Transmission Open Access* (TOA) and *National Tariff Policy* by Ministry of Power, Government of India (GoI) 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, (3) to attract the required investments in the transmission sector and to provide adequate returns.

This study proposed AC-DC based optimal electricity nodal pricing scheme can be more suitable for similar developing countries including India.

After this introduction, section 2 provides background and motivation of the present work related to electricity nodal pricing. Section 3 provides the need of modeling electricity nodal prices. Section 4 briefs the optimal AC-DC based nodal pricing methodology. In section 5, nodal prices are computed and compared over modified IEEE-30 Bus and real transmission network of India. Impact of incorporating HVDC link and generation addition on electricity nodal prices are computed and compared. Finally, the conclusions are presented in section 6.

2. RELATED WORK

The work on electricity pricing is reviewed as a background of the present work but with no intention to cover all the published work. [1] described a tool named WRATES, to evaluate marginal cost of wheeling. It computed network flows and losses using a modified DC load flow approximation and "sensitivity matrix" obtained from an AC power flow. [2] used a modified Optimal Power Flow (OPF) model which allowed for the price responsiveness of real power demand to analyze the effects of spot pricing policies. [3] developed spot price model by describing the meaning and numerical properties of the generation and transmission components based on "slack bus" and "system lambda". [4] introduced the reactive power pricing and revealed that lagrangian multiplier corresponding to node power balance equations in OPF represent the marginal costs of node power injections. [5] computes reactive power prices using decoupled OPF to obtain the short run marginal costing of active and reactive power respectively. Firstly, it introduced real power loss component into reactive power spot pricing whose objective function is real loss minimization. Secondly, the influence of reactive power on the voltage level appears in the pricing formulas. [6] used a coupled OPF to perform the operation of the *Poolco* model. Result was derived using linear programming theory, namely the decomposition of the Lagrangian multipliers corresponding to power balance equations into components which represented the sum of generation and losses and system congestion. It is interpreted as the sensitivity of the congestion constraints to additional load at the bus times the shadow prices for the constraints. [7] Introduced the concept of spot price into power systems. It provided the foundation and starting point for most successive research. [9] computed firstly time intervals for active generation of the pumped storage unit using incremental cost and pseudo spot price. Secondly the pseudo active generating/pumping incremental cost value of the pumped-storage hydraulic unit is determined according to its net water usage. [10] presented an integrated spot pricing model included derivation of optimal nodal specific real-time prices for active and reactive powers and the method to decompose it into generation, loss, and selected ancillary services such as spinning reserve, voltage control and security control. This scheme is designed by modifying Newton OPF method by Interior Point algorithms. [11] investigated pricing behavior at New Zealand spot market, called "Price Inversion" through the dc power flow and a full ac power flow. It was shown dependent on the physical characteristics of the power system. [12] provided a detailed description of spot price scheme along with the components of nodal price i.e. generation, transmission congestion, voltage limitations and other constraints. [13] presented a new model for efficient calculation of spot prices, animation and visualization of spot price evolution based on the quadratized power flow approach. [14] proposed a novel technique for representing system security in the operations of decentralized electricity markets, with special emphasis on voltage stability. An Interior Point method was used to solve the OPF problem with a multi-objective function for maximizing both social benefit and the distance to maximum loading conditions. This technique is able to improve system security while yielding better market conditions through increased transaction levels and improved Locational Marginal Prices (LMP). [15] discussed the pricing of marginal transmission network losses in the LMP deployed in the ISO New England standard market design project carried out by ALSTOM's T&D Energy Automation and Information Business. This model achieves market-clearing results by introducing loss distribution factors to balance explicitly the consumed losses in the lossless DC power system. The distributed market slack reference is also introduced and discussed. [16] provided explicit formulas to calculate components of LMPs i.e. the reference price, the congestion price, and the loss price based on the single-slack power-flow formulation. [17] provided expressions to compute the sensitivities of LMPs with respect to power demands under OPF market clearing framework. [18] presented an approach for the allocation of transmission network costs by controlling the nodal electricity prices. It introduces generation and nodal injection penalties into the economic dispatch to create nodal price differences that recover the required transmission revenue from the resulting congestion rent. The new electricity prices reflect both the marginal costs of production subject to transmission constraints and the capital costs of the network. [19] presented a new energy reference bus independent LMP decomposition model using an AC OPF to overcome the reference bus dependency disadvantage. The marginal effect of the generators' output variations with respect to load variation was used as the basis. [20] presented various electricity price forecasting techniques which can be useful at different time horizons for price forecasting in LMP spot markets. Fuzzy inference system, least-squares estimation, and the combination of both were proposed to improve the short-term forecasting performance. [21] provided an iterative DCOPF-based algorithm to calculate LMPs and it is employed to analyze the sensitivity of LMP of the system load.

3. NEED OF MODELING NODAL PRICES

In a restructured electricity market, generating companies offer specific amounts of generation to the wholesale (or spot) market at specific cost per unit. An Independent System Operator (ISO) then equilibrates that aggregate market supply (i.e. all the generation offered) with demand (load), setting a spot price where the supply and demand curve intersect and thereby clearing the market.

In the past decade, increased deregulation within electricity markets both in developed and developing countries has resulted in competition between the power generating companies. Also the reductions in regulation and government price setting in the market have led to wholesale electricity spot market prices becoming much more volatile. This further resulted electricity market participants facing increased risk, both in terms of volumes of electricity they can produce and sell, and the prices they will receive for their outputs. To facilitate market participants with respect to operations, risk management, and investment, need is to accurately model spot price behaviour. Aside from generators, investors and consumers, regulatory bodies, also require models of spot prices in order to study market behaviour. Also often forecast and models of spot prices are required for many different applications in the operation of electricity markets. For example, in short-run, generating companies have to make decisions regarding unit commitment. They would only want their generators to be dispatched if it is going to be profitable to do so, and as these decisions are often required hours or days in advance, they require forecast of future spot prices in order to determine profitability. In the medium term, generating companies whose plants need periodic maintenance require spot price forecast in order to determine the time to take their plants offline that will have the least impact on their profit levels. In the longer term, potential investors in new or existing power plants also need forecasts of spot prices in order to determine the potential profitability of (and return on) their investment. Many other industries use and pay for electricity as an important input in their operations, and they also require forecasts of spot prices in order to determine their own profitability. In many markets around the world, these users are able to purchase contracts for electricity at a fixed price over a specified time period. The valuation of such financial derivatives requires estimation of both the likely levels and volatility of spot prices in order to determine what that fixed price should be, as well as fair price for the contract itself.

4. ELECTRICITY NODAL PRICE FORMULATION

To induce efficient use of the transmission grid and generation resources by providing correct economic signals, a nodal price or spot price theory for the deregulated power systems was developed [7]. Nodal pricing is a method to determine market clearing prices for several 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. This pricing provides market participants a clear and accurate signal of the price of electricity at every location on the grid. These prices, in turn, reveal the value of locating new generation, upgrading transmission, or reducing electricity consumption, elements needed in a well-functioning market to alleviate constraints, increase competition and improve the systems' ability to meet power demand. It increases the efficiency of a competitive wholesale energy market. Method also provides greater transparency for regulators seeking to ensure reliability and affordability of energy.

4.1 Problem Formulation:

4.1.1 AC System Equations

Let P = (p_1,…..,p_n) and Q = (q_1,…..,q_n) for a n buses system, where p_i and q_i be active and reactive power demands of bus-i, respectively. The variables in power system operation to be X = (x_1,….,x_m), such as real and imaginary parts of each bus voltage. So the operational problem of a power system for given load (P, Q) can be formulated as OPF problem [12].

Minimize f (X, P, Q) for X

(1)

Subject to S (X, P, Q) = 0

(2)

T (X, P, Q) ≤ 0

(3)

Where S (X) = (s_1(X, P, Q),……., s_{n1}(X, P, Q)$)^T$ and T (X) = (t_1(X, P, Q),……., t_{n2}(X, P, Q)$)^T$ have n_1 and n_2 equations respectively, and are column vectors. Here A^T represents the transpose of vector A.

f (X, P, Q) is a scalar, short term operating cost, such as fuel cost. The generator cost function $f_i(P_{Gi})$ in \$/MWh is considered to have cost characteristics represented by,

$$f = \sum_{i=1}^{NG} a_i P_{Gi}^2 + b_i P_{Gi} + c_i$$

(4)

Where, P_{Gi} is its real power output; a_i, b_i and c_i represents the cost coefficient of the i^{th} generator, NG represents the generation buses.

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

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

S (X, P, Q) = 0 or

$P_G = P_D + P_{DC} + P_L$ and

$$Q_G = Q_D + Q_{DC} + Q_L \qquad (5)$$

Where suffix D represents the demand, G is the generation, DC represents dc terminal and L is the transmission loss.

(2) The vector, inequality constraints including limits of all variables 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 represented as,

T (X, P, Q) ≤ 0 or

(6)

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

$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}$ ($i \in G_B$) and

$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}$ ($i \in G_B$)

(7)

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

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

$\left|V_i^{\min}\right| \le \left|V_i\right| \le \left|V_i^{\max}\right|$ (i= 1,……,N_B)

(8)

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,

$P_f^{\min} \le P_f \le P_f^{\max}$ (f= 1,………, $Noele$)

(9)

Where, $Noele$ represents number of transmission lines connected to grid.

The operating condition of the combined ac-dc electric power system is described by the vector

$$X = [\delta, V, x_c, x_d]^t$$

(10)

Where, δ and V are the vectors of the phases and magnitude of the phasor bus voltages; x_c is the vector of control variables and x_d is the vector of dc variables.

4.1.2 DC System Equations

The following relationship is for the dc variables. Using the per unit system [8], the average value of the dc voltage of a converter connected to bus 'i' is

$$V_{di} = a_i V_i \cos\alpha_i - r_{ci} I_{di}$$

(11)

Where, α_i is the gating delay angle for rectifier operation or the extinction advance angle for inverter operation; r_{ci} is the commutation resistance, and a_i is the converter transformer tap setting.

By assuming a lossless converter, the equation of the dc voltage is given by

$$V_{di} = a_i V_i \cos\varphi_i \qquad (12)$$

Where, φ_i = δ_i-ξ_i, and φ is the angle by which the fundamental line current lags the line-to-neutral source voltage.

The real power flowing into or out of the dc network at terminal 'i' can be expressed as

$$P_{di} = V_i I_i \cos\varphi_i \quad \text{or} \quad P_{di} = V_{di} I_{di} \qquad (13)$$

The reactive power flow into the dc terminal is

$$Q_{di} = V_i I_i \sin\varphi_i \quad \text{or} \quad Q_{di} = V_i a I_i \sin\varphi_i \qquad (14)$$

The equation (4.13) and equation (4.14) could be substituted into the equations (4.5) to form part of the equality constraints.

Based on these relationships, the operating condition of the dc system can be described by the vector

$$X_d = [V_d, I_d, a, \cos\alpha, \varphi]^t \qquad (15)$$

The dc currents and voltages are related by the dc network equations. As in the ac case, a reference bus is specified for each separate dc system; usually the bus of the voltage controlling dc terminal operating under constant voltage (or constant angle) control is chosen as the reference bus for that dc network equation.

Here (1) – (3) are an OPF problem for the demand (P, Q). There are many efficient approaches which can be used to get an optimal solution such as linear programming, Newton method, quadratic programming, nonlinear programming, interior point method, artificial intelligence (i.e. artificial neural network, fuzzy logic, genetic algorithm, evolutionary programming , ant colony optimization and particle swarn optimization etc.) methods [12, 22].

4.1.3 Nodal Price

The real and reactive power prices at bus 'i' is the Lagrangian multiplier value of the equality and in-equality constraints. 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) - (3) defined as,

$$L(X,\lambda,\rho,P,Q) = f(X,P,Q) + \lambda S(X,P,Q) + \rho T(X,P,Q)$$

or

$$\begin{aligned}
L = {} & \sum_{i=1}^{NG} a_i P_{Gi}^2 + b_i P_{Gi} + c_i + \sum_{i\in LB} \lambda pi(P_{Di} - P_{Gi} + P_{DCi} + P_{Li}) + \\
& \sum_{i\in LB} \lambda qi(Q_{Di} - Q_{Gi} + Q_{DCi} + Q_{Li}) \\
& + \sum_{i\in GB} \rho\, p_{li}(P_{Gi}^{\min} - P_{Gi}) + \sum_{i\in GB} \rho\, p_{ui}(P_{Gi} - P_{Gi}^{\max}) + \\
& \sum_{i\in GB} \rho\, q_{li}(Q_{Gi}^{\min} - Q_{Gi}) + \sum_{i\in GB} \rho\, q_{ui}(Q_{Gi} - Q_{Gi}^{\max}) \\
& + \sum_{i=1}^{NB} \rho V_{li}\left(\left|V_i^{\min}\right| - \left|V_i\right|\right) + \sum_{i=1}^{NB} \rho V_{ui}\left(\left|V_i\right| - \left|V_i^{\max}\right|\right) + \\
& \sum_{i=1}^{NB} \rho\,\theta_{li}(\theta_i^{\min} - \theta_i) + \sum_{i=1}^{NB} \rho\,\theta_{ui}(\theta_i - \theta_i^{\max}) \\
& + \sum_{i=1}^{Noele} \rho P_{fli}(P_{fi}^{\min} - P_{fi}) + \sum_{i=1}^{Noele} \rho P_{fui}(P_{fi} - P_{fi}^{\max})
\end{aligned} \qquad (16)$$

Where, 'l' and 'u' are the lower and upper limits; λ= (λ_1, …….,λ_n) is the vector of Lagrange multipliers concerning the equality (power balance) constraints; ρ = (ρ_1, ……….,ρ_n) are the Lagrange multipliers concerning to the inequality constraints. Then at an optimal solution (X,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.

$$\pi_{p,i} = \frac{\partial L(X,\lambda,\rho,P,Q)}{\partial_{pi}} = \frac{\partial f}{\partial_{pi}} + \lambda\frac{\partial S}{\partial_{pi}} + \rho\frac{\partial T}{\partial_{pi}} \qquad (17)$$

$$\pi_{q,i} = \frac{\partial L(X,\lambda,\rho,P,Q)}{\partial_{qi}} = \frac{\partial f}{\partial_{qi}} + \lambda\frac{\partial S}{\partial_{qi}} + \rho\frac{\partial T}{\partial_{qi}} \qquad (18)$$

Here $\pi_{p,i}$ and $\pi_{q,i}$ are active and reactive nodal prices at bus 'i', respectively. The difference i.e. $\pi_{p,i}$ - $\pi_{p,j}$ and $\pi_{q,i}$ - $\pi_{q,j}$ represents active and reactive power transmission charges from bus-j to bus-i. Equation (17) can be viewed as the system marginal cost created by an increment of real power load at bus i. The above formulation was implemented in MATLAB using the '*fmincon*' function available in the optimization toolbox. An advantage of using the '*fmincon*' is that the constraints can be directly evaluated as functions of the state variables which can be separate modules reducing programming complexity.

5. PROBLEMS, SIMULATION AND EXAMPLES

5.1 Test Example1: Modified IEEE 30 Bus system:

The given scheme is tested over modified IEEE 30-bus system. It consists of 6 generators and 43 transmission lines are shown in Fig. A1(Appendix). A dc link is connected between bus 1 and bus 30. The ratings of the converter at buses 1 and 30 were 1.0 p.u. The upper and lower bounds (real power) for generators G1, G2, G13, G22, G23 and G27 are shown in Table A1. Also the upper and lower bounds (reactive power) for all generators i.e. G1, G2, G13, G22, G23 and G27 are $-0.4 \le Q_{Gi} \le 0.4$. The voltage values for all buses are bounded between 0.95 and 1.05. The fuel cost function for generators is expressed as $(f_i = a_i P_{Gi}^2 + b_i P_{Gi} + c_i)$ in ($/MWh) is shown in table A1. The demand at various buses is shown in table A2. All of the values are indicated by p.u. For this system there are 2 × 24 equalities constraints of S corresponding to their respective real and reactive power balances of the buses without a generator, and about 72 inequalities constraints of T corresponding of 30 pairs of voltage, 2 × 6 pairs of generation output and one pair of line flow upper and lower bounds respectively.

By applying the nodal pricing methodology, the optimal nodal prices of real power with and without HVDC links are computed and compared as shown in the Table 5.1. The electricity nodal prices are reduced with the incorporation of DC link in AC system.

Table 5.1: Nodal Price: IEEE 30-Bus Test System

Bus No.	**Nodal Price** ($/MWh)		**Bus No.**	**Nodal Price** ($/MWh)	
	Without DC link	DC Link		Without DC link	DC Link
1	19.54	15.19	16	19.70	15.06
2	19.62	15.27	17	20.03	14.95
3	19.52	15.00	18	19.94	15.05
4	19.51	14.94	19	20.16	15.11
5	20.95	16.17	20	20.16	15.05
6	19.72	14.97	21	19.67	14.04
7	20.30	15.52	22	19.47	13.73
8	19.84	15.07	23	18.88	13.88
9	19.92	14.86	24	18.57	12.84
10	20.02	14.82	25	16.09	9.11
11	19.91	14.86	26	15.29	7.89
12	19.15	15.10	27	15.10	7.66
13	15.20	15.10	28	19.74	14.99
14	19.43	15.19	29	15.49	7.85
15	19.38	14.83	30	15.75	7.99

The voltage behaviour is also shown in figure. 5.1. It was found that with the incorporation of DC link in existing AC system, voltage profiles at several buses are improved.

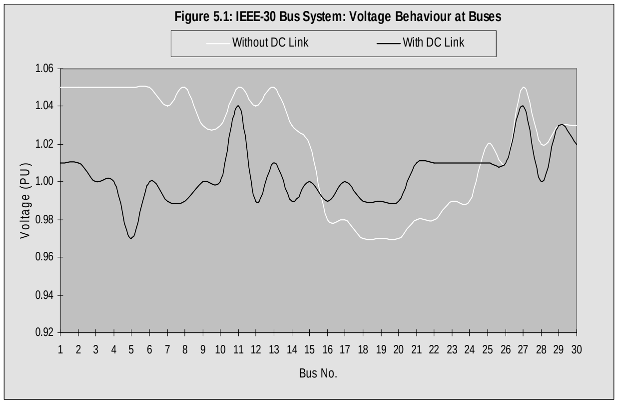
Figure 5.1: IEEE-30 Bus System: Voltage Behaviour at Buses

5.2 Example 2: Indian Electricity sector scenario and Real Transmission Network

India's electricity sector has grown from 1,362 MW in 1947 to 143,061 MW till 30th March 2008. This sector has been characterized by shortage of supply vis-à-vis demand. To improve the techno-financial performances of this sector, *Ministry of Power* GoI enacted EA 2003 and subsequent policy initiatives to outline the counters of a suitable enabling framework for the overall development of wholesale electricity market.

On the electricity transmission front, the Indian grid has been divided into five sub regional grids (Northern, Western, Southern, Eastern and North-Eastern). Each has number of constituents sub grids formed by state and private utility networks. All these sub grids and networks have been connected to form a 400 kV national grid. The constituent systems have their own generation in additional to generation by central government undertakings which have thermal, hydro and nuclear stations in different parts of the country and which feed power in the grid at different locations. Under EA 2003, Central Electricity Regulatory Commission (CERC) allowed open access to power generating and distributing companies, formation of the *National Grid* along with development of inter-regional electricity transmission linkages. To move forward, CERC has recently given approval to establish first power exchange that seeks to mitigate the volatility in power supply by bringing about equilibrium between demand and supply with adoption of uniform pricing.

Maharashtra State utility has the largest installed capacity of 15,580 MW in India. In 2005, it was unbundled into Generation, Transmission and

Distribution Company. At present transmission sector is feeling the strain due to low investment made in the past. The transmission infrastructure consists of ±500 kV HVDC, 400 kV, 220 kV, 132 kV, 110 kV, 100 kV, 66 kV lines, 486 EHV sub-stations, and 35626 ckt-km lines with total transformation capacity of 22,168 MVA.

This study considers a real network of 400 kV *Maharashtra State Electricity Transmission Company Limited* (MSETCL) shown in figure B1 (Appendix). It consists of 19 intra-state and 7 inter-state (BHILY, KHANDWA, SDSRV, BDRVT, TARAPUR, BOISR and SATPR) buses through which power is purchased to fulfill demand. The generator and real demand data have shown in Table B1 and B2 (Appendix). The voltage values for all buses have been bounded between 0.96 and 1.04. The active power flow constraints of intra-state transmission line lie between -0.5 and 0.5 and that for inter-state lines is -1.0 and 1.0. The data for ±500 kV HVDC link that has connected between CHDPUR to PADGE buses is shown in Table B3. All the values are indicated in p.u. CHDPUR has been taken as a reference bus. There are 2 × 16 equality constraints corresponding with their respective real and reactive power balances of the buses without a generator, and 48 inequality constraints of 27 pairs of voltage, 2 × 11 pairs of generation output and one pair of line flow upper and lower bounds respectively. By applying the nodal pricing methodology, the optimal nodal prices of real power with and without HVDC links are presented in following cases.

5.2.1 Case-1: Electricity nodal pricing scheme is implemented over 400 kV MSETCL system without considering HVDC link. The prices obtained at various buses are high (shown in Table 5.2). This is due to huge active power deficit i.e deficient generation at KOYNA-4, CHDPUR and KORDY. Also congestions in the transmission lines i.e. from bus CHDPUR- KORDY, KORDY-BHSWL2, BHSWL2-ARGBD4, PARLY2- SOLPR3 and CHDPUR - PARLY2 are due to less investment made in the transmission sector, rising power demand and costly power purchases from inter-state to fulfill the load demand. In light of the national power shortages, the state of Maharashtra is also facing severe power shortages at peak hours. The state power utility is making all efforts to fulfill load demand through power purchases and effective load management. 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 DABHOL irrespective of rising demand in Maharashtra. Similarly new investment in transmission segment is also needed at above mentioned transmission lines where the nodal prices are high.

Table 5.2: Electricity Nodal Price ($/MWh) and Bus Voltages without HVDC Link

Bus Name	P_G (pu)	Nodal Price	Bus Name	P_G (pu)	Nodal Price
CHDPUR	1.44	23.55	LONKAND	-	168.04
KORDY	0.54	46.18	NGOTNE	-	105.17
BHSWL2	-	89.85	DABHOL	1.44	60.35
ARGBD4	-	103.80	KOYNA-N	-	287.61
BBLSR2	-	118.20	KOYNA-4	0.19	279.15
DHULE	-	116.15	KLHPR3	-	309.33
PADGE	-	139.69	JEJURY	-	223.14
KALWA	-	141.75	KARAD2	-	308.64
KARGAR	-	141.52	SOLPR3	-	526.52
			PARLY2	-	20.80

5.2.2 Case-2: Impact of AC Transmission Investment on Electricity Nodal Prices

The Nodal prices obtained without considering DC link are high for the existing network under study. Also with the pace of rising demand in Maharashtra, existing transmission 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 need to increase i.e. to be double with an investment in reference to lines mentioned in Table 5.3.

Table 5.3: Transmission Line Capacity (MVA) Expansion and Expected Investment

Name of Line	Existing Capacity	Added Capacity	Investment (USD Million)	SPP (Years)
CHDPUR-KORDY (S/C)	500	500	10.30	2.02
KORDY - BHSWL2 (D/C)	500	500	87.28	17.15
BHSWL2-ARGBD4 (S/C)	500	500	14.12	2.78
PARLY2-SOLPR3 (S/C)	500	500	19.47	3.83
CHDPUR - PARLY2 (D/C)	500	500	134.73	26.48
S/C: Single Circuit ; D/C: Double Circuit line				

The return on added investment in years is computed by calculating simple payback period (SPP). Assuming annual cash inflow of Rs. 200 Million for an investment of about 266 USD Million, the SPP for proposed investments is given in Table 5.3. with this, the nodal prices obtained is shown in Table 5.4. The obtained nodal prices are lower at various buses as compared to previous case and transmission congestion is greatly reduced. Though the nodal prices may become lower due to heavy investment in transmission, the prices may go high in future as the demand increases which may cancel the economic advantages.

Table 5.4: Electricity Nodal Price ($/MWh) with proposed Investment

Bus Name	**P_G (pu)**	**Nodal Price**	**Bus Name**	**P_G (pu)**	**Nodal Price**
CHDPUR	1.72	37.72	LONKAND	-	73.21
KORDY	0.40	38.41	NGOTNE	-	83.21
BHSWL2	-	52.07	DABHOL	1.44	102.98
ARGBD4	-	72.98	KOYNA-N	-	105.98
BBLSR2	-	52.98	KOYNA-4	0.19	103.98
DHULE	-	62.75	KLHPR3	-	113.21
PADGE	-	63.21	JEJURY	-	85.21
KALWA	-	63.21	KARAD2	-	114.21
KARGAR	-	63.21	SOLPR3	-	155.52
			PARLY2	-	41.15

5.2.3 Case-3: The electricity demand in the state of Maharashtra is concentrated in the western region and the major generation in the eastern region. The CHDPUR generation has an installed capacity of 2,340 MW. Furthermore, state's share is of 1,700 MW from central generating station is received at CHDPUR. The AC transmission network comprising of three 400 kV circuit between CHDPUR and Mumbai can safely transmit around 1200 MW of power without any contingency outage. Therefore, it was necessary to provide additional transmission capacity of around 1,500 MW. Expansion of 400 kV lines was not feasible due to sever constraints of right-of-way and other cost considerations. The option of ±500 kV HVDC bipole was found to be the most viable. The electricity nodal prices are computed with this HVDC link is shown in Table 5.5. The prices obtained are lower compared to previous cases with no congestion in the above transmission lines. With this DC link, it is now possible to transmit sufficient power available at lower cost i.e. at BDRVT to fulfill the demand at lower cost. This link is vital in peak load condition to maintain the prices within limit.

Table 5.5: Electricity Nodal Price ($/MWh) With HVDC Link

Bus Name	**P_G (pu)**	**Nodal Price**	**Bus Name**	**P_G (pu)**	**Nodal Price**
CHDPUR	1.72	23.55	LONKAND	-	58.99
KORDY	0.54	30.18	NGOTNE	-	64.24
BHSWL2	-	43.67	DABHOL	1.10	70.19
ARGBD4	-	48.01	KOYNA-N	-	73.62
BBLSR2	-	52.13	KOYNA-4	0.19	72.70
DHULE	-	50.99	KLHPR3	-	82.54
PADGE	-	58.99	JEJURY	-	66.07
KALWA	-	58.99	KARAD2	-	82.30
KARGAR	-	58.99	SOLPR3	-	137.86
			PARLY2	-	11.89

5.2.4 Case-4: The nodal prices can further be reduced with addition of hydro generation i.e. KOYNA-4 at its full extent. The prices obtained as shown in Table 5.6 is the lowest and uniform one. At peak condition, hydro generation plays a key role to reduce the prices. This move can promotes competition in the wholesale electricity market from strategically located lower-cost units and demand response can benefit to MSETCL, as the transmission grid is utilized more efficiently. Ultimately, increased competition may result in a more efficient wholesale electricity market with lower costs.

Table 5.6: Electricity Nodal Price ($/MWh) with HVDC link and addition of Hydro generation

Bus Name	**P_G (pu)**	**Nodal Price**	**Bus Name**	**P_G (pu)**	**Nodal Price**
CHDPUR	2.00	23.78	LONKAND	-	25.92
KORDY	0.64	24.30	NGOTNE	-	26.00
BHSWL2	-	25.67	DABHOL	0.10	25.83
ARGBD4	-	26.12	KOYNA-N	-	25.77
BBLSR2	-	26.14	KOYNA-4	1.50	25.71
DHULE	-	26.19	KLHPR3	-	25.93
PADGE	-	25.98	JEJURY	-	25.94
KALWA	-	26.02	KARAD2	-	25.89
KARGAR	-	26.05	SOLPR3	-	25.62
			PARLY2	-	25.02

The bus voltages behaviour is compared for above mentioned cases. This is shown in figure 5.2. Improved voltages at various buses are obtained with addition of hydro generation and HVDC link in the existing network of 400 kV MSETCL.

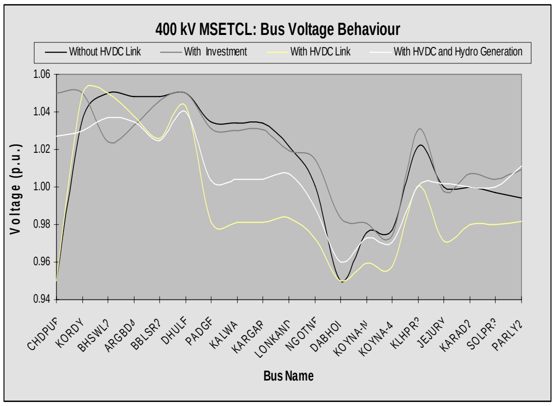

Fig. 5.2 Voltage Behaviour at Buses

The Inter state power purchases considering the cost characteristics of the Interstate/remote generators to satisfy the existing load at optimum cost for above mentioned cases are shown in figure 5.3. the costly inter state power purchases are greatly reduced with addition of hydro generation and HVDC link in the existing network of 400 kV MSETCL.

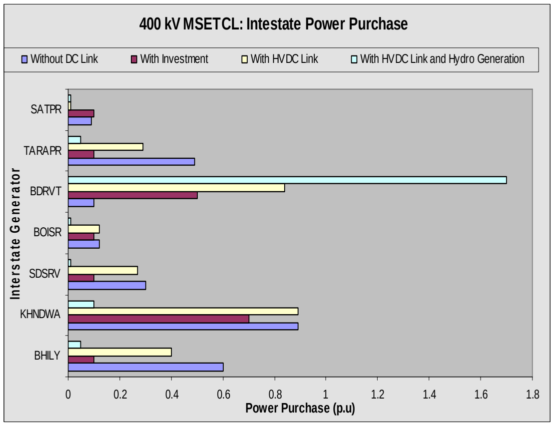

Fig. 5.3 Interstate Power Purchase requirement

6. CONCLUSION

This study presented basics of optimal nodal pricing based on AC-DC OPF. The purpose was (1) To formulate optimal Nodal pricing scheme suitable to real transmission networks for developing countries like India; (2) To contribute and suggest the importance of nodal pricing information to system operator, regulatory commissions and utilities and (3) To suggest the techno-commercial advantages of nodal pricing scheme for development of wholesale electricity markets in developing countries like India. Finally the proposed optimal scheme can ensure to achieve technical objectives, lower and uniform electricity nodal prices. This price behaviour also provides vital information to the market participants about techno-commercial advantages of generation addition and investment in transmission sector, one of the prime requirements to promote competition in the electricity market for developing or transition economy.

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APPENDIX

(A) IEEE-30 Bus Test System:

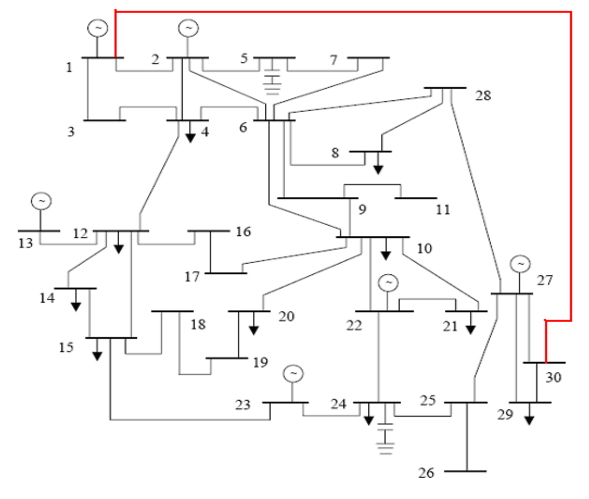

Fig. A1: IEEE 30-bus Modified test system

Table A1: Real Power and Fuel cost of generator

Bus No. (Generator)	Lower Limit (Real Power)	Upper Limit (Real Power)	Generation cost		
			a_i	b_i	c_i
1	1.1	1.5	0.14	20.4	5.0
2	0.0	0.5	0.20	19.3	5.0
13	0.5	1.0	0.14	20.4	5.0
22	0.5	1.5	0.20	19.3	5.0
23	0.1	0.5	0.14	20.4	5.0
27	0.2	0.6	0.20	19.3	5.0

Table A2: Demand $(p_i + jq_i)$ for IEEE 30-Bus System

Bus	Demand	Bus	Demand	Bus	Demand
1	0.0+j0.0	11	0.0-j0.177	21	0.175+j0.112
2	-0.217+j0.13	12	0.112+j0.0	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	0.0+j0.0
6	0.0+j0.0	16	0.035+j0.018	26	0.035+j0.023
7	0.228+j0.109	17	0.090+j0.058	27	0.0-j0.10
8	0.30-j0.30	18	0.032-j0.009	28	0.0+j0.0
9	0.0+j0.0	19	0.095+j0.034	29	0.024+j0.009
10	0.058+j0.0	20	0.022+j0.007	30	0.106+j0.0

(B) A Real Network of 400 kV, MSETCL, India:

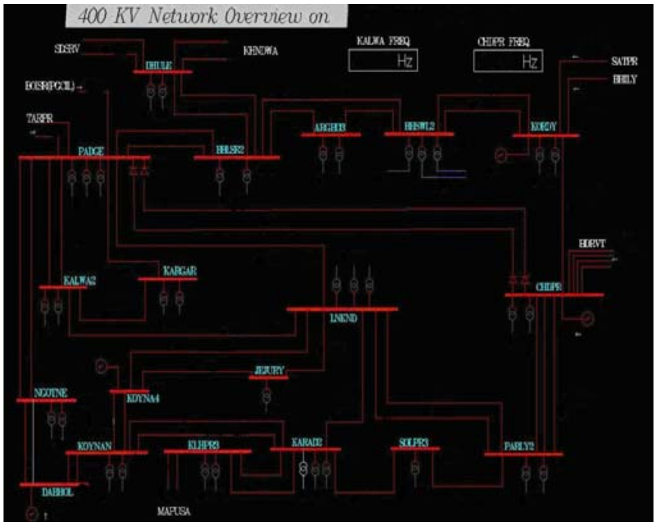

Fig. B1: A 400 kV Network of MSETCL, India

Generator	Generation Capacity (p.u.)		Generation/ Power Purchase Real Power (p.u.)		Generation Cost ($/MWh)		
	Max	Min	Max	Min	a_i	b_i	c_i
CHDPUR	2.30	0.2	1.72	0.2	0.22	22.87	11.43
KORDY	1.06	0.2	0.54	0.2	0.22	25.15	11.43
DABHOL	1.50	0.2	1.44	0.2	1.14	57.16	11.43
KOYNA-4	1.50	0.1	0.19	0.1	0.22	22.87	11.43
BHILY			0.6	0.1	0.22	27.44	11.43
KHANDWA			0.7	0.2	1.14	27.44	11.43
SDSRV			0.5	0.01	1.14	49.84	11.43
BOISR			0.2	0.01	1.14	57.16	11.43
BDRVT			1.7	0.2	0.22	25.15	11.43
TARAPUR			0.4	0.01	1.14	45.72	11.43
SATPR			0.2	0.01	1.14	45.72	11.43

Table B1: Generation Capacity and Cost Characteristics Data

Table B2: Real Power Demand (p.u.)

Bus Name	Load	Bus Name	Load	Bus Name	Load
CHDPUR	0.3	BBLSR2	0.5	LONKAND	0.6
KORDY	0.3	DHULE	0.2	NGOTNE	0.3
BHSWL2	0.2	KALWA	0.3	DABHOL	0.0
ARGBD4	0.5	KARGAR	0.3	KOYNA-N	0.4
KOYNA-4	0.0	SOLPR3	0.3	KARAD2	0.5
KLHPR3	0.4	PARLY2	0.05	PADGE	0.4
JEJURY	0.3				

Table B3: Data: ±500kV CHDPUR-PADGE HVDC Link

Particulars	Data	Particulars	Data
Nominal Continuous Power Flow Rating	1500 MW	Thyristor Valves: Max. voltage	7 kV
Converter Xmer: voltage of each pole of DC line	500 kV	Thyristor Valves: Rated current	1700 A dc
Converter Xmer: Rated power unit	298.6 MVA	Length of the line	753 Km
Operation: Chdpur Converter/Rectifier	12.5 to 15 degree	Number of poles	2
Operation: Padge- Inverter	17 to 22 degree	Resistance: Chdpur-Padge	7.5 Ω