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Research paper

Optimal Pricing of Electricity in Restructured Electricity Market

V.G.Umale*, Dr. S.B.Warkad[2], S.Wadhankar[3], H.S.Sakhare[4]

[1]Research Scholar, Priyadarshini College of Engineering, Nagpur, INDIA
[2]Professor, P.R.Pote College of Engineering, Amravati, INDIA
[3]Assistant Professor, G.H.Raisoni Institute of Engineering &Technology, Nagpur, INDIA
[4]Assistant Professor, Priyadarshini Indira Gandhi College of Engineering, Nagpur, INDIA
**Corresponding author E-mail:virendraumale@gmail.com*

Abstract

An effective pricing scheme that to provide the useful information to generation, transmission section and customers. These transmission pricing depends on generator, load levels and transmission line constraints. Transmission line constraints result is variations in energy prices throughout the network. The proposed approach is based on AC-DC optimal power flow model with considering of losses. Resulting optimization problem is solved by linear programming approach. Locational Marginal Pricing methodology is used to determine the energy price for transacted power and to manage the network congestion and marginal losses. Variation of LMP values with transmission constraint conditions also studied. Simulation is carried out on IEEE 57 bus system, 400/765kV MSETCL system of Maharashtra transmission line for real data bus system and the results are presented.

Keywords: *locational marginal pricing , optimal power flow, transmission pricing, optimization, congestion market*

1. Introduction

By Tradition, power industry is vertically integrated, in which the generation, Transmission and distribution are arranged collectively as a single utility to serve its customers. Due to central operation of transmission and distribution system it will remain in a monopoly mode. Under the deregulated electricity `market environment, transmission networks play a vital role in supporting the transaction between producers and consumers. Due to Transmission Open Access (TOA) the power flow in the lines reach the power transfer limit and so it will leads to a condition known as congestion [1-2]. The congestion may be caused due to a mixture of reasons, such as transmission line outages, generator outages and change in energy demand. Transmission congestion has impact on the entire system as well as on the individual market participants i.e. sellers and buyers. Without congestion low cost GENCOs are used to meet the load demand but if congestion is present in the transmission network then it prevents the demand to be met by the lowest-priced resources due to mentioned transmission constraints and this leads to the allocation of higher price.

Buyers in the market pays ISO based on their price for dispatched energy. The ISO pays sellers in the market based on their respective prices. The LMP difference between two adjacent buses is the congestion cost which arises when the energy is transferred from one location to the other location[3]. Marginal losses represent incremental changes in system losses due to incremental demand changes. Incremental losses yield additional costs which are referred to as the cost of marginal losses. Thus LMP is the summation of the costs of marginal energy, marginal loss and congestion. LMP can be stated as follows:

LMP = generation marginal cost + congestion cost +marginal loss cost

LMP is obtained from the result of Optimal Power Flow (OPF). Either AC-OPF or DC-OPF is used to determine the LMP [7]. To reduce the complexity in the calculation in this paper DC-OPF is used. In DC-OPF only real power flow is considered [6]. Different types of optimization models are used for LMP calculations like LP and Lagrangian[8]. Among these in this paper quadrating programming is used to solve the optimization problem.

2. Real Energy Market

Restructured power market consists of different types of market. An energy market is a place where the financial trading of electricity takes place. It naturally consists of a day-ahead market and real-time market, while the ancillary service markets are able to provide services such as synchronized reserve, regulation and reliable operation of transmission system. The day-ahead market is a type of forward market and runs on the day before the functioning day [1-2]. Generation offers, demand bids, and bilateral transactions are accepted by the Day-Ahead market in the regulated market timeline [9]. Virtual offers and bids are also received to increase the market liquidity. Load forecasting tool is used to predict the load in the submitted bids. As a result of running the optimization model the generation dispatch and electricity prices for each hour of the operating day was calculated [10].

3. Electricity Spot Price Equations

The real and reactive power cost at bus ‘ i ' is the Lagrange multiplier function of the equality and inequality constraints calculated by solving first order condition of the Lagrangian, partial derivatives of the Lagrangian with respect to every variable concerned. So the Lagrange function of equations are defined as a cost

$$
\begin{aligned}
L = & \sum_{i=1}^{NG} (a_i P_{gi}^2 + b_i P_{Gi} + c_i) + \sum_{i=1}^{NB} \lambda_{pi} (P_{di} - P_{gi} + P_{dci} + P_L) \\
& + \sum_{i=NV+1}^{NB} \lambda_{qi} (Q_{di} - Q_{gi} + Q_{dci} + Q_L) \\
& + \sum_{i=1}^{NG} \rho\, p_{li} (P_{gi}^{\min} - P_{gi}) + \sum_{i=1}^{NG} \rho\, p_{ui} (P_{gi} - P_{gi}^{\max}) \\
& + \sum_{i=1}^{NG} \rho\, q_{li} (Q_{gi}^{\min} - Q_{gi}) + \sum_{i=1}^{NG} \rho\, q_{ui} (Q_{gi} - Q_{gi}^{\max}) \\
& + \sum_{i=1}^{NB} \rho\, v_{li} (\left| V_i^{\min} \right| - \left| V_i \right|) + \sum_{i=1}^{NB} \rho\, v_{ui} (\left| V_i \right| - \left| V_i^{\max} \right|) \\
& + \sum_{i=1}^{NB} \rho\, \delta_{li} (\delta_i^{\min} - \delta_i) + \sum_{i=1}^{NB} \rho\, \delta_{ui} (\delta_i - \delta_i^{\max}) \\
& + \sum_{i=1}^{Noele} \rho\, p_{fli} (P_{fi}^{\min} - P_{fi}) + \sum_{i=1}^{Noele} \rho\, p_{fui} (P_{fi} - P_{fi}^{\max})
\end{aligned}
$$

where, l and u are lower and upper limits; $\lambda = (\lambda_1, \ldots, \lambda_n)$ is the vector of Lagrange multipliers concerning equality constraints; $\rho = (\rho_1, \ldots, \rho_n)$ are the Lagrange multipliers concerning inequality constraints. Then at an optimal solution (X, λ, ρ) for a set of given (P, Q), Spot price of real and reactive power for bus is expressed for $i = 1, \ldots, n$ are,

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

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

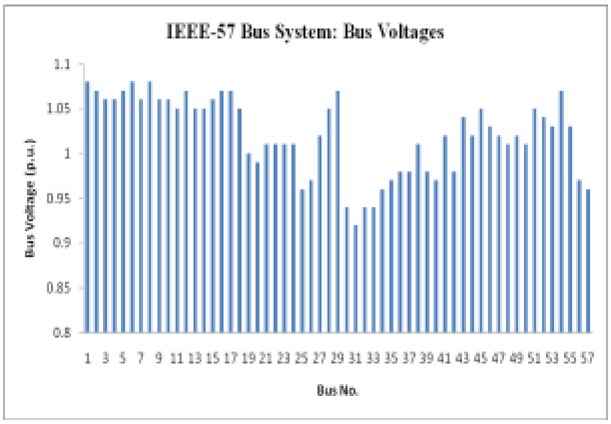
The difference ($\pi_{p,i}$ - $\pi_{p,j}$) represents real transmission charges from bus-j to bus-*i*. The system marginal cost created by an increment of real and reactive power load at bus i respectively.

4. Simulation and Numerical results

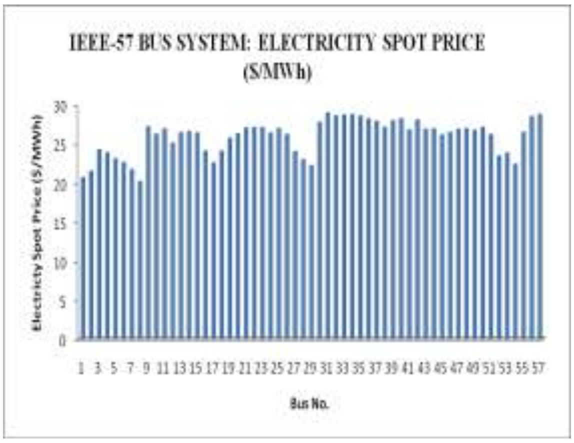
This methodology has been simulated in MATLAB software and results are obtained for several conditions and constraints tested over IEEE-57 bus system, 400kV& 400/765kV MSETCL system and implemented on a Indian power system.
In order to ensure universal applicability of the proposed methodology, this AC-DC OPF based electricity nodal pricing methodology is simulated in MATLAB software for standard IEEE 57 test bus system.

Table 1: AC-DC OPF Electricity Spot Prices for IEEE57 bus system

Bus No.	Voltage	Real Power	Reactive Power	Angle	Real Spot Price ($/MWh)
1	1.08	0.09	-0.001	0.12	20.64
2	1.07		0.4341	0.11	21.47
3	1.06	0.4	0.2981	0.05	24.20
4	1.06			0.03	23.84
5	1.07			0.01	23.08
6	1.08	3.4	0.5	0.01	22.56
7	1.06			0.04	21.67
8	1.08	3.5	0.5	0.08	20.16
9	1.06		0.5	0.03	27.15
10	1.06			0.02	26.20
11	1.05			0.02	26.88
12	1.07	4.7	0.5	0.06	25.07
13	1.05			0.03	26.40
14	1.05			0.03	26.54
15	1.06			0.05	26.36
16	1.07			0.05	24.04
17	1.07			0.07	22.53
18	1.05			-0.03	24.04
19	1.00			-0.04	25.68
20	0.99			-0.03	26.27
21	1.01			-0.03	27.01
22	1.01			-0.02	27.07
23	1.01			-0.02	27.07
24	1.01			-0.02	26.37
25	0.96			-0.11	26.95
26	0.97			-0.02	26.17
27	1.02			-0.00	23.98
28	1.05			0.01	22.95
29	1.07			0.02	22.21
30	0.94			-0.12	27.74
31	0.92			-0.13	28.92
32	0.94			-0.12	28.54
33	0.94			-0.12	28.64
34	0.96			-0.04	28.72
35	0.97			-0.04	28.50
36	0.98			-0.04	28.15
37	0.98			-0.03	27.87
38	1.01			-0.02	27.10
39	0.98			-0.03	27.94
40	0.97			-0.04	28.20
41	1.02			-0.04	26.76
42	0.98			-0.06	28.03
43	1.04			0.00	26.85
44	1.02			-0.01	26.90
45	1.05			0.01	26.11
46	1.03			0.00	26.43
47	1.02			-0.01	26.83
48	1.01			-0.01	26.91
49	1.02			-0.01	26.71
50	1.01			-0.02	27.08
51	1.05			0.00	26.15
52	1.04			0.07	23.43
53	1.03			0.10	23.80
54	1.07			0.20	22.36
55	1.03			0.07	26.45
56	0.97			-0.07	28.45
57	0.96			-0.08	28.73



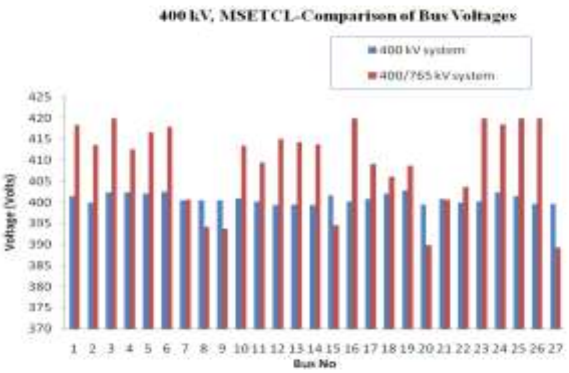
Graph 1: AC-DC OPF based Spot Electricity Prices: Bus Voltage Behavior



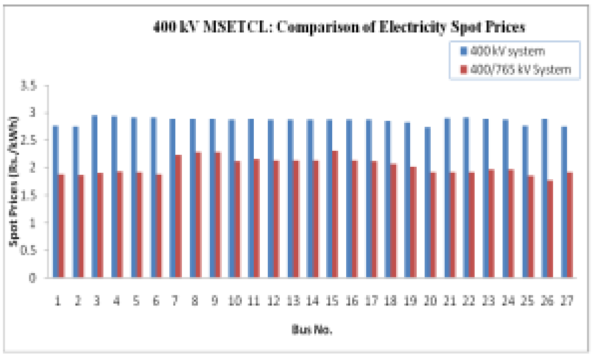
Graph 2: AC-DC OPF based Spot Electricity Prices

Table-2: 400Kv/765kV Maharashtra State Electricity Transmission Company Limited (MSETCL)

Bus No.	Voltage (Volts)	Real Power	Reactive Power	Angle	Spot Price (Rs./kWh)
1	418.38	2.58	1.97	0.14	1.87
2	413.65	2.65	0.54	0.26	1.86
3	420.00			0.00	1.90
4	412.56			0.00	1.92
5	416.71			0.00	1.91
6	417.91			0.00	1.88
7	400.72			0.00	2.23
8	394.12			0.00	2.28
9	393.69			0.00	2.28
10	413.43			0.00	2.12
11	409.39			0.00	2.15
12	415.07			0.12	2.13
13	414.33			0.00	2.13
14	413.72			0.17	2.13
15	394.60			0.00	2.30
16	420.00			0.00	2.13
17	409.14			0.00	2.12
18	406.21			0.00	2.06
19	408.75			0.00	2.02
20	389.81	2.59	0.40	0.41	1.91
21	400.69			0.00	1.91
22	403.75			0.00	1.91
23	420.00			0.00	1.96
24	418.58			0.00	1.97
25	420.00	2.59	0.39	0.11	1.85
26	420.00	2.91	0.50	0.02	1.77
27	389.24	2.54	0.12	0.50	1.91
28	420.00			0.13	1.78
29	409.12	2.68	0.10	0.24	1.88
30	401.54	1.90	0.19	0.15	2.21
31	401.37	1.86	0.19	0.01	2.23



Graph 3: Comparison and analysis of voltage behavior of Transmission line power flows



Graph 4: Comparison and analysis of Spot Electricity Prices of Transmission line power flows

5. Conclusions

The paper presented optimal electricity pricing methodology suitable for real power systems. The methodology has been tested on IEEE 57-Bus system and implemented on a real power system of MSETCL, Maharashtra. The optimal electricity prices are simulated for with 400/765 kV transmission line. Numerical results are compared as shown in result Tables. This paper concludes that optimal electricity prices at several buses are lower with incorporation of 400/765 kV in an existing AC transmission system. In order to assess bus voltage behavior, transmission lines power flows, results are shown in Tables and Figures. This concluded that voltage profile at several buses has improved and congestion in several transmission lines is reduced. This is a healthy sign for development of competition in wholesale electricity market. This paper can be useful to the Transmission System Operator in understanding Spot electricity market in restructured electricity market.

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