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EVALUATION OF GENERATION AND TRANSMISSION ASSETS ON NODAL PRICES IN ELECTRICITY MARKETS

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A B S T R A C T

Electric utilities are going through a phase of quick changes, especially in the marketplace and rigid policies. Under such circumstances, electricity carrying prices can profile the level of contest in the electricity marketplace. Nodal pricing in such circumstances is one of the valuable schemes to reach transmission pricing goals. The performance of the Electricity Act 2003 has started the entry of the general electricity market in the Indian electricity sector. The implementation of the Transmission Open Access (TOA) regulation in India aims to confirm the required infrastructure and appropriate pricing strategies to support competition in this market. This study seeks to: (1) address the transmission pricing concerns that are prevalent and Nodal pricing that is exacting; (2) formulate the most advantageous Nodal price; and (3) implement the Nodal pricing methodology via IEEE-57. (4) to examine how transmission and generating assets affect nodal prices. Paper finalized that Nodal pricing is easy to execute over real network conditions and precious in achieving transmission pricing objectives.

1. INTRODUCTION

Electric power needs in a range of advanced and growing international locations have skilled a time of fast changes in market association and regulatory policies. Under a competitive electricity marketplace, it is necessary to control and regulate the transmission economies. These days the development of the strong market is in a direction closer to Transmission Open access (TOA) whereby transmission providers may be vital to bid on the transmission pricing (Hamoud, 2000; Areekul et al., 2010;) To make optimum utilization of the transmission grid by supplying accurate economic signals, a Nodal Pricing statement for the reorganized electric power system is developed (Sarkar & Khaparde, 2009) To reach the objectives (1) to ensure the best progress of the transmission network, (2) to endorse the efficient operation of generation and transmission assets in the country, and (3) to draw the required investments in the transmission sector and to offer adequate profits. The states in India are to follow the policy laid down by the central sector. Subsequent to this introduction, section II gives a summary of the Indian electricity market as well as the electricity restructuring status in Maharashtra state. Section III highlighted the issues and aims of transmission pricing under destructive electricity markets. Section IV briefs the

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Nodal pricing methodology with problem formulation and estimation of Nodal prices. In section V, Spot prices are computed over IEEE-57 Bus. The outcome of generation and transmission investment on Nodal prices is likewise evaluated for the network under study. Finally, we provide several general statements and standard comments to close this paper.

2. INDIAN ELECTRICITY SECTOR RESTRUCTURING: AN OVERVIEW

An important step was achieved toward bringing about a steady growth of the power supply business throughout the nations with the adoption of the Electricity Act 2003. There were many multipurpose projects created, and when thermal, hydro, and nuclear power plants were built, the amount of power generated significantly increased. All current and prospective transmission activities in the Middle Sector as well as the design of the Nationwide Power Grid are under the control of the Power Grid. The Rural Electrification Corporation provides financial support for rural electrification projects (REC). Projects in the electricity sector might receive term financing from Power Finance Corporation (PFC). The Ministry of Power additionally has managerial supervision over the autonomous organizations (societies), Central Power Research Institute (CPRI) and National Power Training Institute (NPTI) (MoP). Additionally, Power Trading Corporation (PTC) has been added with the main purpose of supporting Mega Power Projects in the private sector by functioning as a single entity to enter into Power Purchase Agreements(PPAs). (Williams & Ghanadan, 2006; Zhang et al., 2002; Bacon & Besant-Jones, 2001; Srivastava, 2002)

3. ELECTRICITY TRANSMISSION PRICING: AN OVERVIEW

The electricity industry continues to operate in many emerging nations as a centralized monopolistic utility. The cost of energy is determined by a variety of factors, including social policies, employment issues, economic spillovers, fundamental equity considerations, and occasionally political goals. Bringing the cost down to the reasonable cost of service is typically the main obstacle to market improvement in developed nations. To make sure that payment is processed and that prices are set high enough to cover all of the costs of providing the service, however, are issues in underdeveloped nations. Of course, this needs to be done in conjunction with appropriate steps to deal with specific issues with price and convenience. The cost of transmitting power between any location on the electricity network is not fixed; rather, it depends on the system's total demand and generation patterns. This complicates the topic of transmission pricing. There is constant discussion among utilities, consumers, and suppliers about how to best integrate transmission into this market-based structure. For clear reasons, constructing a separate transmission network for each generator load pair is neither practical nor cost-effective. Therefore, techniques that enable the combined use of the transmission service by several users must be developed. These techniques should not only guarantee the technical prowess of the transmission service but also generate enough money to cover the current transmission expenditure and give incentives for economic expansion.

There are many different cost components reported in prose that one needs to consider when it comes to the presentation of transmission transactions. These are the costs that transmission companies incur in order to provide a satisfactory deal laid down in the contractual terms. The major mechanisms of transmission transaction are:

3.1 In-use cost

It is the Production (fuel) cost that the transmission usefulness incurs in order to lodge the deal. It is coupled with the putting off and re-dispatch of participating generators for change in losses and some other operating constraints such as transmission flow and limit of the bus voltage. Besides these, the need for reactive power hold which in the end will add to the operating cost has to be considered as well. Apart from that the factors like start–up time, start-up cost and necessities of the spinning reserve play a part in influencing the rescheduling of generation.

3.2 Occasion cost

This cost corresponds to the profit that the transaction utility has to forgo due to operating constraints caused by the deal. The benefit could also come from unrealized proceeds from the firm transaction which the transmission utility could not support due to system in service constraints. However, if the transaction is able to alleviate transmission congestion and enable additional transactions to take place, it will provide some payback and reduces cost. Opportunity cost is the most elusive component among all other costs in a transmission deal.

3.3 Strengthening cost

It refers to the capital cost of all new amenities needed by the transmission utility in order to house the transaction. Reinforcement cost only applies to firm transactions. This cost can also be the cost of intended new installations of transmission facilities being deferred by the transmission deal.

3.4 Obtainable system cost

It refers to the cost of the existing transmission facilities that are being allocated to house the particular transaction. It is the largest cost part of the overall cost of transmission transactions. Several factors are being linked to the cost of accessible transmission facilities, such as investment injected into the transmission amenities that are involved and maintenance costs for the existing transmission system that are life form used.

The term "incremental cost of the transmission transaction" refers to operational costs, opportunity costs, and reinforcing costs. Operating and opportunity costs are referred to as Short-Run Incremental Costs, opportunity costs and strengthening costs are referred to as Long-Run Incremental Costs, congestion costs are referred to as Opportunity Costs, and Embedded Costs are referred to as a portion of the cost of the current system.

Economists also use terms such as the Marginal Cost of transmission deal. It is the cost of helpful a marginal increase in the transacted power. (Manikandan, 2008; Kumar & Srivastava, 2002, 2004)

4. NODAL PRICING METHODOLOGY

The term "optimal power flow" typically refers to an optimization issue that is constrained by the physical limits of the power system. An objective function, equality constraints like power balance equations, and inequality constraints like power flow thermal limits, generator ramp rate, and generator output limit are all included in the OPF model.

Since the ACOPF model is typically believed to be the most diplomatic mathematical representation of the real-world scheduling problem. Its comparative results are believed to be reliable and can be used as reference information. Despite the accuracy of its conclusions, ACOPF is a non-linear programming problem that requires a solid foundation to be solved.

In order to determine nodal prices both for real and reactive power with an optimal solution, this paper first describes the process problem of a power system as an OPF problem. (Monticelli et al, 1987; Vaahedi et al, 2001; Hur et al., 2001; Yuan et al., 2003).

5. PROBLEM FORMULATION

For AC System
For a system with n buses, let $P=(p_1,\dots,p_n)$ and $Q=(q_1,\dots,q_n)$, where p_k and q_k are the active and reactive power demands at bus-k. Then the OPF problem for a power system for given load (P,Q) can be formulated as

minimize

$$f=(X,P,Q) \quad \text{for } X \quad \text{(Objective Value)} \tag{1}$$

subject to

$$S(X,P,Q)=0 \quad \text{(Equality constraints)} \tag{2}$$

$$T(X,P,Q)\le 0 \quad \text{(Inequality constraints)} \tag{3}$$

Where

$$S(X)=(s_1(X,P,Q),\dots,s_{n1}(X,P,Q))^T \tag{4}$$

$$T(X)=(t_1(X,P,Q),\dots,t_{n2}(X,P,Q))^T \tag{5}$$

have $n1$ and $n2$ equations, and are column vectors. AT is the transpose of vector A.

$f=(X,P,Q)$ is a scalar, generator cost function $f_k(P_{gk})$ having cost characteristics denoted by,

$$F=\sum_{k=1}^{NG}F_k=\sum_{k=1}^{NG}(a_kP_{gk}^2+b_kP_{gk}+c_k) \tag{6}$$

The constraints i.e. $T(X,P,Q)\le 0$ to be fulfilled are-

(1) Equality constraints Vector i.e. power flow balance are,

$$P_g=P_d+P_{dc}+P_L \tag{7}$$

$$Q_g=Q_d+Q_{dc}+Q_L \tag{8}$$

Here suffix 'g' is the generation, 'd' represents the demand, 'dc' represents dc terminal and 'L' is transmission loss.

(2) Inequality constraint Vector as

(i) Minimum and maximum limits on real and reactive power generations is

$$P_{gk}^{\min}\le P_{gk}\le P_{gk}^{\max} \quad (k=1,2,\dots,NG) \tag{9}$$

$$Q_{gk}^{\min}\le Q_{gk}\le Q_{gk}^{\max} \quad (k=1,2,\dots,NG) \tag{10}$$

(ii) Minimum and maximum limits on bus voltage magnitudes is,

$$V_k^{\min}\le V_k\le V_k^{\max} \quad (k=NV+1,\ NV+2,\dots,NB) \tag{11}$$

(iii) Transmission line power flow (MVA) limits is,

$$p_f^{\min}\le p_f\le p_f^{\max} \quad (f=1,2,\dots,Noele) \tag{12}$$

In general, for the buses n and kconnected by a convenient transformer with tap ratio $1:t_{ki}$, the real and reactive power injection at buses into the ac network are as follows

$$\begin{aligned}P_n=&V_n\sum_{\substack{k=1\\ j\ne n\\ j\ne i}}^{N}V_j(G_{nj}\cos\delta_{nj}+B_{nj}\sin\delta_{nj})\\ &-V_nV_kt_{nk}(g_{nk}\cos\delta_{nk}+b_{nk}\sin\delta_{nk})\\ &+V_n^2(G_{nn}+t_{nk}^2g_{nk})\end{aligned} \tag{13}$$

$$Q_n = V_n \sum_{\substack{k=1 \\ j\neq n \\ j\neq i}}^{N} V_j (G_{nj} \sin\delta_{nj} - B_{nj} \cos\delta_{nj}) - V_n V_k t_{nk} (g_{nk} \sin\delta_{nk} + b_{nk} \cos\delta_{nk}) + V_n^2 (B_{nk} + t_{nk}^2 b_{nk}) \quad (14)$$

$$P_k = V_k \sum_{\substack{k=1 \\ j\neq n \\ j\neq i}}^{N} V_j (G_{kj} \cos\delta_{kj} + B_{kj} \sin\delta_{kj}) - V_k V_n t_{nk} (g_{nk} \cos\delta_{kn} + b_{nk} \cos\delta_{kn}) + V_k^2 (G_{kk} + g_{nk}) \quad (15)$$

$$Q_k = V_k \sum_{\substack{k=1 \\ j\neq i \\ j\neq n}}^{N} V_j (G_{kj} \sin\delta_{kj} - B_{kj} \cos\delta_{kj}) - V_k V_n t_{nk} (g_{nk} \sin\delta_{kn} - b_{nk} \cos\delta_{kn}) - V_k^2 (B_{kk} + t_{ni}^2 b_{nk}) \quad (16)$$

where the transformer admittance $y_{nk} = g_{nk} + jb_{nk}$, and $G_{nn} + jB_{nn}$ and $G_{kk} + jB_{kk}$ are the total admittance of the line connected to buses n and k respectively, excluding transformer admittance.

Consequently, the vector represents the state of operation of the combined AC-DC electric power system.

$$X = [\delta, V, x_C, x_d]^T \quad (17)$$

where, δ is the vectors of the phase angles and V is the vectors of the magnitude of the phasor bus voltages; x_C is the control variable vector such as those on TCUL transformers, generators, shunt reactive sources, and phase shifting transformers; and x_d is the dc variable vectors.

c) Electricity Nodal Price Equations

The real and reactive power cost at bus 'k'is the Lagrange multiplier task of the equality and inequality constraints planned by solving first order condition of the Lagrangian, partial derivatives of the Lagrangian with respect to each variable concerned. Thus the Lagrange function of equations as a cost function is

$$\begin{aligned} L = &\sum_{k=1}^{NG} (akP_{gk}^2 + bkP_{Gk} + ck) + \sum_{k=1}^{NB} \lambda_{pk} (P_{dk} - P_{gk} + P_{dck} + P_L) \\ &+ \sum_{k=NV+1}^{NB} \lambda_{qk} (Q_{dk} - Q_{gk} + Q_{dck} + Q_L) \\ &+ \sum_{k=1}^{NG} \rho p_{lk} (P_{gk}^{\min} - P_{gk}) + \sum_{k=1}^{NG} \rho p_{uk} (P_{gk} - P_{gk}^{\max}) \\ &+ \sum_{k=1}^{NG} \rho q_{lk} (Q_{gk}^{\min} - Q_{gk}) + \sum_{k=1}^{NG} k (Q_{gk} - Q_{gk}^{\max}) \\ &+ \sum_{k=1}^{NB} \rho v_{lk} (|V_k^{\min}| - |V_k|) + \sum_{k=1}^{NB} \rho v_{uk} (|V_k| - |V_k^{\max}|) \\ &+ \sum_{k=1}^{NB} \rho \delta_{lk} (\delta_k^{\min} - \delta_k) + \sum_{k=1}^{NB} \rho \delta_{uk} (\delta_k - \delta_k^{\max}) \\ &+ \sum_{k=1}^{Noele} \rho p_{flk} (P_{fk}^{\min} - P_{fk}) + \sum_{i=1}^{Noele} \rho p_{fuk} (P_{fk} - P_{fk}^{\max}) \end{aligned} \quad (18)$$

where, 'l' and 'u' stands for lower and upper bounds; λ= (λ1,…,λn) is the vector of equality constraints; ρ (ρ1,…,ρn) is the inequality constraints.

The optimal solution (X, λ, ρ) for a set of (P, Q), Nodal price of reactive and real power for bus is expressed for $i = 1, \ldots, n$,

$$\pi_{p,k} = \frac{\partial L(X, \lambda, \rho, P, Q)}{\partial_{pk}} = \frac{\partial f}{\partial_{pk}} + \lambda \frac{\partial S}{\partial_{pk}} + \rho \frac{\partial T}{\partial_{pk}} \quad (19)$$

$$\pi_{q,k} = \frac{\partial L(X, \lambda, \rho, P, Q)}{\partial_{qk}} = \frac{\partial f}{\partial_{qk}} + \lambda \frac{\partial S}{\partial_{qk}} + \rho \frac{\partial T}{\partial_{qk}} \quad (20)$$

6. SIMULATION

IEEE 57 Bus System

In Figure 1, the IEEE 57 Bus system is depicted. It comprises of 80 Transmission Lines and 7 Generators. The generator data are shown in Table 1. All buses are designed to operate between 0.95 p.u. and 1.05 p.u. in voltage. A dc link should be assumed and linked between Bus No. 1 and Bus No. 54 or Bus No. 8 to Bus No. 54 in order to examine the impact of the HVDC link. Buses are thought to have converter ratings of 1.0 p.u.

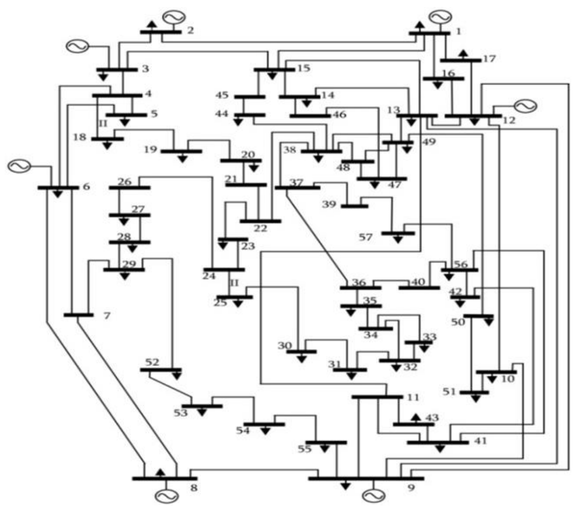

Figure 1. IEEE- 57 Bus System

To ensure that the suggested methodology is applicable to all types of bus systems, this AC-DC OPF based nodal pricing strategy is simulated for an IEEE 57 test bus system. Table 2 displays statistics on generation and load, while Table 3 displays information on transmission lines. The HVDC link be selected from Bus No.1 to Bus No.54. The voltage limits on buses are kept ±5%. The AC-DC OPF based electrical energy nodal pricing results are also shown.

IEEE-57 Bus System Input data

Table 1. Generator Cost Characteristics from IEEE-57 Bus System Data.

Generator	a	b	c
1	0.07758	20	0.0001
2	0.01000	40	0.0001
3	0.25000	20	0.0001
6	0.01000	40	0.0001
8	0.02222	20	0.0001
9	0.01000	40	0.0001
12	0.03226	20	0.0001

Table 2. Generation and Load Data for IEEE-57 Bus System.

Bus No.	PGk	PDk	QDk	Bus No.	PGk	PDk	QDk
1	4.792	0.550	0.170	31	0.000	0.058	0.029
2	0.000	0.030	0.880	32	0.000	0.016	0.008
3	0.400	0.410	0.210	33	0.000	0.038	0.019
4	0.000	0.000	0.000	34	0.000	0.000	0.000
5	0.000	0.130	0.040	35	0.000	0.060	0.030
6	0.000	0.750	0.020	36	0.000	0.000	0.000
7	0.00	0.00	0.000	37	0.00	0.00	0.000
8	4.50	1.50	0.220	38	0.00	0.14	0.07
9	0.00	1.21	0.260	39	0.00	0.00	0.00
10	0.00	0.05	0.020	40	0.00	0.00	0.00
11	0.00	0.00	0.000	41	0.00	0.06	0.00
12	4.70	3.77	0.240	42	0.00	0.07	0.04
13	0.00	0.18	0.023	43	0.00	0.02	0.01
14	0.00	0.10	0.053	44	0.00	0.12	0.01
15	0.00	0.22	0.050	45	0.00	0.00	0.00
16	0.00	0.43	0.030	46	0.00	0.00	0.00
17	0.00	0.42	0.080	47	0.00	0.29	0.11
18	0.00	0.27	0.098	48	0.00	0.00	0.00
19	0.00	0.03	0.006	49	0.00	0.18	0.08
20	0.00	0.02	0.010	50	0.00	0.21	0.10
21	0.00	0.00	0.000	51	0.00	0.18	0.03
22	0.00	0.00	0.000	52	0.00	0.04	0.02
23	0.00	0.06	0.021	53	0.00	0.20	0.10
24	0.00	0.00	0.000	54	0.00	0.01	0.01
25	0.00	0.06	0.032	55	0.00	0.06	0.03
26	0.00	0.00	0.000	56	0.00	0.07	0.02
27	0.00	0.09	0.005	57	0.00	0.06	0.02
28	0.00	0.04	0.023				
29	0.00	0.17	0.026				
30	0.00	0.03	0.018				

Table 3. Electricity Nodal Prices for IEEE 57 Bus System.

Bus No.	Voltage (pu)	Angle (δ)	Active Power (pu)	Reactive Power (pu)	Nodal Price ($/MWh)
1	1.08	0.12	3.18	0.00	20.64
2	1.07	0.11	0.00	0.76	21.47
3	1.06	0.05	0.40	0.26	24.20
4	1.06	0.03			23.84
5	1.07	0.01			23.08
6	1.08	0.01	0.00	0.50	22.56
7	1.06	0.04			21.67
8	1.08	0.08	4.44	0.20	20.16
9	1.06	0.03	0.00	0.50	27.15
10	1.06	0.02			26.20
11	1.05	0.02			26.88
12	1.07	0.06	4.70	0.50	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

The comparison of bus voltages of IEEE 57 system is given away in Figure 2. The figure shows bus voltage behaviour between HVDC link between Bus No. 1 to 54 and Bus No. 8 to 54. The graph shows that the bus voltages starting Bus No. 8 to Bus No. 54 are higher than voltages obtained at Bus No. 1 to Bus No. 54.

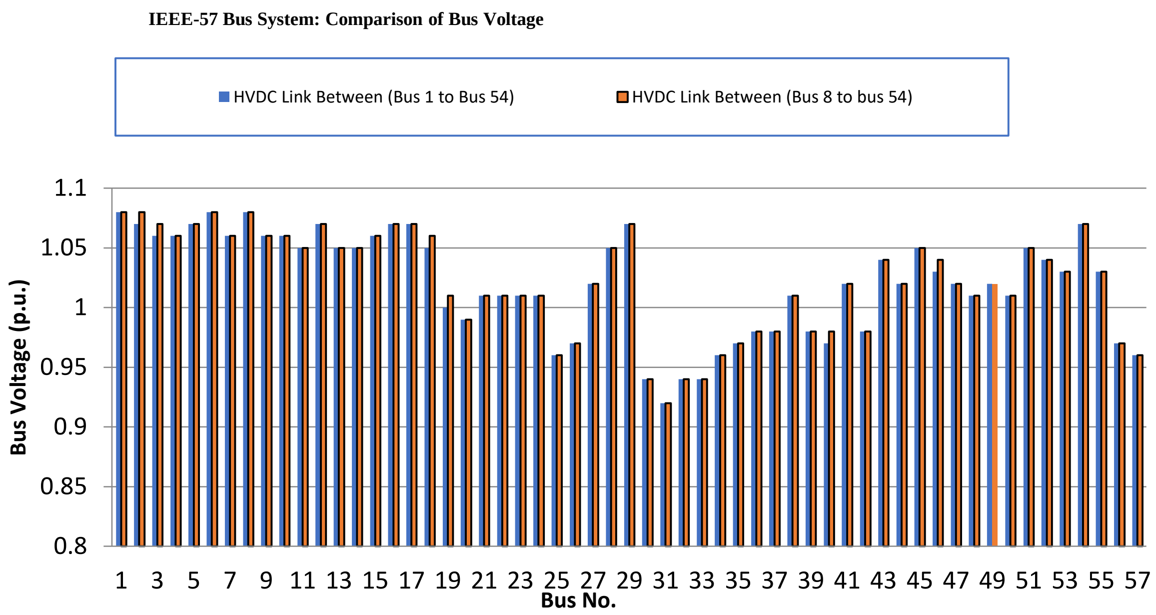

Figure 2. Bus Voltages Evaluation for HVDC Link at Buses Using OPF-Based Nodal Pricing for AC-DC

The comparison of nodal prices of IEEE 57 bus system is shown in Figure 3.The figure shows Nodal prices obtained between Bus No. 1 to 54 and Bus No. 8 to 54. The graph indicates that the nodal prices at Bus No. 8 to Bus No. 54 are higher than Bus No. 1 to Bus No. 54.

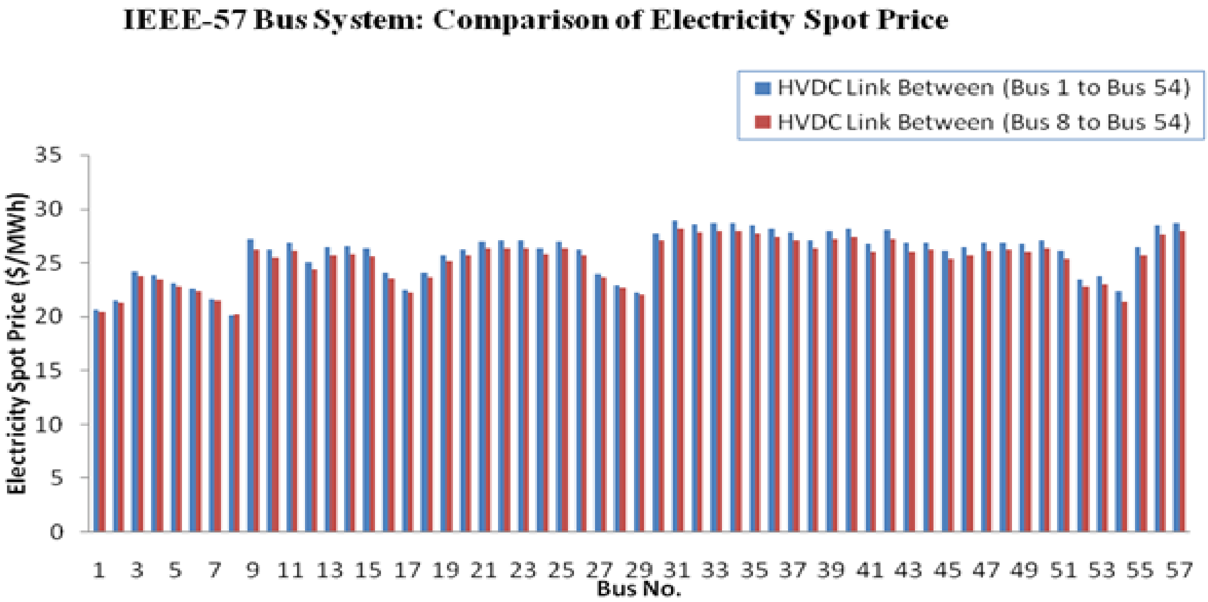

Figure 3. Spot electricity prices based on AC-DC OPF: Bus spot price comparison

7. CONCLUSION

Worldwide electric industry reorganisation has not disrupted transmission, which continues to operate as a controlled monopoly. It has long been a focus of both academia and business, serving as a vital link between vendors and customers. These days, transmission pricing plays a crucial role in influencing traders, the utility, and the growth of the energy market. In this article, the most effective Spot pricing was discussed in detail together with the fundamentals of transmission pricing under energy device restructuring with the impact of DC link between different buses. The comparison of voltage profiles and nodal prices at different buses of the IEEE 57 bus system is carried out. The goal became to develop the best spot pricing system for India's actual transmission network scenario to denote the benefits to the economy of investments in transmission and generation for wholesale electricity markets like India.

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