New Optimization Technique For Nodal Price And Reliability Calculation

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Abstract— **Power system restructuring and deregulation has changed the way in which system reliability management and electricity pricing done over the decades. The main purpose of restructuring is to offer customers with a choice of suppliers based on reliability and price requirement. Load shedding and generation redispatch mechanism used in the existing reliability evaluation technique have to be improved to include these changes. In this paper a planned technique provides an implement to compute the nodal reliability and nodal prices for market participants. The market participants are able to make use of this information to make most favorable trading decisions in market trading and operation. Contingency analysis has been done to determine the selected contingency system states. An optimization technique is proposed to determine the nodal prices for each contingency state obtained from contingency analysis for restructured power system with bilateral model. The objective of the problem is to minimize the generation cost subjected to market and network constraints. The impact of unavailability of generation and transmission system on load point reliability and nodal prices has been shown. Instead of using nodal price for the normal operation state, the expected nodal price and the associated standard deviation are used to represent the volatility of nodal price due to random failures. The 6 bus reliability test system (RBTS) has been analyzed to illustrate the technique.**

Symbols

p_j	Probability for contingency state j
U_c	Unavailability of the unit c
A_c	Availability of the unit c
λ_c	Failure rate of the unit c
μ_c	Repair rate of the unit c
D_j	Departure rate of system leaving state j
d_j	Mean failure duration state j
N_g	Number of generating buses
a_{ig}, b_{ig}, c_{ig}	Generator constant
P_{ig}^j	Generated active power by generator g at bus i for contingency j
N	Number of buses
P_{Li}	Active load
Q_{Li}	Reactive load
Q_{ig}^j	Reactive power generation of unit
$Y_{ik}^j \angle \delta_{ik}^j$	Admittance of line ik for contingency state j
θ_i^j	Voltage angle
V_i^j	Bus voltage
S_{ik}^j	Apparent power on line i–k
L_j	Lagrangian function for state j
ρ_{pi}^j	Active load Reliability indices for a contingency state j
ρ_{qi}^j	Reactive load Reliability indices for a contingency state j
$NENS_i^j$	Nodal Energy Not Supplied at bus i
LC_{pi}^j	Active Load Curtailment at bus for contingency state j
$\overline{\rho_{pi}}$	Expected nodal price of real power
$ENENS_i$	Expected nodal energy not supplied
ρ_{pi}	Standard deviation
σ_{pi}	Standard deviation of nodal price for bus i

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I. INTRODUCTION

Electric power systems are among the most complex and large systems that exist in the world. Broadly speaking, a power system is composed of the three functional zones of generation, transmission, and distribution. Over the years, electric power industry is owned by large utilities which have all the control over all the functions of electric power system. These utilities are referred as vertically integrated utilities. Each utility has one or more control centers that maintain security and reliability of a specific region. The basic function of a power system is to provide electric power to its customers as economically as possible and with an acceptable degree of continuity and quality [6]. Reliability is one of the most important factors considered in power system planning and operation in both vertically integrated and deregulated utility environments.

Reliability is an inbuilt characteristic and a specific measure of any component, device or system, which describes its ability to perform its intended function. In terms of a power system, the measures of reliability indicate how well the system performs its basic function of supplying electrical energy to its customers [9]. The likelihood of customers being disconnected for any reason can be reduced by increased investment during the planning phase and/or the operating phase. Over investment can lead to excessive operating costs. On the other hand, under investment can lead to lower reliability. How to trade off these two aspects is a major challenge to power system managers, planners, designers, and operators.

In order to resolve the problem between the economic and reliability constraints, design, planning, and operating criteria and techniques have been developed and applied over many decades.

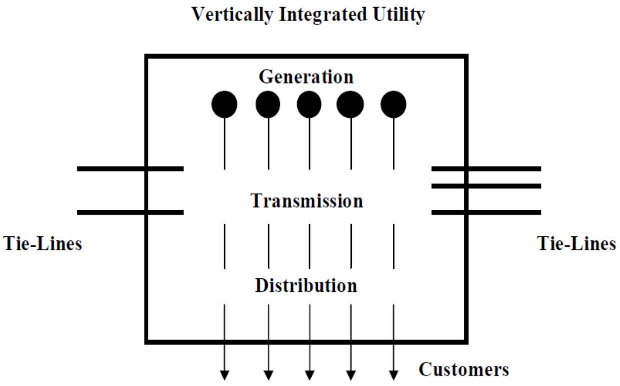


Fig.1 Power System Structure under Vertically Integrated Utilities

Figure 1 shows power system structure under vertically integrated utilities [7]. This paper presents a comprehensive technique to determine both nodal prices and nodal reliabilities of deregulated power systems. The characteristics of customer demand response to nodal price are investigated.

II. POWER SYSTEM RELIABILITY EVALUATION

Power system reliability can be divided into the two aspects of adequacy and security as shown in Figure 2. Adequacy relates to the existence of sufficient facilities within the system to satisfy the customer requirements. It is associated with static conditions and long-term analysis. Security relates to the ability of the system to respond to disturbances. It is associated with dynamic conditions and short-term analysis. An overall power system can be divided into the three basic functional zones of generation, transmission, and distribution.

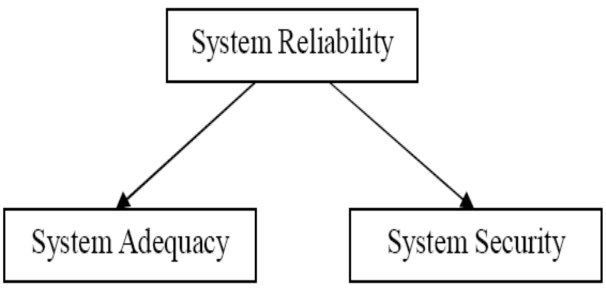


Fig.2 Subdivision of System Reliability

These three functional zones can be organized into the three hierarchical levels (HL) shown in Figure 3.

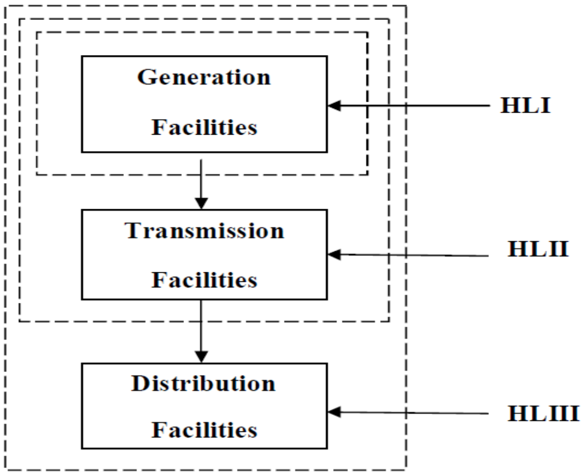


Fig.3 Power System hierarchical levels

Reliability assessment at hierarchical level I (HLI) is normally termed as generating capacity adequacy evaluation and is concerned with only the generation facilities. In an HLI study, the total system generation including interconnected assistance is examined to determine its adequacy to meet the total system load demand.

The transmission network and the distribution facilities are not part of the analysis at this level. Reliability assessment at hierarchical level II (HLII) involves the analysis of the combined generation and transmission system in regard to its ability to serve the system load. The reliability of supply at the individual load points in a composite system is a function of the capacities and availabilities of the individual generation, transmission facilities, and the system topology. Reliability assessment at hierarchical level III (HLIII) includes all of the three functional zones and is not easily conducted in a practical system due to the computational complexity and the scale of the assessment. This thesis is centered on adequacy assessment at HLII.

Various techniques have been developed and applied over many decades for reliability evaluation of power system. Most of these techniques are deterministic in nature and some of them still used today. Deterministic criteria were developed in order to account for randomly occurring failures. Their essential weakness is that they do not and cannot account for the probabilistic or stochastic nature of system behavior, of customer demands, or of component failures.

III. CALCULATION OF NODAL RELIABILITY AND PRICES

General

The function of a power system is to produce electrical energy at the generating sources and then move this energy to the major load points. The purpose of system reliability evaluation is to estimate the ability of the system to perform this function. Assessment of system reliability is very complex since it must consider the integrated impacts of generation and transmission. HLII studies include many aspects such as load flow analysis, contingency analysis, generation rescheduling, transmission overload alleviation, load curtailment etc.

In this paper, contingency enumeration and state selection are used to determine contingency state. AC optimal power flow technique is used to determine the nodal prices. In the case of generation inadequacy and network congestion, generations are re-dispatched and loads are shed to remove network violations for a contingency state.

Calculation

Considering a power system with N_c independent components, the reliability parameters for contingency state j with exactly b failed components can be determined using the following equations:

$$p_j = \prod_{c=1}^{b} U_c * \prod_{c=b+1}^{N_c} A_c \qquad (1)$$

$$D_j = \sum_{c=1}^{b} \mu_c + \sum_{c=b+1}^{N_c} \lambda_c \qquad (2)$$

$$d_j = 1/D_j \qquad (3)$$

The basic problem is to evaluate the nodal reliability and nodal prices for each system state. The basic reliability technique is used to determine state probability, departure rate and duration. For a contingency state, the objective of optimization is to minimize the total system cost including generation cost. For a contingency state j, the nodal prices and the generation re-dispatch can be determined by solving the following optimization problem:

$$Min\ f_j = \sum_{i \in N_g} \sum_{g \in NG_i^j} (a_{ig} * (P_{ig}^j)^2 + b_{ig} * P_{ig}^j + c_{ig}) \qquad (4)$$

Subjected to following constraints:

i) Load flow Equations: At bus i,

$$\sum_{g \in NG_i^j} P_{ig}^j - P_{Li} = \sum_{k=1}^{N} V_i^j * V_k^j * |Y_{ik}^j| * \cos(\theta_i^j - \theta_k^j - \delta_{ik}^j) \qquad (5)$$

$$\sum_{g \in NG_i^j} Q_{ig}^j - Q_{Li} = \sum_{k=1}^{N} V_i^j * V_k^j * |Y_{ik}^j| * \sin(\theta_i^j - \theta_k^j - \delta_{ik}^j) \qquad (6)$$

ii) Generating unit limits:

$$P_{ig,\min}^j \le P_{ig}^j \le P_{ig,\max}^j \qquad (7)$$

$$Q_{ig,\min}^j \le Q_{ig}^j \le Q_{ig,\max}^j \qquad (8)$$

iii) Voltage limits:

$$|V_{i,\min}^j| \le |V_i^j| \le |V_{i,\max}^j| \qquad (9)$$

iv) Line flow constraints:

$$|S_{ik}^j| \le |S_{ik,\max}^j| \qquad (10)$$

Equations (3)–(10) are a non-linear optimization problem with a non-linear objective function, non-linear equality and non-linear equality constraints. This problem can be solved by using various Newton methods with second order convergence properties.

Newton Raphson optimal power flow technique is used to solve the optimization problem. The Lagrangian function L_j of the above problem for state j is formed. The optimal generating unit outputs can be obtained using Newton Raphson OPF technique. The nodal prices of active power and reactive power at bus i under the optimum solution is obtained as follows:

$$\rho_{pi}^j = \frac{\partial L_j}{\partial P_i^j} \qquad \text{(Rs/MW)} \qquad (11)$$

$$\rho_{qi}^j = \frac{\partial L_j}{\partial Q_i^j} \qquad \text{(Rs/MVar)} \qquad (12)$$

The nodal reliability indices for a contingency state j are the nodal load curtailment and nodal energy not supplied. These indices can be calculated using the following equations:

$$NENS_i^j = d_j * LC_{pi}^j \qquad \text{(MWh)} \qquad (13)$$

NR Optimal Power Flow

The above described minimization optimization problem can be solved with Newton Raphson method. The above constrained minimization problem can be transformed into an unconstrained one by augmenting the load flow constraints into objective function [8]. The additional variable is known as Lagrange multiplier function or incremental cost function in power system optimization. The Lagrange function for the above problem is given as

$$L(P_g, |V|, \delta) = \sum_{i=1}^{NG} f(P_{gi}) + \sum_{i=1}^{N} \lambda_{pi}[P_i(|V|,\delta) - P_{gi} + P_{Li}] + \sum_{i=NG+1}^{N} \lambda_{qi}[Q_i(|V|,\delta) - Q_{gi} + Q_{Li}] \qquad (14)$$

In above Lagrange multiplier function, the control variables are $P_{gi}, \delta_i, \lambda_{pi}, \lambda_{qi}, |V_i|$. Any small variation in control variables about their initial values is obtained by forming total differentials which is give below (in matrix form):

$$\begin{bmatrix} H_{Pg\,Pg} & H_{Pg\delta} & H_{Pg\,\lambda p} & H_{Pg|V|} & H_{Pg\,\lambda q} \\ H_{\delta\,Pg} & H_{\delta\delta} & H_{\delta\,\lambda p} & H_{\delta|V|} & H_{\delta\,\lambda q} \\ H_{\lambda p\,Pg} & H_{\lambda p\delta} & H_{\lambda p\,\lambda p} & H_{\lambda p|V|} & H_{\lambda p\,\lambda q} \\ H_{|V|Pg} & H_{|V|\delta} & H_{|V|\lambda p} & H_{|V||V|} & H_{|V|\lambda q} \\ H_{\lambda q\,Pg} & H_{\lambda q\delta} & H_{\lambda q\,\lambda p} & H_{\lambda q|V|} & H_{\lambda q\,\lambda q} \end{bmatrix} * \begin{bmatrix} \Delta Pg \\ \Delta\delta \\ \Delta\lambda p \\ \Delta|V| \\ \Delta\lambda q \end{bmatrix} = \begin{bmatrix} J_{Pg} \\ J_{\delta} \\ J_{\lambda p} \\ J_{|V|} \\ J_{\lambda q} \end{bmatrix} \qquad (15)$$

Or, [H]*[change in control variables] = [J] (16)

Where [H] is Hessian matrix, [J] is Jacobian matrix.

Starting from initial data of an interconnected power system the optimal power flow solution can be obtained by solving the equation (16) for unknown control variables. In this method there no need for separate load flow study. This method is faster and gives accurate solution.

Calculation Of Nodal Reliability And Nodal Prices

In a deregulated power system, the expected values, the standard deviation of nodal prices and nodal reliabilities are important information for the risk analysis of market trading, planning and operation. The expected nodal price is a weighted average of the prices for different states. Unlike many other commodities, electricity cannot be stored in large amounts and needs a continuous balance between supply and demand. The price for a contingency state might be quite different from the price expected. Inadequate generation and congestion in some contingency states result in extreme price volatility or ‘price spikes’. The random nature of failures results in great price uncertainty. As customers and producers face volatile prices, their reactions will depend on their attitude towards accepting risk. A risk neutral participant will value a certain benefit the same as an equal amount of expected benefit that involves risk, whereas a risk adverse participant, who faced with two solutions with the same expected benefit (but different risks), will accept the one with lower risk.

Therefore hedging contracts have become an important tool dealing with price risks. Customers who wish to hedge against price risk and maintain a certain reliability level can sign specific contracts with producers. The producers can also use contracts to hedge against profit volatility. These require measuring the risk of being exposed to high prices. Standard deviation of nodal prices can be used to evaluate the extent of price fluctuating around its expected value.

Considering all possible system states, the expected nodal prices and nodal reliability indices can be determined using the following equations.

The expected nodal price of real power:

$$\overline{\rho_{pi}} = \sum_{j=1}^{SN} p_j * \rho_{pi}^j \qquad \text{(Rs/MW)} \quad (17)$$

The standard deviation of ρ_{pi}:

$$\sigma_{pi} = \sqrt{\sum_{j=1}^{SN} (\rho_{pi}^j - \overline{\rho_{pi}})^2 * p_j} \qquad \text{(Rs/MW)} \quad (18)$$

The expected nodal energy not supplied:

$$ENENS_i = \sum_{j=1}^{SN} D_j * p_j * NENS_j^i \qquad \text{(MWh/Yr)} \quad (19)$$

IV. TEST SYSTEM STUDY

The Reliability Bus Test System has been analyzed to illustrate the technique. The 6-Bus RBTS [5] is shown in the Figure 5.Figure shows the single line diagram of the system.The distribution system is represented as equivalent bulk load point. The nodal reliability and nodal prices of real power and nodal prices for reactive power is calculated. The system consists of 11 generators and 9 transmission lines.

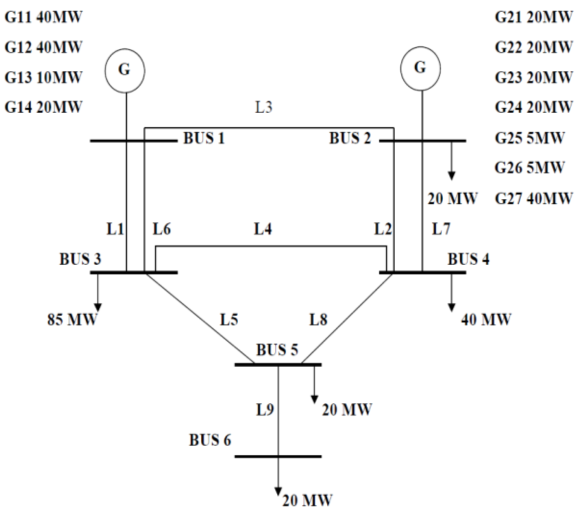


Fig.5 6 Bus RBTS

Nodal Prices and Nodal Reliability

Random failures up to second order are considered in the evaluation. Nodal prices and Nodal reliability for are presented in terms of the first order failure and second order failure respectively. Nodal prices for the first order failure are given in Table 1. The Nodal prices for the second order line failures are shown in Table 2. From the Table 1-2, it can be said that as the distance of the load from the generation increases, the price increases. It can be seen that the second order line outages produces larger price fluctuations.

The load at different buses has to be shed to remove network violations. The Nodal Energy Not Supplied (NENS) for second order outages are given in Table 3. The price fluctuations at Bus 1 due to transmission line failure are small as compared to other buses. Due to failure of Line 5 and Line 8, both load at Bus 5 and Bus 6 are isolated.

Table 1

Nodal prices for first order outages

State	Component Out	ρ_{p1} (Rs/MW)	ρ_{p2} (Rs/MW)	ρ_{p3} (Rs/MW)	ρ_{p4} (Rs/MW)	ρ_{p5} (Rs/MW)	ρ_{p6} (Rs/MW)
1	Line 1	187.668	186.325	201.165	200.868	202.90	204.822
2	Line 2	189.734	184.702	198.142	199.674	200.701	202.514
3	Line 3	189.162	185.056	196.106	196.443	197.993	199.730
4	Line 4	188.390	185.626	195.426	196.703	197.788	199.529
5	Line 5	188.266	185.745	195.209	197.452	201.033	202.852
6	Line 6	187.668	186.325	201.165	200.868	202.909	204.822
7	Line 7	189.734	184.702	198.142	199.674	200.701	202.514
8	Line 8	188.737	185.381	196.119	195.421	199.646	201.437
9	Line 9	187.220	184.794	193.403	193.741	194.397	0
10	G11	191.688	186.564	198.537	198.716	200.368	202.128
11	G12	191.688	186.564	198.537	198.716	200.36	202.128
12	G13	191.688	186.564	198.537	198.716	200.36	202.128
13	G14	189.028	185.695	196.117	196.585	198.07	199.741
14	G21	188.776	186.158	195.996	196.585	198.00	199.741
15	G22	188.776	186.158	195.996	196.585	198.00	199.741
16	G23	189.294	187.440	196.688	197.409	198.00	200.511
17	G24	188.776	186.158	195.996	196.585	198.00	199.741
18	G25	188.776	186.158	195.996	196.585	198.00	199.741
19	G26	188.776	186.158	195.996	196.585	198.00	199.741
20	G27	188.776	186.158	195.996	196.585	198.007	199.741

Table 2

Nodal Prices for second order outages

State	Component Out	ρ_{p1} (Rs/MW)	ρ_{p2} (Rs/MW)	ρ_{p3} (Rs/MW)	ρ_{p4} (Rs/MW)	ρ_{p5} (Rs/MW)	ρ_{p6} (Rs/MW)
1	L1,L2	187.332	184.497	201.154	201.971	203.197	204.846
2	L1, L7	187.332	184.497	201.154	201.971	203.197	204.846
3	L1, L6	180.223	189.037	248.575	239.250	247.923	252.320
4	L2, L6	187.332	184.497	201.154	201.971	203.197	204.846
5	L2,L9	188.245	184.089	195.457	196.619	196.893	0
6	L3, L9	187.740	184.412	193.763	193.951	194.684	0
7	L4, L6	187.310	186.031	200.310	199.644	201.777	203.597
8	L5, L8	185.931	184.077	191.232	191.477	0	0
9	L5, L9	187.081	184.905	193.157	194.341	196.015	0
10	L6, L7	187.332	184.497	201.154	201.971	203.197	204.846
11	L6, L9	186.453	185.487	197.947	197.578	198.651	0
12	L7, L9	188.245	184.089	195.457	196.619	196.893	0
13	L8, L9	187.318	184.724	193.608	193.396	195.286	0

Table 3
NENS for second order outages

State	Component Out	$NENS_1^j$ (MWh)	$NENS_2^j$ (MWh)	$NENS_3^j$ (MWh)	$NENS_4^j$ (MWh)	$NENS_5^j$ (MWh)	$NENS_6^j$ (MWh)
1	L1,L2	0	0	63.365	29.813	14.906	14.906
2	L1, L7	0	0	63.365	29.813	14.906	14.906
3	L1, L6	0	0	185.270	0	12.842	0
4	L2, L6	0	0	63.365	29.813	14.906	14.906
5	L2,L9	0	0	0	0	0	97.085
6	L3, L9	0	0	0	0	0	97.031
7	L4, L6	0	0	17.344	6.879	3.439	3.439
8	L5, L8	0	0	0	0	96.870	96.870
9	L5, L9	0	0	0	0	0	96.870
10	L6, L7	0	0	63.365	29.813	14.906	14.906
11	L6, L9	0	0	0	0	0	96.897
12	L7, L9	0	0	0	0	0	97.085
13	L8, L9	0	0	0	0	0	96.870

Table 4
Reliability and price indices for each bus of RBTS

Bus	1	2	3	4	5	6
ρ_{p0}	188.52	185.52	195.65	196.17	197.63	199.36
$\overline{\rho}_{pi}$	35.188	34.513	36.528	36.616	36.897	37.040
σ_{pi}	65.124	64.866	72.418	72.040	70.818	63.712

Figure 6 - 8 shows the price spikes at Bus1 to Bus 6 in first order outages (line) respectively

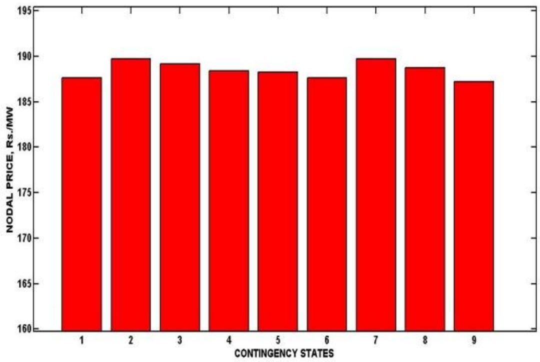
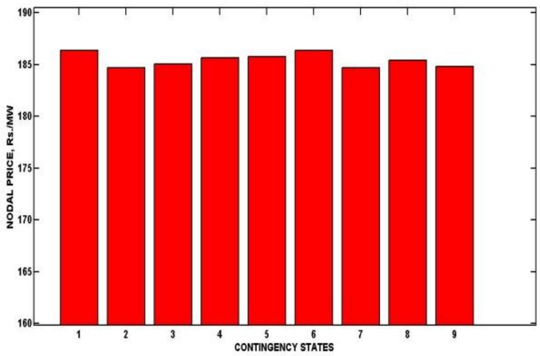


Fig. 6 Nodal Prices at Bus 1



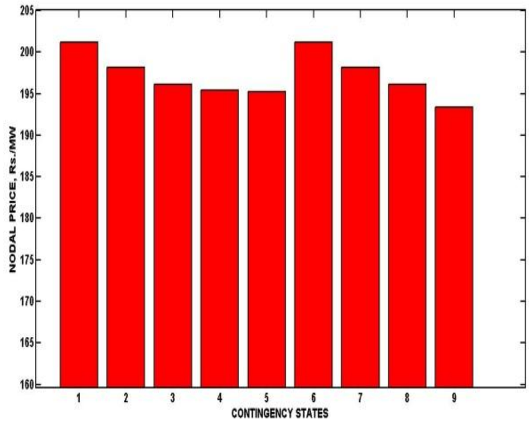


Fig. 7 Nodal Prices at Bus 2
Fig. 8 Nodal Prices at Bus 3

From figure 6 it is clear that a nodal prices hike is more occur at bus 1 in case of failure of line 2 and line 7 since load at bus 4 will be supplied will have to be supplied by generators at bus as a result demand hike occur at bus 1 which result in price hike. In figure 7 as the case happen at bus 1 same occur at bus 2 in case of failure of line 1 or 6, demand rises which result in nodal price hike at bus 2. Bus 3 are load buses so nodal price depends on demand and transmission losses, when transmission losses are more price is more, as can be concluded from the figure 8.

Figure 9-11 shows the price spikes at Bus1 to Bus 6 in second order outages (line) respectively.

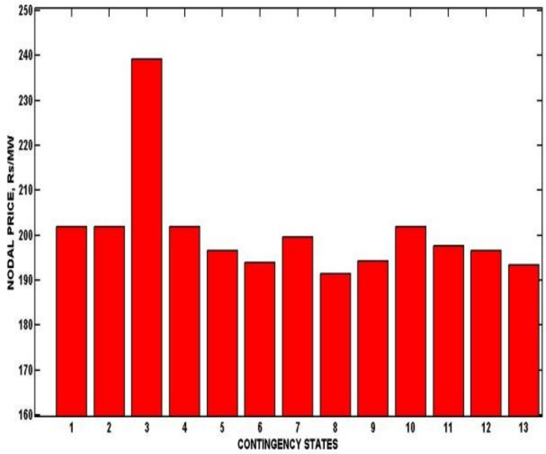


Fig. 9 Nodal Prices at Bus 4

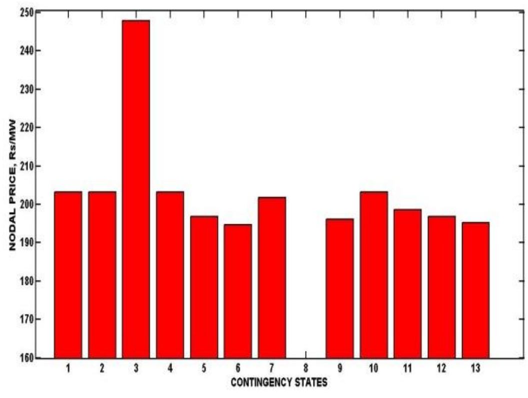


Fig. 10 Nodal Prices at Bus 5

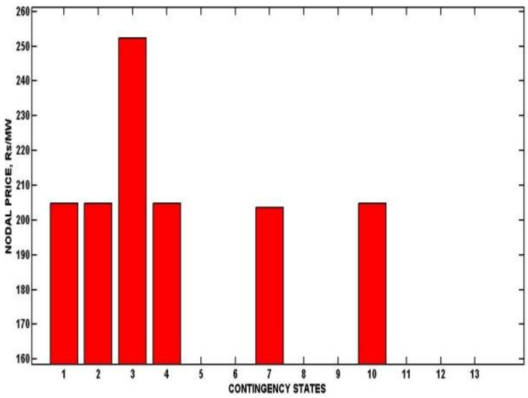


Fig. 11 Nodal Prices at Bus 6

Figure 9-11 shows that real and reactive nodal prices at many load buses are higher than at generator buses and reactive nodal prices are smaller than real nodal prices at all the buses. These nodal prices can be used to calculate significant wheeling charges of real and reactive power (marginal network revenue) as difference of revenue received from real and reactive demand and expenditure for real and reactive generation. Reactive power nodal price is affected by the reactive power production costs of generations and the capital investment cost of capacitors. Reactive power nodal prices can be related to the urgency of the reactive power supply and an incentive can be given to improve load power factor and reduce power demand. The proposed nodal transmission pricing model may forms a basis to calculate network revenue for bilateral and multilateral power transactions in deregulated power systems to wheel the power between the buses.

V. CONCLUSION

Basically, main objective of power system restructuring and deregulation is to introduce competition in the power industry and to allow customers to select their suppliers based on price and reliability. So, this thesis presents a comprehensive technique to evaluate nodal reliability and nodal prices of restructure power system. Many new problems created by customer choice regarding system operation, pricing and reliability planning are also solved by this technique. Optimization problem is used to calculate the nodal reliability and nodal prices. The problem is formulated using Newton Raphson optimal power flow technique. The main objective of the optimization problem is to minimize the total system generation cost. For this purpose six bus reliability test system (RBTS) has been analyzed to illustrate the technique. The analysis of results show that due to congestion in some contingency states causes extreme price volatility or price spikes. The random nature of failure creates price uncertainty. Prices at different nodes of the system can be different due to transmission loss and constraints. Nodal prices and Nodal reliability indices for each state, the expected values and the standard deviations of these indices are very important information for the risk analysis of market trading, planning and operation. The proposed technique provides a tool to calculate all this information for market participants. The information provided by the technique can be used by market participants to make optimal decisions in market trading and operation.

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