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Reliability Evaluation of Deregulated Power System Considering Competitive Electricity Market

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Abstract
In a deregulated electric power system in which a competitive electricity market can influence system reliability, system analysts are rapidly recognizing that they cannot ignore market risks. This paper first proposes an analytic probabilistic model for the reliable evaluation of competitive electricity markets and then develops a methodology for incorporating the market reliability problem into composite power system reliability studies. In order to evaluate the reliability of power system, a system comprising 8 Hydropower plants, 22 transmission lines and 12 load points (Substations) of Nepal Electricity Authority has been considered. The market reliability is evaluated using the Markov state space diagram. Since the market is a continuously operated system, the concept of absorbing states is applied to it in order to evaluate reliability. The market states are identified using market performance indices and the transition rates are calculated using historical data. This research work aims at incorporating the significance of market reliability during the evaluation of reliability of a power system. The key point in the proposed method is the concept that the reliability level of a restructured electric power system can be calculated using the availability of the composite power system and the reliability of the electricity market.

Keywords
Composite Power System – Deregulation – Genco – Disco – ISO – LOLP

1. Introduction

For about a hundred years, the electricity supply industry was in the hands of vertically integrated monopoly utilities. Electricity market restructuring has been underway for more than a decade since the United Kingdom opened a Power Pool in April 1990. Restructuring has resulted in greater competition, emphasis on efficiency and reliability, and the development of a market structure for trading and supplying electrical energy. It can be clearly seen that the thrust towards privatization and deregulation of the electric utility industry has introduced a wide range of reliability issues that will require new criteria and analytical tools that recognize the residual uncertainties in the new environment. The traditional uncertainties associated with equipment availabilities will be augmented by a new set of concerns such as uncertainties associated with a competitive market mechanism. There are many variations on the definition of reliability, but a widely accepted form is as follows: *Reliability is the probability of a device / component / system performing its purpose adequately for the period of time intended under the operating conditions encountered.* The criterion of 'adequate performance' is an engineering and managerial problem. It is evident that the criteria of adequate performance for a restructured power system are not the same as the criteria for a traditional one. Reliability is the probability of a system performing its purpose adequately for the period of time intended under the operating conditions encountered.

Nevertheless, Criterion of adequate performance for electric power system has changed in the restructured system from the traditional system as supply to the customers would suffice as adequate performance of electric power system in traditional system whereas in restructured system apart from supply to the customers as well as facilitate an efficient market for electricity only ensures an adequate performance of electric power system.

There are a wide range of probabilistic tools and indices which can be used to effectively analyze the bulk system reliability. Traditionally, the basic techniques for reliability evaluation have been categorized in terms of their application to the main functional zones of an electric power system. These are: generation systems, composite generation and transmission (or bulk power) systems, and distribution systems. The concept of hierarchical levels (HL) has been developed in order to establish a consistent means of identifying and grouping these functional zones. The first level (HLI) refers to generation facilities, the second level (HLII) refers to the composite generation and transmission (bulk power) system, and the third level (HLIII) refers to the complete system including distribution. The target of this study is the reliability evaluation of HLII in a competitive market environment.

This paper presents a new method for evaluating reliability indices of a competitive electric power system. The key point in the proposed method is the concept that the reliability level of a restructured electric power system can be calculated using the availability of the composite power system (HLII) and the reliability of the electricity market.

2. Methodology

In order to evaluate the reliability of deregulated power system considering competitive electricity market following steps were taken during the research.

2.1 System Selection

In order to carry on this research ,initially a system comprising 8 HPPs considered as Gencos, transmission network consisting 22 transmission lines and 12 substations considered as Load Points of Discos was selected.In order to calculate the Market Power Monitoring Index(MPMI) of different Power Plants considered as Generation Companies(Gencos) their annual generation(MWh) in the period of 2069 Poush to 2070 Marg was collected. The line lengths ,conductor sizes, ampacity, power carrying capacity and availability of the transmission lines and load at the substations (Load Points) considered for the research were collected.

2.2 Evaluation of Market Reliability

Market Reliability can be evaluated on the basis of various market issues and their related market performance indices. However, throughout this research, Market Power has been considered as the Market Issue and Market Power Monitoring Index (MPMI) has been used as the index to determine the market state. Evaluation of MPMI has been done on the basis of Herfindahl Herschmann Index of the whole system of eight Hydropower Plants.

First of all Group HHI was calculated for each Gencos for each day of a year (from 2069 Poush to 2070 Marg) considering the daily unit generations (MWh) of each units employing the relation:

$$HHI_G = \sum_{i=1}^{m} (MWh_i/Total_G \times 100)^2$$

After evaluating the Group HHI of each Gencos for each day of a year(from 2069 Poush to 2070 Marg),System HHI or the MPMI for each day of the year for the same period, was calculated employing the relation:

$$HHI_S = \sqrt{(\sum_{j=1}^{n} (MWh_i/Total_S \times HHI_{Gj}^2))}$$

Since, $HHI_S = MPMI$, On the basis of the value of MPMI the electricity market has been modeled as a Markov Model. Basically three states of Electricity Market modeled to be operating in a Markovian process has been considered as shown below:

Table 1: MPMI Range

Market States	MPMI Values
Competitive	MPMI<4000
Moderately Competitive	4000<MPMI<5000
Anti competitive	MPMI>5000

The MPMI range considered for different market states in this work have been set at the high range as the system and the data considered are related to the system already operated in the monopolistic scenario where the level of competition is very low, hence the standard ranges for different market states was not possible. Thus the calculated MPMI values are expected to be high and the range selected is also at high. On the basis of the above MPMI values the transition rates (rate of transition from one market state into another state) were determined.

The transition rates obtained were used to formulate the differential equations governing the market states of the considered power system whose solution provides the probability of various market states. MATLAB and SIMULINK were used for solution of the differential equation.

MATLAB(MATrix LABoratory) is a programming environment for algorithm development, data analysis, visualization and numerical computation. SIMULINK is the MATLAB toolbox which enables solution of complex numerical equations like differential equations. In this research SIMULINK of MATLAB R2012a has been used.

2.3 Evaluation of Reliability of Composite Power System

Reliability of Composite Power System HLII was evaluated by using the availabilty values of Generators ,Transmission lines, Ampacity and Load Carrying Capacities of Transmission lines as well as the load at various load points(substations) of Discos. Loss of Load Probabilities (LOLP) at various load points were used to determined the probability of system success as defined traditionally. Finally, System Reliability was evaluated incorporating market reliability with the Reliability of Composite Power System.

3. Case Study

In this Research, Case study has been performed under the system comprising 8 HPPs considered as Gencos, transmission network consisting 22 transmission lines assumed to be controlled by ISO and 12 substations considered as Load Points of Discos to be operating in Wholesale market model as shown in Figure 1. Even in NEA Generation Sectors, Transmission Lines, and Distribution Sectors are handled by different Departments. Though it might seem the system considered might not be a perfect case for study as in a purely deregulated power system electricity market drives the system than the other way around. However the limited competition in the system considered for study cannot restrict its application to it. Though, poor market reliability as a result of limited competition cannot be avoided. However, same methodology can be applied to a fully deregulated power system without any modification to the methodology presented.

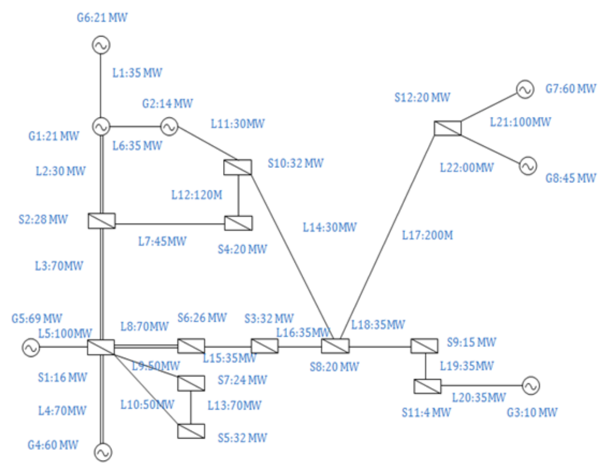

Figure 1: System Used For Reliability Evaluation

In order to calculate the Market Power Monitoring Index (MPMI) of different Power Plants considered as Generation Companies (Gencos) their daily generation (MWh) in the period of 2069 Poush to 2070 Marg i.e. whole year, was collected. The line lengths ,conductor sizes, ampacity, power carrying capacity and availability of the transmission lines considered to be operated and controlled by ISO and load at the substations (Load Points) considered as operated and controlled by Discos, for the research were collected from various departments of Nepal Electricity Authority.

Table 2: Generation Data

S.No.	Group	Hydro Power Plant	No. of Units	Unit Capacity(MW)	Capacity (MW)
1	G1	Trishuli	7	3.00	21
2	G2	Devighat	3	4.66	14
3	G3	Sunkoshi	3	3.33	10
4	G4	Kulekhani	2	30.00	60
5	G5	Marshyangdi	3	23.00	69
6	G6	Chilime	2	11.00	22
7	G7	Khimti	5	12.00	60
8	G8	Bhotekoshi	2	22.50	45

Table 3: Transmission Data

S.No.	Symbol	Transmission Line	Length (km)	Conductor Size (Sq. mm)	(Failure s/Year)	MTTR(hrs)	LCC (MW)
1	L1	Chilime –Trishuli(66 kV)	39.00	150	8	6	35
2	L2	Trishuli-Balaju(66 kV)	58.00	100	8	6	30
3	L3	Balaju-Siuchatar (66 kV) (Double)	7.00	150	4	6	70
4	L4	Siuchatar-Kulekani-I(66 kV) (Double)	29.00	150	8	6	70
5	L5	Marsyangdi-Siuchatar(132 kV)	84.00	300	10	6	100
6	L6	Trishuli- Devighat(66 kV)	4.60	150	10	6	35
7	L7	Balaju-Lainchour(66 kV)	2.00	200	8	4	45
8	L8	Siuchatar-Patan(66 kV) (Double)	13.00	150	4	4	70
9	L9	Siuchatar-K3(66 kV)	6.90	250+500 (XLPE)	8	4	50
10	L10	Siuchatar-Teku(66 kV)	4.10	250	4	4	50
11	L11	Devighat-Chabahil(66 kV)	33.00	100	10	6	30
12	L12	Lainchour-Chabahil(66 kV)	7.70	800(XLPE)	4	4	120
13	L13	Teku-K3(66 kV)	2.80	400	4	4	70
14	L14	Chabahil-Bhaktapur(66 kV)	23.00	100	8	4	30
15	L15	Patan-Baneswor(66 kV)	2.80	120	4	4	35
16	L16	Bhaktapur-Baneswor(66 kV)	11.00	120	4	4	35
17	L17	Bhaktapur-Lamaosangu(132 kV) (Double)	96.00	250	8	6	200
18	L18	Bhaktapur-Banepa(66 kV)	11.00	120	8	6	35
19	L19	Banepa-Panchkhal(66 kV)	8.00	120	8	6	35
20	L20	Panchkhal-Sunkoshi(66 kV)	29.00	120	8	6	35
21	L21	Khimti-Lamosangu(132 kV)	46.00	250	8	6	100
22	L22	Botekoshi-Lamosangu(132 kV)	31.00	250	8	6	100

Table 4: Distribution Data

S.No.	Symbol	Substation	Peak Load(MW)
1	S1	Siuchatar	16
2	S2	Balaju	28
3	S3	Baneswor	32
4	S4	Lainchour	20
5	S5	Teku	32
6	S6	Patan	26
7	S7	K-3	24
8	S8	Bhaktapur	20
9	S9	Banepa	15
10	S10	Chabahil	32
11	S11	Panchkhal	4
12	S12	Lamosangu	20

4. Results and Discussion

The daily generations of all the eight Gencos(HPPS) were used to calculate the Daily System HHIs.System HHI indicates the Market Power Monitoring Index(MPMI). MPMI calculated for the period of 2069 Poush to 2070 Marg is as follows.

Table 5: System HHI

System HHI												
Days	2069/09	2069/10	2069/11	2069/12	2070/1	2070/2	2070/3	2070/4	2070/5	2070/6	2070/7	2070/8
1	4769	5872	6361	4746	4348	4116	3711	4072	3869	3738	3683	3534
2	4788	5166	6377	4623	4800	3998	3592	3679	3665	3624	3605	3496
3	4769	5902	6596	4656	4338	4058	3656	4143	3675	3602	3605	3491
4	4786	5338	6385	4736	4652	3928	3594	3689	3659	3660	3651	3607
5	4751	5142	6387	4761	4360	3964	3560	3670	3707	3643	3599	3506
6	4770	4804	5262	4640	5539	3846	3621	4016	3772	3682	3596	3492
7	5103	5084	5798	4669	4487	3905	3668	3817	4036	3778	3600	4146
8	5205	5178	6052	4688	4066	3899	3711	4107	3673	3578	3588	3795
9	5284	5232	6194	4753	4369	3585	3728	4056	3744	3574	3754	3804
10	4900	5629	6444	4761	4507	4116	3585	3956	3591	3572	3656	3558
11	5172	5541	6621	4767	4304	3615	3653	3747	3630	3672	3730	3915
12	4760	5439	6680	4690	4349	3695	3723	4366	3656	3476	3699	3513
13	4761	5312	6749	4836	4558	3539	3622	3685	3632	3580	3769	3535
14	4770	5848	6576	4597	4410	3615	3583	4118	3696	3581	3726	3566
15	4740	5423	6580	4926	4110	3591	3619	3700	4697	3577	3818	3485
16	4795	5794	6207	4827	4125	3762	3624	3863	3405	3578	3806	3500
17	4916	5545	5837	4805	4064	3676	3928	3988	3627	3597	3708	3496
18	5247	5753	5723	4892	3886	3970	3606	3662	3654	3598	3836	4000
19	5177	6336	5787	4668	3986	3683	3585	3920	3712	3633	4133	4027
20	4842	5824	5978	4721	4387	3671	3775	3699	3676	3617	3864	3627
21	4758	6032	6005	4696	4662	3723	3722	3672	3671	3636	3689	3728
22	4700	5227	6083	4647	4944	3536	3628	4240	3736	3626	3696	3463
23	4842	5361	5517	4675	4403	3574	3795	3700	3695	3668	3859	3401
24	4827	5063	5553	4667	4854	3709	3874	3757	3661	3582	3679	3485
25	4877	5033	5355	4411	4221	3883	3713	4160	3703	3596	3759	3537
26	4718	5772	5637	4249	4447	3628	3800	3703	3690	3591	3729	3506
27	4727	5235	6036	4633	4117	4009	3816	3880	3776	3620	3640	3462
28	5178	5208	5473	4627	4151	3959	3728	4259	3661	3738	3644	3957
29	5049	5679	6112	4613	4117	3856	4007	3984	3575	3813	3891	4273
30			5635	4611	4283	3772	4011	4138	3637	3811		3726
31					4470	3764	3697	3794	3711			
32								3950				

On the basis of the values of MPMI, Market states and their transition rates were determined as presented as follows:

Table 6: Transition Table

S.No.	Market States	Days/year	Transitions
1	Fully Competitive MPMI<4000	195	To state 1: 175
			To state 2: 20
			To state 3: 0
2	Moderately Competitive 4000<MPMI<5000	104	To state 1: 67
			To state 2: 32
			To state 3: 5
3	Anti Competitive MPMI>5000	66	To state 1: 0
			To state 2: 5
			To state 3: 61

Markov Model of the system considered can be formed on the basis of the transition rates shown in preceding table.

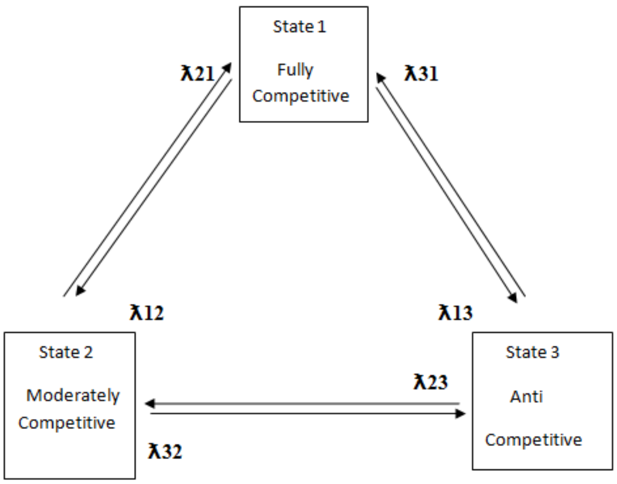

Figure 2: Markov Model of Electricity Market

The transition rates :

$$\begin{aligned} \lambda_{12} &= 0.1026 \\ \lambda_{21} &= 0.6442 \\ \lambda_{23} &= 0.0481 \\ \lambda_{32} &= 0.0758 \\ \lambda_{13} &= 0.0000 \\ \lambda_{31} &= 0.0000 \end{aligned}$$

The differential equations governing the market states is as follows:

$$P_1'(t) = P_1(t) \times (1 - \lambda_{12} - \lambda_{13}) + P_2(t) \times \lambda_{21} + P_3(t) \times \lambda_{31} \quad (1)$$

$$P_2'(t) = P_2(t) \times (1 - \lambda_{21} - \lambda_{23}) + P_3(t) \times \lambda_{32} + P_1(t) \times \lambda_{12} \quad (2)$$

$$P_3'(t) = P_3(t) \times (1 - \lambda_{31} - \lambda_{32}) + P_1(t) \times \lambda_{13} + P_2(t) \times \lambda_{23} \quad (3)$$

The above state probability expressions give the probability of being found in each of the three states at a given time t in the future. In order to calculate the market reliability, the process must come to a halt when state 3 is encountered. This can be achieved by modifying the state space diagram to make state 3 an absorbing state. When state 3 is encountered, the market effectively comes to a halt until the whole process is started again at state 1.

Initially, Market is assumed to be in Competitive State, i.e. $P_1(t) = 1, P_2(t) = 0, P_3(t) = 0$, for the solution of the given differential equations.

The solution of above equation gives the state probabilities of different market states.MATLAB and SIMULINK model used for the solution of the given equations is as follows:

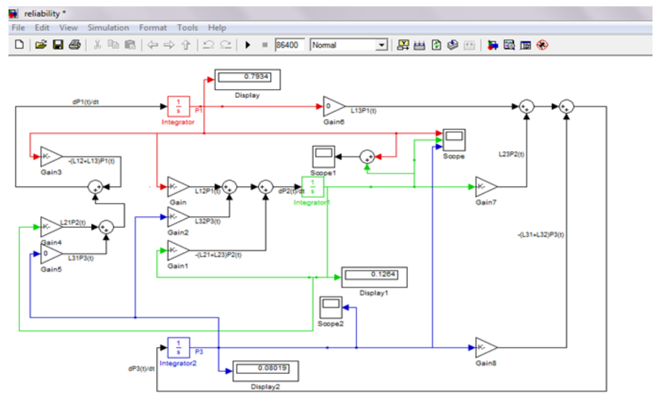

Figure 3: Simulink Model for Solution of Differential Equations

The Market Reliability thus obtained is shown in the graph in the following figure.

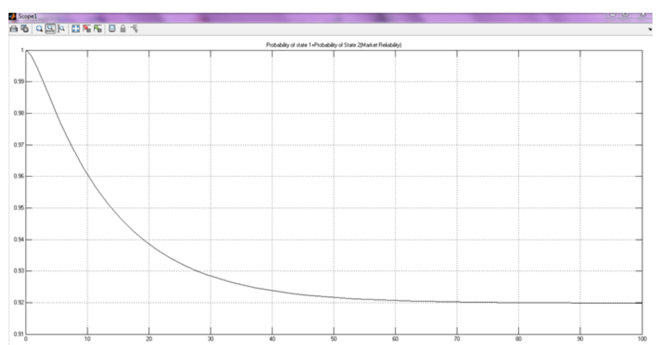

Figure 4: Generation Data

Since, Competitive State and Moderately competitive state have been considered as the reliable market states throughout this research, Market Reliability was given by:

$$P_1(t) + P_2(t) = 0.7934 + 0.1264 = 0.9198$$

4.1 Nodal Evaluation of System Success in a Competitive Environment considering Composite Power System

By using the data of the Generator availabilities of HPPs operated by Gencos, availabilities and load carrying capacities of transmission line managed by ISO and the load at the load points(Substations) managed by Discos the Probability of System success was evaluated by evaluation of Loss of Load Probabilities at various load points.

Table 7: Generation Probability Tables

Trishuli HPP Availability 0.96

State	Capacity In	Capacity Out	Individual Probability	Cumulative Probability
1	21	0	0.75145	1.00000
2	18	3	0.21917	0.24855
3	15	6	0.02740	0.02938
4	12	9	0.00190	0.00198
5	9	12	0.00008	0.00008
6	6	15	0.00000	0.00000
7	3	18	0.00000	0.00000
8	0	21	0.00000	0.00000

Devighat HPP Availability 0.97

State	Capacity In	Capacity Out	Individual Probability	Cumulative Probability
1	14	0	0.91267	1.00000
2	9.34	4.67	0.08468	0.08733
3	4.67	9.34	0.00262	0.00265
4	0	0	0.00003	0.00003

Kulekhani I HP Availability 0.98

State	Capacity In	Capacity Out	Individual Probability	Cumulative Probability
1	60	0	0.96040	1.00000
2	30	30	0.03920	0.03960
3	0	60	0.00040	0.00040

Sunkoshi HPP Availability 0.97

State	Capacity In	Capacity Out	Individual Probability	Cumulative Probability
1	10	0	0.91267	1.00000
2	6.66	3.33	0.08468	0.08733
3	3.33	6.66	0.00262	0.00265
	0	10	0.00003	0.00003

Marshyangdi HI Availability 0.98

State	Capacity In	Capacity Out	Individual Probability	Cumulative Probability
1	60	0	0.94119	1.00000
2	40	20	0.05762	0.05881
3	20	40	0.00118	0.00118
4	0	60	0.00001	0.00001

Khimti HPP Availability 0.98

State	Capacity In	Capacity Out	Individual Probability	Cumulative Probability
1	60	0	0.90392	1.00000
2	48	12	0.09224	0.09608
3	36	24	0.00377	0.00384
4	24	36	0.00008	0.00008
5	12	48	0.00000	0.00000
6	0	60	0.00000	0.00000

Chilime HPP Availability 0.98

State	Capacity In	Capacity Out	Individual Probability	Cumulative Probability
1	22	0	0.96040	1.00000
2	11	11	0.03920	0.03960
3	0	22	0.00040	0.00040

Bhotekoshi HPI Availability 0.98

State	Capacity In	Capacity Out	Individual Probability	Cumulative Probability
1	60	0	0.96040	1.00000
2	30	30	0.03920	0.03960
3	0	60	0.00040	0.00040

Finally considering the load at various load points the Loss of Load Probabilities at 12 load points considered for this research were calculated. In order to calculate the Loss of Load Probability at those Load Points concept of Composite System Reliability Evaluation has been considered.

Conditions:

- Loads are Constant
- Transmission loss is zero
- Two simultaneous outages are considered
- All load deficiencies are shared equally if possible

Table 8: Transmission Line Availability

S.No.	line	Availability	Unavailability
1	L1	0.9946	0.0054
2	L2	0.9946	0.0054
3	L3	0.9973	0.0027
4	L4	0.9946	0.0054
5	L5	0.9931	0.0069
6	L6	0.9931	0.0069
7	L7	0.9964	0.0036
8	L8	0.9981	0.0019
9	L9	0.9931	0.0069
10	L10	0.9981	0.0019
11	L11	0.9931	0.0069
12	L12	0.9981	0.0019
13	L13	0.9981	0.0019
14	L14	0.9964	0.0036
15	L15	0.9981	0.0019
16	L16	0.9981	0.0019
17	L17	0.9946	0.0054
18	L18	0.9946	0.0054
19	L19	0.9946	0.0054
20	L20	0.9946	0.0054
21	L21	0.9946	0.0054
22	L22	0.9946	0.0054

4.2 System Success Probability Evaluation

Consider A as the event that the service is available at load point K and B as the event that the electricity market is efficient. The probability of system success is equal to the probability that both A and B occur: For Node K:

$$\begin{aligned} \mathrm{P}_{\text{system success}} &= \mathrm{P}(A \cap B) \\ &= \mathrm{P}(A/B) \times \mathrm{P}(A) \\ &= \mathrm{P}(B/A) \times \mathrm{P}(B) \end{aligned}$$

The probability of market success for a specified period of time given that the service has been available at load-point K as well as the probability of service being available at load-point K given that the market has been efficient for a specified period of time are difficult to determine. It is evident that market performance indices depend on the adequacy and security of a composite Generation and Transmission system, but the mechanism of this dependency is not clear and it is a very difficult task to analyze it quantitatively. However for the system considered since the interdependence between the market mechanism and the technical parameters seems very limited, in order to simplify, it can be assumed that A and B are independent events, then

$$\begin{aligned} \mathrm{P}_{\text{system success}} &= \mathrm{P}(A) \times \mathrm{P}(B) \\ &= (1 - \mathrm{LOLP}_k) \times \text{Market reliability}|_t \end{aligned}$$

Since the electricity market is usually scheduled and operated for 24-hour time periods, it is an appropriate assumption that mission time, $t = 24 hours$. Hence, the load point index of system success can be found using the above equation.

From the MATLAB Simulation on SIMULINK; Market Reliability result were obtained:

$$\begin{aligned} \mathrm{P}_1(t) &= 0.7934|_{t=24hrs} \\ \mathrm{P}_2(t) &= 0.1264|_{t=24hrs} \\ \mathrm{P}_3(t) &= 0.0802|_{t=24hrs} \end{aligned}$$

Market Reliability is given by $(\mathrm{P}_1(t) + \mathrm{P}_2(t)) = 0.9198$ The System Success Probability thus evaluated is presented in the Table below:

Table 9: System Success Probability at Load Points

S.No.	Load Point	LOLP	1-LOLP	Market Reliability	Probability of System Success
1	Siuchatar	0.313992	0.686008	0.9198	0.63099
2	Balaju	0.313992	0.686008	0.9198	0.63099
3	Baneswor	0.313992	0.686008	0.9198	0.63099
4	Lainchour	0.316867	0.683133	0.9198	0.628346
5	Teku	0.316927	0.683073	0.9198	0.628291
6	Patan	0.313992	0.686008	0.9198	0.63099
7	K3	0.324616	0.675384	0.9198	0.621219
8	Bhaktapur	0.313992	0.686008	0.9198	0.63099
9	Banepa	0.319596	0.680404	0.9198	0.625836
10	Chabahil	0.313992	0.686008	0.9198	0.63099
11	Panchkhal	0.313992	0.686008	0.9198	0.63099
12	Lamosangu	0.313992	0.686008	0.9198	0.63099

5. Conclusion and Recommendation

This paper primarily is aimed at specifying that the traditional definition of power system reliability may not be appropriate for deregulated electricity markets. The key point in the proposed method is the concept that the reliability level of a restructured electric power system can be calculated using the availability of the composite power system (HLII) and the reliability of the electricity market.

Since, the market of a small power system of Nepal (vertically integrated) comprising only 8 Gencos was considered the Market Reliability computed has been found to be fairly low at the value of 0.9198 despite setting the MPMI value for competitive market at considerably higher range of 0 to 4000, moderately competitive at range of 4000 to 5000 and anti competitive at range greater than 5000. As, expected the LOLP at the 12 load points considered has been found to be considerably high in the range of 0.313992 to 0.324616, which has resulted in the low value of System Success Probability in the range of 0.621219 to 0.63099.

The impact of failure of major transmission lines viz Khimti-Lamosangu(132 kV), Botekoshi-Lamosangu(132 kV), Bhaktapur- Lamosangu(132 kV) and Kulekhani I – Siuchatar(132 kV) and the failure of the largest units of Bhotekoshi HPP and Kulekhani HPP caused Loss of Load on all the Load Points (Discos) also had the huge impact on the Loss of Load Probability at the Load Points(Discos). Hence, Capacity Reserve Margin needs to be enhanced along with new transmission lines for improvement of System Reliability.

Thus, the methodology presented in this thesis would be helpful for the Deregulated Power System as the results obtained would be more meaningful and helpful in short term as well as long term planning and operation of the system.

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