RELIABILITY ASSESSMENT OF DEREGULATED GENERATING SYSTEMS USING RELIABILITY NETWORK EQUIVALENT AND PSEUDO-SEQUENTIAL SIMULATION TECHNIQUES

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Abstract – This paper presents a technique to evaluate reliability of restructured generating systems. The proposed technique is based on the combination of reliability network equivalent and pseudo-sequential simulation approaches. The reliability-network equivalents can be used to reduce the computational burden associated with conducting reliability analysis and easily include various agreements among market participants in a restructured power system. The equivalent multi-state generation provider (MG) is introduced to represent each generation company (Genco) using network equivalent technique. The equivalent techniques have been extended in this paper to determine the reliability model of a market participant possessing reserve agreement with other market participants. The pseudo-sequential simulation retains the computational efficiency of non-sequential simulation method and the ability to model the chronological aspects. In this paper, it is utilized to include chronological aspects of a MG in reliability evaluation. The proposed approach can be easily implemented and is suitable for the reliability evaluation of a restructured power system. The IEEE reliability test system (RTS) is used to illustrate the techniques.

Keywords: reliability assessment, deregulated power system, network equivalent, pseudo-sequential simulation

1 INTRODUCTION

Electric utilities are experiencing restructuring throughout the world. As a result of this reorganization, what was then a conventional monopoly generation utility is now economically separated into different generation companies (Gencos). In this new environment, each Genco should provide its reliability and associated price to ensure customer satisfaction and personal preference. Even though the techniques used to evaluate the reliability of a conventional power system have already been well developed, the restructuring process to a deregulated power system has generated much need to improve these techniques.

Ref [1] presents a method to evaluate the customer reliability in a deregulated power system considering customer choice on reliability. The method is based on the reliability network equivalent techniques proposed by Ref [2]. A generation company (Genco) is represented by an equivalent multi-state generation provider (MG).

There are two approaches to evaluate the system reliability – direct analysis and Monte Carlo simulation [3]. Direct analysis based on the state enumeration is used in the Ref [1] to approximate the reliability indices in a deregulated power system. However the system operation states and associated strategies such as loads and the reserve agreements are time varying in nature. The assessment of the unreliability cost indices requires knowledge of the chronological evolution of the system states, or at least, the chronological evolution of the system failure states [4].

The sequential Monte Carlo method can simulate chronological aspect of system operation, and produce the specific interruption durations [3]. However the sequential Monte Carlo requires more substantial computational effort than the non-sequential Monte Carlo and analytical methods [4]. The method may be infeasible for some applications in larger systems [5]. The pseudo-sequential simulation proposed in [4] [6] retains the accuracy of sequential simulation while keeping the computational efficiency of non-sequential simulation method. In this method, non-sequential sampling is used to select system states and chronological simulation is only applied to determine the sub-sequence associated with failure states that define the complete interruption. The computational efficiency of the non-sequential simulation technique can be further enhanced [4] by combining it with a state transition Monte Carlo technique [7].

This paper proposes a technique to evaluate reliability of restructured generating systems. The approach is based on the combination of reliability network equivalent and pseudo-sequential simulation techniques. The chronological aspects of a MG can be easily included in the reliability evaluation by using pseudo-sequential simulation. The reliability network equivalent of a Genco is extended to incorporate the reserve agreements among Gencos. A procedure to determine a MG and the associated reliability indices by using pseudo-sequential simulation has been developed. Case study on the IEEE RTS [8] for a deregulated power system is presented and discussed.

2 RELIABILITY EQUIVALENTS OF GENERATION COMPANIES

The generation function of a restructured power system is provided by many different independent Gencos. A Genco usually owns one or more generating units and provides electricity and reserve to its customers. A Genco with many generating units can be represented by an equivalent multi-state generation provider (MG) [1]. The states of a MG can be determined based on the failure rate and repair rate of each generating unit in the Genco using the equations [1]. The reliability of a Genco can increase when it has reserve agreements with other Gencos. The reserve agreements can be bilateral or multilateral. A restructured generating system, which has *h* Gencos and *p* bulk load points is represented by *h* equivalent multi-state generation providers ($\mathrm{MG}_1, \dots \mathrm{MG}_h$) as shown in Fig.1.

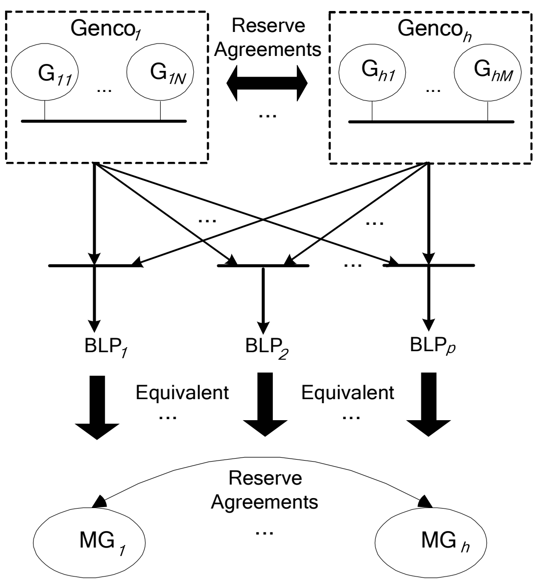

Figure 1: Reliability equivalents of generation companies

3 TIME VARYING LOAD MODELS

Any load model is an approximation of the actual load. The accuracy of a load model depends on the amount and quality of data available [4]. The average load is only an approximate representation of the actual load. A relative accurate representation is the hourly time varying load used in [9]. A detailed customer load profile varies with the customer location, time of the day, the day of the week and the week of the year. The time sequential simulation techniques (TSST) are usually used to calculate reliability indices considering the chronological load models. However the computational price using TSST is huge for large power systems. A multilevel non-aggregate Markov load model (ML) shown in Fig. 2 was proposed in [4] to reduce the computing time. This model considers a set of multilevel load states sequentially connected in the same chronological order as they appeared in the historical sequence. A constant load transition rate of λ_L, which is once an hour, is used in the ML. $L_T(A_p)$ represents the load level of BLP *p* at hour T. If a load transition occurs from T to T+1, the load level in all BLPs will be changed from $L_T(A_p)$ to $L_{T+1}(A_p)$.

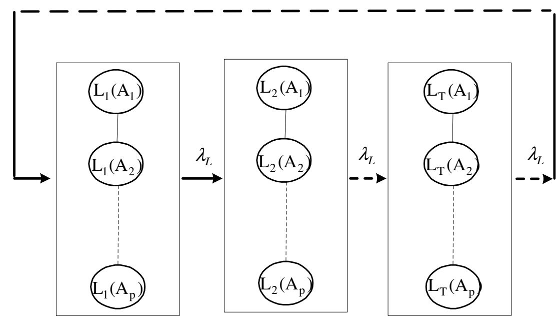

Figure 2: Multi-level non-aggregated Markov load model

4 MARKOV MODELS FOR RESTRUCTURED GENERATING SYSTEMS

MG is combined with its ML to form an equivalent multi-state generation provider with ML (MGML). If an MG has g_m states and ML has H states, the number of MGML states can be determined as:

$$g_M = g_m \cdot H \tag{1}$$

The probabilities, frequencies and other statistical indices for the MGML states can be determined using basic reliability techniques. The state-space diagram for the MGML is shown in Fig. 3. μ_{g_i,g_j} is the transition rate from the state g_i to the state g_j and λ_{g_j,g_i} is the transition rate from the state g_j to the state g_i respectively.

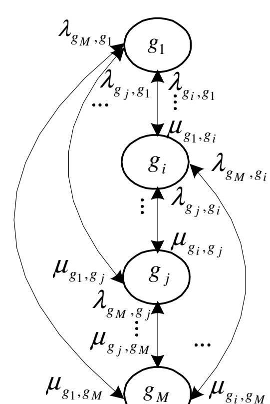

Figure 3: State-space diagram for MGML

A MG usually has reserve agreements with other MGs. The MGML which is used as the reserve provider of another MGML is designated as an equivalent multi-state reserve provider with ML (MRML). The MGML that has reserve agreements with other MGMLs can be represented as a MGML with reserve agreements (MGMLWR). The state of a MGMLWR is the combination of the related MGML and MRML states. If the reserve provider of a MRML has r_N states, the the associated MGMLWR will have $g_M \cdot r_N$ states. Considering all the $g_M \cdot r_N$ states in the simulation is very time-consuming and maybe impossible for a larger power system. Fortunately the computational burden can be reduced by considering only failure states of the MGML. If the MGML has g_c failure states, the number of the states for the MGMLWR is reduced to $g_c \cdot r_N + (g_M - g_c)$. The state-space diagram is shown in Fig. 4. $\lambda_{g_i r_N, g_i r_1}$ is the transition rate from the state $g_i r_N$ to the state $g_i r_1$ and $\mu_{g_i r_1, g_i r_N}$ is the transition rate from the state $g_i r_1$ to the state $g_i r_N$ respectively.

$$\lambda_{g_i r_N, g_i r_1} = p_{g_i} \cdot \lambda_{r_N, r_1} \tag{2}$$

$$\mu_{g_i r_1, g_i r_N} = p_{g_i} \cdot \mu_{r_1, r_N} \tag{3}$$

where λ_{r_N, r_1} is the transition rate from the state r_N to the state r_1, μ_{r_1, r_N} is the transition rate from the state r_1 to the state r_N and p_{g_i} is the probability in the state g_i, respectively. $\lambda_{g_j r_1, g_i r_1}$ is the transition rate from the state $g_j r_1$ to the state $g_i r_1$ and $\mu_{g_i r_1, g_j r_1}$ is the transition rate from the state $g_i r_1$ to the state $g_j r_1$ respectively.

$$\lambda_{g_j r_1, g_i r_1} = p_{r_1} \cdot \lambda_{g_j, g_i} \tag{4}$$

$$\mu_{g_i r_1, g_j r_1} = p_{r_1} \cdot \mu_{g_i, g_j} \tag{5}$$

where λ_{g_j, g_i} is the transition rate from the state g_j to the state g_i, μ_{g_i, g_j} is the transition rate from the state g_i to the state g_j and p_{r_1} is the probability in the state r_1, respectively. The proposed Markov model for the MGMLWR is the extension of the Markov model shown in Fig.3. The main advantage of the proposed Markov model is very flexible and makes the reliability evaluation for the generating system with reserve providers quite easily.

5 SIMULATION PROCEDURES

In pseudo-sequential simulation technique, non-sequential simulation is used to select failure states, and sequential simulation is applied only to determine the interruption sequence of neighboring states and the failure duration. A technique named the forward/backward simulation is used in the sequential simulation [4]. The forward simulation is a process to identify a sequence of failure states after leaving the selected failure state, until it finds a successful state. The backward simulation is a process to identify a sequence of failure states before arriving at the selected failure state, until it finds a successful state. The improved pseudo-sequential simulation procedures for evaluating reliability indices of an MGMLWR considering multiple reserve agreements consist of the following steps:

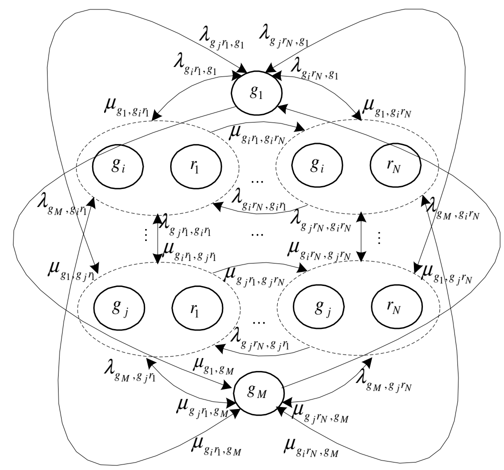

Figure 4: State-space diagram for a MGMLWR

Step1: Sample the MGML state g_i based on its distribution p_{g_i}.

Step2: Evaluate the performance of the sampled state g_i. If the state g_i is a success state return to step 1; if the state g_i is a contingency state, go to the next step.

Step3: Sample a state r_n from the reserve providers based on its distribution p_{r_n}.

Step4: Combine the state g_i and the state r_n into the state $g_i r_n$. If the state $g_i r_n$ is a success state return to step 1; if the state $g_i r_n$ is a failure state, go to the next step.

Step5: Obtain an interruption sequence and duration *D* using the sub-steps: (1). carry out a forward/backward simulation starting from the selected state $g_i r_n$; (2). obtain the interruption sequence and calculate the total duration *D*.

Step6: Estimate the reliability indices

Step7: If the confidence interval for the estimates is satisfied, calculate the reliability indices; otherwise return to step 1.

6 RELIABILITY INDICES

The reliability indices used in this paper are: the loss of load probability ($LOLP$), the loss of load frequency ($LOLF$), the expected energy not supplied ($EENS$) and expected customer interruption cost ($ECOST$).

These indices can be estimated using the following equations during the simulation procedures.

$$LOLP = \sum_{j=1}^{N} LOLP_j / N \quad (6)$$

where $LOLP_j = \begin{cases} 0 & \text{if } j \in \text{Success states} \\ 1 & \text{if } j \in \text{Failure states} \end{cases}$ (7)

and N is the number of simulation samples.

$$EENS = \sum_{j=1}^{N} EENS_j / N \quad (8)$$

where $EENS_j = \begin{cases} 0 & \text{if } j \in \text{Success states} \\ LS_j \cdot T & \text{if } j \in \text{Failure states} \end{cases}$ (9)

and LS_j is the load shedding in the failure state *j*, T is the period of analysis.

$$ECOST = \sum_{j=1}^{N} ECOST_j / N \quad (10)$$

where

$$ECOST_j = \begin{cases} 0 & \text{if } j \in \text{Success states} \\ \sum_{s \in S} K_s / E(D) & \text{if } j \in \text{Failure states} \end{cases} \quad (11)$$

and K_s is the customer sector *s* interruption cost and is given by:

$$K_s = \sum_{i \in I} CDF_s(D_i) \cdot D_i \cdot LS_{i,s} \quad (12)$$

and I is the sequence of failure states, CDF_s is the associated customer damage function [3], D^i is the duration of the state i and $LS_{i,s}$ is the load shedding of customer sector s in the failure state *i*. $E(D)$ is the expected value of the total duration for the sequence I and is given by:

$$E(D) = \sum_{i \in I} E(D_i) \quad (13)$$

where

$$E(D_i) = T / (\sum_{h} \lambda_h) \quad (14)$$

and λ_h is the transition rate between the state i and the directly connected state *h*.

$$LOLF = \sum_{j=1}^{N} LOLF_j / N \quad (15)$$

where $LOLF = \begin{cases} 0 & \text{if } j \in \text{Success states} \\ 1/E(D) & \text{if } j \in \text{Failure states} \end{cases}$ (16)

The uncertainties of the reliability indices are usually represented as the coefficient of variation:

$$\beta_{LOLC} = \sqrt{V(LOLC)} / LOLC \quad (17)$$

$$\beta_{EENS} = \sqrt{V(EENS)} / EENS \quad (18)$$

$$\beta_{ECOST} = \sqrt{V(ECOST)} / ECOST \quad (19)$$

$$\beta_{LOLF} = \sqrt{V(LOLF)} / LOLF \quad (20)$$

where $V(LOLC)$, $V(EENS)$, $V(ECOST)$ $V(LOLF)$ are the variance of $LOLP$, $EENS$, $ECOST$ and $LOLF$ respectively.

7 SYSTEM STUDIES

The proposed techniques have been used to analyze the IEEE-RTS [8]. The IEEE-RTS generation system is restructured into three Gencos. Genco 1 owns plants at buses 15, 16, 18, 21 and 22. The eleven generating units connected to buses 1, 2 and 7 belong to Genco 2. Genco 3 owns six plants at buses 13 and 23. It is assumed that BLPs 14 – 16 and 18 – 20 select Genco 1 as their generation providers, BLPs 1, 2, 4, 5 and 7 choose Genco 2 as their generation providers and BLPs 3, 6, 8 – 10 and 13 select Genco 3 as their generation providers. The chronological load curve for the RTS has been used. A year is represented in this load curve by three seasons: winter, spring/fall and summer. The annual hourly load curve can be developed after the annual peak load, weekly percentage, daily percentage and 24 hour load profile are determined. The RTS load model has 8736 hours and is represented as 8736 chronological states.

Four cases are studied to analyze reliabilities for the customers of Genco1 at different scenarios. It is assumed that the load priorities for the BLPs of Genco 1 are the same. In Case1, there are no reserve agreements among Genco 1, Genco 2 and Genco 3. In this case, Genco 1 with time varying loads is represented as MGML1. In Case2, there is a reserve agreement between Genco 1 and Genco 2 for sharing reserves in contingency states. In Case3, there is a reserve agreement between Genco 1 and Genco 3 for sharing reserves in contingency states. In Case4, Genco 1, Genco 2 and Genco 3 can share reserves in contingency states through a multilateral reserve agreement as shown in Fig. 5. The MGML1 with reserve providers is represented as the MGMLWR1.

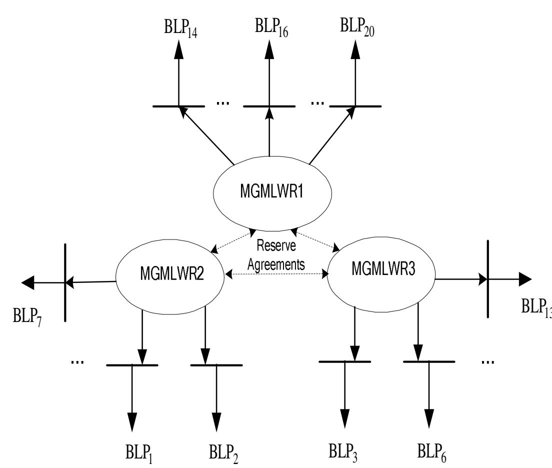

Figure 5: Reliability model of the restructured RTS

The *LOLP*, *EENS* and *LOLF* for the Genco1 have been evaluated and presented in Table 1. It can be seen from the Table 1 the customers of the Genco1 will be served with the maximum reliability in case 4 whereas with the lowest reliability in case 1. The reserve agreements among Gencos can greatly affect the customer reliabilities.

	LOLP	*EENS* (MWh/yr)	*LOLF* (occ/yr)
Case 1.	0.02034787	19923.05	9.8805
Case 2.	0.00198270	1614.25	0.9376
Case 3.	0.00395814	3694.11	5.0263
Case 4.	0.00036662	303.380	0.6357

Table 1: The reliability indices of the Genco1 for four cases

The *EENSs* and *ECOSTs* for the BLPs of the Genco1 for Cases 1 and 2 are shown in Table 2. It can be seen from the Table 2 that the BLP reliabilities increase significantly.

	Case 1		*Case 2*	
BLP	*EENS (MWh/yr))*	*ECOST (k\$/yr))*	*EENS (MWh/yr))*	*ECOST (k\$/yr))*
14	*3615.89*	*7687.1*	*270.79*	*461.44*
15	*3658.61*	*8837.9*	*270.79*	*461.44*
16	*3248.82*	*6451.4*	*268.80*	*460.28*
18	*3658.61*	*8837.7*	*270.79*	*461.44*
19	*3658.61*	*8837.7*	*270.79*	*461.44*
20	*3248.82*	*6451.4*	*268.81*	*460.28*

Table 2: The BLP reliability indices for case 1 and case 2

The *EENSs* and *ECOSTs* for the BLPs of the MGMLWR1 for Cases 3 and 4 are shown in Table 3. Comparing the reliability indices of case 3 with those in case 4, it can be seen from that the BLPs reliabilities increase with using the multilateral reserve agreements.

	Case 3		*Case 4*	
BLP	*EENS (MWh/yr))*	*ECOST (k\$/yr))*	*EENS (MWh/yr))*	*ECOST (k\$/yr))*
14	*644.99*	*938.655*	*51.039*	*50.947*
15	*654.40*	*1075.97*	*51.039*	*50.947*
16	*603.90*	*844.21*	*50.456*	*50.771*
18	*654.40*	*1075.97*	*51.039*	*50.947*
19	*654.40*	*1075.97*	*51.039*	*50.947*
20	*603.90*	*844.21*	*50.456*	*50.771*

Table 3: The BLP reliability indices for case 3 and case 4

8 CONCLUSIONS

A technique to obtain reliability indices for deregulated power systems by considering reserve agreements among Gencos and time varying loads is presented and illustrated in this paper. The reliability network equivalent and pseudo-sequential simulation approaches are the foundations of this technique. The technique retains the computational efficiency of non-sequential simulation and accuracy of sequential simulation. By using reliability network equivalents it is easily to include various agreements among market participants. A new Markov model is proposed for the representations of the generating system considering reserve providers in this paper. The technique provides flexibility and accuracy in evaluating reliabilities in the new environment. The proposed technique can be easily used to assess the reliability, and to manage and price system reserves of large-scale and practical systems. The simulation program was written by Matlab. All simulation results were obtined by a 3G MHz PC. The exectution time for Case 4 is 6 minutes and 37 seconds.

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