Efficient Evaluation of Nodal Reliability Index based on AC-OPF by Fast Monte Carlo Method

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Abstract: - Accurate and equitable evaluations of power system operation taking account of failures and constraints of transmission networks are increasingly demanded by power industries due to the recent deregulation. Conventionally, computations for indices of reliability and economics are generally performed by the Monte Carlo method, which however needs time-consuming simulations especially for large systems considering a large number of contingencies. This paper aims to develop a fast Monte Carlo method for obtaining nodal reliability indices of power systems by exploiting the properties of power system operation. In contrast to the conventional Monte Carlo simulation, the proposed method in this paper, not only improves the computational efficiency in terms of CPU time considerably, but also attains the high accuracy from a statistical point of view.

Key-Words: - fast Monte Carlo for reliability evaluation (FMCR), nodal reliability index, deregulation, AC-OPF

1 Introduction

Reliability index and production cost are the key indicators in the decision of power development and power supply plans. The decision and assessment depending on these indices are being valued furthermore especially in the progress of power market liberalizations because it is related to the market price of supply capability and the criterion of power quality.

Reliability of electricity supply is ability in a power system that supplies electric power to consumers for a specific period of time, and it is divided into two types; the deterministic index and the probabilistic index. The deterministic index is represented by the system supply margin, such as the capability margin of power generations and the transmission capacity etc. The probabilistic index is assessed by the expected value and the possibility of power failures, such as frequency of power failures due to outages of the power equipments as the well-known N-1 criteria. As the evaluation method that calculates these reliability indices, analytical calculation methods and simulation methods [1] have been developed.

Analytical calculation methods are used for the power development and supply plans which disregard constraints on transmission systems and networks, because a fast evaluation is possible for large-scale systems, however it is difficult for those methods to process constraints of transmission systems. For instance, in the Gram Charrier series approximation method, the Fourier series approximation method, and the fast Fourier transform method, the equivalent load curve have been used in many power development planning packages [2][3][4].

There is a trend that constraints on networks such as heavy currents and power transmission bottlenecks are valued more in the problem to form facilities. Also, the necessity for considering transmission failures and network constraints has risen in the reliability evaluation in the management of electric power systems brought by the liberalizing in recent years. In the operational evaluation that considers failures in transmission facilities, simulation methods are adopted. Those simulations evaluate whether the system is able to supply power by adjusting the system operation against many situations of failures in transmission facilities, and calculate the probabilistic reliability index as a result. There are two methods for the assumption of facilities in dropout. One is the deterministic assumption that dropped out facilities are specified and enumerated. The other is the stochastic assumption, e.g. the Monte Carlo method which samples accidents using random numbers based on the failure probability of facilities [5]. The Monte Carlo method is applied not only to the calculation of the reliability index but also to the operational evaluation of electric power systems, such as released assessment packages for deregulated electric power industries. Monte Carlo method is available in simulation of restoration work duration in the time series model. [6]. This paper doesn't target this.

To enhance the accuracy of the index by the Monte Carlo method, the great number of simulations have to be conducted by taking account of complex network restrictions, therfore, a lot of processing is needed in each simulation to satisfy the constraint on system operation. So, one of the critical problems for the Monte Carlo method is that the computation time becomes huge as the increase of the system dimension.

An efficient method is needed to achieve evaluations with high accuracy for assessing the power supply value in the market and power quality.

Some methods are proposed to accelerate the efficiency of the method for the reliability evaluation of generation and transmission facilities. In one of them, the whole system is aggregated into one, and only network constraints at link points of multi-areas are taken into consideration [7]. The other introduces a special statistical process into the expected value calculation to improve the computation speed [8].

In such a situation, authors are proposing fast Monte Carlo method for reliability evaluation (FMCR) that can consider transmission facility accidents and network constraints. In FMCR, firstly, a divided contingency sampling of generators and transmission facilities using the outage characteristic has been introduced. At the same time, statistics process proposed by reference [8] has been introduced.

In this paper, a new calculation method of the reliability index at each load bus is proposed, and the effectiveness of the proposal technique is verified by applications to IEEE-Reliability Test Systems (RTS). It is shown that the proposed method is applicable not only to the reliability evaluation but also to the assessment of economics and quality of deregulated electric power systems, as the AC optimal power flow (OPF) has been used in the proposed method. In Chapter 2, FMCR and the proposed procedure are introduced and numerical examples are shown in Chapter 3. The summary concerning this method is shown at the end of Chapter 4 of this paper.

2 Proposed method

In this paper, FMCR that makes the best use of features of electric power systems is proposed to the problem where the computational complexity of the Monte Carlo method becomes huge. Figure 1 shows

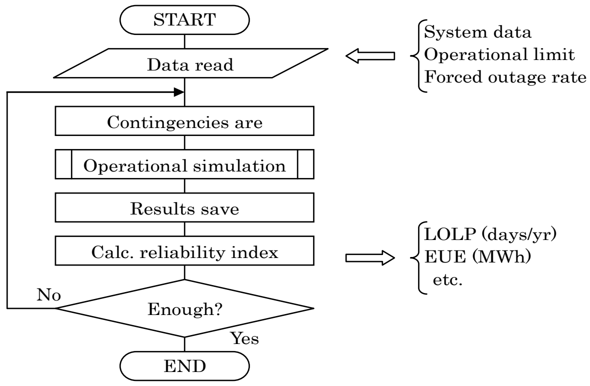

Fig. 1 Flow for Conventional Monte Carlo Method

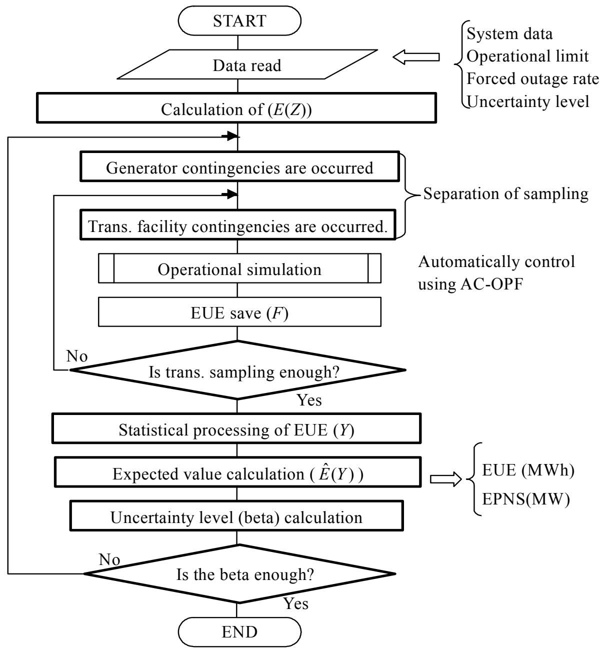

Fig. 2 Flow for FMCR

the flow of the conventional Monte Carlo method. Equation (1) shows an estimated value of expectation (or expected value) as a reliability index.

$$\hat{E}(F) = \frac{1}{NS}\sum_{i=1}^{NS} F(\boldsymbol{x}_i) \tag{1}$$

where, $\hat{E}(F)$: Estimated value of expectation, NS: Number of sampling, x_i: the probability state at sampling i, $F(x_i)$: evaluation value in the state at sampling i.

Two following functionalities have been introduced in FMCR. One is the contingency sampling separation of power supply and transmission facilities, and the other is the statistical process of the expected value that uses the regression variable proposed by reference [8]. The flow for FMCR is shown in Figure 2. The alternating current optimal power flow (AC-OPF) that can automatically consider the constraint on system operation is used for the system operation simulation [9]. In contingency cases where supply capability is insufficient, AC-OPF automatically maximizes the power supply or minimizes unserved energy. The condition of the sampling termination is a relative error of the expected value (It is called the uncertainty level β). Each element and a concrete calculation method of FMCR are shown below.

2.1 Contingency sampling separation

In a large number of sampled contingencies in the Monte Carlo method, most of states after contingencies are sound (normal), because the forced outage probability of each facility is small in general. In FMCR, when the same contingency that has already occurred occurs again, the system operation simulation (AC-OPF) is omitted. In general, as the forced outage probability of the transmission facility is smaller than the forced outage probability of generators, the contingency of transmission facilities don't occur so frequently while the contingency of generators occurs comparatively frequently when the contingency is sampled by using a conventional Monte Carlo method. To obtain the reliability index with sufficient accuracy, it is necessary to sample a large number of contingencies one by one until the accident occurs in each transmission facility. As a result, the system operation simulation is executed for each system configuration newly generated, and this leads to a problem that the computing time becomes huge, too. A sampling separation is introduced to cope with this problem in FMCR as shown in Figure 2. Contingencies in transmission facilities are sampled multiple times in each contingency sampling for generators. The reliability index value of one time of the contingency sampling of generators is calculated as an average value divided by the number of times of sampling of the transmission facility. Same generators are dropping out during the transmission facility contingency sampling of n times. The influence of the outage of generators of n times takes the above-mentioned average, and becomes the same dimension as the transmission facility outage sampling. The contingency sampling of generators is repeated until the reliability index value becomes sufficient accuracy. The separation decreases the frequency of generator accidents, and increases the frequency of transmission facility accidents without influencing the expected value of the reliability index. The system configuration newly generated decreases, and reducing the number of executions of system operation simulation (AC-OPF) that comparatively requires large computing time. FMCR can reduce the computing time than that by the conventional method.

2.2 Statistical process using regression variable

In FMCR, the statistical process proposed in reference [8] is introduced and remarkable computational speed-up is achieved. In general, the forced outage probability of transmission facilities is smaller than the outage probability of generators though the influence by transmission facility accidents is comparatively large. When the reliability index is given as an expected value, the relevancy of the reliability index concerning only generators and the reliability index concerning both generators and transmission facilities is strong. It is thought that there is a strong correlation between the index by generators and transmission facilities sampling and the index by generators sampling. Paying attention to this correlation, the statistical process is introduced as a regression variable of the reliability index when the network is disregarded. To calculate the reliability index with high-speed, an analytical calculation method is used in this process [10]. By a more rapid convergence method, it is possible to obtain the estimated value of the expected value for the reliability index with sufficient accuracy. The statistical process is as follows. The reliability index by outages of generators and transmission facilities is defined as stochastic variable *F*. The reliability index by outages of generators that there is a correlation in *F* is defined as stochastic variable *Z*. Equation (2) defines stochastic variable *Y* as a reliability index of statistical processing.

$$Y^i = F^i - Z^i + E(Z) \qquad (2)$$

where, Y_i: Short supply power of statistical processing of accident sampling i, F_i: Short supply power (calculation from AC-OPF) due to accident of generators and the transmission facilities of accident sampling i, Z_i: Short supply power when network is disregarded, $E(Z)$:EPNS (expected power not supply) or EUE (expected unserved energy) obtained by analytical calculation method, i: Accident sampling frequency

At this time, *Y* and *F* have the same expected value respectively.

$$E(Y) = E(F - Z + E(Z)) = E(F) \qquad (3)$$

where, $E(Y)$: statistical processed EPNS, $E(F)$:EPNS due to accident of generators and transmission facilities

Expected value $E(Y)$ of Y is calculated by using equation (3) in FMCR instead of requesting expected value $E(F)$ of F as a reliability index. The duration of the demand is assumed to be one hour in this paper and EPNS is read in a different way as EUE.

2.3 Outage Sampling Termination by uncertainty level (β)

To maintain calculation within reasonable time, the precision of the estimate value for the expected value in each sampling is quantified. A relative error of the expected value shown in equation (4) as an accuracy index (uncertainty level) is used in FMCR. The uncertainty level is a relative value of the estimate value variance of the expected value calculated by the outage sampling, and it means the uncertainty of the estimate value. The calculation is ended if β satisfies the precision that the user desires, and sampling is continued if it doesn't satisfy it.

$$\beta = \frac{\sqrt{V(\hat{E}(X))}}{\hat{E}(X)} \qquad (4)$$

where, β: uncertainty level(relative error), V: variance, $\hat{E}(X)$:Estimated value of expected value of stochastic variable X.

2.4 Reliability index (nodal EUE) calculation

In FMCR, Expected Unserved Energy (EUE) in the accident sampling is calculated by using Y defined in equation (3). When the network is disregarded, EUE is calculated by using Z in equation (5).

$$Z^i = Max\left\{0,\, D - \sum_{j=1}^{NG} G_j^i\right\} \qquad (5)$$

where, D: Demand, G^i_j: Capacity of generator j that occurs by accident sampling i, NG: Number of total generators.

$E(Z)$ is a value of EPNS or EUE calculated by using the high-speed, analytical calculation method. The estimated value of the expected value of the reliability index up to the sampling frequency is calculated from equation (6).

$$\hat{E}(Y) = \frac{1}{NS'}\sum_{i=1}^{NS'} Y^i \qquad (6)$$

where, $\hat{E}(Y)$: Estimated value of expected value Y, NS': number of accident sampling.

The nodal reliability index (nodal EUE) is calculated from the (7) equation. Nodal EUE is an expected value of the amount of the load reduction of the load bus, and it means the reliability index for customers can be estimated by using nodal EUE as a customer-oriented reliability index. In the expansion of transmission facilities, nodal EUE offers important information similar to the locational marginal price (LMP).

$$\hat{E}(U_k) = \frac{1}{NS'}\sum_{i=1}^{NS'} U_k^i \qquad (k = 1,\ldots, ND) \qquad (7)$$

where, $\hat{E}(U_k)$: Estimated value of expected unserved energy (EUE) U of bus k, U^i_k : the amount of the load curtailment of bus k calculated by AC-OPF that occurs by accident sampling i, k : Bus number, ND : Number of buses.

3 Numerical Example

To confirm the effectiveness of the proposed method, we applied to the reliability evaluation using IEEE-RTS [12] of Figure 3, and the condition shown in Figure 4.

To execute AC-OPF as shown in Figure 4, buses and branches of each generator were added. Table 1 shows the result of the reliability evaluation. 43 minutes were required with Pentium-4 3.2GHz by processing AC-OPF of 12,905 times. Figure 2 shows EUE according to the passing of sampling and the transition of uncertainty level β. E(Z) has calculated by an analytical calculation method in the preprocessing phase and is constant. $\hat{E}(Z)$ is an estimated value in which only the dropout of generators is considered.

$\hat{E}(F)$ is an estimated value in which the dropout of generators and the transmission facilities by AC-OPF is considered. In this figure, it is clear that $\hat{E}(Y)$ to which the statistical process is applied has already converged near a final expected value at the early stage of sampling. β decreases gradually whenever sampling advances, and terminates the calculation when becoming 0.01 by the set condition.

Table 2 shows the result of nodal EUE of each load bus calculated by the proposed procedure. Nodal EUE has not been occurred in the bus with generators basically. Some EUE occurred in bus 18 only of a single generator. In the bus with a large load, a lot of EUE doesn't necessarily occur. This is thought that the condition on system configurations of the transmission loss and the capacity etc. of transmission line affects it because load shedding OPF used for the evaluation this time attempts the supply amount maximization. Moreover, because nodal EUE can be calculated, information is thought to be able to offer it

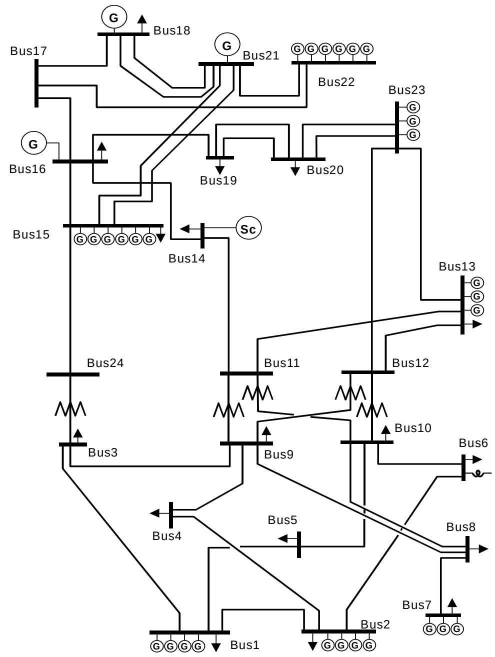

Fig.3 IEEE RTS

Number of generator :32
Number of SC : 2
Number of branch : 68
(Transmission line 33, Transfer : 5, added branch by authour : 33
Number of bus : 58 (original: 25, added : 33, load : 16)
Load demand 2,850MW(peak time)
Number of sampling of transmission contingency : 1000
Uncertainty level(beta) : below 1%
Range of voltage : 90% < |V| < 110%
Capacity of transmission line : Value of "Long term" of IEEE-RTS

Fig.4 Conditions of examples

as a signal of the facility formation in the transmission expansion plan.

Table 3 shows the frequency of a multiple outage that occurs by sampling. It is little, and the dropout of two generators or more and two transmission facilities or more occurs, too.

Figure 6 and Figure 7 show the frequency in which it drops out because of sampling each equipment and each forced outage rate. In this case, when the dropout frequency is compared with the correlation coefficient of the forced outage rate, only little of transmission facility (R=0.999) is larger than that of generator (R=0.990). In the separation sampling, it is thought that it was redundant to have assumed the sampling frequency of the transmission facility to be 1000.

Then, the simulation result that changes the sampling frequency of the transmission facility is shown in case 1 in Table 4. Somewhat, the frequency of AC-OPF needed to achieve the uncertainty level 1% has decreased in dramatic form though the change occurs in the value of EUE. The sampling frequency

Table 1 A result of reliability evaluation (outline)

number of sampling	2,073 x 1,000
EUE	17.44 MWh
Number of execution of AC-OPF	12,905
Computation time	43min. (Pentium-4 3.2GHz)

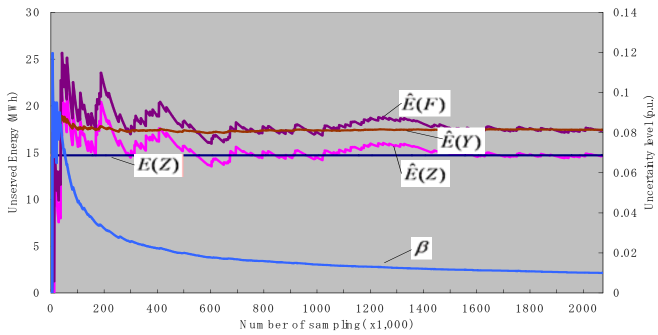

Fig.5 Estimated statistical EUE and uncertainty level(β)

Table 2 A result of reliability evaluation (nodal index)

No de	EUE (MWH)	PL (MW)	Gen. (MW)	No de	EUE (MWH)	PL (MW)	Gen. (MW)
1	**0.00**	108.0	192	10	**0.56**	195.0	-
2	**0.00**	97.0	192	13	**0.00**	265.0	591
3	**3.47**	180.0	-	14	**2.00**	194.0	-
4	**1.57**	74.0	-	15	**0.00**	317.0	215
5	**0.22**	71.0	-	16	**0.00**	100.0	155
6	**6.90**	136.0	-	18	**0.83**	333.0	400
7	**0.02**	125.0	300	19	**0.00**	181.0	-
8	**1.23**	171.0	-	20	**0.00**	128.0	-
9	**0.58**	175.0	-				

Table 3 The detail of multiple contingency

		Num. of transmission facility dropped		
		0	1	2 or more
Num. of generator droped	0	481,664	12,174	162
	1	721,473	18,282	245
	2 or more	817,884	20,861	255

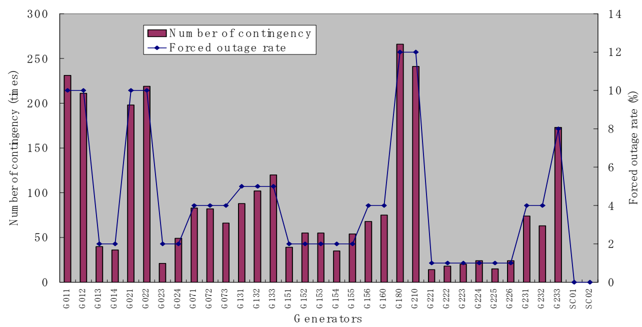

Fig. 6 The histogram of forced outage of generator.

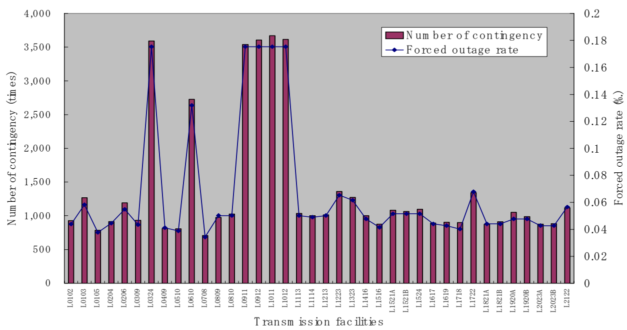

Fig. 7 The histogram of forced outage of transmission.

of the transmission facility was judged enough as a result by about 50 times in this exercise.

The condition of the studies was changed and the reliability evaluation was executed. The results completely became the same though the constraint on the transmission capacity was changed from "Long time capacity" to "Ordinary capacity" as case 2 in Table 4. It is proved that the capacity of transmission line is comparatively secured for the given load level in IEEE-RTS used this time.

Because AC-OPF was used, the range of voltages was narrowly reset from "90 %< V < 110%" to "95 %< V < 105%" as case 3. As a result, some EUE rose. This result shows the trend that EUE increases because the operating condition becomes severe.

Table 4 Results of case study of the reliability evaluation

case		No. of Gen. sampling	No. of Tras. sampling	EUE(MWh)	No. of exec. OPF	Computation time
1	1	2,073	1,000	17.44	12,905	43’00”
	2	1,839	100	17.00	2,860	8’22”
	3	2,060	50	17.42	2,136	6’12”
	4	2,092	20	17.46	1,336	3’53”
	5	1,926	1	17.17	583	1’42”
2		2,060	50	17.42	2,136	6’12”
3		2,329	50	17.60	2,335	6’54”

4 Conclusion

In this paper, a nodal EUE was proposed as a nodal reliability index in FMCR, and the effectiveness was examined with the reliability test system (IEEE-RTS). It is shown that as the IEEE-RTS has loop architecture, and holds comparatively large margins for transmission capacity, the influence on reliability concerning transmission lines is few. However, it is very difficult to consider highly accurate dynamic security [13], because a great number of calculations for nodal EUE are necessary to solve OPF with load shedding. It is mandatory in the future to develop transmission expansion planning methods for the system of which the constraint is nodal EUE.

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