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Supply Reliability Evaluation of Power System under Competitive Market Condition

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Abstract - In this paper, Expected Unserved Power (EUP) is introduced as an index to evaluate the supply reliability of power system. A probabilistic approach by using EUP is proposed to evaluate supply reliability of power system and customers. EUP in the proposed approach is derived from forced outage rate of generators connecting power grid, and to deal with the uncertainty of customers' consumption, EUP calculation is extended to include demand variation of the customers in the proposed approach. Extension of EUP calculation makes it possible to evaluate supply reliability from customers' side. Transmission congestion also has influences on supply reliability of power system. In the proposed approach, Transmission line Reliability Sensitivity (TRS), that is calculated using EUP, is proposed to evaluate the influences of transmission congestion on supply reliability of power system. Several numerical simulations using a test system demonstrate the effectiveness of the proposed approach.

Keywords: - Supply reliability, Expected Unserved Power (EUP), Transmission congestion, Transmission line Reliability Sensitivity (TRS), Demand Uncertainty, Customer

1. Introduction

Competitive market has been introduced in the power industry in many part of the world.

The purpose of introducing competition into the power industry is to reduce the electricity price by reducing generation and transmission costs. However, concerns have been raised that one result may be that there will not be enough reserve secured for dealing with unexpected demand changes, disconnection of generators, or transmission outages. An additional concern is that many new power producers participating in the market may negatively influence grid operations in such areas as maintenance of electricity voltage and overload power flow.

Stable operation of the power grid requires having some method for eliminating overload power flow and for securing supply reliability. Some entity similar to the Independent System Operator (ISO) in the United States takes on the role of stabilizing the operation of the power grid.

Under deregulation, some entity similar to the ISO in the United States needs to have some method for securing supply reliability on the grid to eliminate overload power flow so as to operate the grid in a stable fashion.

The influence on supply reliability of the new PPS participating in the newly deregulated market needs special attention, since it greatly influences planning for generation and transmission expansion by utilities and increases the importance of assessing the supply reliability under different scenarios for generation or transmission outages. It is necessary to establish indices for evaluating supply reliability of electric power system under such situations.

At first, research to evaluate reliability was limited to evaluating generation reserve capacity, but then the importance of doing probability analysis was recognized. The areas of research have been expanded to include transmission and distribution. As the range of research has expanded, methods of evaluation have also improved. For example, methods were developed (1) - (4) for doing Monte Carlo simulations.

Research based on probability computation uses as its major indexes for reliability evaluation Loss of Load Probability (LOLP) and Expected Unserved Energy (EUE, sometimes called Expected Energy Not Supplied, or EENS). The research on reliability evaluation of the grid and power transactions using these indexes has been reported (5). These supply reliability evaluation indexes are used in evaluation when the objective is to evaluate the situation where required power cannot be delivered due to technical reasons such as power outages or transmission system equipment outages.

In the past, conventional evaluations of supply reliability focused on the supply reliability of the entire power system from the supplier's viewpoint (system-oriented reliability criteria). When the generation market was vertically integrated, utilities planned and operated the entire grid system carefully with consideration for reserve capacity, so this type of reliability evaluation of the total grid system was sufficient.

However, under deregulation, new power producers may enter the generation market. Thus, it becomes necessary to consider the impact on the reliability of the entire grid system of each individual power producer connected to the grid and to consider consumer-oriented reliability criteria (6) - (8).

In the recently deregulated power market, it is increasingly necessary to consider economics when doing reliability evaluations, so that elimination of transmission congestion and reduction in the cost of supply are increased in importance alongside technical issues. In addition, reliability evaluation and power-generation planning under deregulated power markets are beginning to incorporate more of consumer requests and information rather than those of suppliers. Each consumer differs in its level of demand for reliability; therefore, power quality is increasingly being measured by different economic standards.

With this as a background, increasing importance is being placed on establishing a method of supply reliability evaluation from the consumer's viewpoint. Conventional grid reliability evaluations focused on structural elements, such as generator outage rates. However, when looking at reliability from the consumer point of view, one can come up with such elements as the decision of grid operating points, the safety margin for stability, and maximum load capacity. Indexes of reliability geared toward consumers reflecting such elements have been proposed in the past (8), (9).

Evaluations using such indexes must involve detailed computations and must account for a grid structure with some degree of uncertainty in some of its elements. Because of this, methods that shorten computation time are effective for online operation, but attempts to shorten computing time will adversely affect accuracy. In other words, for the operation analysis that considers the grid structure, there is a tradeoff between computation time and accuracy, and we must select our method according to the purpose.

In this paper, Expected Unserved Power (EUP) is introduced as the index to evaluate the supply reliability of the entire grid. EUP expresses principally the expected value of electricity not supplied to the consumers due to generator outages.

Therefore, EUP is extended, which is computed based on the generator outage rate, into a supply reliability evaluation index. The rates of change for consumers' load consumption are computed to turn EUP into an evaluation index that includes the uncertainties of the consumers and the influence on each consumer.

EUP is the index to assess reliability at one-hour intervals where computing time is considered important. By repeating the computation every hour, evaluation over extended periods becomes possible. The probability computation can be combined with Monte Carlo simulation to permit more detailed analysis.

A method to evaluate each consumer's supply reliability by allocating EUP to each of customers is proposed. Additionally, a method for using EUP to evaluate the influence of transmission congestion on supply reliability is also proposed. By applying them to a model network, the effectiveness of evaluating supply reliability by the above method and by the proposed supply reliability index is examined.

2. Supply Reliability Index

2.1. Computation of EUP

LOLP and EUE are typical supply reliability index concerning to generator contingencies. These indices focus on the capacity of generators and maximum demand of power system. However, they don't consider such cases that generation output is not equivalent to its rating or the composition of generators connecting to power system changes. In this paper, EUP is introduced as the index of supply reliability to handle the cases described above.

When a generator, which is under operation with an outage rate FORi, is connected to power system and dispatched output of $Gi(t_k\text{-}1)$ at time $t_k\text{-}1$, $EUPi(t_k)$, that is the expectation of unserved power caused by the outage of the generator, at time t_k is given by following procedures.

To compensate the unserved power due to the outage of the i th generator, other generators connected to the network increase their output of ΔGj, and the available supply power of the power system, $Spi(t_k)$, is :

$$SPi(t_k) = \sum_{j \neq i} (Gj(t_k) + \Delta Gj) \tag{1}$$

Provided that the load requirement of a customer is Di, the required power supply RP (t_k) is

$$RP(tk) = \sum_i Di \tag{2}$$

so unserved power due to the outage of the i th generator, $UPi(t_k)$, is represented as follows:

$$UPi(t_k) = RPi(t_k) - SPi(t_k) \tag{3}$$

Multiplying FORi to $UPi(t_k)$, Expected value of unserved power of the i th generator's outage, $EUPi(t_k)$, can be expressed as equation below.

$$EUPi(t_k) = UPi(t_k) * FORi \tag{4}$$

Expected Unseved Power of the whole system, EUPsys (t_k) is expressed as the total of the $EUPi(t_k)$,

$$EUPsys(t_k) = \sum_i EUPi(t_k) \tag{5}$$

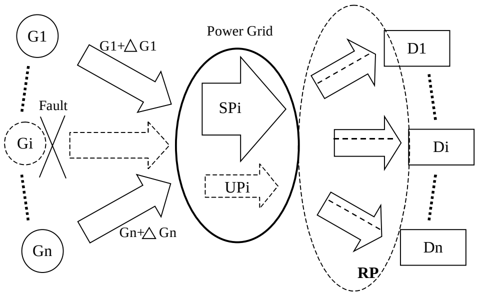

Fig.1 Relationship among UPi, RP, and Spi

The same procedure gives EUPsys for multiple-generator outages, making use of FORm, which gives the probability of multiple-generator outages.

2.2. Extension of EUP computation accounting for consumer uncertainties

Under the deregulated market, consumers might experience increased volatility in power prices when compared with prices before deregulation. This leads to variances between actual demand and expected demand. Changes in demand of this type may be expressed as a function, but given that the relationship between power price and demand is at present unclear, in this paper we will use the discrete probability distribution for the uncertainty of demand in assessing reliability.

Figure 2 shows the model for the probability distribution for the power demand by the hypothetical consumers in this paper. As shown in Figure 2, when the continuous consumption of power by consumers is given as a discrete probability distribution, the load requirements of the consumers, Di, in the EUP computation previously described can be computed by the following formula:

$$D_i = \sum_j Dp_{ij} * P_{ij} \tag{6}$$

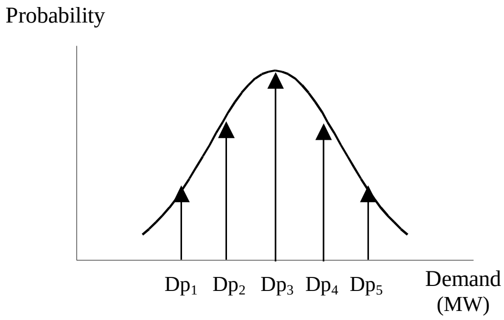

Fig. 2 Probability Model for Customer

Here Dp_{ij} represents load consumed by consumers, which occurs with the probability of P_{ij}. Di computed from formula (6) is the expected volume of power consumed by consumers where it is changing at a certain probability rate for various reasons. Therefore, the required power RP, where the uncertainty of the consumer's load requirements is accounted for, can be computed by the following formula:

$$\begin{aligned} RP(t_k) &= \sum_i D_i \\ &= \sum_i \sum_j Dp_{ij} * P_{ij} \end{aligned} \tag{7}$$

EUP computed using RP in formula (7) is the supply-reliability index that considers not only generator accidents but also the uncertainty of the load requirements of the consumers.

2.3 Supply reliability evaluation for individual consumers

Power consumers are beginning to have different levels of reliability requirements and may evaluate the need for quality of power based on individual economics. Thus the need for supply reliability evaluations for individual consumers arises. In this paper, supply reliability evaluations are performed for individual consumers as follows. After EUP of the entire grid (EUPsys) is calculated, EUP for each consumer connected to the system is obtained from EUPsys.

When there are no differences in supply reliability among consumers, it is possible to evaluate supply reliability for each consumer by allocating the EUP to consumers by load. Allocated expected unserved power $EUP_{Dj}(t_k)$ for each consumer is as follows:

$$EUP_{Di}(t_k) = \frac{EUPsys(t_k)}{\sum_{j}^{ND} Dj(t_k)} * Di(t_k) \tag{8}$$

When consumers' requirements for supply reliability differ, it is possible to achieve the level of reliability that a consumer requires by defining a virtual power flow path X from a generator to a consumer to satisfy the following formula and by allocating the EUP accordingly.

However, if the consumers are looking for a high level of reliability, EUP allocation may be insufficient to satisfy their requirements. In such a case, it is necessary for the grid operator to heighten the supply reliability of the entire grid by rescheduling output from the generator. It is also necessary to define rules for allocating the newly incurred cost of rescheduling the output. However, since this paper focuses on evaluating supply reliability, this study deals only with situations where the grid operator does not need to reschedule the output.

The relationship between generator output and supplied power to a customer is represented by using virtual power flow path X.

$$Gi(t_k) = \sum_{j}^{ND} X_{ij}(t_k) \tag{9}$$

The demand of a customer is also represented by using virtual power flow path X as follows.

$$D_j(t_k) = \sum_{i}^{NG} X_{ij}(t_k) \tag{10}$$

Virtual power flow path X has to satisfy the following condition.

$$X_{ij} \geq 0 \tag{11}$$

Determining virtual power flow path makes it possible to obtain EUP of each customer by the same procedure to calculate EUP of the whole system. EUP of each customer, $EUP_D(t_k)$, is expressed by:

$$EUP_{Dj}(t_k) = D_j(t_k) - \sum_{i}^{NG} EUPi(t_k) * \frac{X_{ij}(t_k)}{Gi(t_k)} \tag{12}$$

3. Supply Reliability Evaluation with Transmission Congestion

3.1 Sensitivity of transmission congestion on supply reliability

A shortage of power to satisfy consumer requirements can be caused by generator outages, resulting in a shortage of supply. But when there is transmission congestion, rescheduling generator output may eliminate the congestion but consumer requirements may not be fulfilled. If a generator outage occurs, the output from the other generators connected to the same grid will be adjusted to cover the shortage. However, when the transmission line is congested, it is possible that insufficient power will be delivered. Considering this situation, it is possible that transmission congestion will have no small influence on supply reliability. Therefore, it becomes necessary to have the grid reliability evaluation index for the transmission line that may incur the congestion.

In this paper, the transmission line supply reliability sensitivity is calculated in the following formula when the evaluation of grid reliability for the transmission line is performed. First, the rescheduling of the generator output based on the economical load distribution is calculated for the case where the transmission power flow constraint is not considered. Assuming that the fuel cost function of power production from a generator which supplies power and is connected to the grid is CGi (Gi), the solution for economical operation of the generator without considering transmission line power flow constraints is the allocated generator output Gi.

$$\min \sum_{i} CGi(Gi) \tag{13}$$

Subject to

$$\sum_{i} Gi = \sum_{j} Dj \tag{14}$$

$$Gi\min \leq Gi \leq Gi\max \tag{15}$$

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Next, we will find EUPsys of the generator output allocation without any transmission line power flow constraints on the grid, and calculate EUPi, the expected unserved power for each generator outage, and use these as the base case.

Starting from the base case, we then calculate the rescheduling of generator outputs responding to the transmission congestion constraints as follows:

$$PFi \leq PFi\max \qquad (16)$$

When transmission congestion occurs on the j^{th} transmission line, the system operator reschedules generator outputs to clear the congestion, causing EUPsys and EUPi values to change. Using these values, we compute EUP for the congestion rescheduling case. EUP for the base case and EUP for the congestion rescheduling case are expressed as EUPb and EUPc respectively. TRSj is given by

$$TRSj = \frac{EUPc - EUPb}{EUPb} \qquad (17)$$

3.2 Supply reliability evaluation using EUP and TRS

The system operator performs the necessary operations to eliminate congestion on the transmission lines when generator outages or similar accidents occur on the grid. However, in some situations, it is difficult to eliminate congestion by rescheduling generator outputs, as it may create economic losses. If this type of situation occurs frequently on the specific transmission line, that line is recognized as vulnerable. This leads to the necessity of expanding transmission capacity or installation of FACTS devices such as UPFC. The proposed TRS is the index for clarifying the level of vulnerability of transmission lines and is an effective way of prioritizing candidate locations for expansion of transmission capacity and control device installation.

The following algorithm is used to select the transmission line best suited as a candidate for expansion using the above-described EUP and TRS through evaluation of the supply reliability of the demand pattern for different hourly periods.

Step 1: Read in the status of generators, transmission lines, and demand.

Step 2: Compute the generator output scheduling without considering transmission line capacity limitations.

Step 3: Compute EUP at Step 2 and use this as the base case.

Step 4: Compute the generator output rescheduling, accounting for transmission line capacity constraints.

Step 5: Compute EUP in Step 4 and use this as the transmission congestion case.

Step 6: Use the base case EUP and transmission congestion case EUP to compute TRSj. Store this value in memory.

Step 7: Execute Steps 1 through 6 for the demand for each hourly period. Select the transmission line with the largest total value for TRSj as being the candidate with the highest priority for expansion.

Figure 3 shows the process of selecting the candidate for transmission line expansion.

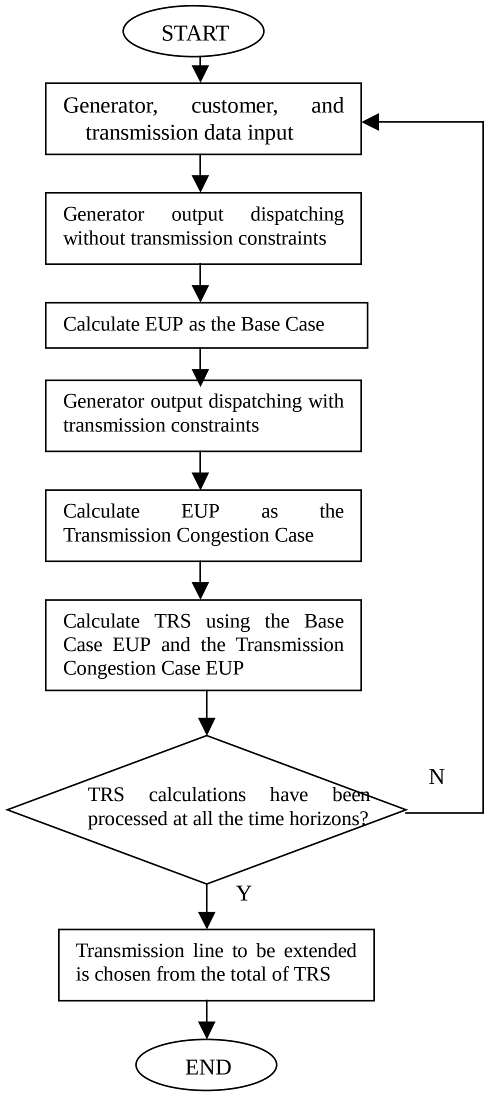

Fig. 3 Procedure to Obtain the Transmission Line to be Extended

4 Application For Evaluating Supply Reliability On A Model Grid

4.1 Establishing the pattern of generators and transmission lines

In order to examine the effectiveness of the method of evaluation of supply reliability proposed in this paper, we used the 8 nodes, 12 branches model grid shown in Figure 4.

In our simulation, we have assumed generators with three different outage rates, cost functions, and output responses. Generator 1 has a high cost for generating power but the outage rate is low and the output response time is rapid. Generator 2 is inferior to Generator 1 in terms of its outage rate and output response time, but its cost of generation is lower. The power generating cost for Generator 3 is the lowest of all three but it has a high outage rate and has the slowest output response.

The features of these generators are shown in Tables 2. The upper limits of transmission capacity for each transmission line are shown in Table 2. In the case of transmission congestion, the system operator makes decisions regarding rescheduling of output for the generators so that output does not exceed the upper limit of transmission capacity. The number of power consumers connected to the grid is set to three. It is assumed that consumer 3 consumes an uncertain amount of power, but that his power consumption changes within a certain range of probability.

4.2 Establishing the consumer power consumption load pattern

It is assumed that consumer 3's power consumption does not follow a pattern and therefore its consumption fluctuates within a certain range of probability.

Table 3 shows the power consumption for different consumers during different time periods. For consumer 3, Table 3 shows the different values of power consumption increasing or decreasing from the standard power consumption according to the different probabilities.

When there are no elements such as changes in the weather to influence demand, then consumer 3's power consumption becomes the standard power consumption. This is the reason that the standard power consumption amount is given the highest probability.

4.3 Evaluation of transmission line supply reliability sensitivity using the model grid

Figure 5 shows the power flow status for the base case and the transmission congestion elimination case. The upper values represent the base case and the lower values represent the transmission congestion elimination case. Figure 5 shows the following. In the base case, the congestion occurs on transmission line 3 (between node 1 and node 4) and transmission line 7 (between node 4 and node 6). But the system operator rescheduled the generator outputs and eliminated the congestion. The outputs from each generator are shown at the bottom of Figure 5.

EUP for the base case is 7.969MW and is 1.547% of the entire demand. EUP for the transmission congestion case is 8.564MW and is 1.663% of the entire demand. This shows that the supply reliability decreases due to transmission congestion.

Table 4 shows the TRS of transmission lines for the daytime period. In contrast with the morning period, TRS for congested transmission lines 3 and 7 is high as the total demand increases, so that there is an increase in the number of transmission lines experiencing congestion.

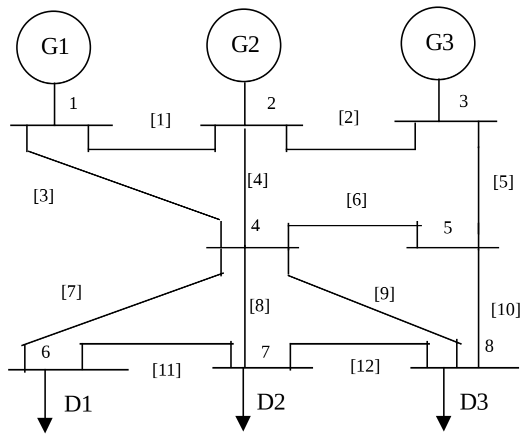

Fig. 4 Structure of Model System

Table 1. Characteristic of Generator 1

Coefficients of Generation Cost Function		G1	G2	G3
	a	0.020	0.017	0.014
	b	2.0	2.5	2.9
	c	50	30	70
Forced Outage Rate (%)		1.0	2.0	2.5
Output Upper Limit (MW)		250	300	400
Output Lower Limit (MW)		10	10	10
Ramping Rate (MW)		20	15	10

Generation cost CGi(Gi) is given by the equation below

$$CGi(Gi) = Gi*(a*Gi+b)+c$$

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Table 2. Transmission Line Parameters

Branch No.	Capacity (MW)	Reactance (pu)
1	100	0.500
2	100	0.500
3	120	0.417
4	250	0.200
5	250	0.200
6	100	0.500
7	100	0.500
8	200	0.250
9	150	0.333
10	185	0.270
11	150	0.333
12	100	0.500

Table 3 Customers Consuming Capacity (MW)

	D1	D2	D3		
Demand (MW)	130	155	215 20(%)	230 60(%)	245 20(%)

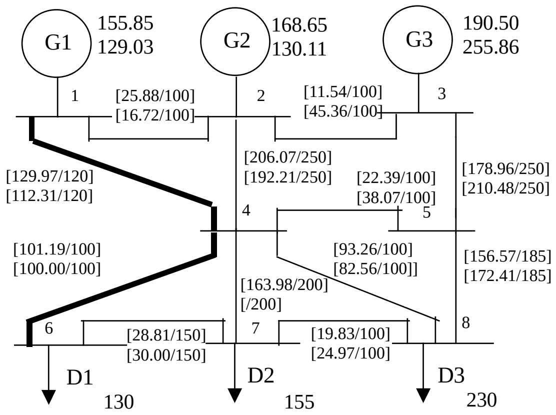

Fig. 5 Power Flow Condition

Table 4. TRS of Transmission lines

Blanch No	TRS (%)	Blanch No	TRS (%)
1	0	7	7.466
2	0	8	0
3	7.466	9	0
4	0	10	0
5	0	11	0
6	0	12	0

4.4 Evaluation of supply reliability by consumers

Table 5 shows the EUP of generators and the whole system. EUP allocated to each consumer based on formula (8), which eliminates differences in supply reliability between consumers. The EUP percentage for each consumer's power consumption is equal since there is no difference in supply reliability between the different consumers. It becomes 1.663%. Table 6, based on Formula (12), shows an example of EUP allocation when supply reliability differs by consumer. With the example shown in Table 6, it is assumed that consumer 3 requires the high supply reliability, thus EUP is allocated to place the highest priority on the supply reliability of consumer 3.

Table 5. EUP for Each Generator outage (MW)

	G1	G2	G3	System
EUP	1.043	2.002	5.522	8.564

Table 6.Example of EUP allocations for different supply reliability (MW)

	D1	D2	D3
EUP	2.723	3.247	2.594

From Table 6, we can see that EUP allocation to consumer 3 is 2.594MW. The allocated EUP to customer 3 is 1.128% of total required demand of customer 3. Therefore the supply reliability of customer 3 is improved by the different EUP allocation.

Some ways to utilize the allocated EUP value are to prioritize load shavings or to adjust the degree of load shaveing according to the allocated EUP values. Caution must be taken when utilizing this value to maintain fairness on the grid. If there are any differences in the EUP values allocated to the different consumers, we must try not to give significant disadvantages to any specific consumer.

5 Conclusions

In this paper, EUP has been introduced as the index for the system operator to evaluate supply reliability on the grid, as well as the concrete method for evaluating supply reliability using EUP.

It has been shown that the EUP calculation method might be extended to account for uncertainty of demand by treating it as a probability. The effectiveness of the proposed method is examined with a simulation using EUP and TRS as indexes to evaluate the influence of supply reliability on transmission congestion. TRS, by highlighting the vulnerabilities of transmission lines on the grid, can be used for decision making on prioritizing expansion.

For the EUP introduced in this paper, allocation of EUP as a method of evaluating each consumer's supply reliability was found to be useful within both the consumer focus and the conventional supply side focus.

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