Proceedings of the 2006 IASME/WSEAS International Conference on Energy & Environmental Systems, Chalkida, Greece, May 8-10, 2006 (pp402-408)

Evaluation of Onsite Generation Introduction for Improving Reliability on the Customer Side

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Abstract
On-site generator is an alternative to improve the supply reliability of customer. But that has been considered to be too expensive comparing with purchasing power from electric power suppliers. This paper proposes a new evaluation method for the supply reliability of customers and the cost efficiency of on-site generator installation. Based on the proposed reliability index, on-site generator installation is verified to have cost efficiency and to improve the supply reliability of customers through numerical examples by using a test system.

Keywords: Reliability, customers, onsite generator, cost efficiency, outage risk

1. Introduction

The range of the competitive market application in customers is now growing. Prior to the introduction of the principles of competition, electric power companies, which have had regulated regional monopolies, have moved forward with operation and facilities design in order to maintain supply reliability. As a result, the frequency and scale of supply outages has been extremely small, and the need for measures for reliability on the customer side has been relatively low. However, at present investment in transmission equipment has decreased and active improvement of facilities to maintain supply reliability is no loner pursued. There are therefore concerns about outages due to inadequate facilities should this situation persist. Thus, even as electric power companies continue to be suppliers with the responsibility for a stable supply of electric power as they were in the past, customers must also take into consideration not only economics but also measures to maintain reliability when purchasing electric power.

In order to provide measures to maintain reliability on the customer side, measures to improve reliability must be evaluated in combination with methods to evaluate reliability when selecting suppliers to contract with. Moreover, when economic mechanisms are used actively to maintain reliability, or when services such as reliability differentiated supply [1], [2] are introduced, a method to evaluate reliability which can take into consideration economic balance, including the costs versus benefits, is needed.

Because economics and maintaining reliability often represent a tradeoff, finding an appropriate equilibrium point for economics and reliability when determining the amount of power to purchase in a bilateral contract or when introducing on-site power sources is extremely important for customers in a competitive market environment.

The reliability of an electric power system can be considered from the supply side or the customer side, and an index of reliability for each side has been proposed [(3)~(8)].

For the supply side, because there is considerable discussion of the latent outage risk, various evaluation indices for reliability based on stochastic methods are in use. Among them, a method for evaluating reliability using the expected values for the amount of power difficult to supply has been proposed repeatedly [(4)~(6), (9)~(13)]. For the customer side, the apparent risk, that is to say the reliability based on outages, is evaluated, and so a quantitative index of reliability is often used. [(3), (7), (8)].

With respect to stochastic evaluation methods, use has been attempted in fields in which quantitative evaluation methods have been widely used, including reliability evaluation for customer contact points, and in the field of distribution systems, and proposals to clarify the relationship between cost and reliability for the quantitative evaluation of supply reliability have been made [(1), (6), (9) ~(13)]. The stochastic evaluation method and quantitative method each have advantages. The reliability evaluation methods previously proposed perform evaluations using one of these methods. However, if the characteristics involving the load composition for customers vary, the probability is high that the method to be used for the reliability evaluation will be different.

In this paper, on-site generator installation is focused on, as the reliability improvement method for customers and evaluated its efficiency of cost and reliability by comparing with purchasing power from electricity suppliers in accordance with the proposed reliability index based on outage risk of customers.

2. Reliability Evaluation on the Customer Side

2.1 Settings for the Reliability Evaluation Index

The customer must identify the appropriate reliability level for himself in order to determine the amount of power to purchase while taking into consideration reliability. In general, there is a trade off between supply reliability and supply cost at the planning stage for a power system. As a result, one idea is to use the point at which the social costs, the sum of the supply costs and the outage costs, are at a minimum as the most desirable reliability level when using the outage cost as the supplier reliability index [(1), (9)]. In the bilateral contract model used here, the determination of how much power to purchase, with a focus on economics and reliability, is treated almost the same as the determination of the economic distribution of generator output with consideration for supplier reliability by system operators. Therefore, if the outage cost for customers is used as the reliability index and the sum of the electricity price and the outage-related costs is used as the electricity costs on the customer side, then the reliability level when the electricity cost is at a minimum can be taken as appropriate.

In this paper, in the evaluation of outage costs for customers, the authors define the "costs for outages" with consideration for not only damage estimates due to imagined outages but also for the latent outage risk as calculated based on the generator outage rate at a supplier. They then perform a reliability evaluation that reflects the characteristics of customers using the cost above as a reliability evaluation index for customers.

As can be seen in Equation (1), a definition using the sum of the purchased electricity price *EP* and the outage-related cost *OC* during the period in which the electricity cost *EC* on the customer side is focused on results in

$$EC = EP + OC \tag{1}$$

The point at which the electricity cost *EC* is at a minimum can be thought of as the optimal reliability level on the customer side.

The electricity price *EP* given by a supplier is the sum of *VC*, the fuel costs to generate power, *FC*, the fixed costs such as depreciation of equipment, the *WC*, such as consignment costs, and *PROF*, operator profit. Therefore,

$$EP = VC + FC + WC + PROF \tag{2}$$

represents the electricity price.

In general, when determining the amount of power to purchase, power procurement should minimize the losses due to supply curtailments caused by imagined outages. However, in addition to the percentage of customer load being heavy, when the load is run synchronously, even a small curtailment in supply can have an effect, and when a loss equivalent to when a supply curtailment occurs in al loads is expected, a reduction in the damage may not be possible under the conditions imagined even if the amount of power purchased from a supplier is varied. In such cases, a measure to improve reliability would involve electricity procurement in which a lot more power is purchased from a supplier with a low probability of having an outage, thus reducing the latent outage risk.

In order to reflect the characteristics of damage to customers from supply curtailments in their decision about how much power to purchase, in this paper the authors propose as the outage-related cost *OC*, the reliability evaluation index, the sum of the expected value for outage costs *ExCOST* which represents the latent outage risk, and the weighted *AcCOST*, the estimate of damage due to an imagined outage. If the weighting coefficients *g* and *h* represent the latent outage risk and the estimated damage due to an imagined outage, then the cost for outages is

$$OC = g * ExCOST + h * AcCOST \tag{3}$$

However, because an evaluation of the latent outage risk includes outages with conditions identical to those in imagined outages, the weighting coefficients g and h must satisfy the following conditions so that their effects are not duplicated in the OC calculations.

$g = 0, h \neq 0$, or $g \neq 0, h = 0$

A reliability evaluation that matches the load characteristics of the customer is possible with an evaluation that uses either the latent outage risk or the damage estimate due to an imagined outage. Moreover, if the reliability is improved, the value of OC falls, and if it deteriorates, the value of OC rises. As a result, the customer can know the effects of measures to improve reliability through the OC value.

2.2 Equivalent Generation Model of Suppliers

Suppliers provide power via distribution systems. Because the power that the customer receives does not depend on the scale of electricity generation at the supplier, the supplier as viewed from the customer's perspective can be seen as providing electricity via a distribution system from a generator with capacity the same as the amount of providing power and with an outage probability FOR (Figure 1).

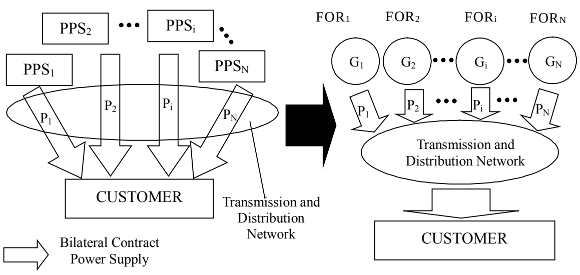

Fig. 1. Equivalent Generator Model

In this paper, the authors propose introducing a equivalent generation model as seen from the customer's side, in which a generator with capacity equivalent to the amount of providing power replaces the supplier, calculating supply outages due to generator outages at the supplier and distribution equipment outages, and then evaluating reliability on the customer's side.

The effects of distribution equipment outages on reliability are handled as follows.

First, when an outage occurs in the transmission line k or in a distribution line, a determination is made as to whether or not there is a transmission route from the customer to the supplier. When there is no route, the supplier, that is to say an equivalent generator in the bilateral contract model used, is deemed to be in a supply outage state due to outage, and the outage rate FOR for an equivalent generator is updated to (the generation equipment outage rate for the supplier + the outage rate for the distribution equipment k). No update occurs if even one route exists.

In this fashion, a reliability evaluation that also takes distribution equipment into consideration is possible through the inclusion of the effects due to distribution equipment outages on the outage rate FOR for equivalent generators.

2.3 Outage Cost Breakdown

The latent outage risk $ExCOST$ can be found as shown below[(6), (10), (12), (13)].

If the load (curtailed load) for customers being affected by the outage rate FOR_j for the equipment j, such as generators or transmission lines, and outages in the equipment j, is CL_j and the outage cost per 1 kW is CD_j, then the expected value $ExCOST_j$ for the outage costs for customers with respect to the inadequacy in the power due to an outage in the equipment j is

$$ExCOST_j = CL_j * CD_j * FOR_j \tag{4}$$

The outage cost CD_j per 1 kW varies depending on the duration of the outage. Therefore, CD_j is a function of the duration of the outage, and as a result the mean recovery time (mean time that an outage lasts) for the equipment j is designated r_j, and the function for outage damage (equivalent to the Customer Damage Function in Reference (10) and elsewhere) is $f(r_j)$. Thus, Equation (4) becomes

$$ExCOST_j = CL_j * f(r_j) * FOR_j \tag{5}$$

For all equipment involved in supplying power to customers, the total here is the latent outage risk $ExCOST$.

$$ExCOST = \sum_{j=1}^{N} ExCOST_j \tag{6}$$

The $AcCOST$, the estimate of damage due to an imagined outage, can be calculated as follows.

When a customer has contracted with N generators (supplier N), if a number, 1, 2, …, N, is given in order of greatest contracted power level, then the maximum value for the supply curtailment resulting from a generator outage can be represented as

For one outage: G_1

For two outages: $G_1 + G_2$

For i outages: [mathematical expression]

For N outages: [mathematical expression]

Here, if the maximum value for the outage cost for i outages is designated $AcCOSTi$, then the following relationship holds.

$$AcCOST_1 < AcCOST_2 < \ldots < AcCOST_i < \ldots < AcCOST_N \tag{7}$$

$AcCOST_i$ can be represented as

$$AcCOST_i = \sum_{j=1}^{i} G_j * f(r_i) \tag{8}$$

using the outage damage function for the continuous time r_i for i outages.

A weighting coefficient h_m is available for m overlapping outages, and if

$$h * AcCOST = h_m * AcCOST_m \quad (9)$$

then by determining the weighting coefficient h_m, the second item in Equation (3), which represents m generator outages, can be found.

3 Outage Damage Function

The amount of damage DM for a power supply curtailment caused by, for instance, a generator outage can be assumed to be relatively small when the amount of the load cut off outside of the heavy loads exceeds the power supply curtailment, and can be assumed to rise sharply when the heavy loads must be curtailed. As a result, the amount of damage is thought to vary along an approximation using the Sigmoid function given below.

$$DM(CL_i, r) = \frac{DM\max(r)}{1 + e^{a*(z - CL_i)}} \quad (10)$$

Here, DMmax is the maximum value for the outage cost per 1 kW when the duration of the outage is r, a is the rising slope of the Sigmoid function, CL_i is the supply curtailment due to the outage, D is the total load, and z is the percentage of the load excluding the heavy load.

The curve for the power supply curtailment – outage-related cost represented in Equation (10) varies depending on the duration of the outage even when the load composition is identical. If a power supply curtailment – outage-related cost curve corresponding to the outage duration r in Equation (5) is used, then the outage cost corresponding to CL_j, the amount of the load curtailed, is defined, and CD_j in Equation (4) can be found.

Based on the results in Reference (10) and Reference (15), which describe the outage costs based on a questionnaire-style survey, the maximum value for the outage cost per 1 kW with respect to the duration of the outage is highest immediately after the outage occurs, and then falls off as the outage grows longer. In Reference (10) and Reference (15), a graph with such variations is not shown, but if the amount of damage per 1 kW is plotted, then it is found to decrease as time passes. As a result, in this paper the maximum value DMmax(r) for the outage costs per 1 kW is approximated using an exponential function.

If the generators where an outage occurs cease supplying power for the time r, then the maximum value DMmax for the outage cost per 1 kW is

$$DM\max(r) = OCcst * A^{-k(r-Tc)} \quad (11)$$

Here,

$OCcst$: outage cost coefficient
A: bottom of the exponential function
k: outage cost attenuation coefficient
T_C: time required for the outage cost per 1 kW to stabilize

The outage cost coefficient is defined to be the outage cost per 1 kW after the time T_C has passed. The outage cost attenuation coefficient is defined to be the outage cost per 1 kW with respect to the shortest possible outage duration for DMmax. If DMmax in Equation (10) is used for a particular amount of load curtailed CL, then the outage damage function $f(r)$ becomes

$f(r) = DM(CL, r)$

4. Examples of Calculations

4.1 Architecture of the Transmission System

Figure 2 shows the architecture of the test system used for verification. The test system used is a revision of the IEEE Reliability Test System (RTS-96) [16]. In the simulations, the authors assumed that there were five generator nodes connected to suppliers, and that there were two load nodes that customers could connect to. Table 1 lists the outage rate for the transmission lines connecting each node and the mean outage duration.

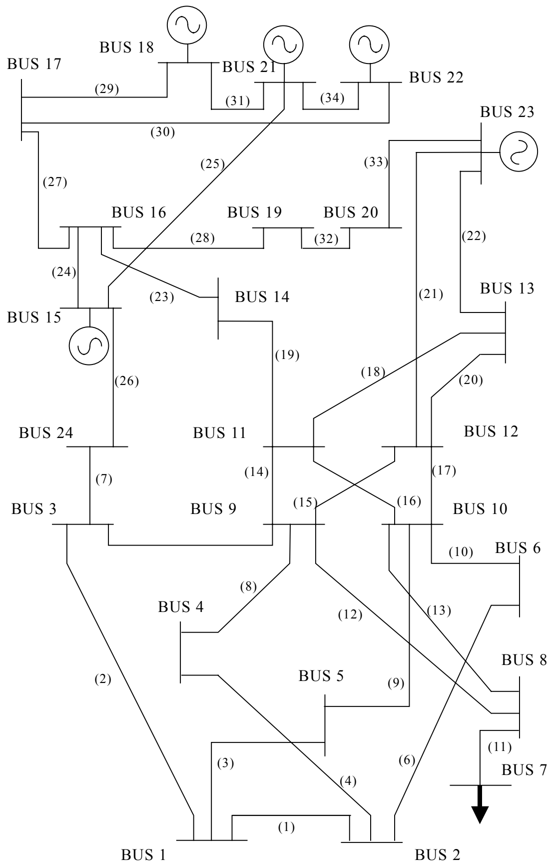

Fig. 2. Architecture of the test system

Proceedings of the 2006 IASME/WSEAS International Conference on Energy & Environmental Systems, Chalkida, Greece, May 8-10, 2006 (pp402-408)

Table 1. Characteristic of Transmission Line

No	Outage Rate (%)	Outage Duration (Hours)	No	Outage Rate (%)	Outage Duration (Hours)
1	0.24	16	18	0.40	11
2	0.51	10	19	0.39	11
3	0.33	10	20	0.40	11
4	0.39	10	21	0.52	11
5	0.48	10	22	0.49	11
6	0.38	10	23	0.38	11
7	0.38	10	24	0.33	11
8	0.36	10	25	0.41	11
9	0.34	10	26	0.41	11
10	0.33	10	27	0.35	11
11	0.30	10	28	0.34	11
12	0.44	10	29	0.32	11
13	0.44	10	30	0.54	11
14	0.38	10	31	0.38	11
15	0.38	10	32	0.38	11
16	0.38	10	33	0.34	11
17	0.38	10	34	0.45	11

4.2 Supplier Characteristics

Suppliers are assumed to present their price for selling power in one hour increments. Moreover, in the electricity price model adopted in this paper, the supplier generators are assumed to be thermal powered generators, and the fixed costs FC, consignment costs *WC*, and the profit *PROF* per 1 kW are assumed to be constant regardless of the amount of power sold. Given this, the electricity price *EP* when purchasing power at time T for *x*(kW) is given by

$$EP = \{ax^2 + (b + d + e + f)x + c\} \cdot T \qquad (12)$$

where

a: quadratic coefficient for the cost of fuel
b: linear coefficient for the cost of fuel
c: constant coefficient for the cost of fuel
d: coefficient for depreciation of fixed costs FC
e: coefficient for consignment costs WC
g: coefficient for profit

Table 2: Electricity price and FOR of electric power suppliers

No	a	b	c	d	e	f	FOR	Bus
1	0.030	2.0	350	1.0	4.0	0.40	0.5	15
2	0.018	2.2	400	1.0	4.0	0.39	0.7	18
3	0.014	2.5	450	1.0	4.0	0.37	1.0	21
4	0.009	3.2	500	0.8	4.0	0.34	2.0	22
5	0.007	3.6	500	0.8	4.0	0.32	3.0	23

Table 2 lists the electricity price data and outage rates for the various suppliers, and Table 3 lists the upper and lower limits for power sold by each supplier. In order to make the effects of the supplier outage rate on reliability significant, the authors set the outage rate so that the difference in the outage rate among supplier would be large, and set the upper and lower limits so that as the outage rate for a supplier rose, the upper and lower limits for power sales rose.

4.3 Distribution System Characteristics

The distribution system was assumed to be a single-line radiating system. Its structure is shown in Figure 3, and the outage rate and duration time for outages are given in Table 3. The data for the outage rate was set based on Reference (17).

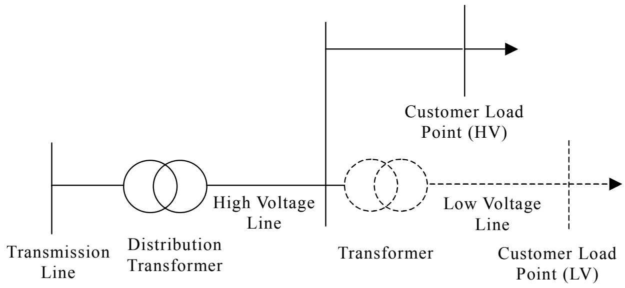

Fig. 3: Structure of distribution system

Table 3: Characteristics of distribution system outage

	Failure Rate (%)	Repair Time (hr)
High Voltage Line	4.6	4

4.4 Customer Characteristics

Customers are connected to either node 1 or node 7 as seen in Figure 6, and they receive power at high voltage. The load composition for customers is assumed to come in two types: a high firm load and a low firm load, with particular characteristics for each time period. Table 5 lists the total load and the firm load for customers. The total load and the firm load for a customer is assumed to be constant with no variations in a given time periods. Moreover, because the amount of the firm load is assumed to be the same during all time periods, when the total load is low, the percentage that the firm load represents with respect to the total load is higher, and when the total load is high, the percentage is lower.

Based on Table 4, the coefficients in Equation (10) to determine the amount of damage DM with respect to a supply outage are given in Table 6, and the coefficients in Equation (11) used to find *DM*max are given in Table 7. Each value is determined by using as a reference cases for industrial customers as found in Reference (10).

For the outage duration, the duration *r* was set to four hours for all generator outages in each time period (divided into three sections). Moreover, the slope *a* for the sigmoid function is assumed to be inversely proportional to z, and a value of 500/z is used.

When the coefficients in Table 5 and Table 6 are used, the maximum value for the outage damage function f is roughly 5900 (¥/kW).

The weighting coefficients for the outage-related cost *OC*. When a firm load must be curtailed under the assumption that one generator has failed, the weighting coefficient *g* for *ExCOST* is set to 1.0, and the weighting coefficient *h* for *AcCOST* is set to 0. When a firm load does not have to be curtailed, *g* is set to 0, and *h* is set to 0.05 with consideration for an outage in two generators.

Table 4: Customer's load configuration

	Capacity (kW)
Total Load (kW)	1500
Firm Load (kW)	900

Table 5: Coefficients for DM

r (hours)	z (%)	a
4	40	12.5

Table 6: Coefficients for DMmax

Coefficient	OCcst	A	k	Tc (hrs)
Value	13	100	0.003	4

4.5 Effects of Introducing an On-Site Power Source

To verify the efficiency of reliable re-dispatch, two kinds of EC value are compared. The result of economic electricity power purchase, EP minimizing case, is shown in Table 7. EP is 159433 (Yen). EC is 656597 (Yen). In this case, the applied value of weighting coefficients, g, h, are 1.0 and 0.0 for light load, and 0.0 and 0.05 for heavy load.

Table 7. Result of EP minimizing

EP	EPS1	EPS2	EPS3	EPS4	EPS5
159433	134.25	218.48	270.90	395.29	481.08
ExCost	AcCost1	AcCost2	AcCost3	AcCost4	AcCost5
19314	1625387	9943287	14169773	17015716	18709652

Table 8 describes the result of EC minimizing case. EC is 391050 (Yen). AcCOST1 and AcCOST2 become smaller. It means that reliable re-dispatch is carried out according to the characteristic of customer's load.

Table 8. Result of EC minimizing

EP	EPS1	EPS2	EPS3	EPS4	EPS5
165787	250.0	300.0	316.4	316.8	316.8
ExCost	AcCost1	AcCost2	AcCost3	AcCost4	AcCost5
16214	341407	4505243	11248530	15531625	18709652

Fig. 8 demonstrates the electricity price (EP) comparison of on-site generator (DG) installation, economic electricity purchase, and reliable re-dispatch. Assumptions of the on-site generator in this simulation are as follows.

- The output is constant.
- It supplies power for 24 hours.
- Introduction cost is 120000Yen/kW
- Forced outage rate is 0.2%
- Operating cost is 15Yen/kWh
- Installed capacity is 300kW

Fig 4. Curve of EP by on-site generator installation

Introduction of an on-site generator makes ExCOST 14727 (Yen) and AcCOST 167420 (Yen). On-site generator introduction is effective on both potential outage risk and damage of contingency. It can be said that installation of on-site generation is of great use to improve reliability. From Fig. 4 on-site generator introduction becomes more economic than reliable re-dispatch when term of depreciation is longer than about 2.5 years under assumptions of this simulation. Moreover, Fig. 8 shows that on-site generator introduction can have economic advantages around 10 years depreciation time length. EP with on-site generator introduction is very close to that of economic electricity purchase.

Customers are able to compare the cost efficiency of reliability improvement options, and to know an optimal setting of depreciation for on-site generator installation by taking advantage of the proposed approach.

5. Conclusion

The efficiency of cost and reliability improvement by on-site generator installation has been evaluated using the reliability index based on the outage risk of customers.

On-site generator installation has been verified to have a cost efficiency when considering the outage risk. That means on-site generator can be a reliable and cost effective alternative for customers.

Future topics include an evaluation of the balance between economic viability and maintaining reliability in the long term, and the need for a reliability evaluation, which takes into consideration the effects of other participants in the market. In addition, the authors want to perform an evaluation of the costs versus benefits in measures to improve reliability and a detailed investigation into the into the outage costs for customers, which will have a significant impact on the discussion surrounding appropriate reliability levels.

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