The Seventh Asian-Pacific Symposium on Structural Reliability and Its Applications (APSSRA2020)
October 4–7 2020, Tokyo, Japan
T. Takada, I. Yoshida & T. Itoi (editors)

Evaluation of Electricity Supply Resilience during an Earthquake for an Individual User

T. Matsumoto[1], T. Uetake[2], Y. Shikama[3] and T. Nakamura[4]

[1]*Shinozuka Research Institute. Email: matsumoto@shinozukaken.co.jp*
[2]*Tokyo Electric Power Company Holdings, Inc.. Email: uetake.tomiichi@tepco.co.jp*
[3]*Tokyo Electric Power Company Holdings, Inc.. Email: shikama.yasuhiro@tepco.co.jp*
[4]*Shinozuka Research Institute. Email: naka@shinozukaken.co.jp*

Abstract: Citizens, manufacturers, local governments, etc. want to know the information about the possibility of a power outage and its recovery schedule at early stage of a disaster. This is because it greatly affects their appropriate decisions and actions to the disaster. We describe the restoration process of the supply power of each user as a power supply curve, and proposes an analytical technique as its calculation method. In addition, the power supply curve (power supply resilience) of the entire distribution network is evaluated by summing up the power supply curves of individual users. Using a part of the JST-CREST 126 Distribution Feeder Model for the distribution network simulation model, we compare the changes in the power supply curve with and without distributed power resources, and discuss the effect of them on the power supply curve of individual users and the entire distribution network.

Keywords: Electricity supply resilience, Earthquake disaster, Viewpoint of users, Distributed power resources.

1. Introduction

Long-term electric power interruption has a serious impact not only on economic activities but also on citizen life. In fact, the typhoon Faxai in 2019 caused the serious blackout in Chiba Prefecture, Japan and it took about sixteen days to recover the power supply (METI 2019). In addition, repeated change of recovery due date of electric power had increased user's discontent. Citizens, manufacturers, local governments, etc. want to know the information about the possibility of a power outage and its recovery schedule at early stage of a disaster. This is because it greatly affects their appropriate decisions and actions to the disaster. On the other hand, with the spread of distributed power resources such as solar power generation and electric storage equipment in recent years, users are not unilaterally supplied from the grid, but are becoming important players in the supply and demand of electric power. Distributed power resources are automatically disconnected from the grid when grid power is interrupted due to accidents or natural disasters, but are expected to improve power supply condition. In addition, we consider that if users are damaged and power demand is reduced and power required supply will also be reduced.

In the research on the power supply interruption in the disaster until now, the evaluation of the power supply interruption in the wide area considering only the damage of the supply equipment side was mostly seen from the supply side. For example, Tohma et al.(1991) studied on reliability evaluation of electric power supply focusing on connectivity of electric wires including substations due to earthquake disasters, Shoji and Tabata(2011) studied on effects on reliability of electric power networks by modeling substations, switches, etc. as nodes and changing the number of such damages, and Shinozuka and Hwang (1998) analytically evaluated and verified the restoration process of power supply hindrance caused by the 1989 Roma Prieta Earthquake for Los Angeles City. These studies generally use Monte Carlo simulations (MCS) for probabilistic evaluation. On the other hand, in the case of Shumuta (2000), information about where and when power outages occur during an earthquake is one of the information that users and local governments most want to obtain. Based on the same viewpoint as this paper, a prediction model using multiple regression analysis has been constructed for restoration time for high-voltage distribution lines. However, user damage is not taken into account in Shumuta (2000).

Thus, there are no studies evaluating the possibility of a power failure from the viewpoint of individual users. In addition, we have not found any research on the power supply interruption in the event of an earthquake targeting the next generation power distribution network where the spread of distributed power resources is anticipated. Under these circumstances, the authors proposed a method for evaluating analytically the power supply interruption of a distribution network in which distributed power resources are arranged, including the damage of users (Matsumoto et al. 2019a). We evaluate the process of restoring the electric power supplied after an earthquake to each user by using the method which has been developed up to now.

The contents of this paper first detail the notation of the restoration process of the power supply of individual users (referred to as the power supply curve in this paper) and an analytical technique as a calculation method of the power supply curve. Then, we simulate the power supply restoration process using a part of JST-CREST 126 Distribution Feeder Model (ACROSS 2017). We also compare and examine the changes in the power supply curves with and without the distributed power resources, and consider the effects of them on the power supply curves of individual users and distribution networks as a whole.

2. Method of describing the power supply for a user

We assumed that the power grid, including power plants, is sound even in the event of an earthquake. In this case, in order for individual users to receive electric power, the distribution facilities from the substation for distribution to the said users must be sound and also the users must be sound.

Factors that cause users to lose power (no electricity is supplied) include the disruption of power systems due to damage to distribution lines, and power load shutdown that are performed when the rapidly voltage rises due to users' suddenly break down and exceeds a reference voltage. Users belonging to the grid subject to distribution line damage or power load shutdown become power outage regardless of the soundness and unsoundness of user facilities and distribution facilities, etc.

Fig. 1 is a conceptual diagram showing the demand power and supply power of users at the time of the disaster with the elapsed time from the occurrence of the disaster. It is intended for users who do not have a distributed power resources. The vertical axis is power which normalized the demand and supply power in terms of usual demand. The horizontal axis represents the elapsed time since a disaster. The curve of the supply power in the figure is called the power supply curve in this paper. As shown in the figure, after a disaster, the demand electric power decreases, and then a constant value is taken. This represents the demand power that decreases due to the damage of the user, and is obtained as the product of the soundness probability of the user and the usual demand power, that is, the expected value. The constant value is because the restoration of users is assumed to be longer than the restoration time of distribution facilities. On the other hand, in the power supply curve, the supply power temporarily drops rapidly just after the disaster. This is the effect of the interruption of the system power and the power load shutdown of the previous describes. Afterwards, investigation and confirmation of the damage situation, avoidance of the damaged equipment by the operation of the sectional switch, etc. are carried out, and the electric power supply is resumed. This term is called the initial movement term in this paper. Thereafter, the restoration of damaged distribution facilities will gradually improve the power supply. This term is called the repair term in this paper. The power supply curve is obtained by the product of the power supply probability and the usual demand power. Further, the supply interruption is obtained by the difference between the demand power and the supply power. In the case of a user having a distributed power resources, the power supply interruption will be avoided. This point will be described in detail in 3.3. Demand and supply power of the entire distribution network is obtained by summing up the demand and supply power of all users belonging to the distribution network.

It should be noted that power supply probability at initial movement term are attributed to the judgment for system maintenance, while those in the repair term are attributed to the physical connectivity of the power distribution equipment. For this reason, both probabilities are evaluated separately. In addition, the vertical axis in Fig. 1 is normalized by the usual demand power, hence it is equal to the demand power probability and supply power probability.

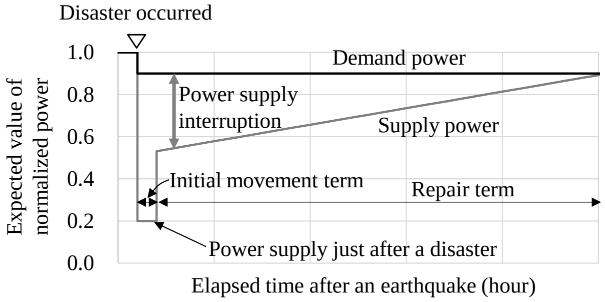


Figure 1. Image of power supply curve for a user.

3. Evaluation of the power supply curve for a user

3.1 Power load shutdown due to voltage fluctuation in the initial movement term (Matsumoto et al. 2019b)

Power load shutdown due to voltage fluctuations is performed by circuit breakers installed on multiple distribution lines extending from the distribution substation. The range in which power transmission is interrupted by one circuit breaker is called a unit system in this paper. The standard voltage of the circuit breaker is 6000V and the power load shutdown when it exceeds 6420V in the unit system. When this threshold is converted to power, it becomes as follows.

$$w_a = \left(\frac{6000}{6420}\right)^2 w_u \tag{1}$$

Where, w_u is the total power demand of the unit system. The power supply probability p_B just after a disaster is calculated by using the threshold w_a as follows.

$$p_B = \sum_{w_a < w_k} P_W\left(w_k\right) \tag{2}$$

Here, $P_W(w_k)$ is a probability function of the supplied power at the circuit breaker location, and is determined by the method shown in 3.2, taking into account the distribution lines damage and the users damage.

Originally, there are other factors to be considered, such as current and frequency, reverse power flow from distributed power resources, etc., for power load shutdown. However, in this paper, only voltage rise is targeted.

3.2 Probability function of the supply power in the initial movement term

The users belonging to the unit system are basically arranged in a linear sequence, and Fig. 2 shows an example of this. The "SS" in the diagram are substations for power distribution and "Breaker" shows a circuit breaker. ● is a pole transformer. ○ denotes an individual user (e.g., a detached house, a apartment, an office, etc.), and W_1, W_2,..., W_n is a random variable of the user's power consumption. As shown on the left in Fig. 3, when the user is damaged, it represents 0, and when it is soundness, it represents w_i power demand. p_{Ui} represents the soundness probability of user i. The right in Fig.3 shows the probability function $P_W(w_k)$ of the power supply at the circuit breaker. L_0, L_1,..., L_{n-1} are distribution lines (hereinafter referred to as links). In addition, links from pole transformers to users are assumed to be damaged when the users are damaged.

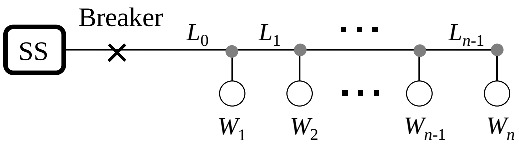


Figure 2. Example of unit system.

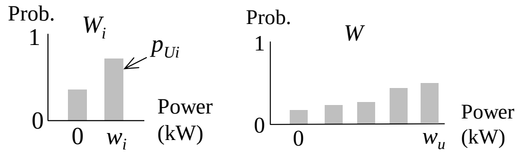


Figure 3. Probability function (left) user *i* demand power (right) unit system supply power.

If the soundness probabilities of the links L_0, L_1, L_2,... are p_0, p_1, p_2,... and L_0 is damaged, power is not supplied downstream from L_0, and this event is defined as N_0. The probability of occurrence of the event N_0 and the suppliable power random variable Z_0 are as follows.

$$p(N_0) = (1 - p_0), \quad Z_0 = 0 \tag{3}$$

If L_0 is soundness and L_1 is damaged, it is supplied power upstream from L_1. This event is defined as N_1, the occurrence probability and the suppliable power random variable Z_1 are as follows.

$$p(N_1) = p_0(1 - p_1), \quad Z_1 = W_1 \tag{4}$$

Also, event when L_0 ~ L_{n-1} are soundness is defined as N_n, the occurrence probability and the suppliable power random variable Z_n are as follows.

$$p(N_n) = p_0 p_1 p_2 \cdots p_{n-1}, \quad Z_n = W_1 + W_2 + W_3 + \cdots + W_n \tag{5}$$

Generalize the above. The probabilities of occurrences of each events (N_j , j = 0 ~ n) are as follows.

$$p(N_j) = (1 - p_j) \cdot \prod_{i=0}^{j-1} p_i \qquad ; j = 0 \sim n \tag{6}$$

Here, p_n=0. N_j; j=0~n in Eq. 6 covers the damage event of the distribution equipment as a set of exclusion events. In addition, when the random variable of the available power is generalized, it is as follows.

$$Z_j = \sum_{i=0}^{j} W_i \qquad ; j = 0 \sim n \tag{7}$$

Here, W_0 is 0. Finally, the probability function $P_W(w_k)$ of the supply power at the circuit breaker considering the damage status of each link is calculated as the conditional supply power (Z_j , j=0~n) of each event (N_j , j=0~n) as follows.

$$P_W(Z_j \mid N_j) \qquad ; j = 0 \sim n \tag{8}$$

In the above description, W_i is a binary random variable, but a multi-valued random variable is also applicable.

3.3 Supply power during the repair term

Taking up arbitrary users *i*, combinatorial events (four events) of each event of damage to distribution facilities and damage to users are represented by event trees, and the results are shown in Fig. 4. In the figure, $p_{Si}|t$ is the soundness probability of the power distribution equipment from the distribution substation to the user *i* under the condition of the restoration time *t*, and p_{Ui} is the soundness probability of the user. w_i is the power demand at all times, κ_i is the ratio of the power supplied from the distributed power resources to w_i, and κ_i is referred to as the utilization rate of the distributed power resources (hereinafter simply referred to as utilization rate) in this paper. The demand power and supply power values are shown for each result. "-" indicates a situation where no demand power or supply power occurs. From the Fig. 4., if the distribution facilities are sound and the users are sound, the power demand is covered by the power supplied from the distribution network. On the other hand, when the power distribution facilities are damaged even though the users are soundness, the power supply is disrupted from the power distribution network, and the power in accordance with the utilization rate κ_i is supplied from the distributed power resources.

Route	User	Demand	Supply from distribution network	Supply from distribution power resource
$p_{Si}\|t$	p_{Ui}	w_i	w_i	-
	$1\text{-}p_{Ui}$	-	-	-
$1\text{-}p_{Si}\|t$	p_{Ui}	w_i	-	$\kappa_i w_i$
	$1\text{-}p_{Ui}$	-	-	-
	Expected value	$w_i p_{Ui}$	$w_i p_{Si}\|t \cdot p_{Ui}$	$\kappa_i w_i (1\text{-}p_{Si}\|t) p_{Ui}$

Figure 4. An event tree that calculates the expected value of demand and supply power for user *i*.

The expected value in the Fig. 4 is obtained by multiplying the occurrence probability of each event by the demand power and the supply power, respectively. The power supply to user $w_{Ei}|t$ depending on restoration time is obtained by adding the power supply from the distribution network and the power supply from the distributed power resources, and is expressed as follows. Here, assuming that the utilization rate κ_i is 1.0, Eq. 9 becomes equal to the expected value of the demand power in the Fig. 4, and indicates that no power supply interruption occurs. Since the purpose of this paper is to evaluate the power supply resilience during an earthquake, we assumed that the demand power and the supply power are always in balanced during normal times without considering the use of distributed power resources.

$$w_{Ei} \mid t = w_i p_{Si} \mid t \cdot p_{Ui} + \kappa_i w_i \left(1 - p_{Si} \mid t\right) p_{Ui} \tag{9}$$

p_{Ui} of the sound probabilities of the users is divided into low-voltage power receiving users and high-voltage power receiving users (hereinafter referred to as low-voltage users and high-voltage users), and each is evaluated using a statistically determined Fragility Curve. The soundness probability $p_{Si}|t$ of one distribution facility is expressed as the sum event probability of the MPS (Minimal Path Set) of the distribution route from the distribution substation to the user, and is calculated as follows.

$$p_{Si} \mid t = p(M_{i1} \mid t \cup \cdots \cup M_{im} \mid t) \quad (10)$$

Here, $M_{ij}|t$ and (j=1~m) are the soundness events of each MPS, and because they are improved by the restoration of the power distribution system as the elapsed time progresses, the conditional on the restoration time t;. m is the total number of MPS. In calculating the sum event probability of Eq. 10, we use BDD (Binary Decision Diagram) (Bryant 1986) in this paper.

Refer to Matsumoto et al. (2019a) for the distribution line soundness probability required to determine the MPS soundness probability.

4. Procedure of supply power evaluation for the entire distribution network

4.1 Evaluation of Supply Power

$w_E|t$ of electric power supplied to the entire distribution network under the condition of the restoration time t is obtained by summing the restoration time t of the users, and is as follows.

$$w_E \mid t = \sum_{all\ i} w_{Ei} \mid t \quad (11)$$

The power loss due to the resistance of the distribution line itself is not considered in this paper since the size of distribution network model used in this study is not large enough to consider transmission losses.

4.2 Procedure of supply power evaluation Including Initial movement term

Fig. 5 shows the evaluation procedure of the supply power including the response in the initial movement term. First, the target distribution network is modeled into node links to create an MPS for the distribution path from the distribution substation to each user. The damage probability of users and distribution facilities under seismic ground motion are evaluated. In the initial movement term, the power supply probability function $P_W(w_k)$ and the power load shutdown threshold w_a are calculated for each unit system, and the power supply probability just after the disaster for each unit system is evaluated. In the repair term, first, the MPS and the damage probability of distribution facilities are applied to the BDD, and the soundness probability $p_{Si}|t$ of the distribution route from the distribution substation to the user is obtained. Considering the user's soundness probability p_{Ui}, the user's power supply curve is obtained. This operation is repeated for each user. The power supply curves for all users are obtained and applied to Eq. 11 to obtain the supply power of the entire distribution network $w_E|t$.

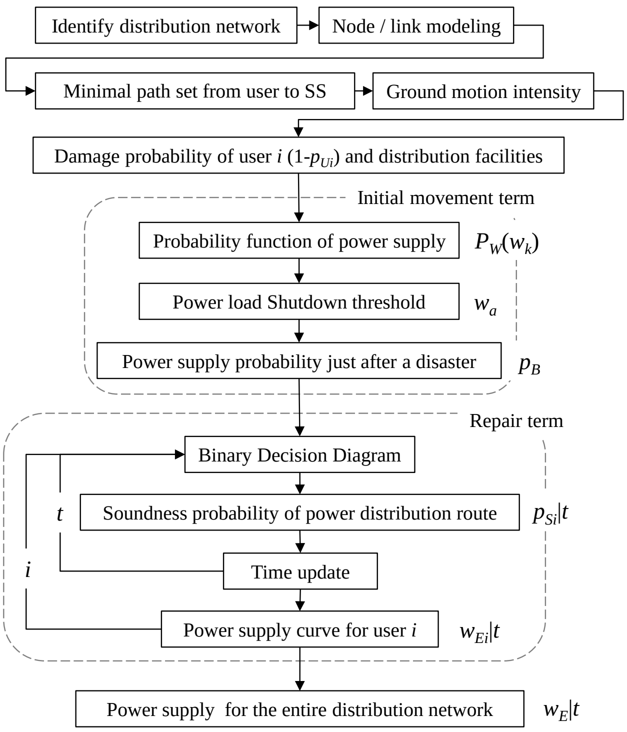


Figure 5. Procedure of supply power evaluation.

5. Analytical model

5.1 Distribution network model

We adopts a part of JST-CREST 126 Distribution Feeder Model (ACROSS 2017) as the distribution network model for power supply curve analysis. The model is shown in Fig. 6. The SS in the figure is a distribution substation, which is assumed not to be damaged even in the event of a disaster and to be supplied with power from the upstream (power plant). The number of users is 327, of which 289 are low-voltage users and 38 are high-voltage users. The number of links is 667 and the sectional switch is 18, of which 15 are usually closed and 3 are usually open. The line connecting the pole transformer and the user shall be a service line, and shall be damaged by the user damage. In addition, the power load shutdown due to voltage fluctuation in the initial movement term of the disaster shall be carried out by a circuit breaker shown by ✕ in the figure. We assumed that the sectional switches and circuit breakers are not damaged even in the event of a disaster.

5.2 Other specifications

As shown in Fig. 6, we set the restoration time of distribution lines for each area separated by a sectional switch. We also set the demand power for the entire distribution network at 18,497 kW.

The parameters ‘user soundness probability’, ‘ground motion intensity’, ‘user demand power’, and ‘distributed power resources spread rate’ were the same values as those in Matsumoto et al. (2019a).

6. Calculation result

6.1 Supply power of individual users

User10, 142 (see Fig. 6 for these locations) is taken up, and power demand and power supply curves are shown in

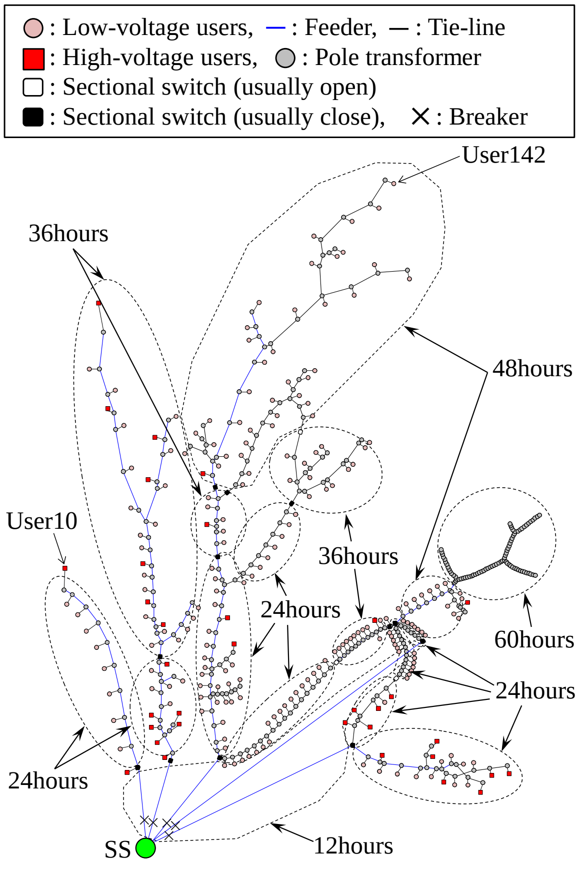


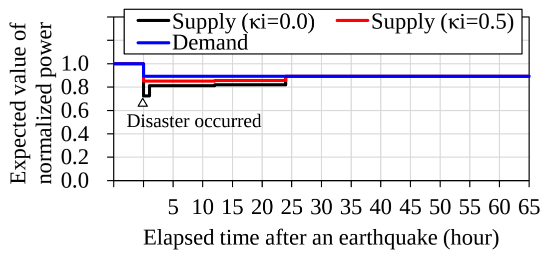
Figure 6. Distribution network model for simulation
(The Part of JST-CREST 126 Distribution Feeder Model)

Fig. 7. The vertical axis is normalized by the usual demand power. The utilization rate κ_i shows the cases of 0.0 (no distributed power resources) and 0.5. Incidentally, the κ_i =1.0 cover all the power required by the user, so it corresponds to the curve of the demand power showing for comparison.

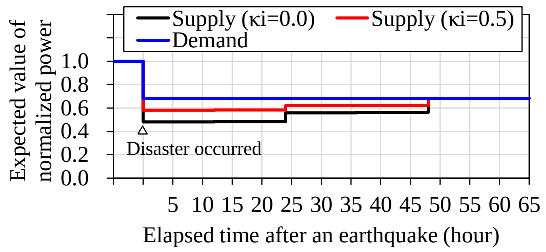
After the disaster, the supply power (black line) in the case of not having a distributed power resources decreased with a spike like dip. This is the effect that the load is disconnected at the each unit system as a result of damage to the user or distribution facility. The supply power in the initial movement term of users with distributed power resources has decrease without a spike like dip. Subsequently, during the repair term, power will be supplied from the extent to which the distribution line damage has been restored, and the supply power will recover. The power recovery for each user depends on the location of the user in the distribution network. On the other hand, in User142 shown in Fig. 7(b), a temporary decrease in the electric power supplied during the initial movement term does not appear. This is probably because the system to which the user142 belongs is a large system in which the number of users belong, so that the influence of distribution lines and users damage is reduced.

Comparing the power supply curves at the utilization rates κ_i = 0.0 and 0.5, the power supply is improved at the utilization rate κ_i = 0.5, and the results show the effect of the distributed power resources.

We consider that presenting the electric power supply in the event of a disaster from the viewpoint of users will help the citizens to take appropriate measures and take appropriate actions, such as evacuation planning and procurement of necessary materials. We also consider that showing the superiority of users having a distributed power resources will help spreading the distributed power resources.



(a) User10



(b) User142

Figure 7. Power supply curve for the users (Demand power curve is also shown for comparison).

6.2 Supply power of the entire distributed network

To evaluate the power supply curves of the entire distribution network, for convenience, we assume that the utilization rate κ_i for users with distributed power resources is 1.0. This is meaning that demand power is covered 100% by distributed power resources. For comparison, Fig. 8 shows the results of evaluating the spread of distributed power resources in the distribution network at 0%, 14%, 50%, and 70%. The figure also shows the curve of demand power. According to the figure, the supply power asymptotic the demand power in proportion to the increase in the spread rate of the distributed power resources, and in the case of the spread rate of 70%, the result almost correspond with the demand power. In other words, this indicates that there is almost no supply interruption when the spread rate of the distributed power resources is 70%.

On the other hand, the supply power in the initial movement term decreasing with a spike like dip shows the same trend as the change over time in the number of power outages and power supply interruption due to earthquakes in the past (e.g., METI (2016) and Usuta (1995)). It should be noted, however, that these past earthquakes include damage to hydropower stations, substations, and high-voltage transmission towers that were not included in this analysis. If there is a distributed power resources in the distribution network, the supply power in the initial movement term has decrease without a spike like dip. This is probably because we did not consider that the distributed power resources are automatically disconnected from the grid when grid power is interrupted due to accidents or natural disasters. Although there is room for improvement in the modeling of distributed power resources, the results in Fig. 8 is a numerical representation of the effect of the spread of distributed power resources on the power supply resilience in the event of a disaster, and suggest the necessity of distributed power resources.

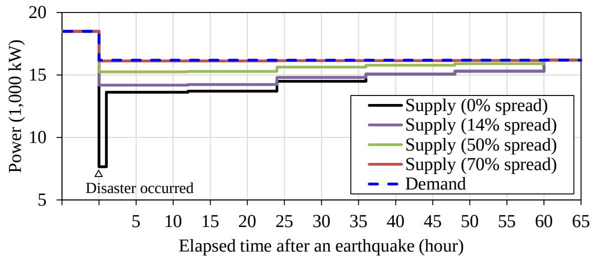


Figure 8. Power supply curve entire distribution network.

7. Conclusion

We evaluated the supply power to users considering the distributed power resources and users damage in this paper. In addition, demand/supply power of the whole system was obtained by summing up demand/supply power of users in the distribution network. In the evaluation of the temporary decreasing of the supply power just after the disaster, the probability function of the supply power at the circuit breaker was analytically obtained, and the power supply probability just after the disaster was evaluated using w_a, which is the power load shutdown threshold. Moreover, the connection probability of the distribution line was analytically obtained using BDD. In order to examine the applicability of the proposed methods, part of JST-CREST 126 Distribution Feeder Model was used to evaluate the supplied power. The results are summarized as follows.

1. The difference of power recovery to users is shown by the location in the distribution system.
2. In this analysis, although the damage to equipment for power generation and transmission was not included, the supply power in the initial movement term decreasing with a spike like dip shows the same trend as the change over time in the number of power outages and power supply interruption due to earthquakes in the past.
3. From the power supply curves of the entire power distribution network, calculated as the utilization rate κ_i =1.0, the supply power asymptotic the demand power in proportion to the increase in the spread rate of the distributed power resources.

Though it is necessary to bear in mind that these results depend on the analytical model, the necessity of the distributed power resources in aiming at the city which is resistant to the disaster is suggested. We also expect that the results of this paper will be useful for the appropriate response and behavior of citizens, such as evacuation planning and procurement of necessary goods.

As a future problem, it is necessary to reflect more realistic figures for distribution line restoration time and distributed power resources utilization rate κ_i. Also, in the evaluation of power load shutdown, it is necessary to consider not only voltage fluctuations but also frequency fluctuations, reverse power flow by distributed power resources, etc. In addition, it is necessary to consider that the distributed power resources are automatically disconnected from the grid when grid power is interrupted due to accidents or natural disasters.

References

Advanced Collaborative Research Organization for Smart Society (ACROSS). 2017. "JST-CREST 126 Distribution Feeder Model" is published. http://www.waseda.jp/across/en/news/2554/ (accessed Mar., 12, 2020)

Bryant,R. E. 1986. Graph-Based Algorithms for Boolean Function Manipulation. *IEEE Transactions on Computers*, Vol. C-35, No. 8, pp.677-691.

Matsumoto, T., Uetake, T., Shikama, Y. and Nakamura, T. 2019a. A Study on Seismic Resilience Evaluation Method of Electrical Distribution Network with Distributed Power Resources. *Journal of Japan Association for Earthquake Engineering*, Vol.19, No.7, pp.14-26. (In Japanese)

Matsumoto, T., Uetake, T., Shikama, Y. and Nakamura, T. 2019b. Title in Japanese. *Proceedings of the 14th Annual Meeting of Japan Association for Earthquake Engineering*, General Session O-4. (In Japanese)

Ministry of Economy, Trade and Industry (METI). 2016. Title in Japanese. https://www.meti.go.jp/shingikai/sankoshin/hoan_shohi/denryoku_anzen/denki_setsubi/pdf/009_02_00.pdf (In Japanese) (accessed Mar., 29, 2019)

Ministry of Economy, Trade and Industry (METI). 2019. Title in Japanese. https://www.meti.go.jp/shingikai/enecho/denryoku_gas/denryoku_gas/resilience_wg/pdf/007_03_00.pdf (In Japanese) (accessed Nov., 21, 2019)

Shinozuka, M. and H.H.M. Hwang. 1998. Seismic Performance of Electric Power Systems. *MCEER Monograph Number2*, pp.33-43.

Shoji, G. and Tabata, M. 2011. Evaluation of System Reliability of Lifeline Networks in Views of a Seismic Hazard. *The Twelfth East Asia Pacific Conference on Structural Engineering and Construction*, Procedia Engineering 14, Elsevier, pp.590-597.

Shumuta, Y. 2000. Basic Study of an Estimation Model for Restoration Time of High Voltage Distribution Line. *Journal of Social Safety Science*, No.2, pp.59-68. (In Japanese)

Tohma, J., Ohtomo, K. and Iwatate, T. 1991. Development of Seismic Reliability Analysis Method for Electric Power Supply Systems. *Central Research Institute of Electric Power Industry Research Report*, U90061, 35 p. (In Japanese)

Usuta, O. 1995. Title in Japanese. *The Journal of The Institute of Electrical Engineers of Japan*, Vol.115, Issue 9, pp.578-581. (In Japanese)