Cost-effective Analysis of Countermeasures for Solar Photovoltaic Systems in Distribution Networks

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***Abstract*— The total installed photovoltaic (PV) system capacity of Japan is currently increasing rapidly. However, the reverse power flow from PV systems causes voltage rise in distribution networks. In this paper, we analyze the cost-effectiveness of various voltage rise countermeasures, including increasing conductor sizes, applying VAR compensators, and upgrading voltage levels. We categorize these countermeasures into two types, namely: Measure 1, in which the existing 6-kilovolt line is used, and Measure 2, in which a 22-kilovolt line is partially used. We compare the cost-effectiveness of Measure 1 and Measure 2 in a distribution feeder, and then in a distribution substation area. The results show that in a concentrated PV scenario, Measure 2 is more cost-effective than Measure 1. In addition, the PV hosting capacity is larger for Measure 2 than it is for Measure 1.**

***Index Terms*—cost effectiveness, distribution network, economic evaluation, photovoltaics, voltage control.**

I. Introduction

The installed photovoltaic (PV) system capacity has been increasing rapidly in Japan due to the country's feed-in tariff scheme. However, reverse power flows from PV systems are causing distribution network voltages to both rise and deviate from the regulated upper limit. Many studies have been conducted on maintaining voltages under the regulated value by using the existing power system infrastructure. However, in order to improve both the future reliability and economic performances of distribution systems, we consider a completely new network structure. In a previous study, we investigated distribution network hosting capacity by assuming various improvements, including increasing conductor sizes, applying VAR compensators, and upgrading voltage levels [1][2]. The hosting capacity is defined as the maximum capacity of a PV system that is installed in a distribution network, which does not experience power quality deterioration [3].

In this paper, we analyze the cost-effectiveness of various voltage rise countermeasures, which are categorized into two main types: distribution networks in which the existing 6 kilovolt line is used (referred to as Measure 1), and distribution networks in which a 22-kilovolt line is partially used (referred to as Measure 2).

We assume two scenarios for the PV system locations. The first is a concentrated PV scenario in which a large-scale PV system is installed at the end of a feeder, whereas the second is a distributed PV scenario in which rooftop PVs are installed evenly across a feeder. Based on the result of hosting capacity [1], we evaluate the cost-effectiveness of Measures 1 and 2.

II. Economic Evaluation Methods

Voltage problems are local (e.g., feeder scale) problems, so we first evaluate cost-effectiveness on a feeder scale. However, for Measure 2, the use of a newly built 66/22 kilovolt transformer, which can provide multiple feeders, can be excessive. Therefore, we proceed to evaluate cost-effectiveness in a substation area in which effective use of an over-performing 66/22 kilovolt transformer can be made. Evaluation methods performed on both feeder and substation area scales are described in the following subsection.

A. Feeder Scale Evaluation

Fig. 1 shows a basic simulation model representing a typical rural distribution network in Japan. The nominal voltages in medium voltage (MV) and low voltage (LV) systems are 6.6 kilovolt and 100 volt, respectively. We assumed 17 concentrated PV scenarios and five distributed PV scenarios, detailed descriptions of which are provided in [1][2].

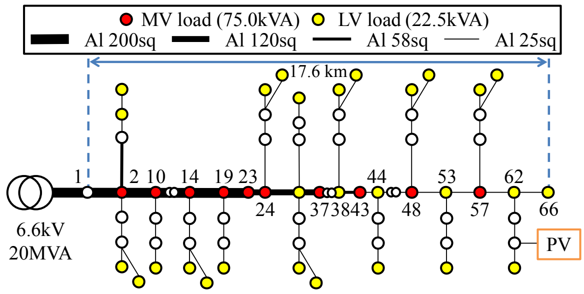

Figure 1. Basic simulation model for Case 1.

We evaluate cost-effectiveness based on annual cost, which consists of both initial and operational costs.

1) *Initial cost*: The initial cost consists of both the equipment and labor costs of construction. Table I shows the equipment list for the concentrated PV scenario, and Table II shows the equipment list for the distributed PV scenario.

TABLE I. EQUIPMENT LIST FOR CONCENTRATED PV SCENARIO.

(a) Measure 1

		Specifications	Quantity					Unit
			Case 2	Case 3	Case 4	Case 9	Case 10	
Electric line	6-kV overhead lines	AL 400 mm^2	0	0	0	17.6	19.1	km
		AL 200 mm^2	8	11.6	13.1	1.5	0	km
	6-kV sectioning switches	600 A	15	22	25	37	37	unit
	SVR	5000 kVA	1	2	2	2	2	unit

(b) Measure 2

		Specifications	Quantity			Unit
			Case 15	Case 16	Case 17	
Substation	66/22-kV transformers	20 MVA	1	1	1	unit
	22-kV feeders	600 A	1	1	1	feeder
Uni-substation	22/6-kV uni-substation	5000 kVA	3	3	3	unit
Electric line	22-kV overhead lines	AL 120 mm^2	13.1	13.1	13.1	km
	22-kV sectioning switches	400 A	2	2	2	unit
	6-kV overhead lines	AL 200 mm^2	0	3.62	0	km
		AL 400 mm^2	0	0	3.62	km
	6-kV sectioning switches	600 A	0	6	6	unit

TABLE II. EQUIPMENT LIST FOR DISTRIBUTED PV SCENARIO.

(a) Measure 1

		Specifications	Quantity		Unit
			Case 2	Case 3	
Electric line	6-kV overhead lines	AL 400 mm^2	11.6	0	km
		AL 200 mm^2	0	17.6	km
	6-kV sectioning switches	600 A	22	34	unit
	SVR	5000 kVA	2	2	unit

(b) Measure 2

		Specifications	Quantity		Unit
			Case 4	Case 5	
Substation	66/22-kV transformers	20 MVA	1	1	unit
	22-kV feeders	600 A	1	1	feeder
Uni-substation	22/6-kV uni-substation	3000 kVA	3	0	unit
		10000 kVA	0	3	unit
Electric line	22-kV overhead lines	AL 120 mm^2	13.1	0	km
		AL 400 mm^2	0	13.1	km
	22-kV sectioning switches	400 A	2	2	unit
	6-kV overhead lines	AL 400 mm^2	0	12.8	km
	6-kV sectioning switches	600 A	0	23	unit

In these tables, we have omitted the cases in which the STAtic synchronous COMpensator (STATCOM) installation numbers differed from those in other cases. For all of the cases, we assume both that the span lengths are 45 meter and that sectioning switches on the 6-kilovolt line are installed at 500 m intervals. Thus, the replacement numbers of both the sectioning switches and the Step Voltage Regulators (SVRs) depend on the distance when the conductor size increases. In addition, for Measure 2, we assume that the 6-kilovolt and 22 kilovolt lines are installed together on the same pole. We calculate the initial costs for each case shown in Tables I and II based on their publicly available references [4]–[8]. After that, we convert the initial cost into the annual cost using the annual expense ratio. The annual expense ratio of STATCOM is set to 0.079, which is calculated assuming both an 18 year lifetime [8] and a 4% interest rate [8]. Similarly, for the other power system equipment, the annual expense ratio is set to 0.058, which is calculated assuming 30 year lifetimes and 4 percent interest rates.

2) *Operational cost:* The operational cost consists of both the repair and distribution loss costs. These costs are calculated based on their differences from Case 1 (the basic case). The repair cost is calculated by multiplying the initial cost by the repair cost factor. The repair cost factor is set to increase from 1.45%–4.35% of the initial cost in proportion to the number of elapsed years [8][9]. After all of the repair costs incurred over all of the components' lifetimes are converted to current values, the annual costs are calculated using an interest rate of 4 percent. The distribution loss costs are calculated by multiplying each of the annual losses by the avoided energy cost, which is 10 yen per kilowatt-hour.

B. Substation Area Scale Evaluation

Fig. 2 shows the distribution substation model assumed in this study that contains three 10-MVA distribution transformers. Each transformer has three feeders, resulting in a total of nine distribution feeders. The method for evaluating the substation area is described as follows. First, a case that offers the maximum hosting capacity is selected, respectively, in Measure 1 and in Measure 2. Next, assuming that PVs are introduced into five feeders, F1–F5, the cost of the entire substation area is calculated based on the installed PV capacity. In this cost calculation, the capacities of distribution transformers are also taken into account. Therefore, when the installed PV capacity exceeds the distribution transformer capacity, the replacement cost of the distribution transformer is added to the cost.

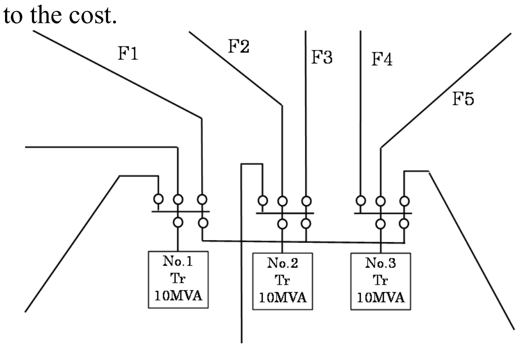

Figure 2. Distribution substation.

III. RESULTS AND DISCUSSION

A. Feeder Scale Evaluation

Fig. 3 shows the annual costs for the concentrated PV scenarios, and Fig. 4 shows the annual costs for the distributed PV scenarios. Because the purpose of this study is conducting a relative comparison of these types of cases, the vertical axis is set to a relative scale with a maximum annual cost of 1. The annual costs of Measure 2 (Cases 15, 16, and 17) are more than twice as high as that of the highest cost of Measure 1 (Case 14). However, these results consider only cost. Therefore, they are not sufficient to provide a comparison of cost-effectiveness between the cases. In order to consider effectiveness as well,

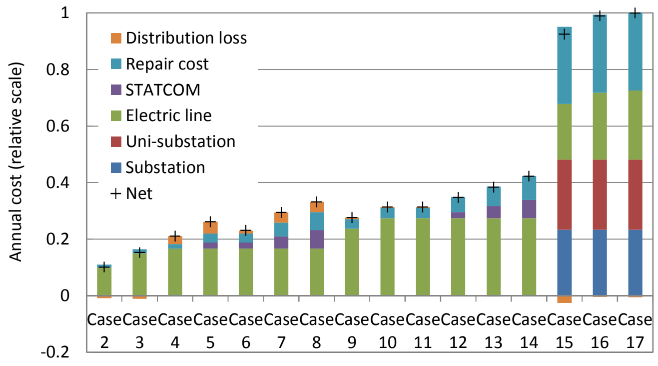

Figure 3. Annual costs for concentrated PV scenarios.

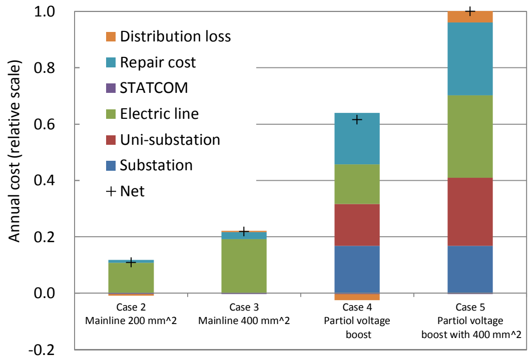

Figure 4. Annual costs for distributed PV scenarios.

TABLE III. Hosting Capacities and Annual Costs for Concentrated PV Scenarios.

Case	Partial voltage boost	Cross section of line (m²) Terminal	Trunk	Connection	STATCOM (kVA)	Hosting capacity (kW)	Annual cost (relative scale)
(1)						300	
(2)		200				600	0.10
(3)		200	200			600	0.15
(4)		200	200	200		1000	0.21
(5)		200	200	200	Variable(158)	4200	0.27
(6)		200	200	200	300	3200	0.24
(7)		200	200	200	600	3600	0.31
(8)		200	200	200	900	3100	0.36
(9)		400	400	200		4000	0.28
(10)		400	400	400		4000	0.31
(11)		400	400	400	Variable(0)	4000	0.31
(12)		400	400	400	300	3600	0.36
(13)		400	400	400	600	3300	0.40
(14)		400	400	400	900	2800	0.45
(15)	○					300	0.92
(16)	○	From uni-substation to PV: 200				2000	0.99
(17)	○	From uni-substation to PV: 400				5000	1.00

the hosting capacity is integrated into the cost results. Table III shows both the hosting capacities and the annual costs for the concentrated PV scenarios, and Table IV shows them for the distributed PV scenarios. Here, the cases in which the hosting capacity decreases despite the cost increasing are omitted, leaving only the cases framed in red. Based on the red-framed cases in Tables III and IV, graphs that illustrate the relationship between the annual cost and the hosting capacity are constructed, as shown in Figs. 5 and 6. The horizontal axis in each figure represents the ratio of the introduced PV capacity to the load. These figures indicate that the costs of Measure 2 are generally higher than those of Measure 1. This occurs because the capacities of both the newly built 66/22 kilovolt transformer and the 22-kilovolt line are excessively large compared to the hosting capacities, resulting in over-performance. Therefore, when the cost-effectiveness of the measures is compared for a distribution feeder, Measure 1 becomes overwhelmingly advantageous. Therefore, economic evaluation for a substation area is needed. When a large amount of PV capacity is installed in substation area and countermeasures are needed for more than one feeder, effective use of over-performing 22-kilovolt equipment can be made.

TABLE IV. Hosting Capacities and Annual Costs for Distributed PV Scenarios.

Case	Hosting capacity (kW)	Annual cost (relative scale)
(1) Basic	4000	
(2) Mainline 200 sq	4500	0.11
(3) Mainline 400 sq	7500	0.22
(4) Partial voltage boost	5000	0.62
(5) Partial voltage boost with 400 sq	24500	1.00

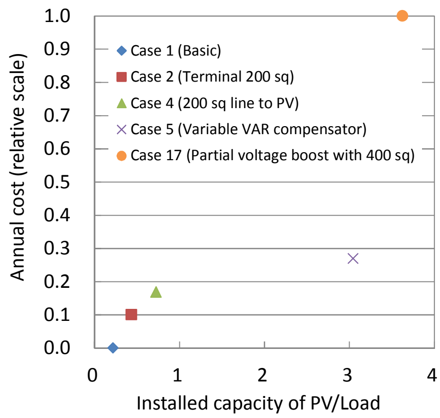

Figure. 5. Relationship between hosting capacities and the annual costs for concentrated PV scenarios with costs compared for a distribution feeder.

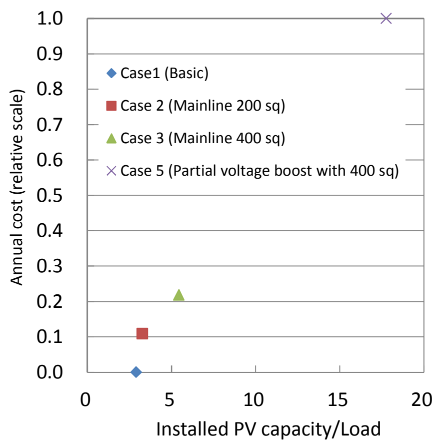

Figure 6. Relationships between hosting capacities and annual costs for distributed PV scenarios with costs compared for a distribution feeder.

TABLE V. INSTALLED PV CAPACITY AND NECESSARY COUNTERMEASURES FOR CONCENTRATED PV SCENARIOS.

(a) Enhanced 6-kV measures.

	Installed PV capacity (MW)	Countermeasures					Capacity of 6−kV transformers (MVA)		
		F1	F2	F3	F4	F5	No.1	No.2	No.3
①	4.2	1 line 200 sq					10	10	10
②	8.4	1 line 200 sq	1 line 200 sq				10	10	10
③	12.6	1 line 200 sq	1 line 200 sq	1 line 200 sq			10	10	10
④	16.8	1 line 200 sq	1 line 200 sq	1 line 200 sq	1 line 200 sq		10	10	10
⑤	21.0	1 line 200 sq	1 line 200 sq	1 line 200 sq	1 line 200 sq	1 line 200 sq	10	10	10
⑥	25.2	2 line 200 sq	1 line 200 sq	1 line 200 sq	1 line 200 sq	1 line 200 sq	10	10	10
⑦	29.4	2 line 200 sq	2 line 200 sq	1 line 200 sq	1 line 200 sq	1 line 200 sq	10	20	10
⑧	33.6	2 line 200 sq	2 line 200 sq	2 line 200 sq	1 line 200 sq	1 line 200 sq	10	20	10
⑨	37.8	2 line 200 sq	2 line 200 sq	2 line 200 sq	2 line 200 sq	1 line 200 sq	10	20	20
⑩	42.0	2 line 200 sq	2 line 200 sq	2 line 200 sq	2 line 200 sq	2 line 200 sq	10	20	20

(b) Partial voltage boost.

	Installed PV capacity (MW)	Countermeasures					Capacity of 22−kV transformers (MVA)		
		F1	F2	F3	F4	F5	No.1	No.2	No.3
①	21.6	Voltage boost					30	0	0
②	43.2	Voltage boost	Voltage boost				45	0	0
③	64.8	Voltage boost	Voltage boost	Voltage boost			45	30	0
④	86.4	Voltage boost	Voltage boost	Voltage boost	Voltage boost		45	45	0
⑤	108.0	Voltage boost	Voltage boost	Voltage boost	Voltage boost	Voltage boost	45	45	30

Table VI. LIST OF EQUIPMENT PER FEEDER FOR CONCENTRATED PV SCENARIOS.

(a) Enhanced 6-kV measures.

		Specifications	Quantity	unit
Substation	6-kV feeders	600 A	1	feeder
Electric line	6-kV overhead lines × 2-route	AL 200 mm^2	19.1	km
	6-kV sectioning switches	600 A	62	unit
	SVR	5000 kVA	5	unit
	STATCOM	300 kVA	1	unit

(b) Partial voltage boost.

		Specifications	Quantity	unit
Substation	22-kV feeders	600 A	1	feeder
Uni-substation	22/6-kV uni-substation	10000 kVA	3	unit
Electric line	22-kV overhead lines	AL 400 mm^2	13.1	km
	22-kV sectioning switches	600 A	2	unit
	6-kV overhead lines	AL 400 mm^2	9.21	km
	6-kV sectioning switches	600 A	15	unit

B. Cost Comparison for Substation Area

1) *Concentrated PV scenarios:* Economic evaluation for a distribution feeder reveals that the Measure 1 case with the maximum hosting capacity is Case 5 (the variable VAR compensator case) and that the Measure 2 case with the highest hosting capacity is Case 17 (the partial voltage boost with 400sq case). Although the hosting capacity of Case 5 is 4.2 megawatt, when the use of a double line is assumed, the hosting capacity can be regarded as 8.4 megawatt, or double the base capacity. In addition, when a double line is installed, the cost is calculated under the assumption that both lines are installed together on one pole. On the other hand, the hosting capacity of Case 17 is 5 megawatt due to the capacity constraint of the uni-substation at the end of the 22 kilovolt line. Hence, the uni-substations, both on the substation side and at the midpoint of 22 kilovolt line, are potential sites for additional installations of PVs. Assuming that PVs are uniformly installed in the three uni-substations, the resulting hosting capacity is calculated to be 21.6 megawatt . For Measure 2, the 21.6-MW hosting capacity is used. Table V shows the relationship between the installed PV capacity and the necessary countermeasures. In Table V(a), “voltage boost” indicates that the cost is calculated from the equipment list

shown in Table VI(a). Similarly, in Table V(b), "1 line 200sq" indicates that the cost is calculated from the equipment list shown in Table VI(b). Based on Table V, a graph is constructed showing the relationship between the hosting capacity and the annual cost in Fig. 7, which shows that Measure 2 is more cost-effective than Measure 1. In addition, the maximum installed PV capacity of Measure 2 is larger than that of Measure 1. Although this conclusion presumes the condition that Measure 2 makes optimal use of its 22 kilovolt equipment capacity, it shows that Measure 2 can be one of an effective countermeasure against voltage rise caused by reverse power flow from PV systems.

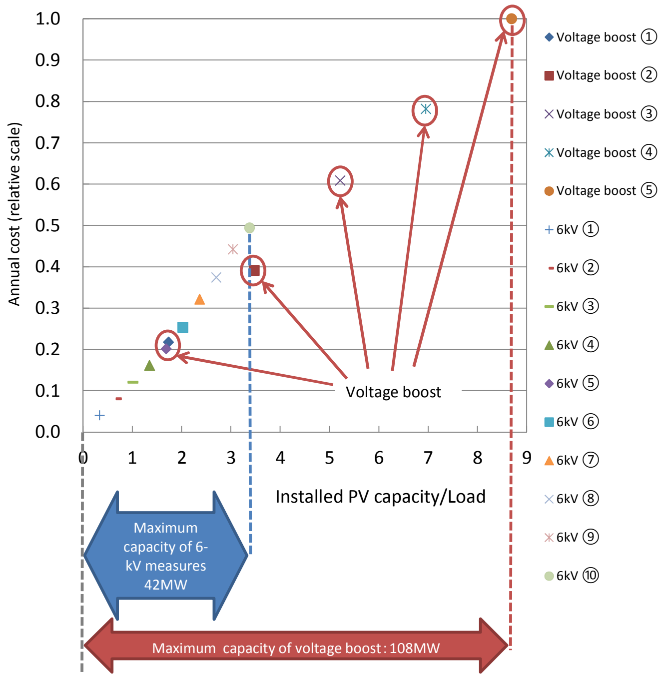

Figure 7. Relationship between hosting capacity and annual cost for concentrated PV scenarios with costs compared for substation area.

2) *Distributed PV scenario:* Economic evaluation for a distribution feeder reveals that the Measure 1 case with the highest hosting capacity is Case 3 (the mainline 400sq case) and that the Measure 2 case with the highest hosting capacity is Case 5 (the partial voltage boost with 400sq case). Although the hosting capacity of Case 3 is 7.5 megawatt, when the implementation of a double line is assumed, the hosting capacity can be regarded as 15 megawatt, or double the base capacity. In addition, when building a double line, the cost is calculated under the assumption that both lines are installed together on one pole. On the other hand, the hosting capacity of Case 5 is 24.5 megawatt because of the voltage constraint. Hence, there is no room for further PV installation, such as in the concentrated PV scenario. A graph of annual costs associated with various installed PV capacities is constructed and shown in Fig. 8. While Measure 1 is more cost-effective than Measure 2, the maximum installed PV capacity of Measure 2 is larger than that of Measure 1.

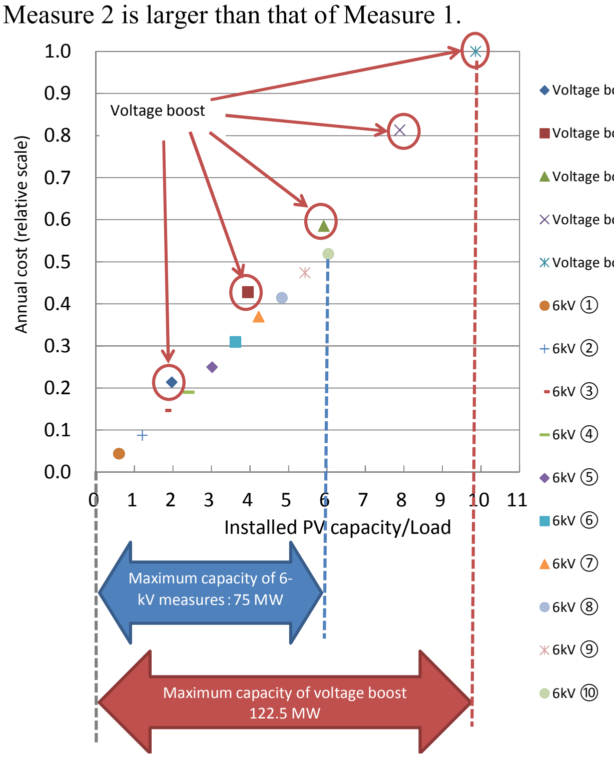

Figure 8. Relationship between hosting capacity and annual cost in distributed PV scenarios with costs compared for a substation area.

IV. Conclusions

Considering both concentrated and distributed PV scenarios, the cost-effectiveness Measures 1 and 2 were compared for both a distribution feeder and a distribution substation area. A summary of the results of an economic evaluation for one feeder is as follows:

- The annual costs of the Measure 2 cases are more than twice as high as the highest Measure 1 cost.
- The reason that the cost of Measure 2 eclipses that of Measure 1 is that the capacities of newly built 66/22 kilovolt transformer and 22 kilovolt line are excessively large compared to the hosting capacities.

A summary of the results of an economic evaluation for a substation area is as follows:

- For concentrated PV scenarios, Measure 2 is more cost-effective than Measure 1. In addition, the maximum installed PV capacity of the Measure 2 is larger than that of Measure 1.
- For distributed PV scenarios, Measure 1 is more cost-effective than Measure 2. However, the maximum installed PV capacity of Measure 2 is larger than that of Measure 1.

Acknowledgment

This research is supported by the NEDO (The New Energy and Industrial Technology Development Organization) project "Experimental Project of Advanced Power Grid with

Distributed Energy Sources, Feasibility Study on Development of Future Smart Grid".

REFERENCES

[1] D. Iioka, K. Miura, M. Machida, S. Kikuchi, M. Imanaka, J. Baba, M. Takagi, H. Asano, "Hosting Capacity of Large Scale PV Power Station in Future Distribution Networks", 2017 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)

[2] S. Kikuchi, M. Machida, M. Imanaka, J. Baba, K. Miura, D. Iioka, M. Tagagi, H. Asano, "Hosting Capacity Analysis of Many Distributed Photovoltaic Systems in Future Distribution Networks", 2017 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)

[3] J. Smith: EPRI Report No. 1026640, 2012.

[4] Construction Research Institute, "Construction prices," 2015(in Japanese).

[5] Zen-nichi publishing company, "Cost calculation Manual for electrical equipment work," 2015 (in Japanese).

[6] Electrical facility publishing, "Electrical facility materials," December 2015 (in Japanese).

[7] Ministry of Land, Infrastructure, Transport and Tourism, "Cost calculation Manual on civil engineering works for telecommunications," 2013 (in Japanese).

[8] New Energy and Industrial Technology Development Organization, "Experimental study on new power network system / Comprehensive survey on new power network technology," 2008 (in Japanese).

[9] Yasuji Sekine, "Distribution technology manual," 1991 (in Japanese).