Hosting Capacity of Large Scale PV Power Station in Future Distribution Networks

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***Abstract*— Configuration of distribution network which has a maximum hosting capacity of large scale PV power station has been investigated. The hosting capacity is expressed by the maximum capacity of PV power station interconnected to the distribution network without power quality deterioration such as violations of voltage constraint and thermal constraint of distribution feeder. Countermeasures such as replacement by a larger conductor size of distribution feeder, application of var compensator and upgrade of voltage level will improve the hosting capacity. The hosting capacity of 17-case distribution networks which are expressed by combination of the countermeasures was obtained by the power flow calculations. It was found that the upgrade of voltage level in part of the distribution network is useful for expanding the capacity of PV power station and reducing the distribution power loss.**

***Index Terms*—distribution system, photovoltaic penetration, power factor, STATCOM, voltage upgrading**

I. Introduction

Installation of photovoltaic (PV) system increases in the world and sometimes causes the power quality problem to the power network system. Since a feed-in tariff (FIT) scheme has been introduced in Japan, the installed capacity of PV system in 2014 reached 8,564 MW [1]. The capacity of large scale PV station whose capacity is over 1MW and roof top PV systems which are installed in residential area is growing steadily. On the other hand, fluctuation of output from PV system may result in the need of advanced control method for voltage regulation in the distribution network [2]-[6]. If the capacity of PV system increases dramatically, the present distribution network should be replaced by advanced one. Various projects of advanced distribution network with the penetration of PV system have been conducted [7]-[9].

From the viewpoint of power quality and power system security, the operation of the distribution network with the penetration of PV system requires the following constraints at least.

(a) Voltage constraint: The voltage in the distribution network will rise by the installation of PV systems. The voltage must be kept within the standard supply voltage. For example, IEC 60038 defines the standard supply voltage of 230 V system as 230 V±10% [10].

(b) Thermal constraint: Power flow through the distribution line will increase by the installation of PV system. The current must be smaller than the current rating of distribution line.

Usually, when the PV system is interconnected to the distribution line, the influence of the PV system on the distribution line will be investigated beforehand. If these constraints cannot be satisfied, the improvement of the present distribution line should be needed.

Several improvements of the distribution line have been applied. The replacement by a larger conductor size of distribution line is useful for mitigating the voltage and thermal problem. The var compensator such as a static var compensator (SVC) and a static synchronous compensator (STATCOM) can control its reactive power and contribute to the regulation of voltage. Although the upgrade of voltage level is a drastic countermeasure, the problem about voltage and current can be clear up. However, a comprehensive understanding of the optimum improvement is still lacking. One of the reasons is the variety of distribution network expressed by the number of customer, size of supply area, geographical characteristic, area characteristics such as shopping street, residential area, commerce and industry area and rural area, capacity of PV system, and so on. Relationship between the capacity of installed PV system and the required minimum replacement may remain unsolved.

The purpose of this work is to investigate the relationship between the hosting capacity and the various improvements such as increase in the conductor size, application of var compensator and upgrade of voltage level of distribution network. The hosting capacity is the maximum capacity of PV system without the power quality deterioration [11]. In this work, the hosting capacity of a large scale PV power station which is interconnected to the end of distribution feeder was found. Simulation model corresponds to a typical rural distribution network in Japan. The hosting capacity of roof top type PV system and the economic evaluation for the improvement will be presented by other works [12] [13].

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II. Simulation Model for Calculation of Hosting Capacity

A. *Expansion of PV Capacity in Distribution System*

Fig. 1 shows a basic simulation model which expresses a typical rural distribution network in Japan. The nominal voltage in medium voltage (MV) system and low voltage (LV) system are 6.6 kV and 100 V, respectively. The distribution network is composed of 3-phase overhead line, step voltage regulators, MV loads and LV loads. The line thickness shown in Fig. 1 corresponds to the conductor size of overhead line. The numbers written around the main feeder show the node number for the power flow calculation. Fig. 2 shows a detail low voltage network model which corresponds to the LV load node in Fig. 1. Although the PV system installed in the distribution networks is categorized into 2 patterns: a large scale PV power station and roof top PV systems, it is assumed that the large scale PV power station is installed at the end of feeder as shown in Fig. 1 in this work.

First method for expansion of PV capacity in the distribution network is improvement of conductor size of overhead line as shown in Fig. 3. Since the voltage drop of feeder decreases with the resistance component of impedance, the application of larger size conductor results in the expansion of PV capacity. The main line of basic model shown in Fig. 1 is replaced by the line with a larger conductor size as shown in Fig. 3(a). In Fig. 3(b), the connection line is also replaced.

Second method is the application of var compensator such as a static var compensator (SVC) and a static synchronous compensator (STATCOM) to the distribution network. The var compensator provides reactive power to the distribution network and controls the voltage. In our power flow calculation, the var compensator can be regarded as PQ node since the time step in the simulation is 1 hour which is much longer than the time constant of general var compensator. The location of var compensator is the same node as the large scale PV power station. The reactive power of var compensator is controlled by 2 methods: variable and constant control. The variable method controls the reactive power so as to regulate the voltage of the node of var compensator within 101±6 V. Under the constant method, the var compensator provides the constant reactive power.

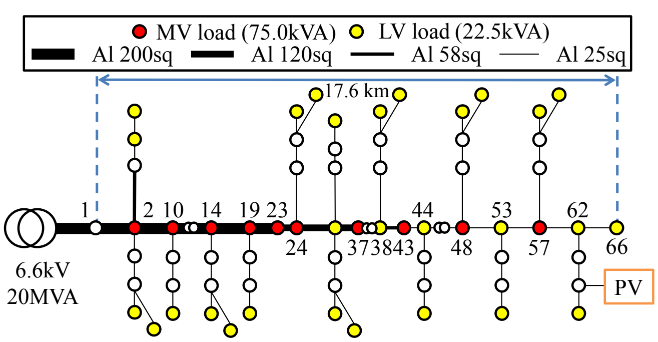


Figure 1. Basic simulation model: Case (1).

Third method is an upgrade of voltage level in part of distribution network. This method has a fine effect on the regulation of voltage since the voltage drop of distribution line decreases with the increase in the voltage level. On the other hand, the construction cost is higher than other methods as mentioned above. Fig. 4 shows the partial boost model in our simulation. The transformer in the substation is replaced by 22 kV one. A new 22 kV main line is installed at near the 6.6 kV line. The 6.6 kV main line is divided into three sections. The electric power is provided to the three sections via a 5 MW uni-substations which are connected to the 22 kV main line. The large-scale PV station is interconnected to the uni-substation located at the end of 22 kV main line. In Fig. 4(a), (b) and (c), the conductor size of line from the uni-subsation to the large scale PV station is 25 sq, 200 sq and 400 sq, respectively.

Various combinations of method as mentioned above are investigated. As a result, 17 cases summarized in TABLE I are obtained.

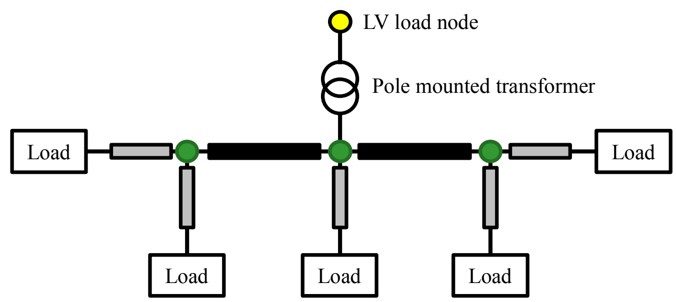


Figure 2. Low voltage distribution model.

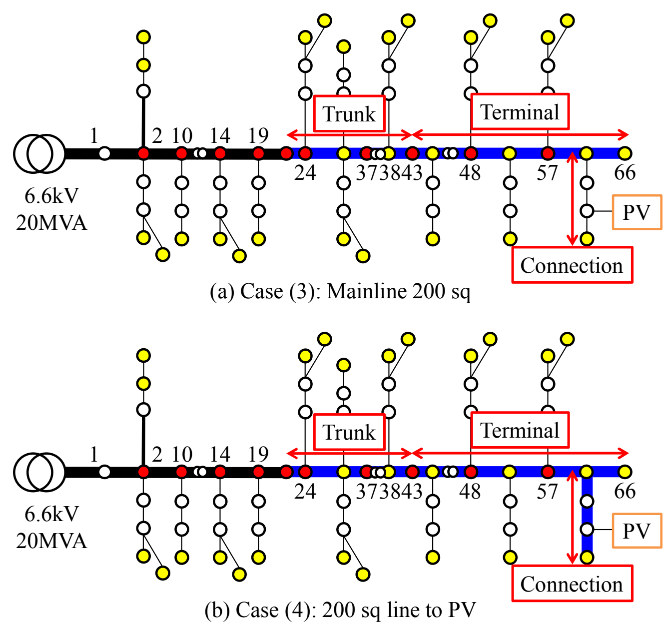
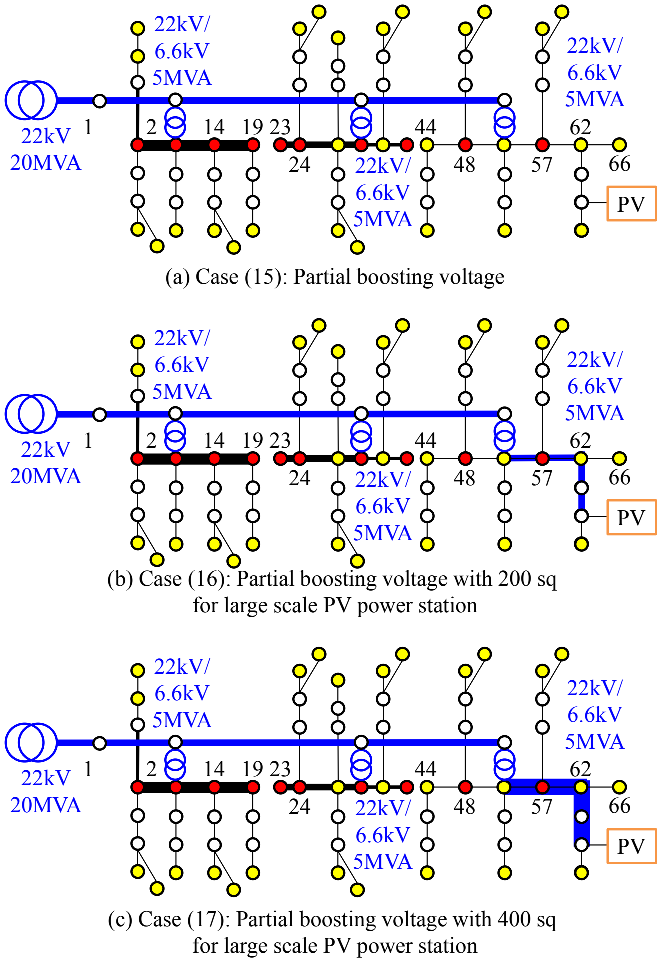


Figure 3. Improvement of conductor size for expansion of PV capacity.



(a) Case (15): Partial boosting voltage

(b) Case (16): Partial boosting voltage with 200 sq for large scale PV power station

(c) Case (17): Partial boosting voltage with 400 sq for large scale PV power station

Figure 4. Upgrade of voltage level in part of distribution network.

TABLE I. OUTLINE OF SOLUTIONS

Case	Partial boost	Conductor size: cross section of line [sq]			Var compensation [kVA]
		Terminal	Trunk	Connection	
(1)					
(2)		200			
(3)		200	200		
(4)		200	200	200	
(5)		200	200	200	Variable
(6)		200	200	200	300
(7)		200	200	200	600
(8)		200	200	200	900
(9)		400	400	200	
(10)		400	400	400	
(11)		400	400	400	Variable
(12)		400	400	400	300
(13)		400	400	400	600
(14)		400	400	400	900
(15)	✓				
(16)	✓	From uni-substation to PV : 200			
(17)	✓	From uni-substation to PV : 400			

B. Load and PV curve models

Fig. 5 shows a load curve model. The vertical axis shows the active power consumed by the MV and LV loads. The load curve is based on the measurement of active power in the 6.6 kV substation in Japan. The base power is the capacity of each MV and LV loads.

Fig. 6 shows a power curve of PV system. The active power is calculated by the measurement of solar irradiance. The base power is the capacity of large scale PV power station.

III. HOSTING CAPACITY

A. Example of simulation results

We have carried out 1 day (24 hours) power flow calculation for 17 cases shown in Table I so as to determine the hosting capacity of distribution network. Fig. 7 and 8 show one of the results of our simulations. Fig. 7 gives voltage profiles of distribution networks at 12 pm. The voltages of base case (1) and partial boost case (16) increase with the 1 MW PV station. Especially, the voltage of the nodes around the PV station increases clearly. Fig. 8 shows the time variation in the voltage of low voltage network at node 65 which is near by node of PV station. It was found that the application of partial boost to the distribution network has an effect on the mitigation of voltage rise.

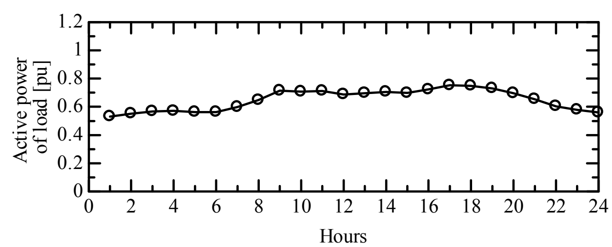


Figure 5. Loar curve model of MV and LV loads.

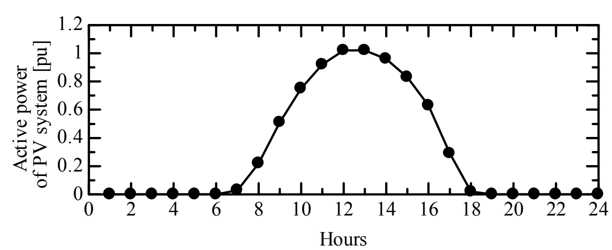


Figure 6. Time variation in output of large scale PV power station.

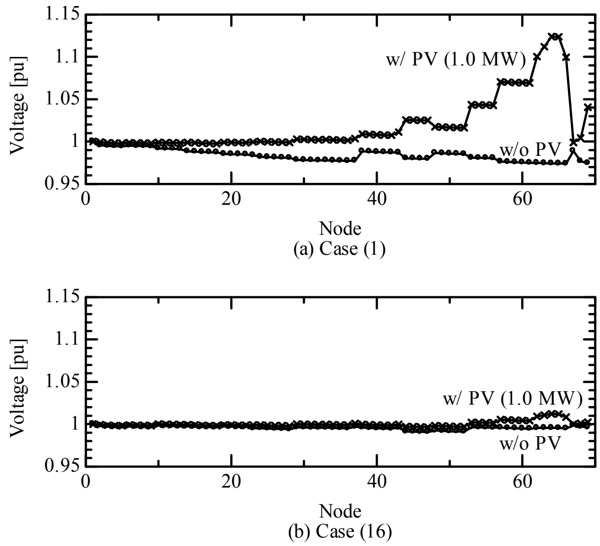


Figure 7. Voltage profiles at 12 pm.

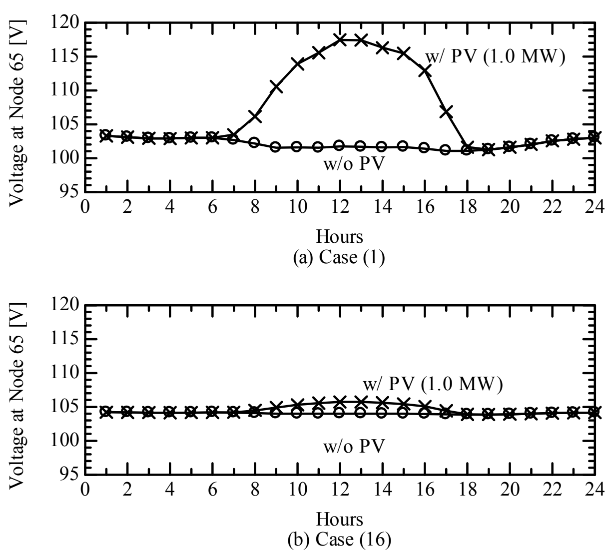


Figure 8. Time variation in voltage of low voltage network at node 65.

B. Definition of hosting capacity

We have defined the hosting capacity of large scale PV power station as the maximum capacity which satisfies the following three criterion from the viewpoint of power quality and power security in our investigation.

(a) Voltage constraint: Voltages of all low-voltage network loads must be kept within 101±6V.

(b) Thermal constraint: Current of all branches must be smaller than the current rating which depends on the conductor size of distribution line.

(c) Voltage stability: Voltage instability due to the reverse power flow from PV system beyond the capability of distribution network must be prevented.

Fig. 9 explains the relationship between the voltage constraint and capacity of large scale PV station. Maximum voltage of distribution network cases shown in Table I can be selected from the voltage of all low-voltage network loads obtained by 24-hour power flow calculations. Fig. 9 shows that the selected maximum voltage increases with the capacity of PV station. It was found that the maximum PV capacity which satisfies the voltage criterion are 0.3 MW and 1.0 MW for case (1) and (4), respectively. The improvement of conductor size expands the hosting capacity from the viewpoint of voltage constraint.

Fig. 10 also show the maximum voltage as a function of capacity of PV station. The horizontal range increases compared with Fig. 9. The maximum voltage for case (4) increases abruptly up to 1.5 MW, above which it increases gradually up to 4.0 MW. If the capacity of PV station is over 4.1 MW, the power flow calculation does not converge. The closer investigation into the cause of non-convergence leads to a conclusion that the non-convergence of power flow calculation may be equal to the voltage reduction phenomena related to the voltage instability problem. First, the increase in the reactive power from substation to main feeder have been confirmed when the capacity of PV station is equal to 4.0 MW. This is because the reverse power flow from PV station to the substation increases drastically. As a result, the apparent power floes in the distribution network beyond the distribution network capability which depends on the impedance and network configuration. Finally, the power flow calculation cannot converge owing to the reverse power flow from the PV station.

Although the phenomenon of case (6) is similar to the case (4) from the view point of non-convergence shown in Fig. 10, the maximum voltage of the case (6) is kept within 101±6V. That's why, non-convergence problem in our investigation has been distinguished from the voltage constraint and defined as one of the criterions which determines the hosting capacity.

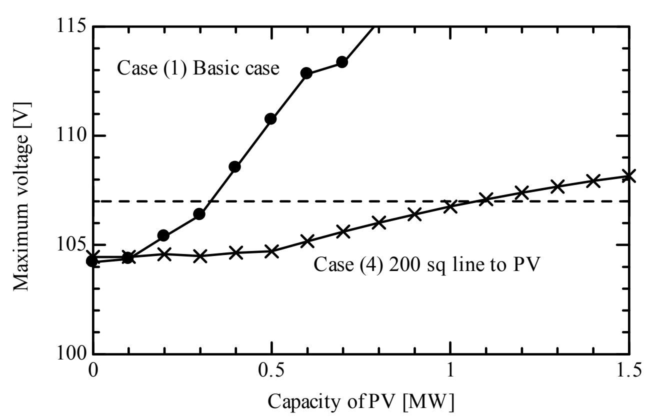


Figure 9. Maximum voltage as a function of capacity of PV.

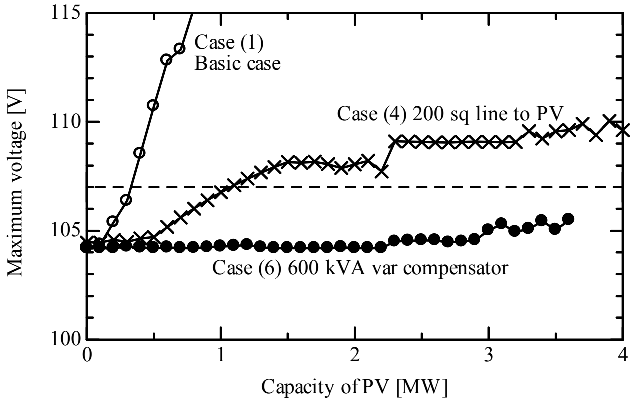


Figure 10. Non-convergence of power flow calculation.

TABLE II. HOSTING CAPACITY FOR DISTRIBUTION NETWORK WITH LARGE SCALE PV STATION

Case	Hosting capacity [MW]	Constraint
(1)	0.3	Voltage
(2)	0.6	Voltage
(3)	0.6	Voltage
(4)	1.0	Voltage
(5)	4.2	Current
(6)	3.2	Voltage
(7)	3.6	Stability
(8)	3.1	Stability
(9)	4.0	Stability
(10)	4.0	Stability
(11)	4.0	Stability
(12)	3.6	Voltage
(13)	3.3	Stability
(14)	2.8	Stability
(15)	0.3	Voltage
(16)	2.0	Stability
(17)	5.0	

C. *Hosting capacity*

Table II summarizes the determined hosting capacity for 17 cases shown in Table I. The power factor of PV station is 1.0. The upper limit of capacity of PV station is 5.0 MW. Case (17) composed of partial boost network with the improvement of conductor size is only one whose hosting capacity reaches to the upper limit of the investigation. The hosting capacity of case (17) is 16.7 times larger than that of basic case (1). Without the partial boost case, the hosting capacity of the case (5) which installs the variable var compensator is the largest and 14 times larger than that of the basic case (1).

The influence of power factor of PV station on the hosting capacity has been investigated since the regulation of power factor may contribute to the reduction of rising voltage due to the PV station. Fig. 11 shows the relationship between the hosting capacity and power factor of PV station. Although the hosting capacity is improved by the regulation of power factor for some cases, the hosting capacity of case (4), (10), (16) and (17) decreases with the power factor over the most part range. This is because the increase in the reactive power from the substation due to the regulation of power factor contributes to the phenomenon of voltage instability mentioned section III.B.

The proposed distribution network shown in Table I has been evaluated from a loss perspective. Fig. 12 shows the annual power loss and hosting capacity of each cases. The power factor of PV system is 1.0. The blue and red column charts show the annual loss without and with PV station, respectively. For example of basic case (1), the annual loss decreases by the installation of PV station whose capacity is equal to the hosting capacity shown in Table II. The annual loss of case (17) with PV station is 0.86 times smaller than that of basic case (1) with PV station. This finding indicates the validity of partial boost method from the viewpoint of both the expansion of hosting capacity and the reduction of power loss. On the other hand, although the hosting capacity of case (5) is a relatively large magnitude, the annual power loss is the largest among the whole cases. The var compensator is useful for expanding the hosting capacity while that contributes to the increases in the power loss.

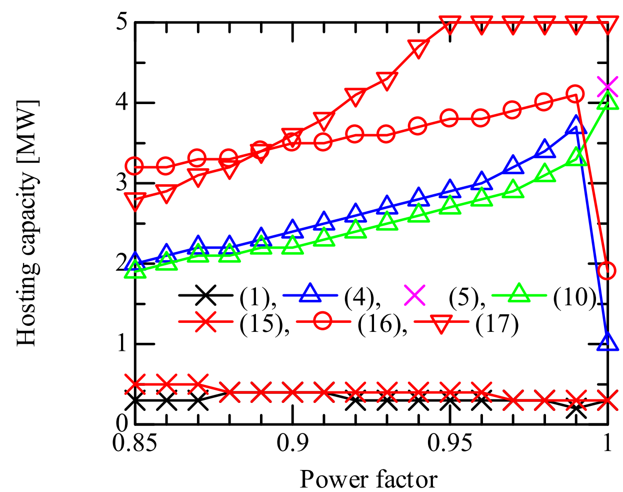


Figure 11. Hosting capacity as a function of large scale PV power station.

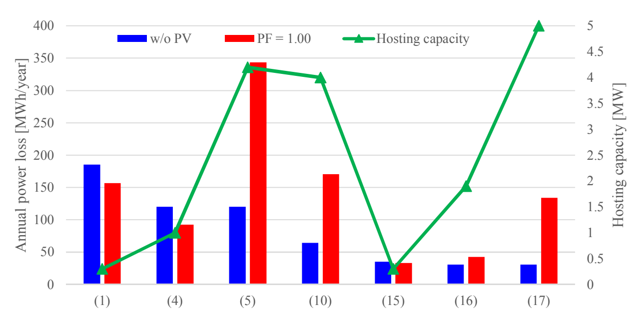


Figure 12. Annula power loss.

IV. CONCLUTION

The hosting capacity of large scale PV power station for 17-case distribution networks which are expressed by combination of replacement by a larger conductor size of distribution feeder, application of var compensator and upgrade of voltage level was obtained by the power flow calculations. It was found that the upgrade of voltage level in part of the distribution network is useful for expanding the capacity of PV power station and reducing the distribution power loss. Without the upgrade of voltage level, the hosting capacity for the case of the var compensator is the largest while the distribution line loss is also largest.

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