Hosting Capacity Analysis of Many Distributed Photovoltaic Systems in Future Distribution Networks

Shota Kikuchi, Mai Machida, Jun Tamura, Masaki Imanaka, Jumpei Baba
The University of Tokyo
Tokyo, Japan
s_kikuchi@asc.t.u-tokyo.ac.jp

Daisuke Iioka, Koya Miura
Tohoku University
Sendai, Japan

Masaaki Takagi, Hiroshi Asano
CRIEPI
Tokyo, Japan

***Abstract*—Installation of photovoltaic (PV) systems need to be accelerated much for the mitigation of climate change. This paper targets on huge penetration of distributed PV systems into feeders, of which the total PV capacity is several or several ten times of the existing load. Three kinds of countermeasures, improvement of conductor sizes, partial boosting voltage, smart invertors, and their combinations were analyzed with the criteria of the PV hosting capacity. Simulation results suggested that, without PV reactive power control, the increase of the hosting capacity for improvement of conductor size and boosting voltage were limited because of voltage rise in low voltage networks. The combination of the three kinds of countermeasures were necessary for the huge penetration of distributed PV systems. In such cases, the voltage needed to drop in the middle voltage networks in order to compensate the voltage rise in low voltage networks.**

***Index Terms*—distribution network, photovoltaic generation, smart inverter, voltage upgrading.**

I. INTRODUCTION

In the past decade, installation of photovoltaic (PV) systems has been increasing dramatically in the world, from 6 GW to 303 GW in 2016, which generated 1.5 percent of the world electricity [1]. PV systems have spread not only in OECD countries, but also in BRICS or in developing countries. Many of the future world energy-mix scenarios show that PV installation need to be accelerated much in the next few decades [2] [3]. Most of the PV systems are connected to the distribution networks. Hence, it is very important to resolve the challenges of PV connection to the distribution networks such as over-voltage, over-current and protection problems. Many experiences and researches have been obtained in many countries[4]. Many kinds of countermeasures have been discussed, especially for over-voltage problems.

One of the key-questions of the PV installation is that "How much PV capacity can be installed in a certain feeder?" In order to answer the question with transparency, the concept of hosting capacity is developed by the EU-DEEP project, which started in 2004 [5], and when PV systems installed dramatically in Italy, AEEG evaluated the hosting capacity of feeders of middle voltage and low voltage [4]. In 2010, EPRI (Electric Power Research Institute) initiated a distributed PV Feeder Analysis project, and hosting capacity has been the key issue of the project [6] [7]. In this project, hosting capacity has defined as "the amount of PV that can be accommodated without impacting power quality or reliability under existing control and infrastructure configurations" [7].

In Japan, voltage problem happens seriously because most of the medium voltage of the distribution networks are 6.6 kV, which is lower than that of many of the countries, and because the voltage restriction of the low voltage is severe (from 95 V to 107 V),. but some of the distribution networks already uses 22 kV or 33 kV, mainly for large loads, but some of them for PV penetration. In future huge PV penetration, boosting voltage for 22 kV or 33 kV partially may be an important option for the mitigation of challenges of PV connection.

This paper focuses on the analysis of the hosting capacity of the distribution feeders with huge penetration of distributed PV systems, which means that the total PV capacity is several or several-ten times of the existing load. Such huge installation would be occurred in future energy mix because the PVs will not be distributed equally This paper compares the countermeasures with 6.6 kV and the countermeasures with 22 kV with criteria of hosting capacity. The authors have analyzed the hosting capacity without reactive power control[8] [9]. This paper focuses on the power factor control of the smart invertors of PV systems and evaluate the effect of combination of smart invertors and the grid reinforcement.

II. SIMULATION MODEL AND METHODOLOGY

A. Countermeasures for PV Over-Voltage

In order to mitigate the over-voltage caused by PV systems, many kinds of countermeasures have been done and researched. Table 1 shows a summary of major countermeasures for PV over-voltage problems in four types [9]. The first type is to change the impedance of the distribution networks such as the grid reinforcement like replacing heavy lines or boosting voltage class of feeders. Though these options are expensive, they can mitigate both voltage and thermal restrictions dramatically. This paper mainly focuses on this type. The

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second type is to change the ratio of transformation like Static Var Regulators (SVRs). The third type is to control reactive power either by additional equipment or PV reactive power control. These two types are familiar to mitigate the PV over-voltage problems. The fourth type is to control active power by Battery Energy Storage Systems (BESSs), demand response or PV curtailment. The control of PV is focused now and smart inverters which can control PV reactive and active power are developing. California Public Utilities Commission has made recommendations for smart inverters [10].

This paper evaluates the effect of the grid replacing heavy lines, partial boosting voltage, PV reactive power control, and their combinations on increasing hosting capacity for distributed PV systems. The active power control is an important option, but isn't focused in this paper.

TABLE I. COUNTERMEASURES FOR VOLTAGE VIOLATION

Types	Countermeasures		
	Grid Reinforcement	***Additional Equipment***	***PV control***
Impedance of distribution network	Replace heavy lines, Multi lines, Boosting voltage	Loop flow controller	
Ratio of transformation	OLTC*, Taps of pole transformer	SVR	
Reactive power		SC*, SR*, SVC, STATCOM, Load reactive power control	Power factor, Reactive power
Active power		BESS, Demand Response	Curtail-ment

*OLTC: On Load Tap Changers, SC: Shunt Capacitor, SR: Shunt Reactor.

B. *Topologies of Middle Voltage Distribution Networks*

1) Basic Topology: Fig. 1 shows a basic topology which expresses a typical rural network in Japan. In this model, any countermeasures for PV over-voltage have not been done. The trunk line length is 17.6 km, and the nominal voltage in middle 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 lines, three step voltage regulators (SVRs), MV loads of 75 kW and LV loads of 22.5 kW. The line thickness shown in Fig.1 represents the conductor size of overhead lines. The numbers written near the main feeder mean node numbers. It is assumed that roof top PV systems are installed at each MV load and LV load nodes in this work.

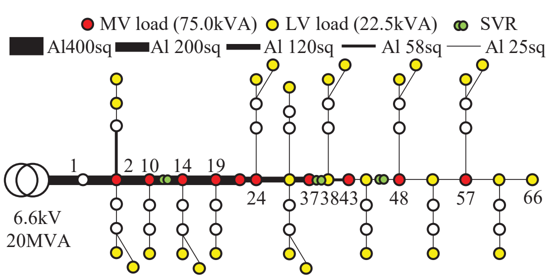

Figure 1. Topology (1): Basic Topology.

2) Improvement of conductor size: Fig. 2 and 3 show the topologies with improvement of conductor sizes of the mainlines, of which the conductor sizes of the mainline are 200sq and 400sq, respectively. Since the voltage drop of the feeder decreases with the resistance component of impedance, the introduction of larger size conductor increases PV capacity.

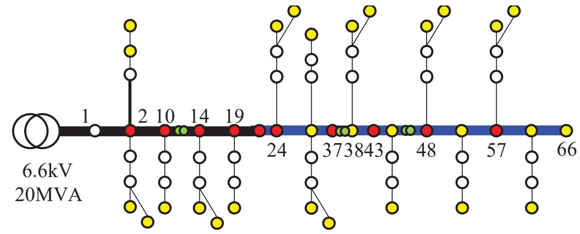

Figure 2. Topology (2): Mainline 200sq.

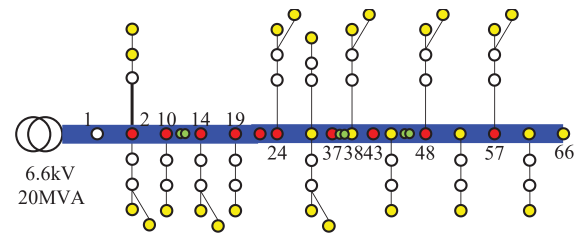

Figure 3. Topology (3): Mainline 400sq.

3) Partial Boosting Voltage: Fig. 4 and 5 show topologies with partial boosting voltage, which means upgrades of voltage level in part of distribution network*s*. These topologies are highly effective on the regulation of voltage since the voltage drop of distribution line decreases when the voltage level is increased. On the other hand, the construction cost of the new line is higher than other countermeasures. Fig. 4 shows the partial boost model*,* of which the transformer at the distribution substation is changed to 66 kV/22 kV. The conventional 6.6 kV mainline is divided into three sections, and *is* connected to the 22 kV line through uni-substations. Fig. 5 shows the topology of combination of partial boosting voltage and improvement of conductor size.

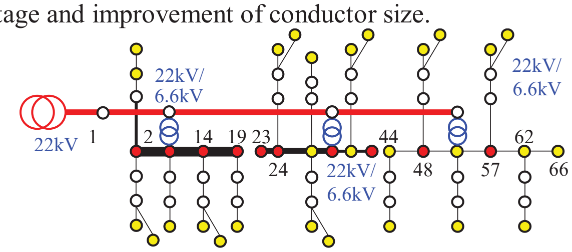

Figure 4. Topology (4): Patial boosting voltage.

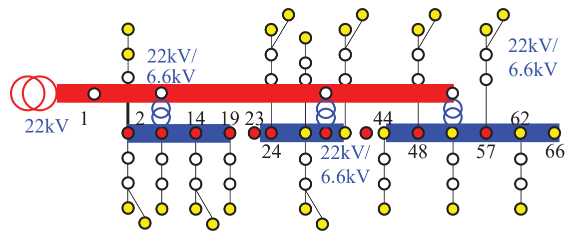

Figure 5. Topology (5): Partial boosting voltage 400sq for distributed PV.

C. Topology of Low Voltage Distribution Network

Fig. 6 shows the topology of low voltage network which is equivalent to a LV node in previously mentioned topologies. In this model, the number of loads is 5 in each phase. The breakdown is that 2 loads are located directly below the pole mounted transformer, and 2 sets of 4 loads are connected 30 m away from the transformer. Assuming that the model of distribution lines is the outdoor weatherproof polyvinyl chloride insulated wire.

When calculating power flow of LV nodes, the voltage of primary side of the transformer is set at 1.00 p.u., and loads and PV are regarded as constant power sources of which power factors are 1.00. The results of power flow calculations of LV nodes are multiplied by those of MV nodes, and the results of multiplication are used to discuss voltage constraints.

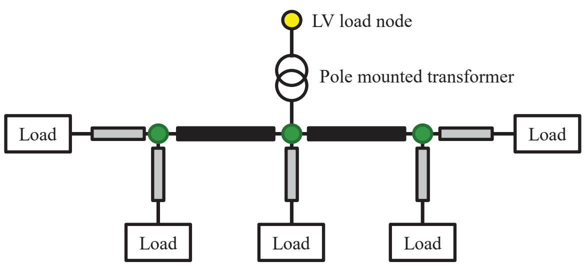

Figure 6. Topology of Low Voltage Network.

D. Other assumptions

The output of PV is assumed as the rated capacity of the panel, but it can also output the reactive power because the rated power of the power conditioning system is larger. The power factor can be changed from 1.00 to 0.85. The load of MV node and LV node at 12 is 51.6 kW and 15.5 kW, respectively. The installed capacity of PV is increased proportionally to the load.

E. Control Strategies of PV Reactive Power

1) No control (power factor = 1.00): Power factor of PV is fixed at 1.00.

2) Constant power factor: Power factor of PV is set to a fixed value which is changed from 1.00 to 0.85 dependent on each simulation.

3) Distributed control: When the voltage of a LV node or a MV node is over 107 V, power factor of PV in the one is dropped. In this strategy, each node is controlled independently.

F. Criteria of Hosting Capacity

The criteria of hosting capacity are different between studies. For example, the criteria of the study of AEEG are line transfer capacity and fast and slow voltage deviation [4], while the EPRI's criteria include many criteria related to protection and tap operations [6]. In this paper, the hosting capacity was defined simply as the maximum capacity which satisfied the following three criteria.

1) Voltage constraint: Voltages of all low-voltage network nodes must be kept between 95V and 107V.

2) Termal constraint: Current of all branches must be smaller than their current rating which depends on conductor sizes of distribution lines.

3) Voltage stability: Voltage instability due to the reverse power flow from PV systems beyond the capacity of distribution networks must be prevented.

The voltage stability risks caused by the reverse power flow of PV were advocated by the papers [11], and studied with this feeder model [9]. In reality, the voltage stability risk may depend on the transient characteristics of the PV systems.

In constant power flow cases, the hosting capacity has been calculated 16 patterns in each case, with the power factor from 1.00, 0.99, 0.98… to 0.85. The hosting capacity of each topology was defined as the average of the top three results.

G. Loss Calculation of MV lines

The reinforcement of the feeders can also reduce losses. In order to estimate the effect, annual losses were calculated in each case. The calculation method was as follows.

1) Weather of the day are classified into four weather groups; clear and sunny, fine, cloudy and rainy.

2) Assume the number of the days and output percentages of each groups shown in table II.

3) Calculate the PV output of each hour by the output percentages as shown in fig. 7 and culculate loss by power flow calculation.

TABLE II. DAYS AND OUTPUT PERCENTAGES OF WEATHER GROUPS

	Number of the day per year	Output Percentage [%]
Clear and sunny	52.7	80
Fine	190.8	50
Cloudy	61.1	20
rainy	60.6	10

*Each number of the day is assumed by reference to the meteorological data of Miyazaki.

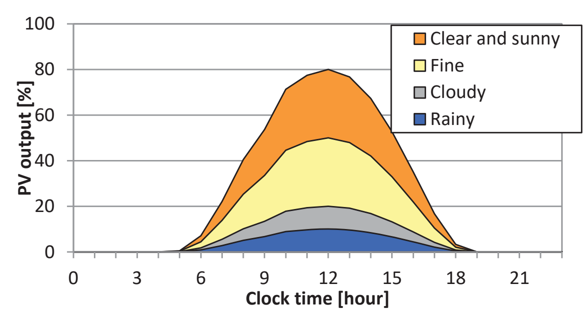

Figure 7. PV output curves in each weather group.

III. RESULTS AND DISCUSSION

A. Hosting Capacity

TABLE III shows the hosting capacity of each topology and each power factor control strategy. When the power factor weren't be controlled, the hosting capacity was only from 1.2 MW to 3.2 MW. Even if the voltage rise of the MV was mitigated largely by the partial boosting voltage, the voltage rise of LV wasn't mitigated, hence the hosting capacity didn't increased dramatically[9].

On the other hand, when the power factor was controlled appropriately, the hosting capacity increased largely in each topology. Even with the basic topology, the hosting capacity increased to 2.3 MW when the constant power factor, and 4.0 MW under the distributed control. Except for the topology (4), the hosting capacity with the distributed control was larger than that of the constant power factor. The reason was that when the distributed control, only nodes of which the voltage mitigation was needed output the reactive power, hence the total reactive power was smaller than that with constant power factor, and the apparent power was also smaller. On the contrary, in (4), as the voltage rise of thin mainline in the end of the feeder was suppressed more effectively with constant power factor than with distributed control because not only over voltage nodes but also the other nodes were controlled.

TABLE III. COUNTERMEASURES FOR VOLTAGE VIOLATION

No.	No Control		Constant P. F.*		Distributed Control	
	HC[MW]*	*Const.*	*HC[MW]*	*Const.*	*HC[MW]*	*Const.*
1	1.2	Vu**	2.3	Vu	4.0	I
2	1.5	Vu	4.1	Vu, I**	4.5	I
3	2.0	Vu	4.9	Vl**	7.5	I
4	2.0	Vu	6.2	Vu, I	5.0	Vu
5	3.2	Vu	22.4	Vl, I	24.5	I

*HC: Hosting Capacity, P.F.: Power Factor.

**Vu: Voltage upper limit, Vl: Voltage lower limit, I: maximum current limit.

B. *Analysis of Voltage Deviation*

Fig. 8 shows the voltage deviation breakdown of each topology with distributed control when the PV was installed in the amount of each hosting capacity. When power factor was controlled, the voltage decreased. Component under lateral axis means voltage reduction, and the sum of components was "total change". Total change of each topology was under 0.019 p.u. because of the voltage upper limit. In order not to exceed voltage upper limit in LV network, the voltage reduced in MV network with distributed control. In partial boosting voltage models, voltage drops in uni-substation were large, and, as a result, the hosting capacity increased.

Fig. 9 shows the voltages of MV nodes which don't have LV loads and the voltage of LV nodes. The voltages of MV node without LV nodes were lower than those of LV nodes in whole because of voltage rises caused by reverse power flow in LV nodes. Some of the LV node voltages were near the upper limit.

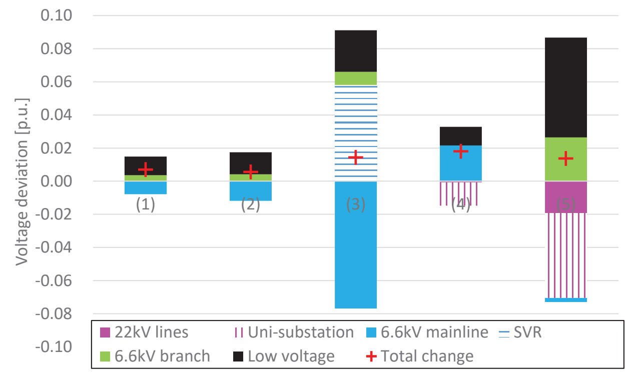

Figure 8. Voltage deviation by each component *(distributed control)*

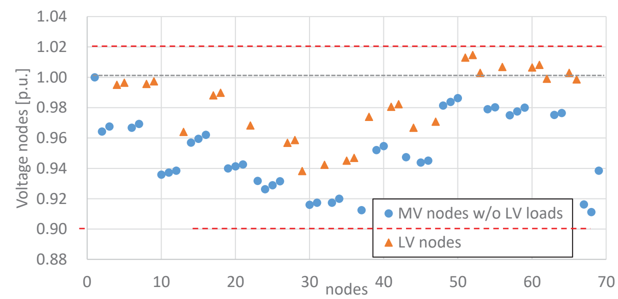

Figure 9. Voltage Distribution with and without LV Loads. *(Mainline 400sq, PV 7.5MW, distributed control.)*

C. *Maximum Voltage Node in Low Voltage Networks*

Fig. 10 and 11 show the relationship between the output of PV and maximum voltages in LV networks with constant power factor and with distributed control, respectively.The results are shown in the graphs. However, the behavior of topology (2) is similar to that of (3). Maximum voltages in topology (1) and (3) fluctuated largely because of the mutual interference of operation of SVR and the power factor control. Since there was nonlinear relationship between PV output and maximum voltages, transitions of maximum voltage were not estimated easily. In Fig 10, the voltage in topology (4) rose straight and reached upper limit. In (5), the voltage rose like (4). However, the voltage didn't reach upper limit and decreased after 13.3 MW because of the non-linearlity of the reactive power sensitivity to the voltage, which became obvious when the reactive power flow was very large. Hence, the hosting capacity of (5) increased very large. Compared to Fig 10, the voltage of each topology fluctuated in Fig 11 because power factor was controlled in each node with distributed control.

D. *Annual Power Losses of MV Power Flow*

Fig. 12 shows calculation results of annual power losses caused by MV power flows with and without PV in each topology. Without PV, the grid reinforcement options reduced annual losses dramatically, especially in (4) and (5), which are boosting voltage topologies. When PV was installed to their hosting capacity, the loss was reduced in topology (1), because of the reduction of the power flow. But, in other topologies, the losses became larger than those without PV because of the large reverse power flow, especially in case (3) and (5), whose hosting capacities are restricted by the current limitations. However, as PV generation was also very large in these topologies, the percentage of loss in PV generation is much lower than that in topology (1). These results confirmed that the grid reinforcement options with suitable PV power factor control can increase the hosting capacity with reducing the percentage of the losses.

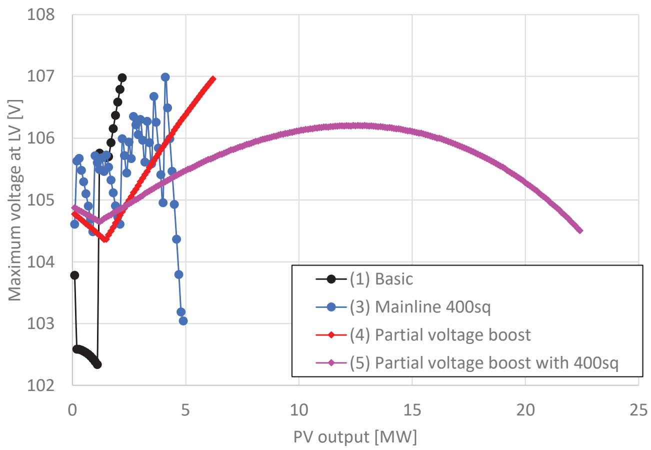

Figure 10. Transitions of Maximum Voltage at LV. *(constant P. F.)*

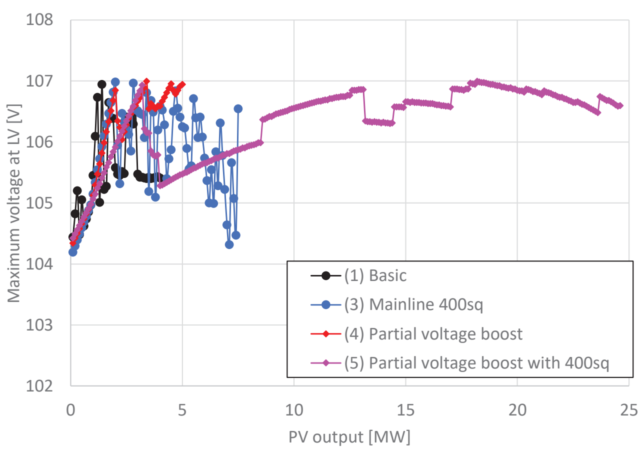

Figure 11. Transitions of Maximum Voltage at LV. *(distributed control)*

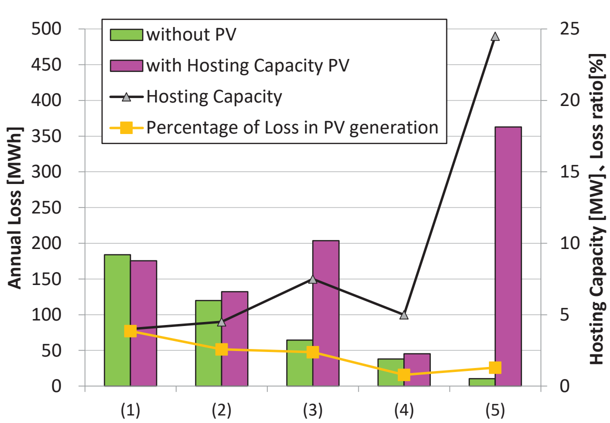

Figure 12. Loss without and with Hosting Capacity PV. *(distributed control)*

IV. CONCULUSIONS

This paper analyzed the hosting capacity of distribution feeders with huge penetration of distributed PV systems. It is confirmed that the combination of improvement of conductor sizes, partial boosting voltage and power factor control could increase the hosting capacity of PV dramatically. Through the voltage analysis, the distributed control of the PV reactive power makes the hosting capacity increase largely in many of the topology because the control can mitigate both the MV and LV voltage rise efficiently. When installation of PV in LV network is increasing, it is confirmed that the voltage in MV networks decreases largely in order to compensate the voltage rise in LV networks. The grid reinforcement options can also reduce the loss of distribution lines dramatically.

Future work includes the analysis with the stochastic methods of the hosting capacity and the analysis with different feeders and loads.

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