VOLTAGE-DROP PHENOMENON AND COUNTERMEASURES IN DISTRIBUTION GRIDS WITH LARGE AMOUNT OF PHOTOVOLTAIC POWER GENERATION

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ABSTRACT

In Japan, rapid voltage drop and reduction in interconnection capacity due to degradation of system stability have occurred in long-distance distribution lines with large amounts of photovoltaic power generation (PV). Distributed energy resources such as PV are regarded as the main energy sources in microgrids. To develop microgrid facilities, we need to understand both the system condition of the voltage-drop phenomenon and the limited interconnection capacity based on system stability. In this paper, we describe the distribution system conditions based on the voltage-drop situation. We propose a method to calculate the limited interconnection capacity of grids without using power flow calculation. The validity of the proposed method was verified by comparison with the power flow calculation. Therefore, good results were obtained.

INTRODUCTION

In Japan, the feed-in tariff system was introduced in 2012. This process has accelerated the introduction of grid-connected Photovoltaic power generation (PV) that exceeds the expected amount [1]. Conventionally, along with the increase in grid-connected PVs, a concern arises in which the distribution grid voltage deviates from the proper range because of the voltage increase caused by reversed power flow [2], [3]. However, a new phenomenon, i.e., rapid voltage drop that occurred in long-distance distribution lines with large numbers of PVs is reported in Japan. This phenomenon has not been considered in the operation, and it causes “mass parallel shutting off of PVs” by the protection relay because of the difficulty in maintaining proper voltage. A concern arises in that this condition will limit the amount of PV interconnections. In particular, PV is an important component in microgrids. We need to construct a facility while understanding the limited interconnection capacity. From the above-mentioned problem, it is necessary to understand both the system condition of the voltage-drop phenomenon and the limited interconnection capacity based on system stability. The limit of the interconnection capacity should consider the voltage-drop phenomenon and voltage stability, which can be determined using the power flow calculation. However, power flow calculation is required for each of the different distribution lines; thus, much effort to verify the limited interconnection capacity based on the system stability and power qualities is necessary.

In this paper, we describe the voltage-drop phenomenon in a distribution line with a large number of PVs based on the analysis of the voltage and current through simulations. In addition, we propose a method to calculate the limited interconnection capacity of the grid without using power flow calculation and a method to improve the stability based on stability analysis.

PRINCIPLE OF OCCURRENCE OF VOLTAGE-DROP PHENOMENON AND SYSTEM CONDITION

Fig. 1 shows a distribution line model and the node voltages calculated using flow calculations. This model is connected to a large-capacity PV at the end of the grid under the assumption of the harshest conditions. When a certain number of PVs are interconnected at the end of the distribution feeder, the voltage drops, instead of increases. We analyze the phenomenon by changing the distribution line lengths, line impedances, interconnection capacities, and PV power factor. Table 1 shows grid and PV conditions for occurrences of voltage drop. Fig. 2 shows the voltage-current vector of each condition. Large distribution line length and X/R ratio cause the phenomenon to occur because of the rotating of the phase of the voltage drops, as shown in Figs. 2(a) and 2(b). Interconnection capacity and the power factor of PV tend to the phase of the current directly in Figs. 2(c) and 2(d). This result shows that the voltage-drop occurs because of the overlapping with the rotation of the phase of the current and voltage drop based on the long distribution line (high impedance) and low power factor. Here, we assume that the lagging power factor is positive when viewed from the substation.

Fig. 3 shows the relationship between PV capacity and the receiving voltage curves calculated by the power flow calculation. A voltage-drop phenomenon occurs when the PV interconnection reaches approximately 1,500 kW. The power flow calculation diverges over 3000 kW of the interconnection capacity. This result shows that the interconnection limit of PVs is 3000 kW considering the stability limit. In the conventional operation, the interconnection capacity is determined by the line capacity. The conventional interconnection capacity exceeds the interconnection limit based on the stability limit.

Large distribution line length and X/R ratio rotate the phase of the voltage drop directly. Interconnection capacity and the power factor of PV rotate the phase of the current.

Table 1 Conditions for occurrence of voltage-drop

Item	Occurrence condition
Distribution line length	Large for longer lines
Line impedance (X/R)	Large when impedance is large
Interconnection capacity	Large when capacity is large
PV operating power factor	Occurrence tendency " Advancement"

Derivation of limited interconnection capacity

The limited interconnection capacity can be derived from the power flow calculation by varying the PV's amount. We need to repeat the power flow calculation until the limit is reached, and much effort to understand the limited value is needed. Therefore, we devised a simple calculation method to estimate the limited interconnection capacity by performing a simple stability analysis. By introducing this method, grid operators can understand the limit value of PV interconnection capacity in a distribution feeder. The derivation process is shown below.

The equation for the grid shown in Fig. 1 is as follows:

$$\sqrt{3} \times \dot{E}_r \overline{\dot{I}} = P + jQ \qquad (1)$$

where $\dot{E}_s$ and $\dot{E}_r$ are the phase voltages, $\dot{V}_s$ and $\dot{V}_r$ are the sending voltage and the receiving voltage, and $P + jQ$ is the terminal load.

By substituting $\dot{V}_s = V_s e^{j\theta}$ and $\dot{V}_r = V_r$ into (1), we obtain

$$V_r \overline{\left(\frac{V_s e^{j\theta} - V_r}{R + jX}\right)} = P + jQ \qquad (2)$$

We rewrite (2) using P and Q.

$$P = \frac{RV_sV_r cos\theta - RV_r^2 + XV_sV_r sin\theta}{(R^2 + X^2)} \qquad (3)$$

$$Q = YV_r^2 + \frac{(-XV_r^2 + XV_sV_r cos\theta - RV_sV_r sin\theta)}{(R^2 + X^2)} \qquad (4)$$

Deleting "sin θ" and "cos θ" from (3) and (4) yields

$$\{P(R^2 + X^2) + RV_r^2\}^2 + \{Q(R^2 + X^2) - YV_r^2(R^2 + X^2) + XV_r^2\}^2 = (RV_sV_r)^2 + (XV_sV_r)^2 \qquad (5)$$

Equation (5) can be organized according to V_r and each coefficient of V_r is replaced based on (6)-(8).

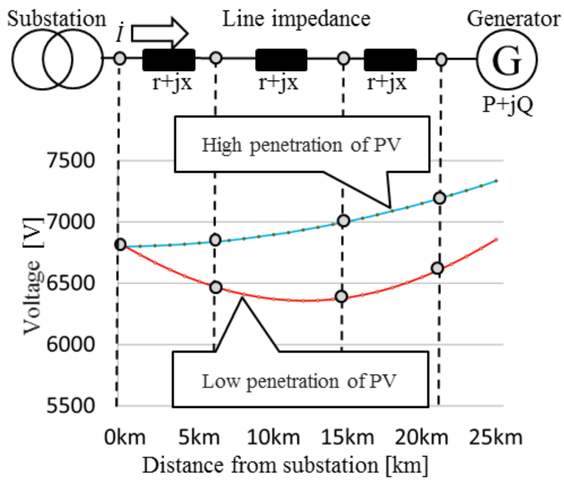
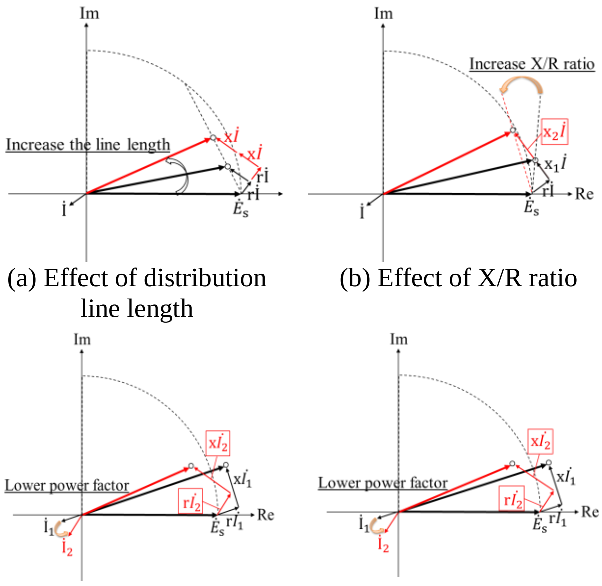


Fig. 1 Node voltage with the introduction of PV



(a) Effect of distribution line length (b) Effect of X/R ratio

(c) Effect of PV capacity | (d) Effect of power factor

Fig. 2 Voltage-current vector diagram of each condition

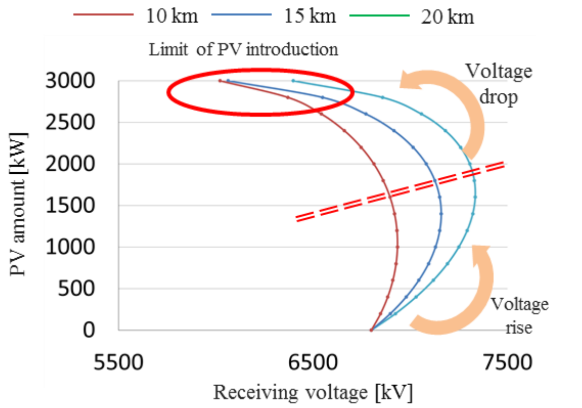


Fig. 3 Receiving voltage of each PV amount

Table 2 Error rate of each power factor and sending voltage

V_s	Power factor = 0.96			Power factor = 0.98			Power factor = 1		
	PV_{fc} [kw]	PV_{fm}[kw]	ER [%]	PV_{fc} [kw]	PV_{fm}[kw]	ER [%]	PV_{fc} [kw]	PV_{fm}[kw]	ER [%]
6800	2,600	2,579	0.8	3,000	2,952	1.6	4,300	4,152	3.4
6600	2,400	2,429	-1.2	2,800	2,780	0.7	4,000	3,911	2.2

Table 3 Effect of change of branch point under each power factor and sending voltage

V_s	Branch point [km]	Power factor = 0.96			Power factor = 0.98		
		PV_{fc} [kw]	PV_{fm}[kw]	ER [%]	PV_{fc} [kw]	PV_{fm}[kw]	ER [%]
6800	20	3,200	3,223	-0.7%	3,700	3,689	0.3%
	15	4,300	4,297	0.1%	4,400	4,400	-
6600	20	3,100	3,036	2.1%	3,500	3,476	0.7%
	15	4,100	4,049	1.2%	4,400	4,400	-

$$a = 1 - 2XY + Y^2(R^2 + X^2) \quad (6)$$

$$b = 2RP + 2Q\{X - Y(R^2 + X^2)\} - V_s^2 \quad (7)$$

$$c = (R^2 + X^2)(P^2 + Q^2) \quad (8)$$

The condition for stable solution of "$aX^2 + bX + c$" is" $b^2 - 4ac > 0$," and the limiting condition is expressed as (9).

$$b^2 - 4ac = 0 \quad (9)$$

Equation (10) is derived from (6)–(9).

$$(2RP + 2QX - V_s^2)^2 - 4(R^2 + Q^2)(P^2 + Q^2) = 0 \quad (10)$$

By denoting the power factor of the load as "cos α," Q can be expressed as

$$Q = P\tan\alpha = PA \quad (11)$$

We substitute (11) into (10). If the power flow seen from the substation is positive, PV becomes negative. We set $P = -P$" and solve for P.

$$P = \frac{V_s^2}{2(\sqrt{(R^2 + X^2)}\sqrt{1 + A^2} - R + AX)} \quad (12)$$

We can confirm that the limited connection capacity consists of the delivery voltage of the distribution substation, impedance of the line, and PV power factor. The maximum error rate (ER) is 3.4% compared with the estimated values calculated by (12) and those calculated by the power flow calculation (Table 2):

$$\mathrm{ER} = \frac{PV_{fc} - PV_{fm}}{PV_{fc}} \times 100 \quad (13)$$

where ER is the error rate between the limited capacity calculated by the power flow calculation and the proposed method. PV_{fc} is the limited capacity based on the power flow calculation, and PV_{fm} is the acceptable capacity based on the proposed method. Considering that the output of the power flow calculation is carried

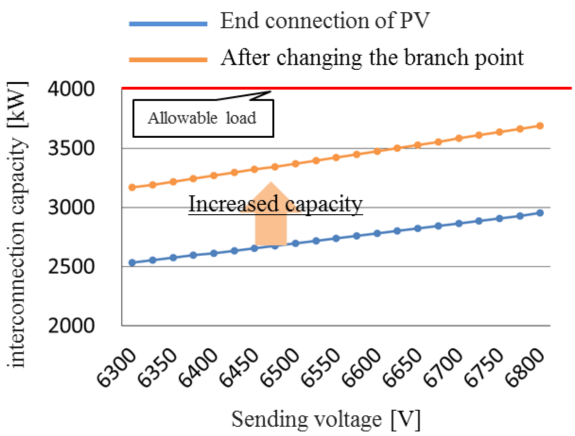


Fig. 4 Node voltage with the introduction of PV

out in increments of 100 kW, we confirmed that an accurate value can be calculated by using the proposed method and predetermined conditions without repeating the power flow calculation.

Method to increase the limited interconnection capacity

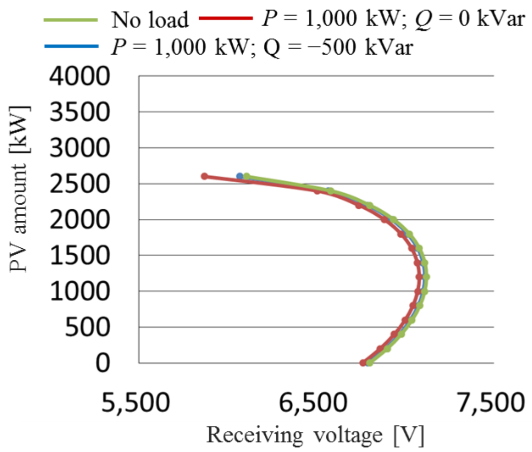
The simulation model used is presented in Fig. 1. We can confirm that the limited interconnection capacity can be increased by reducing the impedance in (12). We can possibly reduce the impedance by changing the branch point of the PV to the substation side by implementing distribution grid switching. Fig. 4 shows an example of the result, and Table 3 lists the result of the changing the branch point and power factor. The maximum ER is 2.1% compared with the values calculated using the proposed method and those of the power flow calculation (Table 3). We confirmed that accurate values can be calculated from the equation even when the branch point of the PV is changed. Table 4 lists the increased capacity rate. By changing the branch point 20% closer to the substation side, we confirmed that the limited interconnection amount increased by 20%. From the above discussions, we can possibly understand the effect of changing the branch point of the PV by conducting improved simulation before the distribution grid switching. Further, we can expect considerable reduction in the effort compared with that of the power flow calculation.

CONSIDERATION

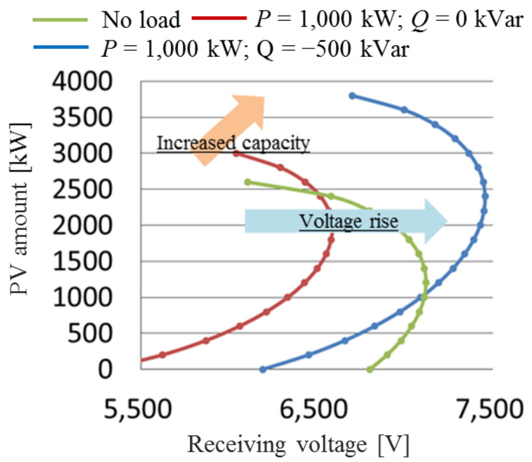
In Japan, because PV is interconnected while proper voltage must be maintained, we set a lagging power factor and control voltage using reactive power. In the system where the interconnection amount is limited, we should pay attention to the fact that the set lagging power factor further reduces the interconnection capacity. By using a simple derivation method, we could possibly calculate the limited interconnection capacity using only the system and the PV condition. However, the distribution system is complex, and we need to consider the situation of the branch lines and loads. We call the 0 km point from the substation head point (HP), and the 25 km point the end point (EP). Fig. 5 shows the change in the limited interconnection capacity when various loads are attached to the HP and EP. In the case of the HP load, little influence on the limited interconnection capacity and system voltage is exerted regardless of the type of load. On the one hand, in the case of the EP load, the limited interconnection capacity and system voltage vary significantly depending on the type of load. In particular, in the case of a capacitive load, as the interconnection capacity increases by 1200 kW and the voltage increases by 600 V compared with the case without load, we must be careful about voltage rise. One of the methods of grasping the detailed phenomena of a real system is incorporating the power flow calculation into the operating system. The development of a simple method using various types of loads must be studied in the future.

CONCLUSIONS

In this paper, we clarified the system condition in which the voltage-drop phenomenon occurs and presented a simple calculation method for the PV limited interconnection capacity. We should state that we were able to reduce the effort to calculate the limited interconnection capacity based on the system stability, which is an effective method for dealing with the increase rate of limited interconnection capacity during switching of the system. Distribution lines include branching and loading, and various models exist. We need to develop new control methods that can deal with these phenomena in the future.



(a) P-V curves of the HP



(b) P-V curves of the EP

Fig. 5 P-V curves of each PV introduction position

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