Study on Voltage Stability Limit of 6.6 kV Distribution System by Reverse Power Flow from a Group of Photovoltaic Generators

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ABSTRACT

When a large capacity photovoltaic generator is connected to a long distance distribution line, there is a possibility that it reaches the voltage stability limit caused by the large amount of reverse power flow. We conducted experiments to investigate what will happen to these generators in cases of such occasions using actual inverters. As a result, it was confirmed that inverters could not continue to generate power when it reaches the voltage stability limit, and analysis was carried out in order to prevent such problems in various conditions.

1. INTRODUCTION

For Japanese 6.6 kV distribution system, it has been recognized that the distance between substations and electric power loads are too close for voltage collapse phenomena to occur. Therefore, it is not necessary for the distribution system operators (DSOs) to consider such phenomena in planning and operating distribution networks.

However, the situation has changed today. After the introduction of Feed-in Tariff (FIT） scheme in 2012, large capacities of photovoltaic generators (PV) have been constructed in rural areas. The majority of them are connected directly to 6.6kV MV distribution lines or to 0.2kV LV distribution lines, which is also connected to 6.6kV MV lines through pole-mounted transformers. These rural areas are relatively far from load centres that the substation are located, and so, large capacities of PV are connected near the end of 6.6 kV distribution feeders.

In these feeders, a large current close to the thermal limits of the distribution wires flows from PV during daytime due to reverse power flow. In some feeders recently, frequent disconnections of PV connected to the end of them have occurred, and this is suspected that they have reached the voltage stability limit. Here, as a result, necessity in taking into account of voltage stability limit due to the reverse power flow has arisen for distribution system.

It is known that when the system reaches voltage stability limits due to heavy loads, voltage drops significantly and collapses in the end. In the preceding studies, analytical investigation has already been carried out on voltage drops caused by reverse power flow from a large capacity of PV or hosting capacities of PV connecting to the distribution lines taking into account of voltage stability [1]-[4].

However, since the behaviour of inverters equipped with various relays (Power Conditioning System or PCS) in cases of voltage stability limits due to reverse power flow from PV is unknown, it is difficult to determine whether the frequent disconnection of PV are the results of voltage stability limit or not.

Also, in order to prevent problems caused by the voltage stability limit, it is necessary to establish a criteria to diagnose whether the cause of frequent disconnections of PVs is due to voltage stability or not practically on the field.

Moreover, in order to prevent problems caused by the voltage stability limit, it is necessary to establish a criteria to determine whether or not a PV system could be connected to the network without reinforcing it during planning phases. Therefore, it is necessary to evaluate the voltage stability limit of various conditions.

This paper investigates how PCS responds in cases of such events, and how we have to manage them.

2. EXPERIMENT OF VOLTAGE STABILITY LIMIT

Experiment were carried out to confirm the behaviour of PCS when the voltage stability limit was reached.

2.1 Experimental method

In preliminary experiments, PCS complied with Japanese grid code equipped with anti-islanding function and other protective relays was used.

However, when it was connected to an experimental circuit with high impedance and the output power was increased, harmonics and the active signals of the anti-islanding function greatly affected current and voltage waveforms of the circuit.

As a result, various protective relays operated before it reached the voltage stability limit, and the aim of the experiment could not be accomplished with this inverter.

Instead, experiments were conducted using an experimental single-phase PCS (rated 1 kW) developed proprietarily that anti-islanding functions were not implemented.

Experimental circuit is shown in Figure 1. A single-phase PCS was connected to a voltage source (AC 100 V), which simulates a distribution substation and a reference impedance (4.6 + j 10 Ω), which simulates MV and LV distribution line. A transformer with turn ratio of 1:1 for cutting DC was installed at the PCS connection point. DC power source simulating solar cell was used for DC side input of PCS.

DC side input was gradually increased until the AC reverse power flow reaches the voltage stability limit, and the changes in the connection point voltage V_r, power generation current I, and power generation P of the PCS were confirmed.

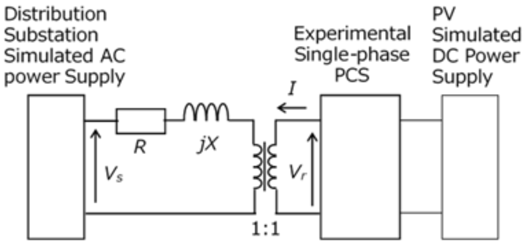
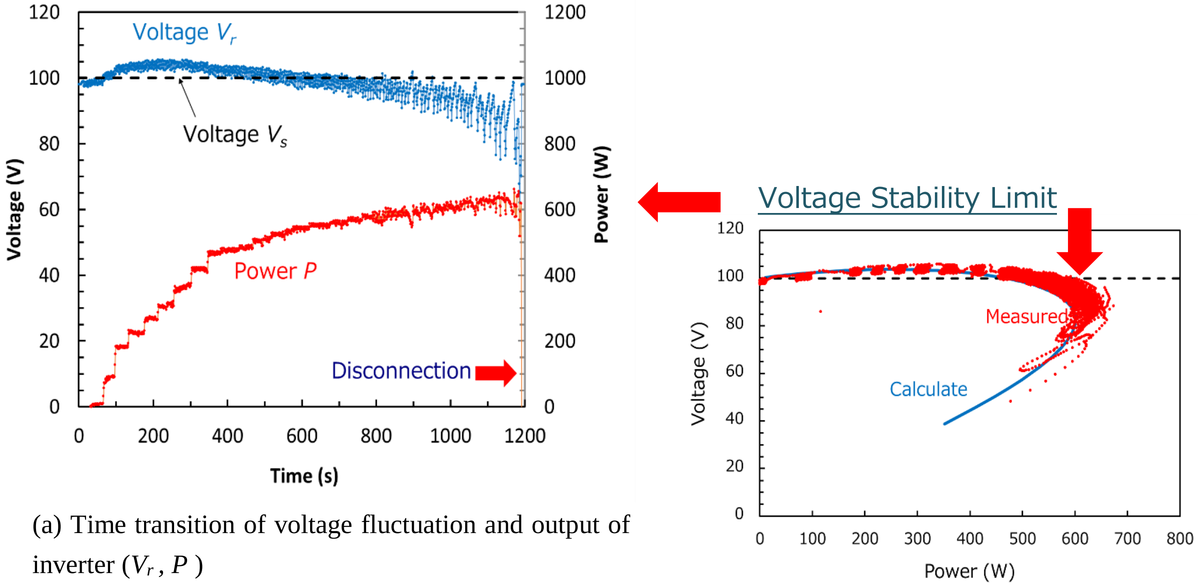


Fig. 1 Voltage stability limit experiment circuit using a single-phase PCS.

2.2 Experimental results

The experimental results are shown in Fig. 2.



(a) Time transition of voltage fluctuation and output of inverter (V_r , P)

(b) P-V curve of the experimental circuit

Fig. 2 Experimental results when reverse power flow was increased to voltage stability limit.

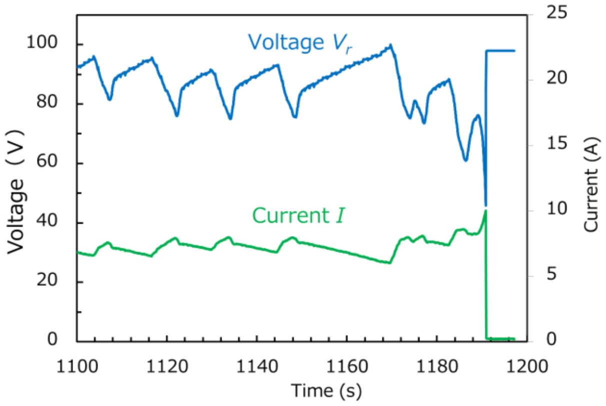
Fig. 2 (a) shows the time transition in the connection point voltage V_r and output power P. Fig. 2 (b) plots experimental data for 0.1 second sampling on a P-V curve of the experimental system.

When the output power P is small, connection point voltage V_r was higher than the power supply voltage V_s, but a large drop in connection point voltage V_r was observed from the point where the output power P exceeded about 500W. Furthermore, as the output power increased, the output of the PCS became unstable, and the connection point voltage fluctuated largely. These measured values generally shifted on the P-V curve on Fig. 2 (b).

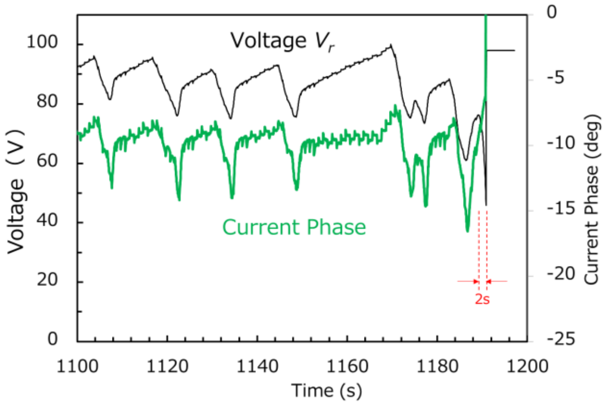
Connection point voltage and output power decreased suddenly when the output power was as high as 600W, which is the analytical limit of voltage stability. Then, the PCS disconnected due to a significant decrease in the connection point voltage. After the PCS disconnection, the connection point voltage returns to the power supply voltage (AC 100 V).

The experimental results near the voltage stability limit are shown in Fig. 3 (a) shows the time transition of the connection point voltage V_r and the power generation current I. Current I has a variation in the direction opposite to V_r. The rapid increase of I can be confirmed when V_r immediately before disconnected is rapidly lowered.

Fig. 3 (b) shows the time transition of the connection point voltage V_r and the current phase to V_r. The current phase is not controlled at a constant level, and the increase or decrease is repeated. This increase / decrease is substantially coincident with the connection point voltage V_r, and a high correlation is observed. However, it changes in the direction to 0 degrees opposite to the change in V_r for about 2 seconds immediately before the PCS disconnections.



(a) Time transition of connection point voltage V_r and power generation current I



(b) Time transition of the connection point voltage V_r and current phase

Fig. 3 Voltage and current fluctuations near the voltage stability limit.

2.3 Examination of experimental results

2.3.1 Gradual fluctuation of the connection point voltage before reaching the voltage stability limit

The slow fluctuation of the connection voltage before reaching the voltage stability limit is correlated with the variation of the current phase. Therefore, it is assumed that the fluctuation of the reactive power due to the change of the current phase is the main cause of this phenomena.

As the current phase is controlled to be constant, the reason why the current phase fluctuates slowly has not yet been clarified. It is necessary to perform experiments and simulations using different PCS in the future.

2.3.2 PCS behavior when voltage stability limit is reached

It was confirmed that voltage rapidly decreased along the *P-V* curve when the voltage stability limit was reached by the reverse power flow from the PCS in the experiment.

For approximately 2 seconds immediately before the PCS disconnection, the current increased in the constant phase of 0 degree, so the abrupt drop in the connection point voltage was not a result of the current phase change. The main cause is assumed to be the rapid increase in current *I*. The mechanism by which the current *I* rapidly increases can be estimated as follows.

1. When the voltage stability limit is reached, the PCS increases the current in order to increase the output power of the PCS.
2. Due to the increase in current, the connection point voltage decreases greatly, so that the output power from PCS decreases.
3. PCS increases the current, to gain the target output power.
4. As PCS repeats the control in a short time, the current rapidly increases, resulting with great decrease in connection point voltage and output power.

This voltage drop causes the PCS's UV relay to operate, causing the PCS to disconnect. As the PCS disconnects and the voltage will be restored, it is considered that voltage fluctuation occurs instead of causing the voltage collapse phenomena of the distribution line. If the PCS is set to resume power generation after a predetermined time, it is assumed that the voltage stability limit is reached again, and the PCS disconnection is repeatedly occur.

3. ANALYSIS OF VOLTAGE STABILITY LIMITS

3.1 Creating *P-V* Curve

The stability limit power is analysed in order to prevent problems caused by voltage stability limit.

Simple circuit shown in Fig. 4 was examined. Sending-end (distribution substation) Voltage V_s was set to constant value of 6,600 V. Large capacities of PV was connected only to the receiving-end (distribution system terminal, voltage V_r). V_r, and the PV output current I was examined. The resistance and reactance of the circuit are respectively R, X, and the power factor of the PCS is set to $\cos\theta$. Fig. 5 shows a vector diagram at the instant.

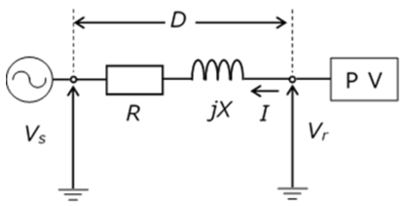


Fig. 4 Single-phase equivalent circuit of power distribution system.

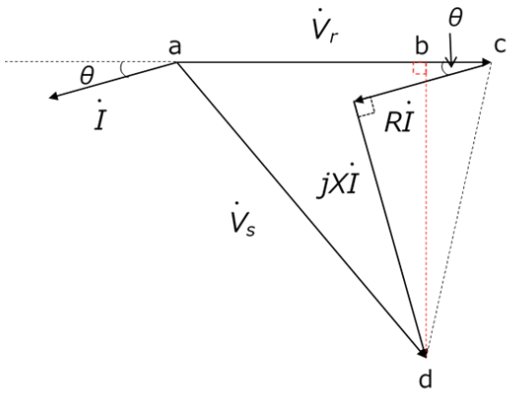


Fig. 5 Vector diagram of voltage and current for power factor cosθ.

The intersection of the perpendicular lines drawn from point d to V_r is denoted by b. The connection point voltage V_r and the output power P can be expressed by the following equation.

$$V_r = \overline{\mathrm{ab}} + \overline{\mathrm{bc}}$$

$$= \sqrt{{V_r}^2 - (R^2 + X^2)I^2 \sin\left(\theta + \tan^{-1}\frac{X}{R}\right)}$$

$$+ \sqrt{R^2 + X^2} I \cos\left(\theta + \tan^{-1}\frac{X}{R}\right) \quad (1)$$

$$P = V_r\, I \cos\theta \quad (2)$$

Using equations (1) and (2), the *P*-*V* curve of each condition was prepared and analysed.

3.2 Analysis results

Fig. 6 shows various *P*-*V* curves when the distance of the distribution line from substation to PV connection point is changed. Power factor cosθ was set to 1. Impedance of the distribution copper wire of 125 mm^2 is 0.149+ j0.381 Ω / km, and the allowable current I_{limit} determined by the thermal capacity is 490 A. The point at the time of the allowable current I_{limit} is indicated by "○" and the stability limit power Pr_{max} (the maximum power point on the *P*-*V* curve) is denoted by "●".

10 km feeder has a larger allowable current I_{limit} than Pr_{max}. Therefore, in the normal operation, the voltage stability limit will not be reached. On the other hand, at a feeder of 20 km, the stability limit power Pr_{max} is smaller than the allowable current I_{limit}, which can lead to voltage stability limit in conventional planning and operation taking into account of allowable current I_{limit}. Therefore, it is necessary to perform current limiting in consideration of the voltage stability limit.

When the distance (or impedance) of the distribution line is increased by *n* times, Pr_{max} will be 1/*n* times. The reason for this can be confirmed by the fact that when *R* and *X* are set to *n* times, the voltage vector (*RI* and *jXI*) does not change when the current *I* is 1/*n* times the size.

Therefore, the value <Pr_{max} × *D*> obtained by multiplying the voltage stability limit Pr_{max} [kW] by the distance *D* [km] from the substation to the PV connection point would be a constant value (83,740 under the condition of Fig. 6). Thus the value multiplying PV capacity and distance of a feeder can be utilised as an indicator to omit the detailed examination for various feeders with various distances.

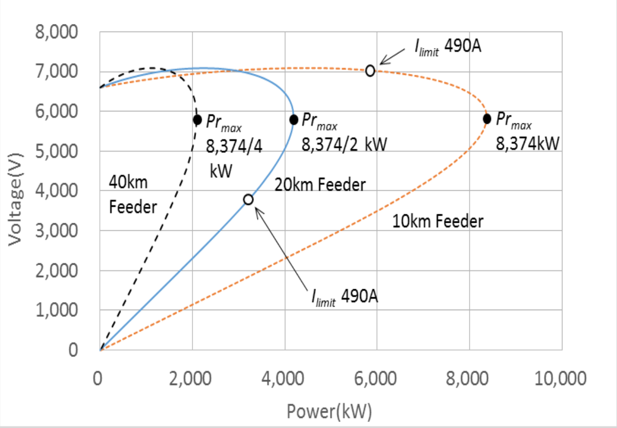


Fig. 6 *P-V* curve when the distance of a distribution line from a substation to a PV connection point is changed.

In Japan, the voltage rise of the power distribution system due to reverse power flow from PV has become a problem with the popularization of PV. In recent years, it has been common to operate PV at leading-power factor constantly to prevent voltage rise. Power factor is generally in the range of 0.9 to 1.

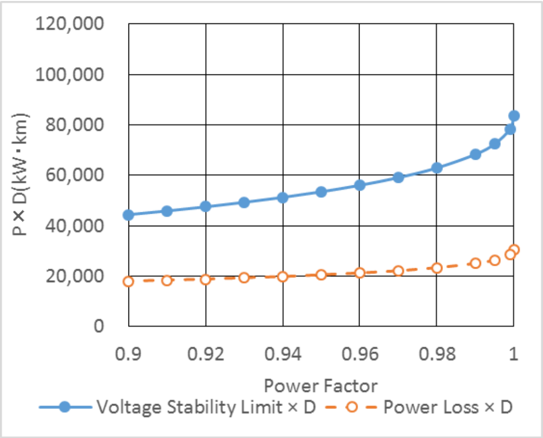
To evaluate the effect of power factor in voltage stability, <Pr_{max} × *D*> was analysed by using 2 types of wires when the power factor was changed from 0.9 to 1. For 2 types of wires, large capacity type of 125 mm^2 wire generally used for the main line and medium capacity type of 60 mm^2 wire were chosen. Distribution line loss P_{loss} [kW] at the voltage stability limit for each condition was calculated, and the value <P_{loss} × *D*> obtained by multiplying the distance *D* [km] was obtained. Results are shown in Fig. 7 and Table 1.

Under the condition of the leading power factor, the value <Pr_{max} × *D*> reaching the voltage stability limit decreased significantly. In the case of leading power factor of 0.9, the value was almost half of that when operated in power factor of 1. Especially, at around power factor of 1, slight change in the power factor decreases <Pr_{max} × *D*> significantly. This is influenced by a large shift in phase angle caused by a slight change in power factor near at around 1.

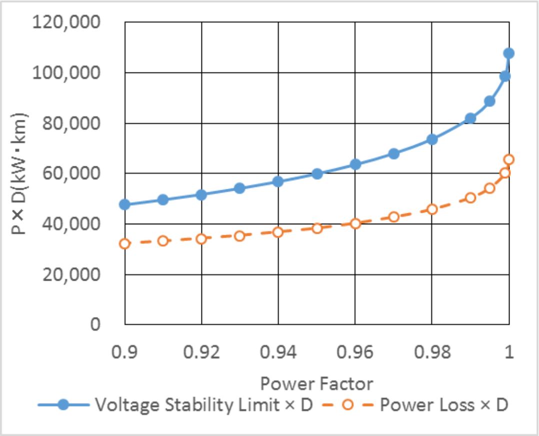
From this result, if the voltage profiles of a distribution line has a margin in the upper limit value, it is possible to increase the capacity of the PV connection by bringing the power factor closer to 1.

The value <$Pr_{max} \times D$> when it reached the voltage stability limit was larger with 60 mm^2 wire than 125mm^2 wire. Therefore, making the diameters of wires larger cannot be a countermeasure to preventing voltage stability limit.

However, the power loss <$P_{loss} \times D$> of the 60 mm^2 wire was doubled, and the power reaching the substation became small. In addition, the loss rate (P_{loss} / Pr_{max}) in the voltage stability limit was around 40% for 125 mm^2 wire, and was as much as around 60 ~ 70% for the 60 mm^2 wire. This loss rate tends to increase under the condition of leading power factor operation.



(a) 125mm^2 copper wire



(b) 60mm^2 copper wire

Fig. 7 Relation between power factor of inverter, voltage stability limit and power losses.

Table 1 Calculation Results

	Power Factor	0.9 leading	1
125mm^2 copper wire (0.149+j0.381 Ω/km)	$Pr_{max} \times D$ (kW・km)	44,440	83,740
	$P_{loss} \times D$ (kW・km)	17,740	30,500
	P_{loss} / Pr_{max}	39.9%	36.4%
60mm^2 copper wire (0.313+j0.409 Ω/km)	$Pr_{max} \times D$ (kW・km)	47,620	107,790
	$P_{loss} \times D$ (kW・km)	32,690	66,260
	P_{loss} / Pr_{max}	68.6%	61.5%

4. SUMMARY

It was experimentally confirmed that the connection point voltage rapidly decreases along the *P-V* curve when the voltage stability limit was reached by the reverse power flow from the PCS, and the PCS cannot continue to operate in such occasions. It is considered that voltage collapse phenomena does not occur because the voltage will be restored by the disconnection of the PCS.

The voltage stability limit of various conditions was calculated in order to prevent frequent disconnections of PCS due to the voltage stability limit. It was confirmed that the distance from the substation was inversely proportional to the amount of PV that could be connected. Moreover, it was confirmed that the capable capacity of PV connection decreases when the leading power factor generation is applied for PV, or when a larger diameter of wires are applied for distribution.

In addition, power loss of distribution lines could be a large value when it is near the stability limit. Therefore, it is necessary to take into account of power losses in planning and operating of distribution networks with high penetration of PV.

These analysis has been carried out on a system where PV is connected only at the end of distribution lines. So, in the future, it is necessary to carry out more examination on various cases where the PV is dispersed and/or the load is applied.

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