Impact of Dynamic Behavior of Photovoltaic Power Generation Systems on Short-Term Voltage Stability

K. Kawabe, Member, IEEE, and K. Tanaka

Abstract—In this study, we investigate the impact of the dynamic behavior of photovoltaic (PV) power generation systems on short-term voltage stability of the transmission system. First, the impact of the fault ride-through capability of a PV model is studied by setting several recovery speeds of the active current output when the operation of the PV system is interrupted because of a voltage sag. The results are analyzed by using transient P-V curves and a stability boundary, which has been proposed in our previous research. Further, we show that the installation of PVs severely impairs the short-term voltage stability if the PVs shut off after a voltage sag, and its recovery speed is low. Next, two countermeasures to control short-term voltage instability phenomena are tested. One is the operation of the PV system at a leading power factor in the normal state, and the other is the dynamic reactive power control by the inverters of the PV system after a voltage sag. Numerical examples are carried out for a one-load in finite-bus power system and a five-machine five-load power system. The results show that these countermeasures can play a substantial role in preventing the voltage instability phenomena caused when a PV system is suddenly interrupted because of a fault.

Index Terms—Induction motors, photovoltaic system, power system stability, reactive power control.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>Voltage behind electric filter of PV.</td>
</tr>
<tr>
<td>$v$</td>
<td>Voltage at PV-connected bus.</td>
</tr>
<tr>
<td>$X$</td>
<td>Reactance of electric filter.</td>
</tr>
<tr>
<td>$P_{PV}$</td>
<td>Active power output of PV.</td>
</tr>
<tr>
<td>$Q_{PV}$</td>
<td>Reactive power output of PV.</td>
</tr>
<tr>
<td>$P_{ref}$</td>
<td>Reference value of active power output of PV.</td>
</tr>
<tr>
<td>$Q_{ref}$</td>
<td>Reference value of reactive power output of PV.</td>
</tr>
<tr>
<td>$I$</td>
<td>Current output of PV.</td>
</tr>
<tr>
<td>$I_{max}$</td>
<td>Current rating of PV inverter.</td>
</tr>
<tr>
<td>$K_P$</td>
<td>Gain constant in automatic power regulator.</td>
</tr>
<tr>
<td>$T_P$</td>
<td>Time constant in automatic power regulator.</td>
</tr>
<tr>
<td>$K_C$</td>
<td>Gain constant in automatic current regulator.</td>
</tr>
<tr>
<td>$T_C$</td>
<td>Time constant in automatic current regulator.</td>
</tr>
<tr>
<td>$P_{ref,pre}$</td>
<td>$P_{ref}$ before voltage sag.</td>
</tr>
<tr>
<td>$Q_{ref,pre}$</td>
<td>$Q_{ref}$ before voltage sag.</td>
</tr>
<tr>
<td>$V_{pre}$</td>
<td>Voltage at PV-connected bus before voltage sag.</td>
</tr>
<tr>
<td>$t$</td>
<td>Time.</td>
</tr>
<tr>
<td>$t_{cl}$</td>
<td>Fault clearing time.</td>
</tr>
<tr>
<td>$Q_C$</td>
<td>Reactive power injected by shunt capacitor.</td>
</tr>
</tbody>
</table>

I. INTRODUCTION

The rapid increase in the installed capacity of renewable power generation systems is a key driving factor in the move towards sustainable electric power systems. Photovoltaic (PV) power generation is one of the promising power sources, and a large number of PV systems are increasingly installed as dispersed power generation systems in medium- and low-voltage transmission networks.

This high penetration of PV systems is expected to have a significant impact on power system stability. Several studies have been conducted focusing on the impact of PVs on different categories of stability such as transient stability [1], [2] and small-signal stability [3]. Nevertheless, few papers have investigated the impact of PVs on the short-term voltage stability. The short-term voltage stability is one of the areas of concern during the transient period after a large disturbance. Dispersed power generation systems are installed in medium- and low-voltage networks and are prone to stop their operation after voltage sags. This can have an undesirable effect on the short-term voltage stability of these networks. To ensure the short-term voltage stability even with a large installed capacity of PVs, it is essential to study the impact of the dynamic behavior of PV systems and develop countermeasures for controlling voltage instability phenomena.

Currently, Japanese grid codes require the PV systems to stay connected to the grid when a fault occurs and to continue supplying power to the grid as soon as possible even if the systems temporarily stop their operation owing to the fault. The fault-ride-through (FRT) capability was originally proposed for preventing a cascading frequency drop after a disturbance. The impact of the FRT capability on other instability phenomena has not been fully studied yet. Reactive power control by PV inverters is expected to gain traction to provide dynamic voltage support (DVS). The favorable effects of the DVS capability on steady-state voltage regulation have been confirmed in many papers. A dynamic analysis has also been carried out at the distribution network level for improving the short-term voltage sta-
Fig. 1. Equivalent circuit for the PV model.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Fig. 2. Control system of the PV inverter.

TABLE I
CONTROL PARAMETERS IN THE CONTROL SYSTEM OF PV INVERTER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_p$</td>
<td>0.10</td>
</tr>
<tr>
<td>$k_q$</td>
<td>0.05</td>
</tr>
<tr>
<td>$T_p(s)$</td>
<td>0.10</td>
</tr>
<tr>
<td>$T_q(s)$</td>
<td>0.10</td>
</tr>
</tbody>
</table>
When the operation stops, the power output recovers by changing $P_{ref}$ in the APR in Fig. 2 according to (1):

$$P_{ref}(t) = \begin{cases} P_{ref,pre} \times \frac{t - t_{st}}{\tau} & (P_{ref}(t) \leq P_{ref,pre}) \\ P_{ref,pre} & (P_{ref}(t) > P_{ref,pre}) \end{cases}$$

(1)

The time constant $\tau$ is set to satisfy an assumed $T_{FRT}$ for the voltage change shown in Fig. 3. Fig. 3 shows the change in the active power output of the PVs that have two types of FRT capability, where $T_{FRT}$ is 0.2 s and 1.0 s. These values have been selected by referring to the technical targets recommended in the newly proposed Japanese requirements for PVs before and after 2016 [11]. As can be seen from Fig. 3, the power output reaches up to 80% of the terminal voltage within $T_{FRT}$.

III. IMPACT OF FRT CAPABILITY ON SHORT-TERM VOLTAGE STABILITY

A. Numerical Example

Numerical simulations are carried out on the single-load infinite-bus system shown in Fig. 4 to focus on how the integration of the PV system affects the short-term voltage stability. The extra-high-voltage (EHV) network is represented by the infinite bus, and the dynamic characteristics of the generators are neglected to focus on the short-term voltage stability. The load center is modeled by a dynamic load [9] that is connected through aggregated transmission and subtransmission lines. The dynamic load consists of a first-order IM, which is modeled using the IM equations derived in [12] and a constant impedance ($Z$), as shown in Fig. 4. The ratio of the IM load to the total load is set at 50%, although the composition of the loads varies with the load center, season, and time of the day. The load center is assumed to include both industrial and residential loads. The aggregated PV system is connected to the load bus.

A 3LG fault in the EHV network is represented by specifying the voltage of the infinite bus at 0.10 p.u. for 0.10 s. Fault clearing is modeled by returning the specified voltage to that in the normal state. The simulation cases presented in Table II are carried out for a 3LG fault. Several FRT capabilities are assumed for studying the impact of the FRT capability on the short-term voltage stability. As the initial power flow conditions are different for the different simulation cases owing to the installation of the PVs, the voltages at buses 2, 4, and 6 are set at 1.01 in the normal state by adjusting the reactive power by varying the shunt capacitors at these buses, as shown in Table III.

Fig. 5 shows the change in the voltage at bus 6. The voltage drops down to approximately 0.1 p.u. owing to the fault. Therefore, the PV system stops in cases B, C, and D. It is observed from the comparison between cases A and B that the installation of the PV system speeds up the voltage recovery if the PV system rapidly returns its power output. On the other hand, the installation of the PV system causes a voltage instability owing to the stalling of the IM load in cases C and D.

Figs. 6 and 7 show the change in the current and the active power output of the PV system, respectively, in cases B, C, and D. The PV system increases its current output up to its rating after fault clearing in cases B and C. It is also observed that the PV system brings its active power back to the reference value in case B, but the PV cannot do so because of the voltage instability phenomena in case C. In case D, the PV does not restart.

The critical clearing time (CCT) for the IM stalling under the 3LG fault is also investigated, and the results for cases A–D are tabulated in Table IV. As seen from the comparison, a large-capacity installation of the PV system improves the short-term voltage stability when the output recovery speed of the PV system is sufficiently fast. On the other hand, the
installation of the PV system adversely affects the stability when its FRT capability is low.

B. Discussion on P-V Plane

Figs. 8–10 illustrate the change in the operating point of the dynamic load in the P-V plane for cases A–C under the 3LG fault for 0.10 s. Here, \( P \) and \( V \) represent the active power consumption and the magnitude of the terminal voltage of the load, respectively. The stability boundary, which we have proposed in [9], divides the P-V plane into stable and unstable regions. In the unstable region at the left side of the boundary, the IM load decelerates and causes a voltage instability. The transient P-V curves indicate the power transmission capability at a given time. The overview of the analytical method is explained in the Appendix. In this section, the previously proposed analytical method is applied to investigate impact of the FRT capability on the short-term voltage stability.

Fig. 8 shows the result for case A. The operating point lying on the stability boundary at \( t = 0 \) s jumps to the lower left owing to the 3LG fault at \( t = 0 + \) s. The operating point during the fault is in the unstable region at the left side of the stability boundary. Therefore, the IM decelerates, and the operating point further shifts downward. After clearing the fault at \( t = 0.10 \) s, the operating point jumps to the upper right. The operating point moves upward along the P-V curve because it lies in the stable region at the right side of the boundary.

Fig. 9 shows the results for case B. In this case, the operating point at the fault clearing time \( t = 0.10 + \) s lies in the unstable region because the PV system stops; therefore, the P-V curve shrinks. Note that the P-V curve expands with the increase in the PV system’s current output, as shown in Fig. 6. As a result, the operating point enters the stable region, implying that the voltage returns to the normal operating range. It should also be noted that the P-V curve at \( t = 0.40 \) s is wider than that in case A, indicating that the transmission capability of the system improves with the increase in the current output up to its rating.

This effectively improves the short-term voltage stability, as demonstrated by the comparison of the CCT in Table IV.

Fig. 10 illustrates the results for case C. The trajectory of the operating point until \( t = 0.10 + \) s in case C is the same as that in case B. Nevertheless, it can be seen that the expansion of the P-V curve in case C is less than that in case B owing to the slower current recovery, which is shown in Fig. 6. As a
result, the operating point cannot shift out of the unstable region and moves downward in case C because the IM load largely decelerates, and its equivalent impedance becomes small.

The result of case D is close to that of case C. Although an analytical result in the \( P-V \) plane is not shown here, the trajectory of the operating point until \( t = 0.10 \) s in case D is the same as that in case C. In case D, the transient \( P-V \) curve after the fault remains unchanged because the PV system remains disconnected, and a voltage collapse occurs.

The analysis in the \( P-V \) plane reveals the following points:

- The integration of the PV system severely impairs the short-term voltage stability when the PV system shuts off. This is because the total capacity of the shunt capacitors connected in the normal state is reduced by the PV system at the load center, as summarized in Table III, and the shut off of the PV system degrades the transmission capability to the load center.

- The improvement in the recovery speed has a large impact on short-term voltage stability. If the recovery speed is sufficiently fast, the installation of the PV system improves the voltage stability because the PV system enhances the transmission capability by increasing current output of the PV up to its rating.

### IV. COUNTERMEASURES USING PV INVERTERS

#### A. Leading Power-Factor Operation and DVS Capability

As shown in the previous section, the installation of a PV system can adversely affect the short-term voltage stability, especially in the case where the PV system remains disconnected after a voltage sag. In this section, we test the two countermeasures using the inverters of the PV system with respect to the voltage instability phenomena caused when the PV system is suddenly interrupted because of a fault.

The capacity of the shunt capacitors connected in the normal state is reduced by the installation of the PV system. This is one of the reasons for the deterioration of short-term voltage stability, as shown in the previous section. The operation of the PV system at a leading power factor can avoid the reduction in the capacity of the shunt capacitors. This operation has been proposed for ensuring steady-state voltage regulation in distribution systems in Japan [13] as an economical countermeasure because the operation requires less apparent power capacity of the inverter than the absorbed reactive power. In this paper, we verify its effect on the short-term stability improvement.

It is also shown in the previous section that the fast increase in the active current output of the PV system improves the short-term voltage stability because it enhances the transmission capability to the load. One possible method to further enhance transmission capability is the injection of reactive current by the PV inverters. This function is called the DVS. Although it may not be feasible to equip all PV systems with FRT and DVS capabilities because of the cost factor, equipping at least part of the PV systems with these capabilities may significantly help in maintaining the short-term voltage stability of the entire power system. The DVS capability applied in this study is modeled by changing \( Q_{ref} \) in the APR shown in Fig. 2 according to (2):

\[
Q_{ref}(t) = Q_{ref,pre} + K \times I_{n,ax} \times (V_{pre} - V(t)) (K - 5).
\]  

(2)

The constant \( K \) determines the rate of change in the reactive power with respect to the change in the terminal voltage. In this study, \( K \) is set at 5 to output the maximum reactive current when the voltage deviation is 0.2 p.u., i.e., \( K \) is calculated by dividing the rated current output of 1 p.u. by the voltage deviation of 0.2 p.u.

#### B. Numerical Example

The effects of the two countermeasures are studied in the power system shown in Fig. 4. A 3LG fault in the EHV network is assumed by setting the voltage of bus 1 at 0.01 p.u. for 0.10 s. The simulation cases summarized in Table V are carried out under the 3LG fault. Case I is the base case that is identical to case D in Table II. In case II, the aggregated PV system operates at the leading power factor of 0.96 in the normal state and does not have the FRT capability. In case III, the aggregated PV system operates at the leading power factor, and 50% of the PV system, which is assumed to be a utility-scale PV system, has FRT and DVS capabilities. The voltages at buses 2, 4, and 6 are set at 1.01 in the normal state by adjusting the reactive power \( Q_c \) with the shunt capacitors at those buses, as summarized in Table VI.

Fig. 11 compares the change in the voltage at bus 6. A voltage collapse occurs in cases I and II. The leading power-factor operation does not seem to be effective from this comparison. On the other hand, the voltage is restored to the value in the normal state after the clearing of the fault owing to the DVS capability.

The change in the reactive power output from the PV system is compared between cases II and III in Fig. 12. It is observed that 50% of the PV system in case III achieves an increased reactive power output after fault clearing, and the reactive power output gradually converges to the leading power output.

The CCT for the IM stalling under the 3LG fault is also investigated, and the results for cases I–III are tabulated in Table VII. As seen from the comparison, the PV operation.
at a leading power factor and equipment with DVS improve short-term voltage stability.

Note that the leading power factor operation in case II slightly improves the short-term voltage stability, as summarized in Table VII, although we cannot observe it in Fig. 11. The stabilizing effect by leading power factor operation can be physically explained by applying the proposed analytical method in the $P$-$V$ plane, as shown in the next subsection.

C. Discussion on $P$-$V$ Plane

Figs. 13–15 are the analytical results in the $P$-$V$ plane for cases I–III under the 3LG fault for 0.10 s. The figures explain the transition of the operating point of the load by using transient $P$-$V$ curves and the stability boundary.

The operating point in the normal state lies at the intersection of the stability boundary with the transient $P$-$V$ curve in the normal state. The intersection is the stable equilibrium point (SEP). The operating point jumps to the lower left owing to the 3LG fault at $t = 0 + s$. The operating point moves downward during the fault because the operating point is in the unstable region at the left side of the stability boundary. The operating point jumps to the upper right after fault clearing at $t = 0.10 + s$ and moves in different directions in each case.

A comparison between Figs. 13 and 14 show the effect of the leading power-factor operation in the normal state. The $P$-$V$ curves at $t = 0.10 + s$ in both cases shrink from those in the normal state owing to the shutoff of the PV system. Nevertheless, the $P$-$V$ curve at $t = 0.10 + s$ in case II is wider than that in case I. As a result, the operating point at $t = 0.10 + s$ in case II is closer to the stable region than that in case I. Although a voltage collapse occurs in both cases, this effect due to the leading power-factor operation improves the short-term voltage stability, as summarized in Table VII. It is also observed that the SEP after fault clearing in case II lies at a higher position than that in case I. This indicates that the leading power-factor operation has a preferable effect on the steady-state voltage after fault clearing for a stable case.

A comparison between cases II and III shows the effect of the DVS capability with which 50% of the PV system is equipped. By injecting reactive power after the restart of the operation, as shown in Fig. 12, we observe that the $P$-$V$ curve expands in case III, as shown in Fig. 15. This improves the short-term voltage stability by shifting the operating point of the load to the stable region. The result shows that the DVS capability of
the PV system can improve the short-term voltage stability, even if only part of the PV system in the load center is equipped with the DVS capability.

V. NUMERICAL EXAMPLES ON MULTI-MACHINE SYSTEM

A. Short-Term Voltage Stability Improvement by PV Inverters

Numerical examples are carried out for the five-machine five-load power system shown in Fig. 16. The test system is created by reference to a test system published in [14]. To analyze the impact of PV on the short-term voltage stability, the impedance between the transmission system and the load centers, which are represented with the lighter color, is newly considered, unlike conventional test systems used for a transient stability analysis. The generators are modeled as a fifth-order model, and an automatic voltage regulator and a governor of the first-order model are incorporated in each generator. Each load center consists of an IM and a constant impedance. The ratio of the IM to the total load is set at 50% at L1, L2, L3, and L4 and 20% at L5.

At each load center, we assume the installation of PV systems of the same capacity and the same generating active power. Table VIII tabulates the simulation cases and lists the generating power and current rating of the PV system at each load center. The total generating power of the PV system is 1.0 p.u. (0.2 p.u. × 5), i.e. approximately 20% of the total load shown in Fig. 16. The three simulation cases are carried out to verify the effect of the two countermeasures using PV inverters. In case II, the PV systems operate at the leading power factor. In case III, 50% of each PV system is equipped with the DVS capability in addition to the leading-power-factor operation under the assumption that the 50% of the PV systems at each load center are utility-scale PV power plants, and the rest are the small-scale PV systems in the residential area.

Table IX compares the CCT under 3LG faults at various locations. The CCT is used as an index for the short-term voltage stability because a voltage collapse occurs within 3 s when the system is unstable. The notation “n − m” represents the 3LG fault that occurs near bus n and is cleared by opening one circuit of the line n − m. Here, we select fault locations where the CCT in case I is less than 0.07 s—a value that is close to the general fault clearing time in Japan. As summarized in Table IX, CCTs are improved by the PV operation at the leading power factor and by adding the DVS capability. In particular, the DVS capability significantly helps in maintaining the stability of the entire power system.

Figs. 17–19 show the results in each comparative case under the fault “11–15” for 0.07 s. In case I, a voltage collapse occurs before 1 s owing to the interruption of all the PV systems. The voltage collapse causes the step-out of generators. In case II, although every PV system shuts off as it does in case I, voltage collapses occur at limited load centers (L1, L2, L3, and L5) near the fault location owing to the effect of the leading-power-factor operation. These voltage collapses lead to the large excursion of the rotor angles, but the generators maintain synchronism in case II. The abovementioned instability is avoided in case III by the dynamic control of reactive power using the inverters. Half of the PV system at L3, L4, and L5 triggers reactive power injection right after the fault occurs because the voltage at the load bus does not fall below 0.2 p.u. The rest of the PV systems at these buses and the PV systems at L1 and L2 shut off during the fault and start to control the reactive power after the voltage recovers subsequent to fault clearing. Although hunting of the PV systems is not observed in this study, coordination between the PV systems should be considered for other instability phenomena such as small-signal stability.
B. Discussion on Location of DVS

To investigate the impact of the location of the PV system that has the DVS capability on the effect of the stability improvement, we compare several simulation cases for the five-machine five-load power system, as summarized in Table X. Here, we assume that 50% of the PV system at one of the load centers has the DVS capability. The PV systems operate at the leading power factor in every case; therefore, the base case in Table X is identical to case II in Table IX.

As summarized in Table X, the effect of the DVS capability is dependent upon the location of the PV power plant that has the DVS capability. For the fault “11–15,” reactive power injection at L1, L2, or L3 is effective between the comparative cases. This is because reactive power injection at L1, L2, or L3 contributes to the deceleration of the critical generators such as G1–G3 (see Figs. 17–19) in addition to its effect on the local voltage support. Because the short-term voltage stability is closely related to the transient stability [15], reactive power injection by the PV inverter tends to be effective for the short-term voltage stability when the control action simultaneously improves the transient stability.

VI. CONCLUSION

This study analyses the impact of PV installation on the short-term voltage stability and tests the effect of two countermeasures using PV inverters on the short-term voltage stability. Numerical examples show that the installation of PVs severely impairs the short-term voltage stability of the power generation system if the PV system shuts off after a voltage sag, and its FRT capability to return to the specified power output is low. Under such an unstable condition, operating the PV system at a leading power factor and deploying PV equipment with the DVS capability can be effective ways of improving the short-term voltage stability. The countermeasures are preferable in terms of cost because they require less apparent power capacity of the inverter than its controlled reactive power, though the control action can be taken only at load centers and may not necessarily be effective for maintaining the stability of bulk power systems, such as transient stability.

In our future works, other countermeasures such as emergency control of a battery energy storage system will be studied to facilitate the installation of a large amount of PV capacity while simultaneously ensuring transient stability. Coordination between PV systems that have the DVS capability and other controllers should also be considered to avoid other instability phenomena such as small-signal instability.
The transient \( P-V \) curve that has been proposed in [16] can be depicted for a given time step during the transient period by changing the slip of the IM load over the entire operating range. When we depict the transient \( P-V \) curve for the test system shown in Fig. 4, the internal voltage of the PV system is fixed at the given time step. The transient \( P-V \) curve represents the power transfer to the load at a given time while reflecting the operating condition of the PV system.

On the other hand, the stability boundary that we have proposed in [9] enables us to distinguish the sign of the time derivative of the IM speed in the \( P-V \) plane. Given that the conductance of the induction motor load takes the maximum value when the rotor speed \( \omega \) is equal to \( \omega_1 \), the stability boundary is depicted for two operating ranges, as shown in Fig. 20. The stability boundary in Fig. 20(a) divides the region above the load characteristic curve at \( \omega = \omega_1 \) into two areas. The left side of the region represents the unstable region where the induction motor decelerates, whereas the other side represents the stable region. The stability boundary for the operating range of \( \omega \geq \omega_1 \) also defines the stable and unstable regions, as shown in Fig. 20(b). In this paper, the stability boundary for the operating range of \( 1 > \omega > \omega_1 \) is shown in the numerical examples because the unstable equilibrium point (UEP) for a voltage instability phenomenon exists on the stability boundary for the operating range of \( 1 \geq \omega > \omega_1 \) in the numerical examples.

The analytical method using the transient \( P-V \) curves and stability boundary has been applied to a single-load infinite bus system which neglects dynamic characteristics of synchronous generators in [9]. The analytical method should be developed for multi-machine systems to make it applicable to a practical network analysis, evaluation, and control in our future works. So far, a related fundamental study have been carried out in [15] where the method to depict the transient \( P-V \) curves for a multi-machine system is proposed.

REFERENCES


K. Kawabe (M’12) received the B.S. degree from Waseda University, Tokyo, Japan, in 2007 and the M.S. and Ph.D. degrees from the University of Tokyo, Tokyo, Japan, in 2009 and 2012, respectively. He has been with the Graduate School of Science and Engineering, University of Toyama, since 2012 as a visiting assistant professor and teaches power system engineering.

K. Tanaka received the B.S., M.S., and Ph.D. degrees in engineering from the Graduate School of Kyushu University, Fukuoka, Japan, in 1974, 1976, and 1996, respectively. He joined the Central Research Institute of Electric Power Industry (CRIEPI) in 1976 and served as a visiting researcher at the University of Texas, Arlington, TX, USA, from 1981 to 1982. He served as a visiting professor at Tohoku University from 2006 to 2009. He has been with the Graduate School of Science and Engineering, University of Toyama, since 2012 as a visiting professor and teaches power system engineering.