Transient Stability Assessment of Synchronous Generator in Power System with High-Penetration Photovoltaics

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Abstract: As photovoltaic (PV) capacity in power system increases, the capacity of synchronous generator needs to be reduced relatively. This leads to the lower system inertia and the higher generator reactance, and hence the generator transient stability may negatively be affected. In particular, the impact on the transient stability may become more serious when the considerable amounts of PV systems are disconnected simultaneously during voltage sag. In this work, the generator transient stability in the power system with significant PV penetration is assessed by a numerical simulation. In order to assess the impact from various angles, simulation parameters such as levels of PV penetration, variety of power sources (inverter or rotational machine), and existence of LVRT capability are considered. The simulation is performed by using PSCAD/EMTDC software.

Key words: High-penetration photovoltaics, low-voltage ride-through (LVRT), synchronous generator, transient stability.

1. Introduction

Photovoltaic (PV) is a simple, low risk and a clean power source with few environmental impact. With the increasing concerns about global warming, the number of PV installations is, therefore, rapidly growing worldwide [1]. However, the expanding installation of PV can have a significant impact on the power system behavior.

With the increasing of PV capacity in the power system, several thermal power plants need to be closed down or at least the output power of thermal unit must be decreased in order to maintain power supply-demand balance. However, as the generator operation with low output leads to an increase in operating costs, reduction of the generator capacity would mainly be taken. As a result, the transient stability would negatively be affected due to the lower system inertia and the higher generator reactance. On the other hand, when a fault occurs in the power system, some parts of PV systems may be disconnected from the power system due to the voltage sag. The disconnection causes a drop in PV generation, and hence a further drop in terminal voltage may be induced. Eventually, the considerable amounts of PV systems may be disconnected from the power system. In this case, not only the transient stability would be affected, but also the frequency stability would significantly be affected due to the large power imbalance and the fewer frequency control generators. In order to prevent the frequency drop, power system operators would require PV systems to be equipped with low-voltage ride through (LVRT) capability. LVRT requirements stipulate that PV needs to stay connected during a temporary fault to provide post-fault voltage support [2]. The LVRT
capability of PV, therefore, would reduce the negative impact on the frequency stability. On the other hand, the transient stability may negatively be affected because the generator output after a fault clearing cannot be enlarged due to the active power from PV systems with LVRT capability.

This paper presents a case study assessing the impact of high-penetration PV on the transient stability. In order to assess the impact from various angles, simulation parameters such as levels of PV penetration, variety of power sources (inverter or rotational machine), and existence of LVRT capability are considered. The simulation is performed by using PSCAD/EMTDC software. The paper is organized as follows: Section 2 describes the simulation model; section 3 presents the simulation results and discussions; section 4 gives conclusions.

2. Simulation Model

2.1 Power System Model

Fig. 1 shows the power system model used in the simulation analysis. A synchronous generator (SG1) is connected to an infinite bus through a transformer and a double circuit transmission line. To the single-machine infinite-bus system, a large-scale PV plant (PV) or another synchronous generator (SG2) is connected via a transformer and a short transmission line. In the case with PV connected, three levels of PV capacities (10%, 30% and 50% for the power system capacity of 1000 MVA) are considered. Here, the transformer capacity in each case is also changed depending on changed generation capacity. In addition, the existence of LVRT capability is considered for PV inverter. The PV inverter without LVRT capability is disconnected from the power system when its terminal voltage drops below the specified value. The value is set to 70% of the nominal voltage [3]. In the case with SG2 connected, three levels of generation capacities (10%, 30% and 50%), same situation as those in the case of PV connection, are considered. Per unit values on the power system base of 1000 MVA are shown in Table 1. Automatic voltage regulator (AVR) and governor (GOV) control system models [4] shown in Fig. 2 have also been included in each generator model. In the power system model, the symmetrical three-line-to-ground (3LG) fault is assumed as network disturbance. The fault occurs near SG1 at 0.1 sec, the circuit breakers on the faulted lines are opened at 0.17 sec, and at 1.17 sec, they are reclosed.

2.2 PV System Model

The PV system model is shown in Fig. 3. It consists of PV module, inverter and low-pass (LC) filter. The PV module is represented with a voltage source, and hence the PV output is constant under the steady state. This means irradiation and PV cell temperature are constant during the simulation period. The assumption, therefore, may be valid for the transient stability analyses.

The genetic pulse-width modulation (PWM) voltage source converter is used as PV inverter. The inverter controls the active and reactive power injected from the PV module to the system. To maintain the active and reactive power at the reference set points, the currents of the inverter are controlled by using vector control technique. A phase lock loop (PLL) is used to obtain the theta which is used for abc to dq0 transformation of grid side current. The error
Table 1  Synchronous generator parameters.

<table>
<thead>
<tr>
<th>Generator parameters</th>
<th>Ra (pu)</th>
<th>Xd'' (pu)</th>
<th>Xl (pu)</th>
<th>Xq'' (pu)</th>
<th>Xd (pu)</th>
<th>Td' (sec)</th>
<th>Td'' (sec)</th>
<th>Xq (pu)</th>
<th>Tq'' (sec)</th>
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<td>Tq'' (sec)</td>
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<td>H (s)</td>
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Fig. 2  AVR and governor models.

Fig. 3  Control block diagram of PV inverter.

3. Simulation Results

3.1 Impact of PV Penetration Level

Fig. 4 shows load angle responses of the generator SG1 in three simulation conditions in terms of PV capacity. Here, PVs do not have LVRT capability (i.e., PV is disconnected from the power system when its terminal voltage drops below the specified voltage of 0.7 pu). As can be seen, the load angle swings are restrained in the cases of the lower capacity PV (i.e., the higher penetration PV). This is because of the following reasons: (1) If the generator output is low, the difference between the mechanical input power and the electrical output power in the generator during the fault becomes small. Therefore, also the kinetic energy stored during the period of acceleration becomes small; (2) The initial load angle of the generator becomes small. Therefore, the first peak of the load angle swing is restrained. In general, the phase angle between the induced voltage in generator and the infinite bus voltage decreases if the generator output is reduced.

On the other hand, the synchronous reactance becomes large and the rotational inertia becomes small in the cases of the lower generator capacity. In this work, the rotational inertia is changed in proportion to the generator capacity as described in Table 1. In general, the transient stability would negatively be affected for these operating conditions. Fig. 5 shows the rotor speed responses of SG1 for each case. In the case of SG1 with capacity of 500 MVA, the first peak of rotor speed swing becomes large so much because the rotor inertia is small. However, the convergence of swing is faster than others. As mentioned earlier, this is because the kinetic energy stored in the rotor during the fault is small.
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Fig. 4 Load angle of SG1 for each PV capacity case.

Fig. 5 Rotor speed of SG1 for each PV capacity case.

In Ref. [5-6], the authors proposed a stability index, \( W_c \), given by

\[
W_c \text{ (sec)} = \int_0^T \frac{d}{dt} \left[ \frac{d}{dt} W \right] dt / \text{system base power} \tag{1}
\]

where \( W \) is kinetic energy and \( T \) is the simulation time. \( W_c \) is an integrated variation of the energy exchanged between the generator rotor and the power system; thus, the lower the value of the parameter, the smaller the transient swing. Table 2 indicates \( W_c \) for each case. Here, \( T \) is selected as 10 sec. As can be seen, \( W_c \) becomes small in the cases of the smaller generator capacity. Therefore, it can be considered that the value of the output power of SG1 exerts a dominant influence on the transient stability compared with the synchronous reactance and the rotational inertia.

| Table 2 Stability index \( W_c \) for each PV capacity case. |
|-----------------|-----------------|-----------------|
| SG1(MVA):PV(MW) or SG2 (MVA) | 900:100 | 700:300 | 500:500 |
| SG1-SG2 | 0.75 | 0.83 | 0.52 |
| SG1-PV with LVRT | 0.79 | 0.73 | 0.33 |
| SG1-PV without LVRT | 0.72 | 0.48 | 0.28 |

3.2 Impact of Power Source Variety and LVRT Capability

Fig. 6 shows the load angle responses of SG1 under the conditions as follows: (1) connecting SG2 instead of PV, (2) connecting PV with LVRT capability, and (3) connecting PV without LVRT capability. Also, three simulation conditions in terms of the penetration level of SG2 or PV are considered. \( W_c \) for each case is shown in Table 2. From the results, it can be said that the transient stability is better in the cases of the higher penetration PV without LVRT. Consideration for the result is as follows.

As can be seen in Fig. 6, the initial value of the load angle in each case is the same because the power flow in the steady state is the same. Also, the terminal voltage of SG1 during the fault becomes almost zero in all of the cases. Therefore, it can be considered that the load angle responses depend on the conditions of the power flow after the fault clearing.

Figs. 7-8 show the responses of the active power of SG1 and PV (or SG2) respectively. In Fig. 7, the average of the active power in the period of a few cycles after the fault clearing in the case of “PV without LVRT” becomes larger than those in other cases. As can be seen in Fig. 8, this is because the active power of PV becomes zero after the fault clearing, and hence the power load of SG1 increases. As the prime-mover mechanical power cannot be increased quickly, the output power of SG1 is supplied from the kinetic energy which is stored during the period of acceleration. The kinetic energy stored in the rotor is released quickly, and hence the load angle swing is restrained.
Fig. 6  Load angle of SG1 for each power source case.

(a) SG1(MVA) : PV(MW) or SG2 (MVA) = 900 : 100

(b) SG1(MVA) : PV(MW) or SG2 (MVA) = 700 : 300

(c) SG1(MVA) : PV(MW) or SG2 (MVA) = 500 : 500

Fig. 7  Active power of SG1 for each power source case.

(a) SG1(MVA) : PV(MW) or SG2 (MVA) = 900 : 100

(b) SG1(MVA) : PV(MW) or SG2 (MVA) = 700 : 300

(c) SG1(MVA) : PV(MW) or SG2 (MVA) = 500 : 500
Fig. 8 shows the responses of phase-A current of PV (or SG2). In the cases of “SG2” and “PV with LVRT”, the power sources maintain the connection with the power system during the fault. Therefore, the current flows from the power source to the system during the fault, and it becomes larger than the steady current due to the low impedance of the power system. Also, in the case of “PV with LVRT”, as PV inverter is controlled to maintain both active and reactive power at the reference set points, the large current flows from PV to the inverter when the voltage drops. In the case of “PV without LVRT”, PV produces maximum peak current between 0.8 to 1.2 pu depending on the penetration level of PV. However, the rate of increase is not large because the steady current is also increased. Also, dc component of the currents in all of the cases is decreased rapidly. On the other hand, SG2 produces the maximum peak current between about 0.8 to 2.8 pu, and the rate of increase becomes larger than that of PV. This is because sub-transient reactance of the generator becomes small in the cases of the larger generator capacity. In this way, as PV inverter does not have sub-transient and transient effects associated with the synchronous generator, the rate of increase of the maximum peak current for the increase of the penetration level is small and the dc component of the current during the fault is decreased rapidly compared with those in the case with the generator connected.

4. Conclusions

PV capacity has been increasing significantly due to the environmental concerns regarding global warming. In response to an increase of PV capacity, the capacity of conventional synchronous generator needs to be reduced relatively. This leads to the lower system inertia, the higher generator reactance and the fewer frequency control generators. Therefore, the analysis of impact of the high-penetration PV on the transient stability has become a very important issue.
This paper presents a case study assessing the impact of high-penetration PV on the transient stability of the synchronous generator. In order to assess the impact from various angles, simulation parameters such as levels of PV penetration, variety of power sources (inverter or rotational machine), and existence of LVRT capability are considered. Through the simulation results, it is concluded that the transient stability is better for the cases of the higher penetration PV without LVRT capability.

Moreover, this paper discusses the fault current characteristics of PV. As PV does not have sub-transient and transient effects associated with the synchronous generator, the maximum peak current is small and the dc component of the current during the fault is decreased rapidly compared with those in the case with the generator connected.

Acknowledgments

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References