Transient Stability Assessment of Synchronous Generator in Power System with High-Penetration Photovoltaics (Part 2)

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Abstract: In the previous paper [1], the transient stability of synchronous generator in power system with high-penetration PV (photovoltaic) was assessed by simulation analysis of a single-machine infinite-bus system model. Through the simulation analysis, we have obtained some conclusions in terms of the impact of high-penetration PV on the stability. However, for more accurate assessment of the transient stability, it is necessary to analyze various simulation models considering many other power system conditions. This paper presents the results of the analysis for the transient stability simulation performed for IEEE 9-bus system model, in which the effects of various conditions, such as variety of power sources (inverter or rotational machine), load characteristics, existence of LVRT (low-voltage ride-through) capability and fault locations, on the transient stability are investigated.

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

1. Introduction

After the Fukushima nuclear power plant accident in Japan, the investment in the field of PV (photovoltaic) power generation has been increasing. During 2013, a total of 6.9 GW of PV was installed in Japan, 400% increase beyond the installation in the previous year (1.7 GW). Cumulative installed capacity of PV systems in 2013 reached 13.6 GW [2].

With the increasing of PV capacity in the power system, the capacity of conventional synchronous generators needs to be reduced relatively. This leads to the lower system inertia, the higher generator reactance and the fewer frequency control generators, and hence the synchronous generator transient stability may negatively be affected.

In the previous paper [1], the results of the simulation analysis of the synchronous generator stability for a single-machine infinite-bus system with

PV installed were presented. Through the simulation analysis, we have obtained the fundamental characteristics of the transient stability in the power system with PV installed, and it was concluded that the transient stability becomes better in the cases of the higher penetration PV without LVRT (low-voltage ride-through) capability. However, this conclusion is for a case study using the single-machine infinite-bus system model. For more accurate assessment of the transient stability and the dynamic characteristics of the power system with PV installed, it is necessary to analyze various simulation models considering many other power system conditions.

In this work, the transient stability simulation is performed for IEEE 9-bus system model [3], in which the effects of various conditions, such as variety of power sources (inverter or rotational machine), load characteristics (constant impedance or power), fault locations (6 fault points) and existence of LVRT capability, on the stability are investigated. The

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Table 1 Synchronous generator parameters.

	Generator parameters				
	SG1	SG2	SG1	SG2	
R_a (pu)	0.003	0.004	X_q'' (pu)	0.171	0.134
X_l (pu)	0.102	0.078	T_d' (sec)	5.9	8.97
X_d (pu)	1.651	1.22	T_d'' (sec)	0.535	1.5
X_q (pu)	1.59	1.16	T_q'' (sec)	0.033	0.033
X_d' (pu)	0.232	0.174	H (s)	3.0	3.0
X_d'' (pu)	0.171	0.134

Fig. 2 Control block diagram of PV inverter.

few seconds to several tens of seconds. The assumption, therefore, may be valid for the transient stability analyses.

The genetic PWM (pulse-width modulation) 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. The current limitation for over current is not considered in this model. Currently, most of the PV inverters are designed to operate at unity power factor [5], and therefore, the reference value of the reactive power is set to zero in each case.

2.3 Load Model

A static load model can be expressed as algebraic functions of the bus voltage magnitude. The voltage

dependency characteristic of load is represented by the exponential model [6]:

$$P = P_0 \left(\frac{V}{V_0} \right)^a \quad (1)$$

$$Q = Q_0 \left(\frac{V}{V_0} \right)^b \quad (2)$$

where, P and Q are active and reactive components of the load when the bus voltage magnitude is V . The subscript 0 means the values of the respective variables at the initial operating condition. The parameters of this model are the exponents a and b . If these exponents equal to 0, 1, or 2, the model represents “constant power”, “constant current” or “constant impedance” characteristics respectively. In this simulation, two load models, the constant power and the constant impedance expressed by exponents of 0 and 2, are considered.

3. Simulation Results

3.1 Impact of LVRT Capability

The phase angle responses of SG1 in the case of fault point F1 are shown in Fig. 3. To compare the effects of the conventional rotating machine and PV system on transient stability, we have considered three simulation conditions in terms of the power sources as follows: (1) connecting SG2 instead of PV, (2) connecting PV with LVRT capability, and (3) connecting PV without LVRT capability. The load models of the constant impedance are used for all of the simulation conditions.

As can be seen, the first peak of the phase angle swing is decreased in the case of PV without LVRT. In other words, risk of out-of-step of the synchronous generator becomes low in the power system with PV without LVRT installed.

Fig. 4 shows the first peaks of the phase angle swings of SG1 in the case of each fault point. In all of the fault point cases, the first peaks of the phase angle swings in the case of PV without LVRT are restrained more than those in other cases. This is because the kinetic energy stored in the rotor of SG1 can be released quickly compared with other cases. Fig. 5 shows the kinetic energy responses of SG1 in the case of fault point F1. As can be seen, in the case of PV without

Fig. 3 Phase angle of SG1 for each power source (fault point F1).

Fig. 4 First peak of phase angle swing of SG1 for each power source.

Fig. 5 Kinetic energy of SG1 for each power source (fault point F1).

LVRT, the kinetic energy stored in the rotor of SG1 can be released quickly compared with other cases.

Fig. 6 shows the stability index, W_c [1, 7-9], in each fault point case. 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 shorter the convergence time of the swing. In this work, the simulation time of $t = 30$ (s) is used to calculate W_c . As can be seen, in most of the fault point cases, W_c is decreased in the case of PV without LVRT. Namely, the convergence of the kinetic energy swing becomes fast in this case.

Fig. 6 Stability index W_c for each fault point.

Fig. 7 Phase angle of SG1 for each load model (fault point F1).

3.2 Impact of Load Characteristics

Fig. 7 shows the phase angle responses of SG1 in the cases where each load model and PV without LVRT are considered. The load model of the constant impedance or the constant power, represented by Eqs. (1) and (2), is used in the simulation. As can be seen, the first peak of the phase angle swing in the case of the constant impedance load is smaller than that in the case of the constant power load.

Fig. 8 shows the active power of SG1. After the fault clearing, the active power of SG1 in the case of the constant impedance load becomes slightly larger

than that in the case of the constant power load. As a result, the kinetic energy stored during the period of acceleration is released quickly.

The kinetic energy responses of SG1 are shown in Fig. 9. The first peaks of the phase angle swings and the stability index W_c of SG1 in the case of the use of each load model are shown in Fig. 10. As a whole, values in the case of the constant power load are slightly larger in most cases than those in the case of the constant impedance load. Namely, the generator stability becomes slightly lower in the case of the constant power load.

Fig. 8 Active power of SG1 for each load model (fault point F1).

Fig. 9 Kinetic energy of SG1 for each load model (fault point F1).

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Fig. 10 Comparison of constant power load and constant impedance load.

4. Conclusions

With the increasing of PV capacity in the power system, the transient stability of the conventional synchronous generator may negatively be affected due to the lower system inertia and the higher synchronous reactance.

In this work, the transient stability simulation is performed for IEEE 9-bus system model, in which the effects of various parameters, such as variety of power sources (inverter or rotational machine), load

characteristics, fault locations and existence of LVRT capability, on the stability are investigated. Through the simulation results, it is concluded that the risk of out-of-step of the synchronous generator becomes low in the case of the use of PV without LVRT capability because the disconnection of PV system after the network disturbance increases the power load of the synchronous generator.

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References

- [1] Yagami, M., Hasegawa, T., and Tamura, J. 2012. "Transient Stability Assessment of Synchronous Generator in Power System with High-Penetration Photovoltaics." *Journal of Mechanics Engineering and Automation* 2: 762-8.
- [2] Photovoltaic Power Systems Programme. 2014. *Trends 2014 in Photovoltaic Applications*. Report IEA-PVPS T1-25.
- [3] Anderson, P. M., Fouad, A. A. 2000. *Power System Control and Stability*. New York: John Wiley & Sons, Inc.
- [4] Website of PSCAD. <https://hvdc.ca/pscad.html>.
- [5] Kobayashi, H., and Suzuki, A. 2010. *Stable Operation Technique for PCS of PV Power Generation at Grid Recovery after Voltage Sag*. System Engineering Research Laboratory, Rep. No. R09015. (in Japanese)
- [6] Kundur, P. 1994. *Power System Stability and Control*. New York: McGraw-Hill, Inc.
- [7] Yagami, M., Murata, T., and Tamura, J. 2004. "An Analysis of Optimal Reclosing for Enhancement of Transient Stability." *Electrical Engineering in Japan* 147: 32-9.
- [8] Yagami, M., and Tamura, J. 2007. "Improvement of Power System Transient Stability Using Superconducting Fault Current Limiter." *Trans. on Systems, Signals & Devices* 2 (2): 197-211.
- [9] Yagami, M., and Tamura, J. 2012. "Hybrid Operation of Fault Current Limiter and Thyristor Controlled Braking Resistor." *Journal of Energy and Power Engineering* 6: 601-8.