

Transient Stability Analysis of Synchronous Generator in Power System with Renewable Power Sources Installed

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Abstract: The impact of large-scale grid-connected renewable power sources, such as wind generators and solar photovoltaic systems, on transient stability of synchronous generators is discussed in this paper. The permanent magnet synchronous generator with variable speed wind turbine is used in the simulation analysis as a wind generator model. The transient stability analysis is performed for IEEE 9-bus system model with high-penetration renewable power sources. The effect of FRT (fault ride-through) capability implemented for each power source on the transient stability is investigated.

Key words: Fault ride-through, variable speed wind generator, photovoltaic, synchronous generator, transient stability.

1. Introduction

In Japan, with the increasing concerns about global warming and the start of the FIT (Feed-in Tariff) program in July 2012, the amount of renewable power sources, such as WG (wind generators) and solar photovoltaic (PV) systems, has been increasing. At the end of 2015, the total cumulative installed capacity of WG and PV in Japan reached 3.0 GW [1] and 34.2 GW [2] (around 0.5% and 3.5% of the total power supply) respectively. From the viewpoint of environmental conservation, the amount of the grid-connected renewable power sources is expected to increase continuously. However, the expanding installation of renewable power sources has a significant impact on power system dynamics and stability [3, 4].

Currently, most of WG and PV systems do not have FRT (fault ride-through) capability. Their impact on the stability may become more serious when the considerable amounts of WG and PV systems are disconnected simultaneously during voltage sag.

Moreover, with the increasing of capacity of renewable power sources in the power system, the total capacity of conventional synchronous generators needs to be reduced relatively. This leads to the higher generator reactance and the fewer frequency control generators, and hence the power system transient stability may negatively be affected.

In this work, the potential impact of large-scale grid-connected WG or PV systems on the transient stability of the conventional synchronous generator is assessed by a numerical simulation analysis using PSCAD/EMTDC software. The PMSG (permanent magnet synchronous generator) with VSWG (variable speed wind turbine) is used in the simulation analysis as a WG model. The simulation analysis is performed for IEEE 9-bus system model with each power source installed. The effect of FRT capability implemented for each power source on the transient stability is investigated.

2. Simulation Model

2.1 Power System Model

Fig. 1 shows the power system model [5], which is

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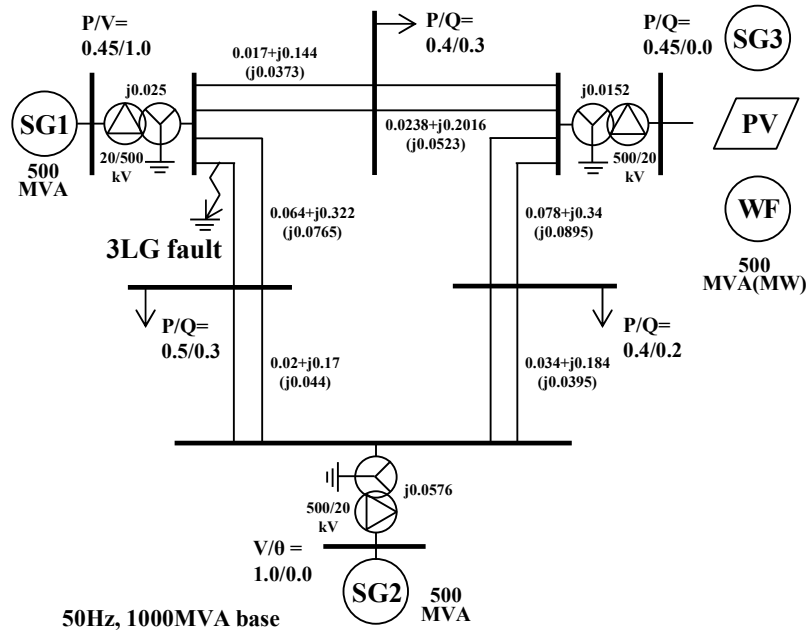


Fig. 1 Power system model.

Table 1 Synchronous generator parameters.

	Generator parameters			
	SG1	SG2, SG3	SG1	SG2, SG3
R_a (pu)	0.003	0.004	X_d'' (pu)	0.171
X_l (pu)	0.102	0.078	X_q'' (pu)	0.171
X_d (pu)	1.651	1.22	T_{do}' (s)	5.9
X_q (pu)	1.59	1.16	T_{qo}' (s)	0.535
X_d' (pu)	0.232	0.174	T_{do}'' (s)	0.033
X_q' (pu)	0.38	0.25	T_{qo}'' (s)	0.078
H (s)	3.0			0.141

composed of three power sources: one synchronous generator of 500 MVA (SG1), another synchronous generator of 500 MVA (SG2), and the third source, which is one of a large-scale PV plant of 500 MW (PV) or a wind farm of 500 MVA (WF) composed of one hundred VSWGs ($5 \text{ MW} \times 100$) or a third synchronous generator of 500 MVA (SG3). Each power source is connected through step up transformer to 500 kV bus and double circuit transmission lines. The impedances and the initial power flows are shown in per unit values on the power system base of 1,000 MVA in the figure.

The parameters used for each synchronous generator are shown in Table 1. AVR (automatic voltage regulator) [6] and governor control systems shown in Fig. 2 are included in each synchronous

generator model. In the cases with PV and WF installed, the existence of FRT capability is considered for each power source. FRT characteristic considered in this work is simple. The power converter with FRT capability maintains connection to the grid even if its terminal voltage is dropped. On the other hand, the power converter without FRT capability is disconnected from the grid when its terminal voltage drops below 70% of the nominal voltage [7].

In the power system model, a symmetrical 3LG (three-line-to-ground) fault is assumed as network disturbance. The fault occurs near SG1 at 0.1 s, the circuit breakers on the faulted lines are opened at 0.17 s, and at 1.17 s, they are reclosed.

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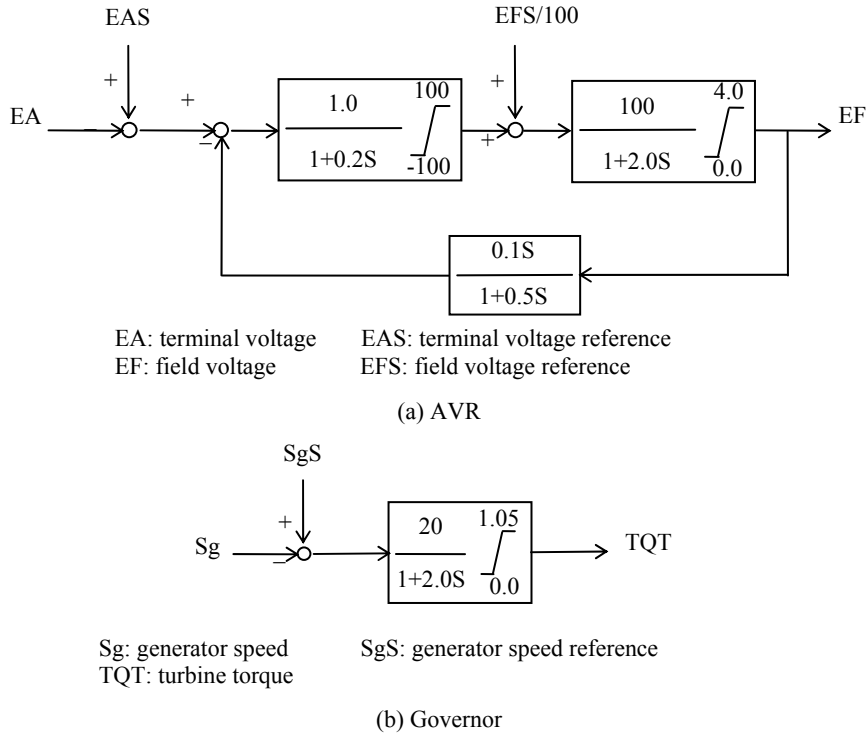


Fig. 2 AVR and governor models.

2.2 PV System Model

PV system model is shown in Fig. 3. It consists of PV module and inverter. 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. In general, transient stability is analyzed in a time window of a 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 [7], and therefore the reference value of the reactive power is set to zero in each case.

2.3 VSWG System Model

A simplified VSWG model composed of a three phase current source [8] shown in Fig. 4 is used in this paper. The simplified model is effective on the analysis of the power system with a large number of wind generators which cannot be analyzed by using the detailed model. In this work, WF is composed of one hundred VSWGs each rated at 5 MW. VSWG parameters are shown in Table 2.

The mechanical output power of wind turbine captured from the wind power can be calculated as follows:

$$P_w = \frac{1}{2} \rho \pi R^2 V_w^3 C_p(\lambda, \beta) \quad (1)$$

where, P_w is the captured wind power, ρ is the air density, R is the radius of rotor blade, V_w is wind speed, C_p is the power coefficient, λ is tip speed ratio and β is blade pitch angle. In this simulation, V_w is kept constant at 11.1 (m/s) at which the VSWG reference power is 0.9 pu (generator capacity base), based on the assumption that the wind speed does not change dramatically within this small time duration.

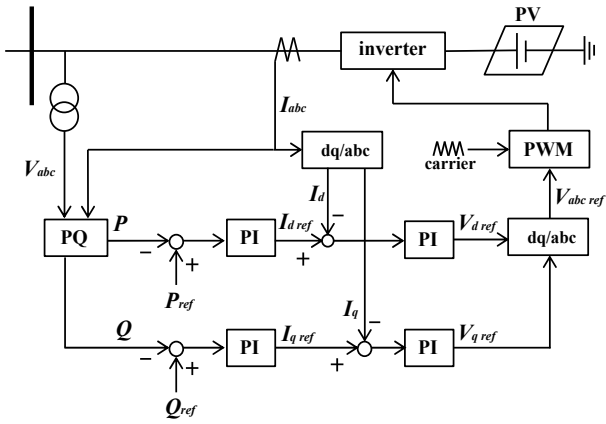


Fig. 3 PV system model.

The drive train composed of wind turbine, shaft and generator is modeled using the single rotating mass model:

$$T_m - T_e = J_t \frac{d\omega_r}{dt} \quad (2)$$

where, T_m , T_e , J_t and ω_r are mechanical torque, electrical torque, total moment of inertia of entire mechanical system, and rotor speed of the wind turbine respectively.

The dynamic model of PMSG in the d-q rotating reference frame is expressed by the following equations.

$$V_{sd} = R_s I_{sd} + L_{sd} \frac{dI_{sd}}{dt} - \omega_e L_{sq} I_{sq} \quad (3)$$

$$V_{sq} = R_s I_{sq} + L_{sq} \frac{dI_{sq}}{dt} + \omega_e L_{sd} I_{sd} + \omega_e \psi_m \quad (4)$$

where V_{sd} and V_{sq} are stator voltages, R_s is the stator winding resistance, I_{sd} and I_{sq} are stator currents, ω_e is the generator rotational speed, L_{sd} and L_{sq} are the synchronous inductances of stator winding, and ψ_m is the flux of permanent magnet.

Active and reactive powers of PMSG are expressed as follows:

$$P_s = V_{sd} I_{sd} + V_{sq} I_{sq} \quad (5)$$

$$Q_s = V_{sq} I_{sd} - V_{sd} I_{sq} \quad (6)$$

The electrical torque of PMSG can be expressed as follows:

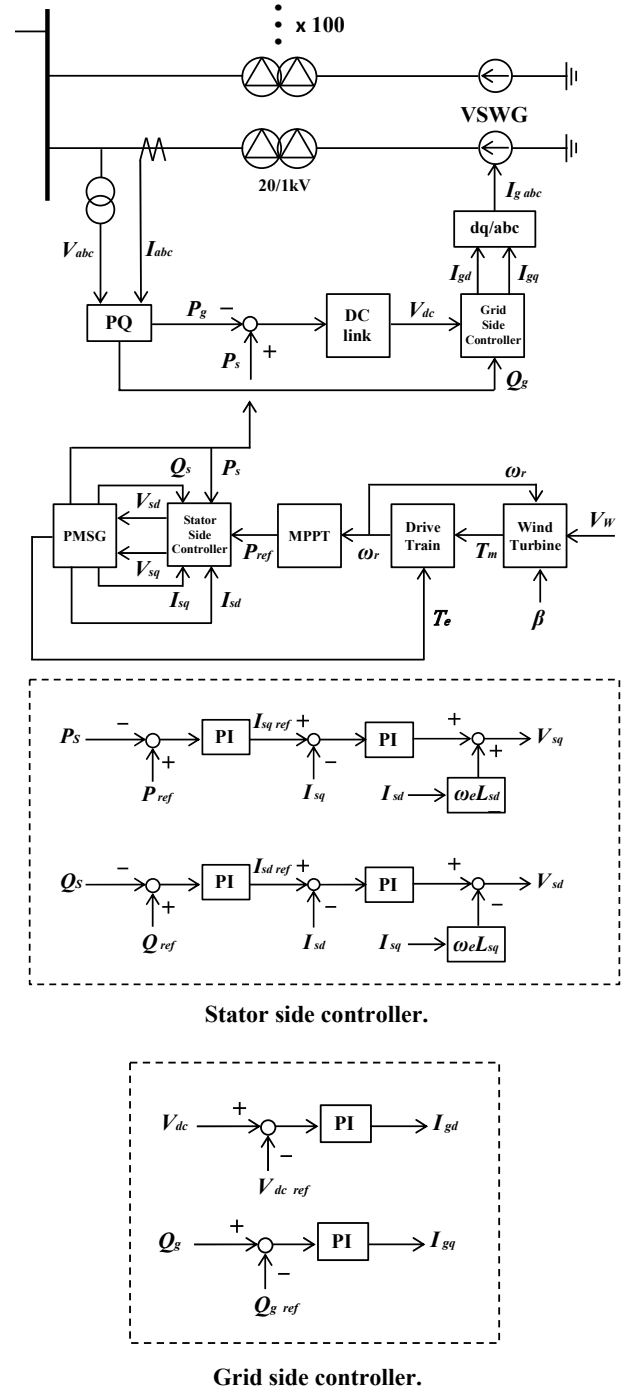


Fig. 4 VSWG system model.

$$T_e = p(\psi_m I_{sq} + (L_{sd} - L_{sq}) I_{sd} I_{sq}) \quad (7)$$

where, p is the number of pole pairs. The dynamic behavior of DC capacitor voltage (V_{dc}) can be expressed by the following equation if the power losses of DC-link are neglected.

Table 2 VSWG parameters.

VSWG parameters		
Wind turbine	R (m)	60
	V_w (m/s)	11.1
	ω_r (rad/s)	1.51
	C_{popt}	0.48
	λ_{opt}	8.2
	ρ (kg/m ³)	1.225
	J_t (kgm ²)	49.5×10^6
PMSG	P_s (MW)	5
	V_s (kV)	1.0
	R_s (Ω)	0.004
	L_{sd} (mH)	1.528
	L_{sq} (mH)	1.21
	ψ_m (Wb)	11.255
	C_{dc} (μ F)	2,500
	V_{dc} (kV)	1.75

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}V_{dc}}(P_s - P_g) \quad (8)$$

where, C_{dc} is the value of DC-link capacitor and P_g is active power delivered to the grid.

3. Simulation Results

3.1 Simulation Results in Case with FRT Implemented

First, the transient stability of SG1 in the power system with each power source installed with FRT capability implemented is discussed. In the case with FRT capability implemented, the power supply from each power source (SG3, PV, WF) is maintained after the fault.

Figs. 5 and 6 show the responses of phase angle and kinetic energy of SG1 respectively. The phase angles shown are displacement angle with respect to the phase angle of the swing generator SG2. As shown in Fig. 5, the first peaks of the phase angle swings of SG1 in the cases with PV and WF installed are restrained more than that in the case with SG3 installed. Namely, the risk of out-of-step of the synchronous generator becomes low in the power system with PV or WF installed with FRT capability implemented. However, the kinetic energy swings of SG1 are larger than that in the case with SG3 installed as shown in Fig. 6. The acceleration or deceleration of the rotor causes severe mechanical stresses.

Figs. 7-9 show the responses of active power, reactive power and terminal voltage of SG1 respectively. The active power in the case with SG3 installed rises up immediately after the fault clearing. This is because, as shown in Fig. 9, the terminal voltage of SG1 rises also up immediately after the fault clearing. As the period of condition of the unbalance between the mechanical input power and the electrical output power of SG1 is short, SG1 is subjected to the smaller accelerating power. On the other hand, in the case with PV installed, it takes time to recover the active power and the terminal voltage after the fault clearing. Therefore, in the case with PV installed, SG1 is subjected to the larger accelerating power, and hence the kinetic energy swing becomes large.

Figs. 10-13 show the responses of active power, reactive power, terminal voltage of each power source and DC-link voltage of VSWG. In the case with SG3 installed, as shown in Fig. 11, SG3 supplies a sufficient reactive power after the fault. As a result, the terminal voltage of SG3 rises up significantly after the fault clearing. The reactive power of WF also increased after the fault. Moreover, as shown in Fig. 13, DC-link voltage of the grid side converter rises up after the fault due to the power unbalance between the generator side converter and the grid side converter during the fault. For these reasons, the magnitude of voltage sag of WF during the fault is small. On the other hand, as shown in Fig. 12, the magnitude of voltage sag of PV is large. This is because the reactive power of PV cannot increase significantly due to the constant power control of the PV inverter.

3.2 Simulation Results in Case without FRT Implemented

Next, the transient stability of SG1 in the power system with each power source (PV, WF) installed without FRT capability implemented is discussed. It is assumed that each power source is disconnected from the grid when its terminal voltage drops below 70% of the nominal voltage.

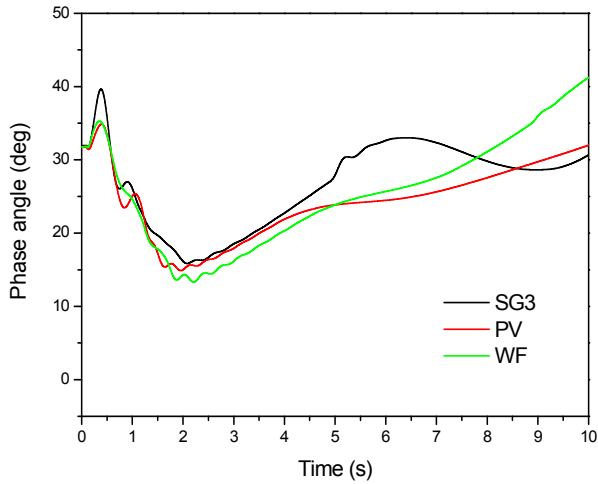


Fig. 5 Phase angle of SG1 in case with each power source with FRT.

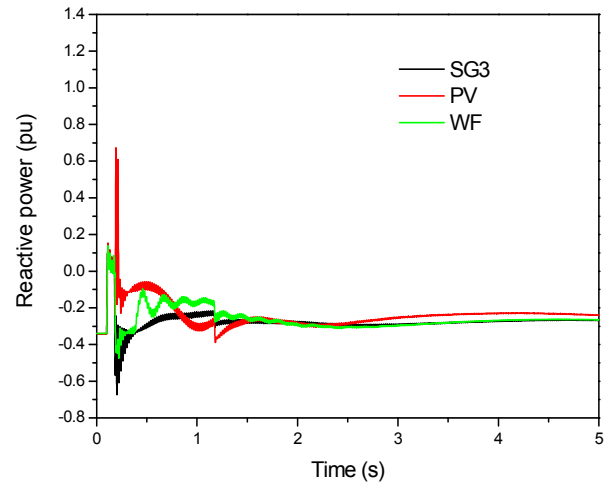


Fig. 8 Reactive power of SG1 in case with each power source with FRT.

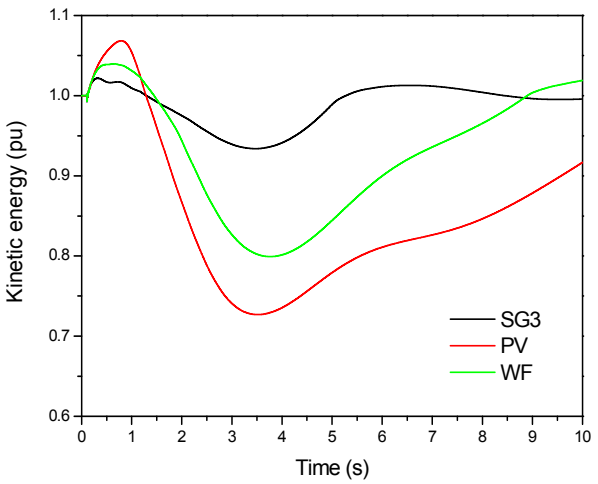


Fig. 6 Kinetic energy of SG1 in case with each power source with FRT.

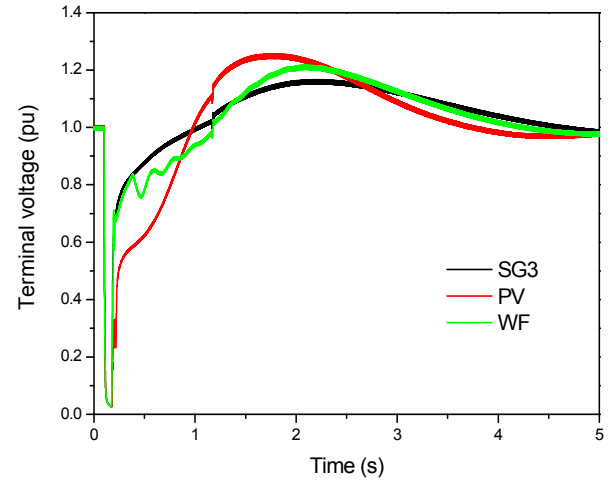


Fig. 9 Terminal voltage of SG1 in case with each power source with FRT.

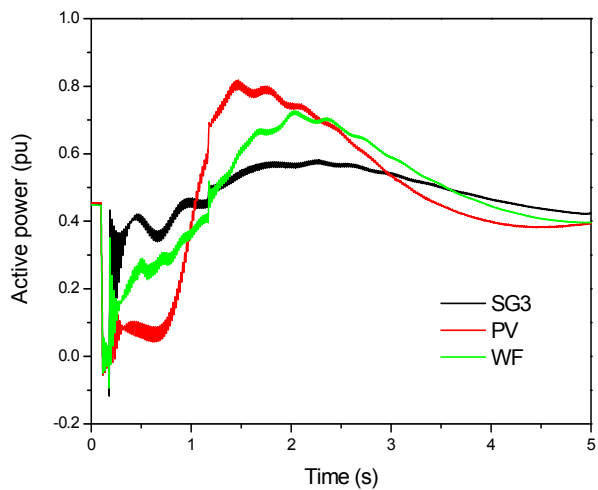


Fig. 7 Active power of SG1 in case with each power source with FRT.

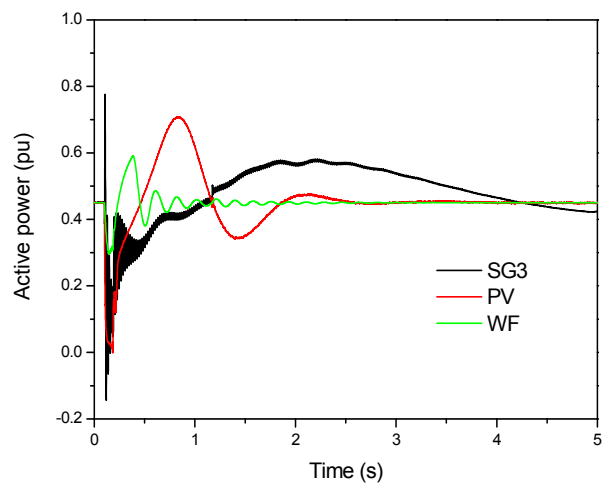


Fig. 10 Active power of each power source.

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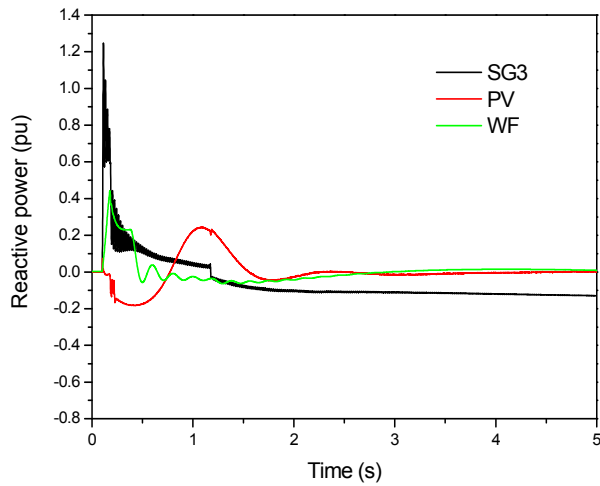


Fig. 11 Reactive power of each power source.

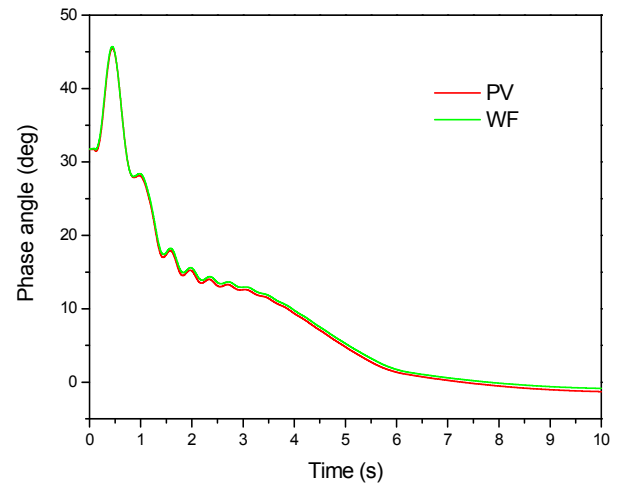


Fig. 14 Phase angle of SG1 in case with each power source without FRT.

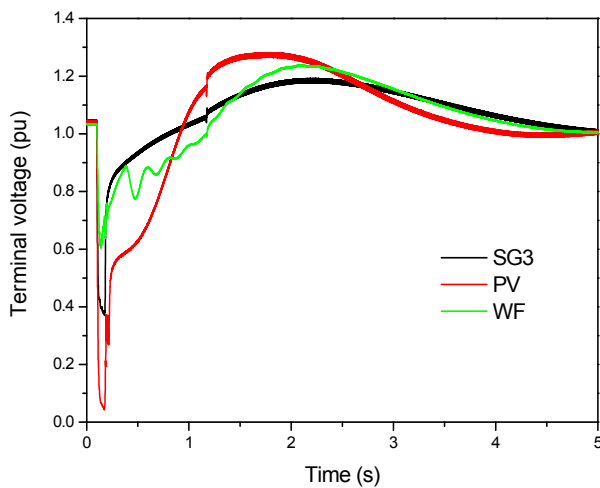


Fig. 12 Terminal voltage of each power source.

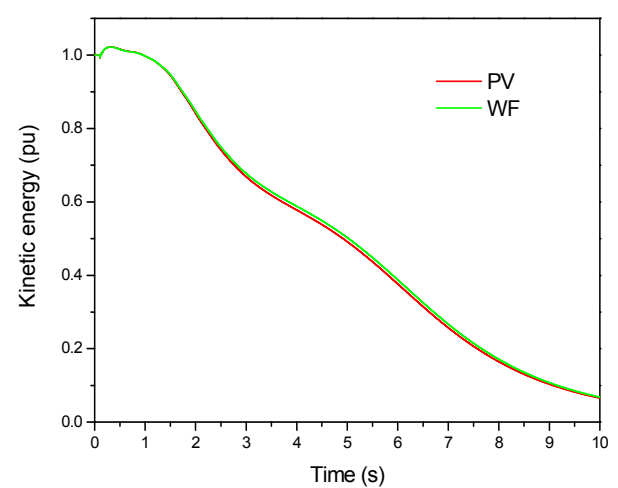


Fig. 15 Kinetic energy of SG1 in case with each power source without FRT.

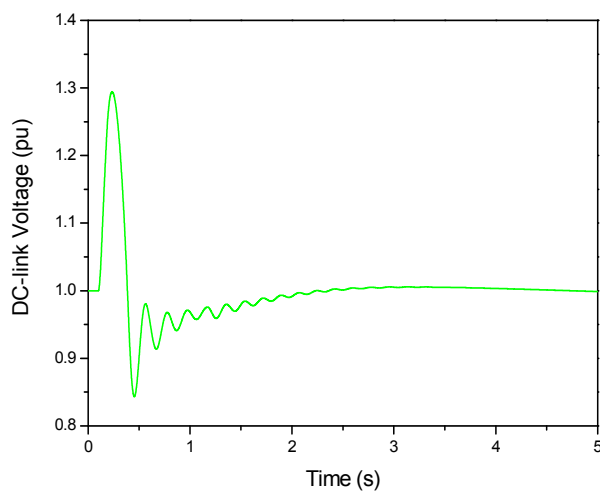


Fig. 13 DC-link voltage of VSWG.

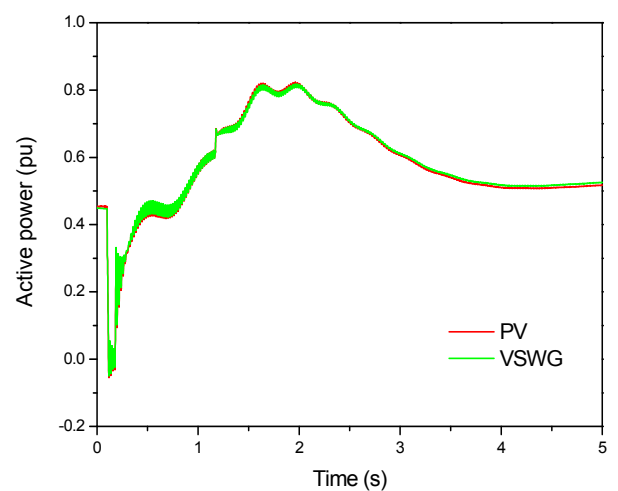


Fig. 16 Active power of SG1 in case with each power source without FRT.

Figs. 14 and 15 show the responses of phase angle and kinetic energy of SG1 respectively. In both cases, as the terminal voltages drop below the specified value, each power source is disconnected immediately from the grid after the fault. Therefore, these transient simulations present the almost same results. As shown in Figs. 14 and 15, the phase angles and the kinetic energies of SG1 in both cases decrease toward zero value. Those of SG2 also decrease toward zero value. Namely, SG1 and SG2 go to out-of-step in the decelerating direction. This is because unbalance between the power supply and the demand becomes very large after the disconnection of PV or WF. The disconnection of PV or WF leads to the power shortage in the power system, and hence the active power of SG1 (and SG2) increases after the disconnection of PV or WF as shown in Fig. 16. However, the prime-mover mechanical power(s) of SG1 (and SG2) is (are) restricted by the turbine load limiter, the rotor is subjected to the large decelerating power due to the unbalance between the mechanical input power and the electrical output power. As a result, the kinetic energy stored in the rotor is extremely released, and hence the generator goes to out-of-step in the decelerating direction.

4. Conclusions

This paper presents a case study assessing the impact of renewable power sources, such as WG (wind generators) and solar photovoltaic (PV) systems, on the transient stability of conventional synchronous generators. The effect of FRT capability implemented for each power source on the transient stability is investigated.

In the cases that WG and PV systems with FRT capability are installed, the risk of out-of-step of the synchronous generator becomes lower than that in the case with the conventional synchronous generator

installed. However, the transient swing of kinetic energy becomes larger.

In the cases that WG and PV systems without FRT capability are installed, especially when their capacities are large relative to the total capacity of power system, the risk of out-of-step of the synchronous generator in the decelerating direction becomes high.

Acknowledgments

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