Synchronous Generator Stability Investigation in Power System with High-Penetration Photovoltaics Under Varying Solar Irradiances

Mr.R.Sandeep
Asst.Professor,EEE,SBIT
Khammam,TS,India
Sandeeprg234@gmail.com

Mrs.P.Gayatridevi
Asst.Professor,EEE,SBIT
Khammam,TS,India
gaya3dava@gmail.com

Mr.B.Hanuman
Asst.Professor,EEE,SBIT.
Khammam,TS.India.
bhanuman205@gmail.com

Abstract

The goal of this study is to examine how synchronous generators that operate in tandem with photovoltaic (PV) power plants in a power system respond in terms of stability. Rotor angle, rotor speed, active and reactive power, terminal current response, excitation current response in the generator, and PV generator responses are the synchronous generator stability features that are measured. Six daily solar irradiation conditions—200 W/m2, 400 W/m2, 600 W/m2, 800 W/m2, and 1000 W/m2—as well as the state of the power system without PV generation—are used to replicate every facet of stability. An inverter is used in one of the substations to power the 10 MWp non-battery PV generator connected to a transmission line. The single-line graphic of the seven buses used to model this study on energy transmission lines.The existing transmission lines are supplied from two synchronous generator capacities, 100 MVA and 25 MVA. This result of this study shows that the high-penetration level of PV generator is able to increase the attenuation of the power oscillations in the synchronous generators. However, the highpenetration of the PV power is depended on the level of the solar irradiances affecting on any change of the synchronous generator stability.

Keywords : Power Transmission, Stability, Synchronous Generator, Photovoltaic, Irradiances

INTRODUCTION

The use of renewable energy sources coupled with the current system has greatly improved the electrical power system but, on the other hand, has posed challenges to the stability of the electrical power system. Photovoltaic (PV) power plants connected to current electrical networks have gained popularity recently. Due to the government's subsidy programme, lower solar panel prices, and greater access to PV technology, that network will have a larger penetration of PV power by consumers. Large-scale PV adoption puts pressure on the national power utility to change the traditional power flow pattern to one that is more controlled. Because it is less expensive, a PV system can be used in an isolated region in tandem with a traditional power generator.The stability of interconnected network in conventional generator with inverter-based renewable energy generator is the main issue in this paper. The small, medium, and largescale of PV inverter penetration in the grid come with different impacts [2]. Large-scale PV power penetration increases steady-state voltage, reduced power losses, and improves system capacity [3]–[5]. The high-penetration of PV power changes operational system on load tap changers (OLTC) and voltage regulation. The negative impact comes in the form of sudden voltage increase and reverse power [6]. The generator stability is an assessment

on the ability of a generator to maintain its synchronization with the other generators during the interruption period. In case of a highpenetration of PV integration, small-signal stability, eigenvalue analysis, time-domain, and load margin are applied to observe the damaging impacts during a transient condition [7]–[9]. The PV integration has both benefiting and disadvantaging impact to the small-signal stability depending on the location and penetration rate of PV and wind turbine [10], [11]. When the small-signal is affected by the integration of solar PV some mitigation steps such as the application of SVC's to maintain low damping from frequency oscillation can be done [12]. Disconnecting the PV system after an interruption on the network can increase the load on a synchronous generator [13], [14]. This surely causes impact in the form of increasing rotor speed on synchronous generator. However, according to paper [15], the effect is more on active and reactive power control along with the frequency-voltage control. PV plant has different operational characteristics from synchronous generator. The fundamental difference is that the PV generator does not have mechanical system. Performance of synchronous generator is affected by mechanical torque and electrical torque. PV power penetration has a positive impact on the active power oscillation damping on the synchronous generator that is controlled by voltage. Large solar photovoltaic generation changes the form of inter-area oscillations synchronous generator [16]. Large solar photovoltaic generation must apply synchronous power controller (SPC) in order to limit the deviation of frequency, improve oscillation damping, and reduce stress on other generator units [17]. In paper [18], the transient stability based.

on response of rotor angle stability in synchronous generator depends on the length of critical clearing time (CCT) and therefore the out of step risk on synchronous generator becomes smaller during the application of PV without the ability of low-voltage ride-through (LVRT). However, the quality and quantity of PV power generator is determined by the fluctuation rate of solar irradiances [19]. Therefore, we need a stability responses analysis of synchronous generator working in parallel with PV generator based on the fluctuation of solar irradiances received by solar panel. The paper aims at assessing the response of rotor angle stability, rotor speed stability, generator active and reactive power response, generator terminal current response, generator excitation current response, and voltage-active power of PV generator responses. The response of timedomain simulation on synchronous generator is observed before, during and after the three-phase fault occurs on transmission line. The measurement of synchronous generator stability response is done based on changes on the intensity of solar irradiance received by PV generator. The research is simulated by using a case of 150 kV transmission line. The power system is supplied from two conventional synchronous generators. The PV generator 10 MWp without batterai connected with a transmission line through a substation uses inverter.

TRANSMISSION SYSTEM WITH A SYNCHRONOUS AND A PHOTOVOLTAIC GENERATOR

PV Generator Power Infiltration

PV generators provide directcurrent power (Pdc), which must be converted into alternating current using a converter. The mechanical energy and moment of inertia in a PV generator are both absent. PV cells' ability to generate electricity is dependent on how intense the sun's radiation is. The fundamental structure of PV generator integrated with electrical transmission network is the solar panel with single and parallel connection, ac/dc inverter and transformer. The model of equivalent circuit on photovoltaic generator that is connected to grid transmission through inverter and transformer is shown in Fig.1 [20]. The network structure of PV cells is shown on DC line blocks part [21]. The PV cells consist of semiconductor materials that can convert solar radiance into electrical energy. In Figure (1), the solar irradiation G, reverse diode, single resistance of Rs, and parallel resistance of Rsh determine the ideal current source of Iph produced by PV cells. Higher solar irradiation tends to be greater than current Iph. Current output from PV cell (IPV) is shown in the equation (2). I0 is a reverse saturation current relies on the temperature (is 10-4 A), q is electron current (1.602 x 10-19 C). ISC is a short circuit current. TC is the working temperature of PV cells.

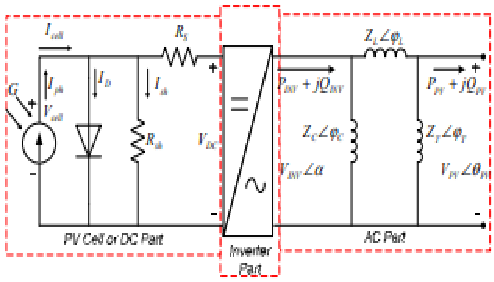

Figure 1. Equivalent circuit power transfered of PV generator

Ta is a referential temperature and G is solar irradiance (W/m2), k is Boltzman constant value (1.38 x 10-23 J/K), A is ideal factor on diode, VDC is output voltage on PV array (direct current-dc). VINV is the output voltage of inverter connected to transformer. VPV is output voltage on network-connected transformer. Active power PPV and reactive power QPV sent from PV generator as described by equation (4) and (5).

$$I_{ph} = G[I_{SC} + Ki(T_c - T_a)] \quad (1)$$

$$I_{PV} = I_{ph} - I_0\left[\exp\left(\frac{q(V_{cell} + I_{cell}R_s)}{AkT_c}\right) - 1\right] - \frac{(V_{cell} + I_{cell}R_S)}{R_{sh}} \quad (2)$$

PV generator power transfer [4], [20];

$$S_{PV} = P_{PV} + jQ_{PV} \quad (3)$$

$$P_{PV} = 3V_{PV}\left[\frac{V_{INV}}{Z_L}\cos(\alpha - \theta_{PV} - \varphi_L) - \frac{V_{PV}}{Z_L}\cos\varphi_L - \frac{V_{PV}}{Z_T}\cos\varphi_T\right] \quad (4)$$

$$Q_{PV} = 3V_{PV}\left[\frac{V_{INV}}{Z_L}\sin(\alpha - \theta_{PV} - \varphi_L) - \frac{V_{PV}}{Z_L}\sin\varphi_L - \frac{V_g}{Z_T}\sin\varphi_T\right] \quad (5)$$

Power Transfer from Synchronous Generator

The equivalent power transfer from synchronous generator is shown in fig. 2. Active power P, reactive power Q, voltage V on synchronous terminal generator, current and power angle are described on equation (6)[22].

$$\bar{I} = \left(\frac{\bar{S}_g}{\bar{V}}\right)^* = \frac{P - jQ}{V}e^{-j\theta_t} \quad (6)$$

The calculation on internal rotor angle of δ g and electromotive force E at the same time can be calculated by using equation (7).

$$\bar{E} = E_g\angle\delta_g = V + jX_S\bar{I} \quad (7)$$

In which $X_S = X_g + X_T + X_{Ech}$ (8)

The equation of transferred power from synchronous generator to transmission grid is displayed on equation (9) and (10) [22].

$$P_g = \frac{\overline{E}V_2}{X_S}\sin\delta_g \tag{9}$$

$$Q_g = \frac{\overline{E}V_2}{X_S}\cos\delta_g - \frac{V_2^2}{X_S} \tag{10}$$

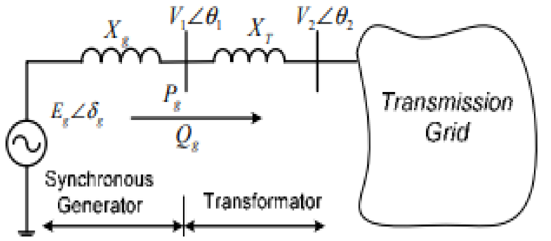

Figure 2. Circuit Equivalent power transfer of Synchronous Generators.

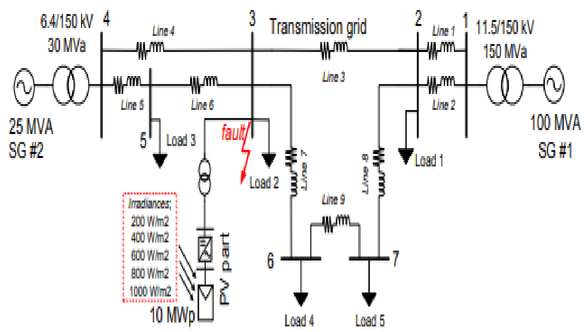

Figure 3. Power system model simulation test

Analysis of the Synchronous Generators' Stability

Power supply provides initial information for all stability studies on power system. PV generator has an ability to transfer active and reactive power and therefore PV generator is assumed to be similar with synchronous generator unit with limits of reactive power. This assumption is made to observe the impact of PV generator high-penetration to the power system connected to a number of synchronous generator. In the analysis impact of PV high-penetration, synchronous generator stability the most important aspect to be considered is the stability of the rotor angle that describes the impact of imbalance between mechanical powers of Pm with electrical power of Pe during the interruption period. The change of rotor angle is shown by the equation (11).

$$\frac{d\delta_g}{dt} = \frac{1}{2H}(P_m - P_e - K_D\delta_g) \quad (1$$

H is inertia constanta, KD is damping factor. The value of Pm is constant during the period of interruption. This is due to the role of governor. However, the Pe will have more impact due to the deviation of rotor speed [23]. Therefore, the active and reactive power output response in synchronous generator is a part that is being analyzed in this paper. In this research, the simulated load is constant. Yet, the load on the synchronous generator may change due to the export of the power resulted from PV generator depending on the solar irradiances. The affected of the power export changing interaction of PV power generator and power output from synchronous generator is the rotor speed of within the synchronous generator [15]. Therefore, the response of rotor speed stability is also investigated. The speed of rotor in the synchronous generator is a part of the frequency stability parameter. In equation (7), it is described that the electromotive force of E is determined by the terminal current on the synchronous generator, and will also be further investigated. Table 1 shows the typical data parameters of the synchronous generator and Table 2 displays data of load and data of resistance-reactance on transmission line.

SIMULATION MODEL

The electrical power transmission simulation test consists of two synchronous generators (SG) is shown in Fig. 3. Synchronous generator 1 (SG #1) has 100 MVA capacity and synchronous generator 2 (SG #2) has capacity of 25 MVA. Simulation is done by comparing response of synchronous generator before and after PV generator is applied into the power system. The PV connected power system is under the value variation of solar irradiances (G). The simulation

TABLE I. SYNCHRONOUS GENERATOR PARAMETERS

Symbol	SG #1	SG #2	Symbol	SG #1	SG #2
R_a (pu)	0.008	0.004	X''_{qo} (pu)	0.11	0.15
X_d (pu)	1.67	1.65	T''_{qo} (s)	0.10	0.17
X'_d (pu)	0.38	0.26	T'_{do} (s)	7.89	11.07
X''_d (pu)	0.11	0.15	T''_{do} (s)	0.07	0.03
X_q (pu)	0.87	1.6	T'_{qo} (s)	0.5	0.35
X'_q (pu)	0.36	0.223	H (s)	3.0	2.6

TABLE II. LOAD DATA, RESISTANCE AND REACTANCE OF TRANSMISSION LINE (100 MVA BASE)

Line Number	R (%)	X (%)	Load Number	P (MW)	Q (MVar)
1	0.13	0.31	1	14.67	8.47
2	0.13	0.31	2	19.98	11.54
3	7.89	18.73	3	37.32	21.55
4	4.46	10.59	4	4.14	2.39
5	2.94	6.98	5	8.85	5.11
6	2.65	6.28	-	-	-
7	5.22	12.39	-	-	-
8	9.31	22.07	-	-	-
9	4.26	10.11	-	-	-

scenario is given, namely: (1) Power system without PV; power system after the integration of PV generator on solar irradiance (2) 1000 W/m2 , (3) 800 W/m2 , (4) 600 W/m2 , (5) 400 W/m2 , and (6) 200 W/m2 . The three-phase fault simulation is determined on the second of 1.00 and fault is cleared on the second of 1.20. The duration of 10-cycles interruption simulation is 10 seconds. Table 2. displays data of load and data of resistance-reactance on transmission line. Synchronous generator within power system is simulated by using swing operation mode. Swing bus is determined on bus number 6. That bus is the interconnecting line point with another generator.

RESULTS OF SIMULATION

Response to Rotor Angle Stability

The response of rotor angle on SG #1 and SG #2 before, during and after three phases fault on bus 3 is shown on figure 4. The result of simulation shows changes on the value of the rotor angle before and after the transmission line is connected to the PV generator. The value of initial rotor angle is highest when the PV system is not connected to the system. After the interruption is cleared on the 1.20 second, there is an oscillation wave of rotor angle that then gradually comes to steady-state condition. The changes of rotor angle in each

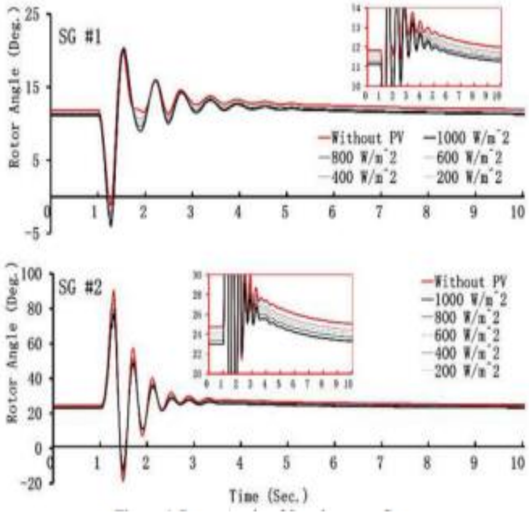

Figure 4. Rotor Angle of Synchronous Generator

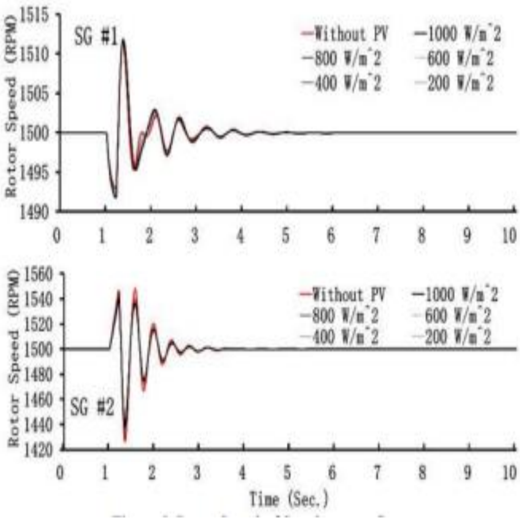

Figure 5. Rotor Speed of Synchronous Generator

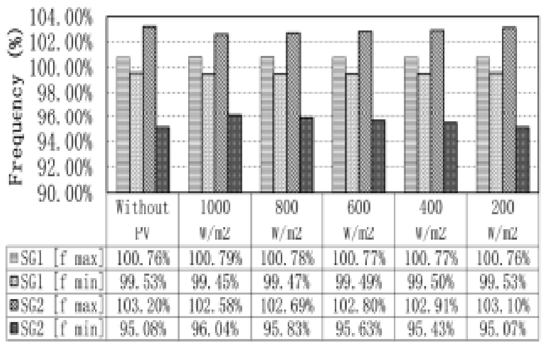

Figure 6. The comparison between maximum and minimum frequency

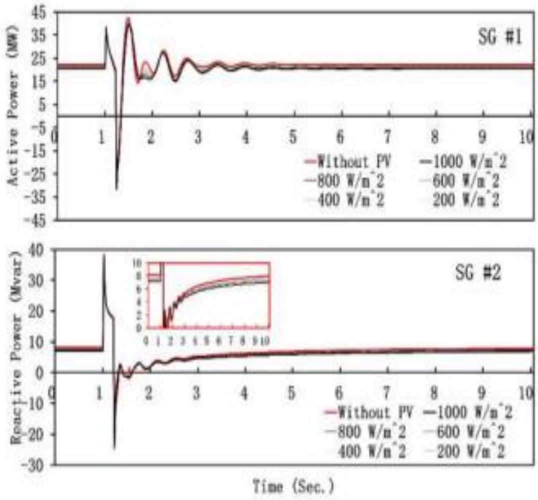

Figure 7. Active power SG #1 and reactive power of SG #2

scenario shows that synchronous generator response experiences decrease of power output due to the addition of PV system. The changes of power output causes inertia moment on the synchronous generator to decrease. In this case, the kinetic energy on rotor synchronous generator gives response to the load changes in the line transmission. The simulation shows that oscillation of rotor angle is more controllable when the PV connected system has higher solar irradiances.

CONCLUSION

The study displays the synchronous generator's stability responses when it operates in tandem with a high-penetration PV system. The fluctuations in sun irradiance provide the foundation for the stability simulation study. Three interruption simulation stages are used to apply the synchronous generator stability analysis to grid transmission. The simulation's findings suggest that after the PV transmission line high-penetration, the changes in the rotor angle stability and rotor speed have become easier to control. The synchronous generator's high power rating has an impact on the increased responses of the active and reactive power oscillation wave. Due to the high solar irradiation, there is a high penetration of PV power on the transmission line, which can lower the load on the synchronous generator.This condition may bring about changes in the terminal current and excitation current in the synchronous generator. A low excitation current may cause an effect on the reactive power of the synchronous generator, which is smaller.

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