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Influence of High PV Penetration and STATCOM on Rotor Angle Stability of SMIB Transmission System

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Abstract – This paper aims is to study the effect of photovoltaic generation penetration and STATCOM on the transient stability of a single machine infinite bus (SMIB) system based on the rotor angle stability. The influence of STATCOM and PV penetration can be seen through damping oscillations, so that the generator remains stable with the rest of the system for various fault conditions. The simulation results obtained make it possible to efficient identify harmful and beneficial impact of increasing the PV penetration and the existence of STATCOM capability. The system model is created in MATLAB/ SIMULINK software.

Keywords: Photovoltaic power system, Synchronous generator stability, STATCOM, Rotor angle stability

1. Introduction

THE proper operation of an electric power system depends on its ability to supply at any time a reliable and stable energy, and maintain voltage levels and frequency within acceptable limits and the corresponding need for consumer. The industrialization and population growth are the primary factors for which the consumption of electricity increases steadily [1]. Grid-connected distributed generation systems are now seriously developed to complement conventional energy generation in many industrialized countries. The participation of large-scale photovoltaic on generation energy is increased because of adverse environmental effects of conventional energy sources [2, 3]. It represents the ideal solution and a significant saving in investment and operation [4]. The connection of PV generation to the electrical networks will include imposing new technical constraints. These constraints have particularly occurred in power systems, since they will have to accommodate a large share of this new type of production [5].

The electrical energy systems are often subject to interference that may cause the serious damage on their constituents, including generators, transmission lines or short circuit in buses [6]. The study of transient stability remains a basic account and of great importance in the design and operation of the power grid [7]. Through this study, we can make a judgment on the network's ability to resist against major incidents that may arise at any time. The disturbances that occur in an electrical system are causing the occurrence of a difference between the mechanical power (production) and electric power (consumption). This power disequilibrium causes a variation of the torques acting on the rotor. Which induces acceleration or deceleration of the rotor, causes a loss of synchronism of the generator with the rest of the system.

Therefore, the growing PV installation has a significant influence on the oscillatory behavior of the electrical power supplied by the generator. With the increase in PV capacity on the power system, power stations need to reduce the power output in order to maintain the balance between production and consumption [8, 9]. During a fault occurrence and when the PV system acts to damp the oscillations, the real power supplied by the PV will increase or decrease from its steady state value in order to control the actual power output of the generator [10].

Transient stability is the ability of the power system to ensure the synchronism when it is subjected to sever transient disturbance [6, 10-12]. It manifests in short term as a widening gap of a periodically certain angles of the rotor. The rotor angle stability relates on the capabilities of interconnected power system synchronous machines to remain in synchronism after being subjected to a disturbance [10]. It depends on the ability to maintain or restore the balance between the mechanical torque and the electromagnetic torque of each synchronous machine.

Until late 1980, the only means of compensation and control of electrical networks were electromechanical devices, namely transformers with support regulator, inductors and capacitors switched by circuit breakers. However, in recent years, another technique of setting and control of reactive power, voltages and power flows based on power electronics known as the Flexible AC Transmission System (FACTS) devices. They are quick response elements used to control the power flow and improve transient stability on power systems, so that the

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alternative power can be transmitted through a long distance [13-18]. Static Synchronous Compensator (STATCOM) is a shunt reactive power compensator used in power transmission system to: improve the reactive power compensation in power systems, provide voltage, increase transient stability and improve damping low frequency oscillation for the transmission system [13, 19-22].

This article presents a proposed strategy for controlling the state and limits of rotor angle stability of synchronous generator in SMIB. This proposed strategy concerns the effects of the insertion of PV generation and the addition of STATCOM compared to conventional generation in power systems. To examine the influence of this proposed method, we conducted a study of transient stability of SMIB for various PV penetration levels and for different power source variety. The essential characteristic of this paper is that the analysis of the transient stability is performed for three simulation models of power system. The first simulation model contains a conventional generator connected to the SMIB for three power levels. In the second simulation model, the conventional generator is replaced by PV penetration connected to the SMIB with three levels of PV capacities without STATCOM and in the last simulation model we studied PV source connected to the SMIB with STATCOM. The Synchronous generator's capacity of SMIB must be reduced relatively with the increase of PV penetration or the conventional generator capacity to maintain the balance between production and consumption.

In order to evaluate this study, various articles are presented in the literature discussing the same subject as in [2, 9, 23-25]. Authors studied the case of SMIB in [2, 9, 23]. The nature of the impact of high PV penetration on rotor angle stability of a large power system, was presented on [2, 9, 26]. Through [21], it is noted the evaluation of the STATCOM influence on improving the margin of the rotor angle stability. the study developed on [2] presented the operating point of the analysis stability for SMIB equipped with high penetration photovoltaic with three successive changes in the intensity of solar radiation. In [9, 25] authors focused on the impact of an increased PV penetration on the performance of the rotor angle stability with various PV penetration levels. Paper [24] discussed the impact of STATCOM on the wind farm performance under various defaults to improve the margin of transient stability.

2. Rotor Angle Stability

2.1. Single Machine Infinite Bus (SMIB) and swing equation

In this section; the case of a SMIB to analyze the rotor angle stability of the power system according to major disturbances is considred. The synchronous machine can be represented by the classical model, i.e. a constant voltage source in series with a constant reactance supplying power to infinite bus through a transformer reactance Xt and a line reactance Xl as shown in Fig. 1. Thus the generator is represented by E and the infinite bus is represented by V. Knowing that the reactance of the line is greater than its resistance, we can neglect the resistance of the line (Rl= 0) without the values being affected.

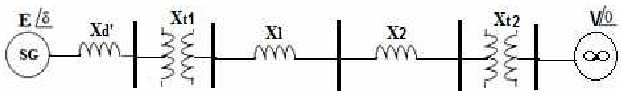


Fig. 1. Single machine infinite bus

In this simple case, $X_s = X_{d'} + X_{t1} + X_l + X_2 + X_{t2}$

$$E = V + jX_S I \tag{1}$$

where

$$I = \frac{E - V}{jX_S} \tag{2}$$

The electrical power of the generator is given by the following Eqs. (3, 4) and (5): [23, 26].

$$P_e = \mathrm{Re}(\overline{E}I) = \mathrm{Re}(\overline{E}\frac{E - V}{jX_s}) \tag{3}$$

$$= \mathrm{Re}(E\angle -\delta \frac{E\angle\delta - V\angle 0}{X_s\angle 90^\circ}) \tag{4}$$

$$= \mathrm{Re}(\frac{E^2}{X_s}\angle -90^\circ - \frac{EV}{X_s}\angle(-90^\circ - \delta))$$

$$= -\frac{EV}{X_s}\cos(-90^\circ - \delta)$$

$$P_e = \frac{EV}{X_s}\sin\delta \tag{5}$$

δ: angle of the rotor, it is the phase difference between the internal voltage E of the generator and the voltage of the infinite bar V.

We have in the generator case:

$$P_e = P_m - P_a \tag{6}$$

P_e : Electrical power transmitted in the line.
P_m : Mechanical power obtained from the generator.
P_a : The acceleration Power.

In the steady state, Pa = 0 and there is no acceleration. The electric power is equal to the mechanical power Pe= Pm. The generator is operating under a stable condition and at a constant speed. It is possible to determine the initial value of δ_0 by Eq. (5). In case of a fault appearance, the electrical power will go to zero. As though Pe= Pm-Pa, therefore Pa= Pm. After removal of the fault, the electrical power and the generator speed become variable. The generator will continue to swing until it finds an equilibrium point. Otherwise, it loses its synchronism [23].

The link between the mechanical and the electrical aspects of the synchronous machine is governed by the dynamic acceleration equation of the alternator's rotor linked to the turbine, so called the swing equation. For the case of a synchronous machine connected to an infinite bus, the swing equation is given by Eqs. (7) and (8):

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \tag{7}$$

where

$$P_e = P_{\max}\sin\delta$$

Thus

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_m - P_{\max}\sin\delta \tag{8}$$

$$\frac{d^2\delta}{dt^2} = \frac{\pi f}{H}(P_m - P_{\max}\sin\delta)$$

where

$$P_{\max} = \frac{EV}{X_s}$$

H : the constant inertia, F : frequency

A plot of δ versus is called the swing curve, which is shown in Fig. 2. Two cases are possible:

If δ starts to decrease after reaching a maximum value, the machine remains stable, and if δ continues to increase indefinitely, the machine loses the synchronism and becomes unstable. So, the system is stable if d δ/dt =0 and the system is unstable if dδ/dt>0 [23].

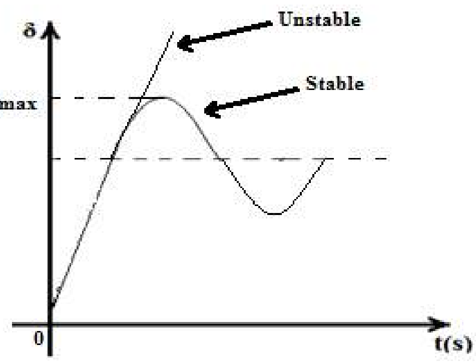


Fig. 2. Swing curve

2.2. Power system model

The proposed power system model presented in Fig. 3 consists of a synchronous generator (SG1) connected to an infinite bus through two transformers and two transmission lines. A large-scale PV system or synchronous generator (SG2) is connected via a transformer of 55KV/500KV and short transmission line (In [8], a large-scale PV system or synchronous generator SG2 is connected via a transformer of 66KV/500KV). The parameters used for each generator are given in Table 1. To evaluate the impact of high PV penetration and STATCOM on rotor angle stability, we have adopted various simulation. The capacity of the synchronous generator (SG1) must be reduced relatively (900~700 MVA) with the increase in output PV penetration (100~300 MW) in order to maintain the power supply-demand balance, as shown in Table 2. In the case of the connected PV, three levels of PV capacities: (10% PV, 20% PV and 30% PV) are considered. In the case of SG2 connected, three levels of generation capacities is also considered (10%, 20% and 30%). The basic unit values of power system is 1000 MVA. The inertia constant of each synchronous generator is changed proportionally to the generator capacity. The capacity of the transformers in each case is also changed according to the change of the generation capacity. The existence of STATCOM located in bus 2 is considered for the case with PV connection. To see the performance of the proposed damping controller, we tested the system for different fault conditions. We considered the three phase fault to ground (3LG) and the

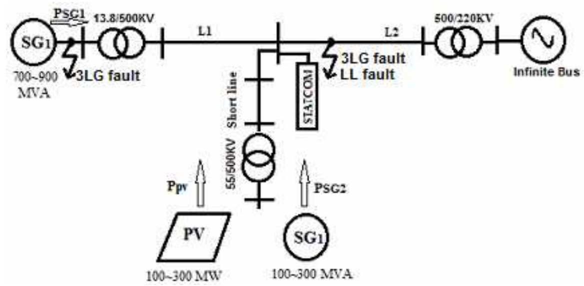


Fig. 3. Power system model

Table 1. Synchronous generator parameters

Generator Parameters			
Ra (pu)	*2.8544.10^{-3}*	*Xd" (pu)*	*0.252*
Xl (pu)	*0.18*	*Xq" (pu)*	*0.243*
Xd (pu)	*1.305*	*Td' (s)*	*1.01*
Xq (pu)	0.474	Td" (s)	0.053
Xd' ((pu)	0.296	Tq" (s)	0.1
H (s)	3.7 (900MVA) / 2.8 (800MVA) / 2.45 (700) / 1.05 (300MVA) / 0.7 (200MVA) / 0.35 (100MVA)		
Power Base	1000 MVA (60Hz)		

Table 2. Simulation condition

SG1			PV or SG2				
P_{SG1} (pu)	*Capacity (MVA)*	*Inertia (s)*	P_{PV} (pu)	*Capacity (MW)*	P_{SG2} (pu)	*Capacity (MVA)*	*Inertia (s)*
0.9	*900*	*3.7*	*0.1*		*0.1*	*100*	*0.35*
0.8	*800*	*2.8*	*0.2*	*300*	*0.2*	*200*	*0.7*
0.7	*700*	*1.45*	*0.3*		*0.3*	*300*	*1.05*

phase-phase fault (L-L) occurs at the input of line 2 and a three-phase fault to ground (3LG) has been imposed near to the generator SG1 (loss of synchronous generator SG1). The circuit breakers of the lines are open at 0.1 s and are closed at 0.17 s.

2.3. PV system model

PV system model is shown in Fig. 4. It consists a PV array represented by a voltage source; inverter converts a V_{dc} output voltage to AC voltage for transferring alternative power to the network and a filter LC filtering harmonic produced by the inverter. During the simulation, irradiation and PV cell temperature are constant. As we mentioned earlier in table 2, three levels of PV capacities are considered, which can be assumed three levels of irradiation in this paper. The inverter controls the active and reactive power generated by the PV module, which is injected to the grid. The error signal between the actual power and the reference power is processed through PI controllers to generate the reference currents I_d* and I_q* and compare it with the actual injected currents I_d and I_q obtained by park's transformation abc converted to dq components. A phase lock loop (PLL) is employed to obtain the angle θ used in the park's transformation. The error signal between the actual injected current and the reference current is processed through PI controllers to produce the reference voltage V_d* and V_q*. The control signals V_d* and V_q* are returned to the starting base (inverse Park transformation) V_a*, V_b* and V_c* to calculate the duty cycles by the PWM pulse generator for inverter. The reference value of the reactive power is equal to zero in each simulation case. [4, 8, 27-29].

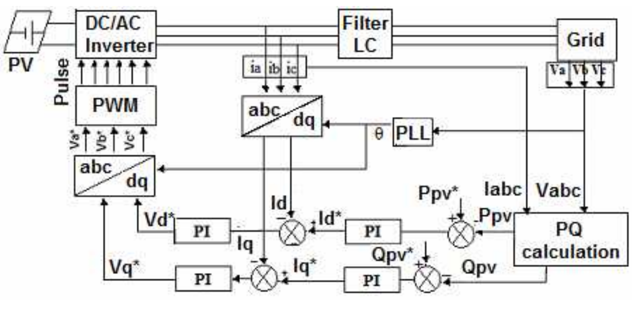


Fig. 4. PV system model

2.4. Statcom

Static Synchronous Compensator (STATCOM) is one of the shunt compensators of the Flexible AC Transmission System (FACTS) family. It can be considered as an ideal synchronous compensator. It is a controlled voltage source in magnitude and phase angle, operating at the fundamental frequency of the network. It can control the flow of active power, regulating the voltage, electromechanically damping oscillations and improve transient stability on

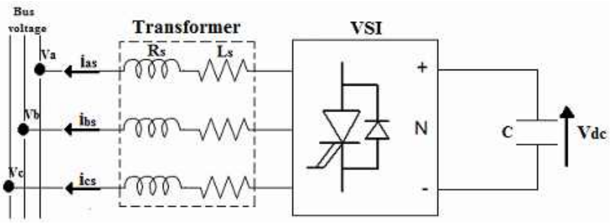


Fig. 5. Basic schematic of STATCOM

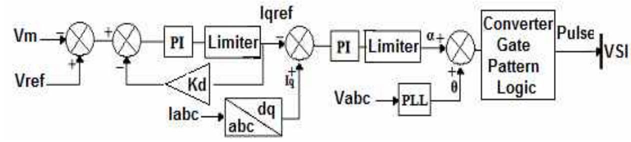


Fig. 6. Control bloc of STATCOM

transmission system. It can also control the injection of the reactive power (absorbing the reactive power if the voltage is high and generating the reactive power if the voltage is low in their connection nodes). [13, 17, 18, 21, 24, 30-32]. A basic schematic of STATCOM is presented in Fig. 5, which is composed of a capacitor bank in the DC side, voltage source inverter (VSI) and couplings transformers. [33]. V_a, V_b and V_c are the three phase bus line voltage; i_{as}, i_{bs} and i_{cs} are the three phase output current of STATCOM.

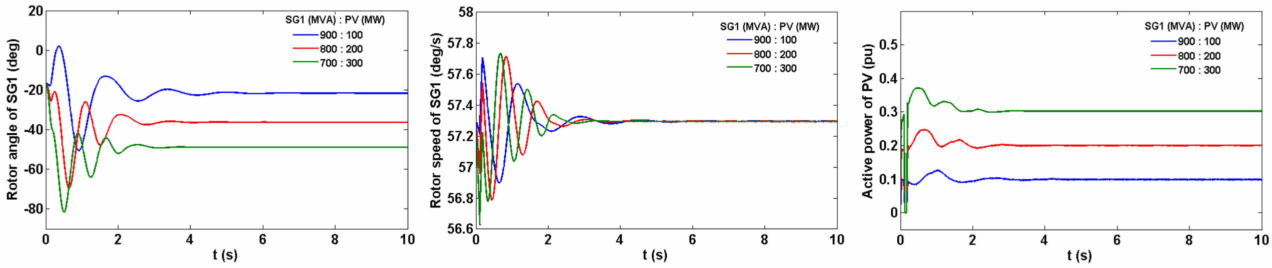
Fig. 6 presents the control bloc for STATCOM. This strategy contains a phase lock loop (PLL) technique employed to provide the synchronization angle θ which is the reference angle of measurement system. The measured bus line voltage V_m compared to the reference voltage V_{ref} and an error occurs. This error is introduced into the PI controller to provide the reference reactive current I_{qref}. The reactive current I_q obtained by park's transformation. The droop factor K_d defined as voltage error allowed by the flow of rated reactive current through STATCOM. The error signal between the reactive current I_q and the reference reactive current I_{qref} is processed through PI controllers to produce the phase angle α. The error signal between the phase angle α and the reference angle θ is introduced into converter gate pattern logic to generate a pulse for controlling the VSI. The limiter used for limit signal I_{qref} and α to the upper and lower saturation values taking into account the maximum reactive power of STATCOM. [13, 34].

3. Analysis, Simulation and Results

3.1. Impact of PV Penetration Level

3.1.1. Three-phase fault on the transmission line

Fig. 7(a), (b) and (c) show respectively the rotor angle, the rotor speed and the electrical power of SG1 in three simulation conditions according to the variation of PV



(a) (b) (c)

Fig. 7. (a) Rotor angle of SG1 for various PV capacity; (b) Rotor speed of SG1 for various PV capacity; (c) Active power of PV for various PV capacity

capacity without STATCOM. Comparing the behavior of the system for a three-phase fault on the transmission line. As it can be seen in fig. 7(a), the initial value of the rotor angle in each case is the same because the steady state power flux is the same. The first peak of the rotor angle decreases as the PV penetration levels increase (i.e. the decrease in generator capacity). In addition, it is observed that at higher levels of PV penetration the rotor angle of the generator tends to obtain smaller and more damped oscillations. (i.e. the oscillations are well damped in the system equipped with 30% of the photovoltaic production).

It can be noted from the responses of the rotor speed in the case of SG1 with a capacity of 700 MVA, that the peaks in the rotational speed of the rotor become large due to the decrease in the inertia of the rotor. Which is low proportionally to the reduction of the capacity of the generator. In other cases, the active power of the PV during the fault becomes zero in all cases. Then it can be said that the rotor angle velocity depends on the power flux after the fault elimination.

3.1.2. Phase-phase fault on the transmission line

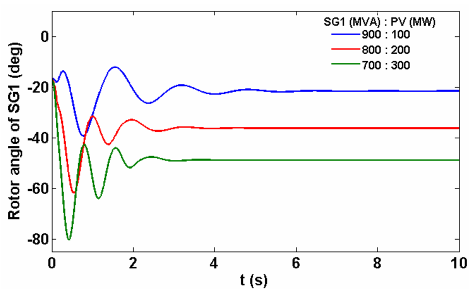


Fig. 8. Rotor angle of SG1 for various PV capacity

3.1.3. Three-phase fault near of SG1

Fig. 8. and fig. 9 show for various PV capacity a rotor angle of SG1 for phase-phase fault on the transmission line and for three-phase fault near to SG1 respectively. It can be observed that the variation in the rotor angle improves when the PV penetration increased. The results of analysis and simulation obtained of the proposed method clearly

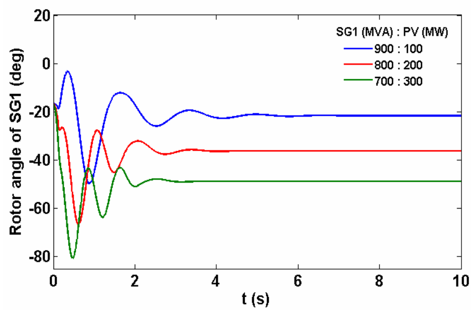


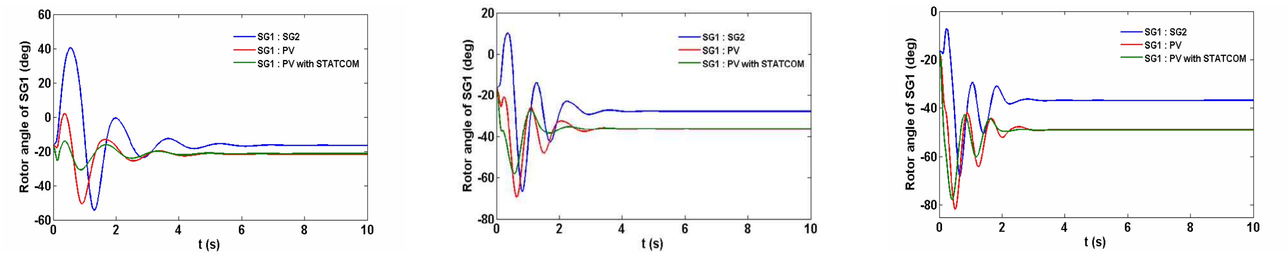
Fig. 9. Rotor angle of SG1 for various PV capacity

show that the increased of PV penetration effectively identify a beneficial impact on the transient stability of the proposed SMIB.

3.2. Impact of different power source variety and STATCOM capability

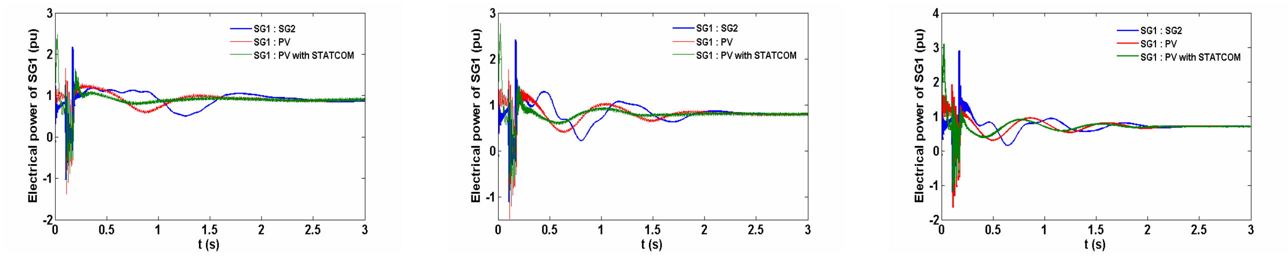
3.2.1. Three phase fault on transmission line

Fig. 10(a), (b) and (c) show the rotor angle of SG1 for different power source under the condition as follows: (1) connecting SG1 with SG2 instead PV, (2) connecting PV without STATCOM, and (3) connecting PV with STATCOM. The simulation results are obtained from three simulation conditions according to the increase in penetration levels of PV or SG2 (10%, 20% and 30%) respectively with decrease in levels of SG1(900 MVA, 800 MVA and 700 MVA) . From simulation results, it is seen that the SMIB transmission system may have a different behavior with the increase in the PV penetration levels and the existence of the STATCOM. This impact is observed by comparing the system compartment to a conventional generation SG2, connecting PV without STATCOM and connecting PV with STATCOM. The angle of the rotor will take a long time for damping according to the increase in the SG1 capacitance (i.e. the decrease in the penetration level of PV or SG2). It can also seen that the oscillations of the rotor angle are well damped and the equilibrium value of the rotor angle is reached in a short time. Consequently, the deviation in the rotor angle has been reduced in the



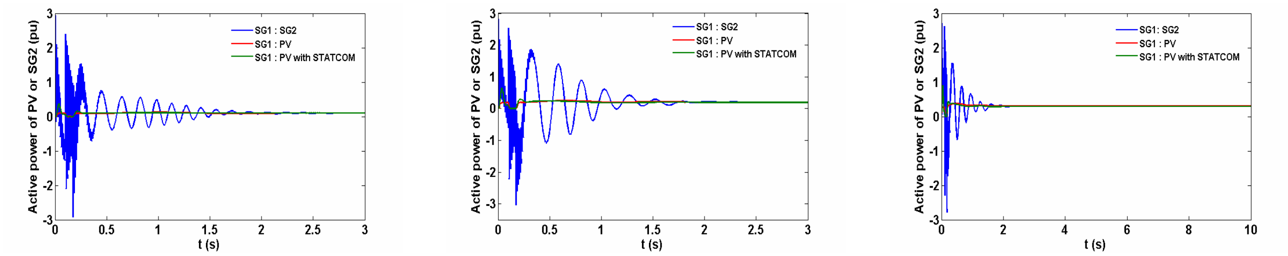
(a) 900(MVA):100(MW) (b) 800(MVA):200(MW) (c) 700(MVA):300(MW)

Fig. 10. Rotor angle of SG1 for different power source: SG1 (MVA) : PV (MW) or SG2 (MVA)



(a) 900(MVA):100(MW) (b) 800(MVA):200(MW) (c) 700(MVA):300(MW)

Fig. 11. Electrical power of SG1 for different power source: SG1 (MVA) : PV (MW) or SG2 (MVA)



(a) 900(MVA):100(MW) (b) 800(MVA):200(MW) (c) 700(MVA):300(MW)

Fig. 12. Active power of PV or SG2 for different power source: SG1 (MVA) : PV (MW) or SG2 (MVA)

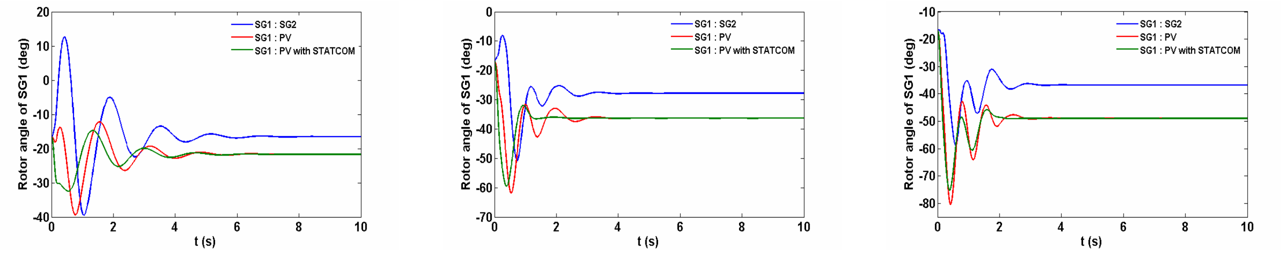
presence of the PV penetration and more in the presence of STATCOM compared with the case of SG2. On the other hand, the deviation in the rotor angle tends to obtain large and slightly damped oscillations with the presence of conventional generation of SG2. This means that the system is more stable by inserting the PV penetration levels and by the existence of the STATCOM.

Fig. 11(a), (b), (c) represent the electrical power of the SG1 for different power source. Fig. 12(a), (b), (c) represent the active power of the PV (or SG2) for different power source. The simulation results show that within the fault time interval of 0.1s to 0.17s, the SG1electric power is equal to zero (Pe=Pm-Pa, the acceleration power is equal to the mechanical power Pm=Pa), as we mentioned in Section (2.1). At 0.17 sec, the fault is cleared; we see that the electrical power begins to oscillate, then it amortizes when it reaches a stable value. We can see that the oscillations are well damped according to the increase in PV penetration and the presence of STATCOM. As it can be seen in Fig. 12(a), (b), (c), the SG2 active power oscillates rapidly. This oscillation due to the kinetic energy stored in the rotor during the period of the fault and released quickly.

3.2.2. Phase-phase fault on the transmission line

Fig. 13(a), (b), (c) and fig.14 (a), (b), (c) show the SG1 rotor angle for different power source in a case of phase-phase fault on the transmission line and for three-phase fault near to SG1 respectively. It can be seen that a smaller rotor angle deviation was obtained under the two conditions: connecting PV without STATCOM and connecting PV with STATCOM. For these two cases, it is clear that the replacement of the conventional generation levels of SG2 by the PV penetration levels and the addition of the STATCOM in the proposed system can effectively damp the oscillations of the rotor angle.

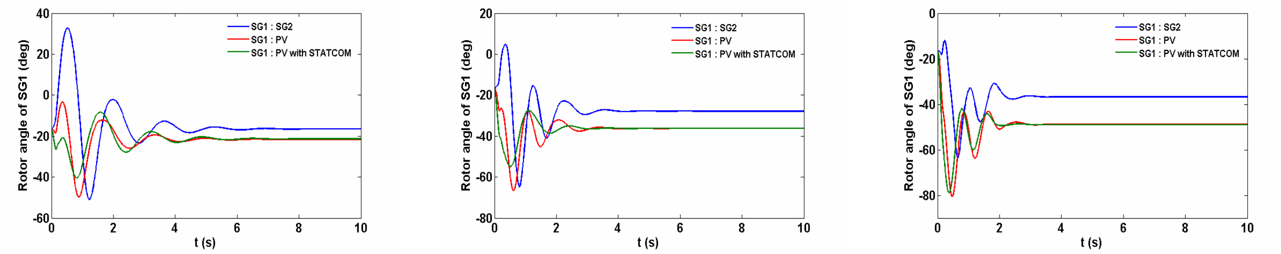
We can see the impact of the integration of PV



(a) 900(MVA):100(MW) (b) 800(MVA):200(MW) (c) 700(MVA):300(MW)

Fig. 13. Rotor angle of SG1 for different power source: SG1 (MVA) : PV (MW) or SG2 (MVA)

3.2.3. Three-phase fault near of SG1



(a) 900(MVA):100(MW) (b) 800(MVA):200(MW) (c) 700(MVA):300(MW)

Fig. 14. Rotor angle of SG1 for different power source: SG1 (MVA) : PV (MW) or SG2 (MVA)

penetration and STATCOM on the transient stability of our proposed system from the various simulations that have been done. The simulation results show that the implementation of the proposed method on the power systems has a good performance in various fault conditions. These results indicate that the presented of the control strategy can improve the transient stability of the system. It is clear that the results obtained with conventional generation emphasize the importance of inserting high levels of PV penetration and that the replacement of SG2 by the PV penetration has no negative impact on the transient stability. As well as the STATCOM has the capability to reduce and improve the rotor angle oscillations. Then according to this study, we can say that the proposed controller provides sufficient damping compared to a conventional generation system. We compared the results with those obtained in [23] and we have reached the same results by studying the rotor angle stability that it is judged from the nature of swing curve. We can also note as shown in [2] that high PV penetration in the power systems can bear the disturbances and damp the oscillations. While [9, 25] show that the impact of the PV penetration can be positive or negative depending on the PV penetration percentage, the topology of the system, the type of disturbance and the fault location. In addition, by comparing the results with those obtained in [24], we can demonstrate the effectiveness of STATCOM for a rapid oscillation damping, improving the margin of the rotor angle stability and increasing the critical clearing time.

4. Conclusion

This article presented a control strategy of transient stability for SMIB system. In this proposed method, we have shown the efficiency of renewable sources such as photovoltaic and FACTS devices like STATCOM to improve the transient stability and to damp a low frequency oscillation of the power system. Therefore, the results obtained from the integration of the PV penetration and the use of FACTS technology (STATCOM), shows the efficiency of the implementation of this proposed method that is able to provide solutions to improve the behavior of networks by damping the transient oscillations of the rotor angle for various fault conditions.

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