Impact of Photovoltaic Generation On The Power System Stability

Eng. Abdelmoezz Ahmed Eid
Dept. of Electrical Engineering
Al-Azhar University
Cairo, Egypt
engabdelmoezz@gmail.com

Dr. Tarek Mahmoud
Dept. of Electrical Engineering
Al-Azhar University
Cairo, Egypt
tarekmahmoud@hotmail.com

Dr. Nasr Mahmoud Rashid
Dept. of Electrical Engineering
Aljouf University, KSA
Dept. of Electrical Engineering
Al-Azhar University, Egypt
nasrrashid@ju.edu.sa

***Abstract*—The paper introduce the analysis of the small signal stability of the power system when the high PVGs penetrate in the power system. Reduced system inertia and altered power flow patterns as a result of the addition photovoltaic generators that replace a portion of conventional generation resources, may lead to decreased damping of the critical modes of the system, and the effect is observed. The eigenvalue analysis of the system is done without any PVGs penetration and with various levels of PVGs penetration and then the results are compared. The transient analysis is also done to substantiate the results obtained by the small signal stability analysis. IEEE-39 bus test system is subjected to this studies. The Power System Analysis Toolbox of MATLAB (PSAT) is used for the simulation.**

Keywords—Photovoltaic generators (PVGs); Small signal stability; Congested lines; PSAT; Eigen values; Transient stability.

I. Introduction

The demand for energy is expected to increase due to a variety of reasons. Such significant increase will lead to local and regional environmental issues [1]. Therefore ,The need for clean, renewable energy has resulted in new mandates to augment, and in some cases replace, conventional fossil based generation with renewable generation resources [2]. One of the consequences of competitive electricity markets is the Photovoltaic generators (PVGs). In fact Photovoltaic generation is among those resources that have been at the center of attention. These resources albeit currently more expensive (in $/MW installed comparison) are environmentally friendly, renewable and it the clean sources of the energy and it gives us the solution to the problems such as solid wastes, greenhouse gas effects [3]. Therefore, PVGs generation is growing rapidly around the world. Therefore, replacing the conventional generation with large scale renewable units has been one of the major aspects characterizing smart grids.

In the other hand, The price of the combustible fossils is increasing because of the increasing worldwide demand for the energy [4].

With the extensive growth in the deployment of the photovoltaic resources, power system operators are expected to deal with a new generation of power system issues due to the different nature of the newly added power generation resources. The ability to reverse the flow of the power from the loads towards the transmission system and the reduced reactive power generation are some of the unique characteristics of the PVGs units that add to the complexity of power systems [3].

Now, connecting the PVGs generation to the already existing power system is going to affect the stability of the system positively or negatively. So, the study of the impact of this photovoltaic generation on the stability is important. Photovoltaic power plant consists of the photovoltaic cell and DC to AC inverters. Hence, they do not possess inertia which the traditional synchronous generators possess. In addition, their behavior and interaction with the power system depend on the dynamics of the inverter. Therefore, it is important to study the effect of the penetration of the PVGs on the power system dynamic performance. There are not many references available on the small signal stability of the power system considering high PVGs penetration. Researchers [3] and [5] discusses the impact of the PVGs systems connected to the utility side and rooftop PVGs generation connected to transmission/sub transmission system.

This paper is organized as follows. Section II describes the concept of the small signal stability analysis. Section III gives the description of the test system and the modeling of the PVGs system. Section IV describes optimal location selection and analysis of the small signal stability of the system. The transient analysis is done in section V and finally conclusions which are drawn from the analysis are given in the section VI.

II. CONCEPT OF THE SMALL SIGNAL STABILITY ANALYSIS

The power system dynamic behavior can be described by a set of n first order nonlinear ordinary differential equations in vector-matrix notation [6]

$$\dot{X} = f(x,u,t) \qquad (1)$$

Where $x = (x_1, x_2 \ldots x_n)^T$ is the vector of state variables,
$Y = (y_1, y_2, \ldots y_m)^T$ is the vector of system outputs variables, $u=(u_1, u_2, \ldots u_r)^T$ is the vector of system input variables, $f = (f_1, f_2, \ldots f_n)^T$ and $g = (g_1, g_2, \ldots g_m)^T$ are the vectors of nonlinear functions defining the states and the outputs respectively of the system, time is denoted by t , and the derivative of sate variable X with respect to time is $\dot{X}$ .if the derivative of the state variables are not explicit function of the time, equation (1) can be simplified as:

$$\dot{X} = f(x,u) \quad , Y = g(x,u) \qquad (2)$$

Where the vector Y is the output of the system.
For small signal stability analysis a small perturbation is considered, the non-linear function f and g can be linearized using Taylor series with the initial points $x=x_0$ and $u=u_0$,

the system can expressed in the following equation:

$$\Delta\dot{x}=A\Delta x+B\Delta u \,, \quad \Delta y = C\Delta x+D\Delta u \qquad (3)$$

Where Δx is a small deviation in the state vector, Δy is a small deviation in the output vector, *A* is the state matrix, *B* is the input matrix, *C* is the output coefficient matrix and *D* is the feed forward matrix.

According to Lyapunov's first method, the eigenvalues of the state matrix *A* can be illustrate the behavior of the system according to small signal stability, The eigenvalues of the state matrix *A* may be :

1- a real eigenvalue corresponds to a non-oscillatory mode where a negative real Eigen value represents a decaying mode, a positive real represents aperiodic instability.

2- Complex eigenvalues occur in conjugate pairs, and each pair corresponds to an oscillatory mode.

a) When the Complex eigenvalues have negative real parts, the original system is stable.
b) When at least one of the Complex eigenvalues has a positive real part, the original system is unstable.
c) When at least one of the eigenvalues has zero value, the original system is critical stable [7].

For any eigenvalue λ_i, the n-column vector Φ_i is called the right eigenvector which gives the mode shape and the n-row vector Ψ_i is called the left eigenvector identifies which combination of the original state variables displays only the i^{th} mode , are satisfies Equations:

$$A\,\Phi_i = \lambda\,\Phi_i \qquad (4)$$
$$\Psi_i\,A = \lambda_i\,\Psi_i \qquad (5)$$

Where $\Psi_i\,\Phi_i = 1$
A measure of the association between the state variables and the modes is the participation factors $p=[p_1 \;\; p_2 \ldots\ldots p_n]$ With

$$P_i = \begin{bmatrix} P1i \\ p2i \\ \vdots \\ pni \end{bmatrix} = \begin{bmatrix} \Phi 1i\,\Psi i1 \\ \Phi 2i\,\Psi i2 \\ \vdots \\ \Phi ni\,\Psi in \end{bmatrix}$$

III. DESCRIPTION OF THE TEST SYSTEM

A. IEEE-39 bus system.

For the analysis of the PVGs penetration *IEEE-39 bus system* is used. The total load of the system is 6710 MW. There are ten generators in the system connected at buses from 30 to 39 as shown in the following fig(1). The ten generators are 6^{th} order and equipped with IEEE type II governors and IEEE type II exciters.

In this paper we will displace the conventional synchronous generators with the utility scale PV plant. The PV generation level is varied to see the impact of the PV system on the small signal stability.
The PV penetration level in the system is defined as,

$$\text{PV Penteration } (\%) = \frac{Total\ PV\ generation\ (MW)}{Total\ generation\ (MW)}$$

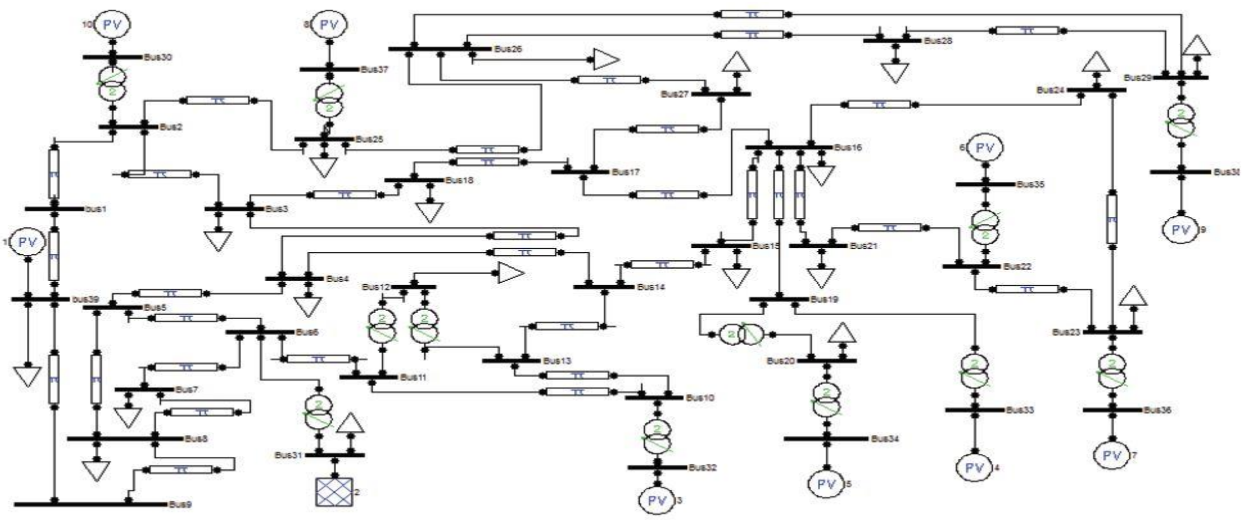

fig. 1. IEEE-39 bus test system

B. Modeling of PVGs systems

The one-line diagrams of the developed PVGs models according to the control modes and their capabilities are depicted in Figs.2 and .3 , for Model 1 (constant PQ) and Model 2 (constant PV) ,respectively.

There are various possibilities for inverter transfer functions; however, the following two are probably the most appropriate [8]:

(a) first order functions with unity steady state gain.

(b) the closed loop controller transfer functions.

Both yield very similar results and hence the first one is adopted here.

Figs.2 and 3 show the block-diagrams of the two developed models.

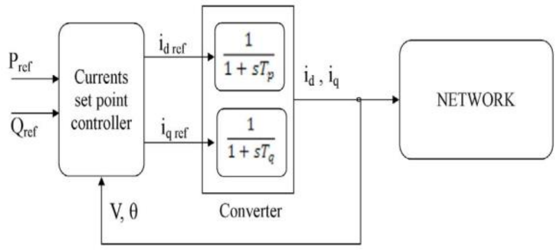

fig. 2. PVGs Model 1 block diagram

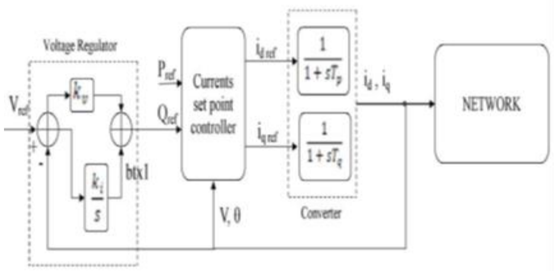

fig. 3. PVGs Model 2 block diagram

In these models, the current set points can be obtained based on the desired active and reactive powers and current measurements of terminal voltage in the dq reference frame.

In Fig. 3, the reference value for reactive power is obtained based on the set-point and actual voltage values through a PI controller [9].

IV. SIMULATION AND RESULTS

A. Selection of PVGs location

Before the study of the impact of PVGs on system stability, determination of the optimal location are discussed.

In this optimization the simulated annealing algorithm is used to find the optimal location of PVGs with varies levels and corresponding losses.

Tables.1 to 4 show the results of power flow analysis and the optimal locations of PVGs replaced conventional generation.

TABLE 1. total load and the total power losses of base case

case	Total load	Power losses
Base case	6710 MW	44.77 MW

As shown , the total load of IEEE 39 bus system is 6710 MW , and has 44.77 MW as normal losses

TABLE 2. optimal locations of PVGs displaced 10% of conventional generation

Case	PVGs Size	Optmal Location	Power Losses
10%	671 MW	Bus 3	36.4 MW

As seen, the optimal location to construct 671 MW PVGs instead of 10% of conventional generation is bus 3

TABLE 3. optimal locations of PVGs displaced 20% of conventional generation

Case	PVGs Size	Optmal Location	Power Losses
20%	1342 MW	Bus 3	36.96 MW

As seen, the optimal location to construct 1342 MW PVGs instead of 20% of conventional generation is bus 3

TABLE 4. optimal locations of PVGs displaced 30% of conventional generation

Case	PVGs Size	Optmal Location	Power Losses
30%	2013 MW	Bus 17	46.36 MW

As seen, the optimal location to construct 2013 MW PVGs instead of 30% of conventional generation is bus 17

B. Continuation power flow

To obtain the congested lines ,CPF test is done and the Maximum Loading Parameter λ_{max} is recorded with disconnecting system lines one by one. The congested lines in this system are shown in table.5.

Also, CPF test gives the voltage magnitude profile , the weakest bus is bus 7. So it's the critical bus of the system.

Fig.4 shows voltages at all buses result from CPF test.

TABLE 5. The congested lines of IEEE 39 bus system

line	From bus	To bus
L1	15	16
L2	21	22
L3	5	6

Table shows the most three congested lines optaind by CPF test applied on the studied system.

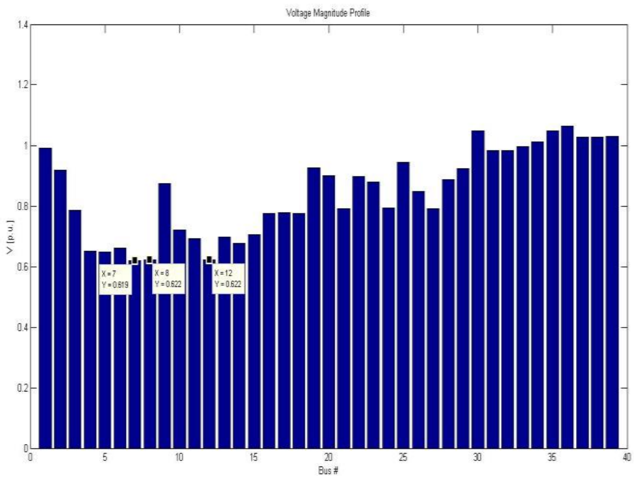

fig. 4. voltage magnitude profile of IEEE 39 bus system

C. Eigenvalue analysis

The objective of the paper is to analyze the small signal stability of the system under various levels of PV penetration. For this using PSAT program, depending on the Eigenvalues of the system the following scenario is implemented.

CASE(1) Represents the base case where all generators in the system are synchronous generator and there is no PVGs in the system.

a) Normal case.

In this case, all lines of the system are connected. Small signal stability of the tested system is computed and Eigenvalues of the system with its dominant states as shown in table.6 and Fig.5.

b) Contingency case

In this case the congested lines 15-16, 21-22 and 5-6, according to table.5 will disconnecting one by one from system in base case and compute the small signal stability of the system, Eigenvalues of the system with its dominant states are shown in table.7.

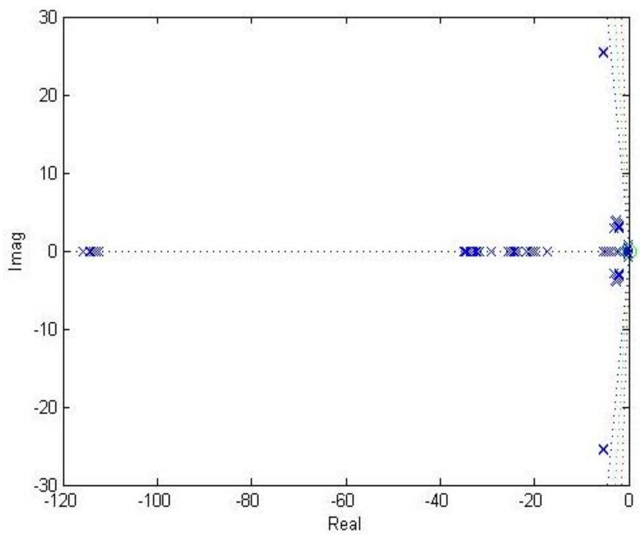

fig. 5. computed Eigen values of base case

TABLE 6. computed Eigenvalues of base case

Zero Eigen		Positive Eign	
number	Dominant states	number	Dominant states
91	delta_Syn_9	--	--

As seen, IEEE-39 bus test system has 110 Eigen number all Eigen numbers are negative except the Eigen number λ 91 is zero value, so the system is critically stable. The participation factors associate the delta of synchronous generator connected at bus 39 with this critically stable of the system.

TABLE 7. computed Eigenvalues of contingency base case

system	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
Disconnecting L1	91	delta_Syn_9	--	--
Disconnecting L2	92	delta_Syn_9	--	--
Disconnecting L3	91	delta_Syn_9	--	--

As shown, all Eigen numbers are negative except the Eigen number ʎ91 is zero value at Disconnecting L1 and L3 , and the Eigen number ʎ92 is zero value at Disconnecting L2 . So the system is critically stable. The participation factors associate the delta of synchronous generator connected at bus 39 with this critically stable of the system.

CASE(2) Replacing 10 % from rating the synchronous generators of the system in case(1) by PVGs with 671 MW at bus 3.

a) Normal case

Small signal stability test is done, Eigenvalues of the system with its dominant states are shown in table.8.

b) Contingency case

In this case the congested lines are disconnected one by one and eigenvalue analysis is carried out, the Eigenvalues of the system with its dominant states are shown in table.9.

TABLE 8. computed Eigenvalues of system with 10% PVGs.

Zero Eigen		Positive Eign	
number	Dominant states	number	Dominant states
96	delta_Syn_9	--	--

The results show that the system has 113 Eigen number all Eigen numbers are negative except the Eigen number ʎ96 is zero value so the system is critically stable. The participation factors associate the delta of synchronous generator connected at bus 39 with this critically stable of the system.

TABLE 9. computed Eigenvalues of Contingency system with 10% PVGs.

system	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
Disconnecting L1	96	delta_Syn_9	--	--
Disconnecting L2	96	delta_Syn_9	--	--
Disconnecting L3	94	delta_Syn_9	--	--

As shown, all Eigen numbers are negative except the Eigen number ʎ96 is zero value at disconnecting L1 and L2 , and the Eigen number ʎ94 is zero value at Disconnecting L3 . So the system is critically stable. The participation factors associate the delta of synchronous generator connected at bus 39 with this critically stable of the system.

CASE(3) Replacing 20% from rating the synchronous generators of the system in case(1) by PVGs with 1342 MW at bus 3.

a) Normal case

After computing of small signal stability test , Eigenvalues of the system with its dominant states shown in table .10.

b) Contingency case

In this case the congested lines are disconnected one by one. The eigenvalue analysis is carried out, the Eigenvalues of the system with its dominant states are shown in table.11.

CASE(4) Replacing 30% from rating the synchronous generators of the system in case(1) by PVGs with 2013 MW at bus 17.

a) Normal case

Small signal stability test is done, Eigenvalues of the system with its dominant states are shown in table.12.

b) Contingency case

Small signal stability test is done after disconnecting congested lines. Eigenvalues of the system with its dominant states are shown in table.13.

TABLE 10 . computed Eigenvalues of system with 20% PVGs

Zero Eigen		Positive Eign	
number	Dominant states	number	Dominant states
96	delta_Syn_9	--	--

As shown, the system is critical stable as all Eigen numbers are negative except the Eigen number ʎ96 is zero value and the dominant states is delta of synchronous generator connected at bus 39.

TABLE 11. computed Eigenvalues of Contingency system with 20% PVGs.

system	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
Disconnecting L1	93	delta_Syn_9	--	--
Disconnecting L2	96	delta_Syn_9	--	--
Disconnecting L3	94	delta_Syn_9	--	--

As shown, all Eigen numbers are negative except the Eigen number ʎ93, Eigen number ʎ96 and the Eigen number ʎ94 are zero value at disconnecting L1 , L2 and L3 respectively. So the system is critically stable. The participation factors associate the delta of synchronous generator connected at bus 39 with this critically stable of the system.

TABLE 12 . computed Eigenvalues of system with 30% PVGs.

Zero Eigen		Positive Eign	
number	Dominant states	number	Dominant states
94	delta_Syn_9	--	--

Table shows that all Eigen numbers are negative except the Eigen number λ94 is zero value so the system is critically stable. The participation factors associate the delta of synchronous generator connected at bus 39 with this critically stable of the system.

TABLE 13 . Computed Eigenvalues of Contingency system with 30% PVGs.

system	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
Disconnecting L1	96	delta_Syn_9	--	--
Disconnecting L2	93	delta_Syn_9	--	--
Disconnecting L3	94	delta_Syn_9	--	--

As shown, all Eigen numbers are negative except the Eigen number λ96, Eigen number λ93 and the Eigen number λ94 are zero value at disconnecting L1 , L2 and L3 respectively. So the system is critically stable. The participation factors associate the delta of synchronous generator connected at bus 39 with this critically stable of the system.

<u>CASE(5)</u> Repeating cases (1) to (4) with increasing loads of the system by 110% of normal system loads. Small signal stability of the tested system is computed.

a) Normal case

Eigenvalues of the system with its dominant states as shown in table.14.

b) Contingency case

Small signal stability test is done after disconnecting congested lines.

Tables.(15) to (17) show the eigenvalues of the system with its dominant states when congested lines L1, L2 and L3 are disconnected respectively .

TABLE 14 . Computed Eigenvalues of system with varies levels of PVGs penetration with increasing load by 110%.

	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
No PVGs	92	delta_Syn_9	--	--
PVGs with 10%	93	delta_Syn_9	--	--
PVGs with 20%	93	delta_Syn_9	--	--
PVGs with 30%	95	delta_Syn_9	--	--

As shown all Eigen numbers are negative except the Eigen number λ92, Eigen number λ93 and the Eigen number λ95 are zero value. So the system is critically stable.

TABLE 15. Computed Eigenvalues of contingency system at disconnecting of L1 with varies levels of PVGs penetration with increasing load by 110%.

	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
No PVGs	92	delta_Syn_9	90 91	e1q_Syn_1, vr2_Exc_1 e1q_Syn_1, vr2_Exc_1
PVGs with 10%	98	delta_Syn_9	--	--
PVGs with 20%	98	delta_Syn_9	--	--
PVGs with 30%	96	delta_Syn_9	--	--

As shown, the system has two positive Eigen numbers at no PVGs penetration so it is unstable, but it is critically stable with the varies levels of PVGs penetration

TABLE 16. Computed Eigenvalues of contingency system at disconnecting of L2 with varies levels of PVGs penetration with increasing load by 110%.

	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
No PVGs	94	delta_Syn_9	90 91	e1q_Syn_1, vr2_Exc_1 e1q_Syn_1, vr2_Exc_1
PVGs with 10%	95	delta_Syn_9	--	--
PVGs with 20%	96	delta_Syn_9	--	--
PVGs with 30%	96	delta_Syn_9	--	--

As shown, the system has two positive Eigen numbers at no PVGs penetration so it is unstable, but it is critically stable with the varies levels of PVGs penetration

TABLE 17. Computed Eigenvalues of contingency system at disconnecting of L3 with varies levels of PVGs penetration with increasing load by 110%.

	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
No PVGs	92	delta_Syn_9	90 91	e1q_Syn_1, vr2_Exc_1 e1q_Syn_1, vr2_Exc_1
PVGs with 10%	95	delta_Syn_9	--	--
PVGs with 20%	93	delta_Syn_9	--	--
PVGs with 30%	95	delta_Syn_9	--	--

As shown, the system has two positive Eigen numbers at no PVGs penetration so it is unstable, but it is critically stable with the varies levels of PVGs penetration

Tables. (15) to (17) show that the Eigenvalues move to the left hand side (LHS) when PVGs are constructed to the system, so the PVGs have a positive effect on small signal stability of the system.

CASE(6) Repeating cases (1) to (4) with increasing loads of the system by 120% of normal system loads.

a) Normal case

Small signal stability of the tested system is computed. Eigenvalues of the system with its dominant states as shown in table.18.

b) Contingency case

In this case, congested lines are disconnected one by one and the eigenvalues are computed.
Tables (19) to (21) Eigenvalues are shown when congested lines L1, L2 and L3 are disconnected respectively.

TABLE 18. Computed Eigenvalues of system with varies levels of PVGs penetration with increasing load by 120%.

system	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
No PVGs	94	delta_Syn_9	63 64	vr2_Exc_1, e1q_Syn_1 vr2_Exc_1, e1q_Syn_1
PVGs with 10%	95	delta_Syn_9	--	--
PVGs with 20%	95	delta_Syn_9	--	--
PVGs with 30%	95	delta_Syn_9	--	--

As shown, the system has two positive Eigen numbers at no PVGs penetration so it is unstable, but it is critically stable with the varies levels of PVGs penetration

TABLE 19. Computed Eigenvalues of contingency system at disconnecting of L1 with varies levels of PVGs penetration with increasing load by 120%.

system	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
No PVGs	92	delta_Syn_2	85 86	vr2_Exc_1, e1q_Syn_1 vr2_Exc_1, e1q_Syn_1
PVGs with 10%	95	delta_Syn_9	93 94	e1q_Syn_1, vr2_Exc_1 e1q_Syn_1, vr2_Exc_1
PVGs with 20%	95	delta_Syn_4	--	--
PVGs with 30%	95	delta_Syn_9	--	--

As shown, the system has two positive Eigen numbers at no PVGs and 10% PVGs penetration so it is unstable, but it is critically stable with 20% and 30% levels of PVGs penetration.

TABLE 20. Computed Eigenvalues of contingency system at disconnecting of L2 with varies levels of PVGs penetration with increasing load by 120%.

system	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
No PVGs	92	delta_Syn_9	63 89	delta_Syn_1 vr2_Exc_1
PVGs with 10%	97	delta_Syn_9	--	--
PVGs with 20%	95	delta_Syn_9	--	--
PVGs with 30%	95	delta_Syn_9	--	--

As shown, the system has two positive Eigen numbers at no PVGs penetration so it is unstable, but it is critically stable with the varies levels of PVGs penetration

TABLE 21. Computed Eigenvalues of contingency system at disconnecting of L3 with varies levels of PVGs penetration with increasing load by 120%.

system	Zero Eigen		Positive Eign	
	number	Dominant states	number	Dominant states
No PVGs	92	delta_Syn_2	63 89	omega_Syn_1 vr2_Exc_1
PVGs with 10%	98	delta_Syn_2	93 94	e1q_Syn_1, vr2_Exc_1 e1q_Syn_1, vr2_Exc_1
PVGs with 20%	95	delta_Syn_9	93 94	e1q_Syn_1, vr2_Exc_1 e1q_Syn_1, vr2_Exc_1
PVGs with 30%	95	delta_Syn_9	--	--

As shown, the system has two positive Eigen numbers at no PVGs , 10% and 20% levels penetration of PVGs so it is unstable, but it is critically stable with 30% level of PVGs penetration.

Tables. (18) to (21) show that the Eigenvalues move to the left hand side (LHS) when PVGs are constructed to the system with 30% level against all odds, so this level is the most proper to construct to the system.

V. TRANSIENT ANALYSIS

For IEEE 39 bus system a fault is making at bus 7. This fault is three phase fault occurs at t = 1sec and its duration is 0.25 s then the fault is clearing. The effect of this fault on voltages of nearing buses, speeds and power angles of generators and active and reactive powers of generation buses when there's PVGs with rating 2013 MW at bus 17 and there's no PVGs as shown in the following figures.

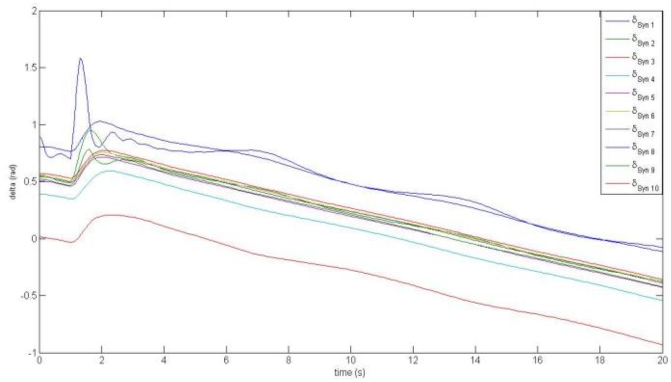

fig. 6. Rotor angles of generators without PV penetration

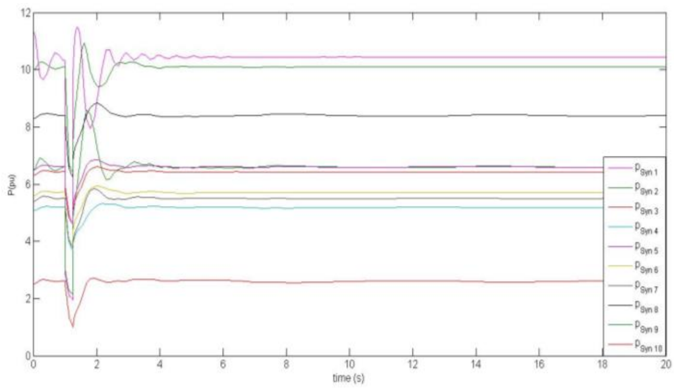

fig. 7. Active power of generators without PV penetration

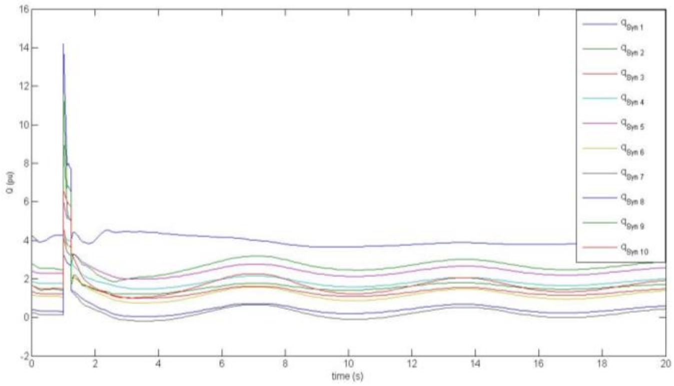

fig. 8. Reactive power of generators without PV penetration

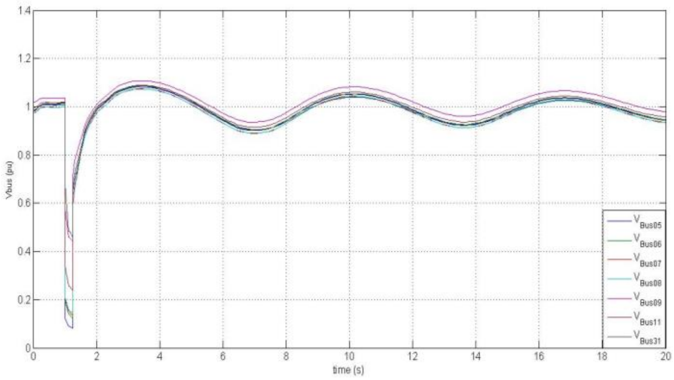

fig. 9. Voltages at nearing buses to bus 7 without PV penetration

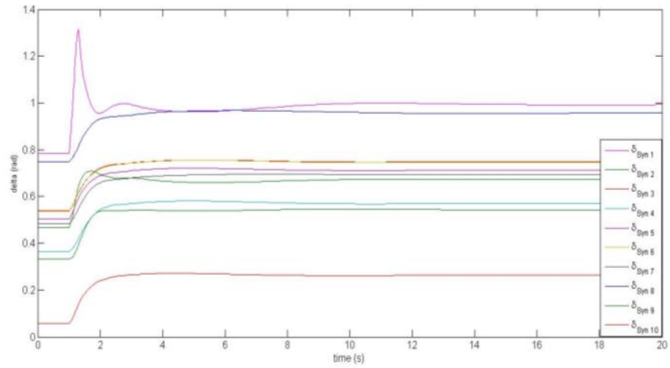

fig. 10. Rotor angles of generators with 30% PV penetration

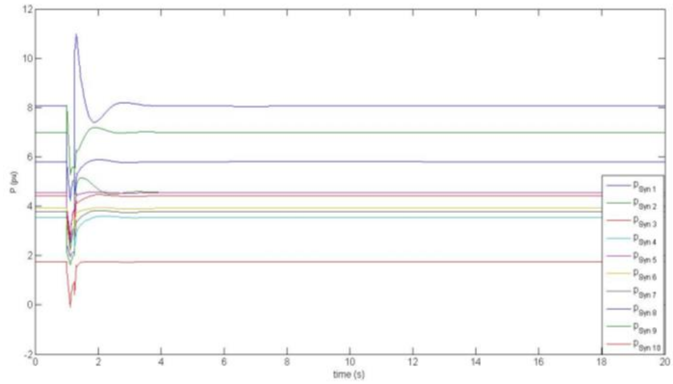

fig. 11. Active power of generators with 30% PV penetration

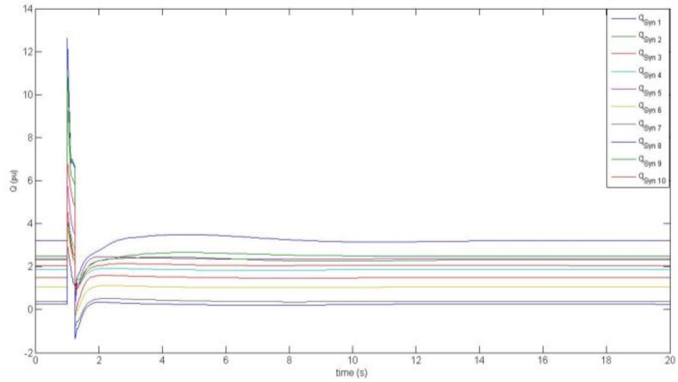

fig. 12. Reactive power of generators with 30% PV penetration

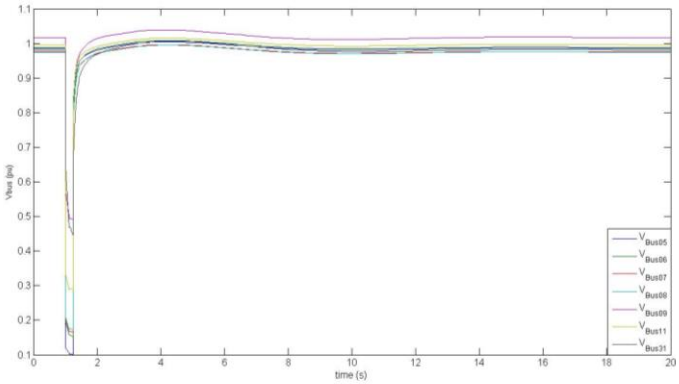

fig. 13. Voltages at nearing buses to bus 7 with 30% PV penetration

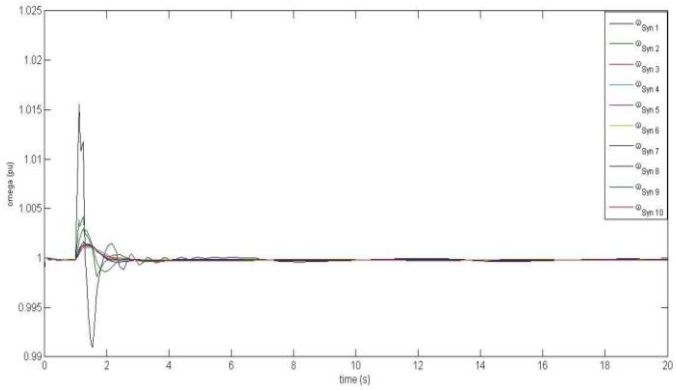

fig. 14. Speeds of of generators without PV penetration

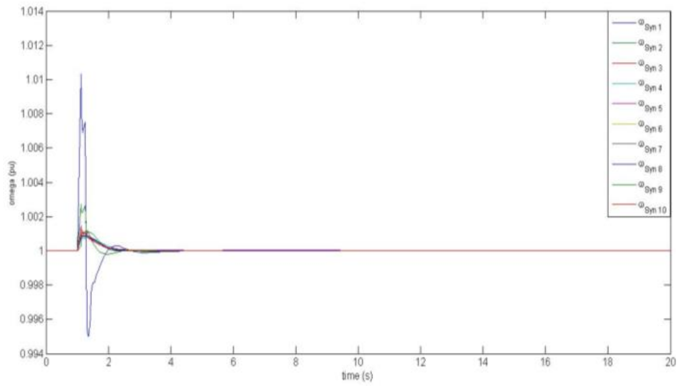

fig. 15. Speeds of of generators with 30% PV penetration

VI. CONCLUSION

Small signal stability analysis and Transient stability analysis has been carried out for IEEE 39-bus power systems with and without injection of Photovoltaic Generation . The eigenvalue sensitivity has been used to observe the effect of Photovoltaic Generation on the small signal stability of the system considering some factors, location of the PVGs , levels of penetration , increase of the load of the system and disconnecting of some congested lines of the tested system. It shown that improvement in small signal stability of the system is dependent on levels of PVGs penetration. The results shown that the best location of PVGs in this system at bus 17 with rating 30% of total load, which have a higher percentage of stability for number of cases done. Transient stability analysis performed through time domain simulations, shown that the system contains PVGs are able to restore rotor angles, voltages, speeds and power after a three phase fault better than conventional generators though a quick response in restoration .

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