

Small Signal Stability Analysis of Grid Connected Photovoltaic

Shalom Lim Zhu Aun, Marayati Bte Marsadek*, Agileswari K. Ramasamy

College of Graduate Studies, Universiti Tenaga Nasional, 43000 Kajang, Selangor, Malaysia

*Corresponding author, e-mail: marayati@uniten.edu.my

Abstract

This paper primarily focuses on the small signal stability analysis of a power system integrated with solar photovoltaics (PV). The test system used in this study is the IEEE 39-bus. The small signal stability of the test system are investigated in terms of eigenvalue analysis, damped frequency, damping ratio and participation factor. In this study, various conditions are analyzed which include the increase in solar PV penetration into the system and load variation. The results obtained indicate that there is no significant impact of solar PV penetration on the small signal stability of large scaled power system.

Keywords: renewable energy; power system stability; small signal stability; photovoltaics; eigenvalues

Copyright © 2017 Institute of Advanced Engineering and Science. All rights reserved.

1. Introduction

This paper represents small signal stability analysis of grid connected photovoltaic. The study involves the investigation in terms of eigenvalue analysis, damped frequency, damping ratio and participation factor for increased solar PV penetration and load variation into the grid. The results obtained would indicate the impact of solar PV penetration on the small signal stability of the power system.

In this modern era, consumption and depletion of the world's fossil fuels have been expanding at an alarming exponential rate. The average 500 MW coal plant annually produces 3.7 million tons of carbon dioxide and other greenhouse gases [1]. This has caused a worrisome issue on greenhouse effects, global warming and even energy shortage in the coming years ahead. Therefore, there is an accelerating need to look for sustainable energy resources such as renewable energy to ensure a sustainable future [2]. Power systems that are dominated by synchronous generators are highly nonlinear and may experience a change in its dynamics and operational characteristics when connected to renewable energy resources. A study done in [3] shows that the integration of wind DFIG-based wind turbine generators into the power system grid does indeed impact the overall performance of the system in terms of small signal stability. Furthermore, another study [4] reaffirms that wind penetration to the grid causes small signal stability problems. The results in [4] showed a dynamically unstable behavior and altered local and inter-area mode shapes.

On the contrary, a study was done on the small stability effects of distributed solar PV and DFIG based wind generation on the grid. It was found that the stability margin of the system is enhanced considerably [5]. Based on [6], penetration of DFIG wind turbines of almost 2MW in a wind farm shows an improvement in the of the power system stability when aggregated under certain conditions on a small grid. Based on [7], integration of wind energy into the power system improves stability by reducing the settling and overshoot time under the action of power system stabilizers. Renewable energy in the distribution level was studied in [8] and it is observed that the dynamics of the wind generator contribute significant system oscillations whereas solar PV generators actually enhances the small signal stability characteristics of the system whereby the eigen sensitivity decreases. As the renewable generation was increased, frequency of modes had an increase whereas the damping ratio was relatively constant. It was also found that there were no negative effects on the increase in renewable generation [9]. Furthermore, another study found that when a PSS equipped wind farm penetration increases, the damping ratio of inter-area modes improves [10]. Based on [11], solar PV and wind energy

conversion system are integrated into a microgrid and it is revealed that the damping performance is enhanced and small signal stability improves.

Thus, it is vital for the power system operator to perform a thorough analysis on the impact of renewable energy resources to the power system before they can be implemented.

Malaysia may not have much potential for wind energy, nevertheless it has potential for solar renewable energy. It lies in the equatorial region making it a hot and relatively humid country that has stable climate change throughout the year. An annual average daily solar irradiation values between 4.21kWh/m² to 5.56kWh/m² encourages the growth of solar PV systems [12]. Thus, solar PV systems have great potential in Malaysia.

In [13], the western North American power system was investigated through two methods whereby two different Western Electric Coordinating Council (WECC) base cases were analyzed. First method was the excitation of oscillation modes and perform ringdown analysis with Prony's method. The second approach was using the analytical linearization technique using Small Signal Analysis Tool. Generation of solar and wind in each base case was increased. It was found that mode frequency increased whereas damping ratio was unaffected as renewable generation increased.

Another study [5], small signal stability analysis for grid connected PV and wind energy was investigated via PSAT Toolbox of MATLAB under 3 cases which is the base case, load disturbance and effect of configuration changed. Results indicate that the stability margin improved.

This brings the need to study the small signal stability interaction of solar PV penetration into a grid. The small signal stability analysis assessment performed in this study should be able to provide an insight on the performance of the power system with the penetration of solar PV renewable energy. The impact of solar PV penetration to small signal stability can be investigated from the eigenvalue of all states computed using modal analysis, damped frequency, damping ratio and participation factor. To facilitate the modal analysis, small signal analysis tool in DlgSILENT Powerfactory is employed.

2. Research Method

2.1. Small Signal Stability Analysis

Small signal stability is defined as the power system's ability to maintain synchronism after being subjected to small variations in load or generation [14]. The stability of the power system can be influenced by load characteristics, discrete and continuous controls. This analysis method investigates the system's response to minor system changes. Forms of instability generally occur under these conditions:

- a) A constant increase in rotor angle because of insufficient synchronizing torque
- b) Increasing amplitude of rotor oscillations because of insufficient damping torque [14]

In a power system, the small signal stability oscillations are either local mode or inter-area mode in nature. There are 3 types of local modes which are associated with:

- a) Rotor angle oscillations of a generator against the rest of the power system. This condition has frequency range of 1Hz to 3Hz
- b) Oscillations between rotors of several generators near one another. Frequency range from 0.7Hz to 2Hz
- c) Inadequate tuning of control systems [14]

Inter-area mode oscillations are due to interactions among two or more large groups of generators swinging against each other in different areas. Inter-area oscillations can be divided into two major forms which are:

- a) Low frequency mode. This occurs when generators in two different parts are swinging against each other. Frequency of oscillations is from 0.1Hz to 0.3Hz
- b) High frequency mode involving subgroups of generators swinging. Frequency of oscillation range from 0.4Hz to 0.7Hz [14]

Table 1 shows the summary of frequency range for both inter-area and local modes.

Table 1. Frequency range for inter-area and local modes [14]

Mode Type	Frequency Range (Hz)
Inter-area	0.1 – 0.3 (Low frequency) 0.4 – 0.7 (High frequency)
Local	0.7 - 3

A complex pole can be written as:

$$s = \sigma \pm j\omega \quad (1)$$

where σ represents the real part of the pole which is the exponential damping frequency and ω represents the imaginary part, called damped frequency of oscillation. Damped frequency of oscillation of any pole is given by:

$$f = \frac{\omega}{2\pi} \quad (2)$$

The damping ratio, ξ is the decay rate of amplitude oscillation. The damping ratio is defined as: [14]

$$\xi = \frac{\text{Exponential decay frequency}}{\text{Natural frequency} \left(\frac{\text{rad}}{\text{sec}}\right)} = \frac{|\sigma|}{\omega_n} \quad (3)$$

or

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \quad (4)$$

2.2. Methodology

A modified IEEE 39-bus test system is adopted in this study. The system has 49 buses, 10 generators, 24 transformers and 32 transmission lines. It consists of 19 impedance loads which totals up to 6097.1 MW and 1408.9 MVar. A turbine governor and type-1 exciters are equipped to all the generators excluding generator 39 because it is an aggregation of a high quantity of generators. Figure 1 shows the 39-bus system. Tables 2 – 4 shows the synchronous dynamic data used. Dig SILENT Power factory software is used to simulate the 39-bus system.

Table 2. Test system machine data

Type	GENROU	GENROU	GENROU
Operation	Sync. Gen.	Sync. Gen.	Sync. Gen.
Default Unit no. (New Unit no.)	30(40)	31(41), 32(42), 33(43) 34(44), 35(45), 36(46) 37(47)	38(48) 39(49)
Rated power (MVA)	590	835	911
Rated voltage (kV)	22	20	26
Rated pf	0.95	0.9	0.9
H (s)	2.3186	2.6419	2.4862
D	2.00	2.00	2.00
r_a (p.u)	0.0046	0.0019	0.0010
x_d (p.u)	2.110	2.183	2.040
x_q (p.u)	2.020	2.157	1.960
x'_d (p.u)	0.280	0.413	0.266
x'_q (p.u)	0.490	1.285	0.262
x''_d (p.u)	0.215	0.339	0.193
x''_q (p.u)	0.215	0.339	0.193
x_t or x_p (p.u)	0.155	0.246	0.154
T'_{d0} (s)	4.200	5.690	6.000
T'_{q0} (s)	0.565	1.500	0.900
T''_{d0} (s)	0.032	0.041	0.004
T''_{q0} (s)	0.062	0.144	0.004
$S(1.0)$	0.079	0.134	0.340
$S(1.2)$	0.349	0.617	1.120

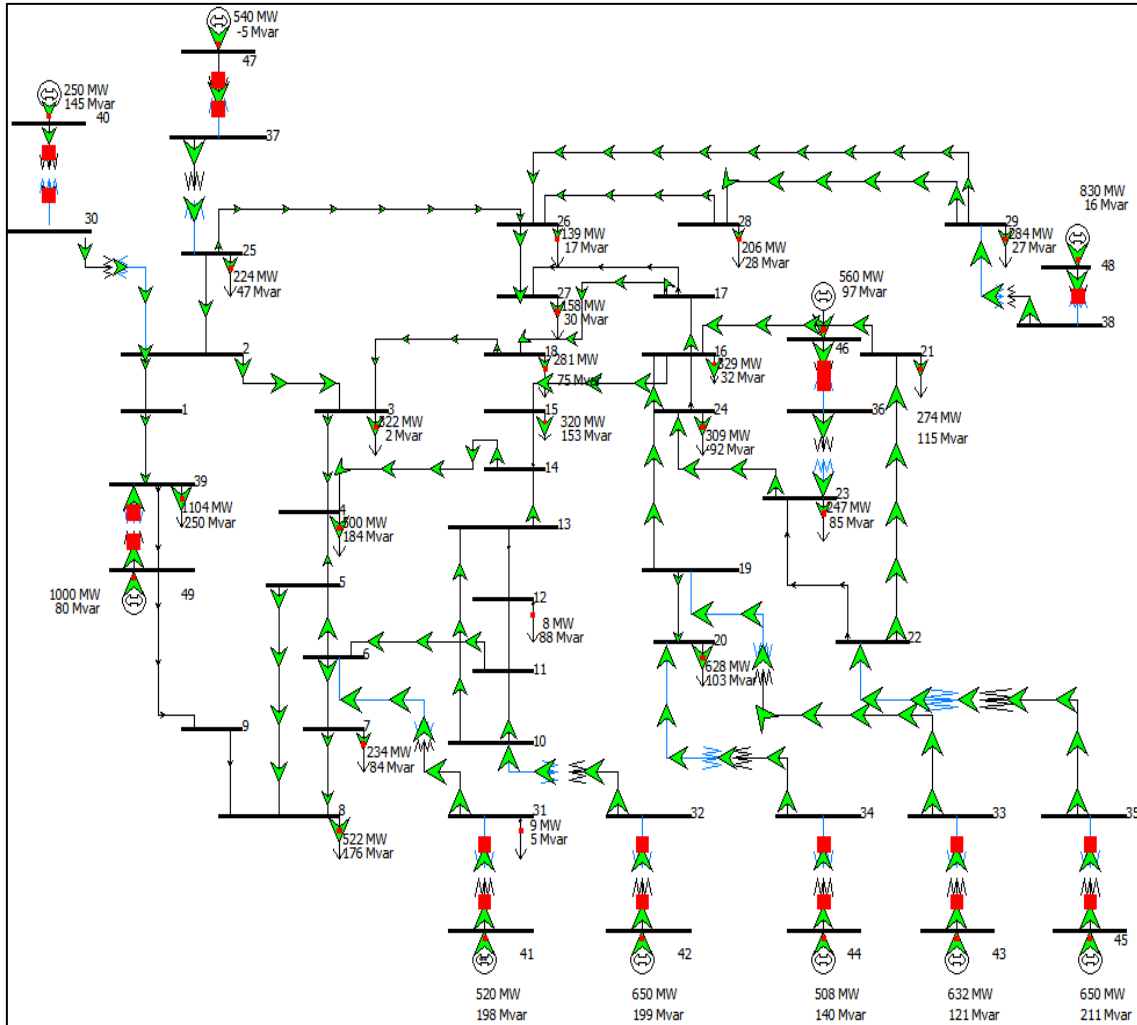


Figure 1. Modified IEEE 39-bus system in Dig SILENT Power factory software

Table 3. Test system governor data

Type	BPA_GG	BPA_GG	BPA_GG
Default Unit no. (New Unit no.)	30(40)	31(41), 32(42), 33(43) 34(44), 35(45), 36(46) 37(47)	38(48)
Rated power (MVA)	590	835	911
Rated voltage (kV)	22	20	26
P_{max} (p.u)	0.9373	0.9177	0.9001
R (p.u)	0.0085	0.006	0.00548
T_1 (s)	0.080	0.180	0.100
T_2 (s)	0.000	0.030	0.000
T_3 (s)	0.150	0.200	0.200
T_4 (s)	0.050	0.000	0.100
T_5 (s)	10.000	8.000	8.720
F	0.280	0.300	0.300

A base case of small signal stability analysis is initially done on the system to ensure that it is stable. Two cases are considered in this study and they are as follows:

Case 1: Incremental penetration of solar PV generation

Case 2: Load variation simultaneously with penetration of solar PV generation on power system

In Case 1, a solar PV plant generating a total of 50 MW is placed on bus 30 that currently is connected to a 250MW synchronous generator. The solar PV plant will replace the active power of the synchronous in increments of 50MW right up to the total capacity of 250MW, whereby the synchronous generator will be removed. In Case 2, the power system load is

increased from 5% up to 15% [15] simultaneously while solar PV penetration increases. In both cases, the small signal stability are analyzed in terms of eigenvalue, damped frequency, damping ratio and participation factor.

Table 4. Test system exciter data

Type	IEEE1	IEEE1	IEEE1
Default Unit no. (New Unit no.)	30(40)	31(41), 32(42), 33(43) 34(44), 35(45), 36(46) 37(47)	38(48)
Rated power (MVA)	590	835	911
Rated voltage (kV)	22	20	26
T_r (s)	0.000	0.000	0.000
K_a (p.u)	200	400	50
T_a (s)	0.3575	0.020	0.060
V_{Rmax} (p.u)	5.730	18.300	1.000
V_{Rmin} (p.u)	-5.730	-18.300	-1.00
K_e (p.u)	1.000	1.000	-0.0393
T_e (s)	0.004	0.942	0.440
K_f (p.u)	0.0529	0.030	0.070
T_f	1.000	1.000	1.000
E_1	4.2975	3.765	3.375
$SE(E_1)$	0.000	0.8147	0.0644
E_2	5.730	5.020	4.5
$SE(E_2)$	0.000	2.6756	0.2363

3. Results and Analysis

The simulations are carried out and the results are analyzed. Eigenvalues with complex imaginary parts having zero are filtered out as the focus is on the oscillatory parts only. Only eigenvalues that are poorly damped (i.e. having less than 10% damping ratio) are examined.

3.1 Case 1

As the penetration of solar PV is increased while reducing the generation of the synchronous generator, the eigenvalues obtained in this case shows that the system is stable. All real parts are negative in nature indicating that the system is stable. Table 5 shows the small signal stability analysis results obtained. The damped frequency for all PV penetration considered in Case 1 is of local mode as it is between the range of 0.7 Hz to 3 Hz. It is observed that the damping ratio increases from 3.59% to 3.88% as the PV penetration increases. The damping ratio indicates how stable a system is. A positive damping ratio implies a stable system for a given oscillation whereas, a negative damping ratio means that the system is unstable. As the damping ratio increases, the system is more stable.

Figure 2 shows the eigenvalues plot for Case 1 with PV penetration of 250MW. It can be seen that all eigenvalues are located on the left side of the plane which indicates decaying oscillation.

Table 5. Small signal stability analysis results for case 1

Sync. Gen. Power (MW)	PV Power (MW)	Real part (1/s)	Imaginary part (rad/s)	Damped Frequency (Hz)	Damping Ratio
250	0	-0.36074	10.0553	1.6003	3.59%
		-0.36074	-10.0553	1.6003	3.59%
200	50	-0.37436	10.0400	1.5979	3.73%
		-0.37436	-10.0400	1.5979	3.73%
150	100	-0.37323	10.0400	1.5979	3.71%
		-0.37323	-10.0400	1.5979	3.71%
100	150	-0.37214	10.0402	1.5979	3.70%
		-0.37214	-10.0402	1.5979	3.70%
50	200	-0.37110	10.0405	1.5980	3.69%
		-0.37110	-10.0405	1.5980	3.69%
0	250	-0.38844	10.0028	1.5920	3.88%
		-0.38844	-10.0028	1.5920	3.88%

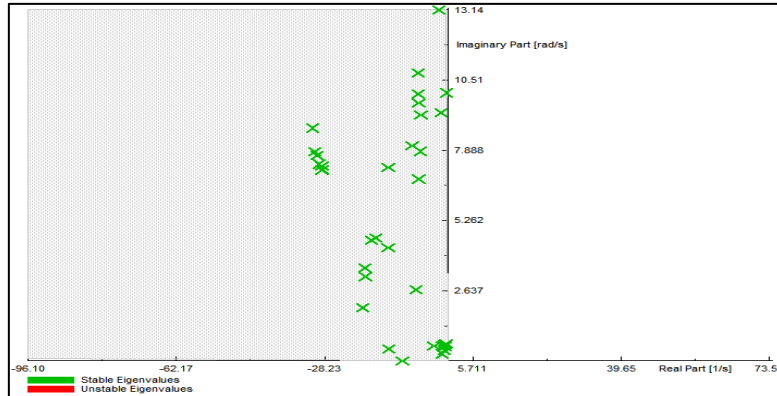


Figure 2. Eigenvalue plot factor for Case 1 with PV penetration of 250MW

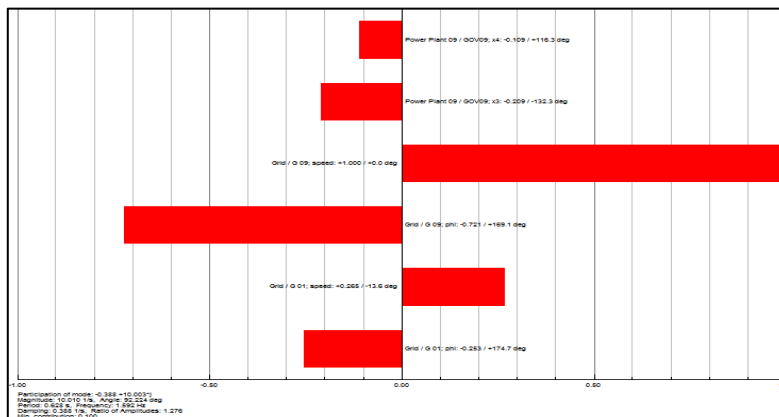


Figure 3. Bar plot participation factor for Case 1 (Positive imaginary mode) with PV penetration 250MW

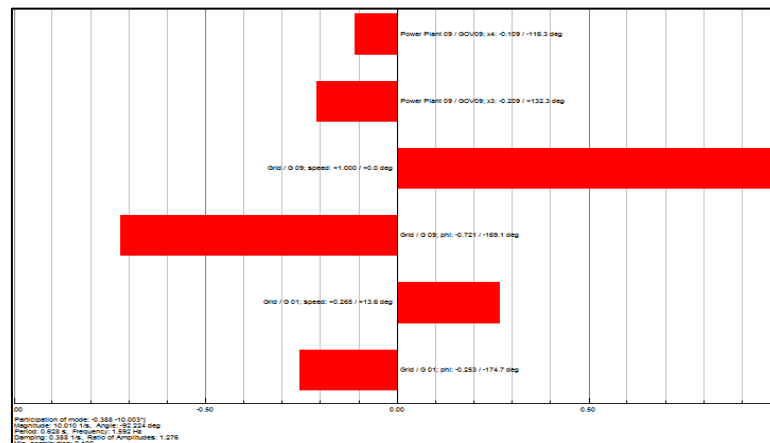


Figure 4. Bar plot participation factor for Case 1 (Negative imaginary mode) with PV penetration 250MW

The bar plot of the participation factor for Case 1 is shown in Figure 3 and Figure 4. Participation factor is a measure of state variable used to identify how each dynamic variable affects a given eigenvalue or mode. Based on the participation factor bar plot in Figure 3 and

Figure 4, it is shown that state variable associated to synchronous generator 9 contributes the highest in this case. The state corresponding to the speed of synchronous generator 9 participates the most. Thus, this is a local mode oscillation of a single generator.

3.2. Case 2

The eigen values obtained in this case shows that the system is stable. Similar to case 1, all real parts of the eigenvalues are negative which indicates system stability. Tables 6 to 11 show the small signal stability analysis results. Damped frequency remains within the local mode frequency range. The variation in load does not have a significant effect on the eigenvalues, damped frequency and damping ratio for each individual specific PV penetration power. It is observed that the damping ratio improves when the PV penetration is at 250 MW and synchronous generator is taken out of service. Synchronous generator 9 still contributes the most to the low damping ratio in this system; refer to Figure 6 and Figure 7.

Figure 5 shows the eigen value plot for Case 2 with PV penetration of 250MW and 15% loading. All eigenvalues are on the left side of the plane which imply a decaying oscillation.

Table 6. Small signal stability analysis results of case 2 for Solar pv penetration at 0 mw (base case)

Load Variation (%)	Real Part (1/s)	Imaginary Part (rad/s)	Damped Frequency (Hz)	Damping Ratio (%)
5%	-0.3680	-10.0670	1.6022	3.65%
	-0.3680	10.0670	1.6022	3.65%
10%	-0.3733	10.0792	1.6042	3.70%
	-0.3733	-10.0792	1.6042	3.70%
15%	-0.3710	10.0827	1.6047	3.68%
	-0.3710	-10.0827	1.6047	3.68%

Table 7. Small signal stability analysis results of case 2 for Solar PV penetration at 50MW

Load Variation (%)	Real Part (1/s)	Imaginary Part (rad/s)	Damped Frequency (Hz)	Damping Ratio (%)
5%	-0.3659	10.0655	1.6020	3.63%
	-0.3659	-10.0655	1.6020	3.63%
10%	-0.3714	10.0776	1.6039	3.68%
	-0.3714	-10.0776	1.6039	3.68%
15%	-0.3694	10.0813	1.6045	3.66%
	-0.3694	-10.0813	1.6045	3.66%

Table 8. Small signal stability analysis results of case 2 for Solar PV penetration at 100MW

Load Variation (%)	Real Part (1/s)	Imaginary Part (rad/s)	Damped Frequency (Hz)	Damping Ratio (%)
5%	-0.3640	10.0642	1.6018	3.61%
	-0.3640	-10.0642	1.6018	3.61%
10%	-0.3698	10.0762	1.6037	3.67%
	-0.3698	-10.0762	1.6037	3.67%
15%	-0.3681	10.0802	1.6043	3.65%
	-0.3681	-10.0802	1.6043	3.65%

Table 9. Small signal stability analysis results of case 2 for Solar PV penetration at 150MW

Load Variation (%)	Real Part (1/s)	Imaginary Part (rad/s)	Damped Frequency (Hz)	Damping Ratio (%)
5%	-0.3623	10.0633	1.6016	3.60%
	-0.3623	-10.0633	1.6016	3.60%
10%	-0.3684	-10.0753	1.6035	3.65%
	-0.3684	10.0753	1.6035	3.65%
15%	-0.3668	10.0795	1.6042	3.64%
	-0.3668	-10.0795	1.6042	3.64%

Table 10. Small signal stability analysis results of case 2 for Solar PV penetration at 200MW

Load Variation (%)	Real Part (1/s)	Imaginary Part (rad/s)	Damped Frequency (Hz)	Damping Ratio (%)
5%	-0.3608	-10.0631	1.6016	3.58%
	-0.3608	10.0631	1.6016	3.58%
10%	-0.3670	10.0751	1.6035	3.64%
	-0.3670	-10.0751	1.6035	3.64%
15%	-0.3657	10.0794	1.6042	3.63%
	-0.3657	-10.0794	1.6042	3.63%

Table 11. Small signal stability analysis results of case 2 for Solar PV penetration at 250MW

Load Variation (%)	Real Part (1/s)	Imaginary Part (rad/s)	Damped Frequency (Hz)	Damping Ratio (%)
5%	-0.4007	10.0131	1.5936	4.00%
	-0.4007	-10.0131	1.5936	4.00%
10%	-0.4131	10.0270	1.5958	4.12%
	-0.4131	-10.0270	1.5958	4.12%
15%	-0.4081	10.0340	1.5970	4.06%
	-0.4081	-10.0340	1.5970	4.06%

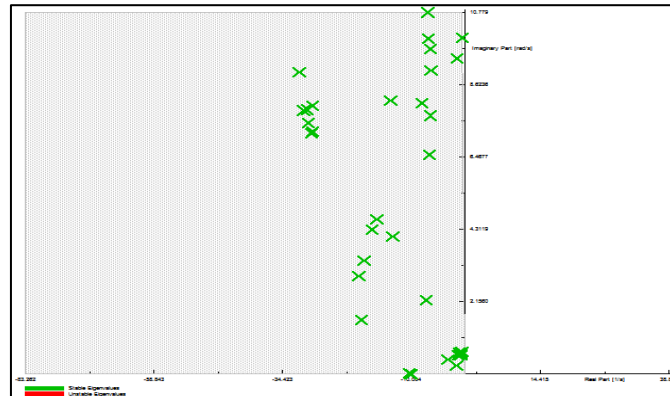


Figure 5. Eigenvalue plot for case 2 with PV penetration of 250MW and 15% loading

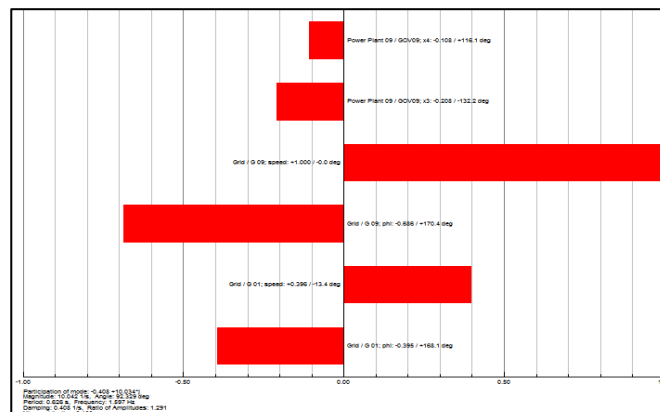


Figure 6. Bar plot participation factor for case 2 (Positive imaginary mode) with PV penetration 250MW and 15% loading

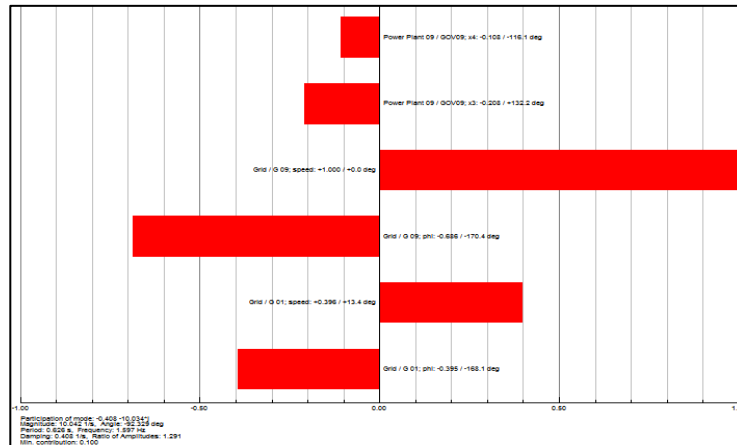


Figure 7. Bar plot participation factor for case 2 (Negative imaginary mode) with PV penetration 250MW and 15% loading

Figure 6 and Figure 7 shows the participation factor bar plot. Similar to Case 1, synchronous generator 9 the participation factor remains unchanged whereby state variable associated to generator speed has the highest contribution. Thus, synchronous generator 9 has a local mode oscillation.

4. Conclusion

In this paper, the impact of increased solar PV penetration on small signal stability is examined in a 39 bus system. Based on the results obtained, it can be concluded that the penetration of solar PV has no significant impact on the system small signal stability. All cases are showing that the system is stable. It is also noted that when the synchronous generator is completely taken out of play, there is a slight increase in damping ratio thereby enhancing the system performance.

References

- [1] Olatona GI, Adegoke CW. Analysis of Solar Radiation Availability for Deployment of Solar Photovoltaic (PV) Technology in a Tropical City. *International Journal of Applied Power Engineering (IJAPE)*. 2015; 4(1); 41-46.
- [2] Sadhu M, Chakraborty S, Das N, Sadhu PK. Role of Solar Power in Sustainable Development of India. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2015; 14(1); 34-41.
- [3] Gautam D. Impact of Increased Penetration of DFIG-Based Wind Turbine Generators on Transient and Small Signal Stability of Power Systems. *IEEE Trans. Power Systems*. 2009; 24(3); 1426-1434.
- [4] Mehta B, Bhatt P, Pandya V. Small signal stability analysis of power systems with DFIG based wind power penetration. *Elsevier Ltd*. 2014; 58; 64-74.
- [5] Krishan R, Verma A, Prasad B. *Small Signal Stability Analysis of Grid Connected Distributed PV and Wind Energy System*. Power India International Conference (PIICON). 2014; 1-6.
- [6] Lopez YU and Dominguez JA. *Small Signal Stability Analysis of Wind Turbines*. 2015.
- [7] Talha A. *Small Signal Stability Analysis of Power System with Wind Generation using Optimized Wind PSS*. Smart Grid (SASG). 2015.
- [8] Dahal S. *Investigation of Small Signal Stability of a Renewable Energy based Electricity Distribution System*. Power and Energy Society General Meeting. 2010; 1-8.
- [9] Byrne RH. *Small Signal Stability of the Western North American Power Grid with High Penetrations of Renewable Generation*. Photovoltaic Specialists Conference (PVSC). 2016; 1784-1789.
- [10] Konstantinou C. *A study on the impact of Wind Generation on the Stability of Electromechanical Oscillations*. 2015; 1-6.
- [11] Krismanto AU, Nadarajah M, Krause O. *Influence of Renewable Energy based Microgrid on Low Frequency Oscillation of Power Systems*. Power and Energy Engineering Conference (APPEEC). 2015; 1-5.

-
- [12] Azhari AW, Sopian K, Zaharim A, Ghoul MA. A New Approach for Predicting Solar Radiation In Tropical Environment Using Satellite Images – Case Study of Malaysia. *WSEAS Trans. Environment and Development*. 2008; 4(4); 373 – 378.
- [13] Elliott R, Byrne R, Ellis A, Grant L. *Impact of increased photovoltaic generation on inter-area oscillations in the Western North American power system*. PES General Meeting Conference & Exposition. 2014; 1-5.
- [14] P. Kundur, *Power System Stability and Control*, McGraw-Hill Inc, 1994
- [15] Bobric EC, Cartina G, Grigoras G. Clustering Techniques in Load Profile Analysis for Distribution Stations. *Advances in Electrical and Computer Engineering*. 2009; 9(1); 63-66.