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Small Signal Stability Analysis of Two Stage PV Generation

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***Abstract*— Integration of photovoltaic (PV) based power plant have been increased significantly over the years. The integration of this devices is ranging on the small-scale capacity such as in distribution system and large-scale capacity such as in transmission system. Although, PV generation could provide sustainable and clean energy to the grid, they could also bring new challenge on the system stability. One of the stabilities of power system that can be affected by integration of this devices is small signal stability. Hence, it is important to capture the dynamic model of PV generation. This paper is on investigation of dynamic model of PV generation for small signal stability analysis. The simulation is carried out in MATLAB/SIMULINK environment. From the simulation results, it is found that by capturing the dynamic model of PV generation, the modes of the PV generation can be captured.**

***Keywords*—Photovoltaic, Small signal, Stability, MATLAB, Simulation.**

I. INTRODUCTION

Integration of power plant based on photovoltaic has been increasing significantly over the past few years. Photovoltaic generation can provide clean and sustainable energy to the environment. However, to transform natural energy into AC electricity, PV generation need power electronics devices. This devices make PV generation has inertia-less characteristic [1]. Furthermore, PV generation also has drawback in term of uncertainty power output [2]. This to characteristic contribute negatively in the stability performance.

The influence of PV generation integration on small signal stability is reported in [3]. In [3], it is noticeable that integration of PV plant could make the damping of the system deteriorated. It is also found that by adding energy storage to the PV generation, the damping can be enhanced. Research effort in [4], attempt to investigate the impact of adding oscillation damping to large-scale PV plant on oscillatory stability. It is observed from Ref [4], by adding oscillation damping to the PV generation the damping performance on weak modes can be enhance. More comprehensive research on design oscillation damping for PV generation is reported in [5].

Authors in [6], investigate the impact of integration of PV generation on voltage stability in distribution system. It is found from Ref [6] that adding PV generation to the distribution network the steady state voltage stability of distribution network can be enhance. Ref [7] is reviewing the impact of integrating PV generation on the frequency, rotor and voltage stability of power system. It is observed that, integration of PV could bring positive and negative challenge on the system stability. It is also found that on small signal stability (small disturbance angle stability) perspective, integration of PV plant mostly contributes negatively on the system performance.

From paper above, it is noticeable that a lack of attention has been made to investigate the oscillatory stability of the PV generation itself. Hence, this paper tries to investigate the small signal stability performance of PV generation. The rest of the paper is organized as follows: Section 2 focused on modelling of PV generation for small signal stability analysis. The overview and method for small signal stability analysis are described in section 3. Section 4 focused on numerical results and discussion. Finally, Section 5 highlight the conclusions and future direction of the research.

II. TWO STAGE PV PLANT MODEL

Mostly PV generation divided into two categories: one stage PV generation and two stage PV generation. One stage PV generation is only using DC to AC inverter as a buffer between PV cells and the grid. While the two-stage PV generation uses both DC to DC and DC to AC converter.

The schematic diagram of one stage and two stage PV generation are depicted in Fig. 1a and 1b [8]. In this paper, two-stage PV generation is investigated thoroughly. For a small signal stability analysis, the dynamic model of each converter of PV generation is crucial. The dynamic model of DC to DC converter can be described using state space representation as shown in equation (1) [8].

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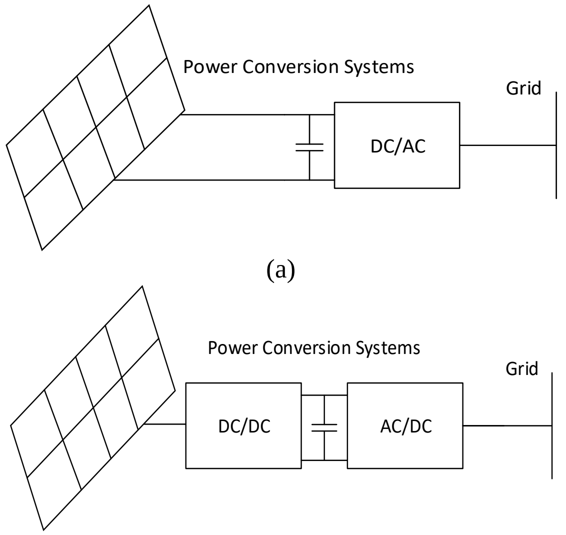

(a)

(b)

Figure 1. Two categories of PV generation.

$$\dot{x} = \{A_1 d + A_2(1-d)\}x + \{B_1 d + B_2(1-d)\}u$$

$$\begin{bmatrix} \dot{i_b} \\ \dot{i_s} \\ \dot{v_b} \end{bmatrix} = \begin{bmatrix} -\frac{(1-d)(R_{Lb}+R_{cb})}{L_b} & \frac{(1-d)R_{cb}}{L_b} & -\frac{(1-d)}{L_b} \\ \frac{(1-d)R_{cb}}{L_b} & -\frac{(1-2d)R_{cb}}{L_s} & \frac{1}{L_s} \\ \frac{(1-d)}{C_b} & -\frac{1}{C_b} & 0 \end{bmatrix} \begin{bmatrix} i_b \\ i_s \\ v_b \end{bmatrix}$$

$$\ldots + \begin{bmatrix} \frac{1}{L_s} \\ 0 \\ 0 \end{bmatrix} v_g \qquad (1)$$

Where state variables of DC/DC converter are consisting of input current (i_b), output current (i_s) and output DC/DC voltage which is similar to capacitor voltage (v_b). R_{Lb} and R_{Cb} represent internal resistance of inductor (L_b) and capacitor (C_b) of boost converter. Input variable of the DC/DC converter is represented by v_g. While, an additional interface inductor (L_s) is considered to provide connection between DC/DC converter with other power electronic devices such as DC/AC inverter in the proposed two-stage PV system [8].

Mostly interconnected power system is in form of AC electricity. Hence, to transform DC electricity into AC electricity, Inverter devices is crucial. In this paper, voltage source inverter (VSI) is used as these devices can provide fast dynamic response and high reliability to supply sensitive loads. Similar with DC to DC converter, for analyzing the dynamic behaviors of VSI, the state space representation of VSI are crucial. The state space representation of VSI on dq reference frame can be established using (2) [8].

In (2), the state variables of DC/AC inverter are represented by DC side voltage (v_{dc}), DC side current (i_s), d_q axis AC side inverter current (i_{id}, i_{iq}), dq axis output voltage (v_{od}, v_{oq}) which is similar to filter capacitor voltage, and d_q axis inverter output current (i_{od}, i_{oq}). Furthermore, the total dynamic mode of two-stage PV generation is combination of DC to DC converter and VSI [8].

$$\begin{bmatrix} \dot{i}_{id} \\ \dot{i}_{iq} \\ \dot{i}_{od} \\ \dot{i}_{oq} \\ \dot{v}_{od} \\ \dot{v}_{oq} \\ \dot{i}_s \\ \dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_f}{L_f} & \omega & 0 & 0 & -\frac{1}{L_f} & 0 & 0 & \frac{m\sqrt{3}}{4L_f} \\ -\omega & -\frac{R_f}{L_f} & 0 & 0 & 0 & -\frac{1}{L_f} & 0 & \frac{m\sqrt{3}}{4L_f} \\ 0 & 0 & -\frac{R_c}{L_c} & \omega & \frac{1}{L_c} & 0 & 0 & 0 \\ 0 & 0 & -\omega & -\frac{R_c}{L_c} & 0 & \frac{1}{L_c} & 0 & 0 \\ \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega & 0 & 0 \\ 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{R_s}{L_s} & -\frac{1}{L_s} \\ -\frac{m\sqrt{3}}{4C_{dc}} & -\frac{m\sqrt{3}}{4C_{dc}} & 0 & 0 & 0 & 0 & -\frac{1}{C_{dc}} & 0 \end{bmatrix} \begin{bmatrix} i_{id} \\ i_{iq} \\ i_{od} \\ i_{oq} \\ v_{od} \\ v_{oq} \\ i_s \\ v_{dc} \end{bmatrix}$$

$$\ldots + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{L_s} \\ 0 \end{bmatrix} [v_{in}] \qquad (2)$$

III. SMALL SIGNAL STABILITY

Generally, oscillatory stability or small signal stability can be emerge due to the insufficient damping torques and synchronization. This stability can be classified into two categories (local and global mode). Local mode has frequency oscillation in the range of 0.7 to 2 Hz. While global mode or inter-area oscillation mostly has frequency oscillation in the range of 0.1 to 0.7 Hz [9].

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- Taiwan in 1984, 1989, 1990, 1991 and 1992 (The incident is classified into local oscillation).
- China in 2003 (inter-area oscillation).
- United Stated in 2003 (inter-area oscillation).
- Italy in 2003 (inter-area oscillation)

The latest incident is happened on 1st December 2016 in Continental Europe (CE) electricity [11]. This incident classified as inter-area oscillation problems. The small signal stability performance of power system can be examined using eigenvalue analysis at a specific operating condition. State space mode of power system has to be conducted to determine the eigenvalue of the system. State space representation of the system can be determined using (3) [9].

$$\begin{bmatrix} \dot{\Delta x} \\ 0 \end{bmatrix} = \begin{bmatrix} A & B \\ C & \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & J_{LF} \end{bmatrix} \end{bmatrix} = \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} + E[\Delta u] \qquad (3)$$

In (3), Δx is a vector of state variables. Meanwhile, Δy represents a vector of algebraic variables. Δu corresponds to the input vector. $\mathrm{J_{LF}}$ is the load-flow Jacobian. A and B are plant and control or input matrices respectively. The output and feedforward matrices are denoted by C and D, respectively. Furthermore, the reduced system state matrix of the entire system can be defined using (4) [9].

$$A_{sys} = \left(A - B\left[\begin{pmatrix} D_{11} & D_{12} \\ D_{21} & J_{LF} \end{pmatrix}\right]^{-1}\right) C \qquad (4)$$

The key information about system stability can be observed through eigenvalue of the system matrix. The Eigenvalue of system matrix can be established using (5) [9].

$$\det\left(\lambda I - A_{sys}\right) \qquad (5)$$

In equation number (5), I is the identity matrix and λ is the eigenvector of matrix A_{sys}. From equation (5), the frequency oscillation (f), and damping ratio (ξ) can be calculate through Eqs (6), (7), and (8) [9].

$$\lambda_i = \sigma_i \pm j\omega_i \qquad (6)$$

$$f_i = \frac{\omega_i}{2\pi} \qquad (7)$$

$$\xi = \frac{-\sigma_i}{\sqrt{-\sigma_i^2 + -\omega_i^2}} \qquad (8)$$

V. NUMERICAL RESULTS AND DISCUSSION

To investigate the small signal stability or oscillatory stability of two-stage PV generation, the PV generation is modelled as mathematical representation. The mathematical representation are described in Section 2. The system is simulated using MATLAB/SIMULINK environment and the two-stage PV generation is modelled as open loop system. Furthermore, the eigenvalue, frequency oscillation and damping ratio of two-stage PV generation are investigated thoroughly in this Section. Fig. 2 illustrates the eigenvalue of two-stage PV generation in complex plane.

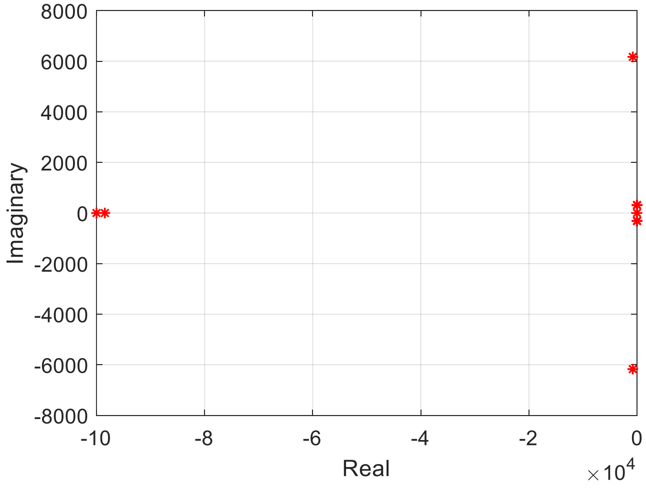

Figure 2. Eigenvalue of two-stage PV generation.

From Fig. 2 the eigenvalue of all state variable of two-stages PV generation indicated by red colours. It is observed that all of the eigenvalues are on left-half plane. Hence, it can be stated that this system is categorized as stable system. Furthermore, it is also noticeable that some of the modes have higher imaginary parts. From those value, it is suspected that some of the modes has high frequency oscillation. Moreover, the detailed features of Fig is described in Table 1.

From Table 1, it is found that the frequency oscillation of the two-stage PV plant is relatively high. It is also observed that all of the eigenvalue have negative value, it is means that the system is stable. However, although the system is stable, the system have 6 weak modes (the damping less than 0.05 is classified as weak modes). If small disturbance emerges, the damping of the system may become 0 and the system can experience unstable condition.

Table 1. Detailed features of Fig. 2.

Index	Eigenvalue ($x10^4$)	Damping	Frequency Oscillation
Mode 1	-0.0781 + 0.6170i	0.1255	982.0271
Mode 2	-0.0781 - 0.6170i	0.1255	982.0271
Mode 3	-9.8440 + 0.0000i	1.0000	0
Mode 4	-0.0010 + 0.0000i	1.0000	0
Mode 5	-9.9990 + 0.0000i	1.0000	0
Mode 6	-0.0000 + 0.0313i	0.0009	49.8187
Mode 7	-0.0000 - 0.0313i	0.0009	49.8187
Mode 8	-0.0001 + 0.0315i	0.0023	50.1813
Mode 9	-0.0001 - 0.0315i	0.0023	50.1813
Mode 10	-0.0001 + 0.0314i	0.0032	50.000
Mode 11	-0.0001 - 0.0314i	0.0032	50.000

VI. CONCLUSIONS

This paper investigates the small signal stability performance of two-stage PV generation. From the simulation results it is found that the modes of the system relative have high frequency oscillation. It is also found that the system have 6 weak modes. Further research need to be conducted by making the system close loop and also design the controller to enhance the weak modes of the system to achieve the minimum standard of the damping.

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