Angular Stability Analysis of a Multimachine System with Distributed and Large-Scale Photovoltaic Generations

Orlando Delgado Fernández
Technical University of Havana
Electric Engineer Faculty
Havana, Cuba
orlando.df.90@gmail.com

Azwirman Gusrialdi
Tampere University
Department of Automation Technology
and Mechanical Engineering
Tampere, Finland
azwirman.gusrialdi@tuni.fi

Antonio A. Mártinez García
Technical University of Havana
Electric Engineer Faculty
Havana, Cuba
amg@electrica.cujae.edu.cu

Miriam Vilaragut Llanes
Technical University of Havana
Electric Engineer Faculty
Havana, Cuba
miriamv@electrica.cujae.edu.cu

Orlys E. Torres Breffe
Technical University of Havana
Electric Engineer Faculty
Havana, Cuba
oetbreffe@yahoo.es

***Abstract*—Nowadays, high-level penetration of photovoltaic (PV) generation is being integrated into the power system due to its economic and environmental benefits. However, this may affect the power system's angular stability in particular when the power system is weak. Motivated by this issue, in this paper a comprehensive angular stability analysis for two-area benchmark system is carried out for a PV penetration level of 30%. Comparisons of the stability impact when the PVs are online and offline are presented. Our simulation results show that both the PVs' location and industry requirements can mitigate the negative effects, that is reduction of power system's inertia, caused by displacement of the conventional generators.**

Keywords—Damping ratio, electromechanical models, small-signal and transient stability

I. INTRODUCTION

A. Motivation

Photovoltaic (PV) generation is considered as future energy as solar resources are available in different geographic regions of many countries which makes the installation of distributed PV generators less difficult in contrast to the large synchronized generators. Furthermore, PV generators require low maintenance and operational cost. They also contribute to carbon-neutral society and can be integrated in a modular manner. Nowadays, large-scale PV generators are often connected to the transmission system. However, PV generators have the following shortcomings: they do not contribute to the system's inertia and force excitation under short circuit conditions; the increase of current due to short circuit is much smaller compared to that of synchronous generator which makes it hard to detect a fault. These shortcomings can decrease both the damping and synchronizing torque of the bulk power systems. Therefore, angular stability studies are imperative to be considered in the planning and operation of the power system [1]. Related work which address this problem is summarized below.

B. Related work on PV generation impact on small signal stability

Multimachine system's small signal stability using Western Electricity Coordinating Council system (WECC) is studied in [2-3]. It is observed in [2] that new oscillation modes appeared when full-converter wind turbine and PV generation are increased until 13,20% of the total online active power generation. It is shown in [3] that when penetration levels of the rooftop PV and large-scale PV is larger than 30%, the critical local mode suffers a significant damping ratio reduction under the acceptable threshold limit (5%) due to inertia reduction as a result of the displacement of conventional generators in this area. However, it is shown that the interarea modes are not affected. On the other hand, an unexpected result is reported in [4] where the low inertia does not have a major impact on the small-signal stability of a system with high shares of converter-based generators. It is observed in [5] that Ontario Power system damping is not affected when centralized large-scale PV generator and small distributed unit are integrated where the penetration levels are varied up to around 2000 MW. It is shown in [6] that 15% penetration of distributed small unit and large scale PV generation reduces the damping of an interarea oscillation mode in New York Power system to under 5% when the PV generators operate at a fixed 0,95 power factor or in voltage control mode. In [7], it is shown that PV generation installed in Indian test system increases the damping of a local mode and decreases the damping of an interarea mode. Moreover, New England power system is studied in [8], where interarea and local modes increase the damping when one PV generator (with 5MW output) is online.

However, the above mentioned work did not analyse whether the location of distributed and large-scale PVs can mitigate the negative effect caused by the reduction of the power system's damping as the conventional generators are being displaced.

The impact of a very large-scale and concentrated PV on the interarea mode is studied in [9-11] using a two-area benchmark system. This benchmark system has poor meshed grid, longitudinal configuration, poor inter-area mode and large angular deviations depending on the initial conditions. Different output powers and locations of PV generation were studied in [9], which changed the power flow distribution but had very little effect on the interarea mode with ultralow-frequency (0,026 Hz). In comparison to the work in [10], it shows that the oscillations can be damped through damping controller by PV generator. In [11], two PV's locations are analyzed where an equivalent of 900 MVA PV generator is installed in area 1 and area 2 respectively. For both cases, interarea mode's damping increases when PV generators displace the active power of the conventional generators which are kept online to maintain the system inertia to be constant in a minimum power operation regime. On the other hand, when the conventional generators are fully replaced and turned off, in the case where PV generator is connected to area 2, interarea mode's damping is significantly affected. Similar result is reported in [12]. Specifically, large-scale and concentrated PV is studied using the IEEE 14 bus standard test system, which is a meshed system. However, both studies have the following limitations: the generator's operation mode produces higher costs and does not satisfy economic operational requirements; it is not clear how the PVs affect the interarea mode; power system stabilizer (PSS) and FACTS are not considered.

C. *Related work on PV generation impact on transient stability*

It is shown in [5] that the transient stability is not improved when large-scale PV penetration level is increased; no matter which control mode (voltage or power factor control) is activated. However, it is shown that distributed small unit penetration improves considerably the stability. Transient stability enhancement due to the generator's reserves is increased when large-scale PV increases its active power but without considering PV's control as shown in [13]. However, the resulting generators's active and reactive powers in the simulation do not coincide with the system load, which makes the results less clear. It is observed in [6] that transient system behaviour does not change when PV generators are either in voltage control or power factor control modes. It is shown in [3] that the generator speeds suffer higher oscillations when the penetration level is larger than 40%. In [14], Solar PV generator impact on the transient stability is analyzed for different scenarios in a microgrid. However, in all the previously mentioned work the impact of large-scale and distributed PV's location on the transient stability is not analysed. Moreover, it is not clear which grid codes (GC) and regulations are considered when studying the transient stability. Grid codes and regulations have been changing and now in many countries PVs generators must provide dynamic grid support during both normal and fault conditions [15]. For example, countries like Germany and Spain defined that the PV must have Voltage Ride Through (VRT), reactive current injection during grid faults, active power reduction and so on [15]. These requirements could result in undesirable control interactions if PV controls are not properly coordinated with the rest of the controls.

D. *Contribution and organization of the paper*

This paper aims at filling the above mentioned gap. Specifically, this paper presents a comprehensive small signal and transient stability analysis of a two-area benchmark system (which has similar characteristic with the Cuban power system) with distributed and large-scale PV whose penetration level equals to 30%. Moreover, we also consider the operational cost, power system stabilizer (PSS) and FACTS. It is shown that the distributed location of large-scale PVs does not affect the interarea and local modes' damping and thus can mitigate the negative effect caused by the reduction of power system damping. Moreover, by analysing the controller interactions under different disturbances, new tuning of the System Voltage Compensator's Automatic Voltage Regulator is provided to improve the power system's performance. Finally, we analyse the controller grid code requirements and the impact of locations of the distributed and large-scale PV penetration on the transient stability.

The rest of the paper is organized as follows. Section 2 describes the PV model. In Section 3, a brief description of the transient and small signal stability studies is presented. Section 4 presents case studies and the most relevant results. Finally, concluding remarks are presented in Section 5.

II. PV GENERATOR ELECTROMECHANICAL MODEL

Since the electromagnetic models of a PV [16] may complicate the numerical calculation for angular stability analysis, in this paper we consider electromechanical model consisting of different elements such as: PV array with non-linear dynamics, converter and control as illustrated in Fig. 1. This model, whose details can be found in [17], allows us to study the PV´s electromechanical behaviour.

One of the paper's objectives is to study how the control interactions and GC can improve the power system's angular stability. Hence, this section discusses the GC´s requirements for the PV's control as shown in Fig. 2. Specifically, the Germany code requirement is implemented since it can be easily found in the literature [15].

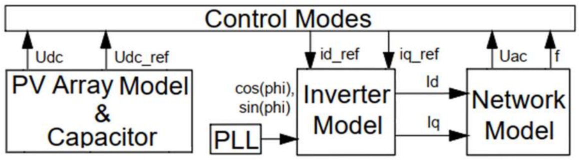

Fig. 1. PV dynamic model diagram

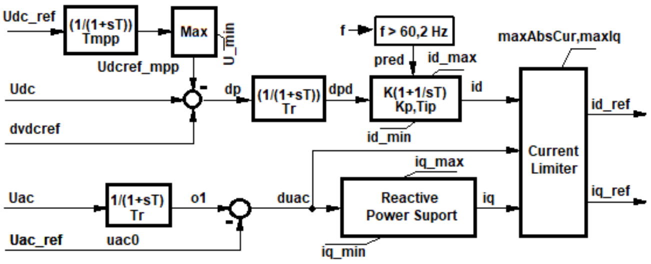

Fig. 2. PV control block diagram

According to Germany code, voltage control is activated when the voltage's drop **(duac)** is larger than 10% of the rated generator value. Furthermore, this control must ensure the reactive current's supply **(iq_ref)** at the Common Connection Point (CCP) with a contribution of at least 2% of the rated current per percent of the voltage drop **(duac)**. If required, it must also be able to supply reactive current **(iq_ref)** of at least 100% of the rated current. For the case of frequency control, when the frequency network **(f)** increases to larger than 60,2 Hz, the PV generator must reduce its active current **(id)** whose reduction has a gradient of 40% P/Hz. This control helps the short term frequency stability and it can also improve transient stability due to the converter's fast response.

III. TRANSIENT AND SMALL SIGNAL STABILITY ANALYSIS

Transient stability can be studied by solving a set of n first-order non-linear differential-algebraic equations of the power system given by (1) with known initial values (x_0, u_0)

$$\dot{x} = f(x,u), y = g(x,u) \tag{1}$$

where $x \in \mathbb{R}^n$ are state variables of generator, PV, load and controls (e.g. Automatic Voltage Regulator (AVR), PV controls among others) and $u \in \mathbb{R}^r$ is the control input.

In this work, critical clearing time (CCT) is used to evaluate the impact of PV penetration on the transient stability. CCT is the maximum time that a fault can be sustained while the system remains to be stable. CCT is calculated through a trial-and-error strategy using time-domain simulation results, see [18] for its computation.

Small-Signal stability is analysed by linearizing (1) using Taylor series. Linearized dynamical model around the equilibrium point (x_0, u_0) is given by

$$\Delta\dot{x} = A\Delta x + B\Delta u, \Delta y = C\Delta x + D\Delta u \qquad (2)$$

Assuming that no damping control is being implemented, i.e., $\Delta u = 0$, small-Signal stability can be evaluated using the eigenvalues of A denoted by $\lambda_i = \sigma_i + j\omega_i$ The power system is considered to be poorly damped when its damping ratio $\xi <$ 5% where $\xi_i = -\sigma_i/\sqrt{\sigma_i^2 + \omega_i^2}$ [19].

Participation factor (p_{ik}) is used to measure the relative participation of the kth state variable in the i-th mode λ_i and is calculated according to $p_{ik} = \phi_{ik}\psi_{ik}$, where ϕ_{ik} and ψ_{ik} denote the k-th elements of right eigenvector ϕ_i and left eigenvector ψ_i corresponding to i-th mode [20].

IV. MAIN RESULTS: CASE STUDY

A. *Power system model used in the case study*

In order to study how the distributed large-scale PV penetration impacts the angular stability, we consider 7 PV generators with individual rated power of 120 MVA and power factor (fp) equals to 0,95. The PV generators are equally distributed at the transmission buses of a two-area system as illustrated in Fig. 3. The conventional generators (6th order) are modelled using Automatic Voltage Regulator (AVR), voltage droop of 1%, turbine and governor given by IEEE type 1 model [20]. AVR's gains are set to be high since it may affect power system's damping. Generators 1 and 3 have Power System Stabilizer (PSS) based on the standard IEEE Type 2A [21] where the PSSs are tuned to damp both the interarea and local modes when there is no PV penetration.

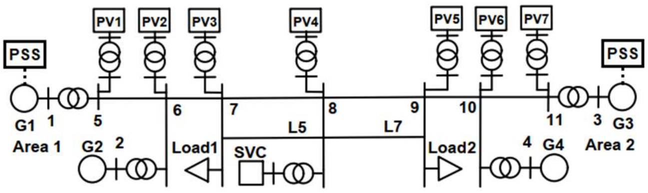

Fig. 3. A simple two-area system with distributed PVs

Furthermore, we set the lines, transformers, parameters and generators' parameters and initial conditions to be similar to the ones used in [20]. The System Voltage Compensator (SVC) capacity is set to +300, -200 Mvar and it is modelled using the model type 2 with a series lead-lag in order to reduce a transient response and with 2% of the voltage droop [22]. All the dynamical models which affect both the angular stability and interaction controls are also considered.

B. *Results and discussions*

Table I shows the two scenarios studied. First scenario is a base case, where synchronized generators are dispatched with a total power of 2815 MW. The second one is the PV case, where a total power of 2804 MW are dispatched by the 4 synchronized generators (2160 MW) and the 7 PV generators (644MW). PV penetration level of 30% is calculated considering rated power given in the column 3. By comparing both cases (column 1 and 3), it can be observed that an inertia's reduction occurs in the PV case as 640 MW of synchronized generators capacity (G1,G2,G3,G4), in which 320 MW belongs to the generators with PSS (G1,G3), are displaced by PVs. Therefore, both factors may impact negatively on the rotor angular stability.

TABLE I. GENERATION SCHEDULE

	Base Case (MW)		**PV Case (MW)**	
Generators	***Rated(1)***	***Dispatched(2)***	***Rated(3)***	***Dispatched(4)***
With PSS	1440	1405	1120	1080
Without PSS	1440	1410	1120	1080
PV	0	0	940	644

In order to evaluate the small-signal stability, eigenvalues of matrix A in (2) are calculated for both the base (122 eigenvalues) and PV cases (220 eigenvalues). As can be observed from Fig. 4, the modes with the worst damping ratio are almost equal for both cases. These modes are electromechanical modes which indicate the rotor oscillations and the lack of damping torque. Specifically, mode 4 and mode 5 are local modes and belong to G3 and G1 while modes 1 through 3 are interarea modes as their participation includes generators state variables in both areas. Moreover, table II shows the conventional generators participation for different modes where the state variables with greater participation are: speed **(ω)**, rotor angle **(δ)**, fluxes **(ψ)** and PSS's variables related with the lead-lag block **(xp, xt)**.

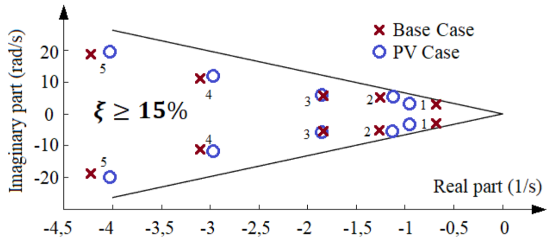

Fig. 4. Eigenvalues with worst damping ratio

It can be seen from Fig. 4 that the power system damping is not reduced even though the system's inertia decreases due to displacement of some of the synchronized generators together with their corresponding PSS. Specifically, the worst modes remain with a damping ratio greater than 15% while the damping ratio of interarea mode 1 increases. Furthermore, Table II shows that the PVs and their corresponding controllers state variables do not participate in these modes. This phenomena can also be observed for the rest of the synchronized generator's modes since the converter decouples the PVs from the power system.

TABLE II. PARTICIPATION OF THE GENERATOR MODES FOR PV CASE

Index	**Modes**	**Conventional generator's participation**
1	-0,95±j3,22	G1, G3, G4
2	-1,13±j5,48	G1, G2, G3, G4
3	-1,86±j5,83	G2, G3, G4
4	-2.96±j11,91	G3
5	-4,03±j19,67	G1

From the above analysis, it can be observed that the PVs' distributed location mitigates the negative effect (i.e., reduction of power system's damping) caused by the displacement of conventional generators, in particular as the generator's transferred power from area 1 toward area 2 is decreased by 180 MW. This result on the effect of PV's allocation is of important and practical since it can be implemented by countries where the available solar resource allows the distributed installation of the large-scale PVs. Hence, a suitable PV's location cannot negatively affect the small-signal stability. Furthermore, as shown in Table III the new modes associated with the PVs' connection have good damping ratio and they only participate in the PV's state variables, i.e., they are not electromechanical oscillation modes. These new local and interarea modes have similar frequencies within the order of 5,5 Hz. This result is interesting since the new modes are totally different compared to the electromechanical modes associated with the synchronized generators.

TABLE III. PV UNITS PARTICIPATION OF THE PV MODES

Mode	Type	PV unit's participation
-29,31±j34,64	Local	PV2, PV3
-29,57±j34,65	Local	PV5, PV6
-29,45±j37,70	Local	PV4, PV2
-29,86±j34,72	Interarea	PV7, PV1
-29,87±j34,76	Interarea	PV7, PV6, PV5, PV1
-29,58±j35,01	Interarea	PV6, PV5, PV4, PV3, PV2, PV1
-30,10±j35,39	Interarea	PV7, PV6, PV5, PV4, PV3

In some cases, eigenvalues alone are not sufficient to show the interactions and undesirables oscillation which affect the power system's dynamic response [23]. These interactions occur due to either poor coordination between the controllers or the nonlinearity of power system. Therefore, analysis of power system behavior must be complemented with a nonlinear time-domain simulation where different disturbances such as load changes, PV output, AVR setpoint changes in generators and SVC were considered.

From the simulation results, it can be seen that for some of the analysed disturbances, SVC reactive power shows stable oscillations for the cases when PVs are online (see Fig. 5, blue line) while for the base case there are no oscillations (see Fig. 6, blue line). In these cases, reactive power of load 1 is increased by 20% at 1 s of the simulation time and the PVs are operating with a power factor pf=0,95 (inductive).

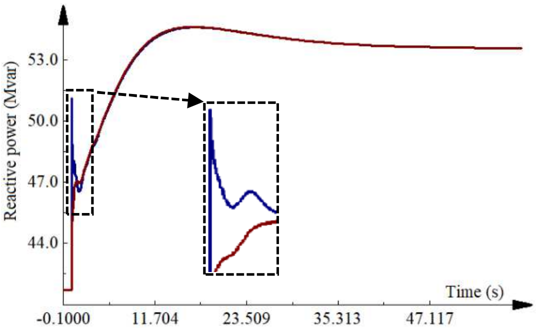

Fig. 5. SVC power response for the PV case, blue line and red line corresponds with $T_n = 0,6\ s$ and $T_n = 0,2\ s$ respectively

Fig. 6 (blue line) shows that oscillations do not occur when only the conventional generators are online which is a consequence of the previous coordination between conventional generators and SVC AVRs. However, SVC has undesirable oscillations when the PVs are online. This is because SVC control actions produce interactions with the PVs installed at buses 7, 8, and 9 connected within a common voltage control area. These oscillations can be eliminated by adjusting the coordination between AVRs of the SVC and the PVs under the new conditions. In this case, SVC's oscillations are caused by its AVR's high response speed which interacts with the PVs installed in its area control. Fig. 5 (red line) shows that these oscillations disappear when SVC AVR's high response speed is reduced. To this end, lead-lag numerator constant of the AVR is decreased from $T_n = 0,6\ s$ to $T_n = 0,2\ s$ while the lead-lag denominator constant is set to $T_d = 1\ s$. Using the above setting, it can be seen from Fig. 6 (red line) that the SVC behaviour is not affected when only synchronized generators are online. In this case, the interactions between SVC and generators can be easily avoided since they are not located close with each other in terms of the electric distance (ohms).

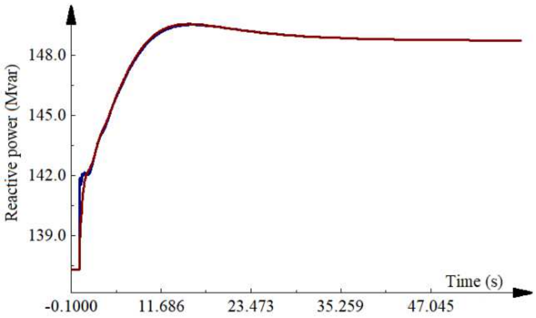

Fig. 6. SVC power response for the base case, blue line and red line corresponds with $T_n = 0,6\ s$ and $T_n = 0,2\ s$ respectively

Finally, the impact of PV penetration on the transient stability for different three phase short circuit locations is analysed. In all the cases, we consider contingencies of order (n-1) and the case where protections clean the fault at both end at 100 ms without reclosing. The simulation results show that the power system does not lose its stability for any of the studied cases. Moreover, the results show that the power system post disturbance regime (Fig. 7) has the lowest oscillations when PV generators are online. This result is in contrast to the one reported in [3] where the greatest oscillations occurs when PV generators are online. This difference is due to the increase of damping for interarea mode 1 (0,4 Hz-0,5 Hz) under these conditions.

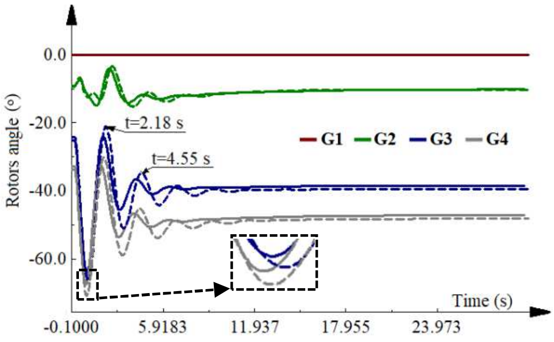

Fig. 7. Response of the relative rotors angle respect to G1, the dotted and straight lines correspond to base case and PV case respectively

Table IV shows the influence of PV penetration on the transient stability, evaluated using the index CCT. In order to evaluate the effect caused by the PV's controller and location, the index is calculated when the PVs operate with and without voltage and frequency control. The short circuit are simulated on lines 5 and 7 close to buses 7 and 9 respectively since they are the worst locations for the system's stability. Table IV shows that when the uncontrolled PV generators are online, the CCTs is increased by 30 ms (resp. 40 ms) compared with the base case, when the short circuit occur in the line 5 (resp. line 7). This means that the PV's location (given that the PVs have equal capacity) improves the transient stability since it reduces the active power flows between the lines. This reduction has greater positive impact over transient stability and compensates the negative impact caused by decrease of system inertia and reactive support via excitation forcing by the generators displacement.

TABLE IV. CCT INDEX FOR THE DIFFERENT CASES STUDIED

Cases	**Short circuit location**	**CCT (ms)**
Base case	(Line 5, Line 7)	(320, 400)
PV (without control)	(Line 5, Line 7)	(350, 440)
PV Case (frequency control)	(Line 5, Line 7)	(350, 440)
PV Case (voltage control)	(Line 5, Line 7)	(380, 580)
PV Case (both controls)	(Line 5, Line 7)	(380, 580)

Since CCTs are similar (350 ms and 440 ms) when the PVs are without control and with activated frequency control, it can be concluded that frequency control does not influence the transient stability despite of its fast speed response. This is because the short circuit lasts for 100 ms which is too short for the generator's speed control actions. However, when PVs are controlling the bus voltage according to the grid code, it can be seen that the CCTs are increased by 30 ms and 140 ms compared with the case when noncontrolled PV generators are online for the two analyzed short circuit. This shows that the voltage control improves widely the stability since the power system is predominantly inductive during the short circuit, related with load active power cutting. Therefore, the PVs are not disconnected during the short circuit due to its Voltage Ride Through capacity implemented in the Germany code. In this way, the PVs help the system in supporting the reactive power which is also avoiding larger voltage drop. This result is different compared to the one reported in [5-6] in which the transient stability is not improved when the PV generators are in the automatic voltage control mode.

V. CONCLUSION

The paper studied the impact of a 30% distributed and large-scale PV penetration in a weak longitudinal system. The results are summarized as follows: a) Distributed location of PVs reduces the active power transfer by 180 MW in the transmission lines. This reduction can mitigate the negative effect caused by decrement of power system's damping due to displacement of the conventional generators; b) Controller coordination between devices already installed and the new ones (PVs in this case) within the same control area must be checked and a reduction of the SVC AVR's response speed damped the oscillation; c) PV location, Voltage Ride Through capacity and reactive current injection of PVs generators during grid faults were the main factors to enhance transient stability in a power system with high penetration of PVs. In the future we aim to extend the analysis to other power system test cases and the case of PVs with different capacities.

REFERENCES

[1] E. Rakhshani, K. Rouzbehi, A. J. Sánchez, A. C. Tobar, and E. Pouresmaeil, "Integration of Large Scale PV-Based Generation into Power Systems: A Survey," *Energies*, vol. 12, no. 8, 2019.

[2] J. Quintero, V. Vittal, G. T. Heydt, and H. Zhang, "The Impact of Increased Penetration of Converter Control-Based Generators on Power System Modes of Oscillation," *IEEE Transactions on Power Systems*, vol. 29, no. 5, pp. 2248–2256, 2014.

[3] S. Eftekharnejad, V. Vittal, G. T. Heydt, B. Keel, and J. Loehr, "Small Signal Stability Assessment of Power Systems With Increased Penetration of Photovoltaic Generation: A Case Study," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 4, pp. 960–967, 2013.

[4] U. Markovic, O. Stanojev, P. Aristidou, E. Vrettos, D. Callaway, and G. Hug, "Understanding Small-Signal Stability of Low-Inertia Systems," *IEEE Transactions on Power Systems*, vol. 36, no. 5, pp. 3997–4017, 2021.

[5] B. Tamimi, C. Cañizares, and K. Bhattacharya, "System Stability Impact of Large-Scale and Distributed Solar Photovoltaic Generation: The Case of Ontario, Canada," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 3, pp. 680–688, 2013.

[6] R. Shah, N. Mithulananthan, and R. C. Bansal, "Oscillatory stability analysis with high penetrations of large-scale photovoltaic generation," *Energy Conversion and Management*, vol. 65, pp. 420–429, 2013.

[7] S. Ravichandran, S. G. B. Dasan, and R. P. K. Devi, "Small signal stability analysis of grid connected Photo Voltaic distributed generator system," in *2011 International Conference on Power and Energy Systems*, 2011, pp. 1–6.

[8] T. He, S. Li, S. Wu, and K. Li, "Small-Signal Stability Analysis for Power System Frequency Regulation with Renewable Energy Participation," *Mathematical Problems in Engineering*, vol. 2021, p. 5556062, Apr. 2021.

[9] S. Wang, X. Wu, G. Chen, and Y. Xu, "Small-Signal Stability Analysis of Photovoltaic-Hydro Integrated Systems on Ultra-Low Frequency Oscillation," *Energies*, vol. 13, no. 4, 2020.

[10] M. Saadatmand, G. B. Gharehpetian, A. Moghassemi, J. M. Guerrero, P. Siano, and H. H. Alhelou, "Damping of Low-Frequency Oscillations in Power Systems by Large-Scale PV Farms: A Comprehensive Review of Control Methods," *IEEE Access*, vol. 9, pp. 72183–72206, 2021.

[11] H. Liu, L. Jin, D. Le, and A. A. Chowdhury, "Impact of high penetration of solar photovoltaic generation on power system small signal stability," in *2010 International Conference on Power System Technology*, 2010, pp. 1–7.

[12] J. Thapa and S. Maharjan, "Impact of Penetration of Photovoltaic on Rotor Angle Stability of Power System," *International Journal of Engineering and Applied Sciences (IJEAS)*, vol. 6, Apr. 2019.

[13] M. Zainuddin, Sarjiya, T. P. Handayani, W. Sunanda, and F. E. P. Surusa, "Transient Stability Assessment of Large Scale Grid-Connected Photovoltaic on Transmission System," in *2018 2nd International Conference on Green Energy and Applications (ICGEA)*, 2018, pp. 113–118.

[14] F. I. Khan and T. Aziz, "Transient Stability evaluation of a Solar PV Integrated Industrial Microgrid," in *2019 IEEE Region 10 Symposium (TENSYMP)*, 2019, pp. 535–540.

[15] E. Troester, "New German grid codes for connecting PV systems to the medium voltage power grid.," in *2nd International Workshop on Concentrating Photovoltaic Power Plants: Optical Design, Production, Grid Connection*, 2008, pp. 1–4.

[16] K. Sano, R. Yonezawa, and T. Noda, "An electromagnetic transient simulation model of grid-connected inverters for dynamic voltage analysis of distribution systems," *Electrical Engineering in Japan*, vol. 206, no. 4, pp. 11–21, 2019.

[17] Farhan Mahmood, "Improving the Photovoltaic Model in PowerFactory," M. S. thesis, KTH Electrical Enginnering, 2012.

[18] Gustav Lammert, "Modelling, Control and Stability Analysis of Photovoltaic Systems in Power System Dynamic Studies," Phd thesis, University of Kassel, Germany, 2019.

[19] SIEMENS, "Small Signal Stability Analysis Module. Network Eigenvalue Analysis for PSS®E siemens." Siemens AG 2017, 2017.

[20] P. Kundur, *Power system stability and control*. McGraw-Hill, Inc., 1994.

[21] ABB, "Computer Representation for Excitation System UNITROL 5000." ABB Switzaerland Ltd.

[22] Ferderico Milano, "Documentation for PSAT version 2.0.0." 2007.

[23] H. Shayeghi, A. Safari, and H. A. Shayanfar, "PSS and TCSC damping controller coordinated design using PSO in multi-machine power system," *Energy Conversion and Management*, vol. 51, no. 12, pp. 2930–2937, 2010.