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Evaluation of a State Observer for Frequency Estimation in a Grid Tied Photovoltaic Inverter

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Abstract—A phase locked loop (PLL) is commonly used to measure the electrical frequency deviations in PV grid tied inverters. However, this control is affected by sudden changes of power that usually happens with this type of power generation as the solar irradiance is intermittent. Thus, the aim of this paper is to estimate the frequency at the point of common coupling by using a state observer. The evaluation of the observer is developed in DigSILENT PowerFactory under variable solar irradiance. The results show that the observer gives a more accurate frequency value than a PLL when quick changes of solar irradiance occur.

Index Terms—PV inverter, phase locked loop, state observer, frequency estimator

I. INTRODUCTION

The performance of large scale photovoltaic power plants (LS-PVPPs) is a main drawback for transmission system operators due to the variation of solar irradiance during the day. The bulk system is commonly based on conventional power plants with synchronous generators as the base units, where the active power can be easily managed depending on the demand. However, in LS-PVPPs the PV generator's active and reactive power depend on the variation of solar irradiance as well as other electrical characteristics. Thus, specific grid codes have been developed to smooth the integration of these power plants into the electrical system [1]. The requirements can be divided into two main areas: (i) voltage and frequency support, and (ii) active and reactive power control.

An adequate measurement of the voltage and frequency at the point of common coupling (PCC) is an important issue to solve in order to design an adequate control. In a PV generator, where the inverter is the basic electronic equipment, a phase locked loop (PLL) is used to synchronize the generator with the grid by the measurement of the phase angle together with the calculation of the frequency. However, the PLL could present some disturbances when phase angles change due to the sudden injection or reduction of active power [2]. For instance, when the solar irradiance changes in a small period of time, the frequency calculation is drastically affected by the

change in voltage drop across the system impedance and does not represent the real value at the point of common coupling [3].

The accuracy of the frequency measurement can affect the control and the response time. Some methods have been developed to detect frequency or phase deviation for small PV applications (lower than 1 MW) interconnected with a microgrid. For passive methods, the system usually measures voltage or phase distortion at the point of common coupling and compares it with previous values. In active methods, the inverter adds an error value to frequency, voltage or phase at its output, interfering with the power quality of the system. The time response of these methods are in between 43 to 50 ms, for passive, and 0.3 to 1 s for active [4].

One method that was recently studied for grid tied inverters is the development of a state observer to estimate the phase shift and the frequency by an adequate model of the interconnection between the PV inverter and the grid. The study developed by [5] details the observer design for a grid tied inverter with an specific LCL filter for voltage, current and phase shift estimation. Another study was developed in [6] where the observer estimates the phase shift to be used in a PLL and thus the general control is improved. In any of this research, the observer has not been applied for the integration of PV generators with the electrical system.

Thus, this article presents the evaluation of a state observer for frequency estimation considering the variation of solar irradiance by comparing it with a PLL. This observer will be tested with a PV generator model under variable solar irradiance. The paper is divided in four main sections: the PV generator model, its control, the observer design and the simulations corresponding to variable ambient conditions. Lastly, some conclusions are presented and discussed.

II. PV GENERATOR MODEL AND CONTROL

In LS-PVPPs, PV generators can present different topologies such as central, string and multistring [7]. For the present study, the configuration studied is the central type, which presents the most cost-effective solution [8]. In this configuration a PV array is connected to a single stage PV inverter. The output of the inverter is interconnected to a transformer through an LCL filter (see Fig.1).

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Fig. 1. PV generator in central configuration

Fig. 2. Simplified model of the PV solar cell

A. PV array model

The electrical equivalent circuit of a PV solar cell corresponds to Fig. 2, where the total current (i_{pv}) depends on the photogenerated current (i_{ph}) [2], the diode saturation current (i_o) and the parallel current (i_p) [3].

$$i_{pv} = i_{ph} - i_o \left(e^{\left(\frac{v_{pv} \cdot N_{par} + R_s \cdot i_{pv}}{N_s \cdot A \cdot k_B \cdot T_c \cdot q} \right)} - 1 \right) - i_p \cdot N_{ser} \quad (1)$$

where;

R_s is the series resistance, N_s is the number of solar cells connected in series, A is the ideality factor, k_B is the Boltzman constant, T_c is the solar cell's temperature, q is the electrical charge of an electron, N_{ser} and N_{par} are the PV panels connected in series or in parallel respectively.

The photogenerated current changes proportionally to the solar irradiance (G) and it is given by:

$$i_{ph} \approx i_{ph_{stc}} \cdot \frac{G}{G_{stc}} \quad (2)$$

where;

$i_{ph_{stc}}$ and G_{stc} are the photogenerated current and the solar irradiance at standard test conditions (solar irradiance of 1000 W/m² and an ambient temperature (T_a) of 25°C).

The point of operation for each solar irradiance depends on the control developed in the PV inverter. The model of this is explained in the following section.

B. PV inverter model and control

For the PV generator configuration, an inverter of one stage of conversion from dc to ac is chosen. The output voltage of the PV inverter is obtained by Sinusoidal Pulse Width Modulation (SPWM), where the ac voltage depends on the modulation index (m_a) and the dc voltage value at its input terminals. Additionally, a filter LCL is connected at the output of the PV inverter helping to reduce the harmonics that the PV generator injects into the electrical system. Additionally, the model of the inverter interconnected with the grid is illustrated in Figure 3 and can be defined by a state vector, where the state variables for the system is given by:

$$x = [i_c \quad v_{pcc} \quad i_g]^T \quad (3)$$

Fig. 3. Grid connected LCL filter considering stationary frame

where;

v_{pcc} is the voltage at the point of common coupling, i_c and i_g are the converter and the grid currents, respectively. The state-space model of the grid tied inverter can be expressed as follows:

$$\frac{d}{dt} \begin{bmatrix} i_c \\ v_{pcc} \\ i_g \end{bmatrix} = \begin{bmatrix} -j\omega_g & -\frac{1}{L_c} & 0 \\ \frac{1}{C_f} & -j\omega_g & -\frac{1}{C_f} \\ 0 & \frac{1}{L_g} & -j\omega_g \end{bmatrix} x + \begin{bmatrix} \frac{1}{L_c} \\ 0 \\ 0 \end{bmatrix} v_c + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L_g} \end{bmatrix} v_g, \quad (4)$$

$$y = [1 \quad 0 \quad 0] x. \quad (5)$$

In stationary reference frame, the grid voltage is defined as:

$$v_g = e^{j\theta_g} v_g \quad (6)$$

where;

θ_g is the phase angle and equal to $\theta_g = \int \omega_g dt$.

For the dynamic control of the PV generator, the three phase voltages and currents are transformed to the rotating direct-quadrature frame. The main tasks of the inverter are related to the control of power and synchronization. In this case, the control of the PV generator consists of a maximum power point tracker (MPPT), outer voltage control, inner current control, voltage modulation, phase locked loop and a frequency estimator (Fig. 4). The MPPT control tracks the dc voltage to have the maximum active power at each solar irradiance and temperature. For the PV inverter control, the algorithm used is the one known as a Perturb and Observe.

The outer controller defines the i_d reference (i_d^{ref}) related to the active power and the dc voltage control, and the i_q reference (i_q^{ref}) related to the reactive power. The dc voltage control has the task to follow the dc voltage reference and to maintain this as constant as possible inside the dc voltage limitation. In this regulation, a PI controller is used: its dynamics depends on the MPPT time response plus the ambient conditions. In this case, the reactive power control only acts when the ac voltage is varied more than $\pm 0.1 p.u.$

The inner current control is the one that gives the signal references (v_d^* and v_q^*) to the voltage modulation block which has to transform this voltage references to three phase voltages with the corresponding modulation technique (Fig.5).

The PLL structure is a feedback control system that has the task to adjust the phase angle between the grid reference (dq) frame and the converter (dq) reference frame (Figure 7). To do this, the controller has to align the grid voltage phasor

Fig. 4. PV generator's general control

Fig. 5. Inner current control of the PV inverter

with one of the two dq axis. In this case, it is aligned with the d-axis which means that the $v_q^g = 0$. With this new angle, then the VSC becomes synchronised with the grid, so $v_q^c = 0$ in steady state [9]. Then, the electric quantities - voltages and current- can use the PLL angle to be transformed from the three phase frame to dq reference frame and vice-versa. The feedback control structure of the PLL uses commonly a PI controller which compensates the error between the reference voltage $v_q^{c*} = 0$ and the new v_q^c considering the new phase angle (Fig. 6).

Fig. 7. dq diagram for AC side inverter

The output voltage of the inverter is directly affected by the changes of power as it is described in eq. 7 and eq.8 [9]. In addition, P and Q depends on the solar irradiance, temperature

and dc voltage according to the capability curves described in [10]. Thus, the output voltage presents small variations when

changes of solar irradiance occur that affects to the information given by the PLL (frequency and phase angle) [3] .

$$v_d^c = \frac{2}{3} \frac{L_f}{v_d^g} \cdot \frac{dP(G, T_a, V_{dc})}{dt} + \frac{2}{3} \frac{L_f \omega_g}{v_d^{pcc}} \cdot Q(G, T_a, v_{dc}) + v_d^g \quad (7)$$

$$v_q^c = \frac{2}{3} \frac{L_f}{v_d^g} \cdot \frac{dQ(G, T_a, V_{dc})}{dt} + \frac{2}{3} \frac{L_f \omega_g}{v_d^{pcc}} \cdot P(G, T_a, v_{dc}) \quad (8)$$

Taking into consideration this behaviour, a frequency estimator is added to the PV inverter control. This estimator has the main task of supporting the frequency and the phase measured by the PLL when quick changes of solar irradiance occur. The objective of this estimator is to calculate the frequency and the phase shift at each instant considering the real interaction between the PV inverter and the grid through the LCL filter. The design of this frequency estimator is explained in the following section.

C. Frequency estimator

In a PV grid tied inverter, the v_q^{pcc} is imposed to be zero, however when disturbances occur this value could change. Then, as it is shown in Fig. 5, the i_{dq} of the converter is directly affected by the ac voltage, the grid frequency, the LCL filter, and the changes of solar irradiance and dc voltage. Thus, the frequency estimator will be constructed on the premise of this relationship (i_{dq} vs f).

The design of the frequency estimator is based on the work developed in [5] which has two parts: (i) a Luenberger observer and (ii) a adaptative controller. The Luenberger observer has the structure represented in Fig. 8, where the variable to observe is the current in dq frame. Every time the solar irradiance changes, the real (i_d^c) and the imaginary components (i_q^c) present some perturbations.

The imaginary component i_q^c is the one that presents a relationship with the angular speed perturbation each time the solar irradiance varies in large proportion. Due to this relationship a PI adaptative controller is linked with the Luenberger observer. The objective of this is to reduce the error of the estimated i_q^c when perturbation occurs.

Then, the phase angle and the frequency are estimated by:

$$\hat{\theta}_g = \int \hat{\omega}_g dt, \quad (9)$$

$$\hat{f} = 2\pi \hat{\omega}_g. \quad (10)$$

Following [5], the mathematical analysis of the observer, together with the linearization to get the transfer function $i(s)/\omega(s)$ is explained in Appendix 1. Additionally, the equations to get k_p and k_i are also detailed. The frequency estimator constructed is then tested in DigSilent PowerFactory together with the PV inverter control explained previously, the following section explains the study case and the results.

TABLE I
PV PANEL AND ARRAY CHARACTERISTICS

PV panel characteristics		PV array characteristics	
V_{oc}	58.8 [V]	P_{array}	0.6 [MW]
I_{sc}	5.01 [A]	N_{ser}	15
I_{mpp}	4.68 [A]	N_{par}	175
V_{mpp}	47 [V]	T_{min}, T_{max}	0-70 [$^{\circ}$ C]
k_v	0.45 [1/ $^{\circ}$ C]	G_{max}	1100 [W/m 2]
L_f	0.03 [p.u]	C_f	0.04[p.u]
L_g	0.05 [p.u]	ω_{go}	$2\pi \times 50$ [rad/s]

TABLE II
GAIN CONTROLLERS

Controller	kp	Unit	ki	Unit
Observer	0.018	[H.rad/Vs 2]	0.01	[H.rad/Vs 2]
PLL (A)	10	[rad/Vs]	30	[rad/Vs 2]
PLL (B)	20	[rad/Vs]	30	[rad/Vs 2]

III. SIMULATIONS AND RESULTS

A PV generator of 0.6 MVA was simulated in DIgSILENT Power Factory as part of a LS-PVPP of 20 MVA. The PV generator's characteristics is summarized in Table I. The complete model and control of the PV generator explained in the previous sections is implemented in DIgSILENT PowerFactory together with the designed frequency observer. For the analysis, the LS-PVPP is connected with a grid that has a short circuit ratio equal to five.

The PV generator together with the frequency observer is tested under two study cases scenarios:

- Study case A: Fast change of solar irradiance from 1000 to 0 W/m 2 and from 0 to 1000 W/m 2 (Fig.9 (a)).
- Study case B: One day of solar irradiance (Fig. 10 (a))

In each of these cases, the frequency calculated by the PLL and the observer are obtained. Additionally, two PLLs with different bandwidths are used. The first one is used for grid synchronization (PLL (A)) and the second one only to calculate the frequency grid (PLL(B)). For each PLL and the observer, the gains used are summarized in Table II. The results are illustrated in Fig. 9(b) and Fig. 10(b) for study case A and B respectively.

For quick changes of solar irradiance (Study case A) from high irradiance to low, the frequency measured by the PLL (A), presents some perturbations due to its quick dynamics. The time that the PLL uses to stabilize is 0.6 s. After this time the frequency came back to be the same as the grid is imposing. With PLL (B) the perturbations reduce but the time of stabilization is almost the same as PLL(A). The maximum perturbation has a value of 0.02 p.u. The observer, however, presents a frequency value with lower perturbations (< 0.001p.u) and a time response of 0.072 s. But, when the irradiance goes from a low to a high value, the frequency calculated by any of the strategies is similar and the perturbations are close to 0 p.u. This behaviour is due to the MPPT that slows the dynamics of the PV generator when quick changes of solar irradiance occur. The power moves smoothly thanks to the dc voltage control. However, when solar irradiance goes

Fig. 8. Frequency estimator for grid tied PV inverter

Fig. 9. Study case A . (a) Solar irradiance variation (b) Estimated and calculated frequency

Fig. 10. Study case B . (a) Solar irradiance variation (b) Estimated and calculated frequency

from high to low, the MPPT by itself cannot control the quick change of power.

For study case (B), the frequency estimated or calculated by any of the strategies (PLL or observer) does not show high perturbations. The dynamics of the MPPT control, permits that the variation of solar irradiance does not affect instantaneously the ac power supplied by the PV generator. However at 13:30 pm in Fig. 10(b), a perturbation can be seen when the solar irradiance goes from 840 to 412 W/m^2 , in ten minutes. Due to this change, the PV generator presents a ramp rate close to 2 MW/min. This change of power makes the ac voltage present some perturbations and thus the PLL (A or B) is affected. The frequency calculated by these two PLLs presents some deviation from the real value. Meanwhile, the frequency estimated by the observer does not present these perturbations and is equal to the one imposed by the electrical system.

IV. CONCLUSIONS

This paper introduced the modelling and the control of a PV generator, where the emphasis is in the electrical frequency estimation. For this purpose, a complete design of the observer is explained. The PV generator is tested under different ambient conditions where the frequency is estimated by the observer and compared with the frequency calculated by two different PLLs.

The observer presents less perturbations and faster response than the PLL when quick changes of solar irradiance occur. The perturbation and the settling time are both substantially reduced. However, this observer depends on the LCL filter and the grid inductance. For future work an estimation of the L_g is going to be studied considering weak grids.

V. APPENDIX

The full order observer estimates the state variables $\mathbf{x} = [i_c \ v_{pcc} \ i_g]^T$, where an additional term is included:

$$\mathbf{L} = [l_1 \ l_2 \ l_3]^T. \quad (11)$$

For this application, the Luenberger observer is written as:

$$\frac{d\hat{\mathbf{x}}}{dt} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{B}_1\mathbf{v}_c + \mathbf{B}_2\hat{\mathbf{v}}_g + \mathbf{L}(\mathbf{y} - \hat{\mathbf{y}}), \quad (12)$$

$$\hat{\mathbf{y}} = \mathbf{C}\hat{\mathbf{x}}. \quad (13)$$

As the measured voltage is at the PCC, the real grid voltage and phase angle is not being measured, thus in the previous equation these variables are also estimated. The observer error $\mathbf{e} = \mathbf{x} - \hat{\mathbf{x}}$ satisfies the equation:

$$\frac{d\mathbf{e}}{dt} = (\mathbf{A} - \mathbf{LC})\mathbf{e} + \mathbf{B}_2(e^{j(\hat{\rho}_g)}\mathbf{v}_g - \hat{\mathbf{v}}_g), \quad (14)$$

where; $\hat{\mathbf{v}}_g$ and $\hat{\rho}$ corresponds to the estimated voltage amplitude and phase angle respectively. The linearization of this error can be done by using the small-signal approach. To linearize, the relationship between the phase angle and the grid frequency is considered. The linearized state-space model of the observer is given by

$$\frac{d}{dt} \begin{bmatrix} \tilde{e} \\ \varepsilon_\rho \end{bmatrix} = \begin{bmatrix} A_o - L_o C_o & jB_2 v_{go} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \tilde{e} \\ \varepsilon_\theta \end{bmatrix} + \begin{bmatrix} B_2 \\ 0 \end{bmatrix} \varepsilon_{v_g} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \varepsilon_\omega \quad (15)$$

where;

$$\tilde{\varepsilon}_\rho = \tilde{\rho} - \hat{\rho}, \quad (16)$$

$$\tilde{\varepsilon}_\omega = \tilde{\omega}_g - \hat{\omega}_g, \quad (17)$$

$$\tilde{\varepsilon}_{v_g} = \tilde{v}_g - \hat{v}_g. \quad (18)$$

From this, the relationship between the current converter and the angular speed error can be determined as:

$$\frac{\tilde{\varepsilon}_{i(s)}}{\tilde{\omega}(s)} = \tilde{\mathbf{C}}(s\mathbf{I} - \mathbf{A}_2)^{-1}\mathbf{B}_\omega \quad (19)$$

where;

$$\mathbf{B}_\omega = \begin{bmatrix} 0 & 1 \end{bmatrix}, \quad (20)$$

$$\mathbf{A}_2 = \begin{bmatrix} A_o - L_o C & jB_2 v_{go} \\ 0 & 0 \end{bmatrix}, \quad (21)$$

$$\varepsilon_{i(s)} = \hat{i}_c - \tilde{i}_c. \quad (22)$$

The selection of the full order observer gains is developed using pole placement. This system has a third order dynamics that corresponds to the error dynamics given as follows:

$$\det(s\mathbf{I} - \mathbf{A} + \mathbf{LC}) = (s + \alpha_o)(s^2 + 2\epsilon_o\omega_o s + \omega_o^2) \quad (23)$$

Considering the gains, the current observer is constructed and the relationship between the current and the angular speed is given by.

$$G_{i\omega}(s) = \frac{\tilde{i}(s)}{\tilde{\omega}(s)} = -\frac{jv_{go}}{s \times CL_c L_g (s + \alpha_o)(s^2 + 2\epsilon_o\omega_o s + \omega_o^2)}. \quad (24)$$

From eq.24, it can be seen that the imaginary component of the current estimation signal depends on the angular speed. The imaginary component is related with the i_q^c in dq frame. So, the angular speed can be estimated from the $\hat{i}_q^c$ value when disturbance occurs (variation of solar irradiance) by the following adaptative controller:

$$\hat{\omega}_g = k_p \tilde{\varepsilon}_{i_q^c} + k_i \int \tilde{\varepsilon}_{i_q^c} dt. \quad (25)$$

The gains are calculated as follows:

$$k_p = -2\epsilon\omega \cdot C_f \cdot L_c \cdot L_g \alpha \omega^2 v_{go}, \quad (26)$$

$$k_i = -\omega^2 \cdot C_f \cdot L_g \cdot L_c \alpha \omega^2 v_g. \quad (27)$$

Then, the phase angle and the frequency are estimated.

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