Stability study of AC grid-connected quasi-Z-source inverter-based photovoltaic power systems

L. Sainz¹, Ll. Monjo², F. Jurado³

¹ Department of Electrical Engineering
E.T.S.E.I.B., UPC
Av. Diagonal 647, 08028 Barcelona (Spain)
Phone/Fax number: +0034 93 4011759, e-mail: luis.sainz@upc.edu

² Department of Electrical Engineering
E.P.S.E.V.G., UPC
Victor Balaguer s/n, 08800 Vilanova i la Geltrú, Spain
Phone/Fax number: +0034 93 4010746, e-mail: lluis.monjo@upc.edu

³ Department of Electrical Engineering
University of Jaén
23700 EPS Linares, Jaén, Spain
Phone/Fax number: +0034 953 64 85 18, e-mail: fjurado@ujaen.es

Abstract. The presence of photovoltaic power systems is currently increasing as green power sources, and quasi-Z-source inverters are commonly used to connect them to AC grids. However, stability concerns can appear due to inverters. Several studies address these concerns but they are not completely solved yet. This paper contributes with a simulation study about stability of AC grid-connected quasi-Z-source inverter-based photovoltaic power systems. The study is based on the PSCAD/EMTDC model of these systems and analyzes the influence of system parameters on subsynchronous and harmonic instabilities. Several solutions to improve these instabilities are discussed.

Key words. Photovoltaic systems, quasi-Z-source inverters, stability, small-signal model, PSCAD/EMTDC model

1. Introduction

Photovoltaic (PV) power systems are currently used as sustainable power sources [1] – [3]. These systems are formed by single- or two-step converters. The latter topology is more common, [4], [5], but the former is becoming increasingly used. Among this type, we find quasi-Z-source inverters (qZSIs) [6] – [9]. These inverters have a semiconductor, capacitor and inductor DC circuit with buck-boost options [6], [10] – [15]. AC grid-connected qZSI-based PV power systems can have stability problems due to the interaction between converters and the AC grid. Several authors analyze this concern in the two-step converter configuration, concluding that changes in control, temperature and irradiance can worsen system stability [3], [10], [11], [16] – [19]. The qZSI dynamics [6] – [8], [10] – [12], [15] and qZSI-based PV power system stability [18] – [24] are also investigated, but AC grid-connected qZSI-based PV power system stability has not been completely analyzed yet. Various AC-side admittance-based matrix approaches are proposed to assess multi-terminal AC grid-connected converter stability in the s-domain (e.g., eigenvalue analysis [25] – [27]), and in the frequency domain (e.g., Generalized Nyquist Criterion [28] – [33]). This paper studies AC grid-connected qZSI-based PV power system stability using the PSCAD/EMTDC model, and several simulations are made with it. The causes of instability and possible solutions are discussed.

2. PSCAD/EMTDC model of AC grid-connected qZSI-based PV power systems

Stability of the AC grid-connected qZSI-based PV power system in Fig. 1 is studied from its PSCAD/EMTDC implementation. The qZSI-based PV power system is connected to a filter capacitor Cf and an AC grid. It has a PV plant (formed by Np parallel strings of Ns PV cells in series, the capacitor Cp and the DC cable resistance Rc [2], [4]) feeding the qZSI [6] – [9], which boosts the output DC voltage at the VSI input. The PV plant is modeled with its equivalent circuit derived from the linearization of the I-V curve of the PV panel around the MPP [4], [23], [24]. The AC grid is characterized by the short-circuit inductance Ls and the supply AC voltage es to be able to represent the connection of the qZSI-based PV power system to the weak parts of the grid. The controls of the qZSI-based PV power system, i.e., MPPT, PV voltage, current and duty cycle controls, are also shown in Fig. 1. Maximum power of the PV plant is obtained by the MPPT algorithm [4], [23] and voltage control of the PV plant. The current control of the VSI imposes the power delivered from the PV plant to the AC grid.
The qZSI duty cycle control adjusts the DC peak voltage at the VSI terminals [6], [12].

The PSCAD/EMTDC implementation of the AC grid-connected qZSI-based PV power system is shown in Fig. 2. The PSCAD/EMTDC model is formed by the power modules of the qZSI-based PV power system and AC grid (see Fig. 2(a)), and the four controls in the qZSI-based PV power system (see Fig. 2(b)). The components
Table I. qZSI-based PV Power System Data

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV installation</td>
<td>Np, Nv</td>
</tr>
<tr>
<td>qZSI source network</td>
<td>L1, L2, r1, r2</td>
</tr>
<tr>
<td>VSC control</td>
<td>L1</td>
</tr>
<tr>
<td>MPPT control</td>
<td>kvp, kvi</td>
</tr>
<tr>
<td>PV control</td>
<td>kp, kvi</td>
</tr>
<tr>
<td>CC control</td>
<td>kp, kvi</td>
</tr>
<tr>
<td>D control (D = 0.06)</td>
<td>V0, kdp, kdi</td>
</tr>
</tbody>
</table>

NOTE: All variables are defined in Figs. 1 and 2. of the PSCAD/EMTDC model in Fig. 2 can be identified with the elements of the qZSI-based PV power system in Fig. 1 by the colour code and the labels. All the components used to build the PSCAD/EMTDC model are from the PSCAD library. PSCAD/EMTDC time domain simulations with the circuit in Fig. 2 make it possible to check the influence of circuit parameters on the dynamic behaviour of AC grid-connected qZSI-based PV power systems, assess system stability and test solutions for improving stability issues. These simulations were carried out using 2 us time step. In order to increase simulation efficiency, a snapshot file was created when the circuit reached its steady-state operation point, and this file was used in subsequent simulations in order not to have to simulate the initial transient every time and speed up the analysis.

3. Frequency domain response of the qZSI-based PV power system

The frequency response of the pn-sequence domain admittance transfer matrix terms of the qZSI-based PV power system allows the influence of this system on AC grid-connected qZSI-based PV power system stability to be analyzed. This frequency response can be obtained from PSCAD/EMTDC simulations made with the model proposed in the previous Section. Based on these simulations, a qZSI-based PV power system with a PV panel supplying a 0.1 MW 1 kV DC PV power system connected to a strong 400 V AC grid is studied (see data in Table I). It must be note that a strong grid is only made for the validation of the model while a weak grid is considered in one of the examples of the next Section.

The pn-sequence domain admittance transfer matrix terms are characterized by two independent PSCAD/EMTDC simulation tests, where frequency domain analysis is performed with the FFT of the involved voltages and currents [35]. In the tests, a series small-signal harmonic perturbation of p- and n-sequence voltages, Up and Un, of frequencies fp and fn, is applied to the qZSI-based PV power system in Fig. 2. Because of these voltages, the qZSI-based PV power system consumes p- and n-sequence currents, Ip and In, of frequencies fP and fn, of frequencies fp = fp – 2fi (mirror frequency) in the p-sequence test with Up, and frequencies fp = fn + 2fi (mirror frequency) and fn in the n-sequence test with Un. Finally, the pn-sequence domain admittance transfer matrix terms of dq-complex domain frequency, f0 = fn – fi (in the p-sequence domain test with U0) and f’ = fn + fi (in the n-sequence domain test with Un) are calculated as follows:

\[
Y_{pp} = \frac{I_p}{U_p} \quad Y_{pn} = \frac{I_p}{U_n} \\
Y_{np} = \frac{I_n}{U_p} \quad Y_{nn} = \frac{I_n}{U_n}.
\]

The frequency response of the pn-sequence domain admittances is shown in Fig. 3. This response reveals two important issues of qZSI-based PV power systems (see Section 4):

- They have a resonance frequency (e.g., at 153 Hz in Fig. 3) which could cause harmonic oscillatory instabilities of the qZSI-based PV power system at this frequency if this resonance is undamped [24].
- They have a negative-damping region (see Fig. 3) which could lead to subsynchronous resonance instabilities of AC grid-connected qZSI-based PV power systems if there are system resonances in this region.

4. Examples

Stability of AC grid-connected qZSI-based PV power systems is analyzed by PSCAD/EMTDC time domain simulations with the model in Section 2 and the data in Table I. The network with a 0.1 MW 1 kV DC qZSI-based PV power system in Fig. 1 is connected to a VSC filter capacitor C1 = 100 μF and a 400 V 50 Hz AC grid with a short-circuit ratio SCR equal to 20. The examples show stability problems in AC grid-connected qZSI-based PV power systems. Three cases are studied

- Case #1: this is the stable reference case, which corresponds to the PV power system steady-state

https://doi.org/10.24084/repqj20.285
operating point with $G = 0.4\ \text{Sun}$, $T = 25^\circ\text{C}$ and $\text{SCR}$ equal to 20.

- Case #2: the irradiance level $G$ is stepped up from 0.4 to 0.8 Sun to study its influence on stability.
- Case #3: the $\text{SCR}$ is stepped down from 20 to 3 to study instabilities due to weak AC grids. Note that this is an interesting example because the location of the PV plants often forces the VSI to be interconnected in the weak parts of the grid.

System stability in the above cases is studied with the PSCAD/EMTDC simulations in Fig. 4. The AC grid-connected qZSI-based PV power system is stable in Case #1 but becomes unstable when the parameter $G$ reaches a value of 0.8 at 1.8 s and the parameter $\text{SCR}$ decreases to 3 at 1 s. The frequency of the unstable oscillations captured by the PSCAD/EMTDC simulations is $f_{\text{osc}} \approx 155\ \text{Hz}$ when $G$ is stepped up (Case #2) and $f_{\text{osc}} \approx 35\ \text{Hz}$ when $\text{SCR}$ is stepped down (Case #3). In Case #2, the AC grid-connected qZSI-based PV power system has a harmonic instability because the parallel resonance of the qZSI-based PV power system in Fig. 3 is undamped [24]. In Case #3, the AC grid-connected qZSI-based PV power system has a subsynchronous instability due to the interaction between the weak AC grid and the negative-damping region of the qZSI-based PV power system at subsynchronous frequencies (see Fig. 3).

The harmonic instability in Case #2 can be improved by increasing the DC-link peak voltage $V_{\text{dc},p}$ because it damps the qZSI-based PV power system resonance in Fig. 3 [23], [24], restoring AC grid-connected qZSI-based PV power system stability. This is verified in Fig. 4, where the step up of the DC-link peak voltage $V_{\text{dc},p}$ from 800 V to 1000 V at 2.75 s enables system stability recovery. The subsynchronous instability in Case #3 can be improved by decreasing the bandwidth $\alpha_t$ of the current control feedforward filter (see Figs. 1 and 2) because this reduces the negative-damping region of the qZSI-based PV power system admittances in Fig. 3 [23], [24], and the harmonic resonance due to the weak grid is damped. This is verified in Fig. 4, where the step down of the bandwidth $\alpha_t$ from 106.1 rad/s to 95.5 rad/s at 1.2 s enables system stability recovery.

4. Conclusion

This paper studies subsynchronous and harmonic instabilities of AC grid-connected quasi-Z-based PV power systems by PSCAD/EMT simulation. The PSCAD/EMT model of the AC grid-connected quasi-Z-based PV power system is proposed and several examples are developed to study the origin of and possible solutions to instabilities. It is concluded that (i) the increase of irradiance level in the PV panels can lead to harmonic instabilities due to qZSI-based PV power system instability; (ii) the decrease of the SCR can lead to subsynchronous instabilities due to the interaction between the weak grid and the qZSI-based PV power system. The former is mitigated by increasing the DC-link peak voltage and the latter is improved by decreasing the bandwidth of the current control feedforward filter.

Fig. 4. PSCAD/EMTDC simulations ($S_0 = 0.1\ \text{MW}, U_b = 800\ \text{V}, f_o = 50\ \text{Hz}$).

Acknowledgement

This work was supported in part by the Ministerio de Ciencia, Innovación y Universidades under Grant RTI2018-095720-B-C33.

References


