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Behavioral modeling of grid-connected photovoltaic inverters: Development and assessment

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ABSTRACT

This paper describes and assesses a behavioral model for grid-connected photovoltaic inverters. The model allows us to simulate the electrical behavior of commercial single-phase and three-phase inverters in accordance with the limits of EN50160 power quality. Regarding power strategies for current inverters, both voltage and current control loops have been explicitly modeled, providing suitable simulations of the injected AC-current waveform under either power dynamics or grid voltage disturbances. Additionally, irradiance oscillations and dynamic Maximum Power Point Tracking performance have been also considered in the proposed solution. Internal inverter variables are not needed to fit the model parameters, being estimated from basic data-sheet information provided by manufacturers and simple AC-collected values from the PV power plants. This characteristic avoids any additional DC-side measurement, being a significant contribution in comparison with previous approaches.

The proposed model is assessed using real data collected in Spanish photovoltaic power plants along several years. The obtained results are compared with previous behavioral model approaches and also included in the paper.

1. Introduction

Nowadays, a relevant percentage of PV generation power plants connected at the distribution level involves a large number of small inverters, which can have a cumulative negative impact on the AC voltage waveform, and thus, on the grid power quality [1]. For this reason, standards for interconnecting this kind of generation to the utility grid are stressing more and more the capability of PV power plants to run over short grid disturbances [2]. Some authors have suggested Behavioral Model (BM) techniques [3,4] to model inverters generally used in PV power plants. These techniques can be used even when inverter-internal parameters are unknown. Moreover, further information about the inverter internal structure or control design, often unavailable, is not required by these models. Additionally, the Computational Time Cost (CTC) as well as the number of parameters is significantly lower in comparison with other approaches [5]. As an example, a single-phase inverter BM including Maximum Power Point Tracking (MPPT) and averaged model of power electronics is proposed in Ref. [6]. This solution reduces significantly the CTC by means of neglecting the Current Control Loop (CCL) and by using a proportional control for the DC voltage. However, the presence of CCL is relevant for the inverter behavior under grid voltage harmonics or disturbances. Recently, Valdivia et al. have proposed another BM solution to study the evolution of input and output currents for three-phase inverters, where MPPT performance and Voltage Control Loop (VCL) are not considered [7,8]. These same hypotheses are assumed in Refs. [9–11], applying BM techniques to simulate a three-phase IGBT voltage inverter fed asynchronous machine and DC–DC converters, where DC-voltage is considered as a constant parameter. From our point of view, it supposes an important drawback of these solutions, since DC-voltage is internally fixed by the own PV inverters and is changing over the simulation time period. Consequently, it should be considered as an output of the model and not assumed as a constant along the simulations.

From the author's point of view, both CCL and VCL are playing a major role in the current electrical behavior of grid-connected inverters, and they should be explicitly considered in the proposed

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models. However, most previous contributions don't include explicitly both control loops, neglecting their global influence on the electrical results [6,7,9–12]. Subsequently, those approaches appear to be unsuitable for simulating purposes of the injected AC-current under power dynamics or grid disturbances. To overcome this drawback, an inverter BM solution with both current and voltage controllers is discussed and assessed in the present paper. The model parameters can be fitted with AC-side inverter measurements, avoiding measurements from the DC-side and being a remarkable contribution of the paper. Efficiency is also modeled and included in our proposal, improving significantly the estimation of the injected AC-current in comparison with contributions, where efficiency is assumed as constant as it will be discussed in the corresponding results.

Finally, grid relays for over(under)-frequency and over(under)-voltage are included in the proposed solution to simulate the protections when grid failures are detected [13]. Real data collected in different Spanish PV power plants along several years are used to assess the proposed model; including power dynamics, grid voltage fluctuations and voltage harmonics. PV modules are modeled following data-sheet information and previous solutions assessed by the authors [14]. This work is based on a previous contribution of the authors, where a simplified BM was discussed and assessed [15], being necessary to measure AC-side and DC-side values.

2. Proposed inverter model: behavioral approach

2.1. General description

The structure of the proposed model is based on the single-power-stage described in Ref. [6], see Fig. 1(a). In our case, it consists of an equivalent losses block, an input DC-filter, an H-Bridge inverter, an output AC-filter and an ideal AC-isolation transformer (1:n). This model is also available for commercial power inverter transformer-less topologies, just considering 1:1 turns ratio.

The equivalent circuit corresponding to the proposed model is shown in Fig. 1(b). In this electric circuit, the equivalent losses current source (I_{ls}) involves control stage, H-bridge, output AC-filter and AC-isolation transformer losses. The input DC-filter is modeled through an equivalent bulk capacitor C_{eq}, the power stage is considered as an averaged unipolar H-bridge, the output AC-filter is deduced from a simplified T-configuration and the AC-isolation transformer is considered as an ideal component. Harmonics content of switching waveforms has not been explicitly considered in the present approach, in a similar way to previous contributions [16].

2.2. Efficiency and losses: I_{ls} discussion and estimation

The inclusion of efficiency and losses in PV inverters are relevant parameters to be considered, for example, in solar PV power estimation tools. According to Fig. 1(b), BM inverter losses are modeled as an equivalent current source (I_{ls}). This equivalent current source can be estimated by adding power losses from the control stage ($P_{\text{ctr-stg}}$), H-bridge ($P_{\text{H-Brg}}$), output AC-filter ($P_{\text{AC-flt}}$) and AC-isolation transformer ($P_{\text{AC-transf}}$). With regard to control stage power losses—involving control, monitoring and communication systems, electrical relays as well as spark gap losses—, they are considered as constant losses, neglecting any dependence with power or voltage values.

The H-bridge losses usually involve switching losses ($P_{\text{H-Brg}}^{\text{sw}}$) and conduction losses ($P_{\text{H-Brg}}^{\text{cdt}}$) [17–20]. Switching losses mainly depend on switching-frequency values. In our case, they have been considered as a constant. Conduction losses are due to the IGBT ($P_{\text{IGBT}}^{\text{cdt}}$) and diode ($P_{\text{Dd}}^{\text{cdt}}$) conduction losses that can be expressed as:

$$P_{\text{IGBT}}^{\text{cdt}} = \left[V_{\text{ce}}\cdot I_{\text{s}}(\text{wt}) + R_{\text{on}}\cdot I_{\text{s}}^{2}(\text{wt})\right]\cdot d(\text{wt}) \tag{1}$$

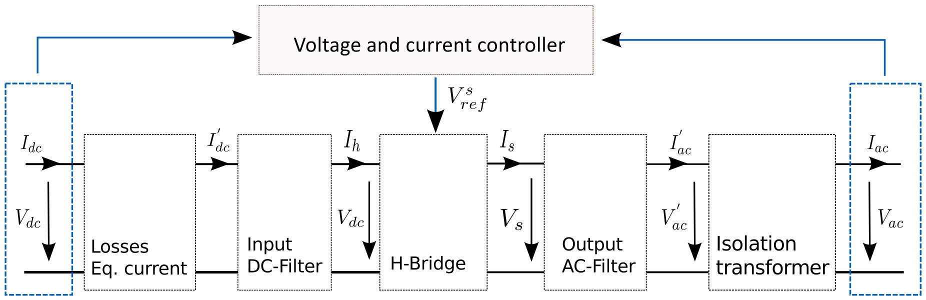
$$P_{\text{Dd}}^{\text{cdt}} = \left[V_{\text{Dd}}\cdot I_{\text{s}}(\text{wt}) + R_{\text{Dd}}\cdot I_{\text{s}}^{2}(\text{wt})\right]\cdot[1 - d(\text{wt})]. \tag{2}$$

Under the assumption of an averaged H-bridge model and $\cos(\phi) = 1$ [21],

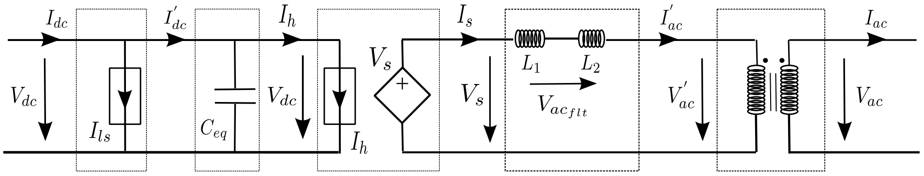
$$d(\text{wt}) = \frac{1}{2}\cdot\left[1 + \frac{\widehat{V}_{\text{s}}}{V_{\text{dc}}}\cdot\sin(\text{wt})\right], \tag{3}$$

where $\widehat{V}_{\text{s}}$ is the AC-voltage peak in the output of the H-bridge.

For each H-bridge branch, the conduction losses can be then expressed according to (1) and (2). Evaluating the corresponding



(a) Block diagram



(b) Equivalent electric circuit

Fig. 1. Proposed behavioral model: architecture and equivalent circuit.