

IDA-PBC controller design for grid connected Front End Converters under non-ideal grid conditions

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ABSTRACT

A passivity-based non-linear controller design for three-phase front-end converters used to connect renewable energy sources to the grid is proposed in this paper. The control objective is to inject all the generated power to the grid, while adjusting the reactive power exchanged with the power system. Besides, generated currents must have very low distortion, in order to satisfy the standards, even when grid voltages are distorted or unbalanced. The proposed controller is first designed using the Interconnection and Damping Assignment strategy, which allows obtaining controller parameters while ensuring the closed-loop system stability. In order to ensure that the output currents have very low harmonic distortion, the obtained control laws are modified based on the fundamental positive sequence grid voltage, obtained from a positive sequence detector. The proposal allows controlling both injected powers and DC-link voltage, from a unique controller design. Simulation and experimental results are presented to validate the proposed controller.

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1. Introduction

The use of power electronic converters to connect renewable energy sources to the electric grid has undergone significant development in recent decades [1,2]. These converters allow flexible and efficient connection between the generation system and the grid, resulting in an important research area in which the control of these converters are concerned [3,4]. In particular the converter that performs interconnection with the grid is known as active Front End Converter (FEC) and generally consists of a Voltage Source Converter (VSC) and an output filter in order to reduce the injected currents ripple (Fig. 1). In these systems, the amplitude and frequency of the voltage at the coupling point are imposed by the grid. Then, the control objectives for the FEC are to inject all of the power available on the DC side to the grid and control the reactive power exchanged with the power system. To achieve these objectives, it is necessary that the FEC synchronizes with the angle of the grid voltage while the waveform of the injected currents must also be controlled. Such currents must be almost sinusoidal, with harmonic content below the limits imposed by the standards. Standard IEEE-1547 [5] establish that the maximum total harmonic distortion (THD) for the current injected by distributed resources must

be below 5%. Besides, this standard sets limits to the amplitude of each harmonic, tolerating a maximum amplitude of 5% each.

If the mains voltage is pure sinusoidal and balanced, and the input DC current is constant, generating sinusoidal output currents (with low harmonic content which does not exceed the values set by the standards) can be achieved by simple strategies such as current control in dq coordinates [6,7]. A better dynamic performance can be achieved when using more complex strategies, which include nonlinear control techniques [8,9]. However, these strategies do not give satisfactory results if the mains voltage is unbalanced, with harmonic distortion and/or the input current has a significant ripple.

In these cases, special control strategies must be designed to generate adequate currents. These control strategies allow the generation of sinusoidal currents at the expense of allowing oscillation in the DC-link voltage, being possible to control only the average value of such voltage. This oscillation in the DC-link voltage occurs because the system has to maintain the power balance between the input and output of the converter.

Control schemes for a grid-connected VSC considering unbalanced voltages are presented in [10,11]. In Yazdani and Iravani [10], two different control objectives are proposed: one tries to balance the line currents controlling only the average value of the DC-link voltage, while the second allows to mitigate the ripple of the DC-link voltage produced due to the imbalance in the grid voltage, but this implies that the injected currents are unbalanced. In this

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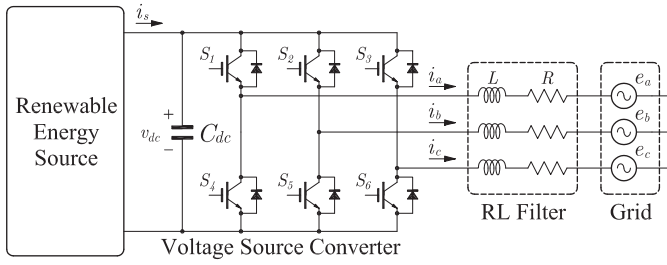


Fig. 1. FEC connected to the grid.

case, sinusoidal currents generation requires decomposition of the system into two subsystems, a positive sequence system and a negative sequence one. Then, a particular controller must be designed for each subsystem [11].

An attempt to avoid schemes with control loops for each sequence component is to use Direct Power Control (DPC) strategies [12–14]. A VSC control using DPC is proposed in Eloy-Garcia et al. [12], in order to achieve symmetrical currents when the voltage is unbalanced. In Shang et al. [13], an improved DPC control method for obtaining symmetric and sinusoidal grid currents, or to eliminate the ripple on the active and reactive powers, is presented. These approaches allow to directly regulate active and reactive powers without taking into account the negative sequence components of voltages and currents. This strategy is improved in Xiao et al. [14], in order to eliminate the DC voltage ripple, and to obtain a constant switching frequency. However, in all these cases, the effect of harmonic distortion in the grid voltage is not considered.

For the case in which grid voltage includes unbalance and distortion, Nguyen et al. [15], tries to solve this problem using a multi-loop current controller that regulates positive-sequence currents, negative-sequence currents and fifth and seventh harmonic, separately, using PI and resonant controllers. A combination of PI and a bank of resonant controllers is also proposed in Trinh and Lee [16]. In Jang and Lee [17], a high performance control scheme is proposed in order to reduce harmonics in the grid current and decrease the DC-link voltage ripple. However, as in Yazdani and Iravani [10] the above methods require implementing a reference frame rotation and a specific controller for each harmonic current to be controlled, plus an additional controller for the DC voltage, thus resulting in computational intensive implementations. To cope this problem, stationary reference-frame proportional-resonant controllers are proposed in Lee et al. [18], while predictive current control is presented in Hu et al. [19]. However, tuning of each control loop is still an issue in these proposals. Furthermore, none of the above cases considered distortion in the DC side current.

In this paper a controller for a grid-connected FEC is proposed using the passivity-based control strategy known as Interconnection and Damping Assignment (IDA) [20,21]. This design methodology was chosen because it is an energy-based control strategy, which allows to give physical interpretation to the control action and to define clearly the conditions for ensuring closed-loop stability. The controller design, following the steps of the IDA strategy, is an organized design using matrix equations, where each of these matrices has a well defined physical meaning. Thus, the designer can modify the structure of the system for simplicity, and thus solve the problem of having more variables than control actions. Also, this methodology simplifies the determination of the parameters of the controller.

The main control objective is to inject all of the available power on the DC side to the grid and control the reactive power exchanged with the power system, while ensuring that the current injected into the grid be practically sinusoidal, with harmonic content below the values imposed by the standards. When the voltage is pure

sinusoidal and balanced, the latter can be achieved by using an IDA controller as proposed by the authors in Serra et al. [8]. However, if the mains voltage is unbalanced and distorted, and the input current is not constant, such strategy does not allow to eliminate the distortion of the injected currents.

Therefore, we propose a modification to the controller presented in Serra et al. [8] to compensate for distortions and unbalance of the mains voltage and the input current. With this modification we achieve a very low distortion of the current injected to the grid, independently of the mains voltage distortion and the ripple of the DC input current. First, control laws are obtained using IDA strategy, based on the selection of the closed-loop energy function in order to ensure system stability. Then, these laws are modified using the information of the fundamental component of the positive sequence voltage, obtained by a positive sequence detector which provides information about angle and amplitude of this component.

The obtained control laws allow relating the state variables of the system in order to obtain an equation to control the DC-link voltage through the direct axis current, thus enabling the injection of all generated power to the grid, but ensuring that the distortion of the injected current is within the allowable values for the standards. Moreover, the quadrature axis current is used to control the reactive power exchanged with the power system.

Simulation and experimental results obtained on a laboratory prototype are presented in order to validate the proposed controller and the implementation of IDA strategy for this kind of systems, which has not yet been presented in the literature.

2. Front End Converter model

The Front End Converter consists of a three-phase universal bridge-reversible PWM Voltage Source Converter (VSC) with Isolated Gate Bipolar Transistor (IGBT) ($S_1, \dots, S_6$) and an RL output filter, as shown in Fig. 1. Current i_s comes from the generation side converter and the grid is modeled using three voltage sources e_a , e_b and e_c .

In order to design a controller for the FEC using the IDA strategy, it must be represented as a port-Hamiltonian (pH) system,

$$\dot{\mathbf{x}} = [\mathbf{J}(\mathbf{x}, \mathbf{u}) - \mathbf{R}(\mathbf{x})] \frac{\partial H(\mathbf{x})}{\partial \mathbf{x}} + \mathbf{g}(\mathbf{x}, \mathbf{u}) \mathbf{e}, \quad (1)$$

$$\mathbf{y} = \mathbf{g}^T(\mathbf{x}, \mathbf{u}) \frac{\partial H(\mathbf{x})}{\partial \mathbf{x}}, \quad (2)$$

where $\mathbf{x}$ is the state vector (energy variables), $\mathbf{u}$ is the control vector, $H(\mathbf{x})$ is the system energy function, $\mathbf{g}(\mathbf{x}, \mathbf{u})$ is the port matrix, $\mathbf{e}$ is the vector of external sources, $\mathbf{y}$ is the port output vector, $\mathbf{J}(\mathbf{x}, \mathbf{u}) = -\mathbf{J}^T(\mathbf{x}, \mathbf{u})$ is the anti-symmetric interconnection matrix and $\mathbf{R}(\mathbf{x}) = \mathbf{R}^T(\mathbf{x}) \geq 0$ is the symmetric positive semi-definite damping matrix. The interconnection matrix represents the internal energy flow while the damping matrix represents the system dissipation.

The total stored energy function, $H(\mathbf{x})$, is given by the sum of the energy stored in the filter inductances and in the DC-link capacitor,

$$H(\mathbf{x}) = \frac{L_d^2}{2} + \frac{L_q^2}{2} + \frac{C_{dc} v_{dc}^2}{2}, \quad (3)$$

Then, the pH model of the FEC can be expressed as follows [8],

$$\begin{bmatrix} \dot{L}_d \\ \dot{L}_q \\ \dot{C}_{dc} v_{dc} \end{bmatrix} = \begin{bmatrix} -R & -\omega_{dq} L & m_d \\ \omega_{dq} L & -R & m_q \\ -m_d & -m_q & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -e_d \\ -e_q \\ i_s \end{bmatrix} \quad (4)$$

where ω_{dq} is the angular speed of the reference frame, which in this case coincides with the grid frequency; i_d and i_q are the currents in

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