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Interconnection and damping assignment control of a three-phase front end converter

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ABSTRACT

A new nonlinear control strategy for a three-phase front end converter used to connect renewable energy sources to the grid is proposed in this paper. The controller is designed in order to inject all the generated power into the grid, while the reactive power can be controlled to meet the power system requirements. The system is represented through its port controlled Hamiltonian model, and the controller is designed by interconnection and damping assignment. This design method allows an intuitive way to remove the undesired couplings between system dynamics while assigning the damping required to achieve the expected convergence rate. The proposed controller allows a direct control of the DC link voltage by proper selection of the controller parameters. Moreover, an integral action is added to the proposed controller in order to eliminate the steady-state error in the system variables. The proposal is validated through simulation tests performed using a realistic converter model.

Introduction

In the lasts years, electronic power converters have become important components in electrical power systems, mainly due to issues related to power quality [1–4]. Even when different converter configurations have been proposed, Voltage Source Converters (VSC) are the most used in energy conversion systems due to its bidirectional power flow capability and its low harmonic distortion [5,6].

Such power converters have allowed the increase of renewable energy sources integration into the grid [7,8]. In those applications, the VSC can be used as a Front End Converter (FEC) for wind energy or photo voltaic generation systems, where the operating mode depend on the application [9,3,10]. In the case of grid connected generation units in strong power systems, voltage and frequency are imposed by the grid, so the FEC must be synchronized and inject all the available DC power to the grid. Besides, it must be able to control the reactive power exchanged with the power system. For weak power systems or micro-grids, droop control is usually used to control the active and reactive powers that the FEC exchange with the grid, thus contributing to grid stability [11,12,10]. In order to fulfill this requirements, it is necessary that the FEC be able to control the waveform of the injected currents.

Due to the actual requirements to connect power converters to the grid [13], precise control strategies are needed. Such strategies require, in several cases, a complex design including nonlinear control techniques [14]. The most used design strategies are Feedback Linearization (FL) [15,16], Sliding Mode Control (SMC) [17], and Passivity Based Control (PBC) [18,19], among others.

Interconnection and Damping Assignment (IDA) is a PBC technique [20] which has been widely used to design controllers for electric power systems stabilization and control [21–24]. More specifically, for controlling VSC this technique has been utilized in rectifiers and inverters. An IDA controller for a three-phase rectifier is presented in [25] in order to obtain unity power factor, sinusoidal phase currents and constant DC output voltage. Simulation results show that the controller is stable and robust against load variations. The controller proposed in [26] is designed with similar objectives, but an integral control loop is added in order to eliminate the steady state error in the DC output. In [27] an IDA controller is designed to control the DC output even in cases of variable load. It is also shown that the controller is robust against input voltage changes. An IDA controller for a three-phase rectifier with LCL input filter is designed in [28], which is also robust to grid impedance variations.

For single-phase rectifiers, an IDA controller is designed in [29], which allows controlling the DC output while obtaining unity power factor, with a reduced number of sensors. IDA is used in [30] to design a controller for a bidirectional power flow single-phase rectifier. In [31] this strategy is used to control the DC voltage in case of complex loads, considering bidirectional power flow, too.

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Proposals to control VSC used in single-phase inverters using IDA can be found in [32,33]. In [32] the controller is designed to control a grid connected inverter, allowing to solve the instability problems introduced by the output filters. In [33] the system robustness against load changes is explored through experimental results.

For three-phase inverters, in [34] a controller for a VSC with a pure resistive load is designed using IDA, whereas [35] presents the design of a passivity-based controller for a three-phase inverter for the connection of a photo voltaic system to the grid. The control objectives are to maintain unity power factor and control of active power to fast track the maximum power of photo voltaic array.

A new control strategy for grid connected FEC based on IDA is proposed in this paper. This strategy is aimed to inject all the available DC power into the grid, while controlling the reactive power exchanged with the power system. To this aim, the system is first represented as a *Port-Controlled Hamiltonian* (PCH) system. In this way, the coupling between the direct and quadrature currents, and the DC voltage dynamics can be clearly seen in the so-called *interconnection matrix*, while the *damping matrix* represents the natural damping of the system.

The IDA technique was chosen because it is a method based on energy, which gives a physical interpretation to the controller and it also has the advantage of showing clearly the structure of the system and the couplings between the system dynamics. Then, interconnection matrix represents the energy flow inside the system, while damping matrix represents the dissipated energy. Thus, control objective can be expressed not only in terms of system stability, but also in terms of controller performance.

The design of this strategy is based on the selection of an energy function for the closed-loop system so that it allows ensuring the system stability. In this way, the control laws for the system are obtained by solving the differential equation that results from the correct choice of interconnection and damping assignments.

Different from previous proposals, the particular design proposed in this paper allows a direct control of the DC link voltage dynamics using the same approach (IDA). In addition, a dynamic extension of the system through a controller with integral action is proposed, which allows eliminating the steady state error produced by parameter variation. The performance of the proposed controller is validated through simulations performed using a realistic model of the system.

Front end converter model

In this section, the FEC model in Park coordinates is first presented using the power invariant transformation. Then, this model is written in the PCH form.

As it can be seen in Fig. 1, the FEC is composed by an electronic power converter with IGBT (*Isolated Gate Bipolar Transitors*), ($S_1 \dots S_6$), and an output RL filter.

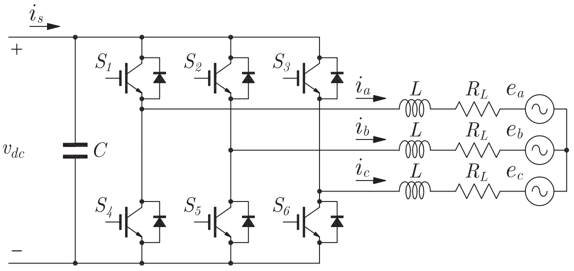

Fig. 1. Front end converter – FEC.

The filter inductance value is selected with the aim of achieving the adequate attenuation of the switching frequencies in the output current. Therefore, in this work we adopted $L = 2.5$ mH.

Current i_s comes from a slowly variant power source, which models the generation system. This current can be obtained through the quotient between the power of this source and the DC bus voltage (v_{dc}). The electric grid is modeled using sinusoidal voltage sources e_a, e_b and e_c.

Model in Park coordinates

The FEC model in Park coordinates (dq) can be written as follows [36],

$$L\dot{i}_d = -R_L i_d - \omega_{dq} L i_q + m_d v_{dc} - e_d, \tag{1}$$

$$L\dot{i}_q = -R_L i_q + \omega_{dq} L i_d + m_q v_{dc} - e_q, \tag{2}$$

$$C\dot{v}_{dc} = i_s - m_d i_d - m_q i_q, \tag{3}$$

where ω_{dq} is the angular speed of the dq reference frame, which is considered equal to the grid frequency in this work; i_d and i_q are the currents in the selected reference frame, which are obtained through the transformation of the i_a, i_b and i_c currents; e_d and e_q are the grid voltages, obtained from transformations of e_a, e_b and e_c; m_d and m_q are the modulation indexes; L and R_L are the filter inductance and resistance respectively, and C is the DC link capacitor.

The system (1)–(3) can be written in matrix form as follows,

$$\begin{bmatrix} L\dot{i}_d \\ L\dot{i}_q \\ C\dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} -R_L & -\omega_{dq}L & m_d \\ \omega_{dq}L & -R_L & m_q \\ -m_d & -m_q & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} + \begin{bmatrix} -e_d \\ -e_q \\ i_s \end{bmatrix}. \tag{4}$$

In order to design the controller for this system using the IDA technique, the system must be represented through its PCH model [20].

PCH model

The PCH model of a dynamic system can be written as,

$$\dot{\mathbf{x}} = [\mathbf{J}(\mathbf{x}) - \mathbf{R}(\mathbf{x})]\frac{\partial H(\mathbf{x})}{\partial \mathbf{x}} + \mathbf{g}(\mathbf{x})\mathbf{u} + \zeta, \tag{5}$$

where $\mathbf{x}$ is the state vector, $\mathbf{u}$ is the input vector, $\mathbf{J}(\mathbf{x})$ is the interconnection matrix, $\mathbf{R}(\mathbf{x})$ is the damping matrix, $H(\mathbf{x})$ is the energy function of the system, $\mathbf{g}(\mathbf{x})$ is the input matrix and ζ is an external disturbance.

In this work, the state vector is defined as follows:

$$\mathbf{x} = \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}^T = \begin{bmatrix} Li_d & Li_q & Cv_{dc} \end{bmatrix}^T, \tag{6}$$

and the input vector is,

$$\mathbf{u} = \begin{bmatrix} m_d & m_q \end{bmatrix}^T. \tag{7}$$

The interconnection and damping matrices are defined from (4) as follows:

$$\mathbf{J} = \begin{bmatrix} 0 & -\omega_{dq}L & 0 \\ \omega_{dq}L & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \tag{8}$$

$$\mathbf{R} = \begin{bmatrix} R_L & 0 & 0 \\ 0 & R_L & 0 \\ 0 & 0 & 0 \end{bmatrix}, \tag{9}$$

where $\mathbf{J}$ is anti-symmetric and $\mathbf{R}$ is symmetric positive semi-definite, that is,

$$\mathbf{J} = -\mathbf{J}^T \quad \text{and} \quad \mathbf{R} = \mathbf{R}^T \geqslant 0. \tag{10}$$