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Stability evaluation of a DC micro-grid and future interconnection to an AC system

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ABSTRACT

This paper presents the stability analysis of a DC micro-grid fed by renewable sources and the future interconnection with an AC micro-grid. This interconnection is realized through a voltage source converter, and the operation of the micro-grid is in island mode. The stability is analyzed by the Nyquist criteria with the impedance relation method. The frequency response of the models was obtained by the injection of a perturbation current at the operation point. Where this perturbation was at the input of the converter used to export power from the DC grid. Other perturbation was applied at the node of the micro-grid to evaluate its impedance. Finally the simulations show the impedance representation of the systems, and the stability for the interconnection of them. The experimental verification shows the impedance of the converter with the same tendency as the representation obtained by the analytical and simulation.

1. Introduction

The stable behavior is one of the most important factors in power systems. Its correct analysis ensures to the designer or operator that the system is going to be under normal conditions. Small signal techniques were developed for classical power systems, where generator to load current flow is always assumed [1]. But, future grids can present a system with power injection into the grid from the side of the costumer. These future grids will exhibit more nonlinear behavior and difficult coordination than the classical power system. In the case of DC distributed power electronics systems used in telecommunications, aircraft or ships the stability had been studied in Refs. [2–5]. Where stable region operation was identified. These methods employ frequency response and Nyquist criteria to present stability analysis. Linearization has been done, due to its simplicity and success record [6,7]. The wide spread choice to predict instability by the application of small signal analysis such as the Nyquist criterion or eigenvalues in AC systems with power electronics has been presented in Refs. [1,8–14]. However, it is necessary to analyze the stability of the distribution system with one of its prominent topology, in this work it is presented a variant of the CIGRE AC benchmark [15] for a DC residential low voltage micro-grid, and its stability has been studied at one of the power exchange nodes.

The paper is organized as follows: the Section 2 describes the modeling by impedance representation, Section 3 presents the grid structure and the method employed to control the DC voltage, and Section 4 describes the numerical results obtained from the simulations.

2. Impedance representation methods

The impedance is determined by the application of an ideal source with a frequency component. This source is a sinusoidal current or voltage type (i_p or v_p respectively), and is denominated the perturbation. The magnitude has to be small with respect to the nominal operation value of the system. The frequency is chosen as f_p varying in a range. The input voltage and current are measured at the DC side of the grid or the VSC. Their Fourier transform is computed. Finally the values at the perturbation frequency determine the input impedance of the inverter for small signal stability analysis or output impedance of the grid [2,8,9]. The current or voltage injection to obtain the impedance for the VSC is presented in Fig. 1. The stability is analyzed with the Nyquist criteria used in Refs. [14,12]. Where the full system is partitioned into a source and a load subsystem, described by a Thevenin equivalent system in the case in which the source is considered

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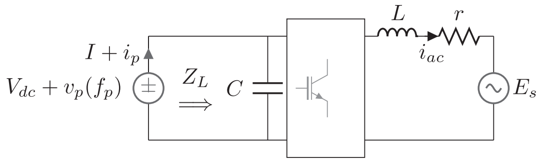

Fig. 1. Perturbation source for impedance measurement.

voltage type and a Norton equivalent system in which the source is considered current type, as is shown in Fig. 2. For voltage source type the analysis has to be realized over the Thevenin circuit and the voltage applied to the load subsystem is calculated in (1), where V_{L} is the voltage in the load, Z_{s} is the output impedance of the source, and Z_{L} is the input impedance of the load.

$$V_{\mathrm{L}} = \frac{1}{1+\frac{Z_{\mathrm{s}}}{Z_{\mathrm{L}}}} V_{\mathrm{s}} \tag{1}$$

The relation $Z_{\mathrm{s}}/Z_{\mathrm{L}}$ is used to realize the stability analysis, if its Nyquist plot counterclockwise encircles the point $-1+j0$ then the system has an instability. And in case of use the Norton equivalent circuit the current in the load I_{L} is (2), where I_{s} is the source current.

$$I_{\mathrm{L}} = \frac{1}{1+\frac{Z_{\mathrm{L}}}{Z_{\mathrm{s}}}} I_{\mathrm{s}} \tag{2}$$

2.1. Voltage source converter

The system used to interconnect the two grids is a power electronics three phase voltage source converter (VSC). This device operates as a rectifier and is used to link the two systems. The equations of a voltage source converter connected at the DC side to a grid and to an ideal AC system are described from (3)–(6).

$$\frac{\mathrm{d}i_d}{\mathrm{d}t} = \frac{E_{sd} - v_d + wLi_q - ri_d}{L} \tag{3}$$

$$\frac{\mathrm{d}i_q}{\mathrm{d}t} = \frac{E_{sq} - v_q - wLi_d - ri_q}{L} \tag{4}$$

$$\frac{\mathrm{d}v_{\mathrm{dc}}}{\mathrm{d}t} = \frac{i_{\mathrm{dc}} + i_{\mathrm{grid}}}{C} \tag{5}$$

$$i_{\mathrm{dc}} = s_{gd} i_d + s_{gq} i_q \tag{6}$$

where $E_{s,k}$ with $k \in \{d, q\}$ is the voltage of the AC grid in the direct and quadrature axis, respectively. The current in the filter inductance L is i_k. The voltage at the switch terminals of the converter is v_k. The DC voltage is v_{dc}, the current at the DC side of the converter is i_{dc}, the switching commands are s_{gk}, and the current flowing from the DC grid is i_{grid}. The controller for this system is design with the set of equations from (7) to (11).

$$v_d = -k_p\left(i_{\mathrm{ref}d} - i_d\right) - k_i\gamma_d + wLi_q - \alpha e^{-\alpha t}E_sd \tag{7}$$

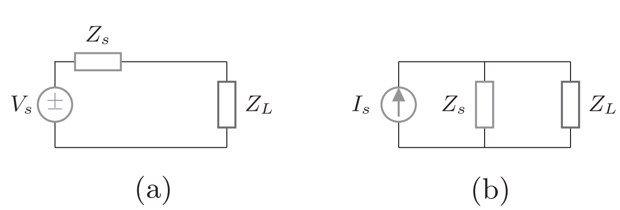

Fig. 2. Equivalent circuits representation to stability, (a) Thevenin, and (b) Norton.

$$v_q = -k_p\left(i_{\mathrm{ref}q} - i_q\right) - k_i\gamma_q - wLi_d - \alpha e^{-\alpha t}E_{sq} \tag{8}$$

$$\dot{\gamma}_d = i_{\mathrm{ref}d} - i_d \tag{9}$$

$$\dot{\gamma}_q = i_{\mathrm{ref}q} - i_q \tag{10}$$

$$s_{gk} = \frac{v_k}{v_{\mathrm{dc}}} \tag{11}$$

The impedance of the load or converter connected to the grid can be estimated by the use of three techniques. They are described in the followed subsections.

2.2. State space linearization

The nonlinear function (12) can be linearized around an operation point and the system described by (13) and (14). For the converter the low frequency impedance is obtained by the method described in Ref. [14], the current of the source (or DC grid at the node) is the input to the system, the states are the AC currents, and the voltage in the DC capacitor; that is chosen as the output of the system. The matrix form of the differential equations for the inverter is (3) and (6).

$$\dot{x} = f(x, u) \tag{12}$$

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{13}$$

$$y = C_{\mathrm{m}}\Delta x \tag{14}$$

For this method the input is equal to the grid current $u = i_{\mathrm{grid}}$, the states are $x = (i_d, i_q, v_{\mathrm{dc}}, \gamma_d, \gamma_q)^T$. The impedance in the frequency domain is calculated with (15).

$$Z_{\mathrm{dc}}(s) = C_{\mathrm{m}}(sI - A)^{-1}B \tag{15}$$

The impedance obtained by this method is:

$$Z_{\mathrm{dc}}(s) = \frac{(s+\alpha)v_{\mathrm{dc}}^2}{s^2Cv_{\mathrm{dc}}^2 + sCv_{\mathrm{dc}}^2\alpha - i_dk_i\gamma_d(s+\alpha) + i_d\alpha\, E_{sd}} \tag{16}$$

2.3. Linearization and transfer functions relation

To obtain the impedance representation by this method the steps used in Refs. [16,17], are described to be applied over the model of the set (3)–(11). First the models are obtained in the time domain. In the second step, the Laplace transform is realized for the states in order to obtain the transfer functions. A linearization around the operation is required in this step. The transfer function that represents the impedance is obtained by the relation between the variables v_{dc} and i_{dc} in Laplace domain. And the impedance of the full converter is obtained by the equivalent parallel between DC capacitance and the impedance of the converter. The obtained impedance for this system is presented from (17) and (18), and the final model is shown in (19).

$$Z_{\mathrm{vsc}}(s) = \left(-\frac{v_{\mathrm{dc}}}{i_{\mathrm{dc}}}\frac{v_{\mathrm{dc}}(r+sL)^2(s+\alpha)^2}{a_4s^4 + a_3s^3 + a_2s^2 + a_1s + a_0}\right) \tag{17}$$

$$a_k = f_k(K_{\mathrm{ptrans}}, G_{\mathrm{a}}, x_0);\quad k \in \{0, \ldots 4\} \tag{18}$$

$$Z_{\mathrm{dc}}(s) = \frac{Z_{\mathrm{C}}(s)Z_{\mathrm{vsc}}(s)}{Z_{\mathrm{C}}(s) + Z_{\mathrm{vsc}}(s)} \tag{19}$$