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Influence of non-dispatchable energy sources on the dynamic performance of MicroGrids

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ABSTRACT

This paper analyzes the influence of non-dispatchable energy sources on the dynamic stability of stand-alone MicroGrids (MGs) with autonomous control of frequency and voltage based on inverters. The analysis considers the use of eigenvalue techniques. Although this methodology is well known, the contribution of this paper is twofold. First, it proposes an algorithm for designing the inverter interface to meet the requirements associated with the harmonic distortion (THD) and dynamic performance of the inverter. Second, it provides an analysis of the dynamic stability of MG considering different levels of penetration of non-dispatchable energy sources, variations in the network parameters and the presence of dynamic loads (i.e., induction motors).

1. Introduction

MicroGrids (MGs) have played an increasingly important role in electricity supply, especially in systems with high penetration of critical loads, in which power outage cannot be tolerated. Unlike large-scale generators, which are almost exclusively synchronous machines, DG units do not naturally produce in 50 or 60 Hz, therefore inverters are needed to provide AC network interface. On the other hand, when MGs are in islanded mode, there is the need to control the voltage and frequency independently, through one or more inverters. The most widely used method to perform this task, due to its versatility and reliability, is the active and reactive power sharing through voltage and frequency droops, so that the inverter can be controlled only by local measurements of voltage and current [1–3]. This way, the inverter control strategies can be divided into two types: (a) *Droop Control*, implemented in the grid-forming units, which define the reference of voltage and frequency and (b) *PQ Control*, implemented in the units that require a reference of voltage and frequency to inject pre-specified values of active and reactive power in the network [4]. Energy sources with intermittent generation characteristics (not associated with a long-term storage system) are non-dispatchable and should ideally be operated at the point of maximum power and generally coupled to the network through inverters with PQ Control [5].

This paper analyzes the influence of non-dispatchable energy sources on the dynamic stability of stand-alone MGs using the eigenvalue approach. Previous works concerning the small-signal modeling of stand-alone Microgrids have assumed an ideal behavior of inverter [6]. This means that the control loops track the voltage and current references perfectly, accurately and quickly. This assumption may lead to omit important inverter dynamics, especially when the bandwidth of the current control loop is small. The modeling approach presented in [7], only analyzes the stability issues for an individual inverter connected to a stiff AC bus. This paper is valuable for understanding the inverter properties, but fails to analyze the interaction between each inverter and, between them and the network. In [8], is presented a systematic approach for modeling an inverter-based MicroGrid. Inverter models include voltage and current controllers. In this paper, the network and the loads are modeled by differential equations. However, only RL (resistive–inductive) loads are considered, and only the *Droop Control* strategy is analyzed. In [9], the authors present a methodology to derive a linearized state-space model of inverter-based MicroGrid, operating in grid-connected mode (i.e., only *PQ Control* is analyzed), considering the control loops as well as the network and the RL loads. The results of the small-signal stability analysis are good, but this paper does not analyze the stability issues of stand-alone MGs, especially the interactions between Droop Control and PQ Control.

Abbreviations: DG, distributed generation; IM, induction motor; LC, inductive–capacitive; LPF, low pass filter; MG, MicroGrid; ODE, ordinary differential equation; PLL, phase-locked loop; PWM, pulse width modulation; RL, resistive–inductive; THD, total harmonic distortion.

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In contrast, this paper analyses the dynamic stability of standalone MGs with autonomous control of frequency and voltage based on inverters. Inverter models include voltage and current controllers, with two control strategies: Droop Control (for grid-forming units) and PQ Control (for non-dispatchable units). The contribution of this paper is twofold. First, it proposes an algorithm for designing the inverter interface to meet requirements associated with harmonic distortion (THD) and dynamic performance of the inverter. Second, it provides an analysis of small-signal stability of MG considering different levels of penetration of non-dispatchable energy sources, variations in the network parameters and the presence of dynamic loads (i.e., induction motors).

For the stability analysis, the inverters are modeled in state space. The switching action is not considered. The inverters are coupled to the internal network through a coupling inductance and an inductive–capacitive (LC) low pass filter to attenuate the high switching frequencies. This is an attractive economical solution; however, it adds complexity to the control system.

Considering the time period under analysis, the DC link of all the inverters can be assumed as an ideal source of DC, supplying a constant voltage Vdc to the inverter [9,10].

2. Inverter model

2.1. Droop control

Fig. 1 shows the block diagram of the Droop Control implemented in the rotating reference frame d–q. The differential and algebraic equations that govern the behavior of each block in Fig. 1 are developed below.

2.1.1. Power calculator

The input signals of this block correspond to measurements of instantaneous three-phase voltage and current at the inverter output (v_o, i_o). After these signs are decomposed in direct and quadrature axis components, the values of instantaneous active and reactive power are estimated. This values of power are then passed through a low pass filter (LPF) with cutoff frequency w_c to obtain the real power (P) and reactive power (Q) corresponding to the fundamental frequency. The corresponding differential equations (ODEs) of the block are (1) and (2):[1]

$$\dot{P} = -w_c \cdot P + w_c \cdot v_{od} \cdot i_{od} + w_c \cdot v_{oq} \cdot i_{oq} \tag{1}$$

$$\dot{Q} = -w_c \cdot Q + w_c \cdot v_{oq} \cdot i_{od} - w_c \cdot v_{od} \cdot i_{oq} \tag{2}$$

2.1.2. Power management

This block has an active power control based on a frequency-droop characteristic with gain m_p and a reactive power control based on a voltage-droop characteristic with gain n_q. The active power control generates the reference angle θ used in the transformation abc/dq. The reactive power control generates the output voltage magnitude reference aligned to the d-axis; q-axis reference is set to zero ($v^*_{oq} = 0$) The equations of the block are (3)–(6), where P_{set}, Q_{set}, V_{set} and w_{set} are respectively the pre-specified values of active power, reactive power, voltage and frequency:

$$\dot{\theta} = w \tag{3}$$

$$w = w_{set} + m_p \cdot (P_{set} - P) \tag{4}$$

$$v^*_{od} = V_{set} + n_q \cdot (Q_{set} - Q) \tag{5}$$

$$v^*_{oq} = 0 \tag{6}$$

[1] The dot above the variables represents the differential operator d/dt.

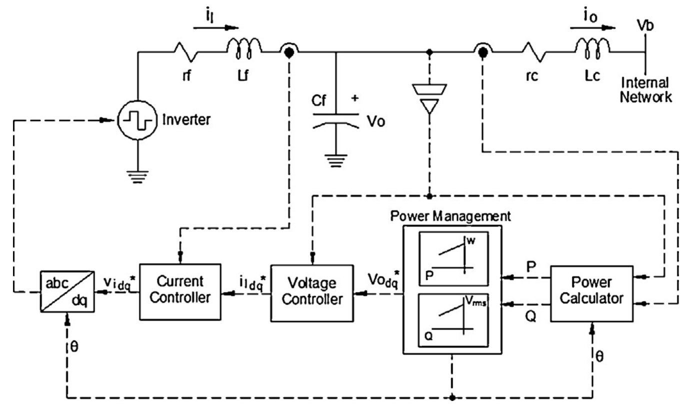

Fig. 1. Droop control block diagram.

2.1.3. Voltage controller and current controller

The voltage and current control loops can be represented by ODEs (7)–(10), and the algebraic Eqs. (11)–(14), where variables $\emptyset_d$, $\emptyset_q$, γ_d and γ_q are created to facilitate the development of state-space model, and do not have a particular physical meaning. Kp_1, Ki_1, Kp_2 and Ki_2, respectively, correspond to the proportional and integral gain of the voltage and current control loop. F_v and F_c represent the gains in voltage and current feed-forward loops, respectively. L_f and C_f are the inductance and capacitance of the filter, respectively, and w is the fundamental frequency of the system

$$\dot{\emptyset}_d = v^*_{od} - v_{od} \tag{7}$$

$$\dot{\emptyset}_q = v^*_{oq} - v_{oq} \tag{8}$$

$$\dot{\gamma}_d = i^*_{ld} - i_{ld} \tag{9}$$

$$\dot{\gamma}_q = i^*_{lq} - i_{lq} \tag{10}$$

$$i^*_{ld} = Kp_1 \left(v^*_{od} - v_{od}\right) + Ki_1 \emptyset_d - w \cdot C_f \cdot v_{oq} + F_v \cdot i_{od} \tag{11}$$

$$i^*_{lq} = Kp_1 \left(v^*_{oq} - v_{oq}\right) + Ki_1 \emptyset_q + w \cdot C_f \cdot v_{od} + F_v \cdot i_{oq} \tag{12}$$

$$vid^* = Kp_2 \left(ild^* - ild\right) + Ki_2 \gamma_d - w \cdot L_f \cdot il_q + F_c \cdot V_{od} \tag{13}$$

$$viq^* = Kp_2 \left(ilq^* - ilq\right) + Ki_2 \gamma_q + w \cdot L_f \cdot il_d + Fc \cdot V_{oq} \tag{14}$$

2.1.4. Inductive–capacitive (LC) filter and coupling impedance

The ODEs (15)–(18) represent the LC output filter and the coupling impedance:

$$\dot{i}_{ld} = \frac{-r_f}{L_f} \cdot il_d - \frac{1}{L_f} \cdot v_{od} + \frac{1}{L_f} \cdot vi_d - w \cdot il_q \tag{15}$$

$$\dot{i}_{lq} = \frac{-r_f}{L_f} \cdot il_q - \frac{1}{L_f} \cdot v_{oq} + \frac{1}{L_f} \cdot vi_q - w \cdot il_d \tag{16}$$

$$\dot{i}_{od} = \frac{-r_c}{L_c} \cdot i_{od} + \frac{1}{L_c} \cdot v_{od} - \frac{1}{L_c} \cdot v_{bd} + w \cdot i_{oq} \tag{17}$$

$$\dot{i}_{oq} = \frac{-r_c}{L_c} \cdot i_{oq} + \frac{1}{L_c} \cdot v_{oq} - \frac{1}{L_c} \cdot v_{bq} - w \cdot i_{od} \tag{18}$$

2.1.5. Complete model of the Inverter

We can obtain the complete linearized model of the inverter by combining Eqs. (1)–(18) linearized. To build the complete model in the common reference frame D–Q, local reference frame d–q of one of the individual inverter is arbitrarily taken as the common reference and the other local references are translated into this common reference. For this, we define in (19) an angle δ for each inverter, where w_i is the frequency of the local rotating reference frame of the ith inverter and w_{com} is the frequency of the common reference.