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A control strategy for stand-alone wound rotor induction machine

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Abstract

A control strategy to regulate the frequency and voltage of a stand-alone wound rotor induction machine is presented. This strategy allows the machine to work as a generator in stand-alone systems (without grid connection) with variable rotor speed. A stator flux-oriented control is proposed using the rotor voltages as actuation variables. Two cascade control loops are used to regulate the stator flux and the rotor currents. A closed loop observer is designed to estimate the machine flux which is necessary to implement these control loops. The proposed control strategy is validated through simulations with satisfactory results.

Keywords: Wound rotor induction machine; Variable speed constant frequency; Stand-alone (autonomous) generator

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1. Introduction

Variable speed generating systems show better efficiency than constant speed generating systems when the primary source of energy is variable [1,2]. This is the case for the generating systems that uses renewable energies like wind, geothermal, hydro, etc.

Those systems can be used to complement other energy generating systems connected to the grid (co-generating systems). In these cases, the grid imposes the frequency and voltage, and the generator control takes care of other tasks like active and reactive power control [3,4] or energy conversion optimization [5,6].

In those cases where the users are far away from the grid and cannot reach the energy provided by it, a stand-alone (isolated) generating system can be used [7]. This kind of systems must be able to provide the users with regulated voltage and frequency [8]. In these cases, wound rotor induction machines (WRIM) present several advantageous characteristics working at variable speed while regulating the generated voltage and frequency [9–11].

WRIM supplying isolated loads can be found in refs. [12–15], where the application feasibility of this machine on stand-alone systems is analyzed. In refs. [16–18], Kawabata et al. propose two cascade loops to control the rotor current and stator voltage. The rotor current control loop is realized using two linear controller with feed forward compensating terms and the stator voltage is realized using a lineal controller with a non-linear feedback. In refs. [19–21], Peña et al. propose an indirect voltage and frequency control achieved by controlling the stator flux while neglecting the stator resistance and imposing slip frequency to the rotor currents through an algebraic relationship.

Using an algebraic relationship to calculate the stator flux, based on the stator and rotor currents, can be considered as to estimate the stator flux using an open loop observer. It is well known that the use of these kind of observers might present significant estimation errors when model uncertainties are present [22]. Then, the use of a closed loop observer is a good choice to improve the steady state and transient behavior of the control system.

In this paper, a control strategy to regulate the frequency and voltage of a WRIM working as a variable speed stand-alone generating system is proposed. A closed loop observer is designed to estimate the stator flux. The paper is organized as follows: the WRIM model is presented in Section 2. The proposed control loops, including the closed loop observer, are presented in

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Section 3. The control performance is evaluated through simulations in Section 4. Finally, conclusions are given in Section 5.

2. WRIM model

The WRIM can be described by the following equations using a dq reference frame rotating at an arbitrary speed ω_{dq} [23]:

$$\frac{d\lambda_{qs}}{dt} = -\frac{1}{\tau_s}\lambda_{qs} - \omega_{dq}\lambda_{ds} + \frac{M}{\tau_s} i_{qr} + v_{qs} \quad (1)$$

$$\frac{d\lambda_{ds}}{dt} = +\omega_{dq}\lambda_{qs} - \frac{1}{\tau_s}\lambda_{ds} + \frac{M}{\tau_s} i_{dr} + v_{ds} \quad (2)$$

$$\frac{di_{qr}}{dt} = \frac{\beta}{\tau_s}\lambda_{qs} + \beta\omega_r\lambda_{ds} - \gamma_2\, i_{qr} - (\omega_{dq} - \omega_r) i_{dr} - \beta v_{qs} + \frac{1}{\sigma L_r} v_{qr} \quad (3)$$

$$\frac{di_{dr}}{dt} = -\beta\omega_r\lambda_{qs} + \frac{\beta}{\tau_s}\lambda_{ds} + (\omega_{dq} - \omega_r) i_{qr} - \gamma_2 i_{dr} - \beta v_{ds} + \frac{1}{\sigma L_r} v_{dr}. \quad (4)$$

where λ_{qs}, λ_{ds}, i_{qr}, i_{dr} are the stator fluxes and the rotor currents, v_{qs}, v_{ds}, v_{qr}, v_{dr} the stator and rotor voltages, respectively, L_s and L_r the stator and rotor inductances, ω_r the rotor mechanical speed, M the magnetizing inductance and

$$\sigma = 1 - \frac{M^2}{L_r L_s}, \quad \beta = \frac{1-\sigma}{M\sigma}, \quad \tau_s = \frac{L_s}{r_s}, \quad \tau_r = \frac{L_r}{r_r},$$

$$\gamma_2 = \left(\frac{1-\sigma}{\sigma\tau_s} + \frac{1}{\sigma\tau_r}\right),$$

where r_s and r_r are the stator and rotor resistances.

3. Proposed control

The objective of this paper is to propose a strategy to implement a generator system using a WRIM. This strategy is designed to regulate the machine stator voltage and frequency. The voltage regulation is achieved, indirectly, by controlling the stator flux vector magnitude and angular speed. The frequency regulation is achieved by keeping the flux vector aligned with a dq reference frame rotating at synchronous speed ($\omega_{dq} = 314$ rad/s), consequently,

$$\lambda_{qs} = 0. \quad (5)$$

While the stator flux vector remains aligned as defined in Eq. (5), the flux magnitude can be calculated as its direct component λ_{ds}.

It can be observed in Eqs. (1) and (2) that the rotor currents (i_{qr}, i_{dr}) can be used to control the machine flux components. Moreover, Eqs. (3) and (4) show that the rotor currents can be controlled by using the rotor voltages (v_{qr}, v_{dr}). Therefore, two cascade control loops can be implemented, one internal to control the rotor currents and the other one external to control the stator flux components.

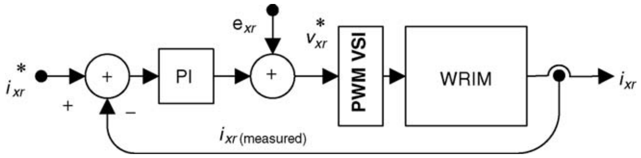

Fig. 1. Current control loop (x = d, q).

3.1. Current control loop

Fig. 1 shows a block diagram of the proposed current control loop.

A PI compensator plus a *feed forward* compensating term, e_{xr}, is proposed to generate the rotor voltage reference (v^*_x) used in the Pulse Width Modulated-Voltage Source Inverter (PWM-VSI),

$$v^*_{qr} = \sigma L_r[k_p(i^*_{qr} - i_{qr}) + k_i x_{qr}] + e_{qr} \quad (6)$$

$$v^*_{dr} = \sigma L_r[k_p(i^*_{dr} - i_{dr}) + k_i x_{dr}] + e_{dr}, \quad (7)$$

where x_{qr} and x_{dr} are the auxiliary variables used to implement the integral control,

$$\frac{dx_{qr}}{dt} = i^*_{qr} - i_{qr} \quad (8)$$

$$\frac{dx_{dr}}{dt} = i^*_{dr} - i_{dr}, \quad (9)$$

i^*_{qr} and i^*_{dr} are the rotor current references, and k_p and k_i are the PI proportional and integral gains. These gains are chosen so that the rotor current control loop is faster than the stator flux control loop. However, there are two trade-offs for the desired loop speed: one with the inverter switching frequency which should be higher than the cut-off of the control loop, and a second one with the available control action, defined as the maximum voltage supported by the rotor windings (voltage saturation).

The feed forward compensating term, added to the PI compensator output, is used to cancel the non-linear terms ($(\omega_{dq} - \omega_r)i_{dr}$, $(\omega_{dq} - \omega_r)i_{qr}$, $\beta\omega_r\lambda_{qs}$ and $\beta\omega_r\lambda_{ds}$) and to reject the perturbations introduced by the stator voltages (βv_{qs} and βv_{ds}) and fluxes ($\beta/\tau_s\lambda_{qs}$ and $\beta/\tau_s\lambda_{ds}$), shown in Eqs. (3) and (4). This compensating term can be deduced from the machine model, yielding to the following expression,

$$e_{qr} = \sigma L_r\left((\omega_{dq} - \omega_r) i_{dr} + \beta\left(-\lambda_{qs}\frac{1}{\tau_s} - \lambda_{ds}\omega_r + v_{qs}\right)\right) \quad (10)$$

$$e_{dr} = \sigma L_r\left(-(\omega_{dq} - \omega_r)\, i_{qr} + \beta\left(+\lambda_{qs}\omega_r - \lambda_{ds}\frac{1}{\tau_s} + v_{ds}\right)\right). \quad (11)$$

Using this control strategy and assuming that the PWM-VSI is not saturated, the closed loop dynamics corresponds to a first-order linear system plus a PI controller, where x_{qr} and x_{dr} are defined in Eqs. (8) and (9),

$$\frac{di_{qr}}{dt} = -\gamma_2 i_{qr} + k_p(i^*_{qr} - i_{qr}) + k_i x_{qr} \quad (12)$$

$$\frac{di_{dr}}{dt} = -\gamma_2 i_{dr} + k_p(i^*_{dr} - i_{dr}) + k_i x_{dr}. \quad (13)$$