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Control strategy of a dual induction motor: Anti-slip control application

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ABSTRACT

The paper deals with a Dual Induction Motor control. A control strategy based on the Average Differential Control (ADC) is developed and adapted to work as an anti-slip control in a railway traction system. In addition to cancel the behaviour deviation between the motors supplied by a single inverter in case of an adhesion loss (or an unbalanced load), the proposed control strategy permits an action on the torque control to cancel the differential torque between the two motors. The control strategy is validated on a laboratory test bench with a Mechanical Railway Traction Load Emulator.

1. Introduction

In embedded systems, cost, size and reliability are the main constraints to satisfy. Most applications require multiple drive units according to the desired power. In addition, they are generally coupled together mechanically and/or electrically, hence the importance given to the drive control of these multi-converter/multi-machine systems. A cooperative control of such a system can allow on the one hand reducing the number of control units and sensors used, to better manage the existing interaction between the different units, on the other hand, the robustness and service continuity aspects can be integrated by considering the overall multi-converter/multi-machine architecture for the system control.

In most of the Dual Induction Motor (IM) Controls proposed in the literature (Ando, Sato, Sazawa, & Ohishi, 2003; Bogiatzidis, Safacas, Mitronikas, & Christopoulos, 2012; Bouscayrol et al., 2006; Xu & Shi, 2011; Yu, Xiang, & Bing-jun, 2010), the drive controls are based on a weighted vector control strategy. The control is applied to a virtual motor chosen by the weighting, in other words, by the contribution of each motor to the control.

In the research work presented in Kelecy and Lorenz (1994) a control methodology for single inverter, dual induction motor drives are presented. This control structure is based on the Field Oriented Control (FOC) and called the Average Differential Control (ADC). Besides to the control of the mean flux and torque through the d- and q-axes respectively, the mean differential variables are used to decrease the behaviour deviation between the motors.

The d-axis is no longer used only for the rotor flux control, but it is also used for the mean differential torque control. The q-axis is used as in the conventional FOC for the mean torque control. This strategy allows us to maintain the differential torque between the two motors as well as to cancel the gap between the motor speeds in case of an unbalanced load.

To improve the control performance of unbalanced load, Xu, Shi, and Li (2013) proposed a control strategy based on the weighted vector control. Comparatively to the study presented in Kelecy and Lorenz (1994), weighted and differential values are used for the control.

In the railway traction sector, to meet the aforementioned requirements, the industry is moving more and more towards a distributed traction system also called Electrical Multiple Units (EMU) (Briginshaw, 2008; Duffy, 2003; Jufer, 2010; Koseki, 2010; Lacôte, 2005; Lee, 2010; Smith, 2001; Uzuka, 2011). The other important point is that this architecture can improve compared to the concentrated traction is energy efficiency with a more efficient regenerative brake system (Sato & Yoshizawa, 2010; Teramoto, Ohishi, Makishima, Uezono, & Yasukawa, 2012).

In railway traction, the traction forces are transmitted to the rail through the contact of the wheels with the rail. So, the transmitted forces depend strongly on the adhesion coefficient μ. The main factor for an unbalanced load in a railway traction system is the adhesion force change. Its properties change greatly according to

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Nomenclature

Symbols

$\mathbf{v_s} = \begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix}$	stator-voltage vector reference frame (d–q)
$\mathbf{i_s} = \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}$	stator-current vector reference frame (d–q)
$\mathbf{i_{mr}} = \begin{bmatrix} i_{mrd} \\ i_{mrq} \end{bmatrix}$	magnetizing rotor current vector reference frame (d–q)
$\mathbf{e} = \begin{bmatrix} E_d \\ E_q \end{bmatrix}$	electromotive force vector reference frame (d–q)
$\mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$	symplectic matrix
$\mathbf{\Phi}_r$	rotor flux vector
L_s, L_r, M_{sr}	stator, rotor and mutual inductances
R_s, R_r	stator and rotor resistances
$T_r = \frac{L_r}{R_r}$	rotor time constant
σ	leakage or coupling factor
n_p	number of pole pairs
V_{dc}	input DC voltage
R_f, L_f, C_f	input filter resistance, inductance and capacitance
v_{Cf}	filter capacitance voltage
i_{Lf}	filter inductance current
P	exchanged power between the motors and the filter
k_d, k_q	coefficients of managing the dq axes contribution
k_{xd}, k_{xq}	coefficients determining a constant contribution of each axis
$\theta_a, \theta_s, \theta_e$	electrical angular position of the reference frame (d–q), stator and rotor
$\omega_a, \omega_s, \omega_e$	electrical angular speed of the reference frame (d–q), stator and rotor
ω_{mi}, ω_{ri}	angular velocities of the motors and wheels
V_t, V_{ri}	linear velocities of the train and wheels
μ_i, ν_i	adhesion coefficient and slip ratio of the axle i
μ_{maxi}	maximum adhesion coefficient of the axle i
$F_{ri/rail}$	the tangential forces between rail and driving wheels
Γ_{em}	electromagnetic torque
Γ_{li}	the load torque
M_i	the fictitious masses reduced to each axles
R_{ri}	the wheel radiuses
$\mathbf{X}$	matrices
$\mathbf{x}$	vectors
x, X	other variables
$\wedge$	vector product
$\mathrm{d}/\mathrm{d}t$	denotes a time derivative
Δ	denotes a differential value between two variables or constants
$\lvert\ \rvert$	absolute value
R_a, R_b, R_c	axis of the three phase rotor
α, β	axis of a static reference frame
S_d, S_q, S_o	axis of a rotating reference frame

Superscripts

*	denotes a reference variable
$\hat{}$	denotes an estimated value
$\bar{}$	denotes an averaged value

Indices

d,q	denote the axis of a rotating reference frame

the variation of the adhesion coefficient, which depends on the slip ratio, rail conditions and axle load. As shown in Fig. 1, the adhesion coefficient increases in the adhesion region and decreases in the slip region as a function of the slip ratio ν_s. In case of a worsening of a rail condition (e.g. from dry to wet condition), the value of the maximum adhesion coefficient greatly decreases.

In the works presented in the literature (Choi, 2008; Kadowaki et al., 2007; Park, Kim, & Choi, 2009, 2008; Villagra, D'Andréa-Novel, Fliess, & Mounier, 2011; Yamazaki, Karino, Nagai, & Kamada, 2005; Yasuoka et al., 2009), the most of the anti-slip algorithms presented are based on estimators, observers or behaviour models with individual traction control. The authors in Bouscayrol et al. (2006) proposed a weighted voltage vector control strategy as an anti-slip strategy of an adhesion loss of one of the two induction motors supplied by a single inverter.

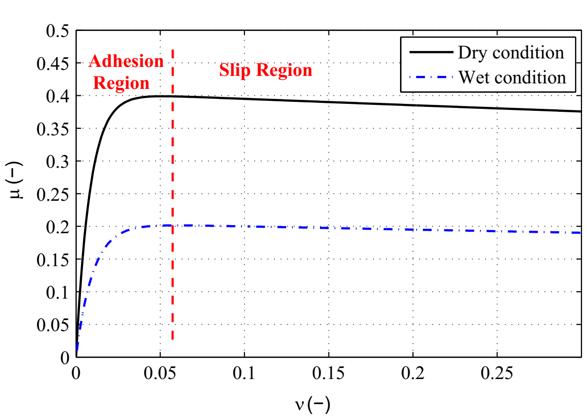

Fig. 1. Characteristics between the adhesion coefficient and the slip ratio for dry and wet conditions.

In this article, a drive control of a dual IM used in a railway traction system is proposed. In addition to cancel the behaviour deviation between the IM, it allows to cancel the difference between the motor torques in case of an unbalanced load. This objective is achieved by acting not only on the d-axis as proposed in Kelecy and Lorenz (1994) but also on the q-axis. This second degree of freedom allowed the use of this control structure as an anti-slip control. Compared to the aforementioned anti-slip algorithms, the proposed solution based on the improved ADC control can be applied in case of a distributed traction with a common supply and in case of a simultaneous adhesion loss of the two drive axles. In addition, only the sensors already available for motor control (current, voltage and speed sensors) are used.

Simulations and experiments are carried out to verify the proposed control method. The system and control description are firstly introduced. Then, the design of the control structure is presented and the system stability is discussed. Thereafter, the simulation results of the system behaviour and of the control sensitivity to the parameters are presented and discussed. Finally, the experimental results carried out on a laboratory test bench with a Railway Traction Mechanical Load Emulator are presented.