Electrical Power and Energy Systems 43 (2012) 230–244

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Towards a global control strategy for induction motor: Speed regulation, flux optimization and power factor correction

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ARTICLE INFO

Article history:
Received 12 July 2011
Received in revised form 11 May 2012
Accepted 14 May 2012
Available online 21 June 2012

Keywords:
Induction machine
Magnetic circuit nonlinearity
AC/DC/AC converters
Speed regulation
Power factor correction
Backstepping technique

ABSTRACT

A great deal of interest has been paid to induction machine control over the last years. However, most previous works have focused on the speed/flux/torque regulation supposing the machine magnetic circuit to be linear and ignoring the machine power conversion equipments. The point is that speed regulation cannot be ensured in optimal efficiency conditions, for a wide range of speed-set-point and load torque, unless the magnetic circuit nonlinearity is explicitly accounted for in the motor model. On the other hand, the negligence of the power conversion equipments makes it impossible to deal properly with the harmonic pollution issue due to 'motor – power supply grid' interaction. This paper presents a theoretical framework for a global control strategy of the induction machine and related power equipments. The proposed strategy involves a multi-loop nonlinear adaptive controller designed to meet the three main control objectives, i.e. tight speed regulation for a wide range speed-reference variation, flux optimization for energy consumption and power factor correction (PFC). Tools from the averaging theory are resorted to formally describe the control performances.

1. Introduction

Induction motors are featured by their interesting power/mass ratio, relatively low cost and simple maintenance (as they include no mechanical commutator). It is widely agreed that these machines have promising perspectives in the industrial actuator field. This has motivated an intensive research activity on induction machine control especially over the last fifteen years. The complexity of this problem is threefold:

- The multivariable and nonlinear nature of the machine dynamics.
- The multiform interaction with its environment: supply grid, power converters, varying load, etc.
- The multiplicity of control objectives: speed regulation, energy consumption optimization, power factor correction, fault detection and diagnostic, etc.

Most previous works have focused only on speed/flux regulation (with constant flux reference) following several control strategies ranging from simple techniques, e.g. field-oriented control [11,14], to more sophisticated nonlinear approaches, e.g. feedback linearization [1], direct torque control [21,4] or sliding mode control [19]. A common point of these works is that the control design relies on a relatively simple machine model, next called standard model, assuming a linear representation of the magnetic circuit (which of course is not true in real machines). Accordingly, most previous control solutions involved flux regulation around constant values (Fig. 1). Specifically, the constant flux reference is equal to its nominal value generally located at the elbow of the machine magnetic characteristic [12,2]. Then, energetic efficiency is actually maximal provided that the machine operates all time in the neighborhood of its nominal point. But, this is not the case in most practical applications because the machine load is generally varying [8]. Indeed, in presence of small loads, the operation point is below the nominal value causing useless energy stored in stator inductances which reduces the machine efficiency. In the case of overloaded machine, this operates in the saturation zone of its magnetic characteristic but, then, the standard model is no longer valid and, consequently, the control performances are no longer guaranteed. To overcome the above shortcomings, it is necessary in speed control to let the flux reference be dependent on both the speed reference and torque-load, i.e. the flux reference must be state-dependent. Examples of speed/flux controllers involving state-dependent flux reference (Fig. 2) have been developed in [15]. The proposed controllers include optimal flux generators the design of which relies on a machine model that takes into account the nonlinearity of the magnetic characteristic.

However, even in the preceding works the control problem has been relatively simplified because the motor is viewed there as a

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http://dx.doi.org/10.1016/j.ijepes.2012.05.022

Nomenclature

c_i, d	design parameters
f_e	voltage network frequency (Hz)
$i_{sd},\ i_{sq}$	d- and q-axis stator currents
i_e	rectifier input current
k	control action of the DC link voltage regulator
R_s	stator resistance
$L_1,\ 2C$	passive components of input converter
s	PWM input signal controlling converter IGBT's
T_L	machine load torque
$v_{s\alpha},\ v_{s\beta}$	α- and β-axis stator voltages
v_{dcref}	reference value of rectifier output voltage v_{dc}
V_i	Lyapunov functions $(i = 1 \ldots 6)$
$\tilde{x}$	the estimate error of x
x_1	average rectifier input current, i.e. $x_1 = \bar{i}_e$
x_2	average rectifier output voltage $x_2 = \bar{v}_{dc}$
x_4	average α-axis stator current $(x_4 = \bar{i}_{s\alpha})$
x_6	average α-axis rotor flux $(x_6 = \bar{\phi}_{r\alpha})$
y	squared DC Link voltage $y = x_2^2 = \bar{v}_{dc}^2$
z_1	input current tracking error $z_1 = x_1 - kv_e$
z_3	rotor speed tracking error $z_3 = \Omega_{ref} - \bar{\Omega}$
z_5, z_6	interns errors
$\phi_{r\alpha},\ \phi_{r\beta}$	α- and β-axis rotor flux
$\bar{\Phi}_{ref}$	average rotor flux reference $\bar{\Phi}_{ref} = F(\bar{I}_s)$
Ω_{ref}	rotor speed reference (rd/s)
f	combined rotor and load viscous friction
I_s	stator current norm (A)
$i_{s\alpha},\ i_{s\beta}$	α- and β-axis stator currents
J	combined rotor and load inertia
R_r	rotor resistance
L_{seq}	leakage equivalent inductance
p	number of pole pairs
T_e	electromagnetic torque
$u_{i=1,2,3}$	duty ratios
v_{dc}	rectifier output voltage
$v_e(t)$	AC line voltage
$\hat{x}$	the estimate of x
$\bar{x}$	average values over cutting periods of x
x_1^*	average input current reference $x_1^* = kv_e$
x_3	rotor speed $(x_3 = \bar{\Omega})$
x_5	average β-axis stator current $(x_5 = \bar{i}_{s\beta})$
x_7	average β-axis rotor flux $(x_7 = \bar{\phi}_{r\beta})$
y_{ref}	reference value of y, i.e. $y_{ref} = v_{dcref}^2$
z_2	DC Link voltage error $z_2 = y - y_{ref}$
z_4	rotor flux norm error $z_4 = \bar{\Phi}_{ref}^2 - \bar{\Phi}_r^2$
$\phi_{rd},\ \phi_{rq}$	d- and q-axis rotor flux
$\bar{\Phi}_r$	average rotor flux norm $\bar{\Phi}_r = \sqrt{x_6^2 + x_7^2}$
Ω	machine rotor angular velocity
ω_e	power supply net pulsation

$a_1 = R_r \quad a_2 = \frac{R_s + R_r}{L_{seq}}; \quad a_3 = \frac{1}{L_{seq}}, \quad b_0 = \frac{E^2}{C}; \quad b_1 = \frac{dC}{E^2}c_2$

$b_2 = \sqrt{2}\frac{E}{C} \quad b_3 = -\frac{d}{E^2}C; \quad \bar{\delta} = \Gamma(\bar{\Phi}_r); \quad \varepsilon = 1/\omega_e$

separated system directly controlled by acting on the stator voltages. As a matter of fact, in practical applications, the motor is physically controlled through a (three-phase) DC/AC PWM switch inverter. Furthermore, the inverter is connected to a power supply net through a AC/DC PWM rectifier (Fig. 3). Ignoring the latter amounts to suppose that the DC-link voltage (i.e. the AC/DC rectifier output voltage) is perfectly regulated. The point is that perfect regulation of such voltage cannot be ensured ignoring the rectifier load which is nothing other than the set 'DC/AC inverter–Motor'. Moreover, the Rectifier–Inverter–Motor association strongly interacts with the AC power supply net (Fig. 3). Accordingly, the power flow is in fact bidirectional: the circulation sense depends on the load variation. Then, undesirable current harmonics are likely to be generated in the AC line, due to the strongly nonlinear nature of the association 'converter–inverter–motor'. This harmonic pollution has several damaging effects on the quality of power distribution along the AC line, e.g. electromagnetic compatibility issues, voltage distortion, reactive power increase, larger power losses, increased voltage drops, etc. In this respect, standards such as IEEE519-1992 and IEC 61000-3-2/IEC 6100-3-4 indicate the current harmonic limits to be complied with, in terms of power factor correction [9,18]. Of course, the power factor can be improved using additional protection equipments (transformers, condensers, etc.) and/or over-dimensioning the converter and net elements. However, this solution is costly and may not be sufficient.

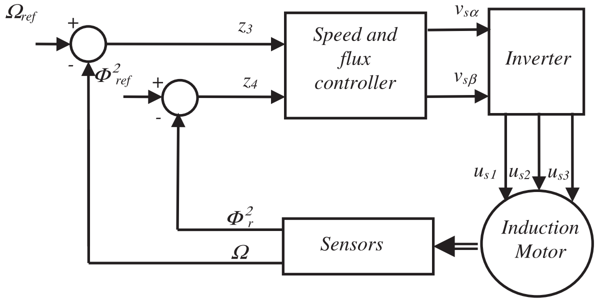

Fig. 1. Control strategy involving constant flux reference (the controller is obtained from the standard model).

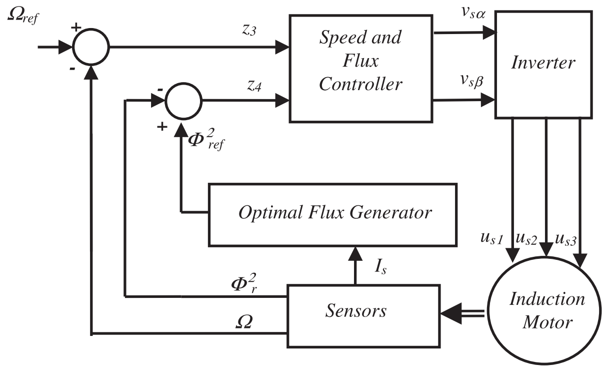

Fig. 2. Control strategy involving state-dependent optimal flux (SDOF) reference.

An attempt to simultaneously deal with speed/flux control and PFC requirement has been done [16]. But, the flux optimization requirement was not coped with there.

In the light of the above remarks, it becomes clear that a convenient control strategy is one that consists in dealing with the control problem for the whole association 'rectifier–inverter–motor', seeking simultaneous achievement of all relevant control objectives, i.e. tight speed regulation for wide set-point variation range, flux optimization despite large load change, satisfactory power factor correction (PFC), fault detection and diagnostic, etc. Such a global control strategy has still to be developed (Fig. 4). This study