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A Speed Control for Variable-Speed Single-Phase Induction Motor Drives

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Abstract— **In this paper, a control strategy is proposed for adjustable speed drives for single-phase induction motors. This strategy guarantees the level of magnetization while improving the machine efficiency. Simulation results are presented to verify the performance of proposed control strategy.**

Keywords— **Single-phase motors, Torque control, Electrical drives**

I. Introduction

The single-phase induction motor (SPIM) can be considered one of most widely used types of machine in the world. It is usual to find it operating several appliances in houses, offices, shoppings, farms and industries. With the advent of low-cost power semiconductor devices, the use of variable speed drives has become interesting in many applications of SPIM's, such as blowers, fans, compressors and pumps.

The SPIM is basically constituted by a squirrel-cage rotor and two stator windings displaced 90^O in space, known as main and auxiliary windings. Usually, these windings have different impedances. If the main winding is fed by a single-phase source, the produced magnetic field is pulsating and stationary, and a starting torque is not developed. To start a SPIM, a second phase must be simulated using the auxiliary winding, which is often open by a centrifugal switch when the rotor reaches 60% to 80% of rated speed. In general, a series capacitor is connected with the auxiliary winding to improve the starting. In many applications, the auxiliary winding and a series capacitor are maintained at running operation to provide higher torque and to overcome any drawbacks related to pulsating torque, such as excessive power loss.

An easy way to regulate the speed of SPIM is to vary the effective voltages applied to stator windings [1], [2]. However, the speed range obtained by this method is very restricted. A more effective manner to control the SPIM speed is by adjusting of the stator frequency. In this case, one needs to establish a convenient control law to provide a constant level of magnetization. In general, the magnetizing currents on SPIMs are fixed using the scalar control law "Volts per Hertz" (V/f). The drawback of this method is that V/f control does not assure a constant slip at a constant load torque in all speed range [3]. Another method, the adjustment of the phase-difference angle (PDA) between stator voltages is rarely used to control the speed of SPIM drives [4]. Although efficient, it presents a nonlinear behavior.

In this paper, a new control strategy is proposed for adjustable speed drive for SPIMs. The torque is controlled by adjusting the currents of both stator windings, aiming to improve the machine efficiency. The proposed control law provides an adequate level of magnetization, assuring a constant slip at constant load for all speed range. Simulation results are used to verify the performance of the proposed control strategy. This paper is organized as follows. In section II is developed a steady-state analysis of the SPIM using the method of symmetrical components. In section III, the proposed strategy to torque control is presented. The robustness of the control scheme to parameter variations is analyzed in section IV. The dynamic model of SPIM used in simulation is shown in section V. The section VI presents results obtained in dynamic simulation of proposed strategy. Any comments for a practical implementation are presented in section VII. Finally, the conclusions are presented in section VIII.

II. Steady-State Analysis

Since SPIMs are asymmetrical two-phase machines, the method of symmetrical components can be used in analysis [5]. The equivalent circuit of an SPIM is shown in Fig.1, where $_s$ is the stator resistance, $_s$ is the stator indutance, $_r$ is the rotor resistance, $_r$ is the rotor indutance, $_{ms}$ is the mutual indutance, $_{aux}$ is the auxiliary winding resistance and $_{aux}$ is the auxiliary winding indutance. Considering all variables and parameters referred to the main winding, the steady-state torque $_E$ developed by an SPIM is:

$$_E = \frac{2}{\omega}\ {}^2_{ms}\left[\ (\ )\ {}^2_1 - \ (2-\ )\ {}^2_2\right] \tag{1}$$

where is the number of pole pairs, $_{ms}$ is the magnetizing reactance, ω is the synchronous speed, $_1$ is the positive sequence current and $_2$ is the negative sequence current. is a function of slip , given by:

$$(\ ) = \frac{\ _r}{\ {}^2_r + (\ \ _{rr})^2} \tag{2}$$

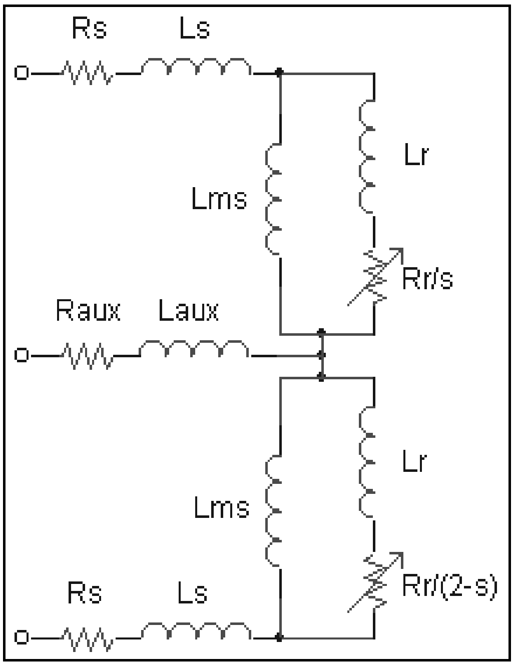

Fig. 1. Equivalent circuit of SPIM

where ${}_r$ is the rotor reactance and ${}_{rr} = {}_{ms} + {}_r$. Converting the sequence currents into stator currents, the electromagnetic torque of an SPIM becomes:

$$
{}_E = \frac{}{2}\frac{{}^2_{ms}}{\omega}\{({}^2_A + {}^2_B)[\ (\ ) - \ (2 - \ )] + 2\ {}_A\ {}_B \sin\varphi[\ (\ ) + \ (2 - \ )]\} \quad (3)
$$

where ${}_A$ and ${}_B$ are the currents in the main and auxiliary windings, respectively, and φ represents the PDA between stator currents. From (3), the starting torque ${}_{ST}$ of SPIM can be computed as:

$$
{}_{ST} = 2\ \frac{{}^2_{ms}}{\omega}\frac{{}_r}{{}^2_r + {}^2_{rr}}\ {}_A\ {}_B \sin\varphi \quad (4)
$$

Examining eqs. (3) and (4), one can notice that the existance of a phase-difference between stator currents is fundamental to start the SPIM and to determine the rotating direction, although its maintainance at running conditions is not necessary. At running conditions, one of windings can be disconnected (usually the auxiliary winding due to its high resistance) without affecting the SPIM operation. However, to improve the electromagnetic torque, it is interesting to maintain both windings and a phase-difference at running operation.

Often, it is required to assure a constant level of magnetization to avoid magnetic saturation and excessive losses. Except during start-up, the negative sequence is very small for any slip and can be neglected to compute ${}_{ms}$. Considering $\varphi = \pm 90^O$ is imposed by current controllers, an approach to the absolute value of ${}_{ms}$ is given by:

$$
|\ {}_m| = \frac{1}{2}\sqrt{{}^2_A + {}^2_B}\sqrt{\frac{{}^2_r + (\ {}_r)^2}{{}^2_r + (\ {}_{rr})^2}} \quad (5)
$$

According to equation 5, both stator currents must vary with slip to obtain a fixed airgap flux on the single-phase machine. To maintain a fixed magnetizing current $|\ {}_m|$ on SPIM, the current on main winding must be:

$$
{}_A = \frac{2|\ {}_m|}{\sqrt{1 + \ {}^2}}\sqrt{\frac{{}^2_r + (\ {}_{rr})^2}{{}^2_r + (\ {}_r)^2}} \quad (6)
$$

where the defines a relationship between the stator currents ${}_A$ and ${}_B$.

III. Torque Control

According to equation (3), the torque machine can be controlled through of magnitudes of stator currents or PDA. Although the PDA method is interesting manner to control the torque, the main and auxiliary stator currents are maintained at quadrature in this proposed strategy to increase the electromagnetic torque.

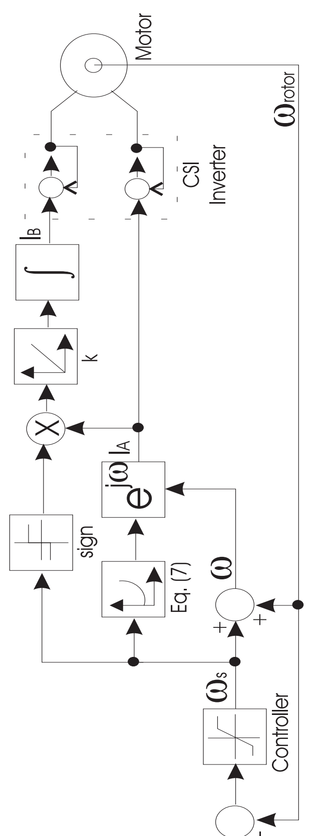

Fig. 2. Block diagram of proposed drive

The Figure 2 shows the schematic diagram for torque control. From the speed error, a PI controller generates a slip speed ω_s, which is added to the rotor speed to determine the stator frequency ω. The slip magnitide is limited on this schema to assure a efficient operation on SPIM and to prevent excessive stator line currents caused by large slip variations. The magnitude of the main current ${}_A$ is computed using the relationship given by equation (6). With values computed for amplitude and frequency, the sinusoidal reference signal for phase current $_A$ is generated. The sinusoidal reference signal of $_A$ is multiplied by and integrated to obtain the sinusoidal reference signal for auxiliary current $_B$ and to assure a PDA between the stator currents of 90^O. Both $_A$ and $_B$ sinusoidal references are applied on hysteresis current controllers to impose the stator currents on SPIM.

The definition of the is very important to determine the performance of the SPIM drive. If the objective is only electromagnetic torque maximization, it is enough to assume $= 1$ and to eliminate the negative sequence component, providing a SPIM operation as a two-phase machine. However, due to unbalanced windings, this choice of can increase excessively the stator copper losses. According to Fuchs et al. [6], the highest efficiency of a single-phase machine is obtained when main and auxiliary windings present almost identical current densities. Thus, can be chosen as:

$$= \frac{1}{} \frac{\Phi_B}{\Phi_A} \tag{7}$$

where Φ_A and Φ_B are wire cross section areas of main and auxiliary windings, respectively. The parameter represents the transformer relationship between both stator windings. In this work, is a constant defined by equation 7. However, this parameters can be defined as variable aiming, for example, to compensate usual variations on parameters $_r$ and $_{rr}$ under various operating conditions. Thus, the auxiliary current is defined as:

$$_B = \quad (\omega_s) \quad _A \tag{8}$$

where $_B$ is made negative to provide the braking capability to the drive and to enable the reversion of the rotating direction when the slip ω_s became negative.

IV. Influence of parameter variations

Considering that stator currents depend on SPIM parameter, this control scheme can be sensitive to parametric variations, mainly the mutual inductance $_{ms}$ and the rotor resistance $_r$. These parameters vary respectively with the flux level and the rotor temperature. Due to these parameter uncertainties, the control performance can deteriorate, resulting in steady-state errors and undesirable oscillations in flux and torque.

The robustness of the control system related to parametric variation can be analyzed using the sensitivity function [7], which represents a measure of the influence of the parameter modifications on system characteristics. Since the magnitude of auxiliary current $_B$ is proportional to magnitude of main current $_A$ in this scheme, the sensitivity of the control system is available from the eq. (6). Considering a fixed parameter , the sensitivity of the main current $_A$ with respect to parameter $_{ms}$ (or $_r$) is computed as the partial derivative of eq. (6) with respect to $_{ms}$ (or $_r$). The normalized sensitivity functions of $_A$ with respect to $_{ms}$ and $_r$ can be approached by:

$$\frac{\partial \ _A \ _A}{\partial \ _{ms} \ _{ms}} \approx \frac{1}{1 + \left(\frac{R_r}{\omega_s L_{ms}}\right)^2} \tag{9}$$

$$\frac{\partial \ _A \ _A}{\partial \ _r \ _r} \approx -\frac{1}{1 + \left(\frac{\omega_s L_r}{R_r}\right)^2} \frac{1}{1 + \left(\frac{R_r}{\omega_s L_{ms}}\right)^2} \tag{10}$$

From expressions (9) and (10), it is noted that both sensitivity functions depend on slip speed ω_s. Considering that, in this control strategy, ω_s is limited at relatively low values to avoid high stator currents, the analysis of sensitivity functions shows that changes on parameters $_{ms}$ and $_r$ have a small influence over magnitude of $_A$, which means that proposed scheme is robust to parametric variations on SPIM.

V. Dynamic Model of SPIMs

The stationary *dq*-axis reference frame can be applied to SPIMs. Considering all rotor variables referred to the stator windings, the dynamic voltage equations of SPIMs are given by [5]:

$$_{qs} = \ _{s} \ _{qs} + \frac{\lambda_{qs}}{} \tag{11}$$

$$_{ds} = \ _{aux} \ _{ds} + \frac{\lambda_{ds}}{} \tag{12}$$

$$_{qr} = \ _{r} \ _{qr} - \frac{\omega_r \lambda_{dr}}{} + \frac{\lambda_{qr}}{} \tag{13}$$

$$_{dr} = \ _{r} \ _{dr} - \ \omega_r \lambda_{qr} + \frac{\lambda_{dr}}{} \tag{14}$$

Since the SPIM has a squirrel-cage rotor, the rotor windings of SPIM are short-circuited and rotor voltages $_{qr}$ and $_{dr}$ are null. The flux equations are:

$$\lambda_{qs} = \ _{s} \ _{qs} + \ _{ms} (\ _{qs} + \ _{qr}) \tag{15}$$

$$\lambda_{ds} = \ _{aux} \ _{ds} + \ _{ms} (\ _{ds} + \ _{dr}) \tag{16}$$

$$\lambda_{qr} = \ _{r} \ _{qr} + \ _{ms} (\ _{qs} + \ _{qr}) \tag{17}$$

$$\lambda_{dr} = \ _{r} \ _{dr} + \ _{ms} (\ _{ds} + \ _{dr}) \tag{18}$$

and the instantaneous electromagnetic torque can be expressed by:

$$_e = \frac{}{2} \ _{ms} (\ _{qs} \ _{dr} - \ _{ds} \ _{qr}) \tag{19}$$

These equations describe the dynamic model of SPIM that is simulated in next section to verify the performance of the proposed control strategy.

VI. Simulation Results

Computer simulations were made using the forth-order Runge-Kutta technique to verify both steady and transient performances of the proposed strategy for SPIM drives. The simulated converter topology is

TABLE I
1/4HP, 110V/60Hz, 4-poles SPIM

Parameter	Symbol	Value
Main Winding Resistance	$_s$	2 02Ω
Aux. Winding Resistance	$_{aux}$	7 14Ω
Rotor Resistance	$_r$	4 12Ω
Main Leakage Inductance	$_s$	7 4mH
Aux. Leakage Inductance	$_{aux}$	8 5mH
Rotor Leakage Inductance	$_r$	5 6mH
Magnetizing Inductance	$_{ms}$	180mH
Aux./Main Turns Ratio		1 18

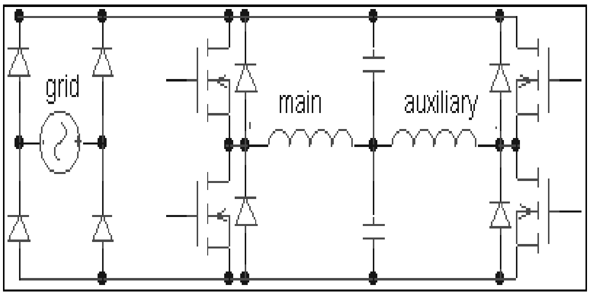

Fig. 3. Converter topology

shown in Fig 3. It consists of a two-phase half-bridge CSI inverter switched by hysteresis current controllers. The voltage of DC link is 250 Vcc. The table I shows the parameters of the SPIM. The magnetizing current is fixed at 1 65 and the slip is limited at ±30 rad/s.

The steady-state characteristics are shown in Figure 4, where the current ratio is considered as $= 0\ 3$. For constant load, the speed-torque curves shows that the slip is maintained constant in a wider speed range. This performance is desirable in many SPIM applications, such as refrigeration compressor [8]. The sets of speed-current curves represent the line current (vectorial sum of main and auxiliary currents). The current characteristic shows that high line currents can occur during start-up or large load variations, which justifies the slip limitation.

The dynamic behavior is presented in Figs. 5 and 6. Initially, with $= 0\ 3$, the SPIM is accelerated from zero to 1800 rpm. Afterwards, the motor is deaccelerated to 900 rpm, maintaining the ratio . For a new acceleration to 1350 rpm, the current ratio is varied to $= 0\ 6$ to increase the acceleration torque. During these operations, the phase difference angle φ is maintained constant at 90^o.

Clearly, the input current is sinusoidal and in anti-phase with the input supply voltage when the motor is in deacceleration. During steady-state running with steady load, the motor supply voltage and current waveforms are in phase. During braking, the supply current becomes out of phase with the supply voltage. It can be noticed that the proposed speed control adjusts adequately the motor rotation according to the desired reference. Due to slip limitation, the main and

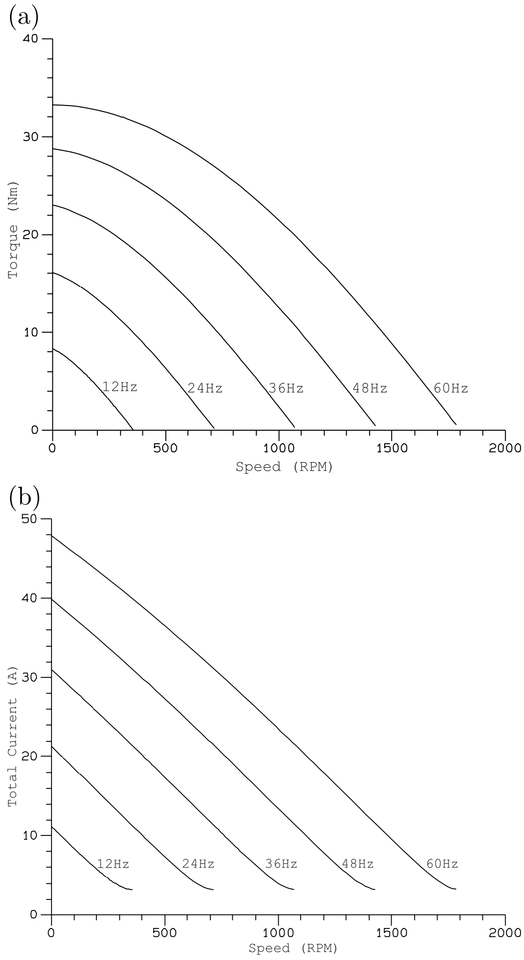

Fig. 4. Steady-State response: (a) Speed-Torque characteristics. (b) Speed-Current characteristics.

auxiliary currents are limited in 7 5 A and 3 A respectively. For any rotor speed, the main and auxiliary currents are 3 5 A and 1 4 A, respectively, in steady state. The pulsating torque is normal in single-phase motor due to negative sequence component.

VII. Comments for a possible hardware implementation

Considering the fractional power nature of SPIM applications, low-cost power MOSFETs can be used in inverter implementation. For higher performance, better reliability and lower cost, microcontrollers or DSP's represent the best option for real-time processing of the proposed control strategy. In many of these processing devices is possible to integrate important peripheral circuits, which simplify the overall implementation. The processing requirements and the implementation cost can be reduced if additional analogue and digital components with "embedded" functions are included in hardware design, which would allow the use of less expensive microcontrollers.

To current measurements, there are many low-cost options. A good suggest is the use of a Hall transducer which do not need a previous conditioning sig-

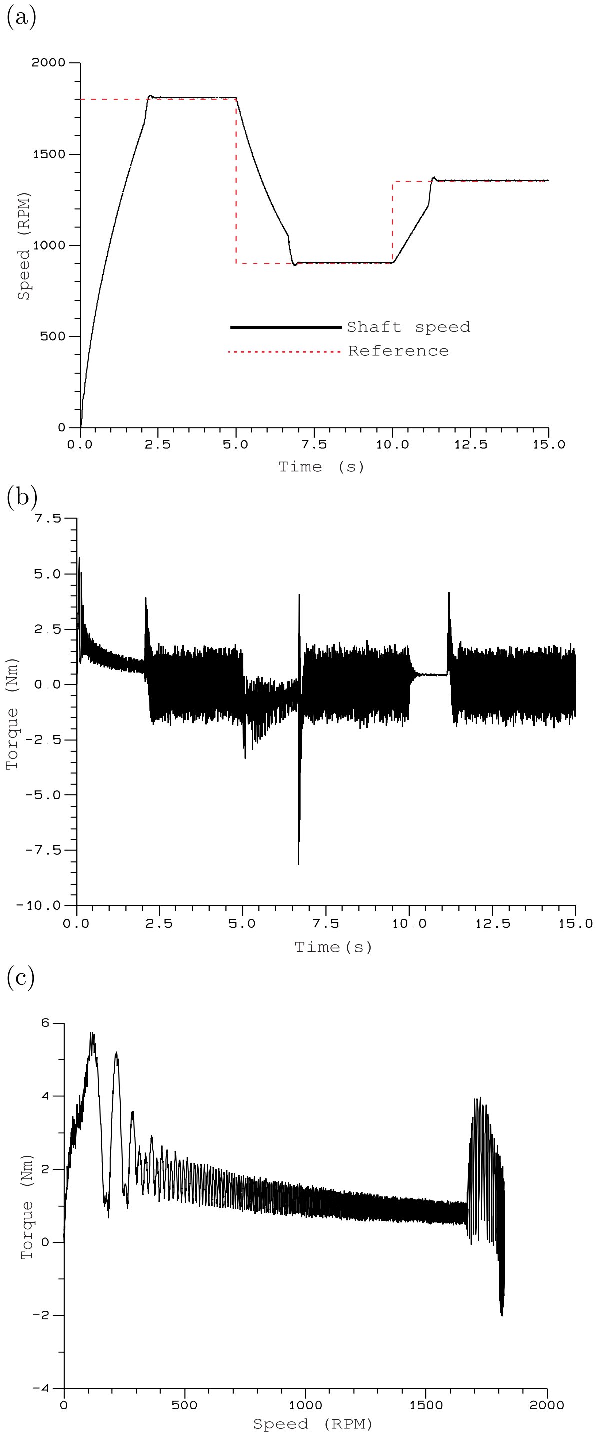

Fig. 5. Dynamic responses: (a) Speed rotor.(b) Electromagnetic torque. (c) Speed-torque during start-up.

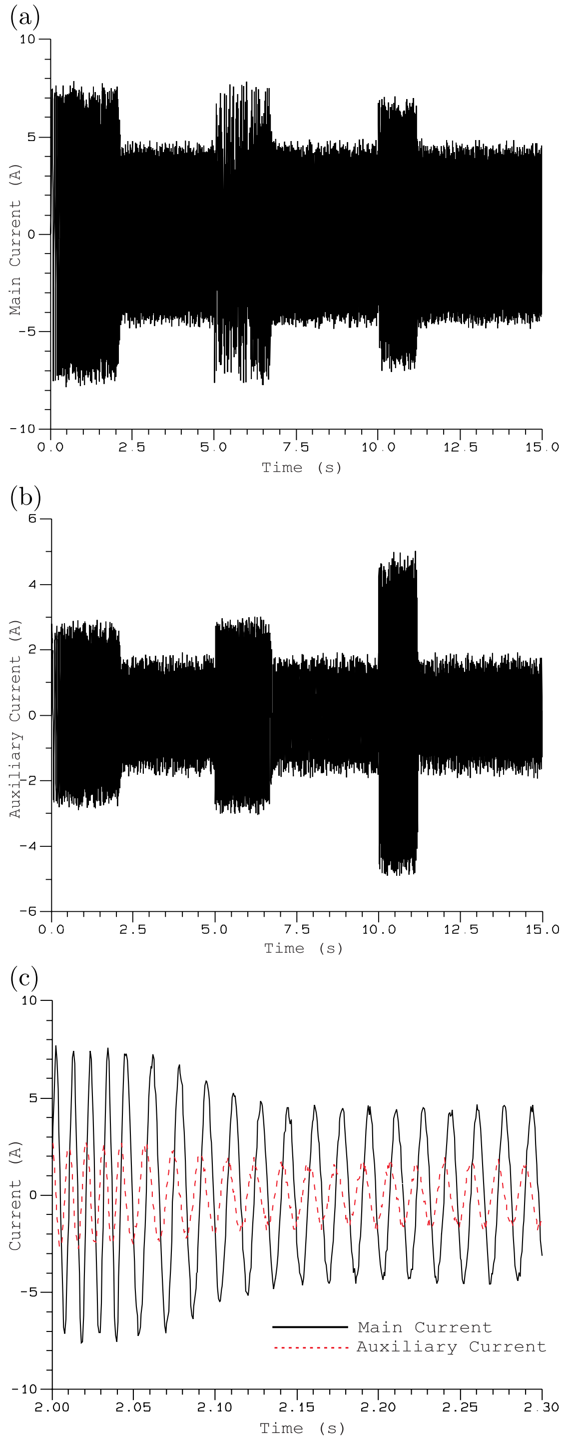

Fig. 6. Dynamic responses:(a) Main current. (b) Auxiliary current. (c) Current details.

nal to feed the signal processor. The speed sensor requirement can become a great problem for a low-cost implementation of proposed scheme. This sensors are very expensives an its use in any SPIM applications, such as hermetic compressors, may not be a possibility due to mechanical restrictions. However, it is possible to eliminate the speed sensor using a speed estimative, obtained from voltage, currents and frequency measurements [9] or using the anisotropic properties of the machine rotor [10]. A sensorless speed control is a emerging technology which can be utilized in SPIM applications.

VIII. Conclusions

This paper presents a strategy to control the speed rotation of SPIMs. The objective is to assure a fixed level of magnetization and provide an efficient operation at variable speed. The proposed control scheme presents a good robustness to parametric variations on SPIM. The simulation results shown a satisfatory performance of the proposed strategy. Comments for practical implementation are presented. Thus, it may represent a good option to speed control in variable-speed drives for SPIMs. Since higher efficiency operation could be achieved reducing air-gap flux, an interesting option is to use a variable parameter to improve the drive performance.

IX. Acknowledgments

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