Speed Regulation with Power Factor Correction of Synchronous Motors Including AC/DC/AC Converters

A. El magri*, F. Giri, A. Abouloifa, I. Lachkar, F.Z. Chaoui

GREYC, University of Caen, 14032 Caen France
*Corresponding author (e-mail: magri_mounaim@yahoo.fr)

Abstract: we are considering the problem of controlling synchronous motors driven through AC/DC rectifiers and DC/AC inverters. The control objectives are threefold: (i) forcing the motor speed to track a reference signal, (ii) regulating the DC Link voltage, (iii) enforcing power factor correction (PFC) with respect to the power supply net. First, a nonlinear model of the whole controlled system is developed in the Park-coordinates. Then, a nonlinear multi-loop controller is synthesized using the backstepping design technique. A formal analysis based on Lyapunov stability and average theory is developed to describe the control system performances. In addition to closed-loop global asymptotic stability, it is proved that all control objectives (motor speed tracking, DC link voltage regulation, and unitary power factor) are asymptotically achieved up to small harmonic errors (ripples). The harmonic errors amplitudes depend on the supply power net frequency: the larger the power net frequency the smaller the error amplitudes. The above results are confirmed by simulations which, besides, show that the proposed regulator is quite robust with respect to uncertain changes of load torque.

Keywords: Control system analysis, Nonlinear control systems, Synchronous motors, AC/DC/AC converters.

1. INTRODUCTION

Permanent magnet synchronous (PMS) motors are more suitable for electric traction compared with induction motors. Indeed, they possess a better mass/power ratio, develop a much higher power level and present a more satisfactory efficiency. The spectacular development of power electronics technology, over the last recent years, has resulted in reliable power electronic converters which make it possible to drive synchronous machines in varying speed mode. Indeed, speed variation can only be achieved for these machines by acting on the supply net frequency. Until the recent development of modern power electronics, there was no effective solution to AC machine speed control because there was no simple way to vary the net frequency. On the other hand, in the electric traction domain, the used power nets are either DC or AC but mono-phase. Therefore, three-phase DC/AC inverters turn out to be the only possible interface (between railway nets and 3-phase AC motors) due to their important capability to ensure a flexible voltage and frequency variation.

As mentioned above, a three-phase DC/AC inverter used in traction is supplied by a power net that can be either DC or mono-phase AC. In the case of AC supply, the (mono-phase) net is connected to the three-phase DC/AC inverter through a transformer and AC/DC rectifier (Fig 1). The connection line between the rectifier and the inverter is called DC link.

The system consisting of the AC/DC converter, the DC/AD inverter and the PMS motor has to be controlled to achieve varying speed reference tracking. The point is that such system behaves as a nonlinear load vis-à-vis to the AC supply line. Then, undesirable current harmonics are likely to be generated in the AC line. These harmonics reduce the rectifier efficiency, induce voltage distortion in the AC supply line and cause electromagnetic compatibility problems. The pollution caused by the converter may be reduced resorting to additional protection equipments (transformers, condensers…) and/or over-dimensioning the converter and net elements. However, this solution is costly and may not be sufficient. To overcome this drawback, the control problem (concerning the system including AC/DC converter, DC/AD inverter and PMS motor) must have as objective not only motor speed control but also rejection of current harmonics. The last objective is referred to power factor correction (PFC), (Singh B et al, 2006).

Previous works on synchronous machine speed control simplified the control problem neglecting the dynamics of the AC/DC rectifier and so making the focus only on the set ‘DC/AC inverter - Motor’. A wide range of control solutions have thus been proposed. These involved as well simple techniques such as field-oriented control (FOC) (Saleh et al, 2004) and sophisticated nonlinear techniques such as feedback linearization (FL) (Kuroe Y et al, 1988), direct torque control (DTC) (Pyrhonen,O et al, 1998) or sliding mode (SM) (Yang Z.P et al, 1992). Ignoring the AC/DC rectifier in the development of a control strategy, is criticized at least from two viewpoints. First, such development relies on the assumption that the DC voltage provided by the AC/DC rectifier is perfectly regulated. The problem is that a perfect regulation of the rectifier output voltage can not be met ignoring the rectifier load which is nothing other than the set ‘DC/AC inverter - Motor’. The second drawback of the previous control strategy lies in the entire negligence of the PFC requirement.

In the present work, we are developing a new multiloop control strategy that deals simultaneously with both controlled subsystems: the AC/DC converter and the combination ‘DC/AC inverter - Motor’. The main feature of our control design is threefold:

i. A current loop is first designed so that the coupling between the power supply net and the AC/DC rectifier operates with a unitary power factor;

ii. A second loop is designed to regulate the output voltage of AC/DC rectifier so that the DC link between the rectifier and inverter operates with a constant voltage despite changes of the motor operation conditions;

iii. A bi-variable loop is designed to enforce the motor velocity to track its varying reference value and to regulate the d-component of stator current to zero in order to optimize the absorbed stator current.

All loops are designed using the backstepping technique and Lyapunov design, (Krstic M et al, 1995). A theoretical analysis will prove that the four-loop controller thus described actually stabilizes (globally and asymptotically) the controlled system and does achieve its tracking objectives with a good accuracy. More precisely, it is shown that the steady-state tracking errors corresponding to rectifier input current and rectifier output voltage, motor speed and stator current d-component are harmonic signals and their amplitudes depend on the supply net frequency: the larger the net frequency the smaller the error amplitudes. It follows in particular that the motor regulation objective and the PFC requirement are actually ensured, up to harmonic errors of insignificant amplitude, provided the net frequency is large enough. This formally establishes the existence of the so-called ripples, which are usually observed in similar practical applications, and proves why this phenomenon is generally insignificant. These theoretical results are obtained making a suitable use of different automatic control tools e.g. averaging theory and Lyapunov stability (Khalil H, 2002).

The paper is organized as follows: the controlled system (including the AC/DC/AC converter and the synchronous motor) is modeled and given a state space representation; the control objectives in Section 2; the controller design and the closed-loop system analysis are presented in Section 3; the controller performances and robustness are illustrated Section 4 through numerical simulations; a conclusion and a reference list end the paper. To alleviate the paper presentation, a list of notations is given hereafter.

Notation list

L	*stator winding inductance*
R	*resistance of the stator windings*
i_d, i_a .	*d- and q- axis currents*
v_d, v_a	*d- and q- axis voltages*
ω	*angular velocity of the rotor*
p	*number of pole pairs*
T_L	*load torque*
J	*combined inertia of rotor and load*
f	*combined viscous friction of rotor and load*
K_M	*flux motor constant*

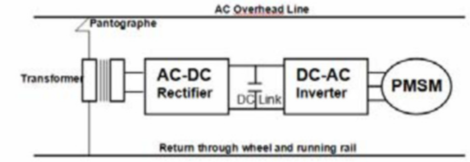

Fig.1. Schematic representation of single phase AC supply powering 3-phase AC motor

2. Modeling the association AC/DC/AC converter-Synchronous motor

The controlled system is illustrated by Fig 2. It includes an AC/DC boost rectifier, on one hand, and a combination ‘DC/AC converter-synchronous’ motor on the other hand. The circuit operates according to the well known Pulse Width Modulation (PWM) principle.

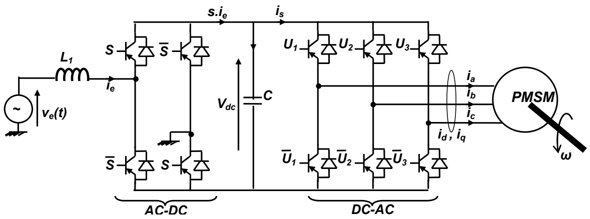

Fig.2. AC/DC/AC drive circuit with three-level inverter

1.1 Modeling the PMW AC/DC Rectifier

The transformer secondary is connected to a H-bridge converter which consists of four IGBT’s with anti-parallel diodes for bidirectional power flow arrangement. This has the following advantages:

- it provides constant DC link voltage
- it offers power factor near unity
- the THD of AC mains current is very low.

This subsystem is described by the following set of differential equations:

$$\frac{di_e}{dt} = \frac{v_e}{L_1} - \frac{1}{L_1} s\, v_{dc} \qquad (1a)$$

$$\frac{dv_{dc}}{dt} = \frac{1}{C} s\, i_e - \frac{1}{C} i_s \qquad (1b)$$

where i_e is the current in inductor L_1, v_{dc} denotes the voltage in capacitor C, i_s designates the input current inverter, v_e is the supply net sinusoidal voltage ($v_e = \sqrt{2}.E.\cos(\omega_e t)$) and s is the switch position function taking values in the discrete set $\{-1, 1\}$. Specifically:

$$s = \begin{cases} 1 \ \text{ if } S \text{ is } ON \text{ and } \overline{S} \text{ is } OFF \\ -1 \ \text{ if } S \text{ is } OFF \text{ and } \overline{S} \text{ is } ON \end{cases}$$

As a matter of fact, existing nonlinear control approaches apply to systems with continuous control inputs. Therefore, control design for the above inverter will be based upon the following average version of (1a-b):

$$\frac{dx_1}{dt} = \frac{v_e}{L_1} - \frac{1}{L_1} u_1\, x_2 \qquad (2a)$$

$$\frac{dx_2}{dt} = \frac{1}{C} u_1\, x_1 - \frac{1}{C} \bar{i}_s \qquad (2b)$$