Sliding-Mode Controls Applied to Induction Machine Fed by Three - Level Inverter

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Abstract. In this paper, the design of a speed control scheme based on sliding mode control for indirect field oriented of a three phase induction motor (IM) fed by three-level inverter is proposed. This type of inverter presents an important novelty in the field of energy control with high voltage and power, and has the advantages of fewer harmonics in the output and low torque ripples. Sliding mode control design is investigated to achieve a speed tracking objective under different load torque disturbance and to make the system more performing and more robust.

Keywords: Sliding mode · Inverter · PI controller · Induction machine
NPC

1 Introduction

Induction motors (IM) have been widely used in industry for variable speed applications due to their inherent advantages such as simplicity of design, reliability, low cost of maintenance, high efficiency and they have become the subject of several researches [1, 2]. PI control have been used, together with vector control methods, for speed control of induction machines, but may be insufficient for nonlinear systems because they are not robust especially when requirements such as precision and other dynamic characteristics of the system are strict [3, 4].

Many robust controls have been proposed in the technical literature. Among them, the variable structure control sliding mode. This control has largely proven its effectiveness through the theoretical studies reported; main fields of application are robotics and electric motors. It is a robust control because the high-gain feedback control input cancels nonlinearities, uncertainty parameters, and external disturbances. [5–7]. Sliding mode control (SMC). Is one of the prospective control methodologies for electrical machines [8, 9]. This is due to its order reduction, disturbance rejection and strong robustness properties, along with its simple implementation by means of power converters; Sliding mode control is a type of variable structure scheme, i.e. one which involves switching between controllers. In general, the design of variable structure controllers consists of two steps, namely the reaching and sliding phases [10, 11]. First, the system is directed towards a switching surface by a feedback control law.

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A switching term is then used to maintain the sliding mode, during which the dynamics of the system are determined by the choice of sliding surface. The sliding mode is relatively independent of parametric uncertainties and load disturbances. SMC has been employed for position and speed control of AC machines. However, the discontinuous nature of the switching feature of SMC causes chattering in the control system [11, 12].

In this paper, a sliding mode controller based on indirect field orientation is proposed for IM speed control. The proposed controller is applied to achieve speed control under disturbances of load torque. The mathematical model of the induction machine is developed and presented in Sect. 2. The following section shows the modeling of an NPC multilevel inverter, Sect. 4 illustrates the development of a PI controller and the application of this induction machine. And the sliding mode controller design for induction machine is given in Sect. 5.

Section 6 shows the simulation results' using Matlab, Simulink, and the conclusion is drawn in Sect. 7.

2 Mathematical Model of the Induction Machine

In order to lighten the mathematical notations, the indices s, r will be used to designate the stator and rotor respectively, while d and q will represent the direct and quadrature axes. In steady state, the electrical equations of an IM expressed in a stator reference are [7]:

2.1 Electrical Equations

$$\begin{cases} v_{ds} = R_s.i_{ds} - \dot{\theta}_s.\varphi_{qs} + \dfrac{d\varphi_{ds}}{dt} \\ v_{qs} = R_s.i_{qs} + \dot{\theta}_s.\varphi_{ds} + \dfrac{d\varphi_{qs}}{dt} \\ v_{dr} = 0 = R_r.i_{dr} - \dot{\theta}_r.\varphi_{qr} + \dfrac{d\varphi_{dr}}{dt} \\ v_{qr} = 0 = R_r.i_{qr} + \dot{\theta}_r.\varphi_{dr} + \dfrac{d\varphi_{qr}}{dt} \end{cases} \tag{1}$$

$$\begin{cases} \varphi_{ds} = L_s.i_{ds} + M.i_{dr} \\ \varphi_{qs} = L_s.i_{qs} + M.i_{qr} \\ \varphi_{dr} = M.i_{ds} + L_r.i_{dr} \\ \varphi_{qr} = M.i_{qs} + L_r.i_{qr} \end{cases} \tag{2}$$

2.2 Mechanical Equation

$$c_e = \frac{3}{2}.p.\frac{M}{L_r}.\left(\varphi_{dr}.i_{qs} - \varphi_{qr}.i_{ds}\right) \tag{3}$$

3 Modeling of a NPC Three-Level Inverter

Multilevel converters have recently increased interest in the research and industry communities [3, 7]. In these kinds of converters, the output voltage can take several discrete levels of equal magnitude. The multilevel converter was aimed at reducing the harmonics content of generated voltage or current waveforms. The harmonics content of such a waveform is greatly reduced compared to a two-level waveform.

The structure of a multilevel inverter makes it possible to synthesize a sinusoidal signal, starting from several levels of tension, the larger the number of levels, the closer the output voltage is to sinusoidal with a minimum of distortion of harmonics. The connection function F_{ki} defines the state of each switch, where k is the arm number and i is the switch number. In the controllable mode, the connection functions of the inverter are linked by [16]:

$$\begin{cases} F_{k1} = 1 - F_{k4} \\ F_{k2} = 1 - F_{k3} \end{cases} \tag{4}$$

The half-arm connection function is defined as follows:

$$\begin{aligned} F^b_{k1} &= F_{k1}F_{k2} \\ F^b_{k0} &= F_{k3}F_{k4} \end{aligned} \tag{5}$$

The potentials of the nodes A, B, C with respect to the mid-points M of the three-phase - inverter are expressed by:

$$\begin{cases} V_{AM} = F^b_{11}U_{c1} - F^b_{10}U_{c2} \\ V_{BM} = F^b_{21}U_{c1} - F^b_{20}U_{c2} \\ V_{CM} = F^b_{31}U_{c1} - F^b_{30}U_{c2} \end{cases} \tag{6}$$

The simple output voltages of the inverter are deduced as a function of the potentials of the nodes with respect to the midpoint by the following relation:

$$\begin{cases} V_A = (2V_{AM} - V_{BM} - V_{CM})/3 \\ V_B = (2V_{BM} - V_{CM} - V_{AM})/3 \\ V_C = (2V_{CM} - V_{AM} - V_{BM})/3 \end{cases} \tag{7}$$

This makes it possible to express the simple voltages by using the functions of connections of the half arms by:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} . \left\{ \begin{bmatrix} F_{11}^b \\ F_{21}^b \\ F_{31}^b \end{bmatrix} U_{c1} - \begin{bmatrix} F_{10}^b \\ F_{20}^b \\ F_{30}^b \end{bmatrix} U_{c2} \right\} \tag{8}$$

4 PI Controller Design to Increase the Speed of an Induction Machine

The speed controller determines the reference torque in order to maintain the corresponding speed. For the cascade to be justified, it is necessary that the loop intern be very fast compared to speed of an induction machine.

The mechanical equation gives:

$$\frac{\omega}{C_{em}} = \frac{P}{f_c + J.s} \tag{9}$$

The block diagram of speed control is therefore carried out as indicated in Fig. 1.

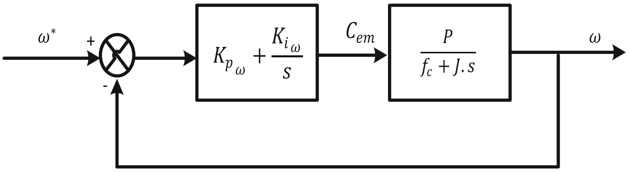

Fig. 1. Block diagram of the speed control.

The closed loop transfer function is given by:

$$\frac{\omega}{\omega^*} = \frac{\left(k_{p\omega}.s + k_{i\omega}\right)\frac{P}{J}}{\rho(s)} \tag{10}$$

The characteristic equation $\rho(s)$ is:

$$\rho(s) = s^2 + \frac{f_c + k_{p\omega}.P}{J}.s + \frac{k_{i\omega}.P}{J} = 0 \tag{11}$$

By imposing two complex conjugated poles $s_{1,2} = -\rho \pm j.\rho$ in closed loop and by identification, the parameters of the regulator PI are obtained as follows:

$$\begin{aligned} k_{i\omega} &= \frac{2.J.\rho^2}{P} \\ k_{p\omega} &= \frac{2.\rho.J - f_c}{P} \end{aligned} \tag{12}$$

5 Sliding Mode Controller

Variable structure control (VSC) with sliding mode, or sliding-mode control (SMC) is one of the most effective nonlinear robust control approaches, because it provides system dynamics with an invariance property to uncertainties once the system dynamics is controlled in the sliding mode [11–13]. The first step of a SMC design is to select a sliding surface that models the desired closed-loop performance in state variable space. Then the control is designed such that the system state trajectories are forced toward the sliding surface and stay on it. The system state trajectory in the period of time before reaching the sliding surface is called the reaching phase. Once the system trajectory reaches the sliding surface, it stays on it and slides along it to the origin. The system trajectory sliding along the sliding surface to the origin is called the sliding mode. The insensitivity of the controlled system to uncertainties exists in the sliding mode, but not during the reaching phase. Thus, the system dynamic in the reaching phase is still influenced by uncertainties [8, 12].

Without loss of generality, the design of a sliding mode controller is considered for the following second order system: $\ddot{x} + a_1\dot{x} + a_2 x = b.u$, where u(t) is the input to the system and we assume that $b > 0$. A possible choice of the structure of a sliding mode controller is: [9, 11].

$$u = u_{eq} + k.\text{sgn}(s) \tag{13}$$

Where u_{eq} is called equivalent control, which dictates the motion of the state trajectory along the sliding surface [11]; k is a constant, representing the maximum controller output required to overcome parameter uncertainties and disturbances; s is called the switching function because the control action switches its sign on the two sides of the switching surface $s = 0$. For a second order system, s is defined as: [8]

$$s = \dot{e} + \lambda.e \tag{14}$$

Where $e = x_d - x$ and x_d is the desired state; λ is a constant, and sgn(s) is the signum function, which is defined as:

$$\text{sgn}(s) = \begin{cases} -1 & s < 0 \\ 1 & s > 0 \end{cases} \tag{15}$$

The design of sliding mode controllers mainly requires three steps [16–19], namely:

- The choice of the sliding surface
- The condition of convergence
- The calculation of control law

5.1 Choice of the Sliding Surface

The switching function is a scalar function, such as the variable to be adjusted to the slides on this surface to reach the origin of the phase plane. A general equation has been proposed to determine the sliding surface, which ensures the convergence of a variable to its desired value defined as follows [19]:

$$S(x) = \mathrm{e}(x) + \lambda_1 . \frac{d}{dt} . e(x) + \ldots + \lambda_m . \frac{d^m}{dt^m} . e(x) \qquad (16)$$

With: $\mathrm{e(x)} = \omega_s^* - \omega_s$
$\lambda_i (i = 1, 2, \ldots, m)$ Is a positive constant, interpreting the control bandwidth desired and m is a relative degree, equal to the number of times to derive the output for command display.

5.2 Condition of Convergence

This is the mode in which the variable to be adjusted moves from any point in the phase plane and tends towards the switching surface $S(x) = 0$.

This mode is characterized by the control law and the convergence criterion. In this paper, the direct switching function is proposed by Emilianov and Utkin [19], can be formulated by the following sufficient condition:

$$S(x).\dot{S}(x) < 0 \qquad (17)$$

5.3 Calculation of Control Law

Once the selected slip surface and the convergence criterion are satisfied, the necessary condition are determined to bring the variable to be controlled to the sliding surface and then to its equilibrium point.

In the VSC theory, there are different ways of choosing the parameters to define switching logic; in the literature there are three types of widespread structures: linear feedback control with switched gain, relay, and equivalent control. In the latter, two approaches are preferred in the control of induction machines because they are more appropriate.

In this case, the method chosen is that of the equivalent command, so we have:

$$u = u_{eq} + u_n \qquad (18)$$

u_{eq} is determined from the convergence condition.

u_n is calculated to ensure the attractiveness of the state variable to be controlled to the switching surface.

Definition of the Speed Control Surface
The structure includes a speed control loop which imposes the control Cemref with slip surface deduced on the basis of the concepts of the reference and is given by [19]:

$$e(\omega) = \omega_{ref} - \omega_r \tag{19}$$

$$s(\omega) = \lambda.e(\omega) + \dot{e}(\omega) \tag{20}$$

$$s(\omega) = \lambda(\omega_{ref} - \omega_r) + (\dot{\omega}_{ref} - \dot{\omega}_r) \tag{21}$$

Considering that the condition of the sliding regime $s(\omega)$ is zero, one obtains the equivalent control law:

$$c_{emeq} = f.\omega_r + c_r \tag{22}$$

During the convergence mode and in order to satisfy the condition $S(x).\dot{S}(x) < 0$, the following equation is adopted:

$$c_{emeq} = k.sat(s(\omega)) \tag{23}$$

This gives us the reference control at the output of the c_{emref} controller for speed control.

$$c_{emref} = f.\omega_r + c_r + k.sat(s(\omega)) \tag{24}$$

6 Simulation Results

In order to evaluate the performance of the indirect speed vector control with adjustment by a PI regulator and a sliding mode regulator, we performed numerical simulations under the following conditions:

- Speed set point change from 200 to −200 rad/s at the instant 3 s
- Variation of the mechanical load from 0 to −10 Nm between times 1 and 2 s.

Figure 2 shows the IM speed setting by the indirect vector control adjustment by a PI regulator, with load variation, supplied with a three-level inverter voltage.

Figure 3 shows measured speed and speed reference of the PI regulator.

The results show that the use of the decoupled model gives satisfactory results:

- The speed of rotation follows the reference speed with an excess of 7.20 rad/s.
- Control ensures good regulation with disturbance rejection of 13 rad/s.
- A response time of 0.3 ms to reach the balanced state.

Figure 4 shows the IM speed setting by the indirect vector control adjustment via a sliding mode regulator, with load variation, supplied with a three-level inverter voltage.

Figure 5 shows measured speed and speed reference of the sliding mode regulator.

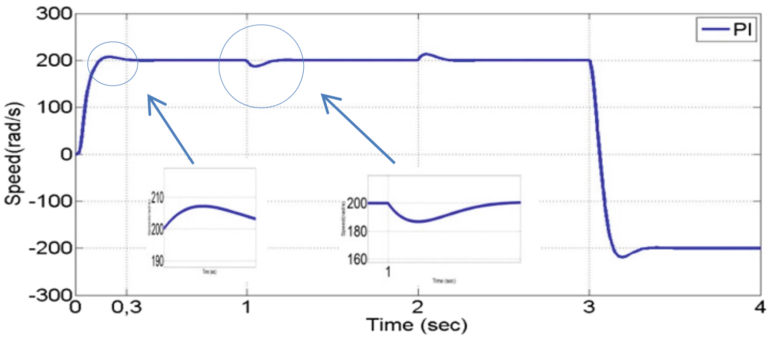

Fig. 2. Speed of IM with PI controller

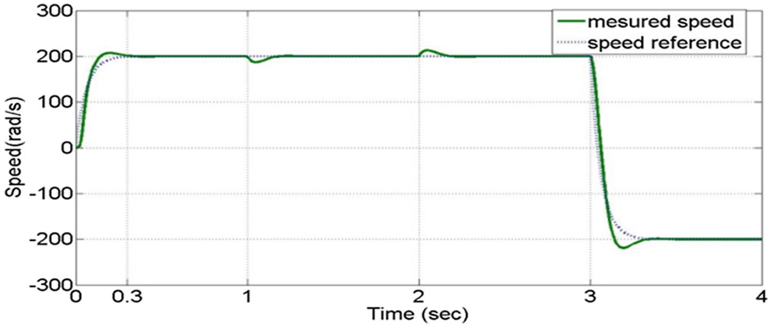

Fig. 3. Measured speed and speed reference of PI

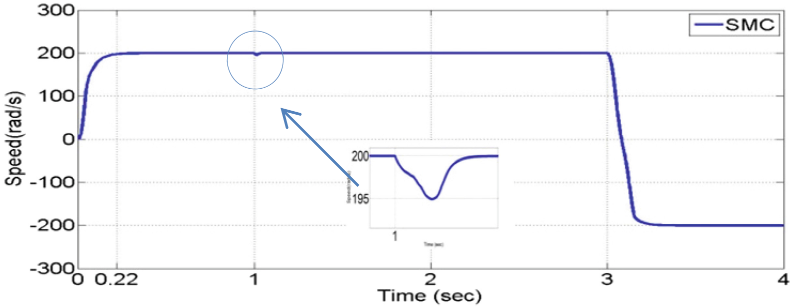

Fig. 4. Speed of IM with SMC controller

Figure 6 shows the difference between the PI regulator and the sliding mode regulator.

The results show that regulation using a Sliding mode regulator gives satisfactory results:

- The speed of rotation follows the reference speed without excess.

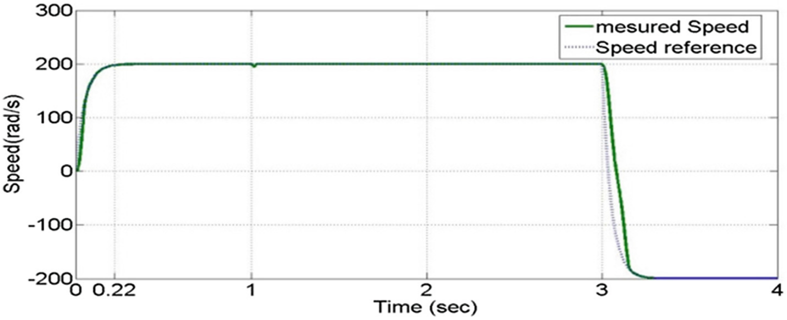

Fig. 5. Measured speed and speed reference of SMC

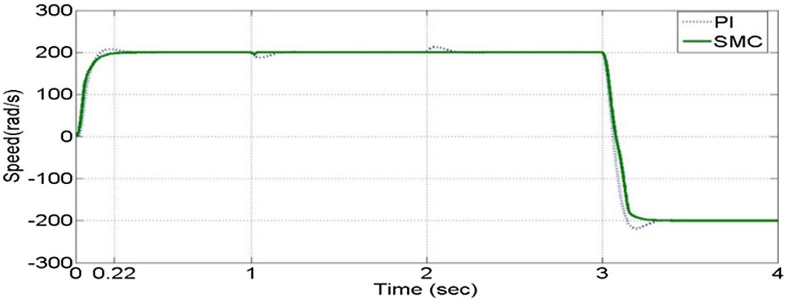

Fig. 6. Difference between the PI and SMC

- The control ensures good regulation with disturbance rejection of 5 rad/s.
- A response time of 0.22 ms is needed to reach the balanced state.

7 Conclusion

In this paper, the PI and SMC have been tested in simulation; the sliding mode is a controller for nonlinear systems with non-constant parameters; it leads to precision and robustness, and allows solving problems caused by PI controller. The simulation results indicate that the sliding mode control gives better results compared to the PI regulator.

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