

Design of Sliding Mode Observer Based Controller of Single-Phase Induction Motor

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To Cite this Article

P. D.V. Seshasai, Ch. V. N. Raja and G. Anand, "Design of Sliding Mode Observer Based Controller of Single-Phase Induction Motor", *International Journal for Modern Trends in Science and Technology*, 6(9): 119-124, 2020.

Article Info

Received on 16-August-2020, Revised on 30-August-2020, Accepted on 06-September-2020, Published on 12-September-2020.

ABSTRACT

Single-phase induction motors are simple in construction, cheap in cost, reliable and easy to repair and maintain. Many controllers were designed to control the speed of a single-phase induction motor, but they are sensitive to plant parameter variations and disturbances. Speed control with very less transient response requires non-linear and robust control methods. Sliding mode control is one of the robust control techniques which is insensitive to disturbances. Here we propose a higher order sliding mode (SM) observer-based controller for a single-phase induction motor. The applied control depends on the dynamic model of the induction motor. The controller is structured by applying a blend of input linearization strategy and higher order sliding mode calculation with consistent estimation of rotor speed and stator currents, which limits the vulnerabilities continuously and lessen the chattering phenomenon in the control effort exertion utilizing a super twisting algorithm.

KEYWORDS: Single phase induction motor (SPIM), sliding mode (SM) control, feedback linearization technique, super twisting algorithm.

I. INTRODUCTION

Single-phase induction motors (SPIM) are generally manufactured in fractional kilowatt range and are generally utilized in numerous domestic applications like compressors, pumps, portable drills, hair dryers, refrigerators, washers, and other equipments, which need low-power motors. These motors are fundamentally powered directly from a viable establishment and are sometimes run in open loop configuration. Speed control of the motor with very less dynamic response requires non-linear and robust control methods. One such method is the sliding mode control.

In control systems, sliding mode control is a nonlinear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to slide along a cross section of the system's normal behaviour. The advantage of sliding mode control is that it is less effected to plant and parameter variations. First order sliding mode (SMC-1) is the basic sliding mode control technique applied, but it has a disadvantage of chattering phenomenon. So, we are moving to higher order sliding mode i.e. second order sliding mode control to avoid the chattering phenomenon.

II. LITERATURE SURVEY

V.I. Utkin [1] and Ch. V.N. Raja [20] discussed about the design and analysis of variable structure control systems. C. Edwards, S.K. Spurgeon [2] discussed about the development of a robust control called sliding mode control methodology, a variable structure control and is characterised by a set of feedback control laws and a decision rule. V.I. Utkin [3] discussed the basic concepts, mathematics, and design aspects of variable-structure systems with sliding modes as a principle operation mode. V.I. Utkin et.al [4] proposed a novel sliding mode control method for mechanical systems with electric motors as actuators in such a way it is impervious to plant variations and uncertainties. A. Levant [5] introduced a new class of sliding modes and the concept of sliding mode order.

To estimate the speed, torque, flux, currents we have observers. Different types of observers have been proposed in the literature. Z. Yan and V. I. Utkin [6] presented the review and synopsis of the main approaches used in the sliding mode observer design for electric machines. Y. Feng et.al [7] proposed a non-singular terminal sliding-mode observer for estimating the rotor flux of induction motors. W. Hammuoda et.al [8] proposed a second order sliding mode observer for induction motor. N. Zaidi et.al [9] implemented a second order sliding mode observer for a single-phase induction motor in real time using DSP.

J. Davila et.al [10] proposed the design of velocity observer for uncertain mechanical systems by modifying super-twisting second-order sliding-mode algorithm. R. Marino et.al [11] presented a new estimation algorithm which provides exponential estimation of rotor resistance for induction motor drives in physical operating conditions and may be used as an adaptive observer. T. Floquet et.al [12] proposed a new nonlinear sliding mode observer for induction motors.

A. Levant [13] demonstrated a robust homogeneous differentiator in the control structure which will make the design and investigation of new higher order sliding mode controllers easier with finite-time convergence. Z. Zhao et.al [14] presented a sensorless current-based output feedback sliding mode control for induction motors. A.G. Loukianov et.al [15] presented two sliding mode control algorithms for the (α, β) model

of induction motors using block control linearization technique.

A. Loukianov [16] presented the problems involved in designing sliding mode manifold for uncertain nonlinear system. G. Bartolini et.al [17] proposed a control algorithm which does not require any observer and differential inequalities to evaluate the change of the sign of the derivative of the quantity accounting for the distance to the sliding manifold to abstain from chattering. A. Levant [18] proposed a universal finite-time-convergent controller to control the output of any uncertain SISO system. A. Estrada and L. Fridman [19] presented a new design algorithm based on the block control and quasi-continuous higher order sliding modes techniques. Ch.V.N. Raja and Narendra Kumar Dandu [20] proposed the design of induction machine and detuning of rotor parameters and their effects due to different values of constraints like air gap length (δ) and current density. Ch. V. N. Raja and K. Mohan [21] discussed about speed control technique of an induction motor using DTC strategy to improve the performance characteristics, the speed controller gains are tuned by means of Genetic Algorithm (GA).

III. PROPOSED SYSTEM

The block diagram of the proposed system is shown in Fig 1. consists of a PWM Inverter, single-phase induction motor, rotor speed and stator currents sliding mode observer, flux estimation, block control technique, sliding mode algorithm, rotor flux control. The PWM inverter is given gate pulses which triggers the induction motor and the sliding mode observer calculates the estimates of the rotor speed and stator currents. Then we design a sliding mode controller which involves design of a sliding manifold in conjunction with block control technique to ensure zero error dynamics.

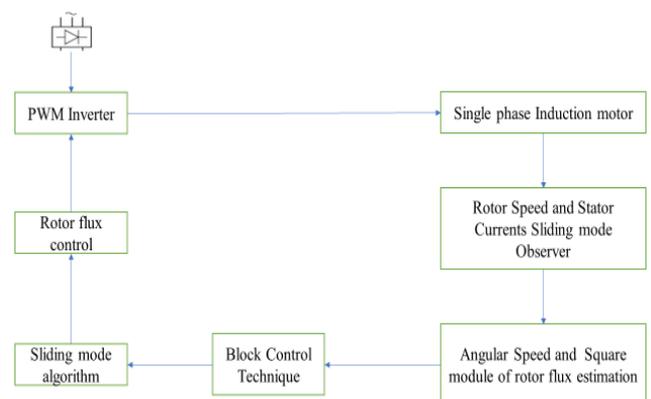


Fig.1 : Block diagram of proposed system

IV. MATHEMATICAL MODELLING

The dynamic model of the single-phase induction motor [21] is often considered as the transformed model of an unsymmetrical two phase (ab) machine into stationary frame ($\alpha\beta$). The single-phase induction motor with stator currents and rotor flux is shown in Fig. 2 and the equations are given by

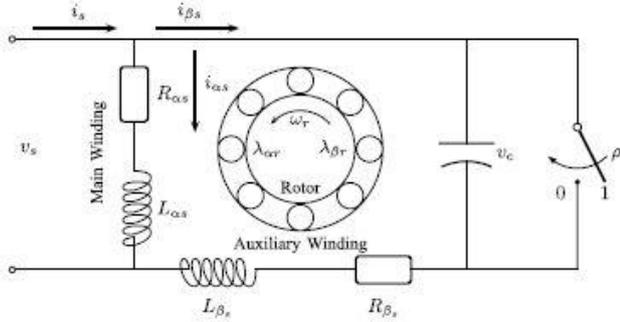


Fig. 2: Single phase induction motor

$$\begin{aligned} \frac{di_{as}}{dt} &= -a_1 c_{10} i_{as} + a_1 a_{40} \lambda_{ar} - a_1 a_3 n_p \omega_r \lambda_{\beta r} \\ &\quad + a_1 v_{as} + \Delta_{as} \\ \frac{di_{\beta s}}{dt} &= -a_2 c_{20} i_{\beta s} + a_2 a_{40} \lambda_{\beta r} + a_2 a_3 n_p \omega_r \lambda_{ar} \\ &\quad + a_2 v_{\beta s} + \Delta_{\beta s} \\ \frac{d\lambda_{ar}}{dt} &= -c_{30} \lambda_{ar} + n_p \omega_r \lambda_{\beta r} + c_{40} i_{as} + \Delta_{ar} \\ \frac{d\lambda_{\beta r}}{dt} &= -n_p \omega_r \lambda_{ar} - c_{30} \lambda_{\beta r} + c_{40} i_{\beta s} + \Delta_{\beta r} \\ \frac{d\omega_r}{dt} &= p_1 p_2 (\lambda_{\beta r} i_{as} - \lambda_{ar} i_{\beta s}) p_2 T_L \end{aligned} \quad (1)$$

Considering the variations in rotor resistance of the form

$$R_r(t) = R_0(t) + \Delta R_r(t)$$

with $\Delta R_r(t)$ an obscure but constrained function of time, prompting to a lot of dubious model parameters

$$\begin{aligned} c_1(t) &= c_{10} + \Delta c_1(t) \\ c_2(t) &= c_{20} + \Delta c_2(t) \\ c_3(t) &= c_{30} + \Delta c_3(t) \\ c_4(t) &= c_{40} + \Delta c_4(t) \\ a_4(t) &= a_{40} + \Delta a_4(t) \end{aligned}$$

where

$$c_{10} = R_{as} + (L_m^2/L_r^2)R_0, c_{20} = R_{\beta s} + (L_m^2/L_r^2)R_0$$

$c_{30} = (1/L_r)R_0, c_{40} = (L_m/L_r)R_0, a_{40} = (L_m/L_r^2)R_0$ are the boundary ostensible values.

The anomalies in the parameters are given by $\Delta c_1(t) = \Delta c_2(t) = (L_m^2/L_r^2) \Delta R_r(t), \Delta c_3(t) = (1/L_r) \Delta R_0(t), \Delta c_4(t) = (L_m/L_r) \Delta R_0(t), \Delta a_4(t) = (L_m/L_r^2)R_0(t)$.

While the model boundaries, which don't rely upon the variations in the resistance are given by

$$a_1 = L_r / (L_{as}L_r - L_m^2), a_2 = L_r / (L_{\beta s}L_r - L_m^2), a_3 = L_m/L_r, p_1 = (L_m/L_r)n_p, \text{ and } p_2 = 1/J.$$

The unidentified terms in (1) are given by

$$\begin{aligned} \Delta_{as} &= \Delta a_4(t) a_1 \lambda_{ar} - \Delta c_1(t) a_1 i_{as} \\ \Delta_{\beta s} &= \Delta a_4(t) a_2 \lambda_{\beta r} - \Delta c_2(t) a_2 i_{\beta s} \\ \Delta_{ar} &= -\Delta c_3(t) \lambda_{ar} + \Delta c_4(t) i_{as} \\ \Delta_{\beta r} &= -\Delta c_3(t) \lambda_{\beta r} + \Delta c_4(t) i_{\beta s} \end{aligned}$$

The capacitor dynamics are given by

$$\frac{dv_c}{dt} = \omega_0 X_c i_{\beta s}$$

where X_c is the capacitive reactance and $\omega_0 = 2\pi f$, and f is the fundamental frequency.

V. SLIDING MODE OBSERVER DESIGN

By using the rotor speed ω_r and stator currents a second order sliding mode observer is intended to assess the rotor flux.

By using the following transformation, let

$$\lambda_{ar}^* = \lambda_{ar} - k_1 i_{as}, \lambda_{\beta r}^* = \lambda_{\beta r} - k_2 i_{\beta s} \quad (2)$$

where k_1, k_2 are the transformation gains

Utilizing (2), (1) is represented using the transformed variables

$$\begin{aligned} \frac{di_{as}}{dt} &= -q_{11} i_{as} - q_{12} n_p \omega_r i_{\beta s} - p_3 n_p \omega_r \lambda_{\beta r}^* + p_4 \lambda_{ar}^* \\ &\quad + a_1 v_{as} + \Delta_{as} \end{aligned}$$

$$\begin{aligned} \frac{di_{\beta s}}{dt} &= -q_{21} i_{\beta s} + q_{22} n_p \omega_r i_{as} + p_5 n_p \omega_r \lambda_{ar}^* + p_6 \lambda_{\beta r}^* \\ &\quad + a_2 v_{\beta s} + \Delta_{\beta s} \end{aligned}$$

$$\begin{aligned} \frac{d\lambda_{ar}^*}{dt} &= -k_{11} \lambda_{ar}^* + k_{12} n_p \omega_r \lambda_{\beta r}^* + \varsigma_{11} n_p \omega_r i_{\beta s} \\ &\quad + \varsigma_{12} i_{as} - p_1 v_{as} - k_1 \Delta_{as} + \Delta_{ar} \end{aligned}$$

$$\begin{aligned} \frac{d\lambda_{\beta r}^*}{dt} &= -k_{21} \lambda_{\beta r}^* - k_{22} n_p \omega_r \lambda_{ar}^* - \varsigma_{21} n_p \omega_r i_{as} + \\ &\quad \varsigma_{22} i_{\beta s} - p_2 v_{\beta s} - k_2 \Delta_{\beta s} + \Delta_{\beta r} \end{aligned} \quad (3)$$

where $q_{11} = a_1 c_{10} - k_1 a_1 a_{40}$, $p_{12} = k_2 a_1 a_3$, $q_{21} = a_2 c_{20} - k_2 a_2 a_{40}$, $q_{22} = k_1 a_2 a_3$, $k_{11} = c_{30} + k_1 a_1 a_{40}$, $k_{12} = 1 + k_1 a_1 a_3$, $k_{21} = c_{30} + k_2 a_2 a_{40}$, $k_{22} = 1 + k_2 a_2 a_3$, $\varsigma_{11} = k_{12} k_2$, $\varsigma_{12} = c_{40} - k_{11} k_1 + k_1 a_1 c_{10}$, $\varsigma_{21} = k_{22} k_1$, $\varsigma_{22} = c_{40} - k_{21} k_2 + k_2 a_2 c_{20}$, $p_1 = k_1 a_1$, $p_2 = k_2 a_2$, $p_3 = a_1 a_3$, $p_4 = a_1 a_{40}$, $p_5 = a_2 a_3$, $p_6 = a_2 a_{40}$

With (3), a nonlinear observer is formulated which forms a secondorder sliding mode structure of the observer. Thus, we define λ_{ar}^* , $\lambda_{\beta r}^*$, i_{as}^* , $i_{\beta s}^*$ as the estimates of λ_{ar}^* , $\lambda_{\beta r}^*$, i_{as} , $i_{\beta s}$ respectively.

VI. SLIDING MODE CONTROLLER DESIGN

The principle objective here is to structure a sliding mode controller, which can adequately follow the anticipated speed ω_{ref} to the square of the rotor flux ϕ_{ref} reference signals by means of the constant basic control v_s and auxiliary control ρ as a spasmodic capacity. Here we design a finite-time sliding manifold to guarantee zero error dynamics.

A. Design of Sliding Manifold

The state variables y_1, y_2 are defined as

$$y_1 = [\omega_r \ \phi]^T, \quad y_2 = [i_{as} \ i_{\beta s}]^T \quad (4)$$

where $\phi = |\phi|^2 = \lambda_{ar}^2 + \lambda_{\beta r}^2$. At that point, utilising (4), (1) can be represented in the form of two nonlinear block structures with disturbances [19],

$$\frac{dy_1}{dt} = G_1(\phi) + M_1(\lambda_r) y_2 + P_1 T_L + \Delta_r$$

$$\frac{dy_2}{dt} = G_2(\omega_r, \lambda_r, i_s) + M_2 u + \Delta_s \quad (5)$$

where

$$\lambda_r = [\lambda_{ar} \ \lambda_{\beta r}]^T$$

$$u = [v_{as} \ v_{\beta s}]^T$$

$$G_1(\phi) = [g_{11} \ g_{12}]^T = [0 \ -2c_{30}\phi]^T$$

$$P_1 = [-p_2 \ 0]^T$$

$$G_2 = [g_{21} \ g_{22}]^T$$

$$\Delta_r = [0 \ 2 \ \Delta_{ar} \ \lambda_{ar} + 2 \ \Delta_{\beta r} \ \lambda_{\beta r}]^T$$

$$\Delta_s = [\Delta_{as} \ \Delta_{\beta s}]^T$$

$$M_1(\lambda_r) = \begin{bmatrix} p_1 p_2 \lambda_{\beta r} & -p_1 p_2 \lambda_{ar} \\ 2c_{40} \lambda_{ar} & 2c_{40} \lambda_{\beta r} \end{bmatrix}^T$$

$$M_2 = \begin{bmatrix} a_1 & 0 \\ 0 & a_2 \end{bmatrix}^T$$

with

$$g_{21} = -c_{10} a_1 i_{as} + a_1 a_{40} \lambda_{ar} - a_1 a_3 \omega_r \lambda_{\beta r}$$

$$g_{22} = -c_{20} a_2 i_{\beta s} + a_2 a_3 \omega_r \lambda_{ar} + a_2 a_{40} \lambda_{\beta r}$$

VII. SIMULATION RESULTS

The efficiency of the suggested controller is verified utilizing the simulation results and the real parameters of the system which are performed using the Euler integration method with a time step $t_s = 1 \text{ ms}$. The parameters of the induction motor are given in the Table I below:

TABLE I: Parameters of the single-phase induction motor

Phase voltage in rms [V]	220
Current in rms [A]	5.1
Frequency [Hz]	50
Power factor [pu]	0.81
Shaft speed [rpm]	1430
Magnetizing Inductance [H]	0.2350
Stator total inductivity [H]	0.2442
Rotor total inductivity [H]	0.2473
Stator resistance [ohms]	3.67
Rotor resistance [ohms]	2.32
Number of pole-pairs	2
Rotor moment of inertia [Nm ⁻²]	0.0069

The phase portrait of the above proposed scheme is shown below:

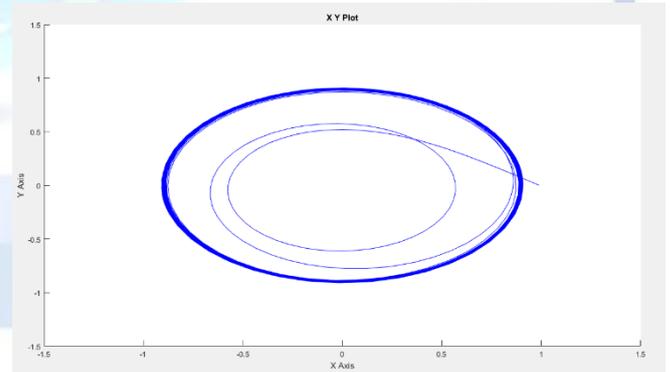


Figure 3 : Phase portrait

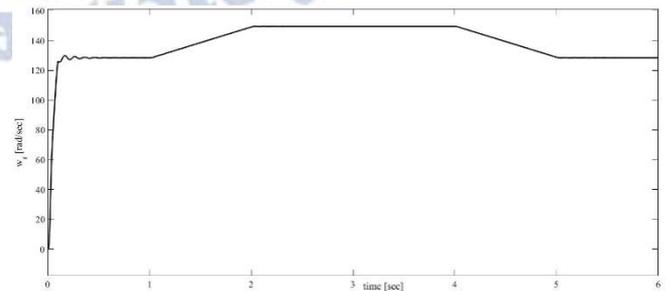


Fig.4 : Speed of the rotor in rpm

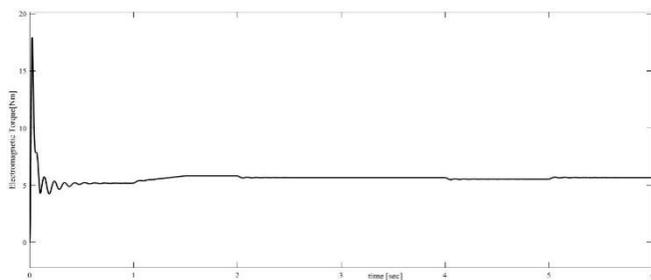


Fig.5 : Electromagnetic Torque in Nm

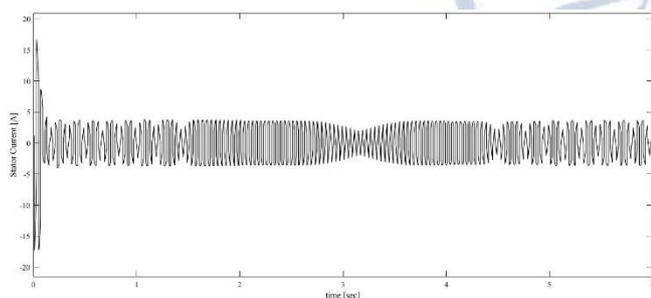


Fig.6 : Stator current in α axis

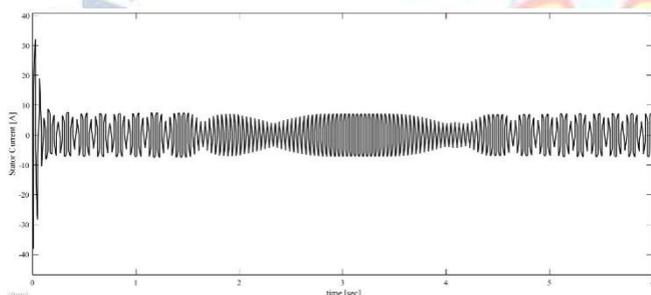


Fig.7 : Stator current in β axis

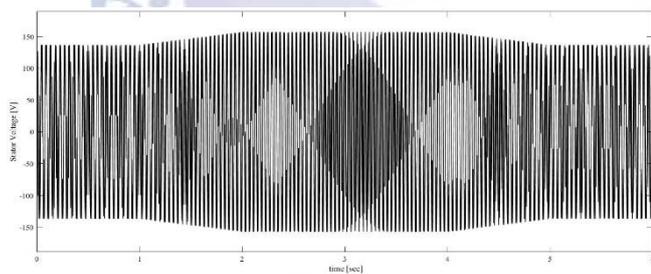


Fig.8 : Stator voltage in α axis

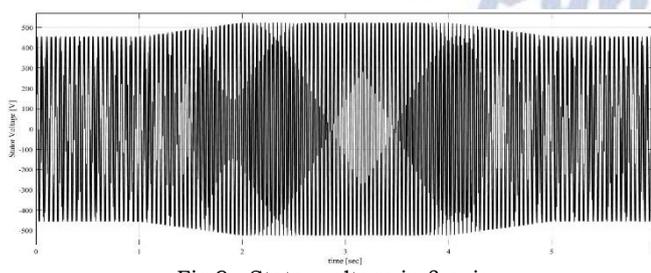


Fig.9 : Stator voltage in β axis

VIII. CONCLUSION

We propose a higher order sliding mode controller for a single-phase induction motor. The controller structure is based on the dynamic model of the motor. The simulation results obtained, exhibit the robustness property of the controller concerning the disturbances caused by the load torque and the rotor resistance variations. In addition, the proposed controller guarantees the constraints on stator currents.

In the near future, the proposed design method may be extended by using intelligent controllers based on fuzzy logic and neural network to encompass flexibility and intelligence.

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