Speed Sensorless Sliding Mode Control of Induction Motor Using Simulink

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Abstract: *AC motors in particular squirrel cage induction motor (SCIM) enjoy several inherent advantages like simplicity, reliability, robust, low cost and maintenance free. The operation of induction motors in the constant volts per hertz (V/f) mode has been known for many decades, and its principle is well understood. V/f control has displaced the dc motor to some extent, particularly in the lower kW range, and the majority of variable speed drives in operation today are of this type. However for high dynamic performance industrial applications their control remains a challenging problem because they exhibit coupled nature of the stator and rotor flux and also significant nonlinearities. Sliding mode control is novel and quite different than the conventional field oriented or direct torques control (DTC) and optimizes the torque response. A new stator and rotor flux observer based on continuous sliding mode which allows Induction motor operation at low speeds is proposed in this project. This model is characterized in the stator reference frame and modeled using MATLAB/SIMULINK.*

Keywords: Induction Motor, sliding mode controller, sliding surface

I. Introduction

Electrical motors play vital role in the development of industrial systems. The DC machine was the first practical machine to convert electrical power into mechanical power, and vice versa. Inherent operating characteristics, flexible performance and efficiency encouraged the use of DC motors in many types of industrial drive application. The later developments of the low cost AC motors have displaced the DC motor to some extent. Induction motors are relatively economical, rugged and reliable machines due to the absence of commutators and brushes. Therefore much attention is given to their control for various applications with different control requirements.

An induction machine, especially squirrel cage induction machine, has many advantages when compared with DC machine. However, because of its highly non-linear and coupled dynamic structure, an induction machine requires more complex control schemes than DC motors. Traditional open-loop control of the induction machine with variable frequency may provide a satisfactory solution under limited conditions. However, when high performance dynamic operation is required, these methods are unsatisfactory. Therefore, more sophisticated control methods are needed to make the performance of the induction motor comparable with DC motors.

II. Sliding Mode Control

Sensorless torque control of an induction motor drive essentially means torque control without any speed sensor. An incremental shaft-mounted speed encoder (usually an optical type) is required for close loop speed or position control in both vector and scalar-controlled drives. A speed signal is also required in indirect vector control in the whole speed range. And in indirect vector control for the low speed range, including the zero speed stat-up operation. A speed encoder is undesirable in a drive because it adds cost and reliability problems, besides the need for a shaft extension and mounting arrangement. It is possible to estimate the speed signal from machine terminal voltages and currents with the help of a DSP or intelligent controller. However, the estimation is normally complex and heavily dependent on machine parameters. Although Sensorless controlled drives are commercially available at this time, the parameter variation problem, particularly near zero speed, imposes a challenge in the accuracy of speed estimation.

A sliding mode control (SMC) with a variable control structure is basically an adaptive control that gives robust performance of a drive with parameter variation and load torque disturbance. The control is nonlinear and can be applied to a linear or nonlinear plant. In an SMM, as the name indicates, the drive response is forced to track or "slide" along a predetermined trajectory or "reference model" in a phase plane by a switching control algorithm, irrespective of the plant's parameter variation and load disturbance. The control is nonlinear and can be applied to a linear or nonlinear plant.

2.1 Control Principle

An SMC is basically a variable structure control system (VSS) [5] where the structure or topology of the control intentionally varied to stabilize the control and make its response robust. Consider a simple second-order undamped linear system, as shown in Figure 2.1. With variable plant gain K. It can easily be seen that system is unstable in either negative or positive feedback mode. However, by switching back and forth between the negative and positive feedback modes, the system cannot only be made stable, but its response can be made independent to the plant parameter K. Consider Figure 2.1 in negative feedback mode with switch 1 closed. We can write

$$X_1 = R - C \qquad\qquad (2.1) \quad or$$

$$R - X_1 = C \qquad\qquad (2.2)$$

Where X_1 =loop error

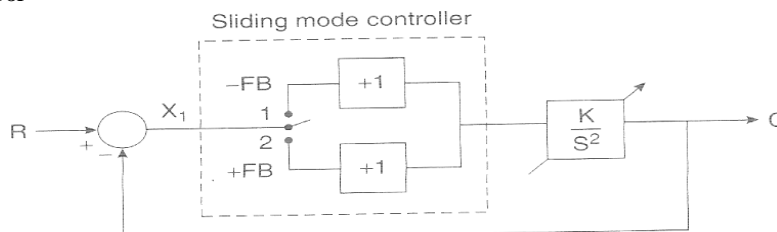**Figure 2.1 Variable structure control of second-order system**

Differentiating equation (2.1)

$$\frac{d}{dt}(R - X_1) = \frac{dC}{dt} = -X_2 \qquad\qquad (2.3) \; or$$

$$\frac{dX_1}{dt} = X_2 \qquad\qquad (2.4)$$

Where R=step input with constant value at time t^+ and $-X_2 = dc/dt$. We can also write the derivative of X_2 in the following form to satisfy the loop relation

$$\frac{dX_2}{dt} = -KX_1 \qquad\qquad (2.5)$$

Combining Equations (2.4) and (2.5)

$$\frac{d^2X_1}{dt^2} + KX_1 = 0 \qquad\qquad (2.6)$$

This gives the second-order system model in terms of the loop error X_1 and its derivative X_2. The general solution of under damped equation, (2.6) is

$$X_1 = A\sin(\sqrt{K}\,t + \theta) \qquad\qquad (2.7)$$

$$X_2 = \frac{dX_1}{dt} = \sqrt{K}A\cos(\sqrt{K}\,t + \theta) \qquad\qquad (2.8)$$

Where A and θ are arbitrary constants. Combining them, we get

$$\frac{X_1^2}{A^2} + \frac{X_2^2}{(\sqrt{K}A)^2} = 1 \qquad\qquad (2.9)$$

Equation (2.9) describes an ellipse with semi-axes A and√kA. Its phase plane trajectory is plotted in fig 2.1, which shows concentric ellipse with arbitrary A. the shape of the ellipse will vary with a variation of gain K.
In the positive feedback mode (switch 2 close) of fig 2.1 we can write the following equations:

$$\frac{dX_1}{dt} = X_2 \qquad\qquad (2.10)$$

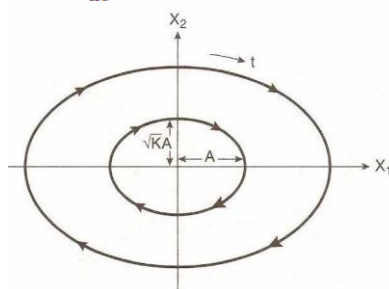$$\frac{dX_2}{dt} = KX_1 \qquad\qquad (2.11)$$

Figure 2.2 phase plane portrait of Figure 2.1 with negative feedback

Combining these equations,

$$\frac{d^2X_1}{dt^2} - KX_1 = 0 \qquad (2.12)$$

The general solution of equation (3.12) is

$$X_1 = B_1 e^{\sqrt{K}t} + B_2 e^{-\sqrt{K}t} \qquad (2.13)$$

$$X_2 = \frac{dX_1}{dt} = \sqrt{K}(B_1 e^{\sqrt{K}t} - B_2 e^{-\sqrt{K}t}) \qquad (2.14)$$

Where B1, B2 are arbitrary constants. Squaring each equation and combing them gives us

$$\frac{X_1^2}{4B_1B_2} - \frac{X_2^2}{4KB_1B_2} = 1 \qquad (2.15)$$

Where B1, B2 term can be positive, negative or zero. Equation (2.15) describes hyperbolas that are plotted in the plane of figure 2.3. The straight line asymptote equations can be derived by substituting as

$$KX_1^2 - X_2^2 = 4KB_1B_2 = 0 \qquad (2.16)$$

$$\text{i.e,} \qquad X_2 = \pm\sqrt{K}X_1 \qquad (2.17)$$

The families of hyperbolas are plotted for B1 B2 > 0and B1 B2 < 0. The system can be switched back and forth between the positive and negative feedback modes for SMC, as explained in Figure 2.4. The operation in Figure 2.4 can be understood by the superposition of Figure 2.2 and 2.3, where the hyperbolic asymptote line is described by the equation $\qquad \sigma = \sqrt{K}X_1 + X_2 = 0 \qquad (2.18)$
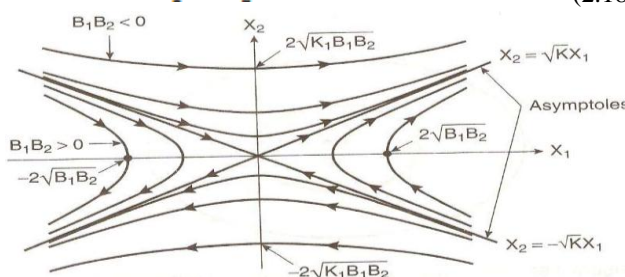

Figure 2.3 phase plane portrait of Figure 2.1 with positive feedback

Where σ =0 is the line. Assume that initially, the system is in negative feedback mode and the operation point is at $X_1 = X_{10}$ on the ellipse. As the operating point moves on elliptic trajectory and touches point B as shown, in the positive mode is invoked. Ideally, it will then moves along the straight line BO and settle at steady-state point O, where X_1 and error velocity are zero. The slope of line BO may vary with variation of K. even with constant K, precision switching at point B is practically impossible to reach the steady-state point O. let us define the sliding line equation as

$$\sigma = CX_1 + X_2 = 0 \qquad (2.19)$$

Where C<K$^{0.5}$ so that the line slope is lower and beyond the range of the K variation. Note carefully that on the sliding line, defined as the "reference trajectory." Describe by hyperbolas and ellipses, respectively, cross in opposite directions. This means that at point B, the control can be switched to positive feedback mode, and then at point D, it can be switched back to negative feedback mode, and so on. The operating point will thus track the sliding line in a zigzag path until the steady-state point is reached at the origin. The time-domain solution of the sliding line is basically a deceleration with exponentially decaying, as indicated by the following equation

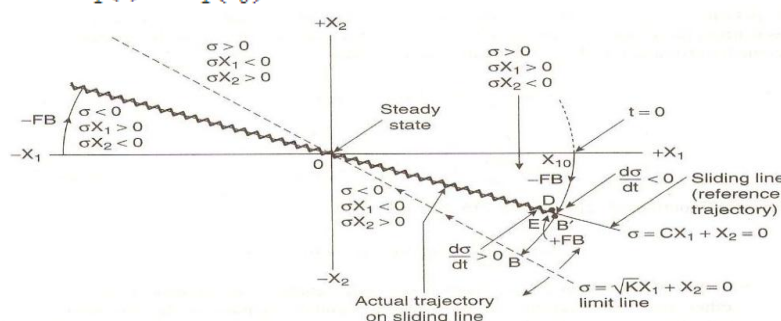$$X_1(t) = X_1(t_0)e^{-c(t-t_0)} \qquad (2.20)$$

Figure2.4 Sliding line control in phase plane

Where t_0 = time at which the trajectory reaches the sliding line. The time-domain response for the sliding line control of two different values of C is shown in Figure 3.6, which reflects the characteristic chattering effect. None that once the operation reaches the sliding line, the response is strictly dictated by slope C, but it is not affected by a variation of parameter K or any load disturbance (robust). The operation of the sliding line control in the second quadrant for − X-1 (reverse position error) is similar to that for the fourth quadrant, and is shown in Figure 2.4. The polarities of parameters σ, σX_1, and σX_2 above and below the sliding line for both $+X_1$ and $-X_1$ are summarized in Figure 2.4. The strategy of switching control is defined by
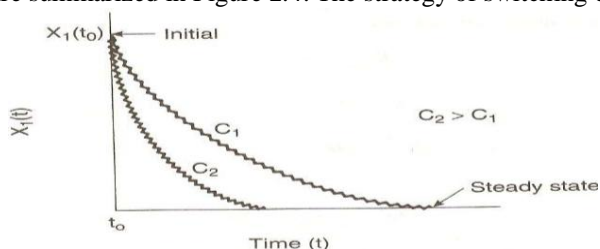
Figure 2.5 Time-domain response in sliding line control for two different values of C

These polarities, which will be described later. Evidently, σ > 0 and d σ/dt<0 , as the trajectory trend to cross the sliding lines from above, where as σ < 0 and d σ/dt<0 , as the trajectory tends to cross the line from below. Mathematically, we can write

$$Lim\frac{d\sigma}{dt} < 0 \; for \; \sigma \rightarrow +0 \qquad (2.21)$$

$$Lim\frac{d\sigma}{dt} > 0 \; for \; \sigma \rightarrow -0 \qquad (2.22)$$

Combining equations (2.20) and(2.21), we get

$$Lim\frac{d\sigma}{dt} < 0 \; for \; \sigma \rightarrow +0 \qquad (2.23)$$

Equation (2.23) is defined as an existence or reaching equation, which must be satisfied for the SMC. In other words, the validity of the reaching equation guarantees that the response will cross the trajectory in each switching transition, and is essentially for a system to be controllable by the sliding mode. In practice, the parameters in the sliding mode controller are designed with the reaching equation.

III.   Simulation Of Various Models

Machine dynamics and problem statement are discussed in the first part of this chapter. Then later part of the chapter focuses on the discussion about sliding-mode control system. Simulink models are developed for the various control circuits based on the equations given for stator flux sliding mode control, sliding mode flux observer.
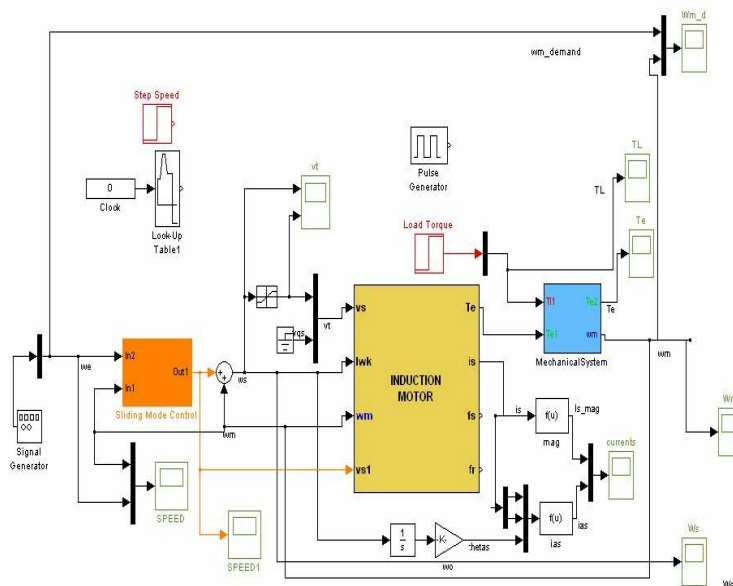

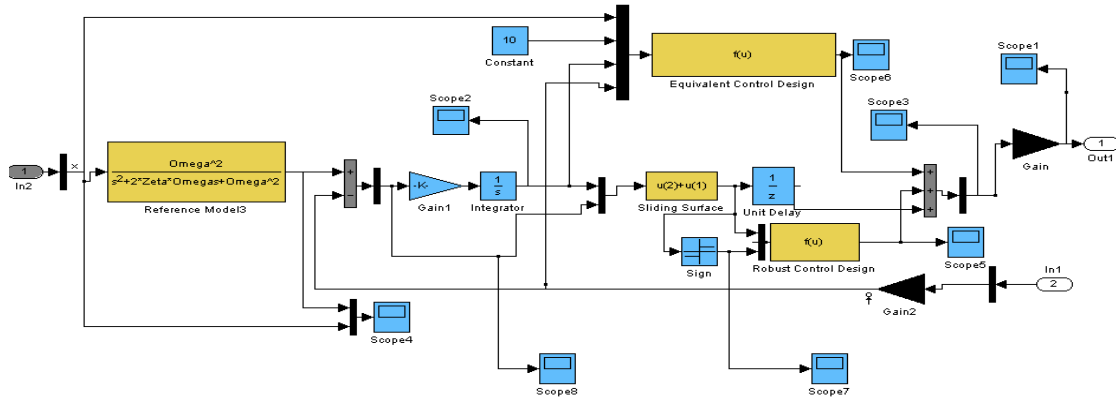**Figure 3.1 Simulink model for closed loop control scheme**

Figure 3.2 Simulink model for Sliding mode control scheme with closed loop
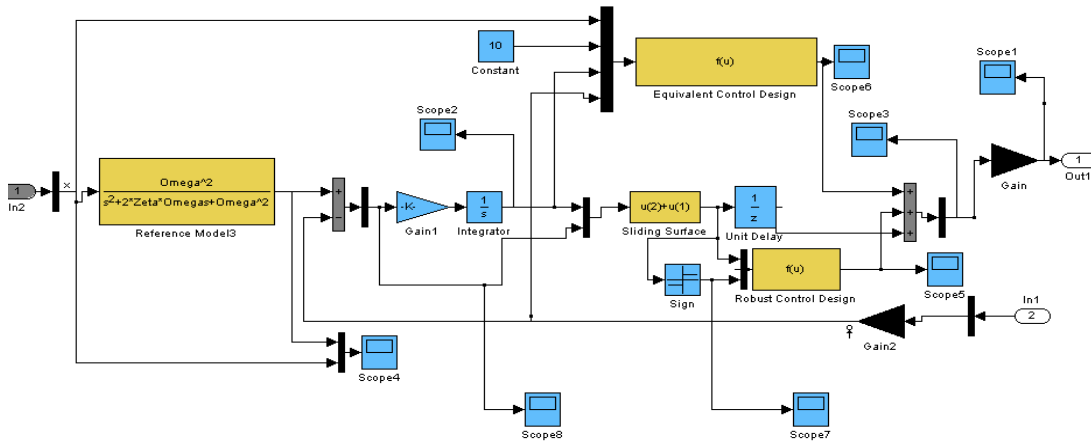

Figure 3.3 Simulink model for Induction Motor

IV. Simulation Results

This control scheme of IM drive is simulated using Simulink. The IM used in simulation is Y connected 50 Hz, 4 pole, 1500 rpm. Parameters in the per phase steady state equivalent circuits are (per unit values): stator resistance Rs=0.025, rotor resistance Rr = 0.015, stator and rotor inductance Ls1=Lr1=0.10, mutual inductance Lm=3.0, motor and load inertia j=0.239.
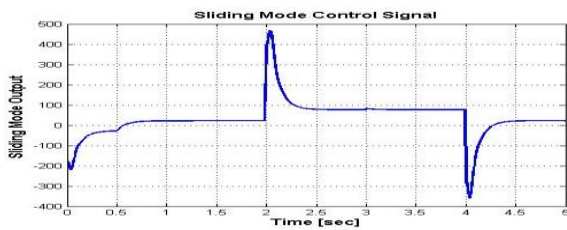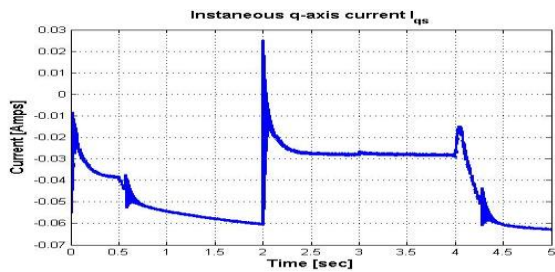

Figure 4.1 Sliding Mode control signal Figure

4.2 instantaneous q-axis currents iqs
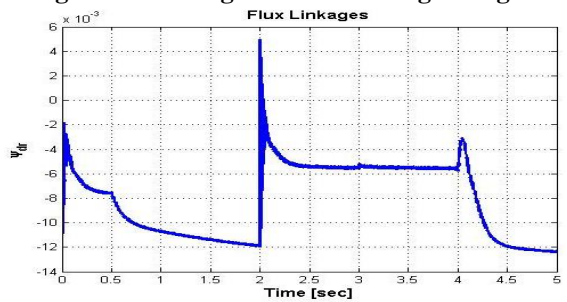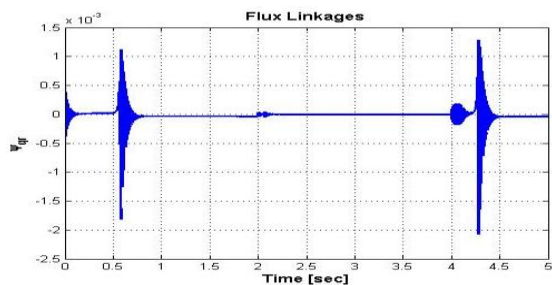

Figure 4.3 flux linkages ψqr
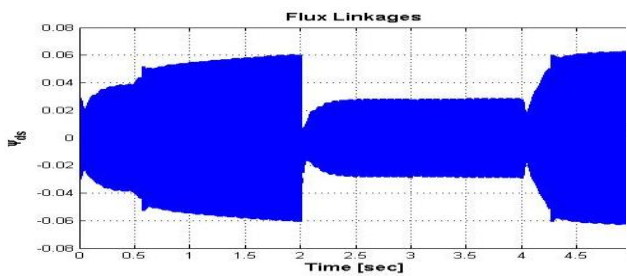

Figure 4.4 flux linkages ψqr
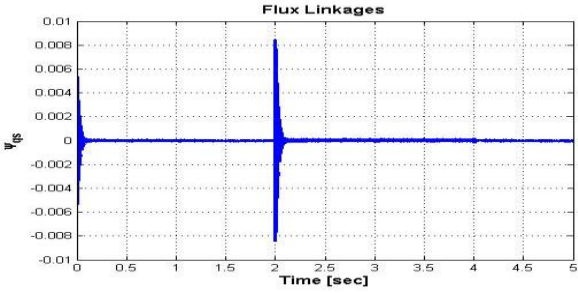
Figure 4.5 flux linkages ψqs   **Figure 4.6 flux linkages ψds**

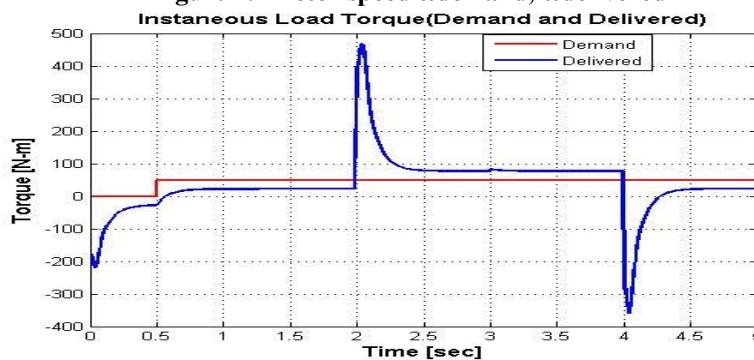**Figure 4.7 Rotor speed ωdemand, ωdelivered**

Figure 4.8 Instantaneous Load Torque and Demand Torque

V. Conclusion

The robust sliding mode control is presented in the stator fixed reference frame so that an easy description for a real-time operation could be found. Combining VSDS and Lyapunov design has developed a new discrete time control algorithm. It possesses all the good properties of the Sliding mode and eliminates the undesired chattering of control input. Sliding Mode Control has low speed tracking error and high control effort when compared to PI controller. In this paper, a speed Sensorless sliding mode control for IM is simulated using Matlab/simulink. The conclusion can be drawn from the results obtained in the previous chapter. New rotor flux observer allows the speed Sensorless operation of IM at low speeds. The same was shown in the graphs drawn in the figure 4.7. It is simple control method and quite different from the FOC and DTC.

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