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Sensorless Sliding Mode Control of Induction Machine Based On SVPWM

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Abstract

In recent years, sensorless modes of operation are becoming most convenient and standard solutions in the areas of electric drives. This paper explains about sensorless speed control of induction motor with a predictive current controller. The closed loop estimation system with at most robustness against any parameter variations is used for the control approach. In this paper further a noval scheme implementing Space Vector pulse width modulation is also proposed increasing overall stability. Here a Space Vector Pulse width modulated VSI is used to feed the IM. The simulation results illustrate the performance of IM on various conditions. The results are then compared with the conventional types verifying this scheme has better performance than the others

Keywords—*MRAS-Model reference adaptive scheme, Lyponauov stability scheme, IM- Induction Motor, VSI-Voltage source inverter, SVPWM-Space vector pulse width modulation*

Introduction

During the past decade, sensorless speed control of induction machine has become a mature technology for a wide speed range. Sensorless control of Induction machine is now attracting wide attention, both in the field of electrical drives and in the field of dynamic control. The advantages of speed sensorless AC drives are reduced hardware complexity, lower cost, elimination of sensor cable, better noise immunity, increased reliability, access to both sides of the shaft, less maintenance requirements and higher robustness. The use of encoders increases the drive‘s price and affects the reliability which is of utmost concern to many operational situations.

Many research efforts have been made for rotor speed estimation in the sensorless speed control.

They can be broadly classified into those based on non-ideal phenomena such as rotor slot harmonics and high frequency signal injection methods which relies on the model of the induction motor. The former require spectrum analysis which is time consuming procedure and allow a narrow band of speed control. The later methods are characterized by their simplicity, but sensitive to parameter variations. The role of stator resistance is important and its value has to be known with good precision for obtaining accurate speed estimation in the low speed region. Any mismatch between actual and set values of stator resistance within the model of speed estimation may lead not only to substantial error in speed estimation but also to instability.

Most of the research works described in the literature for MRAS speed observers employs a simple fixed gain linear PI controller to estimate the rotor speed due to their simple structure and satisfactory performance over a wide range of operation. However, these controllers may drop the performance level due to the continuous variation in the machine parameters and operating conditions in addition to nonlinearities contributed by the inverter. Little interest has been focused on alternative technique for minimizing the speed tuning signal to estimate the speed by MRAS. Furthermore, majority of the study has been devoted with sinusoidal PWM inverter fed induction machines rather than space vector pulse width modulated (SVPWM) inverters, which have good operating characteristics.

Mathematical Modeling Of Induction Machine

The IM cane be modeled by the continuous equations in stationary reference frame (qds),

$$\frac{d}{dt}i_{sq} = -\gamma i_{sq} + \beta\frac{1}{T_r}\phi_{rq} - \beta p\omega_r\phi_{rd} + \frac{1}{\sigma L_s}v_{sq} \quad (1)$$
$$\frac{d}{dt}i_{sd} = -\gamma i_{sd} + \beta\frac{1}{T_r}\phi_{rd} - \beta p\omega_r\phi_{rq} + \frac{1}{\sigma L_s}v_{sd} \quad (2)$$
$$\frac{d}{dt}\phi_{rq} = -\frac{1}{T_r}\phi_{rq} + p\omega_r\phi_{rd} + \frac{1}{T_r}L_m i_{sq} \quad (3)$$
$$\frac{d}{dt}\phi_{rd} = -\frac{1}{T_r}\phi_{rd} + p\omega_r\phi_{rq} + \frac{1}{T_r}L_m i_{sd} \quad (4)$$
$$T_e = \frac{3}{2}\frac{L_m}{L_r}p(\phi_{rd}i_{sq} - \phi_{rq}i_{sd}) \quad (5)$$
$$\frac{d}{dt}\omega_r = \frac{B_n}{J}\omega_r + \frac{1}{J}(T_e - T_L) \quad (6)$$

R_s and R_r are the stator and rotor resistances

L_s and L_r are the stator and rotor inductances

L_m is the mutual inductance

i_{sq}, i_{sd}, φ_{rq}, φ_{rd}, v_{sq}, and v_{sd} are the stator currents, the rotor fluxes, and the stator voltages, respectively

ω_r is the rotor speed

T_e is the electromagnetic torque

T_L is the load torque

J is the moment of inertia

B_n is the friction coefficient, and p is the pole pair number.

The constants are defined as :

$$T_r \triangleq \frac{L_r}{R_r}, \sigma \triangleq 1 - \frac{L_m^2}{L_s L_r}, \beta \triangleq \frac{L_m}{\sigma L_s L_r}, \gamma \triangleq \frac{R_s}{\sigma L_s} + \beta\frac{1}{T_r}L_m.$$

The expressions of back EMF can be calculated from the current and voltage signals as

$$e_{mq} = v_{sq} - R_s i_{sq} - \sigma L_s \frac{d}{dt}i_{sq}$$
$$e_{md} = v_{sd} - R_s i_{sd} - \sigma L_s \frac{d}{dt}i_{sd}$$

It is possible to obtain the back-EMF equations from the magnetizing currents in the form

$$e_{mq} = L'_m \frac{d}{dt}i_q M$$
$$e_{md} = L'_m \frac{d}{dt}i_d M$$

where $L'_m = L^2_m/L_r$, and the magnetizing currents could be given by

$$i_q M = \frac{L_r}{L_m}i_{rq} + i_{sq}$$
$$i_d M = \frac{L_r}{L_m}i_{rd} + i_{sd}$$

Where i_{rq} and i_{rd} are the rotor currents.

The differential equations of magnetizing currents can be given by

$$\frac{d}{dt}i_q M = -\frac{1}{T_r}i_q M - p\omega_r i_d M + \frac{1}{T_r}i_{sq}$$
$$\frac{d}{dt}i_d M = -\frac{1}{T_r}i_d M - p\omega_r i_q M + \frac{1}{T_r}i_{sd}$$

The differential equations of magnetizing currents also can be obtained from the back EMF equations

$$\frac{d}{dt}i_q M = e_{mq}/L'_m$$
$$\frac{d}{dt}i_d M = e_{md}/L'_m$$

Thus from the above equations, it is possible to compute the magnetizing currents using the calculated back EMF. These two set of equations presents two methods to obtain the magnetizing currents. The first method uses the stator currents and a component that include the rotor speed information, while the second method calculates the magnetizing currents directly from the back EMF. The first method cannot be implemented without the rotor speed information. The second method uses only voltage and current signals. As a consequence, an observer based on the sliding mode approach for the magnetizing currents can be used, aiming to obtain the rotor speed information [1].

Stability Analysis of Induction Machine

A. Stability Analysis

Three phase induction motor in stationary dq axis reference frame with air gap flux and stator currents as its states and neglecting core loss is mathematically modeled as following[2]:

$$\frac{di_{ds}}{dt} = \left(\frac{-R_s}{\sigma} - \frac{R_r L_m}{\sigma L_r}\right)i_{ds} - \beta\omega_r i_{qs} + \frac{R_r}{\sigma l_r}\lambda_{da} + \frac{\omega_r}{\sigma}\lambda_{qa} + \frac{1}{\sigma}v_{ds}$$
$$\frac{di_{qs}}{dt} = \left(\frac{-R_s}{\sigma} - \frac{R_r L_m}{\sigma L_r}\right)i_{qs} + \beta\omega_r i_{ds} + \frac{R_r}{\sigma l_r}\lambda_{qa} + \frac{\omega_r}{\sigma}\lambda_{da} + \frac{1}{\sigma}v_{qs}$$
$$\frac{d\lambda_{da}}{dt} = \left(-\beta R_s + \frac{L_{ls}L_m R_r}{\sigma L_r}\right)i_{ds} + \beta L_{ls}\omega_r i_{qs} - \frac{L_{ls}R_r\lambda_{da}}{\sigma L_r} - L_{ls}\omega_r\lambda_{qa} + \beta v_{ds}$$
$$\frac{d\lambda_{qa}}{dt} = \left(-\beta R_s + \frac{L_{ls}L_m R_r}{\sigma L_r}\right)i_{qs} - \beta L_{ls}\omega_r i_{ds} - \frac{L_{ls}R_r\lambda_{qa}}{\sigma L_r} + L_{ls}\omega_r\lambda_{da} + \beta v_{qs}$$

where v_{ds}, v_{qs}, i_{ds}, i_{qs} represent dq stator voltages and currents in stationary frame

λ_{da} and λ_{qa} are dq airgap fluxes

R_r, R_s, L_r, L_s, L_{lr}, L_{ls}, L_m, and ωr stand for rotor and stator resistances, self and leakage inductances, magnetizing inductance, and rotor electrical speed, respectively.

Besides, $\sigma = L_s(1 - L_m^2)/L_sL_r$ represents the leakage coefficient

$\beta = (\sigma - L_{ls}/\sigma)$ is a constant parameter.

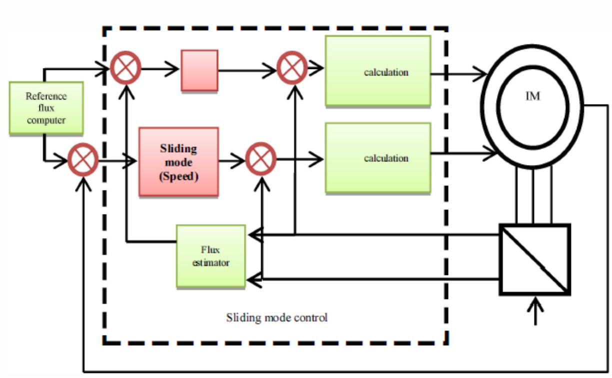

fig.1 General structure of the sliding mode control of induction machine based on Lyapunov theory

The error dynamics for the proposed observer are obtained as

$$\frac{d\tilde{\lambda}_{qa}}{dt} = \left(-\beta\tilde{R}_s + \frac{L_{ls}L_m\tilde{R}_r}{\sigma L_r}\right)\hat{\imath}_{qs} + \left(-\beta\tilde{R}_s + \frac{L_{ls}L_m\tilde{R}_r}{\sigma L_r}\right)\tilde{\imath}_{qs} + \beta L_{ls}\tilde{\omega}_r i_{ds} - \frac{L_{ls}\tilde{R}_r\hat{\lambda}_{qa}}{\sigma L_r} - \frac{L_{ls}\tilde{R}_r\tilde{\lambda}_{qa}}{\sigma L_r} - \frac{L_{ls}\tilde{\omega}_r\hat{\lambda}_{da}}{\sigma} - \frac{L_{ls}\tilde{\omega}_r\tilde{\lambda}_{da}}{\sigma}$$

$$\frac{d\tilde{\imath}_{ds}}{dt} = \left(\frac{-\tilde{R}_s}{\sigma} - \frac{\tilde{R}_rL_m}{\sigma L_r}\right)\hat{\imath}_{ds} + \left(\frac{-\tilde{R}_s}{\sigma} - \frac{\tilde{R}_rL_m}{\sigma L_r}\right)\tilde{\imath}_{ds} - \beta\tilde{\omega}_r i_{qs} + \frac{\tilde{R}_r}{\sigma l_r}\hat{\lambda}_{da} + \frac{R_r}{\sigma l_r}\hat{\lambda}_{da} + \frac{\tilde{\omega}_r}{\sigma}\hat{\lambda}_{qa} + \frac{\omega_r}{\sigma}\hat{\lambda}_{qa} - f_d \quad (3)$$

$$\frac{d\tilde{\imath}_{qs}}{dt} = \left(\frac{-\tilde{R}_s}{\sigma} - \frac{\tilde{R}_rL_m}{\sigma L_r}\right)\hat{\imath}_{qs} + \left(\frac{-\tilde{R}_s}{\sigma} - \frac{\tilde{R}_rL_m}{\sigma L_r}\right)\tilde{\imath}_{qs} - \beta\tilde{\omega}_r i_{ds} + \frac{\tilde{R}_r}{\sigma l_r}\hat{\lambda}_{qa} + \frac{R_r}{\sigma l_r}\hat{\lambda}_{qa} + \frac{\tilde{\omega}_r}{\sigma}\hat{\lambda}_{da} + \frac{\omega_r}{\sigma}\hat{\lambda}_{da} - f_q$$

$$\frac{d\tilde{\lambda}_{da}}{dt} = \left(-\beta\tilde{R}_s + \frac{L_{ls}L_m\tilde{R}_r}{\sigma L_r}\right)\hat{\imath}_{ds} + \left(-\beta\tilde{R}_s + \frac{L_{ls}L_m\tilde{R}_r}{\sigma L_r}\right)\tilde{\imath}_{ds} + \beta L_{ls}\tilde{\omega}_r i_{qs} - \frac{L_{ls}\tilde{R}_r\hat{\lambda}_{da}}{\sigma L_r} - \frac{L_{ls}\tilde{R}_r\tilde{\lambda}_{da}}{\sigma L_r} - \frac{L_{ls}\tilde{\omega}_r\hat{\lambda}_{qa}}{\sigma} - \frac{L_{ls}\tilde{\omega}_r\tilde{\lambda}_{qa}}{\sigma} \quad (4)$$

where the error quantities are shown as $\tilde{x}$; i.e. $x - \hat{x}$

$$z_d = \tilde{\lambda}_{da} + L_{ls}\tilde{i}_{ds} + \int_0^t R_s i_{ds}dt$$

$$z_q = \tilde{\lambda}_{qa} + L_{ls}\tilde{i}_{qs} + \int_0^t R_s i_{qs}dt \quad (5)$$

Time derivatives of z_d and z_q are determined using (3) and (4), as following:

$$\frac{dz_d}{dt} = \frac{d\tilde{\lambda}_{da}}{dt} + \frac{L_{ls}d\tilde{\imath}_{ds}}{dt} + R_s i_{ds} = \hat{R}_s\hat{\imath}_{ds} - L_{ls}f_d$$

$$\frac{dz_d}{dt} = \frac{d\tilde{\lambda}_{qa}}{dt} + \frac{L_{ls}d\tilde{\imath}_{qs}}{dt} + R_s = \hat{R}_s\hat{\imath}_{qs} - L_{ls}f_q \quad (6)$$

Because of residual flux, the initial values for z_d and z_q are generally unknown. So, η_d and η_q are introduced as:

$$\eta_d = z_d - \hat{z}_d = \tilde{z}_d, \eta_q = z_q - \hat{z}_q = \tilde{z}_q \quad (7)$$

Substituting (5) and (7) into (3), the error dynamics of dq currents are rewritten as:

$$\frac{d\tilde{\imath}_{ds}}{dt} = \left(\frac{-\tilde{R}_s}{\sigma} - \frac{\tilde{R}_rL_m}{\sigma L_r}\right)\hat{\imath}_{ds} + \left(\frac{-\tilde{R}_s}{\sigma} - \frac{\tilde{R}_rL_m}{\sigma L_r}\right)\tilde{\imath}_{ds} - \beta\tilde{\omega}_r i_{qs} + \frac{\tilde{R}_r}{\sigma l_r}\hat{\lambda}_{da} + \frac{R_r}{\sigma l_r}\left(z_d - L_{ls}\tilde{\imath}_{ds} - \int_0^t R_s i_{ds}dt\right) + \frac{\tilde{\omega}_r}{\sigma}\hat{\lambda}_{qa} + \frac{\omega_r}{\sigma}\left(\hat{z}_q + \eta_q - L_{ls}\tilde{\imath}_{ds} - \int_0^t R_s i_{ds}dt\right) - f_d$$

$$\frac{d\tilde{\imath}_{qs}}{dt} = \left(\frac{-\tilde{R}_s}{\sigma} - \frac{\tilde{R}_rL_m}{\sigma L_r}\right)\hat{\imath}_{qs} + \left(\frac{-\tilde{R}_s}{\sigma} - \frac{\tilde{R}_rL_m}{\sigma L_r}\right)\tilde{\imath}_{qs} - \beta\tilde{\omega}_r i_{ds} + \frac{\tilde{R}_r}{\sigma l_r}\hat{\lambda}_{qa} + \frac{R_r}{\sigma l_r}\left(z_q - L_{ls}\tilde{\imath}_{qs} - \int_0^t R_s i_{qs}dt\right) + \frac{\tilde{\omega}_r}{\sigma}\hat{\lambda}_{da} + \frac{\omega_r}{\sigma}\left(\hat{z}_d + \eta_d - L_{ls}\tilde{\imath}_{qs} - \int_0^t R_s i_{qs}dt\right) - f_q \quad (8)$$

Now we define f_d and f_q as

$$f_d = \frac{\hat{R}_r}{\sigma L_r}\frac{\omega_r}{\sigma}\left(\hat{z}_d - \hat{R}_s\int_0^t i_{ds}dt\right) + \frac{\hat{\omega}_r}{\sigma}\left(\hat{z}_q + \hat{\eta}_q - \hat{R}_s\int_0^t i_{qs}dt\right) + k_{fd}\tilde{\imath}_{ds}$$

$$f_q = \frac{\hat{R}_r}{\sigma L_r}\frac{\omega_r}{\sigma}\left(\hat{z}_q - \hat{R}_s\int_0^t i_{qs}dt\right) + \frac{\hat{\omega}_r}{\sigma}\left(\hat{z}_d + \hat{\eta}_d - \hat{R}_s\int_0^t i_{ds}dt\right) + k_{fq}\tilde{\imath}_{qs} \quad (9)$$

Where, k_{fd} and k_{fq} are positive gains.

$$\hat{R}_\omega = \hat{R}_s\hat{\omega}_r \quad \hat{R} = \hat{R}_r\hat{R}_s$$

$$\tilde{R} = R_rR_s - \hat{R}$$

$$I_{ds} = \int_0^t i_{ds}dt, \quad I_{qs} = \int_0^t i_{qs}dt, \quad R_\omega = R_s\omega_r - \hat{R}_\omega \quad (10)$$

$$f_d = -\frac{R_rz_d}{L_r\sigma} - \frac{R}{L_r\sigma}Ids + \frac{\omega_r}{\sigma}(z_q + \eta_q) - \frac{R_\omega}{\sigma}I_{qs} - \frac{\omega_r}{\sigma}L_{ls}I_{qs} + k_{fd}I_{ds}$$

$$f_q = \frac{R_rz_d}{L_r\sigma} - \frac{R}{L_r\sigma}Ids - \frac{\omega_r}{\sigma}(z_q + \eta_q) + \frac{R_\omega}{\sigma}I_{qs} + \frac{\omega_r}{\sigma}L_{ls}I_{qs} + k_{fd}I_{ds} \quad (11)$$

Substituting (11) to (8) and using 10), the observer error can be expressed in the matrix form as following:

$$\frac{dX_1}{dt} = A_1X_1 + W_1^T\tilde{\theta}$$

$$X_1 = [\tilde{\imath}_{ds} \quad \tilde{\imath}_{qs}]^T$$

$$\tilde{\theta} = [\tilde{R}_r \quad \tilde{\omega}_r \quad \tilde{R}_s\tilde{R} \quad \tilde{R}_\omega \quad \tilde{z}_d\tilde{z}_q \quad \tilde{\eta}_d \quad \tilde{\eta}_q]$$

$$A_1 = \text{diag}\left[\frac{-R_sL_r+R_rL_m+R_rL_{ls}-k_{fd}}{\sigma L_r}, \frac{-R_sL_r+R_rL_m+R_rL_{ls}-k_{fq}}{\sigma L_r}\right]$$

$$W_1^T = \begin{bmatrix} w_{11} & w_{12} & \frac{-i_{ds}}{\sigma}\frac{-I_{ds}}{L_r\sigma} & \frac{-I_{qs}}{\sigma} & \frac{R_r}{L_r\sigma} & 0 & 0 & \frac{\omega_r}{\sigma} \\ w_{21} & w_{22} & \frac{-i_{qs}}{\sigma}\frac{-I_{qs}}{L_r\sigma} & \frac{I_{ds}}{\sigma} & 0 & \frac{R_r}{L_r\sigma} & \frac{-\omega_r}{\sigma} & 0 \end{bmatrix}$$

$$w_{11} = \frac{-L_m i_{ds} + \lambda_{da} + z_d}{L_r\sigma}$$

$$w_{21} = \frac{-L_m i_{qs} + \lambda_{qa} + z_q}{L_r\sigma}$$

$$w_{12} = \frac{-\beta i_{qs}\sigma + \grave{\lambda}_{qa} + \grave{z}_q + \grave{\eta}_q - L_{ls}\tilde{\imath}_{qs}}{\sigma}$$

$$w_{22} = \frac{\beta i_{ds}\sigma - \grave{\lambda}_{da} - \grave{z}_d - \grave{\eta}_d - L_{ls}\tilde{\imath}_{ds}}{\sigma} \quad (12)$$

B Controller Design

Developed electromagnetic torque and air gap flux are estimated based on the measured and estimated dq air gap fluxes and stator currents, as following:

$$\tilde{\lambda}_a^2 = \tilde{\lambda}_{da}^2 + \tilde{\lambda}_{qa}^2$$

$$\hat{T}_e = \frac{3P}{2}\left(\hat{\lambda}_{da} i_{qs} - \hat{\lambda}_{qa} i_{ds}\right) \quad (13)$$

where P is the number of pole pairs.

The error between estimated and reference torque is defined as following:

$$e_T' = \frac{3P}{2}\left(\hat{\lambda}_{da} i_{qs} - \hat{\lambda}_{qa} i_{ds}\right) - T_{ref} \quad (14)$$

Multiplying the above equation by $3P/2$ yields to:

$$e_T = \left(\hat{\lambda}_{da} i_{qs} - \hat{\lambda}_{qa} i_{ds}\right) - \frac{2}{3PT_{ref}} \quad (15)$$

Consequently, the following torque error dynamics is obtained:

$$\frac{de_t}{dt} = \left(\beta i_{qs} - \frac{\hat{\lambda}_{qa}}{\sigma}\right) v_{ds} + \left(-\beta i_{ds} + \frac{\hat{\lambda}_{da}}{\sigma}\right) v_{qs} - \beta \hat{R}_s \hat{\imath}_{ds} i_{qs} + \frac{L_{ls}L_m}{L_r\sigma}\hat{R}_r \hat{\imath}_{ds} i_{qs} + \beta L_{ls}\widehat{\omega}_r i_{qs}^2 - \frac{L_{ls}\hat{R}_r\hat{\lambda}_{da}}{L_r\sigma} i_{qs} - \frac{L_{ls}\widehat{\omega}_r\hat{\lambda}_{qa} i_{qs}}{\sigma} - \frac{R_s}{\sigma} i_{qs}\hat{\lambda}_{da} - \frac{R_r L_m i_{qs}\hat{\lambda}_{da}}{\sigma L_r} + \beta\omega_r i_{ds}\hat{\lambda}_{da} - \frac{\omega_r}{\sigma}\lambda_{da}\hat{\lambda}_{da} + \frac{R_r}{\sigma L_r}\lambda_{qa}\hat{\lambda}_{da} + \beta\hat{R}_s\hat{\imath}_{qs} i_{ds} - \frac{L_{ls}L_m\hat{R}_r\hat{\imath}_{qs} i_{ds}}{\sigma L_r} + \beta L_{ls}\widehat{\omega}_r i_{ds}^2 + \frac{L_{ls}\hat{R}_r\hat{\lambda}_{qa}}{L_r\sigma} i_{ds} - \frac{L_{ls}\widehat{\omega}_r\hat{\lambda}_{da} i_{ds}}{\sigma} + \frac{R_s}{\sigma} i_{ds}\hat{\lambda}_{qa} + \frac{R_r L_m i_{ds}\hat{\lambda}_{qa}}{\sigma L_r} + \beta\omega_r i_{qs}\hat{\lambda}_{qa} - \frac{\omega_r}{\sigma}\lambda_{qa}\hat{\lambda}_{qa} - \frac{R_r}{\sigma L_r}\lambda_{da}\hat{\lambda}_{qa} - \frac{2}{3P}\frac{dT_{ref}}{dt} \quad (16)$$

The error between the estimated and desired flux is expressed by

$$e_\lambda = \frac{1}{2}\left(\hat{\lambda}_{da}^2 - \hat{\lambda}_{qa}^2 - \lambda_{ref}^2\right) \quad (17)$$

Where λ_{ref} is the reference flux

With similar procedure, the flux error dynamics can be obtained as

$$\frac{de_\lambda}{dt} = (\beta\hat{\lambda}_{da})v_{ds} + (\beta\hat{\lambda}_{qa})v_{qs} - \beta\hat{R}_s\hat{\imath}_{ds}\hat{\lambda}_{da} + \frac{L_{ls}L_m}{L_r\sigma}\hat{R}_r\hat{\imath}_{ds}\hat{\lambda}_{da} + \beta L_{ls}\widehat{\omega}_r i_{qs}\hat{\lambda}_{da} - \frac{L_{ls}}{L_r\sigma}\hat{R}_r\hat{\lambda}_{da}^2 - \beta\hat{R}_s\hat{\imath}_{qs}\hat{\lambda}_{qa} + \frac{L_{ls}L_m}{L_r\sigma}\hat{R}_r\hat{\imath}_{qs}\hat{\lambda}_{qa} - \beta L_{ls}\widehat{\omega}_r i_{ds}\hat{\lambda}_{qa} - \frac{L_{ls}}{L_r\sigma}\hat{R}_r\hat{\lambda}_{qa}^2 - \lambda_{ref}\frac{d\lambda_{ref}}{dt} \quad (18)$$

The input voltages, v_{ds} and v_{qs} are determined based on the following feedback linearization equation:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} -\beta i_{qs} + \frac{\hat{\lambda}_{qa}}{\sigma} & \beta i_{ds} - \frac{\hat{\lambda}_{da}}{\sigma} \\ -\beta\hat{\lambda}_{da} & -\beta\hat{\lambda}_{qa} \end{bmatrix} \begin{bmatrix} g_{d1} + g_{d2} \\ g_{q1} \end{bmatrix} \quad (19)$$

g_{d1}, g_{q1} are calculated from equations (16) and (18), as following:

$$g_{d1} = -\beta\hat{R}_s\hat{\imath}_{ds} i_{qs} + \frac{L_{ls}L_m}{L_r\sigma}\hat{R}_r\hat{\imath}_{ds} i_{qs} + \beta L_{ls}\widehat{\omega}_r i_{qs}^2 - \frac{L_{ls}\hat{R}_r\hat{\lambda}_{da}}{L_r\sigma} i_{qs} - \frac{L_{ls}\widehat{\omega}_r\hat{\lambda}_{qa} i_{qs}}{\sigma} - \frac{R_s}{\sigma} i_{qs}\hat{\lambda}_{da} - \frac{R_r L_m i_{qs}\hat{\lambda}_{da}}{\sigma L_r} + \beta\omega_r i_{ds}\hat{\lambda}_{da} - \frac{\omega_r}{\sigma}\hat{\lambda}_{da}^2 + \beta\hat{R}_s\hat{\imath}_{qs} i_{ds} - \frac{L_{ls}L_m\hat{R}_r\hat{\imath}_{qs} i_{ds}}{\sigma L_r} + \beta L_{ls}\widehat{\omega}_r i_{ds}^2 + \frac{L_{ls}\hat{R}_r\hat{\lambda}_{qa}}{L_r\sigma} i_{ds} - \frac{L_{ls}\widehat{\omega}_r\hat{\lambda}_{da} i_{ds}}{\sigma} + \frac{R_s}{\sigma} i_{ds}\hat{\lambda}_{qa} + \frac{R_r L_m i_{ds}\hat{\lambda}_{qa}}{\sigma L_r} + \beta\omega_r i_{qs}\hat{\lambda}_{qa} - \frac{\omega_r}{\sigma}\hat{\lambda}_{qa}^2 - \frac{2}{3P}\frac{dT_{ref}}{dt} + c_1 e_T \quad (20)$$

$$g_{q1} = -\beta R_s i_{ds}\hat{\lambda}_{da} + \frac{L_{ls}L_m}{L_r\sigma}\hat{R}_r\hat{\imath}_{ds}\hat{\lambda}_{da} + \beta L_{ls}\widehat{\omega}_r i_{qs}\hat{\lambda}_{da} - \frac{L_{ls}}{L_r\sigma}\hat{R}_r\hat{\lambda}_{da}^2 - \beta\hat{R}_s\hat{\imath}_{qs}\hat{\lambda}_{qa} + \frac{L_{ls}L_m\hat{R}_r\hat{\imath}_{qs}\hat{\lambda}_{qa}}{\sigma L_r} - \beta L_{ls}\widehat{\omega}_r i_{ds}\hat{\lambda}_{qa} - \frac{L_{ls}}{L_r\sigma}\hat{R}_r\hat{\lambda}_{qa}^2 - \lambda_{ref}\frac{d\lambda_{ref}}{dt} + c_2 e_\lambda \quad (21)$$

Substituting (20) and (21) into (19), we get

$$\frac{de_t}{dt} = -\frac{\widetilde{R_s}}{\sigma} i_{qs}\hat{\lambda}_{da} - \frac{R_r L_m i_{qs}\hat{\lambda}_{da}}{\sigma L_r} + \beta\widehat{\omega}_r i_{ds}\hat{\lambda}_{da} - \frac{\widetilde{\omega}_r}{\sigma}\hat{\lambda}_{da}^2 - \frac{\omega_r}{\sigma}\tilde{\lambda}_{da}\grave{\lambda}_{da} + \frac{\hat{R}_r}{L_r\sigma}\tilde{\lambda}_{qa}\grave{\lambda}_{da} + \frac{R_s}{\sigma} i_{ds}\hat{\lambda}_{qa} + \frac{\tilde{R}_r L_m i_{ds}\hat{\lambda}_{qa}}{\sigma L_r} + \beta\widetilde{\omega}_r i_{qs}\hat{\lambda}_{qa} - \frac{R_r\tilde{\lambda}_{da}}{L_r\sigma}\hat{\lambda}_{qa} - \frac{\widetilde{\omega}_r}{\sigma}\hat{\lambda}_{qa}^2 - \frac{\omega_r}{\sigma}\tilde{\lambda}_{qa}\grave{\lambda}_{qa} - c_1 e_T - g_{d2} \quad (22)$$

$$\frac{de_\lambda}{dt} = -c_2 e_\lambda \quad (23)$$

From (22), (5) and (7) the following equation is derived

$$\frac{de_t}{dt} = -\frac{\widetilde{R_s}}{\sigma} i_{qs}\hat{\lambda}_{da} - \frac{R_r L_m i_{qs}\hat{\lambda}_{da}}{\sigma L_r} + \beta\widehat{\omega}_r i_{ds}\hat{\lambda}_{da} - \frac{\widetilde{\omega}_r}{\sigma}\hat{\lambda}_{da}^2 - \frac{\omega_r}{\sigma}\tilde{\lambda}_{da}\left(\grave{z}_d + \eta_d - L_{ls}\tilde{\imath}_{ds} - \int_0^t R_s i_{ds} dt\right) + \frac{R_s}{\sigma} i_{ds}\hat{\lambda}_{qa} + \frac{R_r\hat{\lambda}_{da}}{\sigma L_r}\left(z_q - L_{ls}\tilde{\imath}_{qs} - \int_0^t R_s i_{qs} dt\right) + \frac{\tilde{R}_r L_m i_{ds}\hat{\lambda}_{qa}}{\sigma L_r} - \frac{\omega_r}{\sigma}\lambda_{qa}\left(\grave{z}_q + \eta_q - L_{ls}\tilde{\imath}_{qs} - \int_0^t R_s i_{qs} dt\right) - \frac{\widetilde{\omega}_r}{\sigma}\hat{\lambda}_{qa}^2 + \frac{R_r\tilde{\lambda}_{qa}}{L_r\sigma}\left(z_d - L_{ls}\tilde{\imath}_{ds} - \int_0^t R_s i_{ds} dt\right) + \beta\widetilde{\omega}_r i_{qs}\hat{\lambda}_{qa} - c_1 e_T - g_{d2} \quad (24)$$

The torque and flux model are augmented into the following state model:

$$\frac{dX_2}{dt} = A_2X_2 + W_2^T\tilde{\theta}$$
$$X_2 = [e_T \quad e_\lambda]^T$$
$$\tilde{\theta} = [\tilde{R}_r \quad \tilde{\omega}_r \quad \tilde{R}_s\tilde{R} \quad \tilde{R}_\omega \quad \tilde{z}_d\tilde{z}_q \quad \tilde{\eta}_d \quad \tilde{\eta}_q]$$
$$A_2 = diag[-c_1, -c_2]$$

$$w_{31} = \frac{-L_m i_{qs}\hat{\lambda}_{da} + \hat{z}_q\hat{\lambda}_{da} - \hat{\lambda}_{da}L_{ls}\tilde{\iota}_{qs}}{\sigma L_r} + \frac{L_m i_{ds}\hat{\lambda}_{qa} - \hat{z}_d\hat{\lambda}_{qa} + \hat{\lambda}_{qa}L_{ls}\tilde{\iota}_{ds}}{\sigma L_r}$$

$$w_{32} = \frac{\beta i_{ds}\hat{\lambda}_{da}\sigma - \hat{\lambda}_{da}^2 - \hat{z}_d\hat{\lambda}_{da} - \hat{\eta}_d\hat{\lambda}_{da} + \hat{\lambda}_{da}L_{ls}\tilde{\iota}_{ds}}{\sigma} + \frac{\beta i_{qs}\hat{\lambda}_{qa}\sigma - \hat{\lambda}_{qa}^2 - \hat{z}_q\hat{\lambda}_{qa} - \hat{\eta}_q\hat{\lambda}_{qa} + \hat{\lambda}_{qa}L_{ls}\tilde{\iota}_{qs}}{\sigma}$$

$$w_{33} = \frac{-i_{qs}\hat{\lambda}_{da} + i_{ds}\hat{\lambda}_{qa}}{\sigma}$$

$$w_{34} = \frac{-I_{qs}\hat{\lambda}_{da} + I_{ds}\hat{\lambda}_{qa}}{\sigma}$$

$$w_{35} = \frac{I_{ds}\hat{\lambda}_{da} + I_{qs}\hat{\lambda}_{qa}}{\sigma} \quad (25)$$

Sliding Mode Control of Induction Machine

Sliding mode control is an important robust control approach. For the class of systems to which it applies, sliding mode controller design provides a systematic approach to the problem of maintaining stability and consistent performance in the face of modeling imprecision. On the other hand, by allowing the tradeoffs between modeling and performance to be quantified in a simple fashion, it can illuminate the whole design process.

Modeling inaccuracies can have strong adverse effects on nonlinear control systems.One of the most important approaches to dealing with model uncertainty are robust control. The typical structure of a robust controller is composed of a nominal part, similar to a feedback control law, and additional terms aimed at dealing with model uncertainty.

The most important task is to design a switched control that will drive the plant state to the switching surface and maintain it on the surface upon interception. A Lyapunov approach is used to characterize this task.

Lyapunov method is usually used to determine the stability properties of an equilibrium point without solving the state equation. Let V(x) be a continuously differentiable scalar function defined in a domain D that contains the origin. A function V(x) is said to be positive definite if V(0)=0 and V(x)>0 for x. It is said to be negative definite if V(0)=0 and V(x)>0 for x. Lyapunov method is to assure that the function is positive definite when it is negative and function is negative definite if it is positive. In that way the stability is assured.

A generalized Lyapunov function, that characterizes the motion of the state trajectory to the sliding surface, is defined in terms of the surface. For each chosen switched control structure, one chooses the "gains" so that the derivative of this Lyapunov function is negative definite, thus guaranteeing motion of the state trajectory to the surface. After proper design of the surface, a switched controller is constructed so that the tangent vectors of the state trajectory point towards the surface such that the state is driven to and maintained on the sliding surface. Such controllers result in discontinuous closed-loop systems.

Let a single input nonlinear system be defined as

$x^{(n)} = f(x, t) + b(x, t)\, u(t)$ (26)

Here, x (t) is the state vector, u(t) is the control input (in our case braking torque or pressure on the pedal) and x is the output state of the interest (in our case, wheel slip). The other states in the state vector are the higher order derivatives of x up to the (n-1)th order. The superscript n on x(t) shows the order of differentiation. f(x,t) and b(x ,t) are generally nonlinear functions of time and states. The function f(x) is not exactly known, but the extent of the imprecision on f(x) is upper bounded by a known, continuous function of **x** ; similarly, the control gain b(x) is not exactly known, but is of known sign and is bounded by known, continuous functions of x . The control problem is to get the state **x** to track a specific time-varying state $\mathbf{x}_d$ in the presence of model imprecision on f(x) and b(x). A time varying surface s(t) is defined in the state space $\mathbf{R}^{(n)}$ by equating the variable $s(x; t)$, defined below, to zero.

$$s(x;t) = \left(\frac{d}{dt} + \delta\right)^{n-1} \tilde{x}(t) \quad (27)$$

Here, d is a strict positive constant, taken to be the bandwidth of the system, and $\tilde{x}(t) = x(t) - x_d(t)$ is the error in the output state where $x_d(t)$ is the desired state. The problem of tracking the ndimensional vector $\mathbf{x}_d(t)$ can be replaced by a first-order stabilization problem in s. s(x;t) verifying (4.2) is referred to as a sliding surface, and the system's behavior once on the surface is called sliding mode.

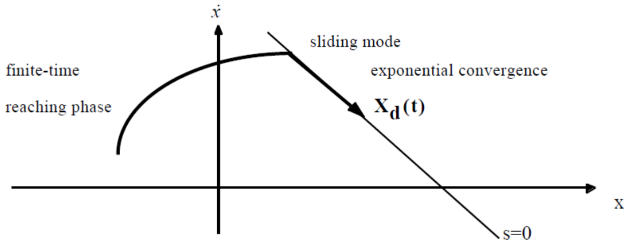

fig. 2 Graphical Interpretation of equation 26

An ideal sliding mode exists only when the state trajectory x(t) of the controlled plant agrees with the desired trajectory at every $t \geq t_1$ for some t_1. The representative point then oscillates within a neighborhood of the switching surface. This oscillation, called chattering, is illustrated on Fig. 3.

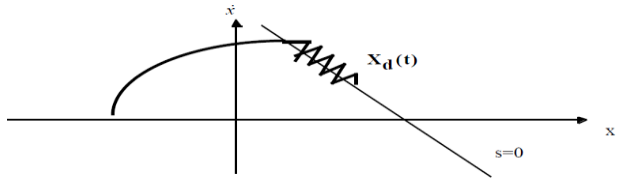

fig.3 Chattering as a result of imperfect control switching.

Space Vector Pulse Width Modulation

SVPWM is the best computational PWM technique for a three phase voltage source inverter because of it provides less THD & better PF. SVPWM works on the principle that when upper transistor is switched ON; corresponding lower transistor is switched OFF. The ON and OFF state of the upper switches (S1, S3, S5) evaluates the output voltages. Switching states and corresponding phase and line voltages are shown in table 1.

In SVPWM the overall power factor & THD has improved as compared to SPWM. Analysis of the output line current Ic in MATLAB Simulink for THD &Power Factor is shown in table 2. It should be noted that power factor reading is overall power factor of the system analyzed by power factor analyzer.

Table 1 switching states and corresponding Phase and Line voltages

Switching states			Phase voltages			Line voltages		
a	b	c	V_a	V_b	V_c	V_{ab}	V_{bc}	V_{ca}
0	0	0	0	0	0	0	0	0
1	0	0	2/3	-1/3	-1/3	1	0	-1
1	1	0	1/3	1/3	-2/3	0	1	-1
0	1	0	-1/3	2/3	-1/3	-1	1	0
0	1	1	-2/3	1/3	1/3	-1	0	1
0	0	1	-1/3	-1/3	2/3	0	-1	1
1	0	1	1/3	-2/3	1/3	1	-1	0
1	1	1	0	0	0	0	0	0

Table 2 Modulation index and corresponding total harmonic distortion with overall power factor.

Modulation Index	THD for Current (%)	Overall PF
0.5	129.62	
0.7	40.71	0.871
0.9	3.42	

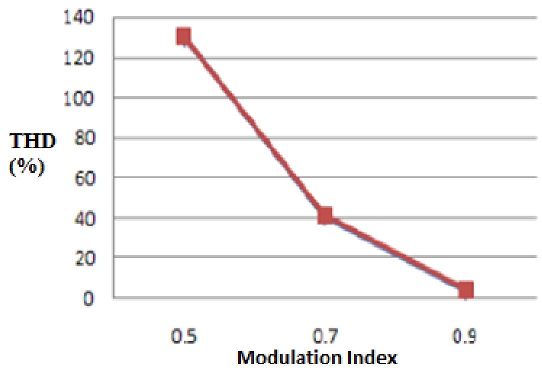

fig. 4 Modulation Index Vs THD in SVPWM

Simulation Results

The developed adaption mechanism has better performance in a wide range of speed compared with that of PI controller, for which performance deteriorates at low speed. The speed estimation by the rotor flux MRAS with sliding mode observer has ensured very good accuracy in both transient and steady state for all ranges of speed control.

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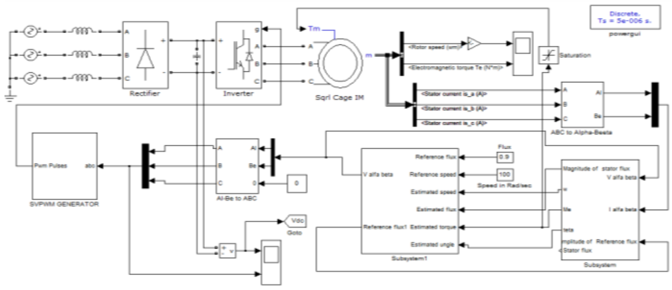

fig.5 Proposed control scheme

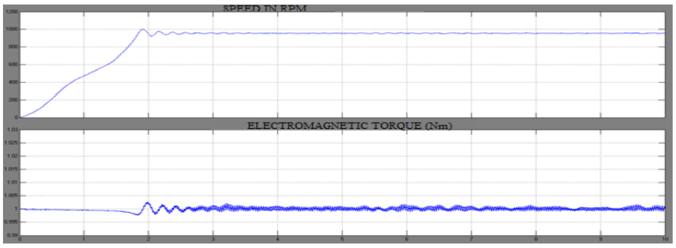

fig. 6 Speed at 980 rad/sec and torque at 1.003 Nm using SVPWM

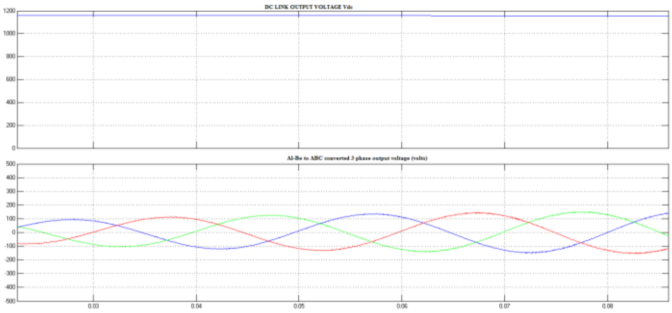

fig. 7 Output voltage of the Rectifier and the three phase voltage after transformation using SVPWM

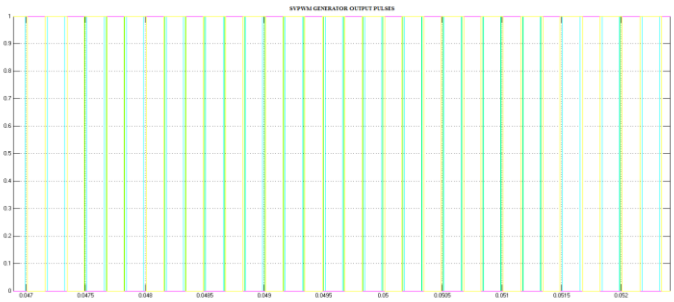

fig. 8 SVPWM generator output pulses

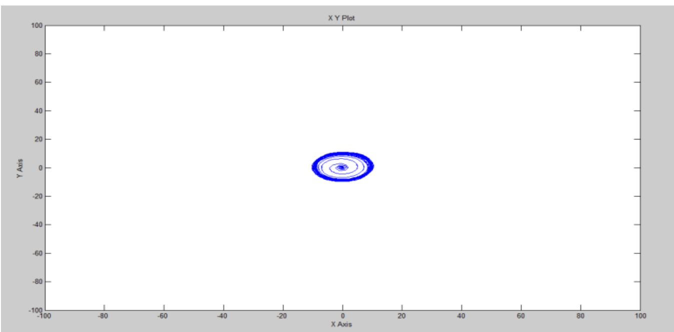

fig.9 overall stability of the system employing SVPWM technique

Comparison with SPWM technique

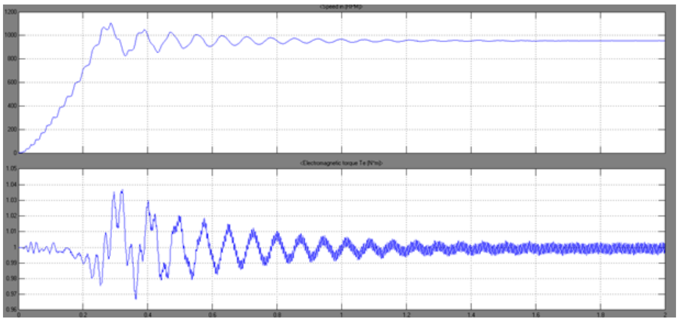

Fig.10 speed and torque output using SPWM technique

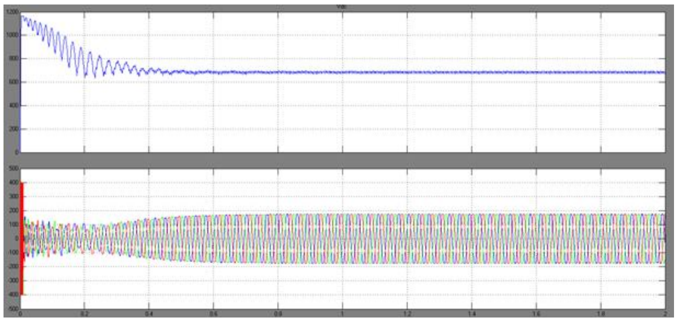

fig. 11 Output voltage of the Rectifier and the three phase voltage after transformation using SVPWM

Conclusion

SVPWM is the best computational PWM technique for a three phase voltage source inverter because of it provides less THD & better PF. SVPMW has greater flexibility to reduce switching losses. The same experiment can be extended by implementing multi-phase inverter. From the stability analysis of the setup, the overall stability of the system is improved and follows the circular trajectory. And the speed of the system is stabled at 980RPM with a torque of 1.003 Nm. The modulation method is carrier-based SVPWM providing unbalanced two-phase output voltages. The simulation results have illustrated the performance of machines both motoring and generating modes. It is found that in case of the motoring mode, the unbalanced voltage SVPWM offers the better machine performance over the balanced voltage SVPWM in terms of torque (T_e) and speed (N_r).

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