International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 02 Issue: 04 | July-2015 www.irjet.net p-ISSN: 2395-0072

Estimation of speed and Parameter identification in Sensorless IM drive By using Second order Sliding-mode Observer and MRAS techniques

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Abstract-***This paper presents a comparitive study of performance of sensor and sensorless IFO IM drives. In case of operation of drives with sensors, has good dynamic performance at high and medium speed operation. Where as at low speed operation, the performance of the drive is not satisfactory. To get satisfactory performance even at low speeds sensorless controlled IM drives with MRAS and Sliding mode observer is designed. Sensorless control has good dynamic response compared to drives with sensor. In a sensorless induction motor drive, A Stator current observer is designed based on the second-order sliding mode which is used as the reference model of the MRAS estimator. The phase angle error between the actual and estimated rotor flux vectors is used to tune the adaptive model of MRAS estimator. The sliding mode observer is insensitive to variation of stator resistance, rotor resistance and perturbation when the states arrive the sliding mode. By making full use of auxiliary sliding-mode surfaces, the proposed observer successfully reduces the chattering behavior. Furthermore, in order to improve the near zero speed operation, a parallel adaptive identification of stator resistance is designed based on derivatives of rotor flux and stator current.***

Key Words: *Induction motors (IMs), model reference adaptive system (MRAS) estimator, supertwisting algorithm Sensorless control, second order sliding mode, parameter estimation, Low speed operation.*

1.INTRODUCTION

Now-a-days induction motors (IM) have replaced DC motors in the industrial applications. High performance sensorless induction motor drives have attracted a great attention in industrial applications due to their advantages such as low cost, less maintenance, and high reliability etc. The sensorless control helps to reduce the cost and resolves installing problems in many applications. There are many different ways to drive an induction motor. The Differences between them are the performance of motor and the cost of implementation. At present efforts are devoted to improve the performance of observer at low speeds, and to develop a robust observer against perturbations and variation of parameters.

Several methods have been proposed to estimate speed and flux of IM such as: Luenberger observer and kalman filter, high gain and adaptive observers, neural networks and signal injection, and sliding mode observer etc. Compared with the other methods, sliding mode techniques has attractive advantage of robustness to disturbances and insensitive to parameter variation when the sliding mode is reached. However, the chattering behavior, that is inherent in standard sliding mode techniques, is often an obstacle for practical applications if neglected. Higher order sliding mode is one of the solutions which does not compromise robustness and avoids filtering estimation considered by other methods.

An improved rotor flux based model reference adaptive system (MRAS) scheme with a parallel rotor speed and stator resistance estimation algorithm is considered. Both the differences in instantaneous phase and amplitudes are used for speed estimation and stator resistance (R_s) identification. In addition, the mismatch of rotor resistance (R_r) introduces errors to the estimated speed in wide speed range operation. Compared with R_s, rotor resistance is more difficult to be identified online since the parallel estimation of speed and rotor resistance is possible only if rotor flux varies, which is not the case in steady state. Since the rotor inductance L_r can be treated as a constant, the rotor time constant identification is equivalent to the R_r identification. So far numerous online parameter estimation techniques have been proposed on the basis of existing speed estimation schemes, which are able to improve dynamic characteristics and noise immunity, as well as insensitivity to parameter variations. In this scheme, both rotor speed and rotor time constant can be estimated by a sliding function based on a second-order system.

Extended kalman filters (EKF) based estimation scheme has significantly increased the accuracy of the estimation of the estimation of the stator and rotor resistances However, they have no specific tuning criteria. Sliding mode observers are recognized for their robustness against parameter variations, yet they suffer from chattering behavior at the same. By using auxiliary sliding mode surface chattering behavior can be reduced.

2. SVM BASED INDIRECT VECTOR CONTROLLED IM DRIVE

Several speed estimation techniques are available, for IM drives. In this case performance of indirect field oriented controlled IM drive specially at low speeds is studied. Simulink diagram of SVM based indirect vector controlled induction motor drive is shown in fig.1.

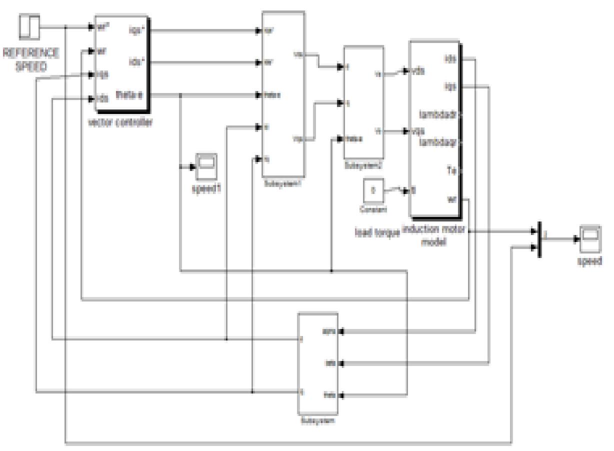


Fig:1 Simulink diagram of IFO IM Drive

This proposed model has good dynamic performance and gives excellent results during high and medium speed operation. But When the drive is operated at low speeds performance of the drive is not satisfactory. To overcome the above disadvantage, Sensorless Induction motor drive is designed by using second order sliding mode observer. Sliding mode observer is robust to perturbations and insensitive to parameter variation. In order to improve near zero speed operation, a parallel adaptive identification of stator resistance is designed based on derivatives of rotor flux and stator current.

2.2 Operation of drive at low speeds

Stator resistance estimation plays an important role in low speed estimation, since the mismatch between the actual value and set value may lead not only to a speed estimation error but also to system instability.

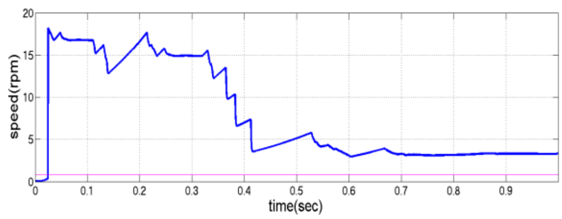


Fig:2 Estimted speed for reference speed of 10 rpm.

In this method, stator resistnace estiamtion is not possible, cosequently operation at low speeds may lead to unstable operation. An improved speed estimation method (especially at low speeds) by using MRAS estimator and sliding mode techiques is discussed in the following case.

3. SENSORLESS IM DRIVE BY USING MRAS AND SLIDING MODE OBSERVER

3.1.second-order smo

The IM in stationary reference frame (α,β) in terms of stator current and rotor flux can be written as follows

$$\begin{cases} pi_{s\alpha} = -(k_1.k_2 + R_s.k_3)i_{s\alpha} + k_3.u_{s\alpha} \\ \qquad +k_2(\psi_{r\alpha}/T_r + w_r.\psi_{r\beta}) \\ pi_{s\beta} = -(k_1.k_2 + R_s.k_3)i_{s\beta} + k_3.u_{s\beta} \\ \qquad +k_2(\psi_{r\beta}/T_r - w_r.\psi_{r\alpha}) \\ p\psi_{r\alpha} = k_1 i_{s\alpha} - \psi_{r\alpha}/T_r - w_r\psi_{r\beta} \\ p\psi_{r\beta} = k_1 i_{s\beta} - \psi_{r\beta}/T_r + w_r\psi_{r\alpha} \end{cases} \quad \ldots.(1)$$

where

$\sigma = 1 - L_m^2/(L_s L_r)$ $\quad k_1 = L_m/T_r$

$k_2 = L_m/(\sigma L_s L_r)$ $\quad k_3 = 1/(\sigma L_s)$

And $i_{s\alpha}, i_{s\beta}, \psi_{r\alpha}, \psi_{r\beta}$ *and* $u_{s\alpha}, u_{s\beta}$ are respectively stator currents, rotor fluxes, and statorvoltages w_r is the angularvelocity. R_s *and* R_r are the stator and rotor resistances. L_s *and* L_r are respectively the stator and rotor inductance. L_m *is*the mutual inductance. σ is the leakage coefficient. T_r is the rotor time constant.

3.2.supertwisting algorithm(STA)

Supertwisting algoritm is generally used in second order sliding mode observer. The finite time convergence and robustness of STA have been proved by geometrical methods, and the continuous stability of STA has been proved by Lyapunov methods.The simplest form of STA can be written as

$$\begin{cases} p\hat{x}_1 = f(\hat{x}_2) + \lambda|x_1 - \hat{x}_1|^{0.5}.sgn(x_1 - \hat{x}_1) + \rho_1 \\ p\hat{x}_2 = \delta.sgn(x_1 - \hat{x}_1) + \rho_2 \end{cases} \quad ...(2)$$

where x_i denotes the state variables, λ and δ are switching gains, and ρ_i represents the perturburation terms. According to Levant and moreno and osorio, it is well known that the STA is robustly stable to perturbations globally bounded by

$$\rho_1 = 0, \quad |\rho_2| \leq L$$

For any positive constant L the gains are approximately selected.

3.3 STA-based observer

The third and fourth terms of (1) can be substituted into the first and second terms; thus(1) is rewritten as

$$\begin{cases} pi_{s\alpha} = -R_s.k_3 i_{s\alpha} - k_2.p\psi_{r\alpha} + k_3.u_{s\alpha} \\ pi_{s\beta} = -R_s.k_3 i_{s\beta} - k_2.p\psi_{r\beta} + k_3.u_{s\beta} \\ p\psi_{r\alpha} = k_1 i_{s\alpha} - \psi_{r\alpha}/T_r - w_r\psi_{r\beta} \\ p\psi_{r\beta} = k_1 i_{s\beta} - \psi_{r\beta}/T_r + w_r\psi_{r\alpha} \end{cases} \quad ..(3)$$

cosidering a variable substitution

$$\begin{cases} z_1 = i_{s\alpha} \\ z_2 = i_{s\beta} \end{cases} \begin{cases} z_3 = -p\psi_{r\alpha} \\ z_4 = -p\psi_{r\beta} \end{cases} \quad ...(4)$$

Where $z_1 - z_4$ *are* the intermediate variables Substituting (4) into (3) yields

$$\begin{cases} pz_1 = -R_s.k_3.z_1 + k_2.z_3 + k_3.u_{s\alpha} \\ pz_2 = -R_s.k_3.z_2 + k_2.z_4 + k_3.u_{s\beta} \end{cases} \quad ...(5)$$

By applying the STA to the IM model (2), a current observer can be constructed as

$$\begin{cases} p\hat{z}_1 = -R_s.k_3.\hat{z}_1 + k_2.\hat{z}_3 + k_3.u_{s\alpha} \\ \qquad +\lambda_1.|e_1|^{0.5}.sgn(e_1) \\ p\hat{z}_3 = \delta_1.sgn(e_1) \end{cases} \quad ...(6)$$

$$\begin{cases} p\hat{z}_2 = -R_s.k_3.\hat{z}_2 + k_2.\hat{z}_4 + k_3.u_{s\beta} \\ \qquad +\lambda_2.|e_2|^{0.5}.sgn(e_2) \\ p\hat{z}_4 = \delta_2.sgn(e_2) \end{cases} \quad ....(7)$$

Where $\hat{z}_1, \hat{z}_2, \hat{z}_3, \hat{z}_4$ *are* the observations. λ_1, λ_2 *and* δ_1, δ_2 are respectively the gains of the primary and auxiliary sliding-mode surfaces. sgn() represents the sign function. e_1 *and* e_2 *arethe* errors, which are defined *as* $e_1 = z_1 - \hat{z}_1$ *and* $e_2 = z_2 - \hat{z}_2$. $R_s, k_2,$ *and* k_3 are treated as constants in the observer.

According to (4), there exists a simple relation between the observations $\hat{z}_3$ *and* $\hat{z}_4$ *andthederivatives* of rotor flux

$$\begin{pmatrix} -\hat{z}_3 \\ -\hat{z}_4 \end{pmatrix} = \begin{pmatrix} p\hat{\psi}^z_{r\alpha} \\ p\hat{\psi}^z_{r\beta} \end{pmatrix} = p\hat{\psi}^z_r \quad .....(8)$$

where $p\hat{\psi}^z_r = \left[p\hat{\psi}^z_{r\alpha} p\hat{\psi}^z_{r\beta}\right]^T$ represents the estimated results with the physicsl significance of "derivatives of rotor flux."

3.4 proposed observer with perturbation

Equations (6) and (7) aredecoupled,so their distrubance characteristics can be analysed independently. Considering (6) only and taking parameter variation into consideration,we get the following form

$$\begin{cases} p\hat{z}_1 = -R_s.k_3.\hat{z}_1 + k_2.\hat{z}_3 + k_3.u_{s\alpha} \\ \qquad +\lambda_1.|e_1|^{0.5}.sgn(e_1) + \rho_{z1} \\ p\hat{z}_3 = \delta_1.sgn(e_1) + \rho_{z3} \end{cases} \quad ...(9)$$

The perturbation caused by variation of the stator parameter can be converted into ρ_{z1}.Similarly, ρ_{z3} represents the perturbation caused by the variation of the rotor parameter.

According to STA, for every positive value of L there exist such gains $\lambda_1$andδ_1 that the observations of(9),i.e., $\hat{z}_1$ *and* $\hat{z}_3$ are robust against perturbation $\rho_{z3} \leq L$.

STA based observer is sensitive to ρ_{z1}, which is primarily composed of the variation of R_s. R_s identification plyas an important role in low speed estimation since the

International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 02 Issue: 01 | Jan-2015 www.irjet.net p-ISSN: 2395-0072

mismatch between the actual value and set value may lead not only to a speed estimation error but also to system instability. On the other hand R_s can still be treated as constant in (6) and (7) because it varies slowly compared to electrical signal.
In discrete time, the kth observation error is calculated by e(k)=z(k)-$\hat{z}(k)$, where z(k) is real component, $\hat{z}(k)$ is estimated one. Thus, e(k-1) is the (k-1)th observation error, which is used to calculate the estimated $\hat{z}(k)$.

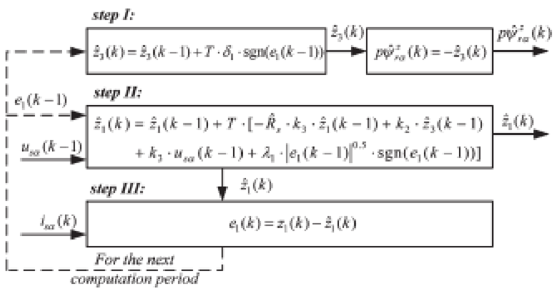


Fig-3:Flowchart of discrete-time STA based observer

If the gains are selected according to the conditions that they presented, the error states are ultimately bounded. In other words, the trajectories of system enter into a boundary layer in the victinity of the sliding mode and stay inside it forever. This algorithm is termed as supertwisting-like algorithm. For The continuous second-order SMO shown in (6) and (7) the discrete observer is obtained. The gains of the discrete STA based observer should satisfy the necessary and sufficient conditions for the existence of the sliding-mode hyperplane in discrete time. The conditons were obtained by using Lyapunov function.

$$V_k = e^2(k) \quad \text{...(10)}$$
$$\Delta V_k = e^2(k+1) - e^2(k)$$

The necessary and suficient conditions to ensure the sliding motion on the hyperplane are obtained

[e(k+1)-e(k)].sgn(e(k))<0

4 SPEED ESTIMATION SHEME

4.1.Standard MRAS speed estimator

MRAS speed estimation makes use of two machine models with different structures that estimate the same motor state. The motor states may be rotor flux, back emf or reactive power etc. Choosing the rotor flux to be the state, the estimation error can be

$$\varepsilon = \psi_{r\alpha}^{i}\psi_{r\beta} - \psi_{r\beta}^{i}\psi_{r\alpha} \text{ ...(11)}$$

The phase angle error between actual and estimated rotor flux vectors is used to tune the speed as is illustrated in fig.4.

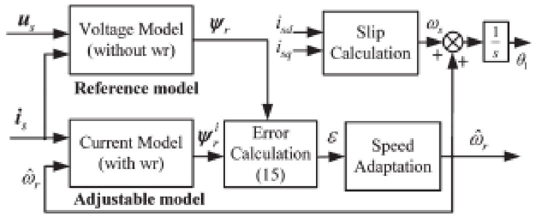


Fig-4:Block diagram of standard rotor based MRAS estimator.

4.2.Proposed MRAS speed estimator

In proposed estimator derivatives of rotor flux is used as state, an adaptive mechanism of speed based on these observations is required. For speed estimation, the output of reference model is regarded as equal to the actual rotor flux vector , and Hence

$$pe_{\psi}^{i} = \begin{bmatrix} p\psi_{r\alpha}^{i} - p\hat{\psi}_{r\alpha}^{i} \\ p\psi_{r\beta}^{i} - p\hat{\psi}_{r\beta}^{i} \end{bmatrix} \begin{bmatrix} p\hat{\psi}_{r\alpha}^{z} - p\hat{\psi}_{r\alpha}^{i} \\ p\hat{\psi}_{r\beta}^{z} - p\hat{\psi}_{r\beta}^{i} \end{bmatrix} \quad \text{...(12)}$$

Eventually the estimation equation of rotorspeed is

$$\hat{w}_r = (k_p + k_i/p).e_w \quad \text{...(13)}$$

where

$$e_w = -p\hat{\psi}_{r\alpha}^{z}.p\hat{\psi}_{r\beta}^{i} + p\hat{\psi}_{r\beta}^{z}.p\hat{\psi}_{r\alpha}^{i} \quad \text{...(14)}$$

Compared with the standard MRAS speed estimation, the proposed speed estimator eliminates the integrators, thus simplifying the system and avoiding the problems caused by integration.

4.3 Parallel R_s identification

Stator resistance (R_s) plays an important role in low-speed estimation since the mismatch between the actual value and set value may lead not only to a speed estimation error but also to system instability. The offline estimation of R_s is not sufficient because the actual value varies due to complex reasons, such as temperature. Parallel R_s estimation is based on derivatives of rotor flux. In case of parallel R_s estimation reference model and adjustable model exchange their roles.

Symbols ψ_r^z and $\hat{\psi}_r^z$ respectively stand for actual and estimated rotor flux vectors of voltage model

The voltage model of IM can be written as

$$p\psi_r^z = \frac{L_r}{L_m}[u_s - (R_s.i_s + \sigma L_s.pi_s)] \qquad ...(15)$$

The observer equation is

$$p\hat{\psi}_r^z = \frac{L_r}{L_m}[u_s - (R_s.\hat{i}_s + \sigma L_s.p\hat{i}_s)] \qquad ...(16)$$

When the estimation error trajectory reaches the sliding mode, we get $\hat{i}_s = i_s$ Eventually the estimation of stator resistance obtaned as

$$\hat{R}_s = (k_p + k_i/p).e_R \qquad ...(17)$$

where

$$e_R = \hat{z}_1.(p\hat{\psi}_{r\alpha}^z - p\hat{\psi}_{r\alpha}^i) + \hat{z}_2(p\hat{\psi}_{r\beta}^z - p\hat{\psi}_{r\beta}^i)..(18)$$

R_s is treated as constant in the STA-based observer because it changes much slower than electric signals such as stator voltage and current.

4.4.SSM scheme

The proposed SSM sheme used in this paper is a combination of STA-based SMO and MRAS estimator which isnamed as SSM scheme. The configuration of the SSM scheme is shown in fig.5.

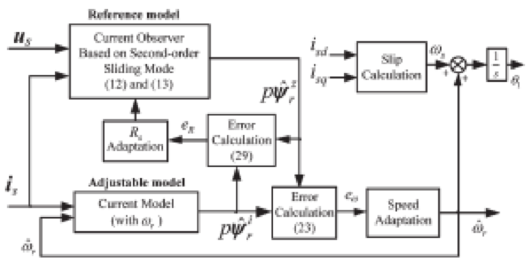


Fig-5:Block diagram of the proposed SSM scheme

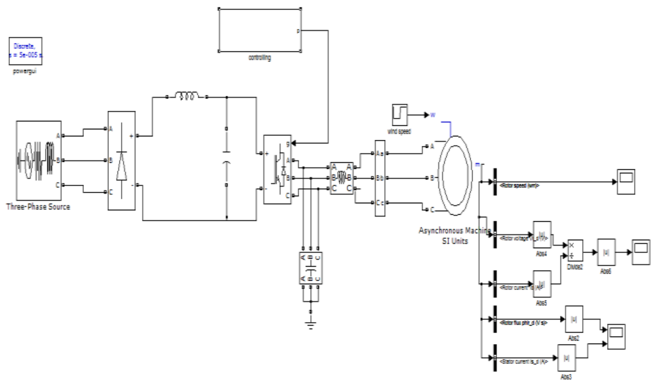


Fig-6:simulink diagram of sensorless IM drive

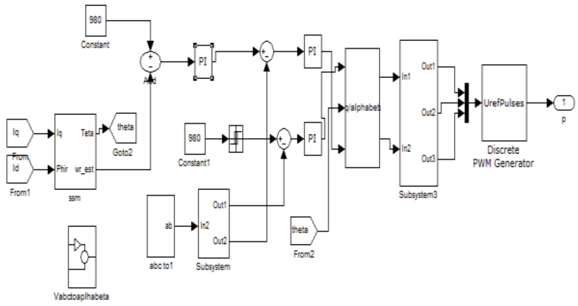


Fig-7:Simulink diagram of controlling technique

TABLE 1

PARAMETERS OF THE IM DRIVE

Parameter	Value	Parameter	Value
Rated power(kw)	15	Stator resistance(Ω)	1.556
Rated voltage(V)	380	Rotor resistance(Ω)	1.31
Rated current(A)	18.5	Stator inductance(mH)	0.156
Rated speed(rpm)	980	Rotor inductance(mH)	0.162
Rated frequency(Hz)	50	Mutual inductance(mH)	0.15
Number of poles	3	Inertia(kg-m^2)	0.06

The mathematical model of IM is built according to the rated parameters given in Table1

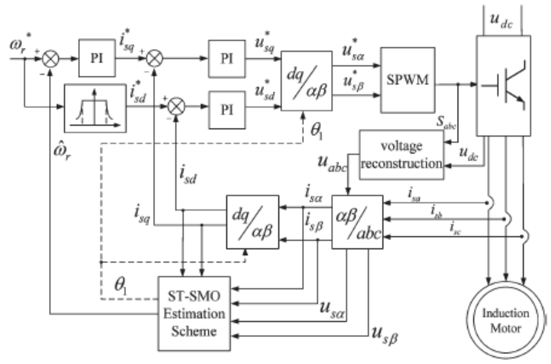


Fig-8: Block diagram of sensorless IFO cintrolled IM drive

5.SIMULATION RESULTS

The proposed scheme is verified by simulation. The Simulink model of sensorless indirct field oriented controlled IM drive is shown in fig.6.

The pulse width modulation (PWM) frequency is set to 10 kHz, which is the same frequency as the sampling rate of the SSM scheme. The motor phase voltages are reconstruced relying on the dc voltage and PWM duty cycles. The gains are set to

$\lambda_1 = \lambda_2 = 6000$ and $\delta_1 = \delta_2 = 40000$
which satisfies the limits discussed in section2.

5.1 Low speed operation

The performance of parallel R_s identification is tested in low speed operation. Which is shownin fig.9. In this case the machine is operating with a torque of 20-N.m load at speed 10 rpm, and the actual R_s is sharply increased from 1.6 to 2.1Ω at t=3sec, the estimated R_s value keeps in step with the actual one, thus consequently eliminating the initial speed estimation error.

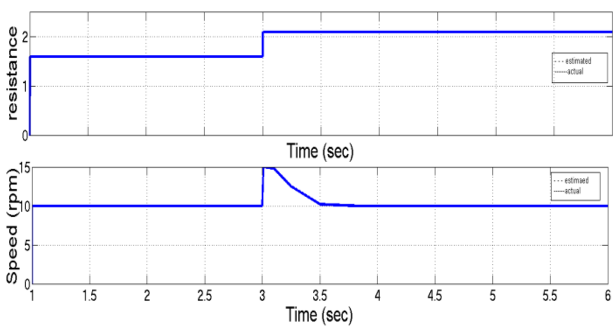


Fig-9: Speed estimation and stator resistance estimation at speed command of 10 rpm and sharp variation of stator resistance

5.2 Observability verification

The IM motor observability cannot be established in the particular case when the rotor fluxes and the speed are constant. Operation of drive in this case can be represented as unobservability curve. It is significant to verify the performance of the proposed SSM scheme in one point of the unobservability curve. The SSM scheme is teseted in open loop in order to achieve the particular case . The test rotor flux is set to 1.5 Wb, and the load is 50 Nm. According to the unobservability curve, an angular speed of -3.21 rps corresponds to the codition of loss of observability.

In fig.10 the IM is tested with an initial speed of 20 rps and a 50 Nm load (start at 0.5sec and ready at 0.7sec), followed by a speed of 80 rps (from 2sec to 3 sec), then by a speed of -3.21rps (from 4sec to 5sec), and finally by a speed of 25 rps (from 6 to 7) . The simulation result show that the proposed scheme is stable under unobservable conditions.

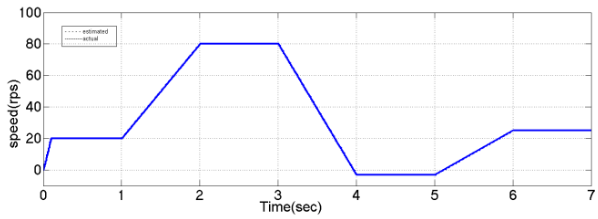
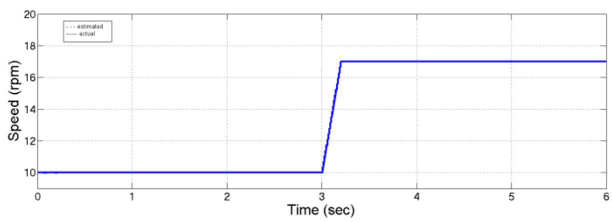


Fig-10:Actual and estimated speeds under the codition of loss of observability

5.3 variation of R_r

The robustness of the proposed observer is tested with sensorless control and a 10 Nm. At time t=3sec the give speed is changed from 9 to 18 rpm; meanwhile R_r is changed from 1.3 to 1.7 Ω during 0.2 sec. The observations $\hat{z}_1(i_{s\alpha})$ and $\hat{z}_3(-p\psi_{r\alpha})$ are insensitive to this perturbation. Furthermore, the STA based observer reaches convergence in a finite time (about 0.1sec), which causes the starting time perturbation of speed estimation in fig.11.



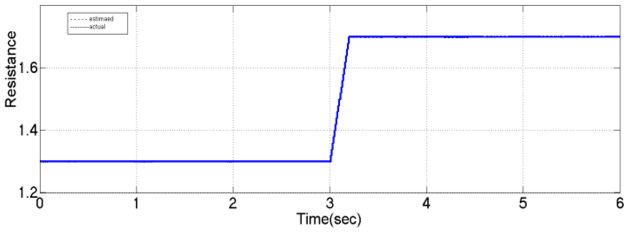


Fig-11: Observation results with R_r variation.

5.4 High speed operation

Fig.12 contrasts the actual and estimated speeds during the acceleration process(150rpm-600rpm-1000rpm) with a 50 Nm load and sensorless control. By utilising the SSM scheme, the system operates stably, and the speed error is acceptable.

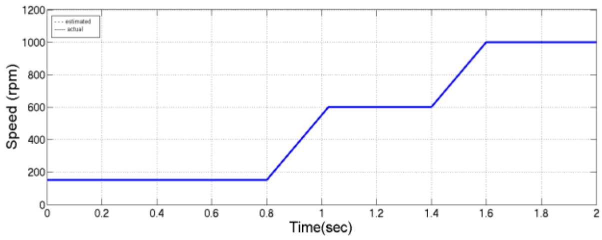


Fig-12:.Actual and estimated speeds at acceleration process (150 rpm-600 rpm-1000rpm).

6.CONCLUSION

The disadvantages of induction motor drives with sensors in low speed operation are overcomed by using sensorless control. Sensorless control has good dynamic performance, robust to perturbations and also insensitive to parameter variations. This paper presents a modified speed-sensorless control scheme based on second order sliding-mode STA and MRAS estimatior. The estimation scheme has been obtained by combinig a second order sliding mode current observer with a parallel speed and stator resistance estimator based on rotor flux based MRAS. Both the error in instantaneous phase position and the error in amplitudes are used respectively for speed estimation and R_s estimation, thus ovecoming the problems of $R_s$variation, paricularly for low speed operation.

The STA based observer is used as the reference model of the standard MRAS. Derivatives of rotor flux are obtained and designed as the states of MRAS, thus eliminating the integration. Moreover, by making full use of auxilary surfaces, the observations are insensitive to rotor parameter perturbation and also the chattering behavior reduced at the same time. However, since the scheme is designed bsed on the mathematical model of IM, its observability is generally lost at zero magnetic field frequency.

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