Analysis of Flux Observers Using Parameter Sensitivity

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Abstract - To achieve a high performance in direct vector control of induction motor, it is essential to correct estimation of rotor flux. The accuracy of flux observers for induction machines inherently depends on parameter sensitivity.
This paper presents an analysis method for conventional flux observers using Parameter Sensitivity. The Parameter sensitivity is defined as the ratio of the percentage change in the system transfer function to the percentage change of the parameter variation. We define the ratio between real flux and estimated flux as the transfer function, and analyzed a parameter sensitivity of this transfer function by simulation.

I. INTRODUCTION

It is very important to note that the performance of the direct vector control drive in induction machines will depend greatly on the accuracy of the estimated rotor flux linkage component, and these depend on the accuracy of the monitored voltages and currents, and also motor parameters.

Motor parameters, which are varied with the operating conditions of induction machine, affect the incorrect rotor flux estimation. Therefore it requires considerations for the influence of the rotor flux estimation according to the variation of the motor parameters.

The paper focuses on the concept of the parameter sensitivity to analyze the influence of the rotor flux estimation according to the variation of the motor parameters. The degree to which changes in system parameters affect system transfer functions, and hence performance, is called system sensitivity. The greater the sensitivity, the less desirable is the effect of a parameter change. In this paper, system transfer function is defined the ratio between real rotor flux and estimated rotor flux, and the estimated rotor flux error involved in the conventional flux observers(Voltage model, Current model, Improved Gopinath model, Modified Improved Gopinath model) is analyzed with the system sensitivity. This analysis is performed with Matlab/Simulink.

II. FLUX OBSERVERS

A. Voltage Model Flux Observer

The voltage model utilizes the stator voltage equation with directly measured stator voltage and stator current.
The rotor flux is obtained by following equations.

$$\begin{aligned} \underline{\lambda}_s^s &= \int(\underline{v}_s^s - R_s \underline{i}_s^s)dt \\ \underline{\lambda}_r^s &= \frac{L_r}{L_m}(\underline{\lambda}_s^s - \sigma L_s \underline{i}_s^s) \end{aligned} \tag{1}$$

At high speed range the machine back emf dominates the measured terminal voltage. But at low speed range the stator voltage drop becomes significant causing the accuracy of the flux estimate to be sensitive to the stator resistance. Therefore it is difficult to estimate accurate rotor flux and the integrator is easily saturated by parameter offset.

B. Current Model Flux Observer

The current model utilizes rotor voltage equation represented by rotor flux and stator current in the stator reference frame. The rotor flux can be calculated by the integration of following equation,

$$P\underline{\lambda}_r^s = -(\frac{R_r}{L_r} - j\omega_r)\underline{\lambda}_r^s + R_r\frac{L_m}{L_r}\underline{i}_s^s \tag{2}$$

Where p is the differential operator. To estimate the rotor flux linkage, it is necessary to use the rotor resistance and rotor inductance, but variation of these parameters affect the accuracy of the estimated rotor flux value.

C. Improved Gopinath Model Flux Observer

The block diagram of "Improved Gopinath model" flux observer is depicted in Fig. 1, which is proposed, by P. L. Jansen and R. D. Lorenz, 1994[3].

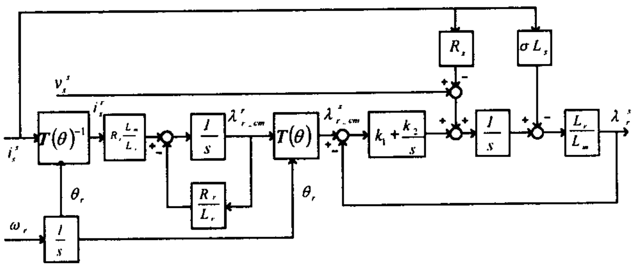


Fig. 1 Closed-Loop "Improve Gopinath model" flux observer

The "Improved Gopinath model" flux observer is seen to provide an automatic transition between the two desirable open-loop flux observer models: the current model at low speeds to the voltage model at high speeds. The transition is determined via the bandwidth of the flux loop.

The estimated rotor flux can be divided the voltage model and the current model respectively by using observer characteristic function [4], as follow

$$\begin{aligned} \underline{\lambda}_r^s &= F(s)(\underline{\lambda}_{r_{vm}}^s - \underline{\lambda}_{r_{cm}}^s) + \underline{\lambda}_{r_{cm}}^s \\ &= F(s)\underline{\lambda}_{r_{vm}}^s + (1 - F(s))\underline{\lambda}_{r_{cm}}^s \end{aligned} \quad (3)$$

$\underline{\lambda}_{r_{vm}}^s$: Estimated rotor flux from the voltage model

$\underline{\lambda}_{r_{vm}}^s$: Estimated rotor flux from the current model

$$F(s) = \frac{s^2}{s^2 + K_p s + K_i} \quad (4)$$

Where, *F(s)* denotes observer characteristic function.

The Frequency response function of the observer characteristic function is as follow,

$$F(j\omega_e) = \frac{\omega_e^2}{\sqrt{(K_i - \omega_e^2)^2 + (K_p\omega_e)^2}} \times e^{j(\pi - \tan^{-1}(\frac{K_p\omega_e}{K_i - \omega_e^2}))} \quad (5)$$

The transition frequency can be determined as the cutoff frequency of the second order Butterworth filter.

$$K_p = K_1\frac{L_r}{L_m}, \quad K_i = K_2\frac{L_r}{L_m}$$

$$K_p = \sqrt{2}\,\omega_c, \quad K_i = \omega_c^2$$

where ω_c is the cutoff frequency of the second order Butterworth filter.

D. Modified Improved Gopinath Model Flux Observer

The block diagram of "Modified Improved Gopinath model" flux observer is depicted in Fig. 1, which proposed by J. H. Kim and J. W. Choi [4].

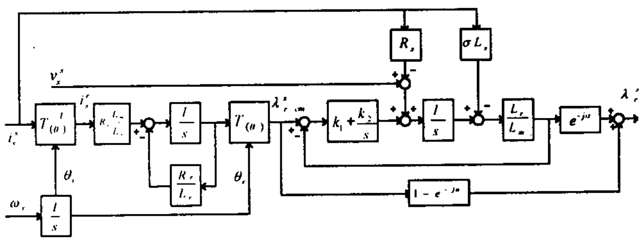


Fig. 2 Closed-Loop "Modified Improved Gopinath model" flux observer

The basic design concept of this flux observer is the same as "Improved Gopinath model".

$$\begin{aligned} \underline{\lambda}_r^s &= F(s)(\underline{\lambda}_{r_{vm}}^s - \underline{\lambda}_{r_{cm}}^s) + \underline{\lambda}_{r_{cm}}^s \\ &= F(s)\underline{\lambda}_{r_{vm}}^s + (1 - F(s))\underline{\lambda}_{r_{cm}}^s \end{aligned} \quad (6)$$

$$F(s) = \frac{s^2}{s^2 + K_p s + K_i} e^{-j\alpha} \quad (7)$$

where $\alpha = \pi - \tan^{-1}(\frac{K_p\omega_e}{K_i - \omega_e^2})$

α is the angle of observer characteristic function of "Improved Gopinath model". The observer characteristic function is represented in the frequency domain as follow

$$F(j\omega_e) = \frac{\omega_e^2}{\sqrt{(K_i - \omega_e^2)^2 + (K_p\omega_e)^2}} \quad (8)$$

III. Parameter Sensitivity

The Parameter sensitivity is defined as the ratio of the change in the system transfer function to the change of parameters, and it is expressed in equation (8).

$$S_\alpha^T = \frac{\Delta T / T}{\Delta \alpha / \alpha} = \frac{\alpha}{T}\frac{\Delta T}{\Delta \alpha} \tag{9}$$

T : *System Transfer function*

α : *System parameter*

S_α^T : *System sensitivity*

For small incremental changes,

$$S_\alpha^T = \frac{\partial T / T}{\partial \alpha / \alpha} = \frac{\alpha}{T}\frac{\partial T}{\partial \alpha} \tag{10}$$

The error of system transfer function caused by system parameter variation can be expressed as follow,

$$\Delta T = S_\alpha^T T \frac{\Delta \alpha}{\alpha} \tag{11}$$

System transfer function is defined the ratio between real rotor flux and estimated rotor flux as follow,

$$T_{vm} = \frac{\hat{\underline{\lambda}}_{r_{vm}}^s}{\underline{\lambda}_{r_{vm}}^s} = \frac{L_m \hat{L}_r}{\hat{L}_m L_r}[1 + \frac{L_r^2}{R_r L_m^2}(\frac{R_r}{L_r} + j\omega_s) \times ((\sigma L_s - \hat{\sigma} \hat{L}_s) - j\frac{(R_s - \hat{R}_s)}{(\omega_s + \omega_r)})] \tag{12}$$

$$T_{cm} = \frac{\hat{\underline{\lambda}}_{r_{cm}}^s}{\underline{\lambda}_r^s} = \frac{(\hat{R}_r \frac{\hat{L}_m}{\hat{L}_r})(\frac{R_r}{L_r} + j\omega_s)}{(R_r \frac{L_m}{L_r})(\frac{\hat{R}_r}{\hat{L}_r} + j\omega_s)} \tag{13}$$

T_{vm} : System transfer function of voltage model

T_{cm} : System transfer function of current model

$\hat{\underline{\lambda}}_{r_{vm}}^s$: Estimated rotor flux from voltage model

$\hat{\underline{\lambda}}_{r_{vm}}^s$: Estimated rotor flux from current model

where, ^ denotes estimated value.

Estimated rotor flux can be divided into real rotor flux and rotor flux error produced by parameter variation.

$$\hat{\underline{\lambda}}_{r_{vm}}^s = \underline{\lambda}_r^s + \Delta \underline{\lambda}_{r_{vm}}^s$$

$$\hat{\underline{\lambda}}_{r_{cm}}^s = \underline{\lambda}_r^s + \Delta \underline{\lambda}_{r_{cm}}^s \tag{14}$$

$$\hat{\underline{\lambda}}_r^s = \underline{\lambda}_r^s + \Delta \underline{\lambda}_r^s$$

Equation (13) can be obtained from equation (10), (11), (12).

$$\frac{\hat{\underline{\lambda}}_r^s}{\underline{\lambda}_r^s} = 1 + \frac{\Delta \underline{\lambda}_r^s}{\underline{\lambda}_r^s} = T = 1 + \Delta T \tag{15}$$

If all motor parameters are exactly estimated T=1 if not T=1+ΔT. Therefore the ratio between the real rotor flux and the rotor flux error can be expressed as follow

$$\frac{\Delta \underline{\lambda}_r^s}{\underline{\lambda}_r^s} = \Delta T = S_\alpha^T T \frac{\Delta \alpha}{\alpha} = S_\alpha^T \frac{\Delta \alpha}{\alpha} \tag{16}$$

$$\Delta \underline{\lambda}_{r_{vm}}^s = \underline{\lambda}_r^s S_\alpha^T \frac{\Delta \alpha}{\alpha}$$

$$\Delta \underline{\lambda}_{r_{cm}}^s = \underline{\lambda}_r^s S_\alpha^T \frac{\Delta \alpha}{\alpha}$$

Equation (17) deduced from equation (3), (6), (14)

$$\underline{\lambda}_r^s + \Delta \underline{\lambda}_r^s = F(s)[(\underline{\lambda}_r^s + \Delta \underline{\lambda}_{r_{vm}}^s) - (\underline{\lambda}_r^s + \Delta \underline{\lambda}_{r_{cm}}^s)] + (\underline{\lambda}_r^s + \Delta \underline{\lambda}_{r_{cm}}^s) \tag{17}$$

Equation (18) can be obtained substituting the error term from equation (17)

$$\Delta \underline{\lambda}_r^s = F(s)\Delta \underline{\lambda}_{r_{vm}}^s + (1 - F(s))\Delta \underline{\lambda}_{r_{cm}}^s \tag{18}$$

Equation (18) can be expressed as follow, concerning parameter sensitivity,

$$S_\alpha = F(s) S_\alpha^{T_{vm}} + (1 - F(s)) S_\alpha^{T_{cm}} \tag{19}$$

$S_\alpha^{T_{vm}}$: Parameter sensitivity of voltage model

$S_\alpha^{T_{cm}}$: Parameter sensitivity of current model

In case of the voltage model and the current model, parameter sensitivity is obtained by equation (10). And In the other case, parameter sensitivity is obtained by equation (19)

IV. Simulation Result

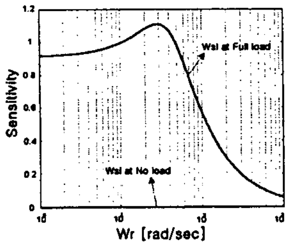
In order to show the influence of parameter variation for flux observers, digital simulation has been carried out digital simulation with the parameter sensitivity. Ratings of the tested induction motor are shown in Table 1.

Table 1. Motor Data

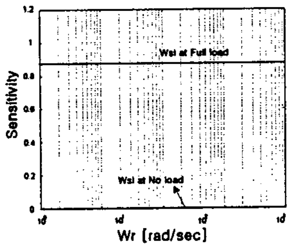
Rated output power	2.2 [kw]
Rated voltage	230 [V]
Rated Current	8.8 [A]
Poles	4
Stator Resistance	0.20 [Ω]
Rotor Resistance	0.20 [Ω]
Stator leakage inductance	1.5 [mH]
Rotor leakage inductance	1.5 [mH]

Mutual inductance	32.3 [mH]
Inertia	0.045 [kg·m^2]
Cutoff frequency	50 [rad/sec]

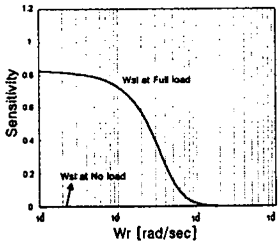
The parameter sensitivity of the conventional flux observers is shown in Figs. 3 ~ 7. R_r, R_s, L_m alternating between ±20% are applied to analysis and L_{ls}, L_{lr} alternating between ±10% are considered too.



(a) Current model

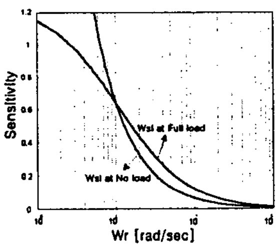


(b) voltage model

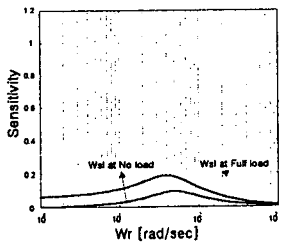


c) Improved Gopinath model

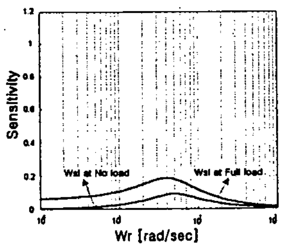
Fig. 3 Sensitivity for R_r



(a) Voltage model

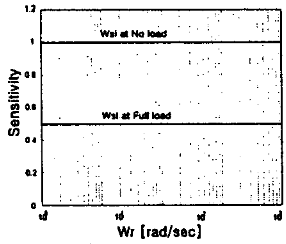


(b) Improved Gopinath model

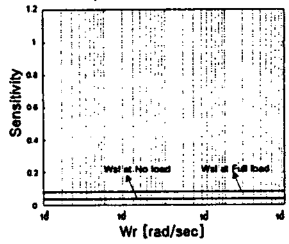


(c) Modified Improved Gopinath model

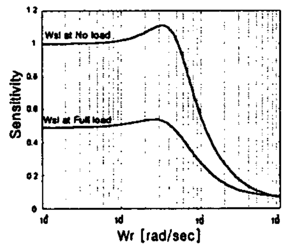
Fig. 4 Sensitivity for R_s



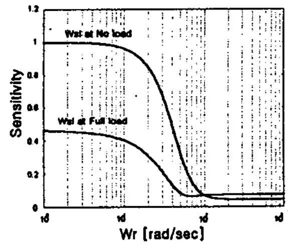
(a) Current model



(b) Voltage model

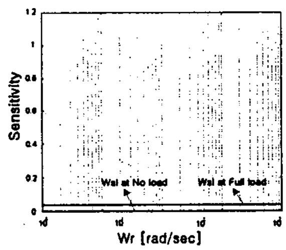


(c) Improved Gopinath model

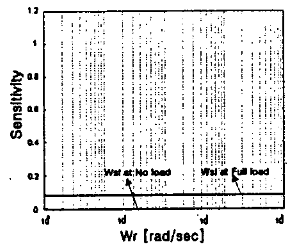


(d) Modified Improved Gopinath model

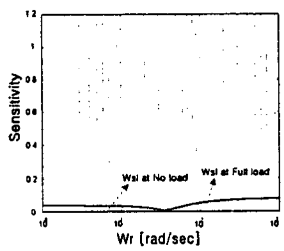
Fig. 5. Sensitivity for L_m



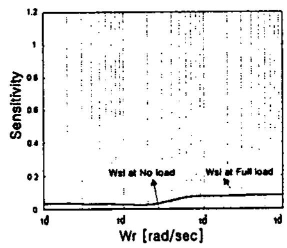
(a) Current model



(b) Voltage model

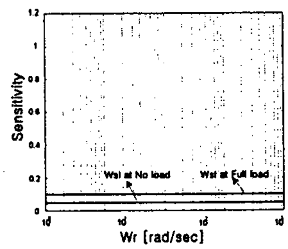


(c) Improved Gopinath model

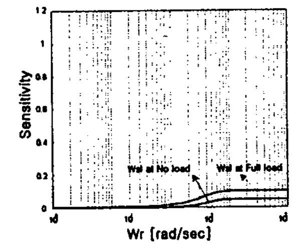


(d) Modified Improved Gopinath model

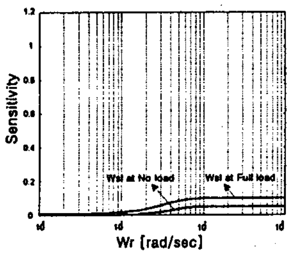
Fig. 6. Sensitivity for L_{lr}



(a) Voltage model



(b) Improved Gopinath model



(c) Modified Improved Gopinath model

Fig. 7. Sensitivity for L_{ls}

V. Conclusion

This paper has presented an analysis method for the effect of motor parameter variation to flux observers and has analyzed conventional flux observers by simulation.

In case of the voltage model, the variation of the stator resistance mainly affect to the parameter sensitivity in a low speed range. The current model produces constant error in a wide speed range. The error associated with the variation of L_m and R_r, is occurred nearby the cutoff frequency for the improved gopinath model. But the modified improved gopinath model shows a good performance nearby the cutoff frequency. The proposed method of the parameter sensitivity analysis can be applied to other flux observers, also it can be used to design the flux observer.

References

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