MICHIGAN STATE UNIVERSITY

Experimental Verification of Sensorless Speed Control of Induction Motor

Sinisa Jurkovic, jurkovi4@egr.msu.edu
Elias G. Strangas, strangas@egr.msu.edu
Hasan K. Khalil khalil@egr.msu.edu

Objective

The speed sensor feedback is replaced by the speed estimate based on the measurements of voltages and currents on motor terminals.

Novel closed loop speed and flux observers are proposed, based on sixth order nonlinear model that describes the motor in field-oriented coordinates.

Speed regulation is simplified by assuming that flux regulation is relatively fast, and regulating q-axis current to its commanded value. This results in simplified third order nonlinear model in which speed and flux errors are state variables, q-axis current is controlled input and speed from high-gain observer is measured output.

Induction Motor Model

$$\begin{aligned} \frac{d}{dt}\lambda_r &= \Big(-\frac{R_r}{L_r}I + p\omega J\Big)\lambda_r + \frac{R_r}{L_r}L_m i_s\sigma \\ L_s\frac{d}{dt}i_s &= -\frac{L_m}{L_r}\Big(-\frac{R_r}{L_r}I + p\omega J\Big)\lambda_r - \Big(R_s + \frac{R_r L_m^2}{L_r^2}\Big)i_s + v_s \\ m\frac{d\omega}{dt} &= -\frac{3pL_m}{2L_r}\lambda_r^T J i_s - b_1\omega - \frac{1}{m}T_L \end{aligned}$$

Field Orientation

Assuming that flux has a magnitude λ_R and it is at the angle ρ in stationary frame of reference we can write the following:

$$\begin{pmatrix} i_{qse} \\ i_{dse} \end{pmatrix} = \frac{2}{3}\begin{pmatrix} sin\rho & sin(\rho - \frac{2\pi}{3}) & sin(\rho + \frac{2\pi}{3}) \\ cos\rho & cos(\rho - \frac{2\pi}{3}) & cos(\rho + \frac{2\pi}{3}) \end{pmatrix}\begin{pmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{pmatrix}$$

$$i_s = \sqrt{(i_{qse})^2 + (i_{dse})^2} \qquad \theta_s = tan^{-1}(\frac{i_{qse}}{i_{dse}})$$

Iq is also known as speed or torque current, while Id is flux current.

Field Oriented Control of Induction Motor is based on controlling these two components of current Is.

Flux Observer

For field orientation it is necessary to know magnitude and angle of rotor flux λ_R. Since λ_R is not measured we use open loop observer to estimate it.

The observer duplicates equation (1) from above, where unknown speed ω is replaced by itís reference ω_{REF}.

$$\frac{d}{dt}\hat{\lambda}_r = (-\frac{\hat{R}_r}{L_r}I + p\omega_{ref}J)\hat{\lambda}_r + \frac{\hat{R}_r}{L_r}L_m i_s$$

Transforming everything in rotor flux, λ_R frame of reference we obtain the sixth order non linear model of the machine

Flux Regulation

λ_d Is regulated to $\lambda_{REF} > 0$. Traditional approach of doing this is using PI Controllers.

First Id is treated as control input and PI controller is designed as:

$$I_d^* = \frac{(K_{fp}s + K_{fi})}{s}[\lambda_{ref} - \lambda_d]$$

And second PI controller is designed as:

$$V_d = \frac{(K_{dp}s + K_{di})}{s}[I_d^* - I_d]$$

With tight feedback loops it ensured that λ_d is regulated to λ_{REF}, and moreover λ_d starts at positive value and approaches λ_{REF} monotonically so is always positive.

Speed Observer

A high gain observer is utilized to estimate rotor speed

$$\begin{aligned} \frac{di_q}{dt} &= -\beta p\omega\lambda_d - f_1(\lambda_d, i_d, i_q, w_{ref}) + \gamma v_q + \delta_1 \\ \frac{d\omega}{dt} &= \hat{\mu} i_q\lambda_d - \hat{b}\omega + \delta_2 \end{aligned}$$

$$f_1(\lambda_d, i_d, i_q, \omega_{ref}) = p\omega_{ref}i_d + (\hat{\alpha_s}\eta + \hat{\alpha_r}\beta L_m)i_q + \hat{\alpha_r}L_m i_d i_q/\lambda_d$$

$$\delta_1 = [(\hat{\alpha_s} - \alpha_s)\eta + (\hat{\alpha_r} - \alpha_r)\beta L_m]i_q + \beta p\omega e_d - \alpha_r\beta e_q$$

$$\delta_2 = (\mu - \hat{\mu})i_q\lambda_d + \mu(-i_q e_d + i_d e_q) - (b - \hat{b})\omega - T_L/m$$

$$\begin{aligned} \Omega &= \omega - \frac{\delta_1}{\beta p\lambda_d} \\ &= (\frac{\lambda_d - e_d}{\lambda_d}) - \frac{1}{\beta p\lambda_d}\Big\{[(\hat{\alpha_s} - \alpha_s)\eta + (\hat{\alpha_r} - \alpha_r)\beta L_m]i_q - \alpha_r\beta e_q\Big\} \end{aligned}$$

$$\begin{aligned} \frac{di_q}{dt} &= -\beta p\omega\lambda_d - f_1(\lambda_d, i_d, i_q, \omega_{ref}) + \gamma v_q \\ \frac{d\omega}{dt} &= \hat{\mu} i_q\lambda_d - \hat{b}\omega + \delta_3 \end{aligned}$$

$$\delta_3 = \delta_2 - \frac{\hat{b}\delta_1}{\beta p\lambda_d} - \frac{d}{dt}(\frac{\delta_1}{\beta p\lambda_d}) \triangleq f_2(\lambda_d, i_d, i_q, \omega_{ref}, e_d, e_q, T_L)$$

$$\begin{aligned} \frac{d\hat{i}_q}{dt} &= -\beta p\lambda_d\hat{\Omega} - f_1(\lambda_d, i_d, i_q, \omega_{ref}) + \gamma v_q + (\frac{\alpha_1}{\varepsilon})(i_q - \hat{i}_q) \\ \frac{d\hat{\Omega}}{dt} &= \hat{\mu} i_q\lambda_d - \hat{b}\hat{\Omega} - (\frac{\alpha_2}{\varepsilon^2 p\beta\lambda_d})(i_q - \hat{i}_q) \end{aligned}$$

Speed Controller

If we assume that flux regulation takes place faster relative to speed, the motor model is simplified to a third order, and for any current Iq* we design the following PI Controller

$$V_q = \frac{(K_{qp}s + K_{qi})}{s}[I_q^* - I_q]$$

For the purpose of experiment Current Iq is limited to the rated value.

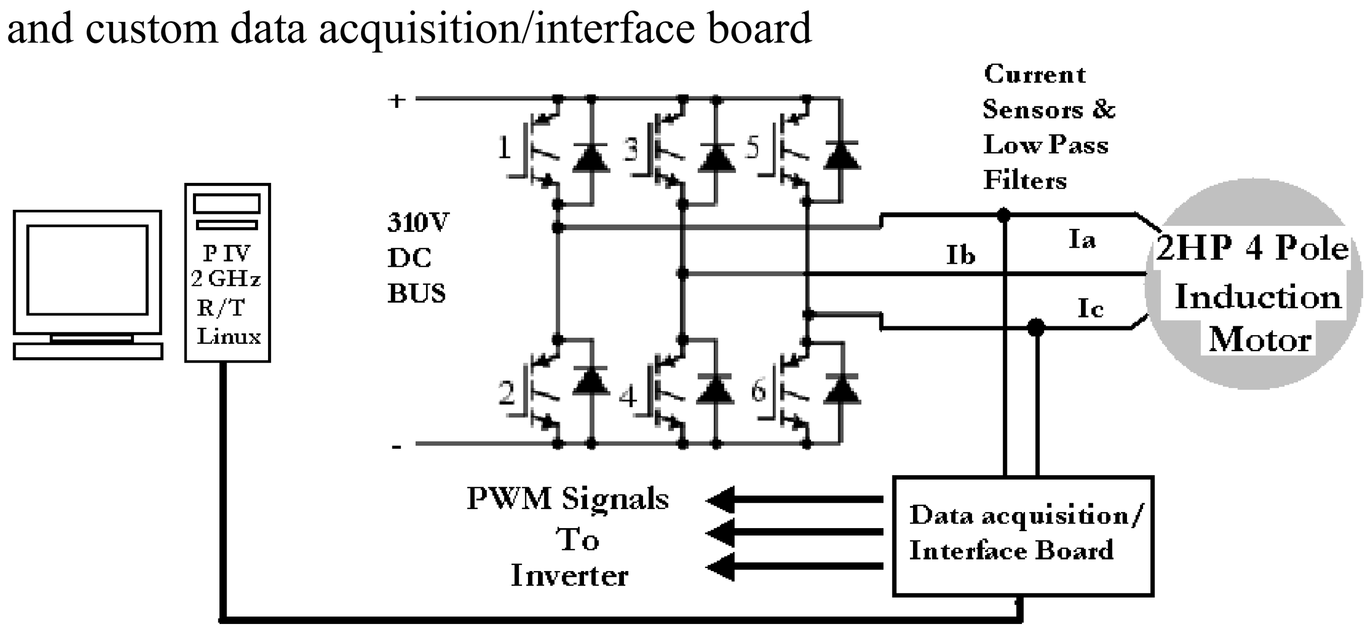
And second PI Controller as:

$$I_q = \frac{(K_{wp}s + K_{wi})}{s}[\omega_{ref} - \Omega]$$

With a condition: $\omega_c\bar{i}_q = \bar{i}_q\left[p\omega_{ref} + \frac{\hat{\alpha}_r L_m\bar{i}_q}{\lambda_{ref}}\right] > 0$

Experimental Setup

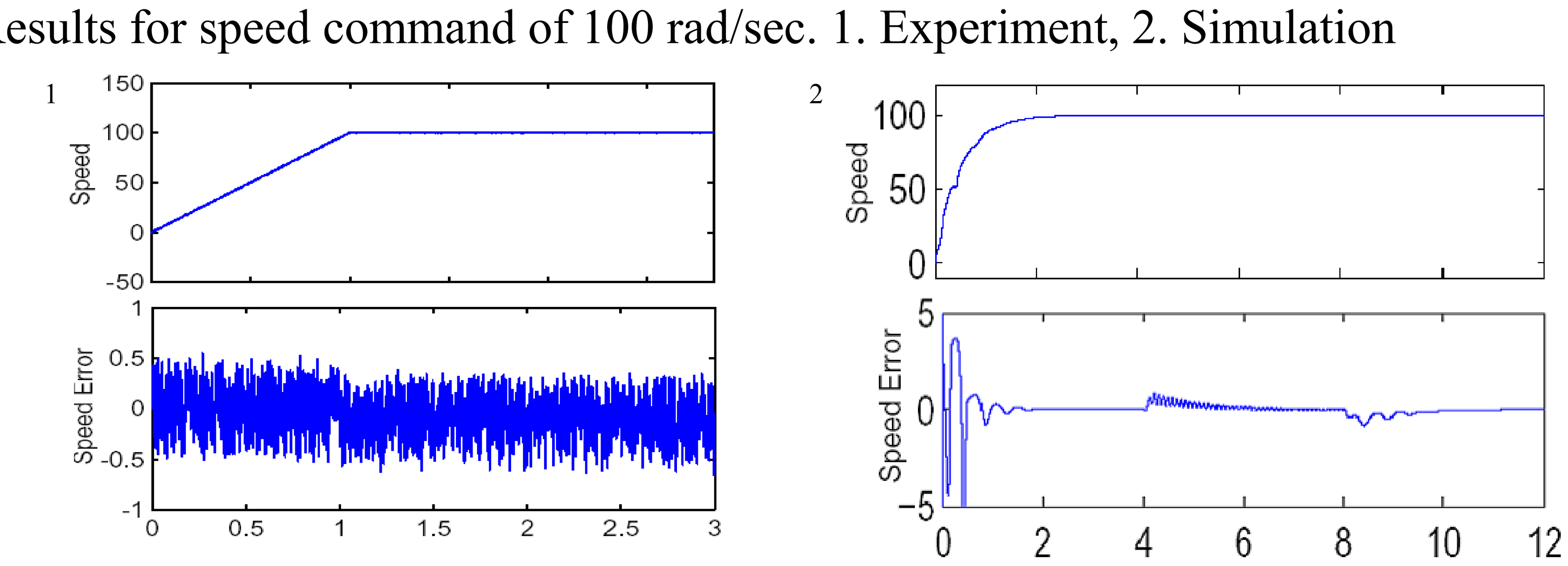
Above described controller is implemented in C on a P4 2 GHz PC with R/T Linux, IGBT Inverter and custom data acquisition/interface board



Traditional PI controllers are used for Vd and Vq regulation, with limits imposed on input variables Id and Iq of 7A.

Experimental Results

Results for speed command of 100 rad/sec. 1. Experiment, 2. Simulation



Conclusion

Novel flux and speed observers were developed and and implemented in the experimental setup

The theoretical analysis is supplemented by simulation and experimental results

Future work challenge would be to use a nonlinear model to design more robust nonlinear controller for wide range of loads and speeds