Application of the simple observer for induction motor drive with LC filter

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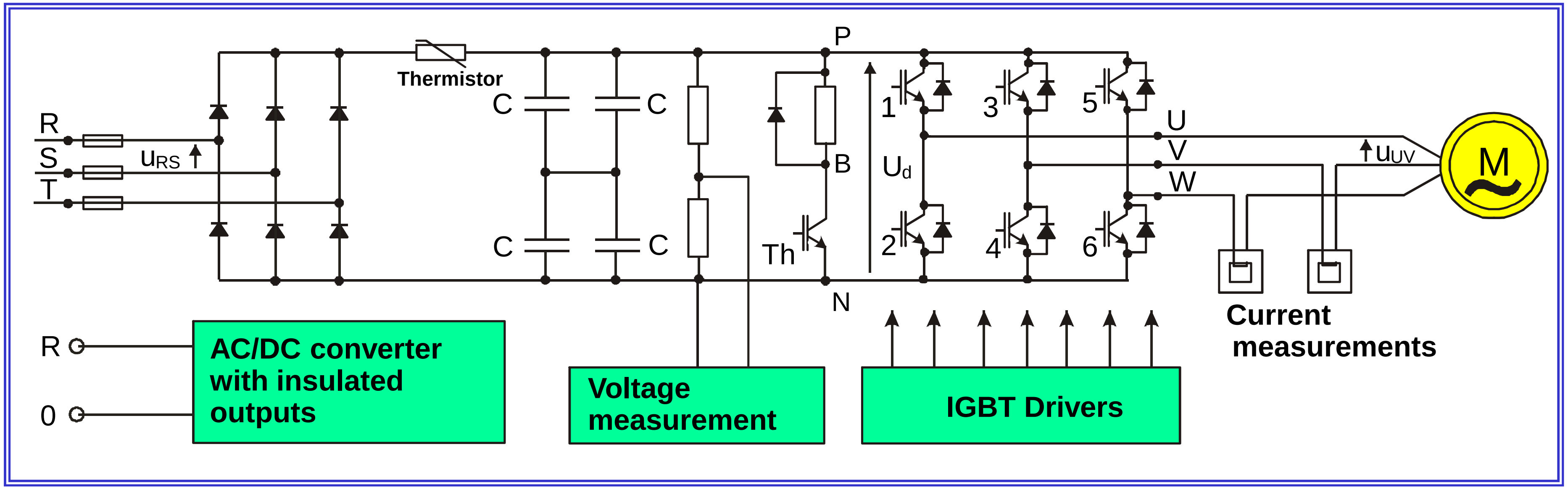
Seminar of Polish Chapter of IEEE IE/PEL Society - 02 March 2011
Politechnika Warszawska, Instytut Sterowania i Elektroniki Przemysłowej

INDUCTION MOTOR FED BY A PWM INVERTER

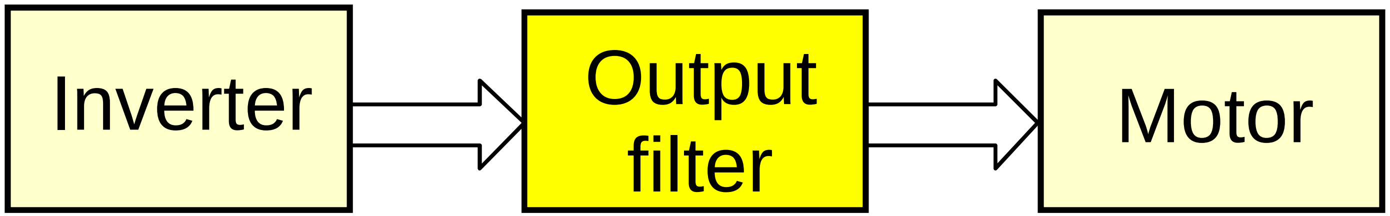


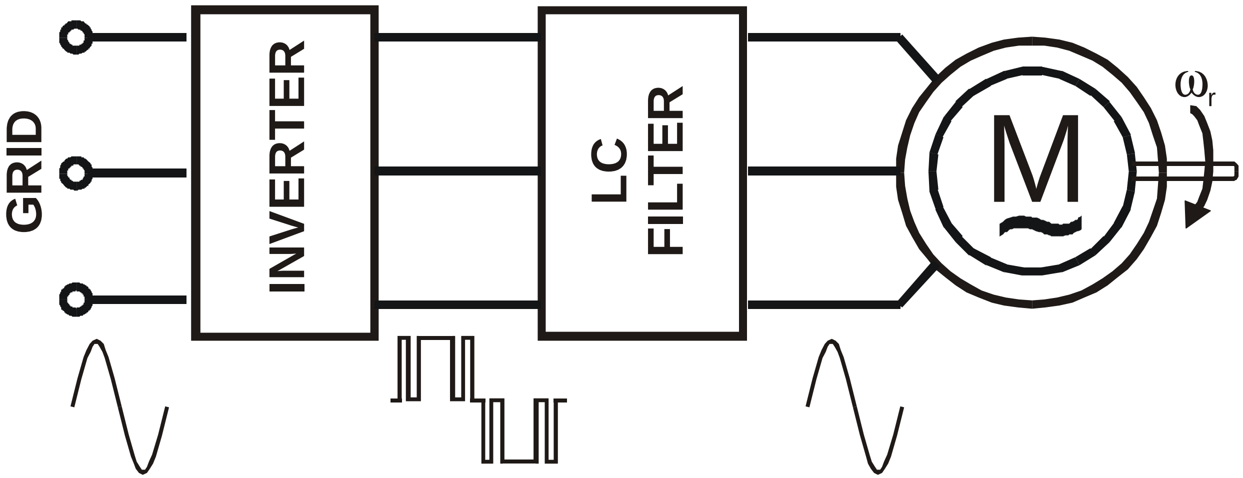
High switching frequency in inverters

Problems

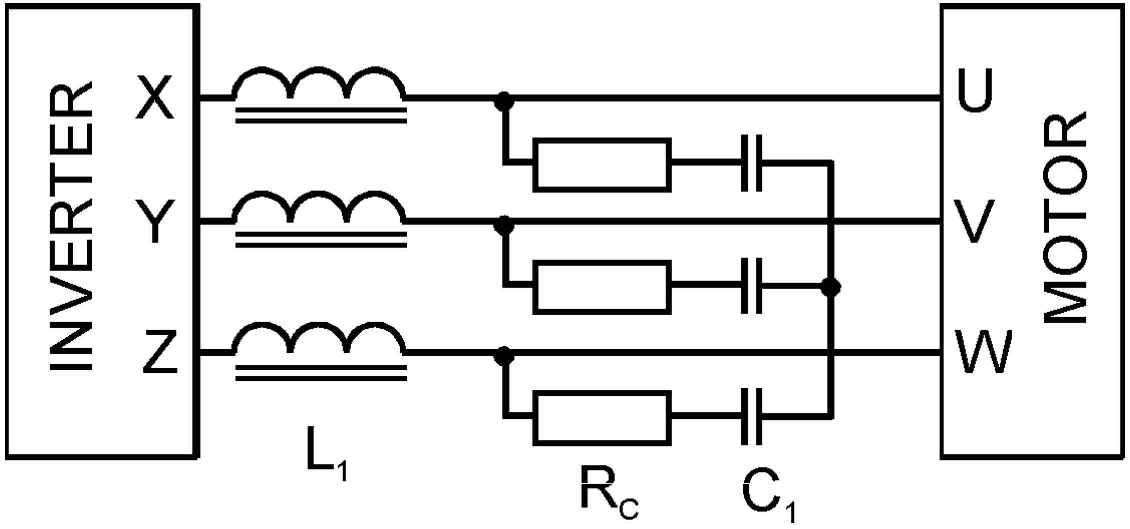
- leakage currents
- bearing currents
- shaft voltages
- motor efficiency decrease
- overvoltages
- disturbances ...

SOLUTION- output filter



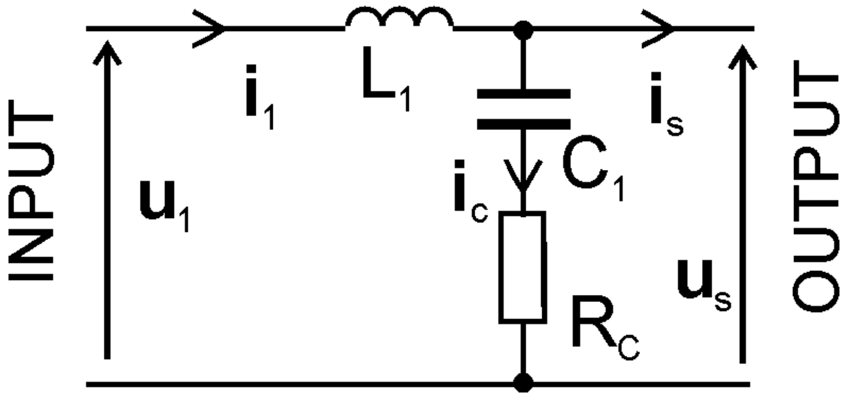


System model



Inductance L_1	5.6 mH
Resistance R_1	0.05 Ω
Capacitance C_1	3 μF
Resistance R_C	1 Ω
Voltage drop ΔU	4.8 %
Voltage THD	≤5 %
Resonance frequency	1.2 kHz

Equivalent circuits



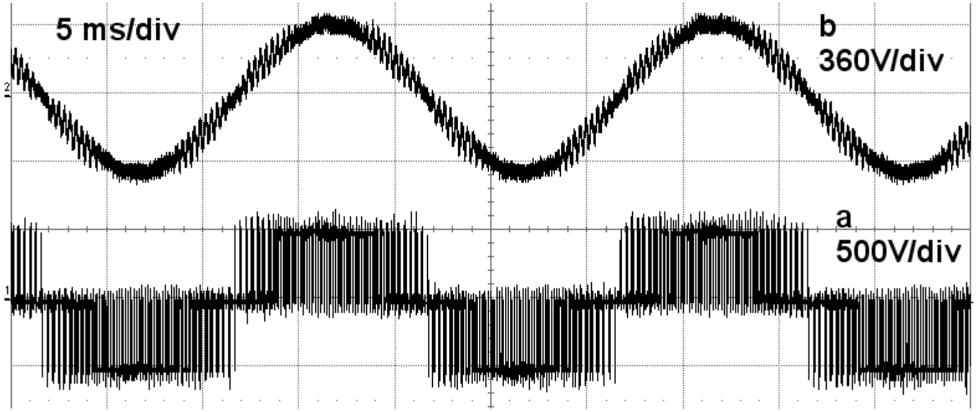
$$d\mathbf{u}_c / d\tau = \mathbf{i}_c / C_1$$

$$d\mathbf{i}_1 / d\tau = \left(\mathbf{u}_1 - R_c \mathbf{i}_c - \mathbf{u}_c\right) / L_1$$

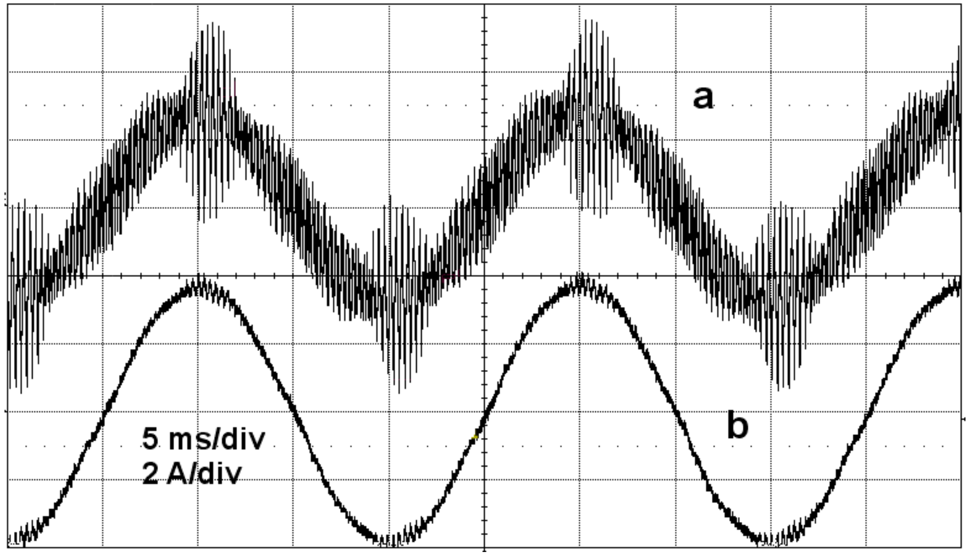
$$\mathbf{i}_c = \mathbf{i}_1 - \mathbf{i}_s$$

$$\mathbf{u}_s = R_c\left(\mathbf{i}_1 - \mathbf{i}_s\right) + \mathbf{u}_c$$

Filter input /output signals

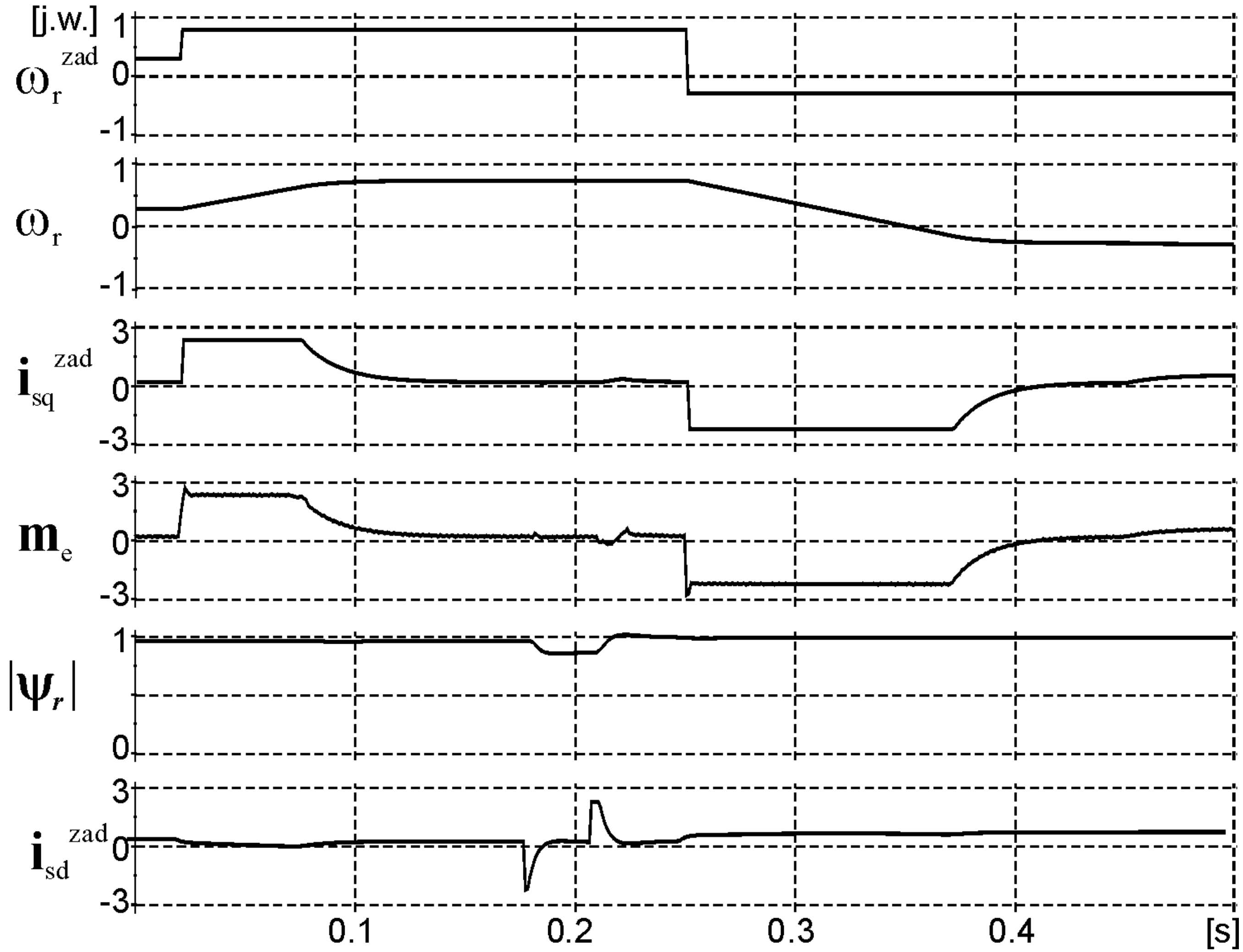


The (a) input and
(b) output LC filter voltages



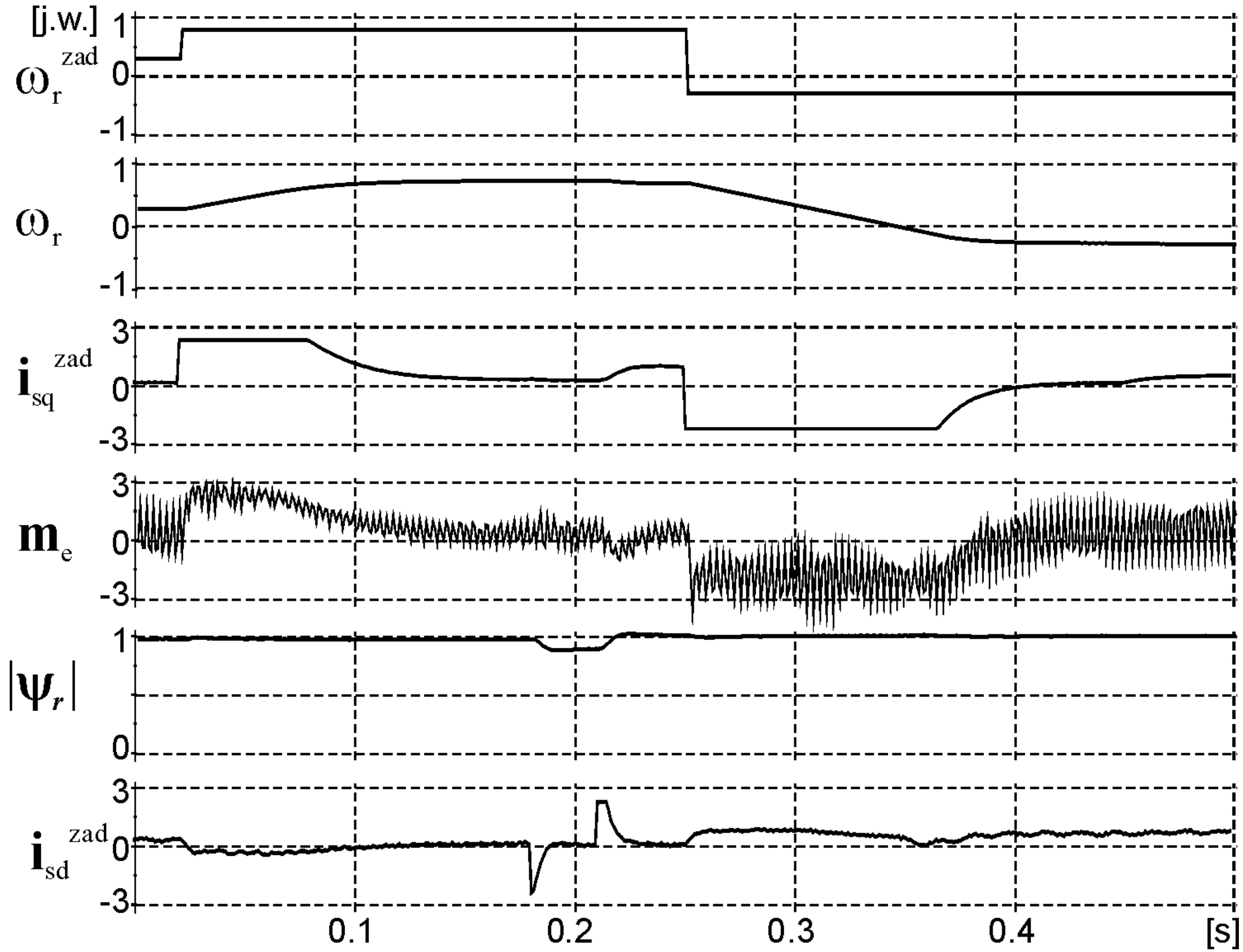
The (a) input and
(b) output LC filter currents

INDUCTION MOTOR DRIVE WITH LC FILTER



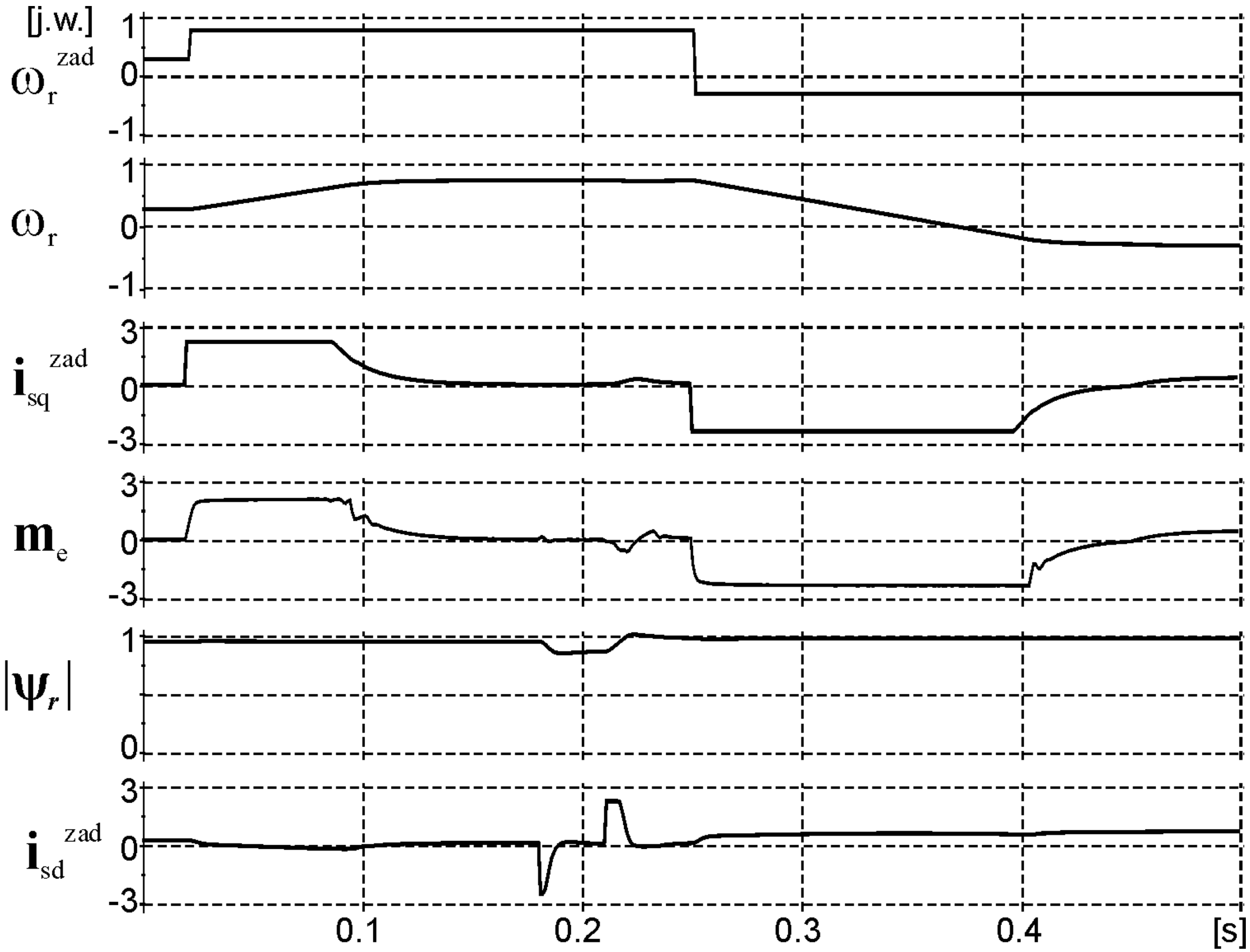
Działanie układu napędowego sterowania polowo zorientowanego napędu silnika asynchronicznego klatkowego bez filtru sinusoidalnego – układ bez obserwatora

INDUCTION MOTOR DRIVE WITH LC FILTER



Działanie układu napędowego sterowania polowo zorientowanego napędu silnika asynchronicznego klatkowego z filtrem sinusoidalnym bez zmian w układzie sterowania – układ bez obserwatora

INDUCTION MOTOR DRIVE WITH LC FILTER



Działanie układu napędowego sterowania polowo zorientowanego napędu silnika asynchronicznego klatkowego z uwzględnieniem filtru sinusoidalnego w procesie sterowania – układ bez obserwatora

INDUCTION MOTOR MODEL

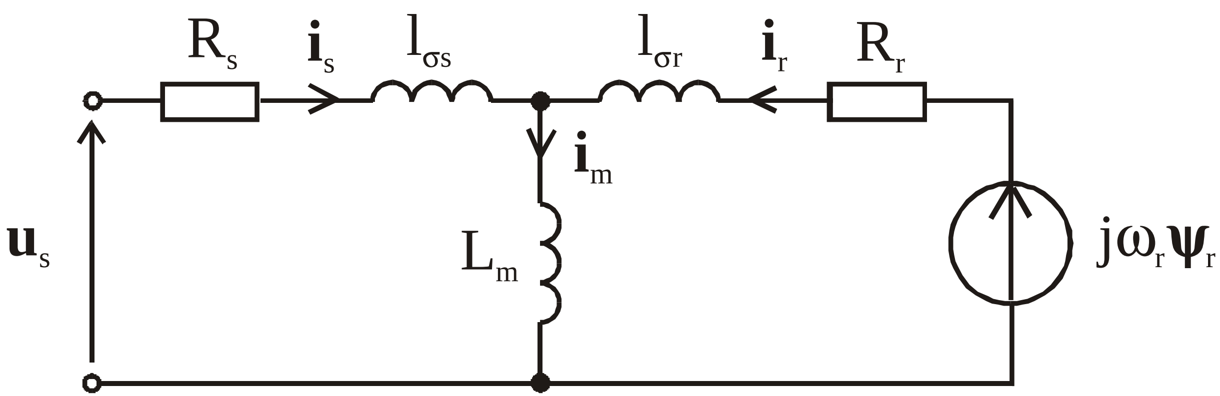
Induction motor model in the stationary αβ reference frame

$$\frac{d\mathbf{i}_s}{d\tau} = a_1\mathbf{i}_s + a_2\boldsymbol{\psi}_r - ja_3\boldsymbol{\psi}_r + a_4\mathbf{u}_s$$

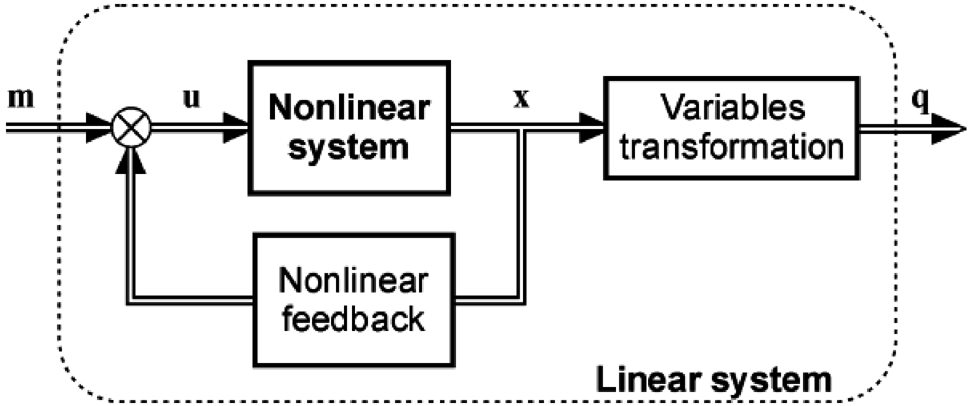
$$\frac{d\boldsymbol{\psi}_r}{d\tau} = a_5\mathbf{i}_s + a_6\boldsymbol{\psi}_r + j\omega_r\boldsymbol{\psi}_r$$

$$\frac{d\omega_r}{d\tau} = \frac{1}{J_M}\left(\frac{L_m}{L_r}\,\mathrm{Im}\left|\boldsymbol{\psi}_r^*\mathbf{i}_s\right| - T_L\right)$$

$$\mathbf{i}_s = \begin{bmatrix} i_{s\alpha} & i_{s\beta} \end{bmatrix}^T \quad \boldsymbol{\psi}_r = \begin{bmatrix} \psi_{r\alpha} & \psi_{r\beta} \end{bmatrix}^T \quad \mathbf{u}_s = \begin{bmatrix} u_{s\alpha} & u_{s\beta} \end{bmatrix}^T$$



CONTROL SYSTEM

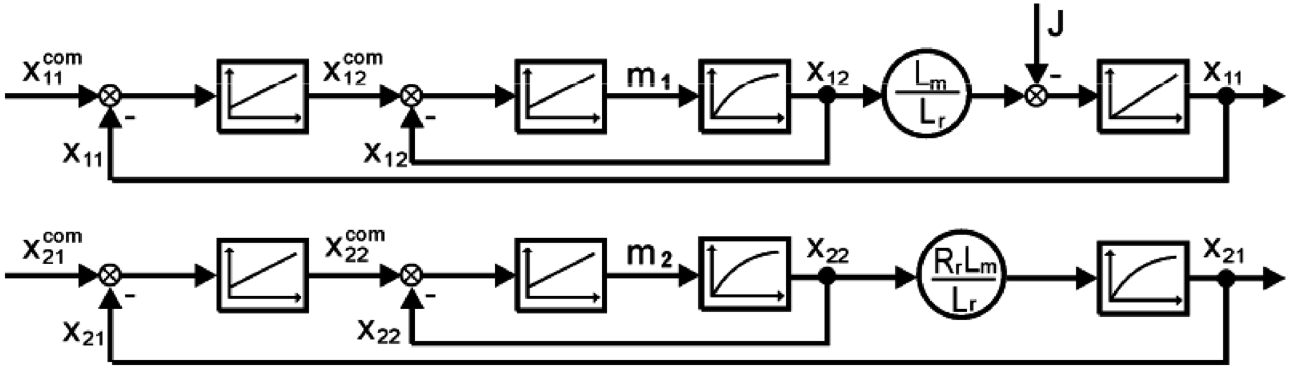


$$x_{11} = \omega_r$$

$$x_{12} = \psi_{r\alpha} i_{s\beta} - \psi_{r\beta} i_{s\alpha}$$

$$x_{21} = \psi_{r\alpha}^2 + \psi_{r\beta}^2$$

$$x_{12} = \psi_{r\alpha} i_{s\alpha} + \psi_{r\beta} i_{s\beta}$$



$$u_1 = w_\sigma [x_{11}(x_{22} + a_3 x_{21}) + m_1]/L_r$$

$$u_2 = w_\sigma / (-x_{11}x_{12} - a_2 x_{21} - a_6 \left(x_{12}^2 + x_{22}^2\right)/x_{21} + m_2)$$

LINEARIZATION OF EQUATIONS

$$\frac{dx_{11}}{dt} = \frac{L_m}{JL_r} x_{12} - \frac{1}{J} m_o$$

$$\frac{dx_{12}}{dt} = -\frac{1}{T_v} x_{12} + m_1$$

$$\frac{dx_{12}}{dt} = -2\frac{R_r}{L_r} x_{21} + 2R\frac{L_m}{L_r} x_{22}$$

$$\frac{dx_{22}}{dt} = -\frac{1}{T_v} x_{22} + m_2$$

m_1, m_1 – control variables

MULTISCALAR MODEL OF THE INDUCTION MOTOR

$$\frac{dx_{11}}{dt} = \frac{L_m}{JL_r} x_{12} - \frac{1}{J} m_o$$

$$\frac{dx_{12}}{dt} = -\frac{1}{T_v} x_{12} - x_{11}\left(x_{22} + \frac{L_m}{w} x_{12} \right) + \frac{L_r}{w} u_1$$

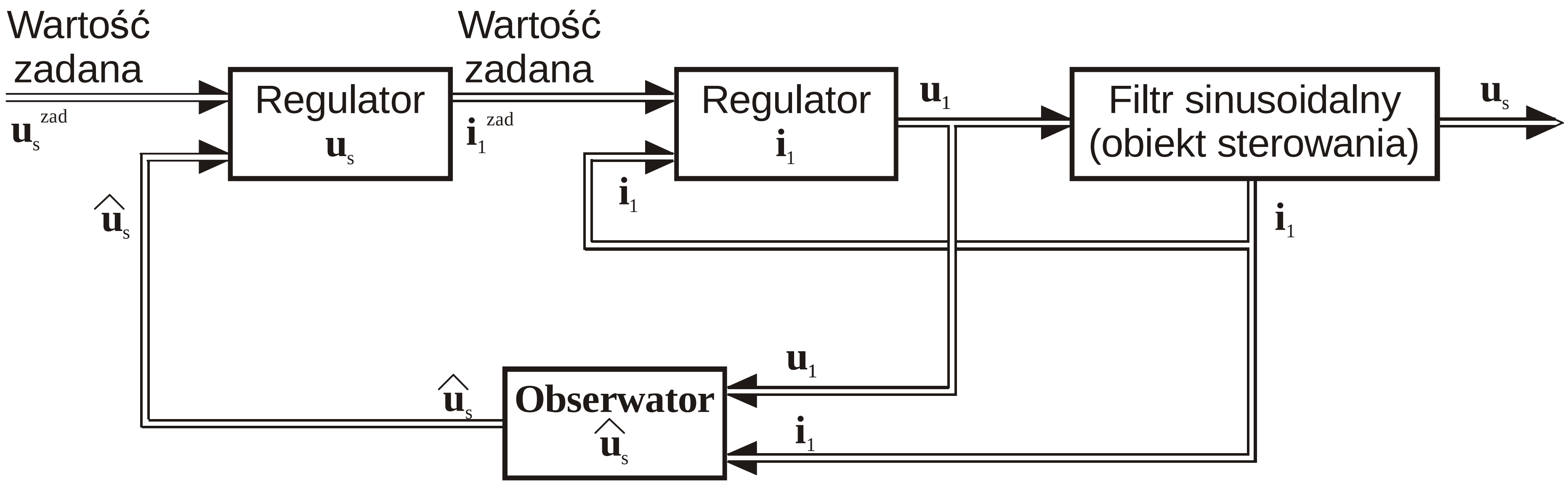
$$\frac{dx_{12}}{dt} = -2\frac{R_r}{L_r} x_{21} + 2R\frac{L_m}{L_r} x_{22}$$

$$\frac{dx_{22}}{dt} = -\frac{1}{T_v} x_{22} + x_{11}x_{12} + \frac{R_r L_m}{wL_r} x_{21} + R_r \frac{L_m}{L_r} \frac{x_{12}^2 + x_{22}^2}{x_{21}} + \frac{L_r}{w} u_2$$

where:

$$T_v = \frac{wL_r}{R_r w + R_s L_r^2 + R_r L_m^2} \qquad u_1 = \Psi_{rx} u_{sy} - \Psi_{ry} u_{sx} \qquad u_2 = \Psi_{rx} u_{sx} + \Psi_{ry} u_{sy}$$

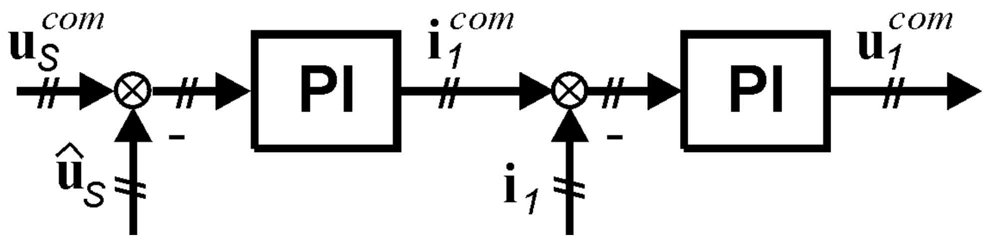
CONTROL SYSTEM



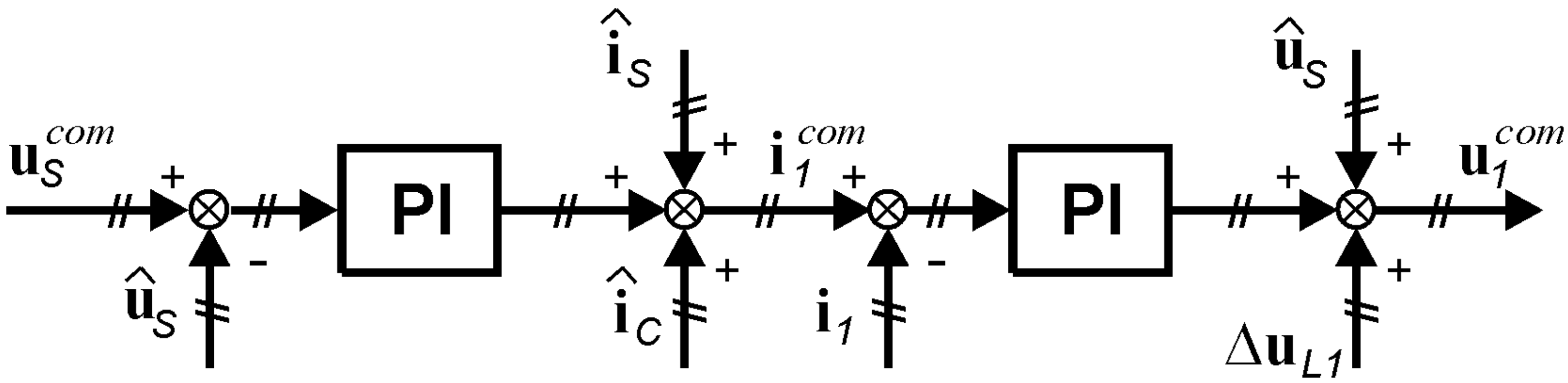
Schemat blokowy zamkniętego, kaskadowego układu regulacji filtru z zastosowaniem obserwatora napięcia silnika

CONTROL SYSTEM

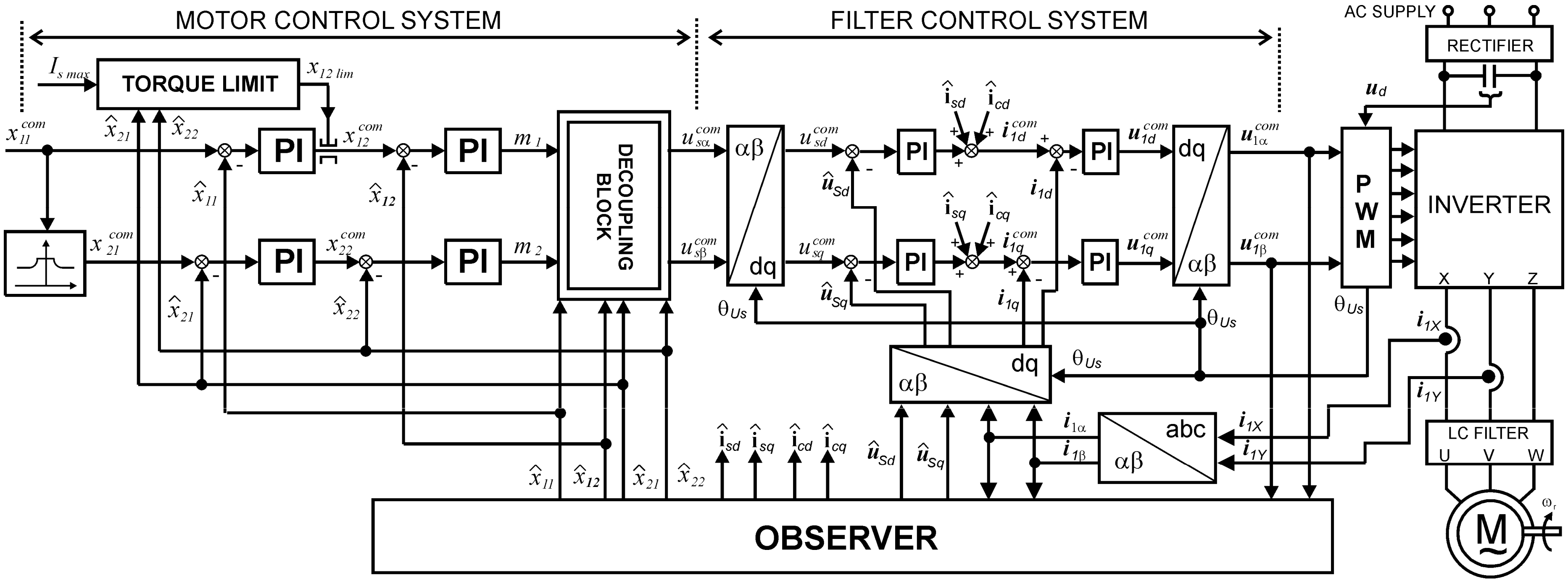
LC filter cascade control structure



LC control system with disturbance compensation

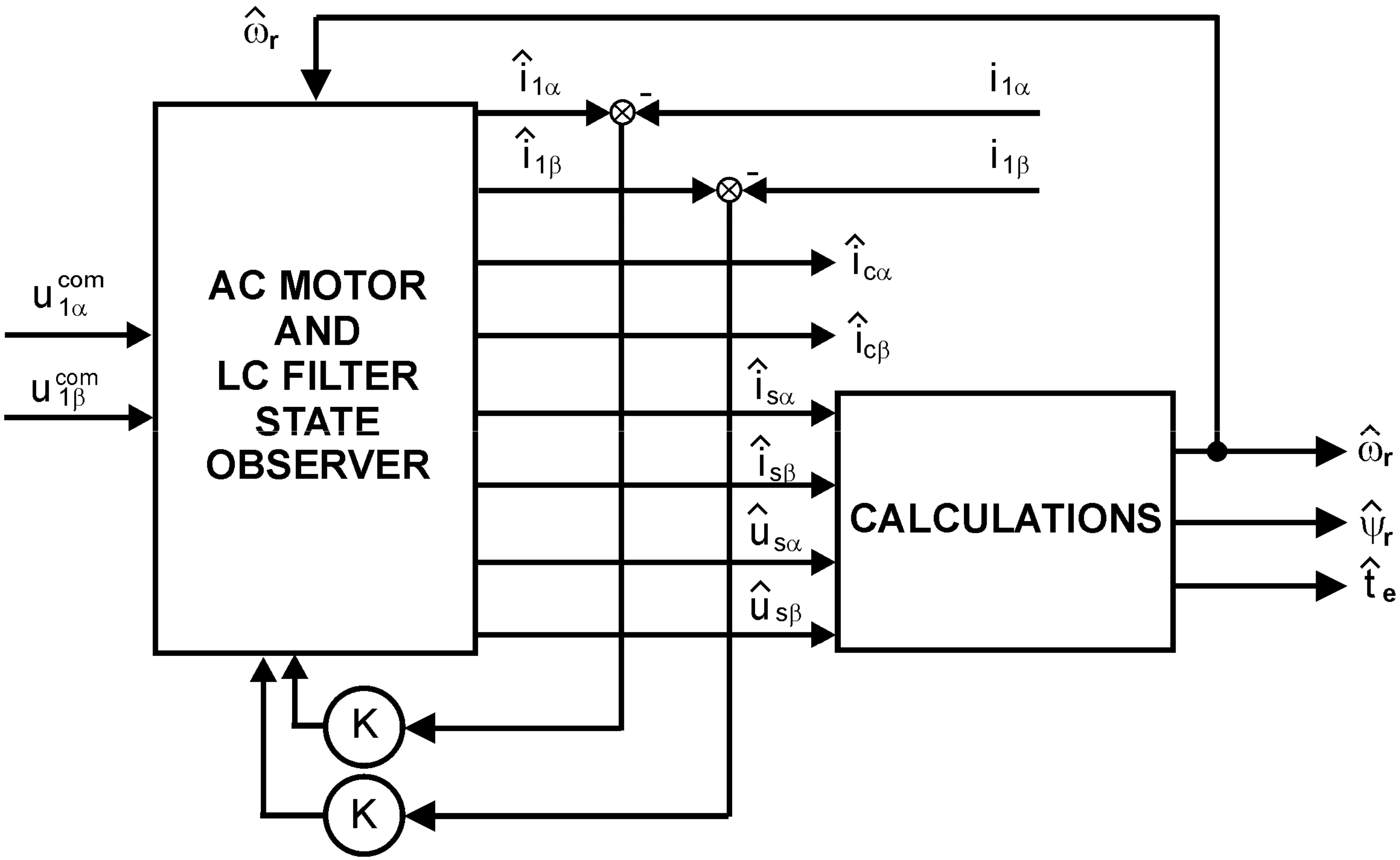


SYSTEM DESCRIPTION



Speed sensorless control system for ac motor including LC filter

STATE VARIABLES OBSERVER



OBSERVER SYSTEM

Speed and flux observer with EMF estimation and LC filter model equations

$$d\hat{\mathbf{i}}_s / d\tau = a_1 \hat{\mathbf{i}}_s + a_2 \hat{\boldsymbol{\psi}}_r - j a_3 \hat{\xi} + a_4 \hat{\mathbf{u}}_s + k_1 \left(\mathbf{i}_1 - \hat{\mathbf{i}}_1 \right)$$

$$d\hat{\boldsymbol{\psi}}_r / d\tau = a_5 \hat{\boldsymbol{\psi}}_r + a_6 \hat{\mathbf{i}}_s + j \hat{\xi} + \mathbf{e}_\psi$$

$$d\hat{\xi} / d\tau = a_5 \hat{\xi} + a_6 \hat{\omega}_r \hat{\mathbf{i}}_s + j \hat{\omega}_r \hat{\xi} + j k_4 \left(\mathbf{i}_1 - \hat{\mathbf{i}}_1 \right)$$

$$d S_{bF} / d\tau = k_{fo} \left(S_b - S_{bF} \right)$$

$$d\hat{\mathbf{u}}_c / d\tau = \left(\mathbf{i}_1 - \hat{\mathbf{i}}_s \right) / C_1$$

$$d\hat{\mathbf{i}}_1 / d\tau = \left(\mathbf{u}_1^{com} - \hat{\mathbf{u}}_s \right) / L_1 + k_A \left(\mathbf{i}_1 - \hat{\mathbf{i}}_1 \right) + j k_B \left(\mathbf{i}_1 - \hat{\mathbf{i}}_1 \right)$$

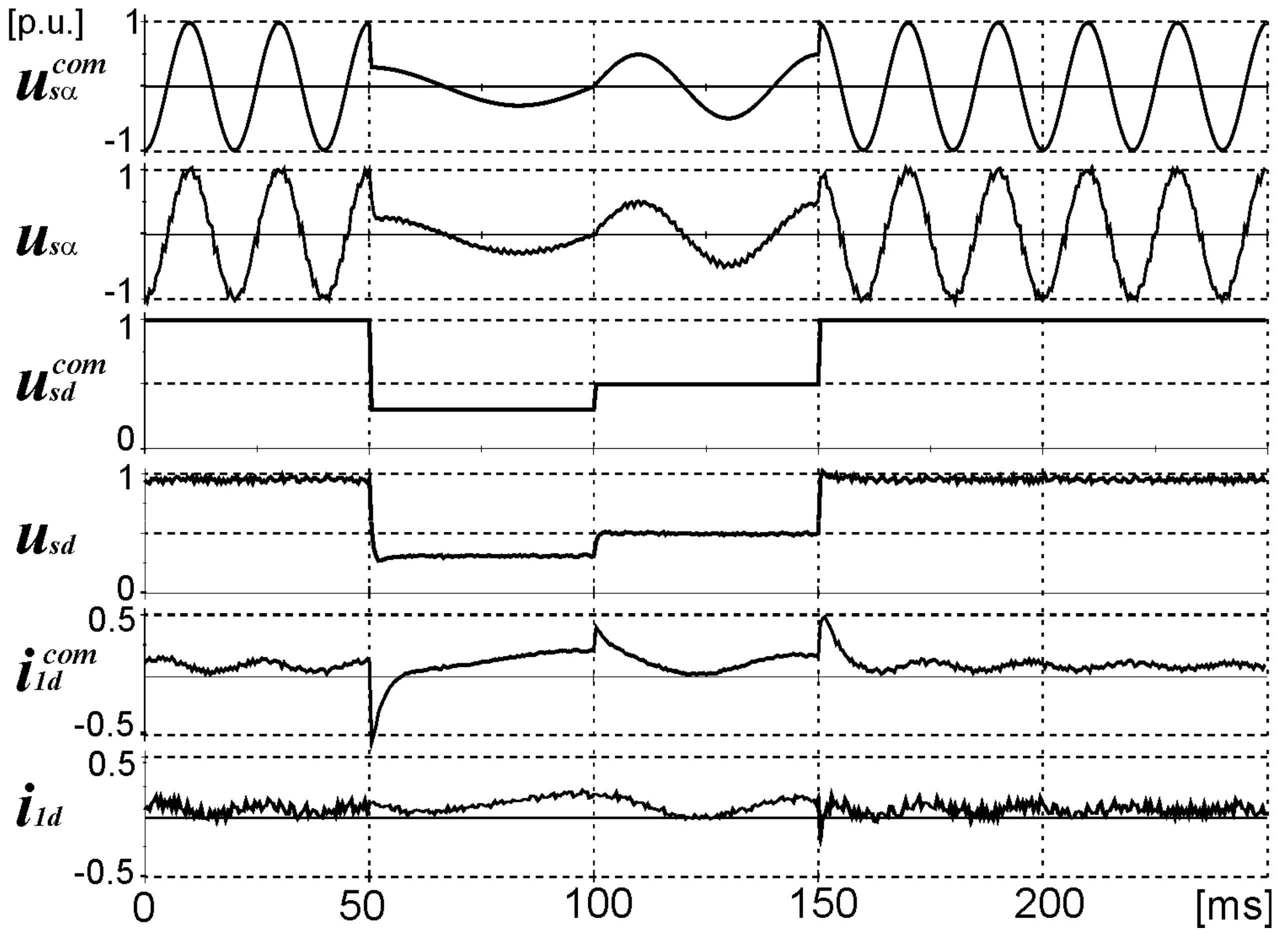
$$\hat{\mathbf{u}}_s = \hat{\mathbf{u}}_c + \left(\mathbf{i}_1 - \hat{\mathbf{i}}_s \right) R_c$$

$$\mathbf{e}_\psi = \begin{bmatrix} -k_2 S_b \hat{\psi}_{r\alpha} + k_3 \hat{\psi}_{r\beta} \left(S_b - S_{bF} \right) \\ -k_2 S_b \hat{\psi}_{r\beta} - k_3 \hat{\psi}_{r\alpha} \left(S_b - S_{bF} \right) \end{bmatrix}$$

$$\hat{\xi} = \hat{\omega}_r \hat{\boldsymbol{\psi}}_r$$

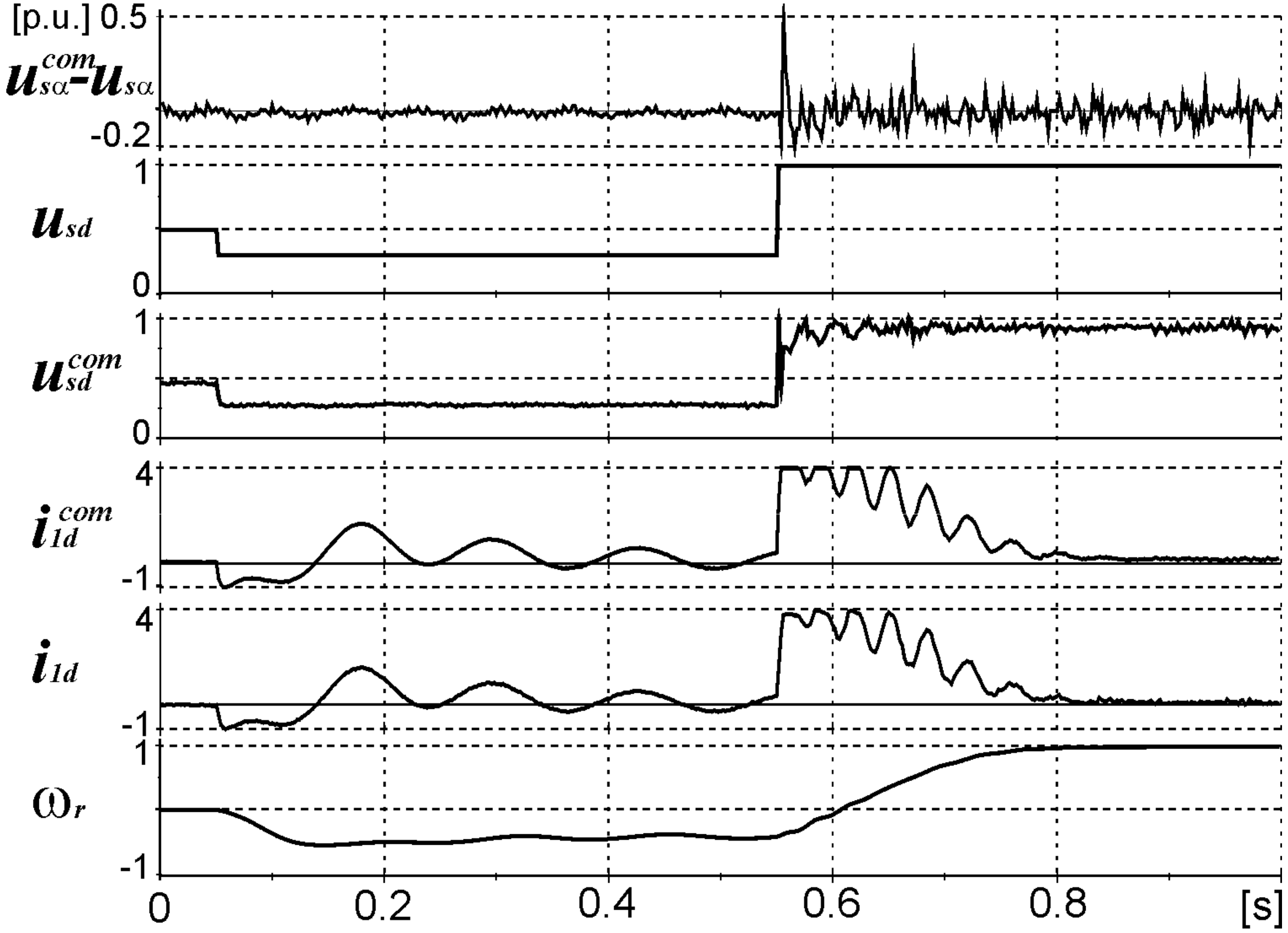
$$\hat{\omega}_r = \left(\hat{\xi}_\alpha \hat{\psi}_{r\alpha} + \hat{\xi}_\beta \hat{\psi}_{r\beta} \right) / \hat{X}_{21}$$

SIMULATION RESULTS



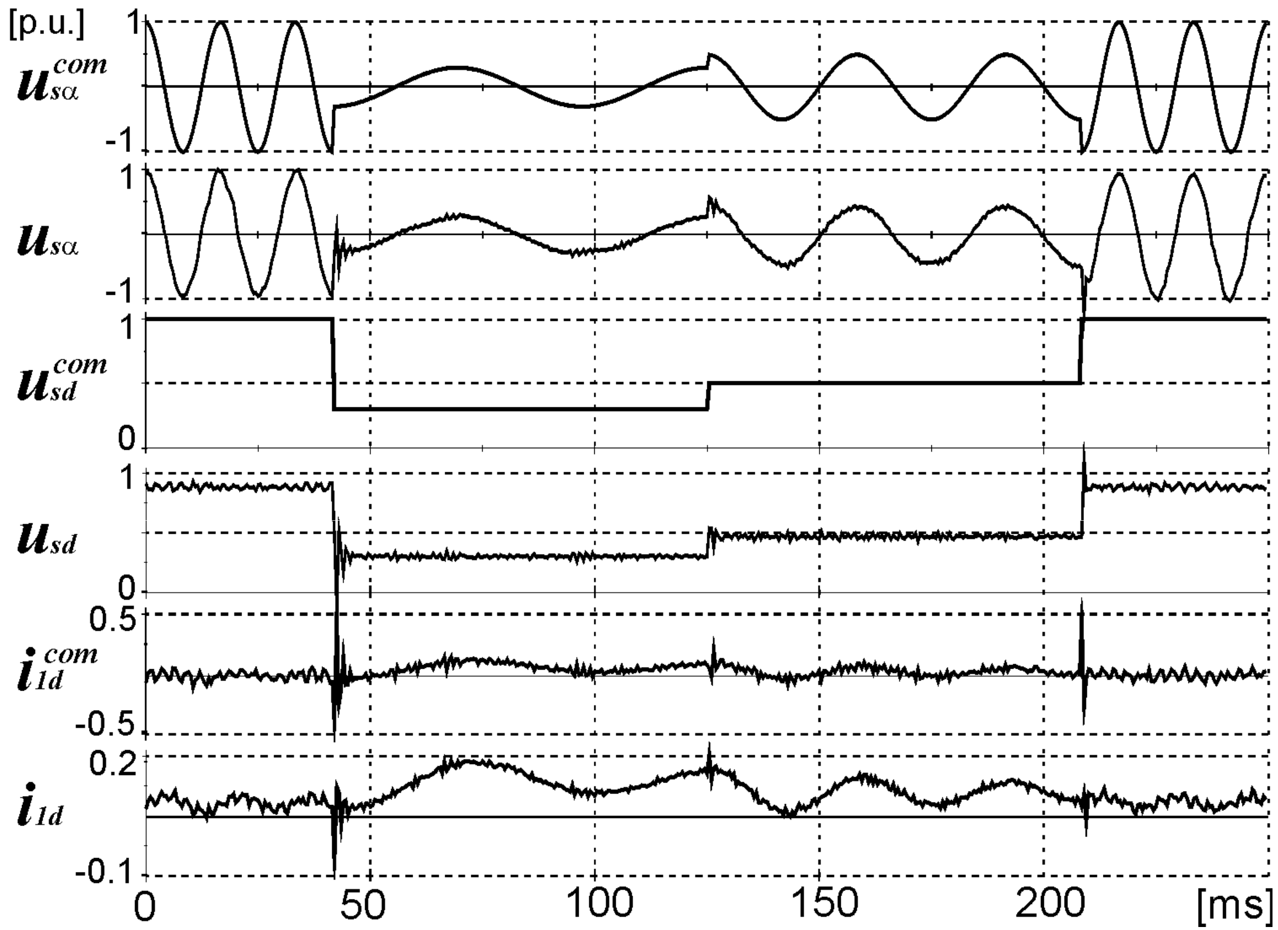
Control of the LC filter variables (RL load)

SIMULATION RESULTS



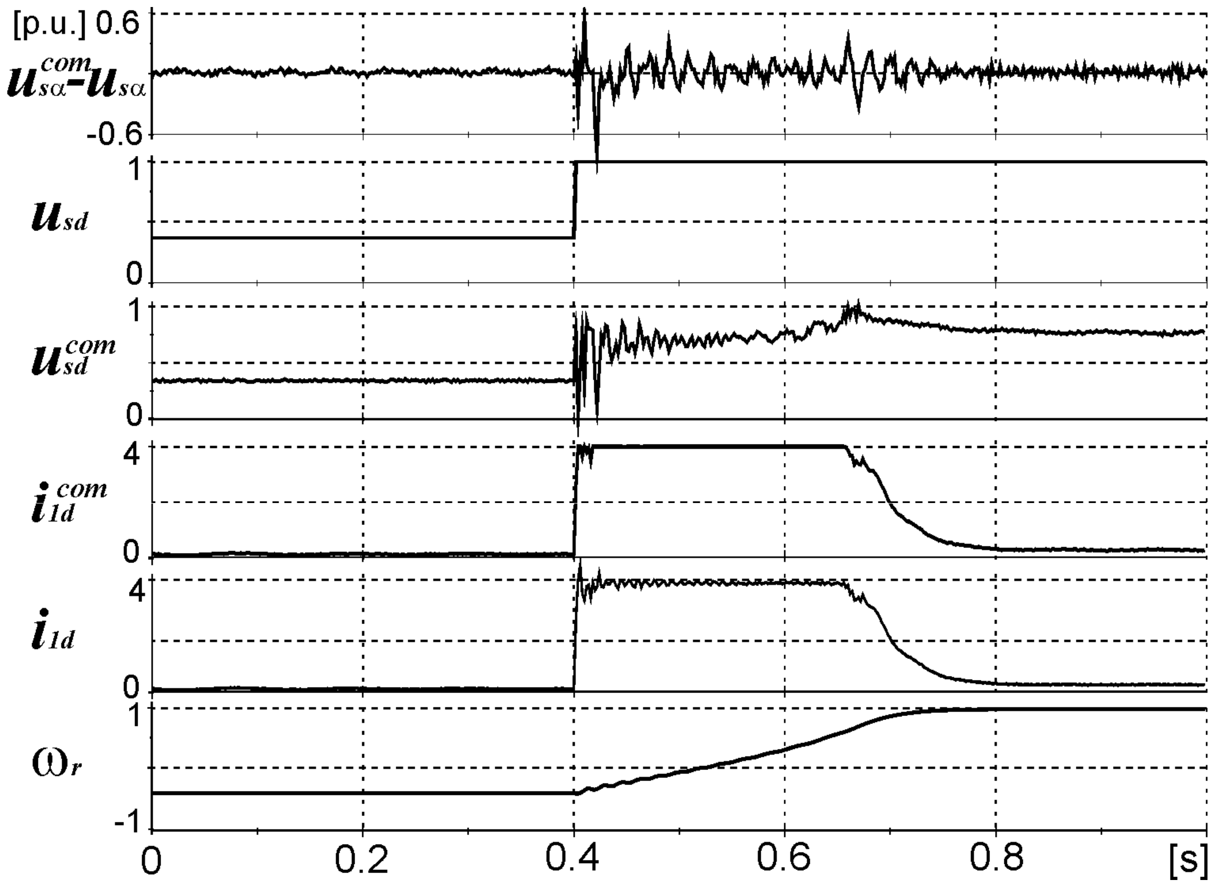
Control of the LC filter variables (load - motor)

SIMULATION RESULTS



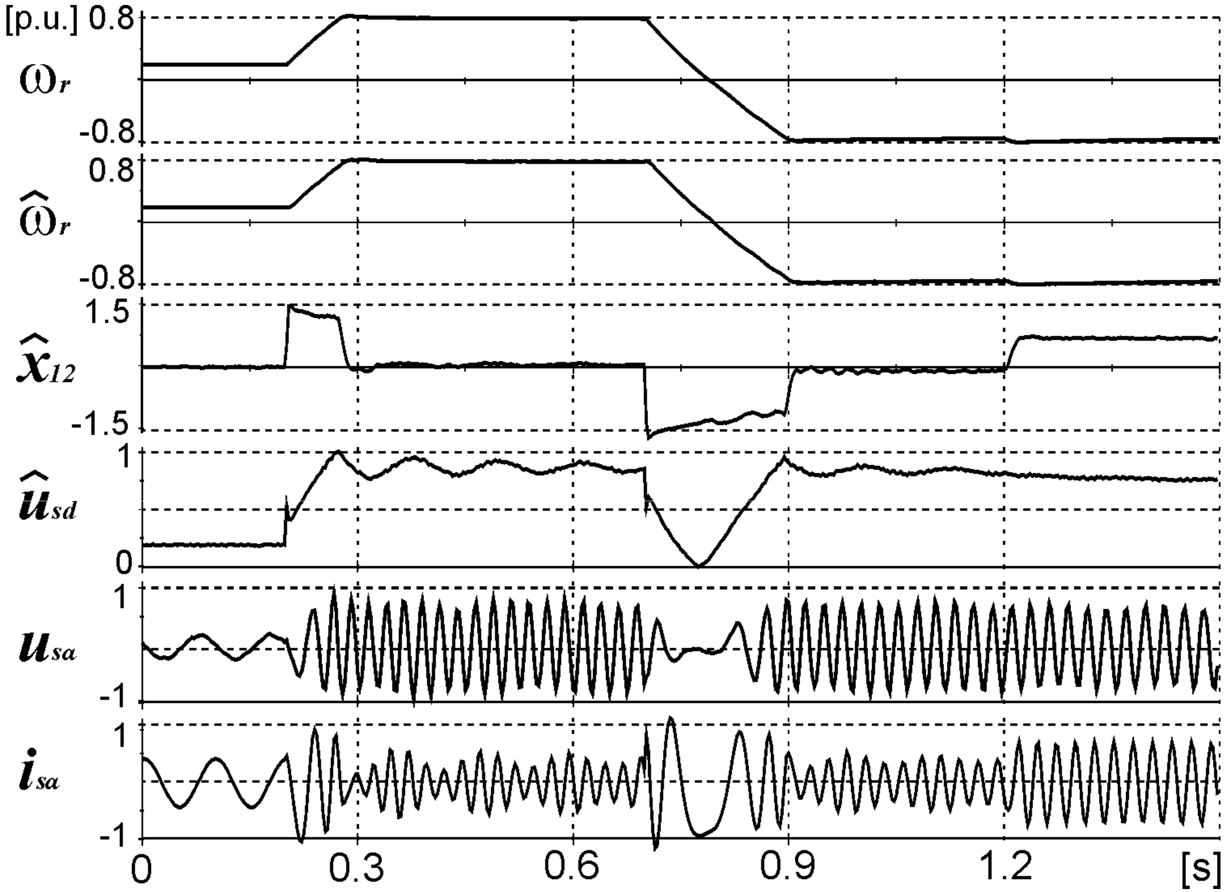
Control of the LC filter variables with disturbances compensation (LR load)

SIMULATION RESULTS



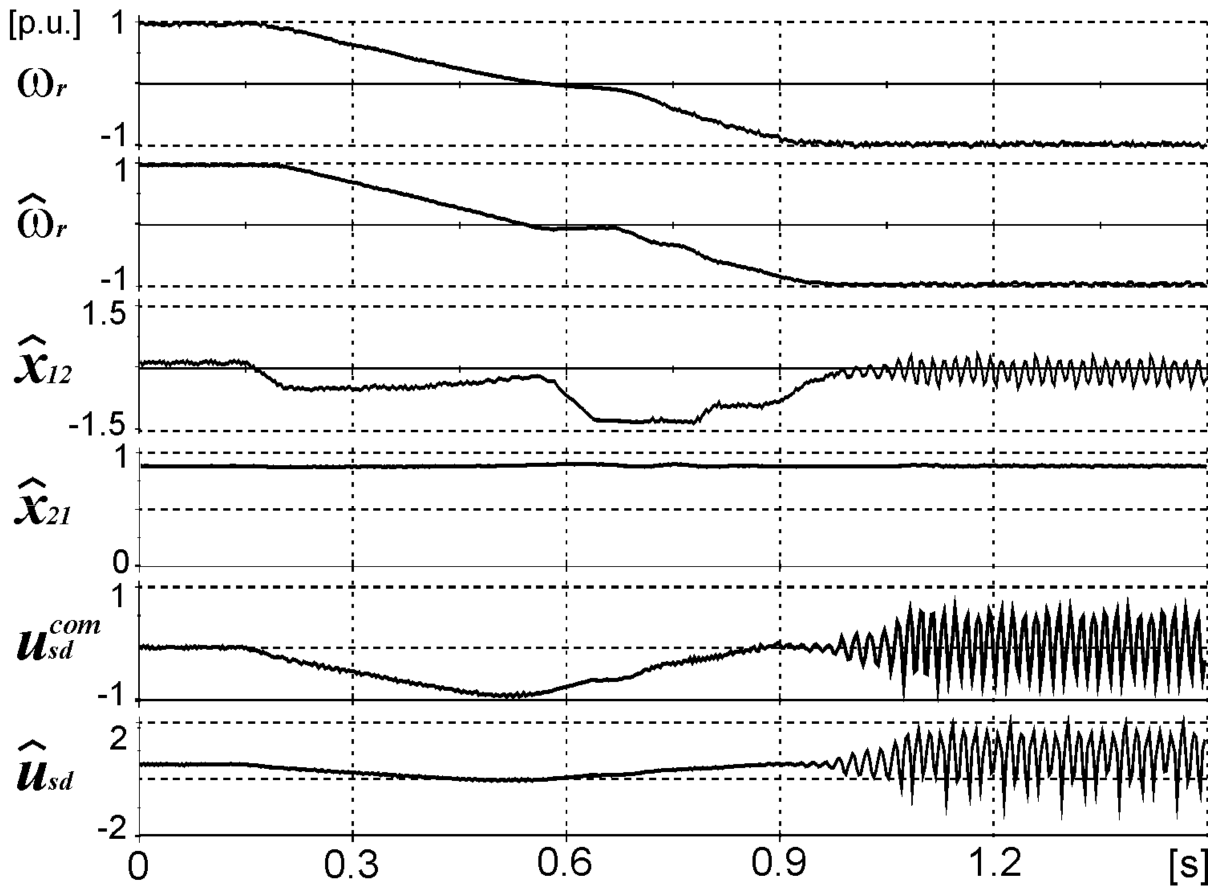
Control of the LC filter variables with disturbances compensation (load - motor)

SIMULATION RESULTS



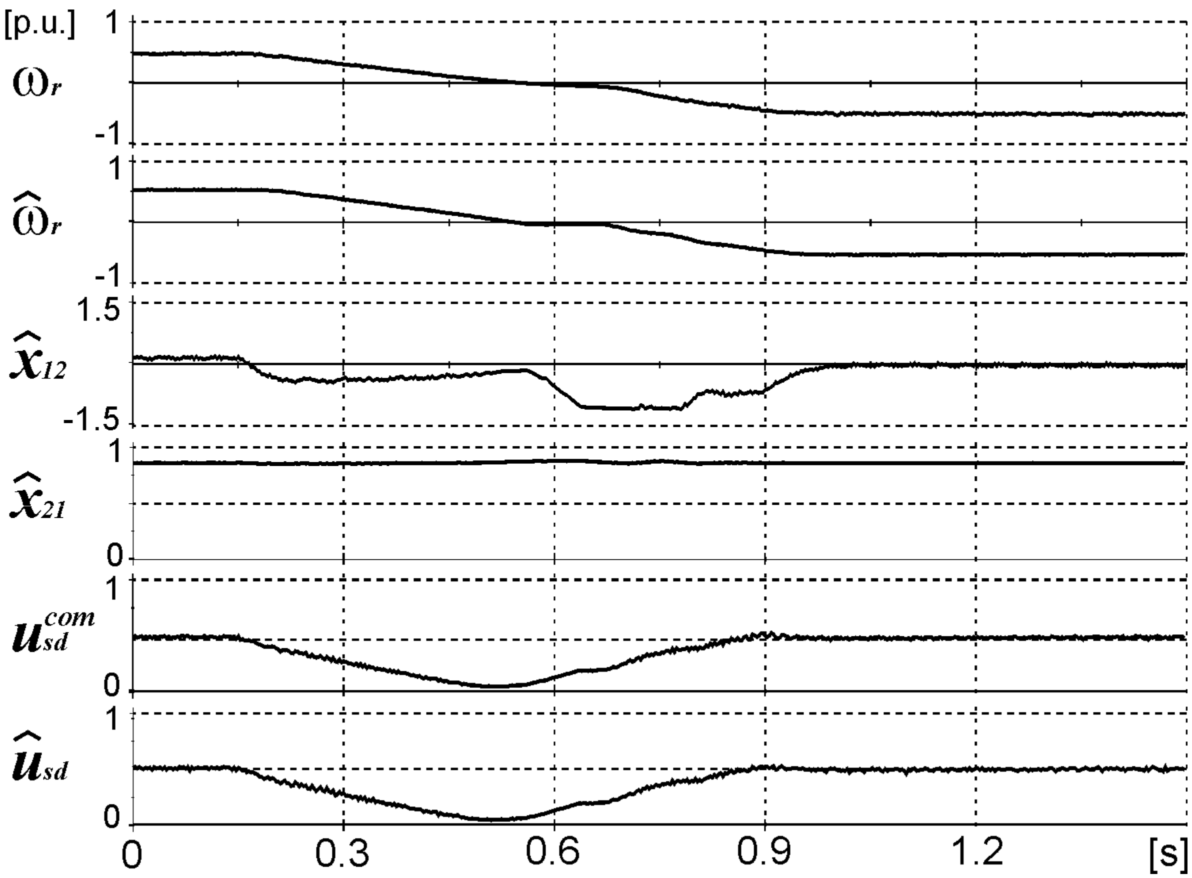
Simulation of the speed sensorless control system for speed and load torque variations

EXPERIMENTAL RESULTS



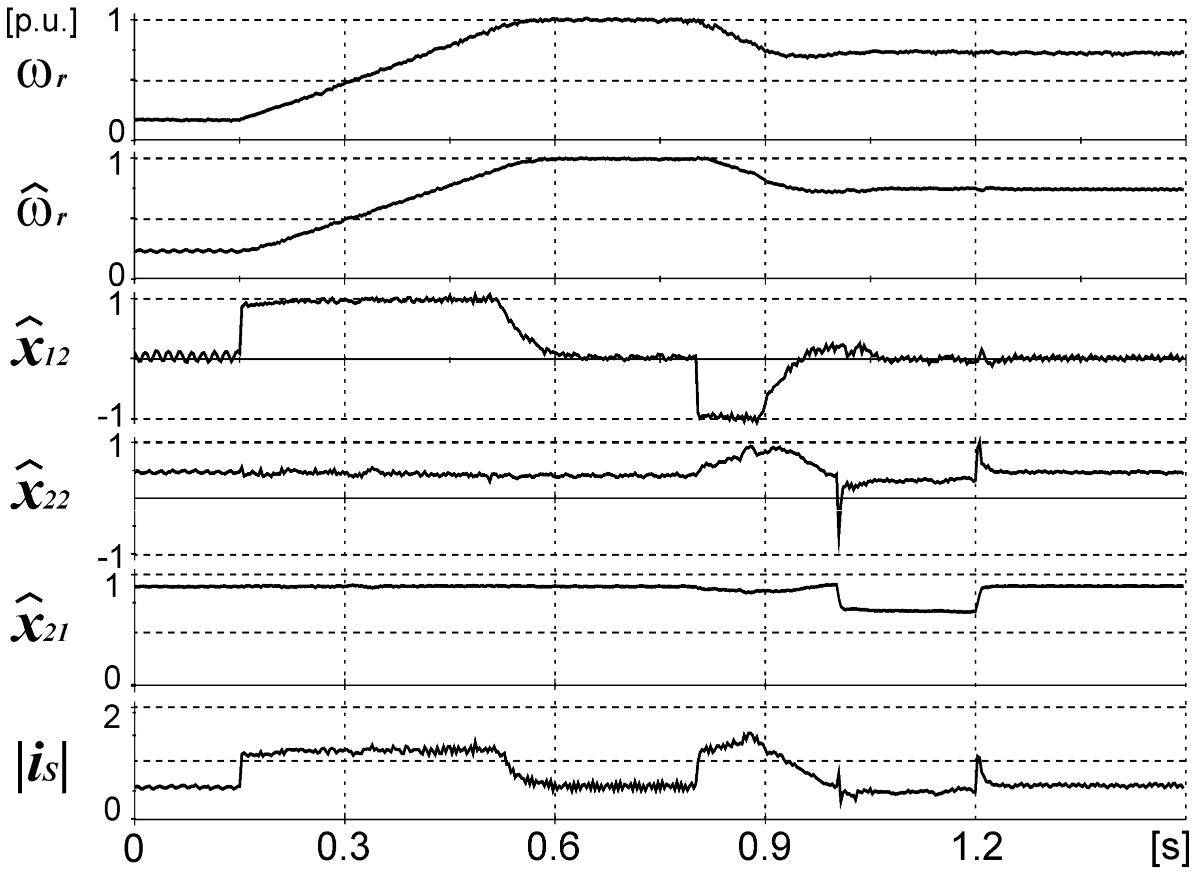
Experiment of the speed reverse for observer with Rc omission

EXPERIMENTAL RESULTS



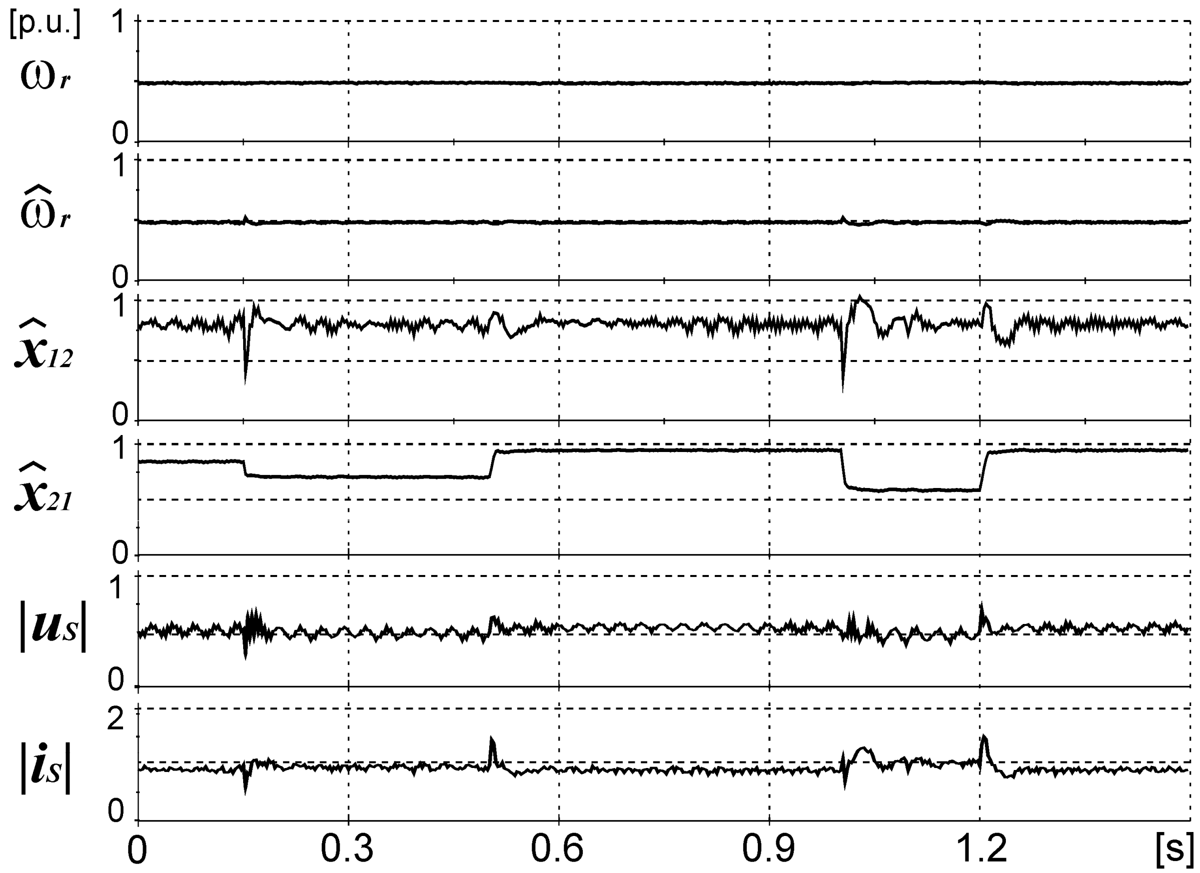
Experiment of the speed reverse for observer with full model of LC filter

EXPERIMENTAL RESULTS



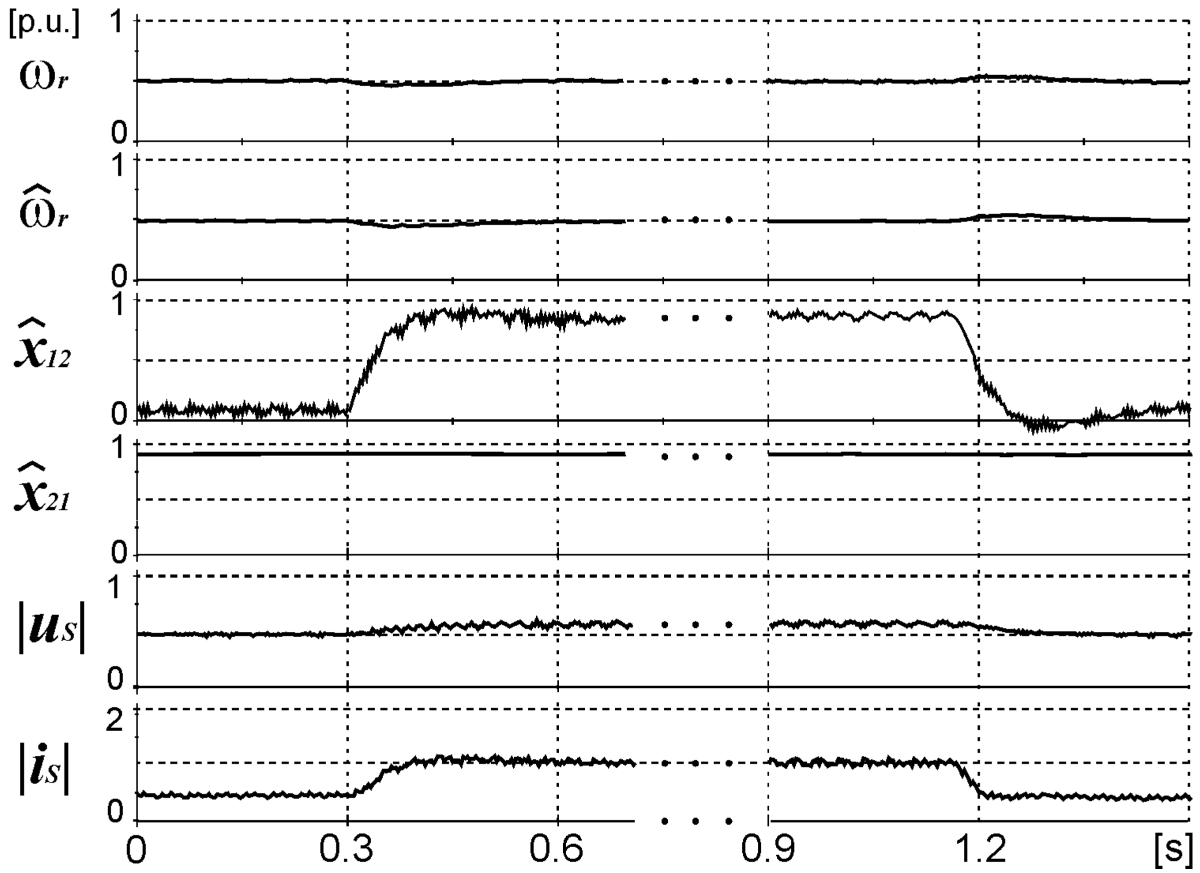
Experimental results of the proposed system
For motor speed and motor flux variations

EXPERIMENTAL RESULTS



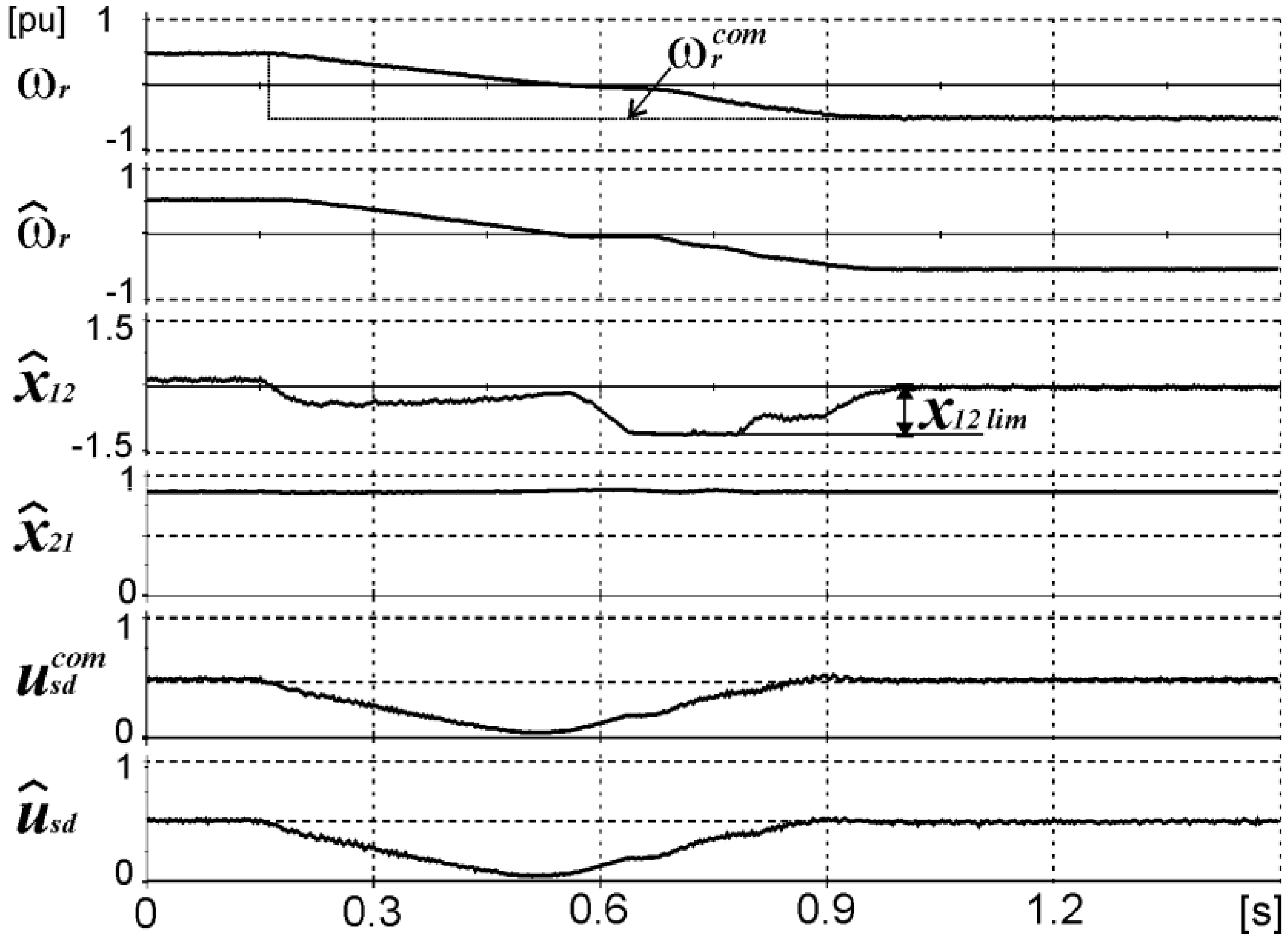
Experimental results of the proposed system for motor flux variations (motor nominal load)

EXPERIMENTAL RESULTS



Experimental results of the proposed system for load torque variations

EXPERIMENTAL INVESTIGATIONS



Experimental results of speed sensorless control system during speed and load torque variations

SIMPLE OBSERVER FOR INDUCTION MOTOR DRIVE WITH LC FILTER

Observer I

$$\frac{d\hat{\psi}_{s\alpha}}{d\tau} = \frac{-\hat{\psi}_{s\alpha} + k_r \hat{\psi}_{r\alpha}}{\tau_s} + \hat{u}_{s\alpha} - k_A\left(i_{1\alpha} - \hat{i}_{1\alpha}\right) + k_B\left(i_{1\beta} - \hat{i}_{1\beta}\right)$$

$$\frac{d\hat{\psi}_{s\beta}}{d\tau} = \frac{-\hat{\psi}_{s\beta} + k_r \hat{\psi}_{r\beta}}{\tau_s} + \hat{u}_{s\beta} - k_A\left(i_{1\beta} - \hat{i}_{1\beta}\right) - k_B\left(i_{1\alpha} - \hat{i}_{1\alpha}\right)$$

$$\hat{\psi}_{r\alpha} = \frac{\hat{\psi}_{s\alpha} - \sigma L_s \hat{i}_{s\alpha}}{k_r} \qquad \hat{\psi}_{r\beta} = \frac{\hat{\psi}_{s\beta} - \sigma L_s \hat{i}_{s\beta}}{k_r}$$

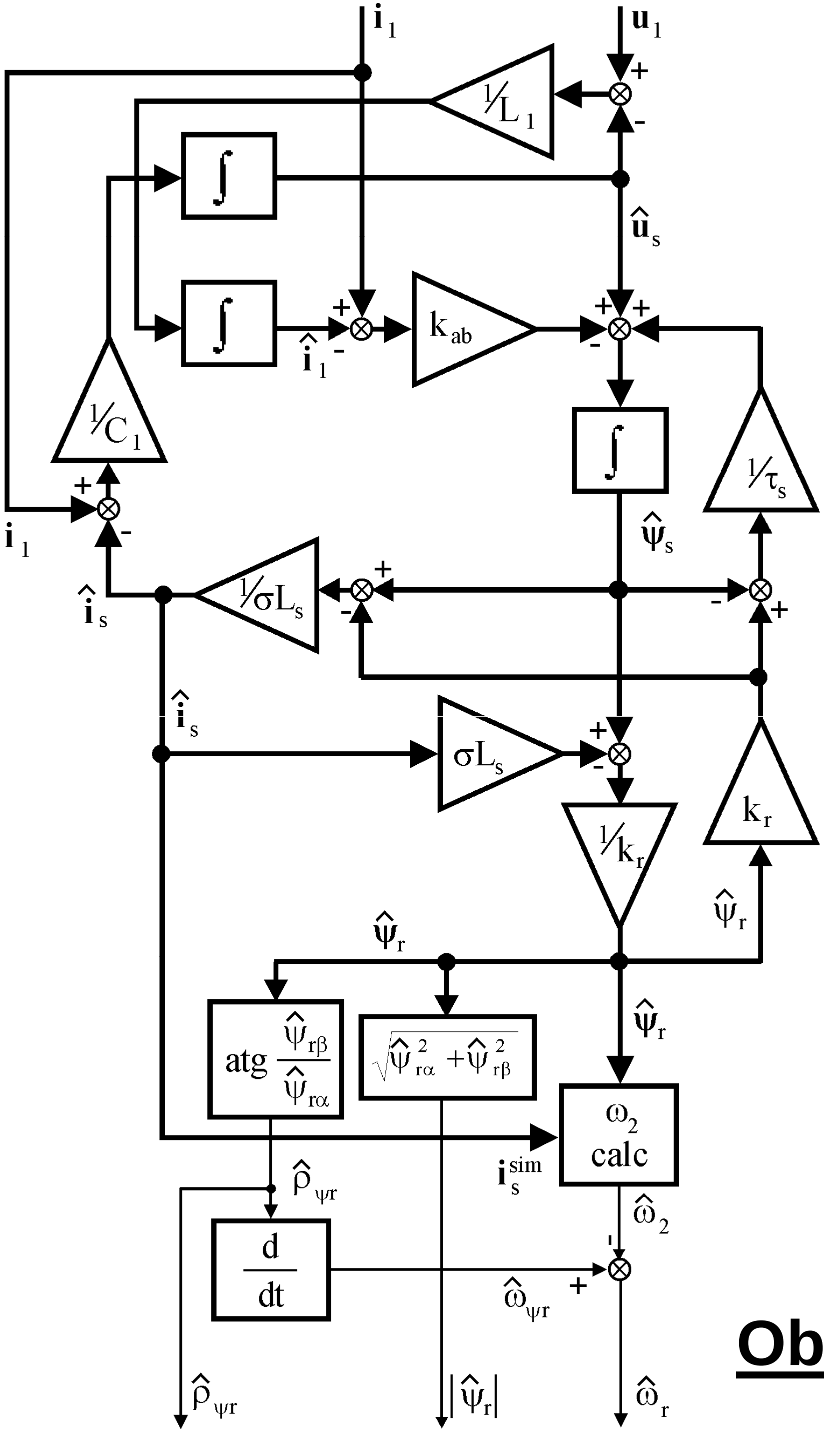
LC filter subsystem

$$\frac{d\hat{u}_{s\alpha}}{d\tau} = \frac{i_{1\alpha} - \hat{i}_{s\alpha}}{C_1} \qquad \frac{d\hat{u}_{s\beta}}{d\tau} = \frac{i_{1\beta} - \hat{i}_{s\beta}}{C_1}$$

$$\frac{d\hat{i}_{1\alpha}}{d\tau} = \frac{u_{1\alpha}^{zad} - \hat{u}_{s\alpha}}{L_1} + k_A\left(i_{1\alpha} - \hat{i}_{1\alpha}\right) - k_B\left(i_{1\beta} - \hat{i}_{1\beta}\right)$$

$$\frac{d\hat{i}_{1\beta}}{d\tau} = \frac{u_{1\beta}^{zad} - \hat{u}_{s\beta}}{L_1} + k_A\left(i_{1\beta} - \hat{i}_{1\beta}\right) + k_B\left(i_{1\alpha} - \hat{i}_{1\alpha}\right)$$

SIMPLE OBSERVER FOR INDUCTION MOTOR DRIVE WITH LC FILTER



Observer I

$$\left|\hat{\boldsymbol{\psi}}_r\right| = \sqrt{\hat{\psi}_{r\alpha}^2 + \hat{\psi}_{r\beta}^2}$$

$$\hat{\rho}_{\psi r} = arc\,tg\,\frac{\hat{\psi}_{r\beta}}{\hat{\psi}_{r\alpha}}$$

$$\hat{i}_{s\alpha} = \frac{\hat{\psi}_{s\alpha} - k_r\hat{\psi}_{r\alpha}}{\sigma L_s}$$

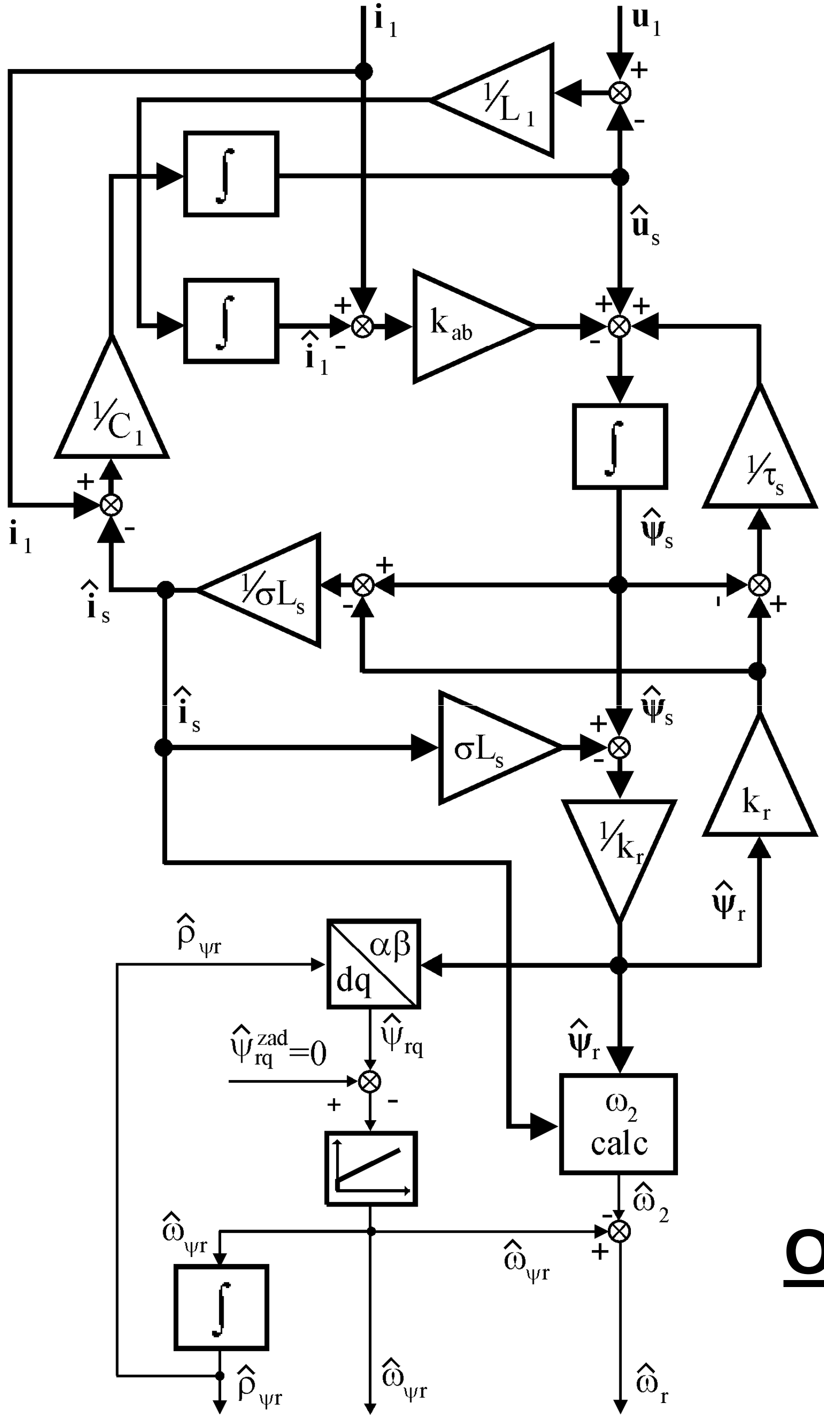
$$\hat{i}_{s\beta} = \frac{\hat{\psi}_{s\beta} - k_r\hat{\psi}_{r\beta}}{\sigma L_s}$$

$$\hat{\omega}_r = \hat{\omega}_{\psi r} - \hat{\omega}_2$$

$$\hat{\omega}_{\psi r} = \frac{d\hat{\rho}_{\psi r}}{d\tau}$$

$$\hat{\omega}_2 = \frac{\hat{\psi}_{r\alpha}\hat{i}_{s\beta} - \hat{\psi}_{r\beta}\hat{i}_{s\alpha}}{\left|\hat{\boldsymbol{\psi}}_r\right|^2}$$

SIMPLE OBSERVER FOR INDUCTION MOTOR DRIVE WITH LC FILTER



$$\hat{\psi}_{rq}^{zad} = 0$$

$$\hat{\omega}_{\psi r} = K_{pq}\left(\hat{\psi}_{rq}^{zad} - \hat{\psi}_{rq}\right) + \frac{1}{T_{iq}}\int\left(\hat{\psi}_{rq}^{zad} - \hat{\psi}_{rq}\right)d\tau$$

$$\hat{\omega}_{\psi r} = -K_{pq}\hat{\psi}_{rq} - K_{iq}\int\hat{\psi}_{rq}\,d\tau$$

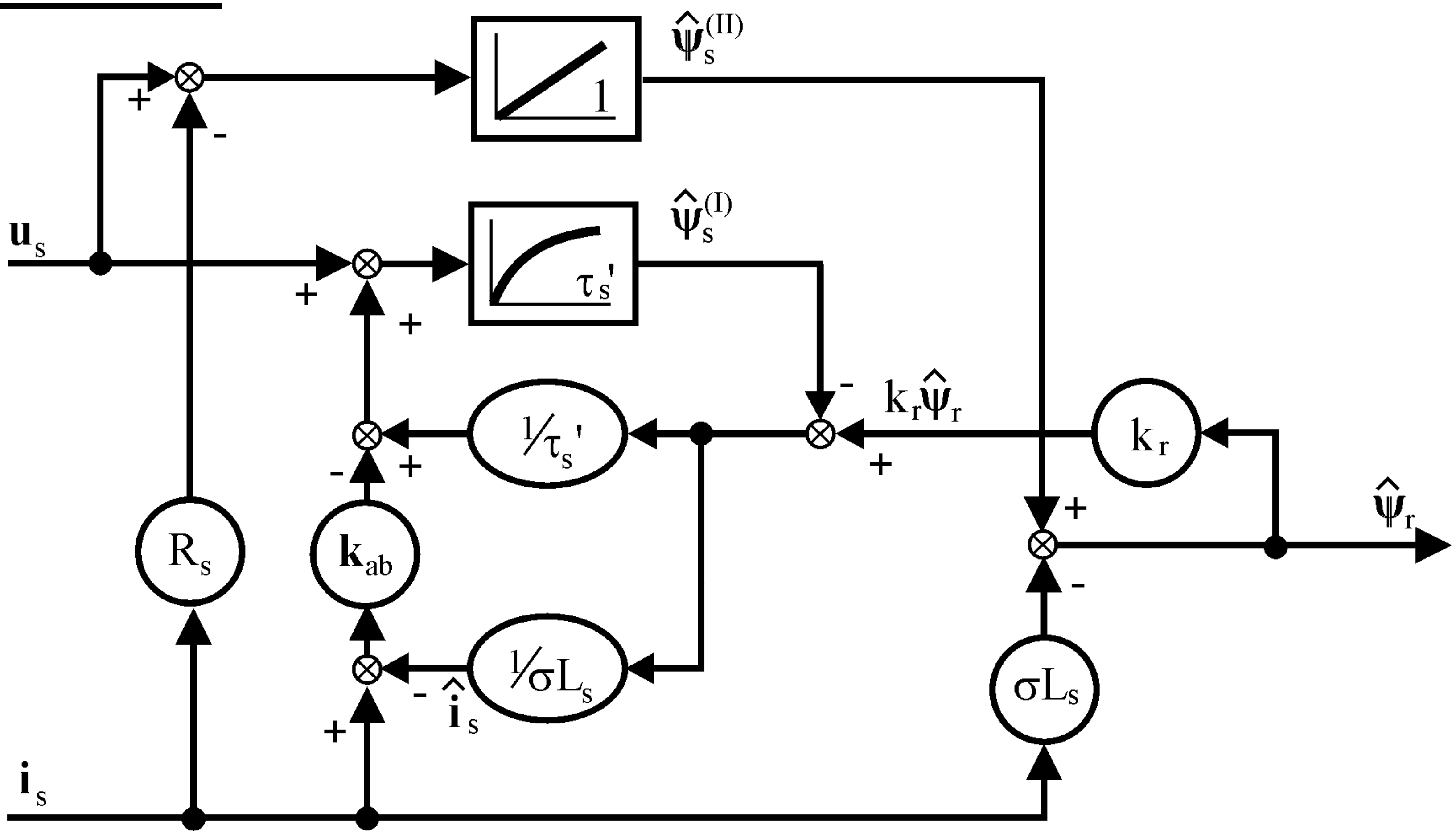
$$\hat{\rho}_{\psi r} = \int\hat{\omega}_{\psi r}\,d\tau$$

$$\hat{\psi}_{rq} = -\hat{\psi}_{r\alpha}\sin\left(\hat{\rho}_{\psi r}\right) + \hat{\psi}_{r\beta}\cos\left(\hat{\rho}_{\psi r}\right)$$

<u>Observer I</u>: without d/dt calc

SIMPLE OBSERVER FOR INDUCTION MOTOR DRIVE WITH LC FILTER

Observer II



SIMPLE OBSERVER FOR INDUCTION MOTOR DRIVE WITH LC FILTER

Observer II

$$\frac{d\hat{\psi}^{I}_{s\alpha}}{d\tau} = \frac{-\hat{\psi}^{I}_{s\alpha} + k_r\hat{\psi}_{r\alpha}}{\tau_s} + \hat{u}_{s\alpha} - k_A\left(i_{1\alpha} - \hat{i}_{1\alpha}\right) + k_B\left(i_{1\beta} - \hat{i}_{1\beta}\right)$$

$$\frac{d\hat{\psi}^{I}_{s\beta}}{d\tau} = \frac{-\hat{\psi}^{I}_{s\beta} + k_r\hat{\psi}_{r\beta}}{\tau_s} + \hat{u}_{s\beta} - k_A\left(i_{1\beta} - \hat{i}_{1\beta}\right) - k_B\left(i_{1\alpha} - \hat{i}_{1\alpha}\right)$$

$$\frac{d\hat{\psi}^{II}_{s\alpha}}{d\tau} = \frac{\hat{u}_{s\alpha} - R_s\hat{i}_{s\alpha}}{k_r} \qquad \frac{d\hat{\psi}^{II}_{s\beta}}{d\tau} = \frac{\hat{u}_{s\beta} - R_s\hat{i}_{s\beta}}{k_r}$$

$$\hat{\psi}_{r\alpha} = \hat{\psi}^{(II)}_{s\alpha} - \sigma L_s\hat{i}_{s\alpha} \qquad \hat{\psi}_{r\beta} = \hat{\psi}^{(II)}_{s\beta} - \sigma L_s\hat{i}_{s\beta}$$

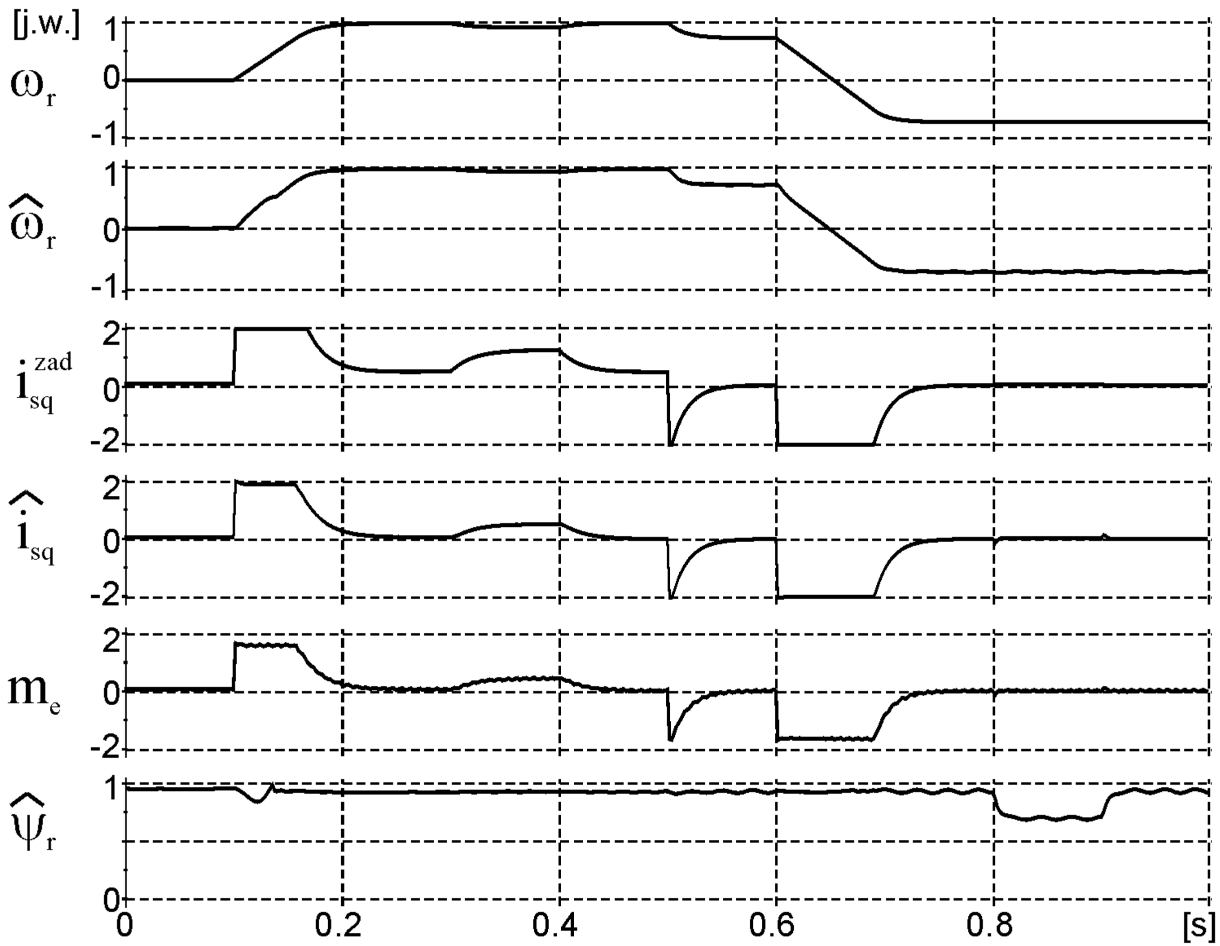
LC filter subsystem

$$\frac{d\hat{u}_{s\alpha}}{d\tau} = \frac{i_{1\alpha} - \hat{i}_{s\alpha}}{C_1} \qquad \frac{d\hat{u}_{s\beta}}{d\tau} = \frac{i_{1\beta} - \hat{i}_{s\beta}}{C_1}$$

$$\frac{d\hat{i}_{1\alpha}}{d\tau} = \frac{u^{zad}_{1\alpha} - \hat{u}_{s\alpha}}{L_1} + k_A\left(i_{1\alpha} - \hat{i}_{1\alpha}\right) - k_B\left(i_{1\beta} - \hat{i}_{1\beta}\right)$$

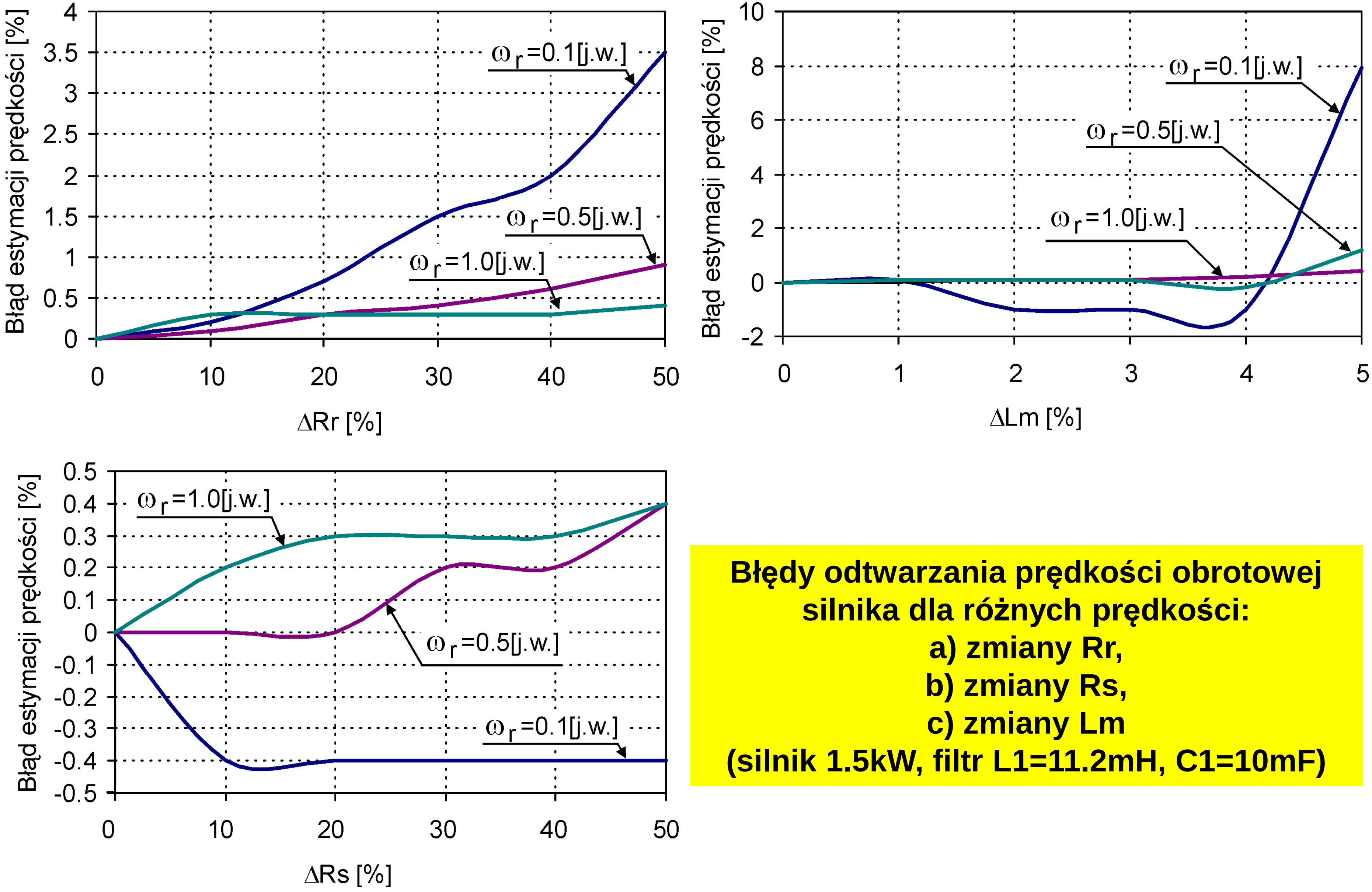
$$\frac{d\hat{i}_{1\beta}}{d\tau} = \frac{u^{zad}_{1\beta} - \hat{u}_{s\beta}}{L_1} + k_A\left(i_{1\beta} - \hat{i}_{1\beta}\right) + k_B\left(i_{1\alpha} - \hat{i}_{1\alpha}\right)$$

SIMPLE OBSERVER FOR INDUCTION MOTOR DRIVE WITH LC FILTER



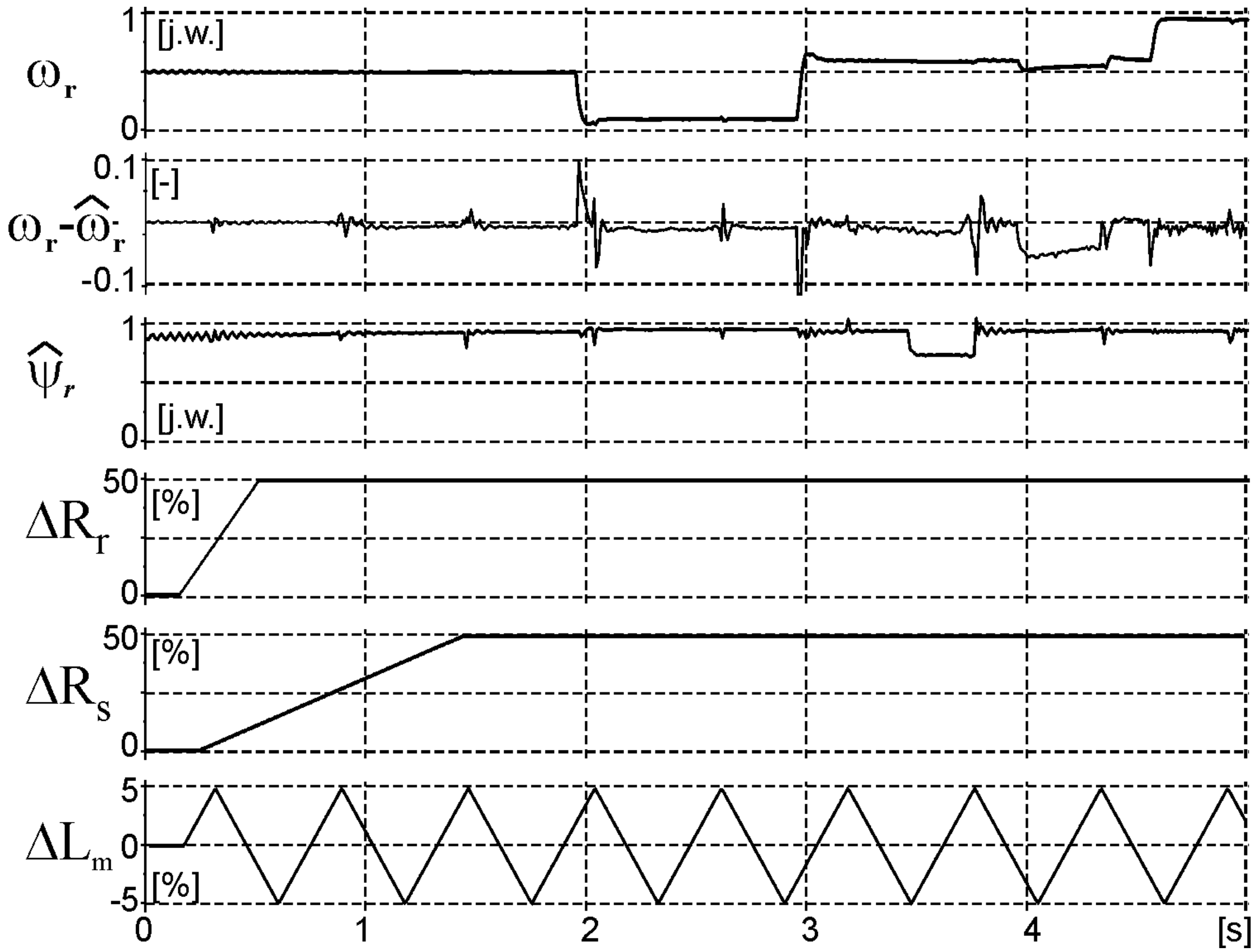
Działanie bezczujnikowego układu napędowego z silnikiem indukcyjnym i filtrem sinusoidalnym (silnik 1.5kW, filtr L1=11.2mH, C1=10mF)

SIMPLE OBSERVER FOR INDUCTION MOTOR DRIVE WITH LC FILTER



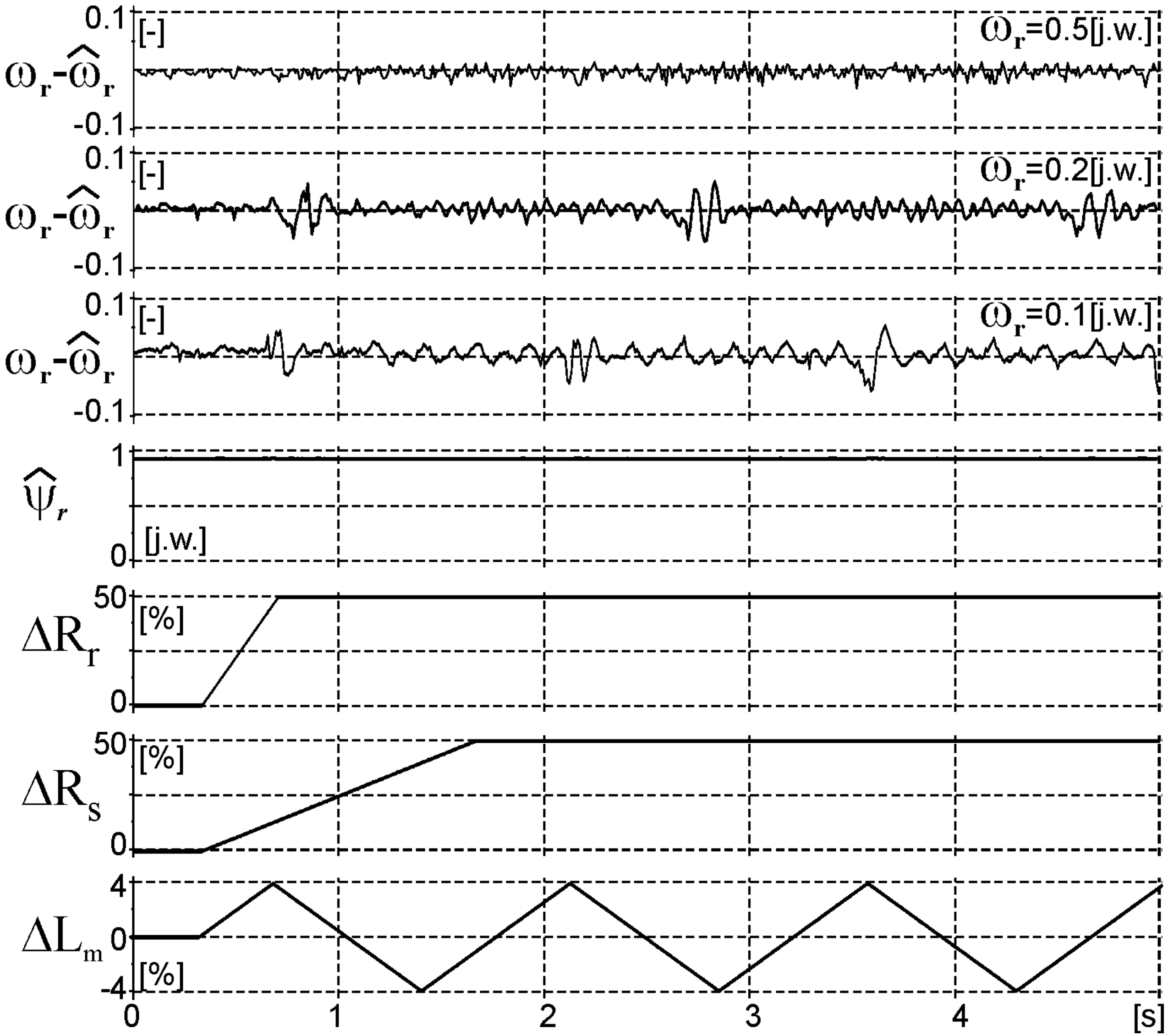
Błędy odtwarzania prędkości obrotowej silnika dla różnych prędkości:
a) zmiany Rr,
b) zmiany Rs,
c) zmiany Lm
(silnik 1.5kW, filtr L1=11.2mH, C1=10mF)

SIMPLE OBSERVER FOR INDUCTION MOTOR DRIVE WITH LC FILTER



Działanie układu bezczujnikowego sterowania polowo zorientowanego z obserwatorem stanu przy zmianach parametrów silnika (silnik 1.5kW, filtr L1=11.2mH, C1=10mF) **symulacja**

SIMPLE OBSERVER FOR INDUCTION MOTOR DRIVE WITH LC FILTER



Działanie układu bezczujnikowego sterowania polowo zorientowanego przy zmianach parametrów silnika użytych w zależnościach obserwatora – dla prędkości: 0.1j.w., 0.2j.w. oraz 0.5j.w. (silnik 1.5kW, filtr L1=11.2mH, C1=10mF)

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