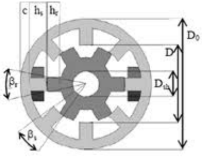
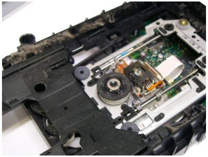
Model elicitation for synchronous machine

Václav Šmídl

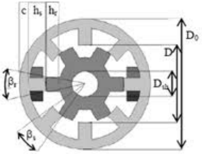
October 29, 2012

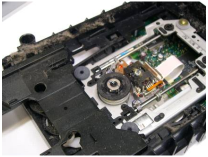
Permanent Magnet Synchronous Machine



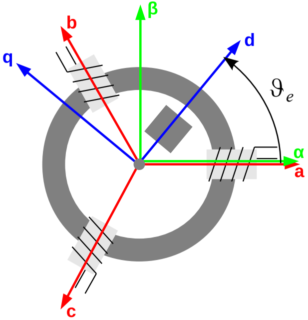


Permanent Magnet Synchronous Machine





Variables (voltages, currents) treated as vectors in 2D space.



Motivation - sensorless control

Model of the drive in $\alpha - \beta$

$$\omega_{t+1} = \omega_t + \frac{k_p p_p^2 \Psi_{pm}}{J} \Delta t \left(i_{\beta,t} \cos(\vartheta) - i_{\alpha,t} \sin(\vartheta) \right) - \frac{p_p \Delta t}{J} T_L,$$
$$\vartheta_{t+1} = \vartheta_t + \Delta t \omega_{me}.$$

Observations

$$i_{\alpha,t+1} = (1 - \frac{R_s}{L_s} \Delta t) i_{\alpha,t} + \frac{\Psi_{PM} \Delta t}{L_s} \omega_{me} \sin \vartheta + \Delta t \frac{u_{\alpha,t}}{L_s},$$
$$i_{\beta,t+1} = (1 - \frac{R_s}{L_s} \Delta t) i_{\beta,t} - \frac{\Psi_{PM} \Delta t}{L_s} \omega_{me} \cos \vartheta + \Delta t \frac{u_{\beta,t}}{L_s},$$

At $\omega = 0$, ϑ_e is unobservable.

Motivation - sensorless control

Model of the drive in $\alpha - \beta$

$$\omega_{t+1} = \omega_t + \frac{k_p p_p^2 \Psi_{pm}}{J} \Delta t \left(i_{\beta,t} \cos(\vartheta) - i_{\alpha,t} \sin(\vartheta) \right) - \frac{p_p \Delta t}{J} T_L,$$
$$\vartheta_{t+1} = \vartheta_t + \Delta t \omega_{me}.$$

Observations

$$i_{\alpha,t+1} = (1 - \frac{R_s}{L_s} \Delta t) i_{\alpha,t} + \frac{\Psi_{PM} \Delta t}{L_s} \omega_{me} \sin\vartheta + \Delta t \frac{u_{\alpha,t}}{L_s},$$
$$i_{\beta,t+1} = (1 - \frac{R_s}{L_s} \Delta t) i_{\beta,t} - \frac{\Psi_{PM} \Delta t}{L_s} \omega_{me} \cos\vartheta + \Delta t \frac{u_{\beta,t}}{L_s},$$

At $\omega = 0$, ϑ_e is unobservable.
Working estimation technique: High-frequency injections with phase-lock-loop.

Physical model of the PMSM drive

Observation equation for currents in dq coordinate system:

$$
\begin{aligned}
i_{d,t+1} &= (1 - \frac{R_s}{L_{s,d}}\Delta t)i_{d,t} + i_{q,t}\omega_t\Delta t + u_{d,t}\frac{\Delta t}{L_{s,d}}, \\
i_{q,t+1} &= (1 - \frac{R_s}{L_{s,q}}\Delta t)i_{q,t} - \left(\frac{\psi_{pm}}{L_{s,q}} + i_{d,t}\right)\Delta t\omega_t + u_{q,t}\frac{\Delta t}{L_{s,q}},
\end{aligned}
\qquad (1)
$$

Inductances in d and q axis slightly differ – cca 2-5%.

Physical model of the PMSM drive

Observation equation for currents in dq coordinate system:

$$i_{d,t+1} = (1 - \frac{R_s}{L_{s,d}}\Delta t)i_{d,t} + i_{q,t}\omega_t \Delta t + u_{d,t}\frac{\Delta t}{L_{s,d}},$$
$$i_{q,t+1} = (1 - \frac{R_s}{L_{s,q}}\Delta t)i_{q,t} - \left(\frac{\psi_{pm}}{L_{s,q}} + i_{d,t}\right)\Delta t \omega_t + u_{q,t}\frac{\Delta t}{L_{s,q}}, \qquad (1)$$

Inductances in d and q axis slightly differ – cca 2-5%.

- Detailed measurement of inductances is difficult
- Restructuring the model:

$$u_d = [L_d, R_s, L_q]\left[\frac{i_{d,t} - i_{d,t-1}}{\Delta t}, i_d, -i_q\omega_{me}\right] + \xi_{ud},$$

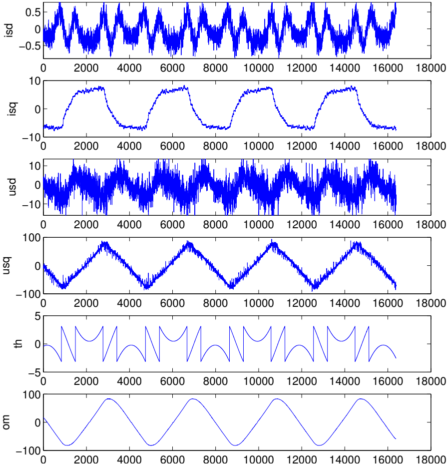
$$u_q = \underbrace{[L_d, R_s, L_q, \Psi_{pm}]}_{\theta}\left[\underbrace{i_d\omega_{me}, i_q, \frac{i_{q,t} - i_{q,t-1}}{\Delta t}, \omega_{me}}_{\psi}\right] + \xi_{uq},$$

Recorded data

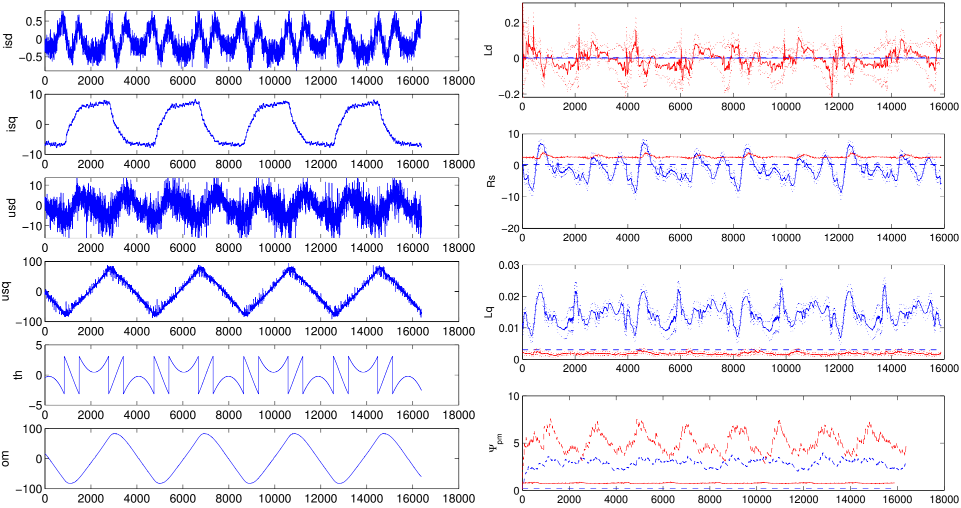
- triangular profile of ω to have maximum range,
- excitation of the inputs by square HF injections

$$u_t = u_{t,opt} + 7V \cdot 1kHz\ squares$$

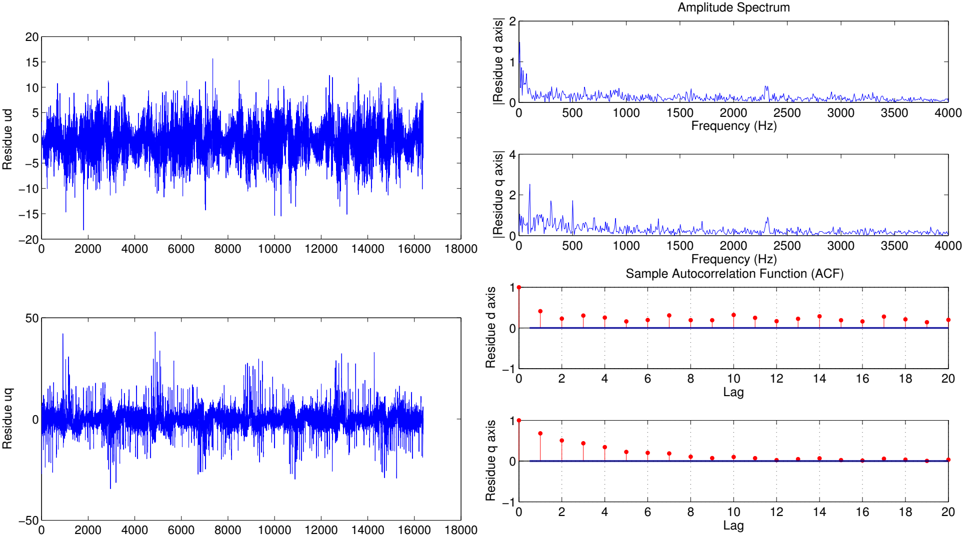
- low currents in i_d axis



Estimation with recorded data



Residues

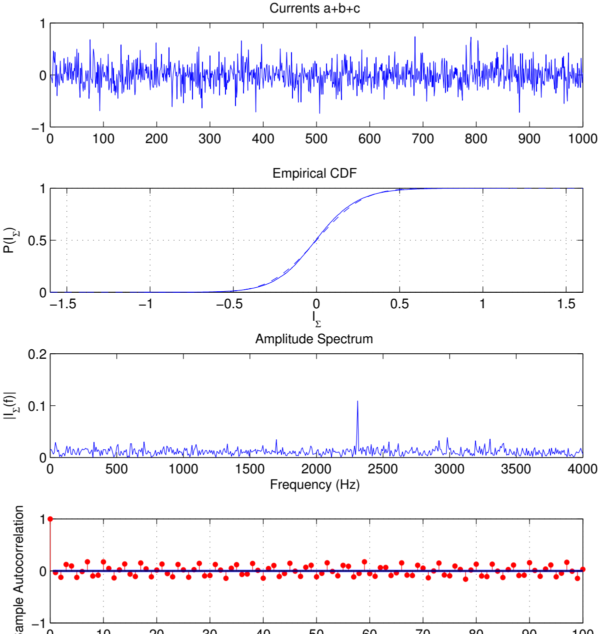

Residue ud
Residue uq
Amplitude Spectrum
|Residue d axis|
|Residue q axis|
Frequency (Hz)
Sample Autocorrelation Function (ACF)
Residue d axis
Residue q axis
Lag

Is the measurement noise Gaussian?

Unique property.
Law of physics:

$$i_a + i_b + i_c = 0.$$

Gaussian cdf.



Different parametrization

Model

$$i_{d,t+1} = (1 - \frac{R_s}{L_{s,d}}\Delta t)i_{d,t} + i_{q,t}\omega_t\Delta t + u_{d,t}\frac{\Delta t}{L_{s,d}},$$
$$i_{q,t+1} = (1 - \frac{R_s}{L_{s,q}}\Delta t)i_{q,t} - \left(\frac{\psi_{pm}}{L_{s,q}} + i_{d,t}\right)\Delta t\omega_t + u_{q,t}\frac{\Delta t}{L_{s,q}},$$

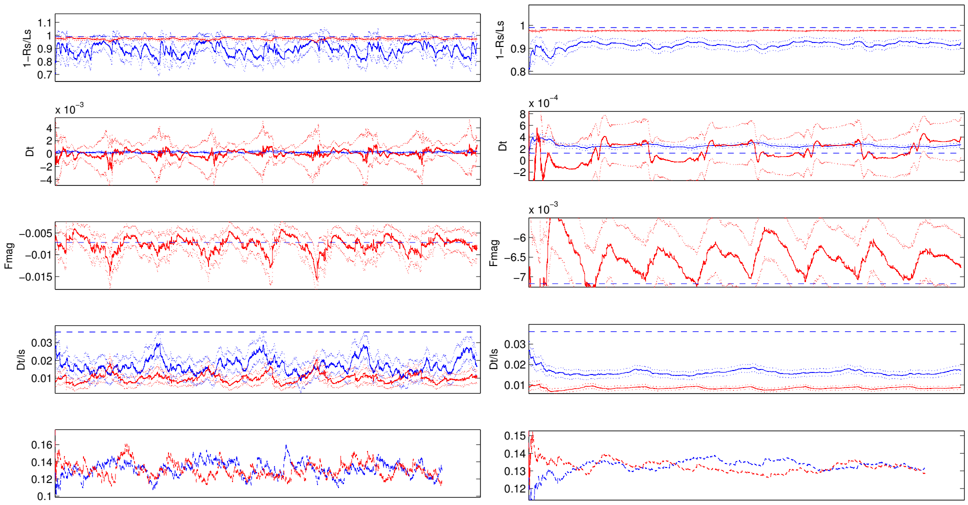
is

$$i_{d,t+1} = [a_d, b_d, c_d][i_{d,t}, i_{q,t}\omega_t, u_{d,t}],$$
$$i_{q,t+1} = \underbrace{[a_q, b_q, f_q, c_q]}_{\theta}\underbrace{[i_{q,t}, \omega_t, i_{d,t}\omega_t, u_{q,t}]}_{\psi},$$

– Parameters have no physical meaning,

+ Directly applicable in a state space estimator.

Results of estimation, $\lambda = 0.995$, $\lambda = 0.9995$



Dead times and voltage drops

- The input voltage is not exact!
- It is transformed by PWM unit.
  - voltage drops,
  - dead times
- Model

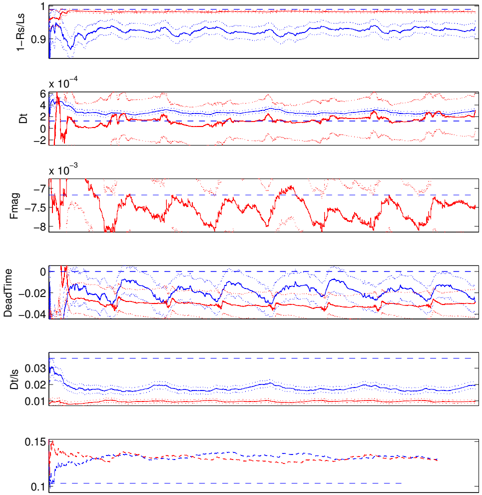
$$u_{x,true} = u_{x,t} - u_{dead\_time} \operatorname{sgn}(i_x).$$

Dead times and voltage drops

- The input voltage is not exact!
- It is transformed by PWM unit.
  - voltage drops,
  - dead times
- Model

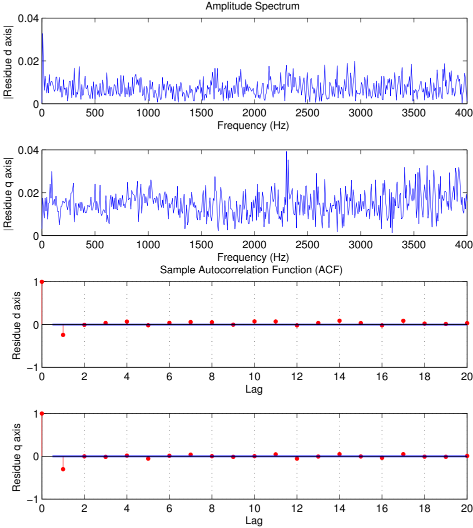
$$u_{x,true} = u_{x,t} - u_{dead\_time}\mathrm{sgn}(i_x).$$

- u_{dead_time} estimated stationary,
- Estimated sampling time Δt matches its true value in the q axis!



Residues

- Dominant frequency on the residues on the q is the measurement peak!
- Dominant frequency on the d axis is 10Hz.
- On both axis, there is still negative correlation with 1-step delayed value.
    - suggests missing element in the equations



Automatic search - hypothesis testing

Correlation of the residue with its previous value suggests a missing element.

Existing regresands in q axis:

$$\psi = [i_{q,t},\ \omega_t,\ i_{d,t}\omega_t,\ u_{q,t},\ \mathrm{sgn}(i_q)],$$

Candidates for extension:

additional element	none	1	i_d	u_d	$i_d u_d$	$\mathrm{sgn}(i_d)$	$i_{q,t-2}$
marginal likelihood	46%	1%	11%	10%	17%	13%	1%
autocorrelation -1	-0.302	-0.301	-0.300	-0.301	-0.301	-0.301	-0.08
autocorrelation -2	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.16

Automatic search - hypothesis testing

Correlation of the residue with its previous value suggests a missing element.

Existing regresands in q axis:

$$\psi = [i_{q,t},\ \omega_t,\ i_{d,t}\omega_t,\ u_{q,t},\ \mathrm{sgn}(i_q)],$$

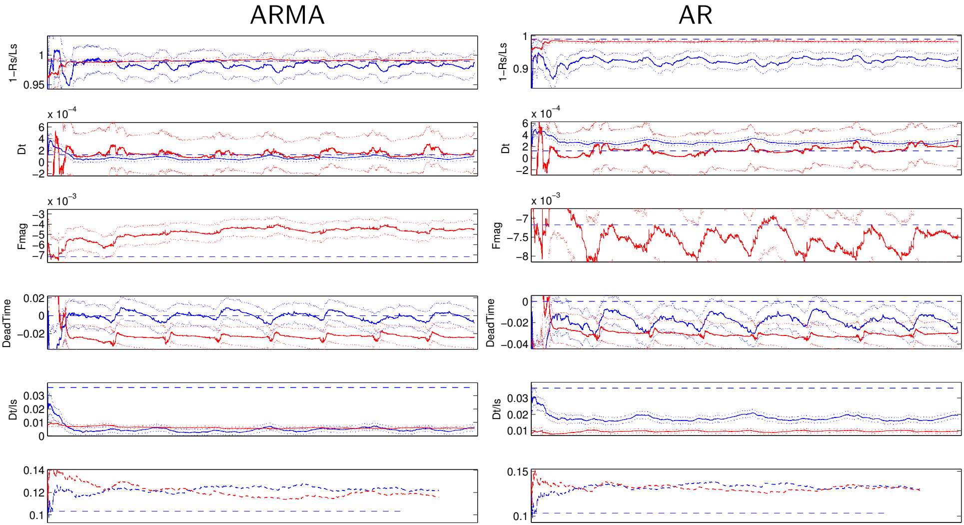
Candidates for extension:

additional element	none	1	i_d	u_d	$i_d u_d$	$\mathrm{sgn}(i_d)$	$i_{q,t-2}$
marginal likelihood	46%	1%	11%	10%	17%	13%	1%
autocorrelation -1	-0.302	-0.301	-0.300	-0.301	-0.301	-0.301	-0.08
autocorrelation -2	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.16

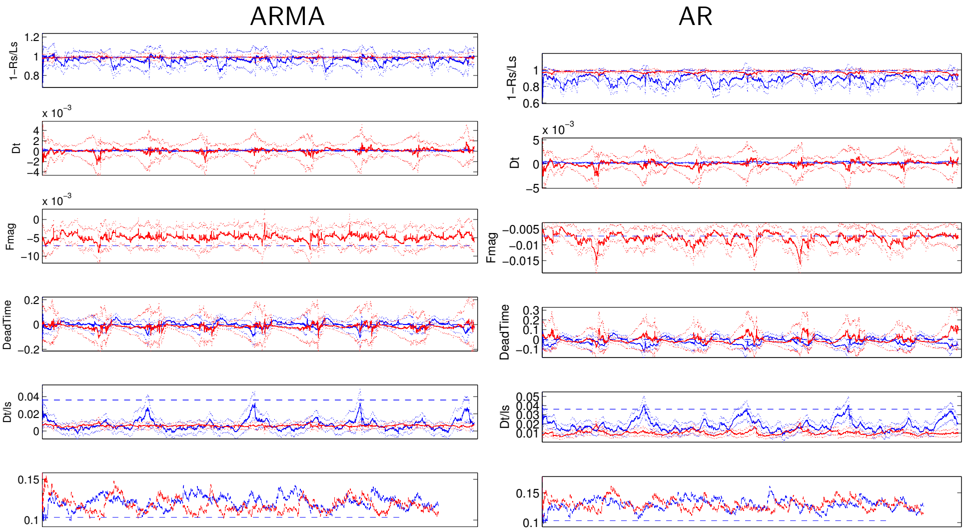
ARMA?

additional element	none	ϵ_{t-1}	ϵ_{t-1} , no $\mathrm{sgn}(i_d)$
marginal likelihood	0%	100.00%	0%
autocorrelation -1	-0.302	-0.124	-0.104
autocorrelation -2	-0.01	-0.08	-0.04

Parameters of the ARMA model, $\lambda = 0.9995$



Parameters of the ARMA model, $\lambda = 0.995$



Conclusion

- Model elicitation from real data is a demanding task
  - experiment design,
  - sensor calibration!
- Poor excitation is the d axis can be improved by inefficient control (exploration),
- PMSM drive model:
  - is it an ARMA process?

$$\epsilon_t - 0.5\epsilon_{t-1}$$

  - can ARMA model replace dead-times and voltage drops?