Control and Parameter Identification of AC Electric Drives under Critical Operating Conditions

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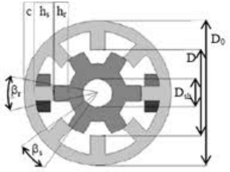
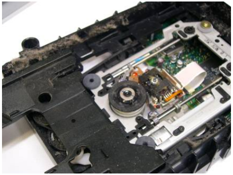
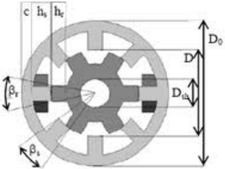
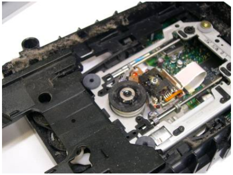
Permanent Magnet Synchronous Machine





Permanent Magnet Synchronous Machine





Sensorless control = control without mechanical sensors (speed, position), with

1. electric currents,
2. **reconstructed** voltages,

Reasons:

- cost, space restrictions, maintenance,

Main issue:

- reliability

Formal approach

State of the art: Kalman filter + PID control + **their tuning**.
We can do better on both parts... can we?

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Formally, the problem is simple application of Bayesian decision making under uncertainty.

Decision making with (quadratic?) loss function:

$$L = (\omega - \omega_{req})^2.$$

Bayesian filtering:

$$p(y_t|x_t)$$

$$p(x_t|x_{t-1}),$$

$$p(x_t|y_{1:t}) = \frac{p(y_t|x_t)p(x_t|x_{t-1})p(x_{t-1}|y_{1:t-1})}{\int -''-}.$$

State space model of the system

Differential equations

$$
\begin{aligned}
\frac{di_\alpha}{dt} &= -\frac{R_s}{L_s} i_\alpha + \frac{\Psi_{PM}}{L_s}\omega_{me}\sin\vartheta + \frac{u_\alpha}{L_s},\\
\frac{di_\beta}{dt} &= -\frac{R_s}{L_s} i_\beta - \frac{\Psi_{PM}}{L_s}\omega_{me}\cos\vartheta + \frac{u_\beta}{L_s},\\
\frac{d\omega}{dt} &= \frac{k_p p_p^2 \Psi_{pm}}{J}\left(i_\beta \cos(\vartheta) - i_\alpha \sin(\vartheta)\right) - \frac{B}{J}\omega - \frac{p_p}{J} T_L,\\
\frac{d\vartheta}{dt} &= \omega_{me}.
\end{aligned}
\tag{1}
$$

Observations (theoretical):

$$i_\alpha, i_\beta, (u_\alpha, u_\beta).$$

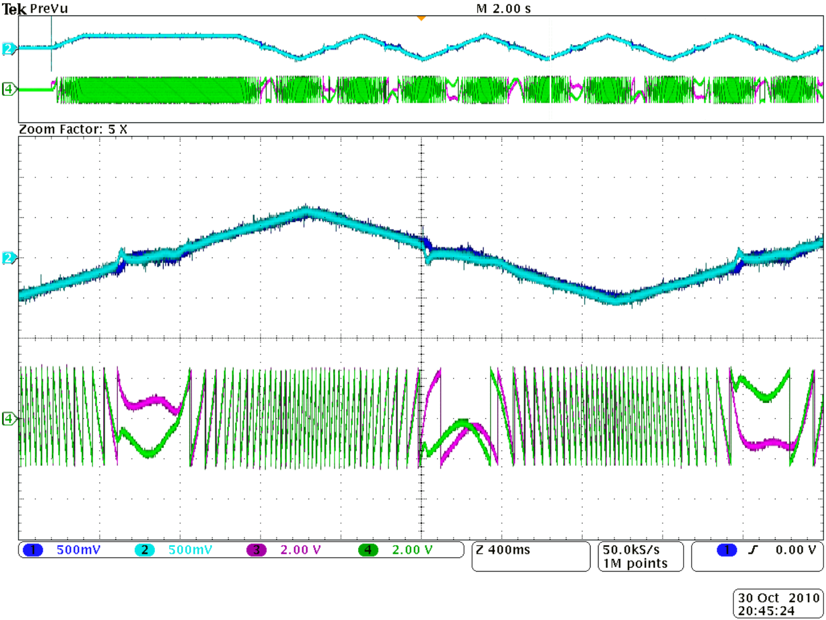
In reality we observe

$$g(u_\alpha), g(u_\beta).$$

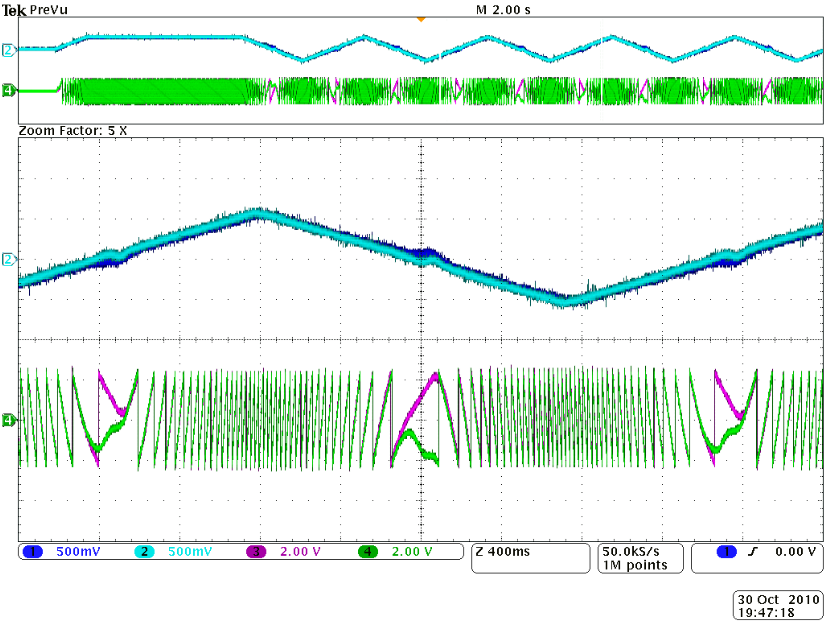
Missing parts of the model

- Voltage reconstruction is unknown depending on low level power electronic models,
- Noise distributions are unknown (variances in Kalman has to be overestimated),
- Magnetic flux equation, ($\Psi_{PM} = \Psi_{PM}(i_\alpha, i_\beta, \omega, \vartheta)$), saturation effect,
  - "solved" by an additional PI controller,
- Anisotropies of the inductance,
  - in rotating reference frame, L_s in different axis differ about 5%,
  - utilized in high frequency injections techniques,
- Dependence of parameters on temperature,
  - sensitivity to "detuned" model,

Kalman filter fixed-point arithmetics



Kalman filter Choleski decomposition



Marginalized Particle Filter

Observation equation dq coordinate system – depends on ϑ_t:

$$
\begin{aligned}
i_{d,t+1} &= (1 - \frac{R_s}{L_{s,d}}\Delta t) i_{d,t} + i_{q,t}\omega_t \Delta t + u_{d,t}\frac{\Delta t}{L_{s,d}}, \\
i_{q,t+1} &= (1 - \frac{R_s}{L_{s,q}}\Delta t) i_{q,t} - \left(\frac{\psi_{pm}}{L_{s,q}} + i_{d,t}\right)\Delta t \omega_t + u_{q,t}\frac{\Delta t}{L_{s,q}},
\end{aligned} \tag{2}
$$

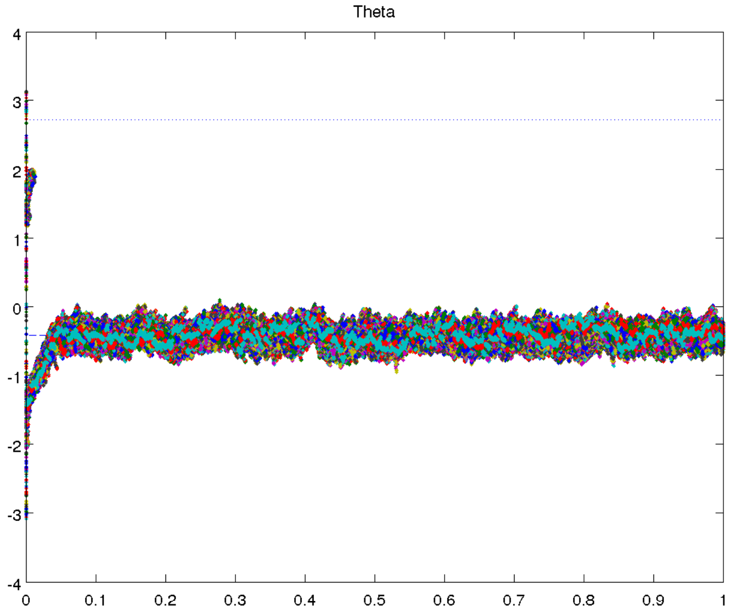
is the observation model, and

$$
\begin{aligned}
\omega_{t+1} &= d\omega_t + e_1 i_{d,t} + e_2 i_{q,t}. \\
\vartheta_{t+1} &= \vartheta_t + \omega_t \Delta t.
\end{aligned} \tag{3}
$$

For known ϑ_t we get 1dimensional Kalman filter.

- Approximating posterior on ϑ_t by empirical pdf yields bank of n Kalman filters,
- The filter is capable of estimating position in zero speed.
- Difficult tuning.

Marginalized Particle Filter



Bicriterial Dual control

Classical technique of high-frequency injection is a sort of “probing”.

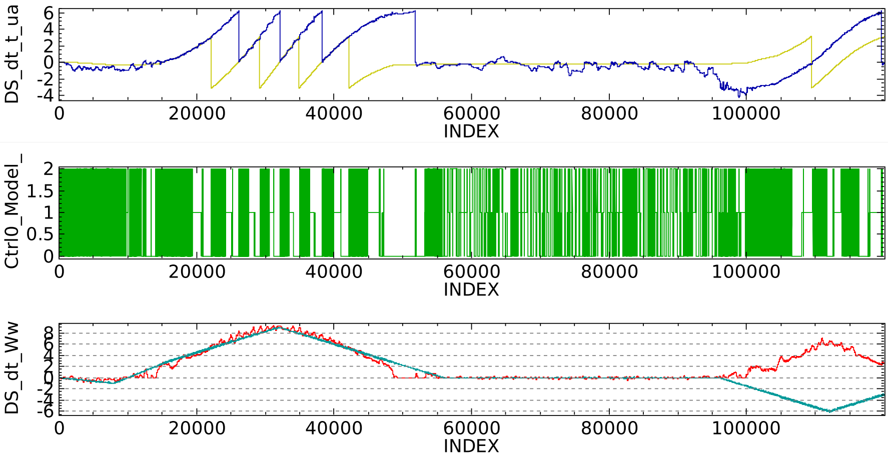
- The estimation technique is designed to match the probing signal,

Can we design probing signal for the Kalman filter?

- Bicriterial approach (Filatov, Unbehauen, 2004),
- Capable of “mixed frequency” switching,
- Preliminary results were promising, not so sure now...
- The hard part is to choose the “second criterion”,

Could be extended for MPF?

Dual control



TODO

- Voltage reconstruction $=>$ model elicitation,
- Uncertain parameters $R_s, L_s, \Psi_{PM} =>$ linear regression
- Bi-modality for $\omega, \vartheta \iff -\omega, \vartheta + \pi$, since

  $$-\omega \sin(\vartheta + \pi) = \omega \sin(\vartheta),$$

  problematic due to signal-to-noise-ratio. $=>$ dual control, better model, multi modality?
- Unobservability at $\omega = 0$, observations are independent of ϑ
  - Estimation is possible due to excitation by injected signal $=>$ dual control,
- Computational issues. Limited power of DSP $=>$ VHDL implementations.