Control of Naval Electric Drives
Status Report
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Aleksandar M. Stanković

Northeastern University
Boston, MA

PEMC Lab., Northeastern University
Overview

- Tasks
- Analytical Background
- Task Status Review
- Planned Activities
**Tasks: General**

**Long range goal:** develop control tools that are enabled by, and which fully utilize the capabilities of new switches (PEBB hardware).

Sharp control design and analysis tools are to be developed as yardsticks for practical design. Those include:

- energy-flow based, dissipative nonlinear controllers,
- robust controllers that tolerate realistic uncertainties,
- global controllers that achieve global exponential stability.
Tasks: Specific

- Dissipative (Lagrangian) control of permanent magnet machines (PMSM):
  - feedback enhancing both dissipative components (resistance, friction) and
    lossless flow between the electrical and mechanical subsystems (inductance).
  - adaptive control using the speed-gradient method,

- Re-examination of the electric drive control structure - quantifying the suboptimality of nested control loops (current - speed - position),

- Torque ripple minimization in switched (variable) reluctance motors (SRM),

- Design of stabilizers for synchronous machines (SM) - dissipativity over a frequency band,

- Experimental verification for SRM and PMSM.

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Analytical background: Dissipativity

\[ x(t) \in \mathbb{R}^n \text{ (state)} \]
\[ u(t) \in \mathbb{R}^m \text{ (input)} \]
\[ y(t) \in \mathbb{R}^r \text{ (output)} \]

\[ V : \mathbb{R}^n \to \mathbb{R}_+ \text{ storage function} \]
\[ s(u, y) \text{ supply rate (often quadratic)} \]

Dissipativity: For any \( t_0 \leq t_1 \)

\[ V(x(t_0)) + \int_{t_0}^{t_1} s(u, y)(t) \, dt \geq V(x(t_1)) \]

\[ s(u, y) = \|u\|_2^2 - \alpha^2 \|y\|_2^2, \quad \alpha \geq 1 \quad \text{Attenuation} \]

\[ s(u, y) = u^T y \quad \text{Passivity} \]

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Theorem An interconnection of dissipative systems (+ some technical conditions) is stable (in a suitably chosen sense).

Large scale system extensions (Vidyasagar 1980).

Corollaries

- A (negative) feedback interconnection of a passive and a strictly passive system is stable.
- A feedback interconnection of contractive systems is stable.

Theorem Linear case - frequency-domain interpretations:

Dissipativity $\iff$ A linear matrix inequality has real symmetric solutions

$\iff$ (Kalman-Yakubovich-Popov) Transfer function is positive real.

A variety of powerful computational methods is available.

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Advantages of dissipativity based control:

- Robustness and relative simplicity of Lagrangians.
- Tolerance of very large, physically motivated uncertainties.
- Utilizes physical intuition.
- Special model structure exploited.

Design steps:

- shape the total, steady state, closed loop stored energy,
- add dissipation and transient shaping to tracking error dynamics.
Permanent Magnet Drives: Passivity in a nonlinear system

Standard d-q model of a permanent magnet synchronous motor:

\[ L_d \frac{d}{dt} i_d = \omega L_q i_q - R i_d + v_d \]
\[ L_q \frac{d}{dt} i_q = -\omega L_d i_d - R i_q - \omega M i + v_q, \]
\[ J \frac{d}{dt} \omega = M I_i_q - (L_q - L_d) i_d i_q - B \omega - T_L. \]

A Lagrangian model form with a normalized state vector:

\[ \dot{x} = -(C(x) + R)x + Bu + FT_L, \]

where \( x = [\sqrt{L_d} i_d \sqrt{L_q} i_q \sqrt{J} \omega] \)

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Permanent Magnet Drives, cont. 1

- "Workless forces": the skew-symmetric \(-C(x)\),
- Dissipative forces: the negative definite \(-\mathcal{R}\),
- Total energy is \((1/2)x^T x\).

Design Steps

1. Select desired (steady state) \(x_d\) for torque tracking, min. losses \(\Rightarrow\) Select \(u_d\).
2. In a transient model (for \(\varepsilon = x - x_d\)) select a transient \(u_e\) to enhance –
   (a) the dissipative component \(\mathcal{R}\),
   (b) the workless mechanical – electrical power flow.

Result:

- global exponential convergence,
- balanced mechanical – electrical convergence rate \(\Rightarrow\) enhanced tracking speed.

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Permanent Magnet Drives, cont. 2

Closed loop transient dynamics

\[ \dot{e} = -(D + S(x, x_d)) \dot{e} \]

where

\[
D + S(x, x_d) =
\begin{bmatrix}
B_1 + \alpha & -\mu C_1 x_8 & -\lambda C_2 x_2 \\
\mu C_1 x_8 & B_2 + \beta & -\kappa (C_2 x_{1, d} + C_3) \\
\lambda C_2 x_2 & \kappa (C_2 x_{1, d} + C_3) & 0
\end{bmatrix}
\]

Total of five tuning parameters allowing:

- Enhanced virtual resistance \((\alpha, \beta)\), current error dissipation,
- Manipulate transient coupling between the currents \((\mu)\),
- Enhanced transient electrical – mechanical coupling \((\kappa, \lambda)\).
Transient motor velocity and control input, using estimated load torque (step 20%), (a) \(\lambda=4\); (b) \(\lambda=6\); (c) \(\lambda=8\).

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Power balance equations of a permanent magnet synchronous motor:

\[
\begin{align*}
L_d \frac{di_d}{dt} &= \omega L_q i_q i_d - R_d i_d^2 + v_d i_d \\
L_q i_q \frac{di_q}{dt} &= -\omega L_d i_q i_d - R_q i_q^2 - \omega M i_q + u_i i_q \\
J \omega \frac{d\omega}{dt} &= \omega M i_q - \omega (L_q - L_d) i_d i_q - B\omega^2 - T_i \omega
\end{align*}
\]

Representation of the power flows:

<table>
<thead>
<tr>
<th>Source Power</th>
<th>Load Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohmic Losses</td>
<td>Static</td>
</tr>
<tr>
<td>$R_s i^2$</td>
<td>$T_i \omega$</td>
</tr>
<tr>
<td>Electromagnetic Power</td>
<td>Dynamic</td>
</tr>
<tr>
<td>$\frac{d}{dt} W_{jed}$</td>
<td>$J \omega$</td>
</tr>
<tr>
<td>Mechanical Losses</td>
<td>$B\omega^2$</td>
</tr>
</tbody>
</table>

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Permanent Magnet Drives, cont. 5

Representation of the power flow components during transients.

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Permanent Magnet Drives, cont. 6

Block diagram of the experimental setup.

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Exploring adaptation in dissipativity-based control:
- actuation might lead to (temporary) lack of dissipativity,
- use of feedback to make a given system (locally) dissipative,
- utilize available on-line data.

Present interest - speed gradient methods (after M.M. Seron, D.I. Hill, A.L. Fradkov):
- allows for parametric uncertainties,
- linearity in terms of unknown parameters is not required,
- based on concepts from differential geometry.

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Control Structure for Electric Drives

Conventional control structure of a (DC) speed servo drive.

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Exploring the suboptimality of the nested loop structure:

- Limits of performance using linear operator-theoretic tools (μ, DC motor example),
- Dissipativity-based tools - considering the mechanical subsystem as a passive perturbation.

Models for the (nonlinear) Pulse Width Modulation (PWM) are critical.
Control Structure - Conventional Design

Current loop

Speed loop

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Control Structure for Electric Drives, cont. 1

Bode plots

Time responses

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DC motor supplied by a (modified) buck converter.

\[ <i_0> = \frac{1}{T} \int_{t-T}^{t} i(\tau) e^{-j\omega \tau} d\tau \]

\[ T = 1/f_{\text{sw}}, \omega = 2\pi/T. \]

"Phasor dynamics" with \( x_1 = <i_0>, x_2 + jx_3 = <i_1> \).
Control Structure for Electric Drives, cont. 6

\[ L_0 \dot{x}_1 = -Rx_1 - E + Vd(t) \]
\[ L_0 \dot{x}_2 = \omega L_0 x_3 - Rx_2 + \frac{V}{2\pi} \sin(2\pi d(t)) \]
\[ L_0 \dot{x}_3 = -\omega L_0 x_2 - Rx_3 + \frac{V}{2\pi} (\cos(2\pi d(t)) - 1) \]
\[ y = \hat{i}_e = x_1 + 2x_2 \cos(\omega t) - 2x_3 \sin(\omega t) \]

Approximates the ripple quite well.

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Switched Reluctance Motor (SRM) Drives

Main characteristics:
- robust, brushless construction,
- fault tolerant,
- nonlinear magnetics,
- hard to control:
  1. torque ripple,
  2. acoustic noise (doubly salient).

Strategies for reducing ripple often ask for:
- substantial actuation effort,
- (vanishingly) small model uncertainty.

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Our results:
- cyclo-dissipative system (but not strictly dissipative),
- parameterization of all ripple-free switching policies (“feedback linearizations”),
- optimization with PWM actuation effort as main criterion,
- graceful performance degradation with an increase in model uncertainty,
- experimental verification (underway).
Torque produced by a single phase:

\[ T_{M_1} = \frac{\partial W}{\partial \theta} \bigg|_{i_1=\text{const.}} \]

\[ T_{M_1} = \frac{1}{2} i_1^2 \frac{dL_1(\theta)}{d\theta} \]  
(linear magnetics)

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SRM Drives, cont. 3

General waveform profile

\[ \theta \in [d_k, c_k], \quad T_a = T_{M_k}(\theta, i_k) \Rightarrow i_k(\theta) \]

\[ \theta \in [c_k, d_k], \quad T_a = T_{M_k}(\theta, i_k) + T_{M_k}(\theta, i_k) \]

\[ \min_{s(\theta)} \left\{ \max_{\theta} \{ |u(\theta)| \} \right\} \]

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SRM Drives, cont. 6

Torque ripple for (optimized) conventional switching:

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SRM Drives, cont. 7

Torque ripple for improved switching:

[Graph of torque ripple]

[Power spectrum graph]

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Dissipativity in linear systems

Dissipativity over a frequency band combine passivity and attenuation

Design requirements:
- closed loop stability,
- passivity over the range $B$,
- attenuation (small gain) over the range $B^c$.

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Synchroneous Machine Stabilization: Passivity in a Linear System

Example of a four machine power system

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Synchronous Machine Stabilization, cont. 1

Open loop Bode plot from $u_{ref} \rightarrow \omega$.  

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Nonlinear simulation of the band-passive power system stabilizer (PSS).

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Synchronous Machine Stabilization, cont. 3

Case E10-0
Two area system
At time = 1.0 sec, a 23 MW and 3 MVAR load is added at Bus 9
At time = 2.0 sec, the same load is removed
Off PSS on Gen 1 and conventional PSS's on all other generators
PSS Control Effort (Gen 1)

Control effort of the band-passive PSS.

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Planned Activities

- modeling of PWM converters in drive applications (theory and experiment),
- permanent magnet drive:
  1. completion of the test bed,
  2. develop controller (self) tuning methodology,
- switched reluctance drive:
  1. torque tracking,
  2. accommodation of structural perturbations (e.g. sustained phase faults),
  3. asymmetric actuation for damping of shaft vibrations.
- adaptation in dissipativity-based control.

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