High Performance Control of Power Electronic Converters and Systems

Galina Mirzaeva

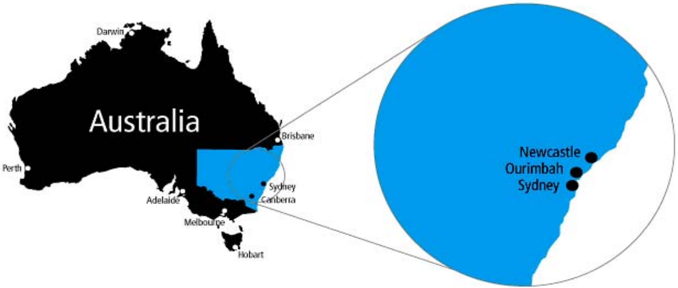
The University of Newcastle, Australia

Outline

1. Introduction
2. General formulation
   - Control in Power Electronics
   - Proposed control design framework
3. Worked examples
   - VSI, RL load, rotating frame (dq)
   - VSI, RL load, stationary frame ($\alpha\beta$)
   - VSI, non-linear (saturated) load model
   - Practical challenges
4. Other topologies
   - CSI with inductive load + capacitor
   - Matrix converter: output VSI + input CSI
5. Conclusions

THE UNIVERSITY OF NEWCASTLE AUSTRALIA

Where is Newcastle?



150 km North of Sydney (1.5 hour by car or 3 hours by train)

How does Newcastle look like?

Newcastle, Nobbys Head, bird eye view

What is special about University of Newcastle

The main campus is on a bushland

What is special about University of Newcastle

NeW Space building in Newcastle CBD

What is special about University of Newcastle

ACADEMIC RANKING OF WORLD UNIVERSITIES SINCE 2003

Home | About | Rankings | Survey | Universities | GRUP | Initiative | Conference | Study in China | Advertise with Us

Home>> Global Ranking of Academic Subjects 2018>> Automation & Control

ShanghaiRanking's Global Ranking of Academic Subjects 2018 - Automation & Control 2018

Field : Engineering Subject : Automation & Control Methodology

World Rank	Institution*	Country/Region	Total Score	Score on PUB
1	University of Illinois at Urbana-Champaign		305.4	51.1
2	Massachusetts Institute of Technology (MIT)		287.7	60.3
3	Swiss Federal Institute of Technology Zurich		278.2	53.5
4	Harbin Institute of Technology		264.2	100
5	University of California, Berkeley		263.4	49.9
6	Imperial College London		262.0	48.9
7	University of Toronto		258.5	44.6
8	The University of Newcastle, Australia		252.4	47.7
9	University of California, Santa Barbara		250.3	37.2
10	University of Michigan-Ann Arbor		244.8	54.4
11	Stanford University		240.4	37
12	Harvard University		237.4	34.2

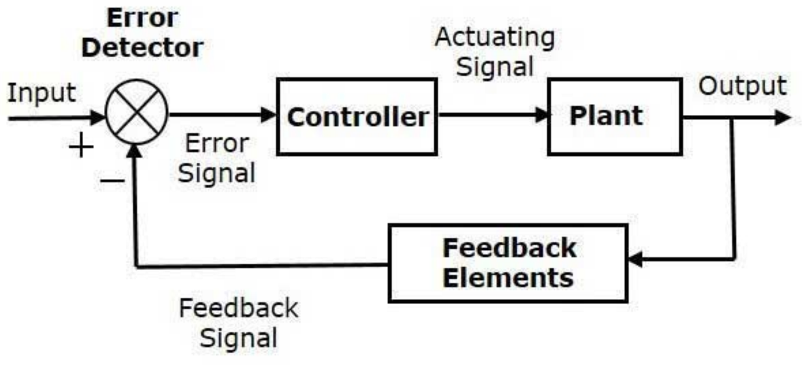
World's number 8 in Automation and Control

THE UNIVERSITY OF NEWCASTLE AUSTRALIA

Outline

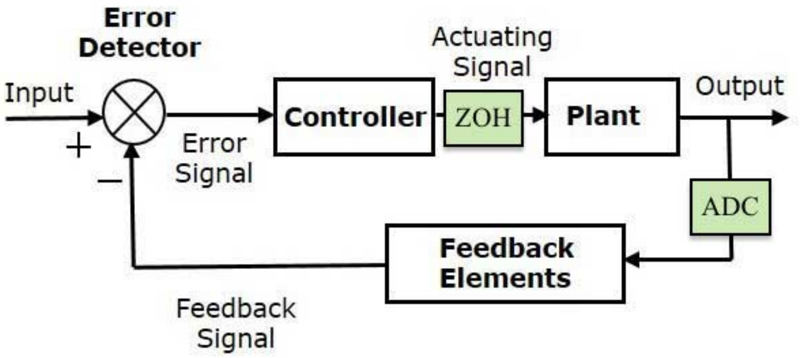
1. Introduction
2. General formulation
   - Control in Power Electronics
   - Proposed control design framework
3. Worked examples
   - VSI, RL load, rotating frame (dq)
   - VSI, RL load, stationary frame ($\alpha\beta$)
   - VSI, non-linear (saturated) load model
   - Practical challenges
4. Other topologies
   - CSI with inductive load + capacitor
   - Matrix converter: output VSI + input CSI
5. Conclusions

Classical Feedback Control system



Feedback Control system

Classical Feedback Control system (digital)



Feedback Control system (hybrid)

Some history of Digital Control

1928 - The Sampling Theorem (Nyquist - Shannon)
1940s - Difference equations; Numeric solutions
1947 - Z-transform (Hurewicz - Tsypkin)
1950 - State space approach (Lefschetz, Pontryagin)
1960 - Optimal and Stochastic control (control formulated as optimisation problem, LQ problem reduces to Riccati equation - Kalman)
1960 -1970 - Algebraic System theory, reestablishing polynomial methods (Kalman, Kucera, etc)
1970s - System Identification
1980s - Adaptive Control
1980s - 2000s Model Predictive Control in process control: optimisation over receding rather than fixed horizon (as in LQG) theory: nonlinear MPC, robust MPC,...

Challenges in Control for PE

- Limited time ($\backsim 100\mu$sec);
- Limited computational power in real-time processing (clock frequency growth saturated, mostly parallel processing);
- Faster switching devices ($\backsim 10\mu$sec, $\backsim 1\mu$sec);
- "Special tricks": cascaded control; frame transformations; axes decoupling, etc;
- In most cases PI control is used.

Challenges in Control for PE

Comfy, practical but style problem

Challenges in Control for PE

Shiny, unpractical and fashion expiry problem

Challenges in Control for PE

Elegant, timeless, reasonably practical

Challenges in Control for PE

Elegant, timeless, practical, professional

Linear system with Gaussian noise and periodic disturbance

Practically every Power Electronics application can be described by a model, in state space form:

$$x_{k+1} = A_o x_k + B_o u_k + n_k \tag{1}$$

$$d_{k+1} = A_d d_k + \omega_k \tag{2}$$

$$y_k = C_o x_k + C_d d_k + \nu_k \tag{3}$$

where x, u and y are state, input and output vectors, respectively;
n, ω and ν are Gaussian white noise sequences;
d is periodic disturbance;
A_o, A_d, C_o, C_d and B_o are matrices of appropriate dimensions.

Steady State Kalman Filter

The corresponding steady state Kalman filter takes the form:

$$\hat{x}_{k+1} = A_o \hat{x}_k + Bu_k + J_o \left(y_k - C_o x_k - C_d \hat{d}_k \right) \tag{4}$$

$$\hat{d}_{k+1} = A_d \hat{d}_k + J_d \left(y_k - C_o x_k - C_d \hat{d}_k \right) \tag{5}$$

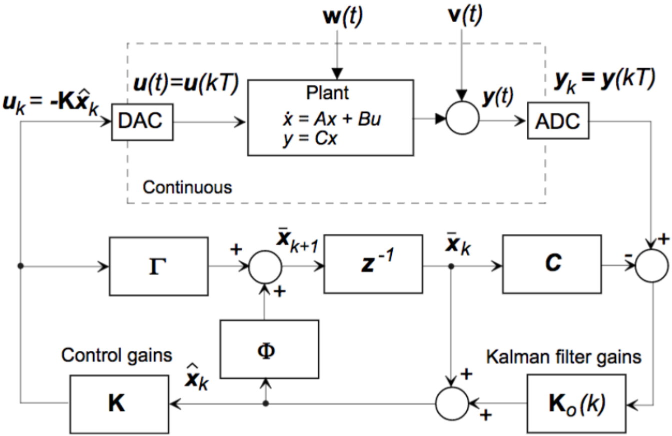
Using this filter, the output can be expressed in innovation form:

$$y_{k+1} = C_o \hat{x}_k + C_d \hat{d}_k + \varepsilon_k \tag{6}$$

where ε_k is a white noise sequence.

Steady State Kalman Filter

Control scheme with Kalman Filter as the state observer:



Steady State Kalman Filter

Polynomial form of the above innovation model:

$$A(z)D(z)y_k = B(z)D(z)u_k + C(z)\varepsilon_k \tag{7}$$

where

$$\frac{B(z)}{A(z)} = C_o\left(zI - A_o\right)^{-1} B_o \tag{8}$$

$$A(z) = \det\left(zI - A_o\right) \tag{9}$$

$$D(z) = \det\left(zI - A_d\right) \tag{10}$$

$$C(z) = \det\begin{bmatrix} zI - A_o + J_o C_d & J_o C_d \\ J_d C_o & zI - A_d + J_d C_d \end{bmatrix} \tag{11}$$

Note: disturbance d_k disappeared in model (7) because $D(z)$ is effectively the "nulling operator" for the disturbance.

Outline

General approach

- 1) Start with the above polynomial form:

$$ADy_k = BDu_k + C\varepsilon_k \tag{12}$$

- 2) Divide both sides by polynomial C:

$$\frac{AD}{C}y_k = \frac{BD}{C}u_k + \varepsilon_k \tag{13}$$

- 3) Factor LHS transfer function as: $\frac{AD}{C} = 1 - \frac{C-AD}{C}$. Then:

$$y_k = \frac{C-AD}{C}y_k + \frac{BD}{C}u_k + \varepsilon_k \tag{14}$$

LHS = the most recent value of y_k. RHS depends only on previous values of y_k and u_k, i.e. the lowest power of $(C-AD)$ and BD is z^{-1}

General approach

- 4) One-step ahead prediction:

$$\hat{y}_{k+1} = \frac{z(C - AD)}{C} y_k + \frac{zBD}{C} u_k + \hat{\varepsilon}_{k+1} \tag{15}$$

The lowest power of $z(C - AD)$ and zBD is z^0.

- 5) Factor transfer function $\frac{zBD}{C} = b_1 - \frac{b_1 C - zBD}{C}$:

$$\hat{y}_{k+1} = \frac{z(C - AD)}{C} y_k + b_1 u_k - \frac{b_1 C - zBD}{C} u_k \tag{16}$$

The lowest power of $(b_1 C - zBD)$ is z^{-1}.

- 6) Apply a quadratic cost function:

$$J = \left[y^*_{k+1} - \hat{y}_{k+1}\right]^2 \tag{17}$$

Clearly, cost function (17) will be minimized if $\hat{y}_{k+1} = y^*_{k+1}$.

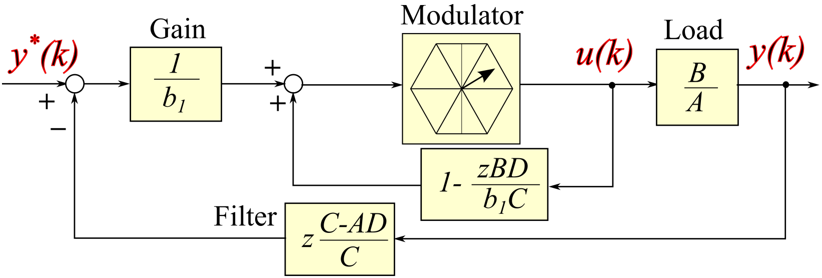
General approach

- 7) The only control value that can be used to minimize the cost function (17) is $b_1 u_k$, i.e the most recent (new) control value. We obtain unconstrained optimal control law which gives $J = 0$ as:

$$u_k^{opt} = \frac{1}{b_1}\left\{\frac{C - zBD/b_1}{C}u_k + y_{k+1}^* - \frac{z(C-AD)}{C}y_k\right\} \qquad (18)$$

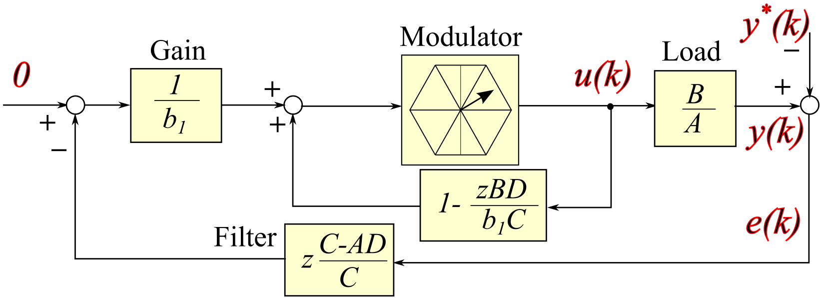
- 8) If u^{opt} is outside the constraint boundary then: u_k^{con} is as close as possible to u_k^{opt} (on the constraint boundary).

General approach



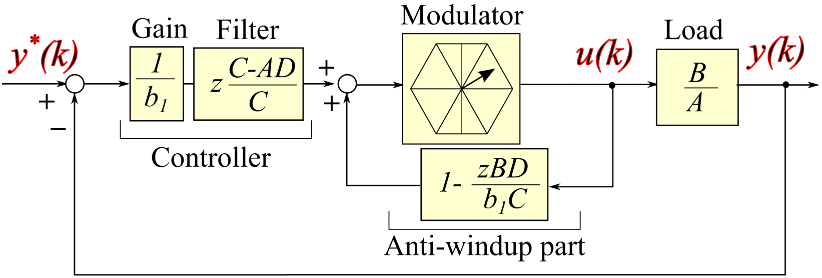
Block diagram of the constrained optimal control

General approach



Transition to the alternative form

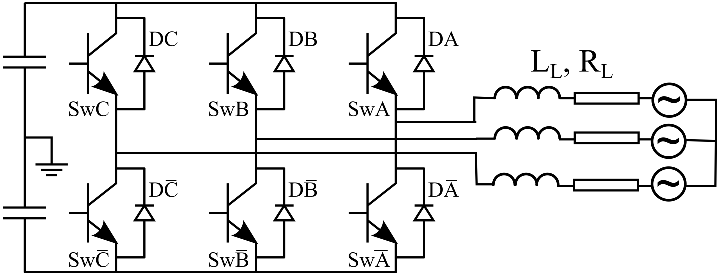
General approach



Alternative form of the constrained optimal control

Outline

RL load with constant disturbance



VSI with RL load

RL load with constant disturbance

- Typical RL plant model (motor, coupling inductor, etc.):

$$i(k) = i(k-1)e^{-\frac{\Delta R}{L}} + \frac{1}{R}u(k-1)\left(1 - e^{-\frac{\Delta R}{L}}\right) \tag{19}$$

- Equivalent to:

$$\left(1 - a_1 z^{-1}\right) i(z) = b_1 z^{-1} u(z) \tag{20}$$

where $a_1 = e^{-\frac{\Delta R}{L}}$ and $b_1 = \frac{1}{R}\left(1 - e^{-\frac{\Delta R}{L}}\right)$

- 1) Polynomial form of ss Kalman Filter:

$$\left(1 - a_1 z^{-1}\right)\left(1 - z^{-1}\right) i_k = b_1 z^{-1}\left(1 - z^{-1}\right) u_k + \left(1 - c_1 z^{-1}\right) \varepsilon_k \tag{21}$$

- 2) Divide both sides by polynomial C:

$$\frac{1 - (1 + a_1) z^{-1} + a_1 z^{-2}}{1 - c_1 z^{-1}} i_k = \frac{b_1 z^{-1}\left(1 - z^{-1}\right)}{1 - c_1 z^{-1}} u_k + \varepsilon_k \tag{22}$$

RL load with constant disturbance

- 4) One-step ahead prediction:

$$\hat{i}_{k+1} = \frac{(1 - c_1 + a_1) - a_1 z^{-1}}{1 - c_1 z^{-1}} i_k + \frac{b_1 (1 - z^{-1})}{1 - c_1 z^{-1}} u_k \quad (24)$$

- 5) Factor transfer function $\frac{zBD}{C}$:

$$\hat{i}_{k+1} = \frac{(1 - c_1 + a_1) - a_1 z^{-1}}{1 - c_1 z^{-1}} i_k + b_1 u_k - \frac{b_1 z^{-1} (1 - c_1)}{1 - c_1 z^{-1}} u_k \quad (25)$$

- 6) All the above is done for d- and q- currents separately. Now apply a quadratic cost function (tracking error squared):

$$J = \left[i^*_{k+1,d} - \hat{i}_{k+1,d} \right]^2 + \left[i^*_{k+1,q} - \hat{i}_{k+1,q} \right]^2 \quad (26)$$

Clearly, cost function (26) will be minimized if $\hat{i}_{k+1,dq} = i^*_{k+1,dq}$.

RL load with constant disturbance

- 7) The unconstrained optimal control law which gives $J = 0$ is:

$$u_{k,dq}^{opt} = \frac{z^{-1}(1-c_1)}{1-c_1 z^{-1}} u_{k,dq} + \frac{1}{b_1} \left\{ i_{k+1,dq}^{*} - \frac{(1-c_1+a_1) - a_1 z^{-1}}{1-c_1 z^{-1}} i_{k,dq} \right\} \tag{27}$$

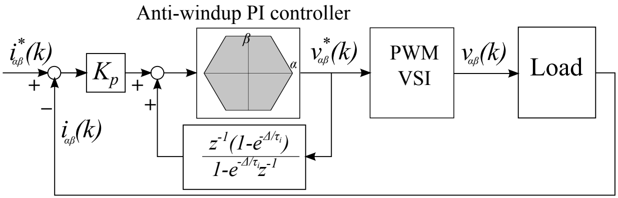
- 8) If u^{opt} is outside the constraint boundary then: u_k^{con} is as close as possible to u_k^{opt}.

As a special case, when $c_1 = a_1$ then

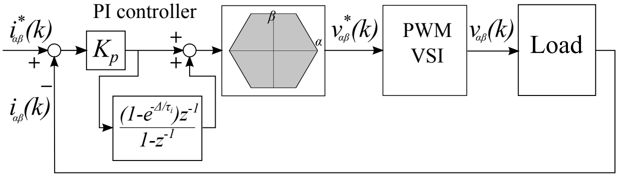
$$u_{k,dq}^{opt} = \frac{z^{-1}(1-a_1)}{1-a_1 z^{-1}} u_{k,dq} + \frac{1}{b_1} \left\{ i_{k+1,dq}^{*} - i_{k,dq} \right\} \tag{28}$$

is easily recognizable as the classical PI controller in anti-windu[p]
form.

RL load with constant disturbance



(a) Anti-windup form



(b) Conventional form

RL load with constant disturbance

Results:

- For a linear **first order plant with constant disturbance**
- One of the possible optimal controllers (for one set of Kalman Filter gains) is PI with
  - time constant matching that of the plant: $a_1 = e^{-\frac{\Delta R}{L}}$;
  - optimal gain $K_p = \frac{1}{b_1} = \frac{R}{1-e^{-\frac{\Delta R}{L}}}$;
- Such a PI controller is, therefore, implicitly Kalman Observer-based Linear Quadratic Regulator and Horizon 1 MPC.

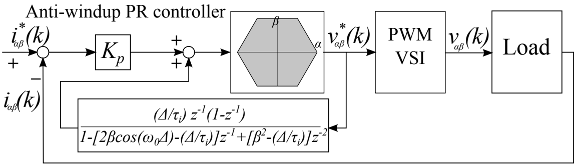
Then it is ok

It is not being lazy, it's a fashion statement!

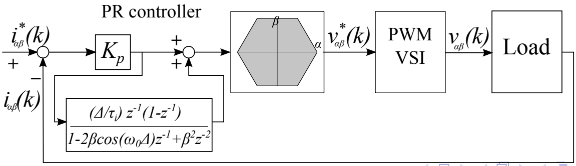
Outline

RL load with sinusoidal disturbance

Repeating the same procedure using sinusoidal disturbance model (nulling operator). Result: the optimal controller is PR.



(a) Anti-windup form



(b) Conventional form

Linear (transport) delay problem

- Transport delay is associated with implementation of the chosen voltage or voltage pattern:
  - cycle 1: current measured, calculations are performed;
  - cycle 2: voltage applied;
- Reduces bandwidth of current controllers.
- Within the presented approach, simply, instead of using the model:

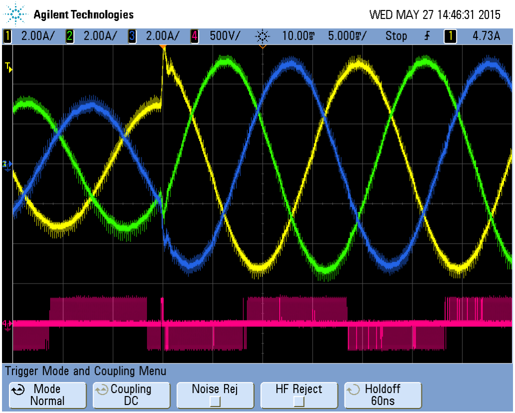
$$\left(1 - a_1 z^{-1}\right) i(z) = b_1 z^{-1} u(z) \tag{29}$$

- We use the model:

$$\left(1 - a_1 z\right) i(z) = b_1 z^{-2} u(z) \tag{30}$$

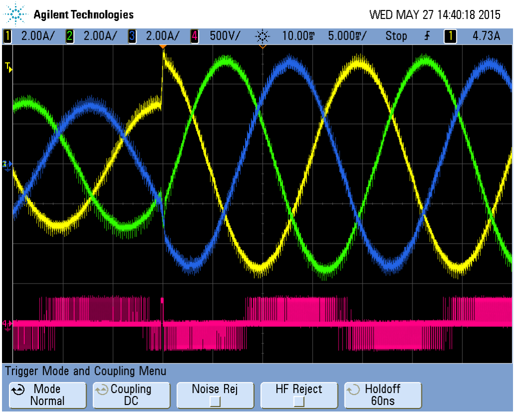
- This automatically results in the control schemes accounting for transport delay. They are no longer standard controllers (PI, PR) and they outperform standard controllers.

Experimental results



Conventional PR controller

Experimental results

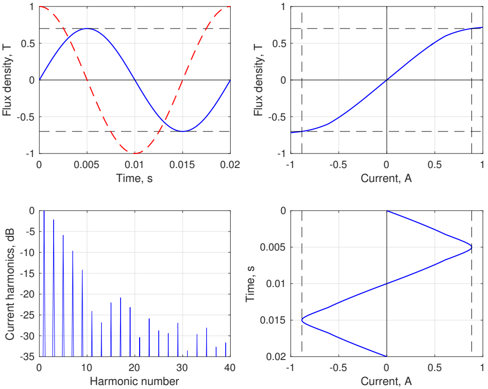


Optimal PR controller

Outline

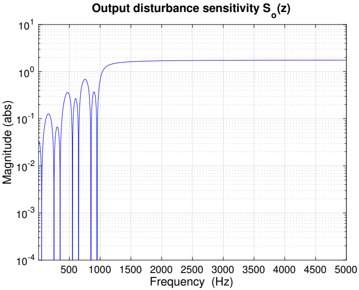
RL load with N sine disturbances

- Loads in PE are not necessarily linear;
- Example: core saturation in inductors, electric motors, etc.

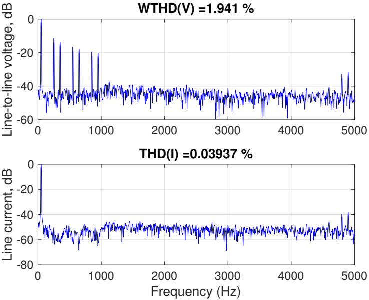


RL load with N sine disturbances

- The way to address this is to include disturbance at multiple frequencies in the disturbance model



(a) Noise sensitivity



(b) Resulting spectrum

Rejection of multiple harmonics

Outline

Kalman Filter gains

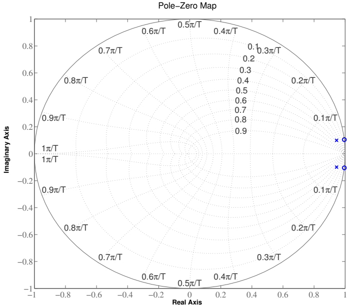
There are practical challenges in selecting appropriate Kalman Filter gains:

$$C(z) = \det \begin{bmatrix} zI - A_o + J_o C_d & J_o C_d \\ J_d C_o & zI - A_d + J_d C_d \end{bmatrix} \qquad (31)$$

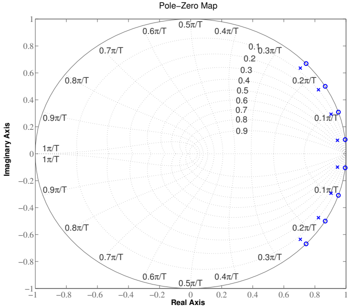
This is due to uncertainties regarding statistical properties of the noises.
Consequently, the optimal controller becomes dependant on a large number of parameters, which cannot be accurately known.

Kalman Filter gains

A "shortcut" in the Kalman Filter gains design is proposed:



(a) For errors at single frequency



(b) For errors at multiple frequencies

Pole-zero map of the noise sensitivity function

Dealing with numeric errors

Two main strategies are proposed:

- Off-line conversion of high order filters into parallel form (2nd order sections):

$$y(z) = x(z)\left[\frac{b_{01} + b_{11}z^{-1}}{1 + a_{11}z^{-1} + a_{21}z^{-2}} + \ldots + \frac{b_{0n} + b_{1n}z^{-1}}{1 + a_{1n}z^{-1} + a_{2n}z^{-2}}\right]$$

- Instead of shift-implementation, use delta-implementation:

$$y(k) = 0.999372y(k-1) + 0.000628x(k-1) \qquad (32)$$

$$y(k) = y(k-1) + 0.000628\left[x(k-1) - y(k-1)\right] \qquad (33)$$

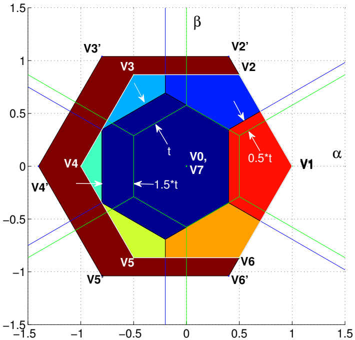
- As a result, up to 8 different frequencies (filter order 16) are successfully rejected in practice (processor TMS320F28332).

Additional objectives

- The proposed control design is based on using quadratic cost function (= tracking error).
- It can be desirable that additional objectives are addresed, such as:
  - reduction of switching losses;
  - capacitor voltage balancing for NPC inverters, etc.
- There are two ways in which this can be included:
  - express the extra objectives in terms of quadratic error;
  - achieve the extra objectives at the modulator level.

Additional objectives

This is how switching can be penalised for. The cost function calculation is "deceived" by making vertices associated with more switching appear further away.



Additional objectives

Extra objectives can be achieved at the modulator level

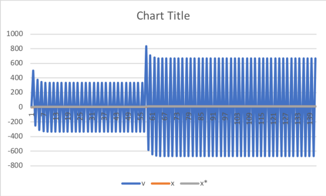
- Modulator has not been mentioned so far;
- Its action is described in step 8: "If u^{opt} is outside the constraint boundary then: u_k^{con} is as close as possible to u_k^{opt} (on the constraint boundary)";
- No limitations were imposed on the modulator, meaning:
  - constraint region can be convex (PWM);
  - or non convex (discrete values, as with FS-MPC);
- Independently from the Control, modulator can be designed to:
  - operate at a given switching frequency (3 x control for PWM);
  - turn one switch at a time (PWM);
  - balance capacitor voltages for NPC inverter (using redundant states).

Outline

1. Introduction
2. General formulation
   - Control in Power Electronics
   - Proposed control design framework
3. Worked examples
   - VSI, RL load, rotating frame (dq)
   - VSI, RL load, stationary frame ($\alpha\beta$)
   - VSI, non-linear (saturated) load model
   - Practical challenges
4. Other topologies
   - CSI with inductive load + capacitor
   - Matrix converter: output VSI + input CSI
5. Conclusions

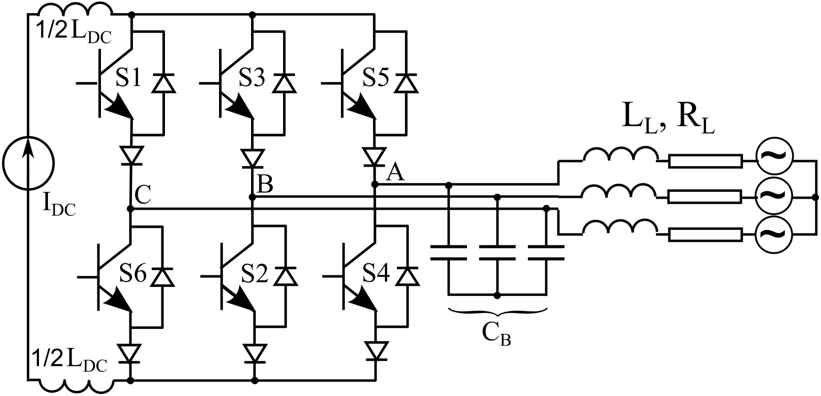
When to use longer horizon?

1. So far, prediction horizon 1 has been used.
   - Linear 1st order plant has only a 1-step memory. If at every step the output is driven in optimal way, the overall optimal tracking is achieved. Horizon 1 = Horizon N.
2. When to use horizon 2?
   - 2nd order (resonant) plant has a 2-step memory. Using horizon 1 will result in intersample oscillations:



   - 2nd order plant needs horizon 2: predict 2-steps ahead; drive y_{k+2} to y^*_{k+2} and "speed" at the end of step 2 - to zero.

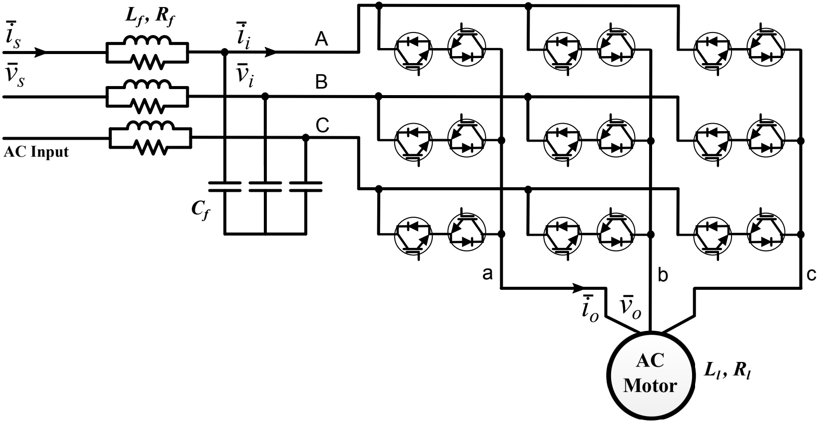
CSI with inductive load + capacitor



CSI with RL load

Outline

Matrix converter: output VSI + input CSI



Matrix Converter

Conclusions

- The presented control design approach is based on:
  - Linear Steady State Kalman Filter (in polynomial form);
  - Internal Model Principle (to reject a disturbance, its model has to be included in the observer);
  - Predictive Control with receding horizon.
- It automatically generates unconstrained optimal control law, for the given load and disturbance, in anti-windup form.
- Constraint is determined by a modulator. Any modulator can be used: PWM (convex) or FCS (non-convex).
- There is a limitation associated with quadratic cost function, which, however, can be overcome.
- Optimal control can be developed for any practical power electronic application (with appropriate plant and disturbance models).

Thank you!

- Prediction horizon should match the order of the plant.
- The proposed control design is elegant, suitably sophisticated but easy to implement within $< 100\mu$sec control cycle.

Thank you for listening!

Hopefully, some useful tips were given today about:

- Control of Power Electronics
- Shoe styles

QUESTIONS ?