PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

Hans Jäckle

Basic powersupply control – Digital implementation of analog controllers

Topics

Digital implementation of analog controllers

Part 1: **Basic Powersupply Controller**

- Essential Tasks of a basic powersupply controller and how to achieve them

Part 2: **Discretization**

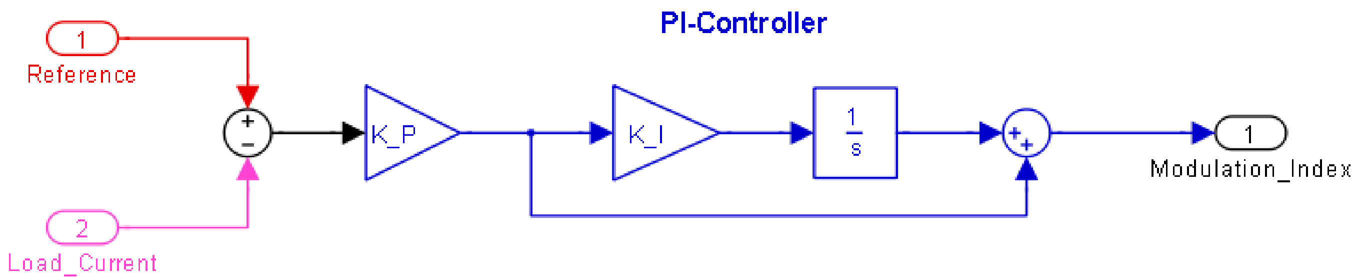
- Paths to discrete controller
- Methods of discretization
- Effects of SamplingTime

Tasks of controller

- Achieve zero steady-state error

  -> Integral action

PI Controller



- $Ki = 1 / T_{Magnet}$
  -> experimentally (step response in open loop)
  -> $Ki = R_{Magnet} / L_{Magnet}$
- Kp can be found manually, starting value:
  $Kp\_init = R_{Magnet} / U_{DC\_Link} * \omega_{CL} / Ki$

Tasks of controller

- Achieve zero steady-state error

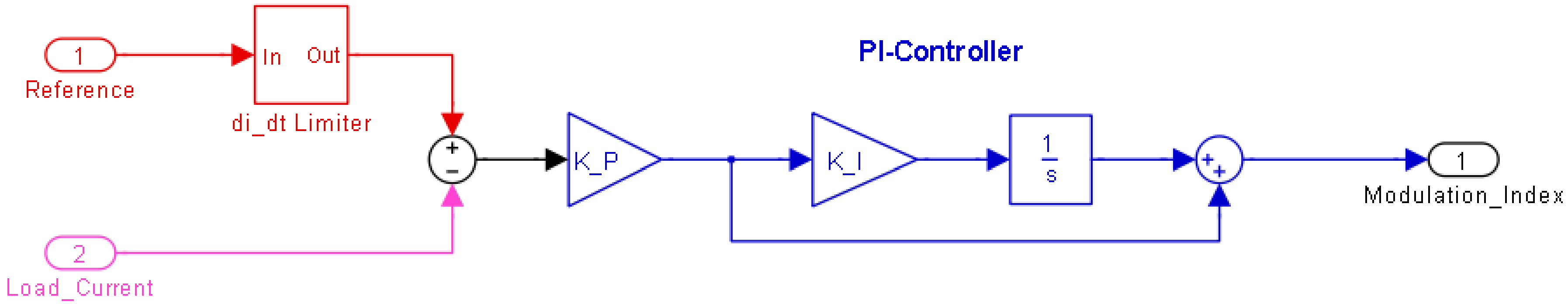
  -> Integral action

- keep operation of controller linear (avoid limitations)

  -> Limit di_{Ref} / dt

  -> Anti-Windup

dI/dt Limiter



- Keeps the controller in the linear regime by preventing actuator saturation

$$\left(\frac{dI}{dt}\right)_{MAX} = \frac{U_{DC\_MIN} - U_{CONV} - I_{NOM} * R_{MAGNET\_MAX}}{L_{MAGNET}}$$

- Anti-Windup is a remedy in case of actuator saturation

Tasks of controller

- Achieve zero error

  -> Integral action

- Stay in linear region

  -> Limit di_{Ref} / dt

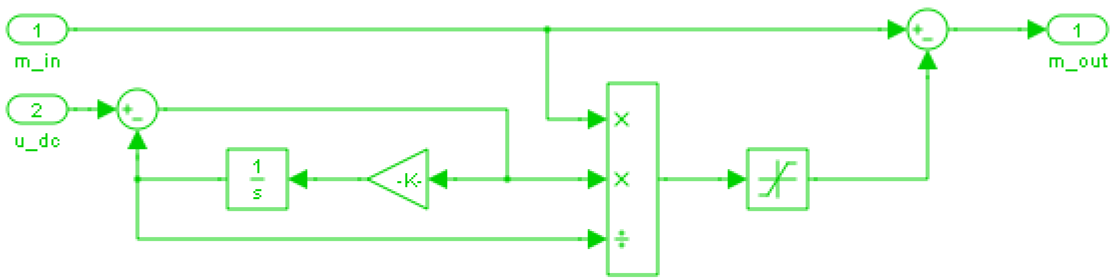
  -> Anti-Windup

- Suppress dc-link voltage disturbances (e.g. 300Hz Ripple)

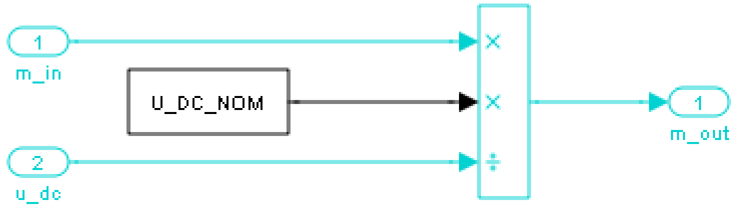
  ->feedforward the dc-link disturbances

DC-Link Feedforwards

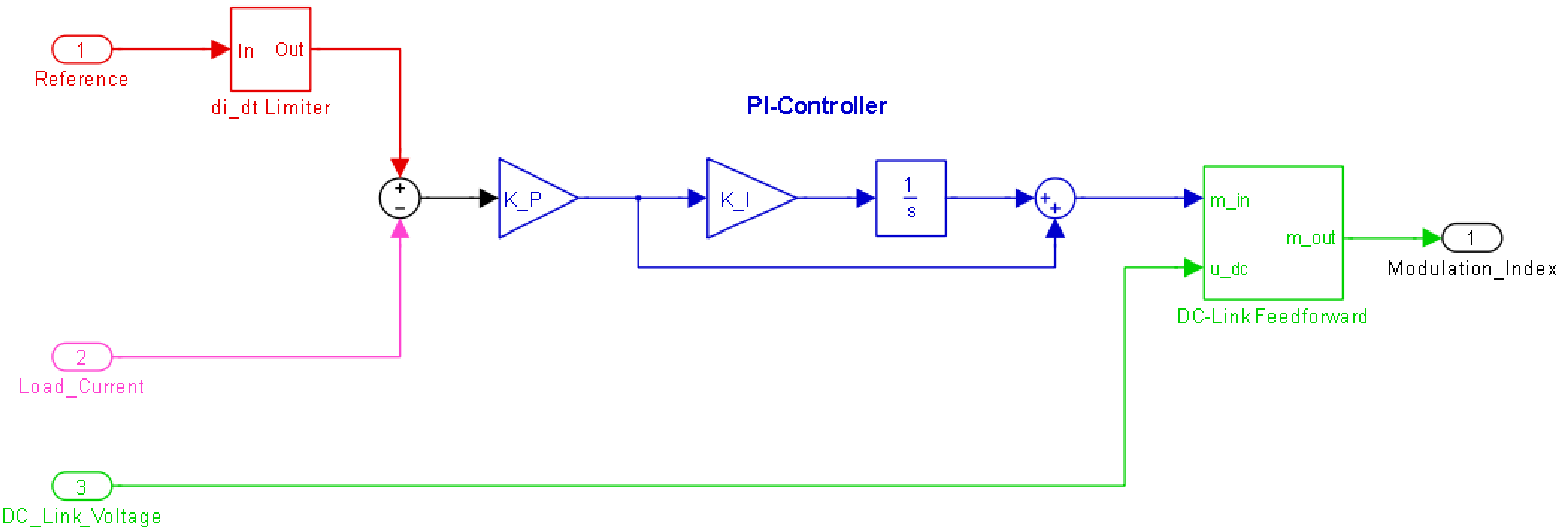
DC-Link Ripple Feedforward I



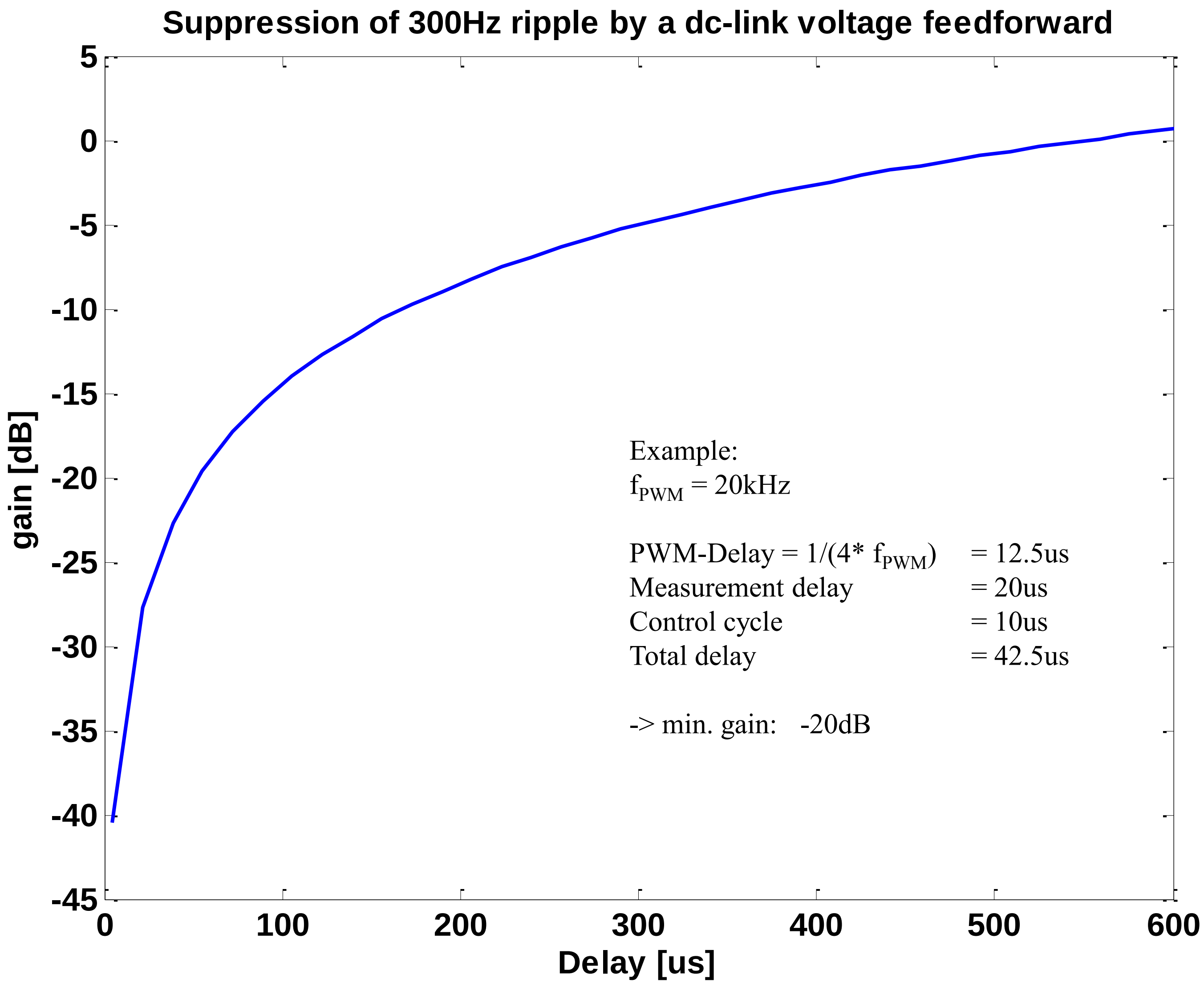
DC-Link Feedforward



DC-Link Feedforward



DC-Link Feedforward + Delay



Tasks of controller

- Achieve zero error

  -> Integral action

- Stay in linear region

  -> Limit di_{Ref} / dt

  -> Anti-Windup

- Suppress dc-link voltage disturbances

  ->feedforward the dc-link disturbances

Protect Output Filter Resistor

  -> Output limiter

- Reduce measurement noise

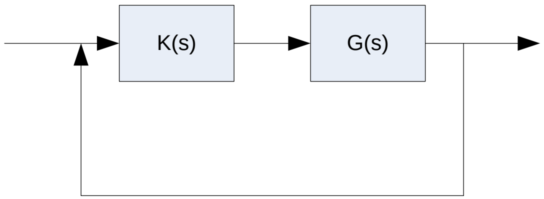
  -> Lowpass-filter for the measured value

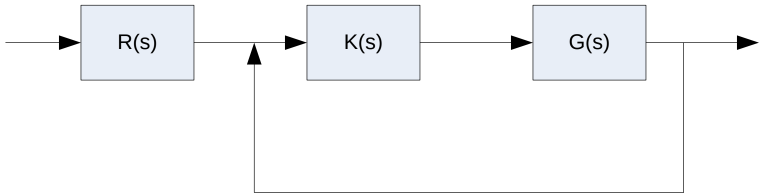
- Reduce overshoot

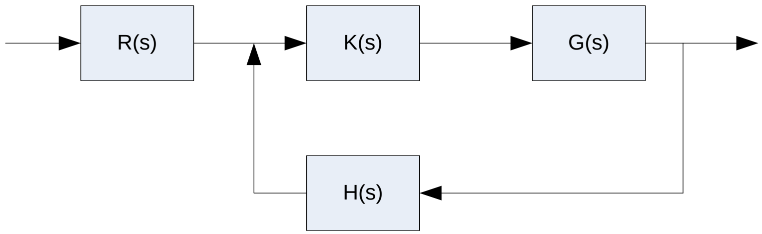
  -> Lowpass-filter for the reference value

Beyond PI

- Compensation of higher order plant dynamics e.g. the output filter
- 2-DOF structure to seperately tune reference tracking and disturbance rejection





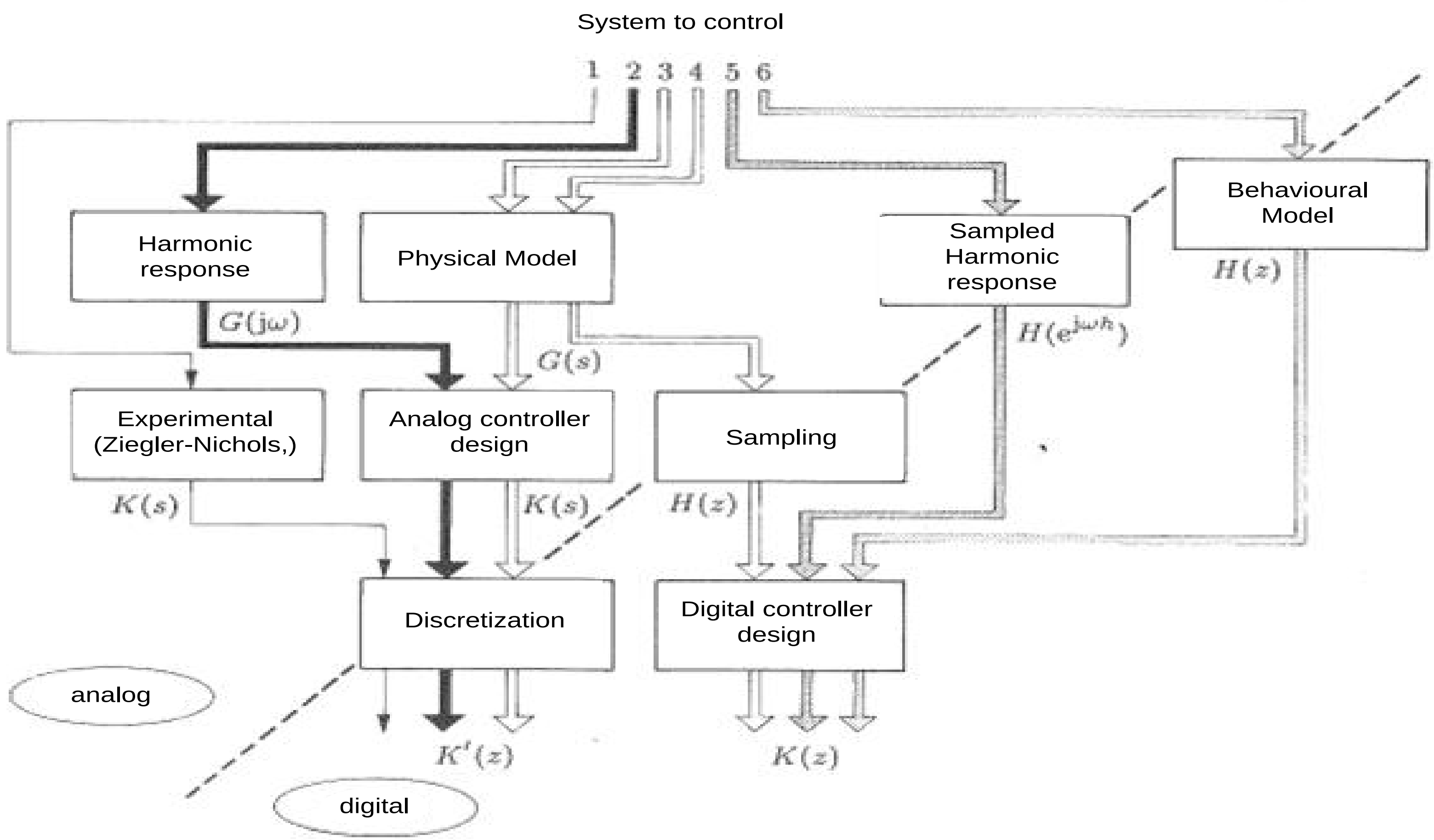


PI

Analog:

$$u(t) = Kp * (e(t) + Ki * \int e(t)dt) \quad \text{<->} \quad K(s) = \frac{U(s)}{E(s)} = Kp * (1 + \frac{Ki}{s})$$

Paths to discrete controller



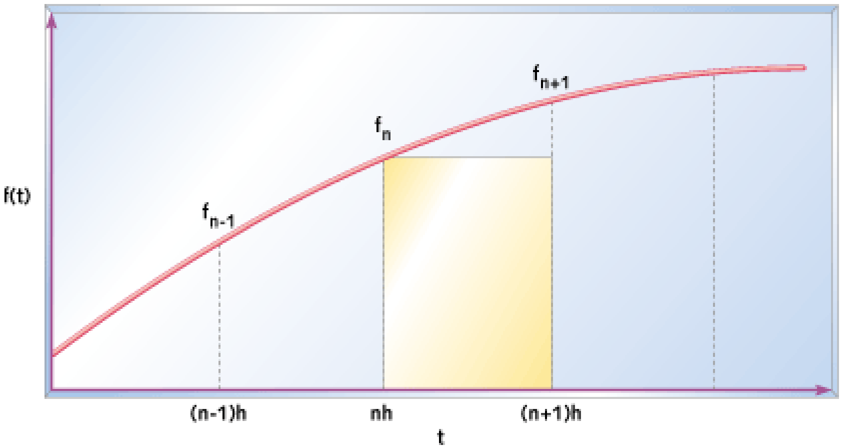
Source:
Commande numérique de systèmes dynamiques, R. Longchamp

Types of discretizations

Area based approximations:
- Forward difference
- Backward difference
- Trapezoidal (Tustin, bilinear)

Response Invariant transforms:
- Step response (zero-order hold)
- Ramp response
- Impulse response

Pole-zero mapping



$$G(z) = \frac{z-1}{z} Z\left\{\frac{G(s)}{s}\right\}$$

Area based approximations

Forward Euler:

$$y(n) = y(n-1) + T_s * u(n-1)$$

$$K(z) = \frac{T_s}{z-1}$$

Backward Euler:

$$y(n) = y(n-1) + T_s * u(n)$$

$$K(z) = \frac{zT_s}{z-1}$$

Trapezoidal:

$$y(n) = y(n-1) + \frac{T_s}{2} * (u(n-1) + u(n))$$

$$K(z) = \frac{T_s}{2} \frac{z+1}{z-1}$$

PI

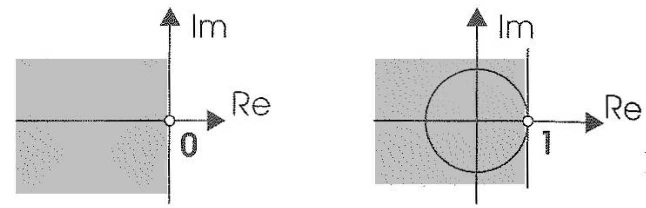
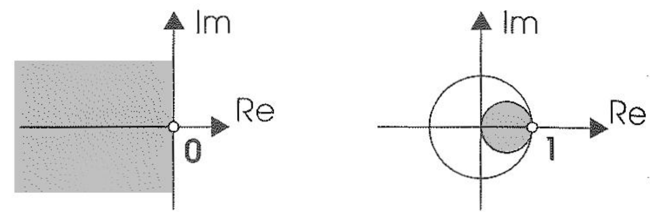
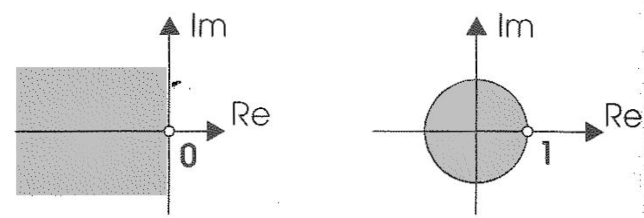
Analog:

$$u(t) = Kp * (e(t) + Ki * \int e(t) dt)$$ <-> $$K(s) = \frac{U(s)}{E(s)} = Kp * (1 + \frac{Ki}{s})$$

Discrete:

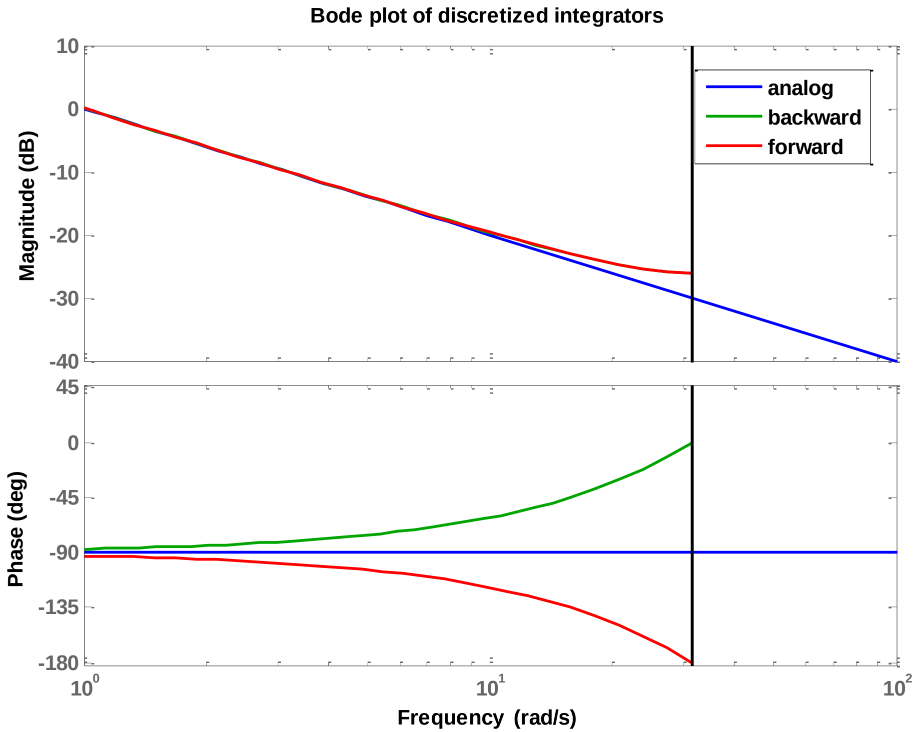
$$u(k) = Kp * (e(k) + e(k-1) * (Ki * T_s - 1) + u(k-1)$$ <-> $$K(z) = \frac{U(z)}{E(z)} = Kp * (1 + \frac{Ki * T_s}{z - 1})$$

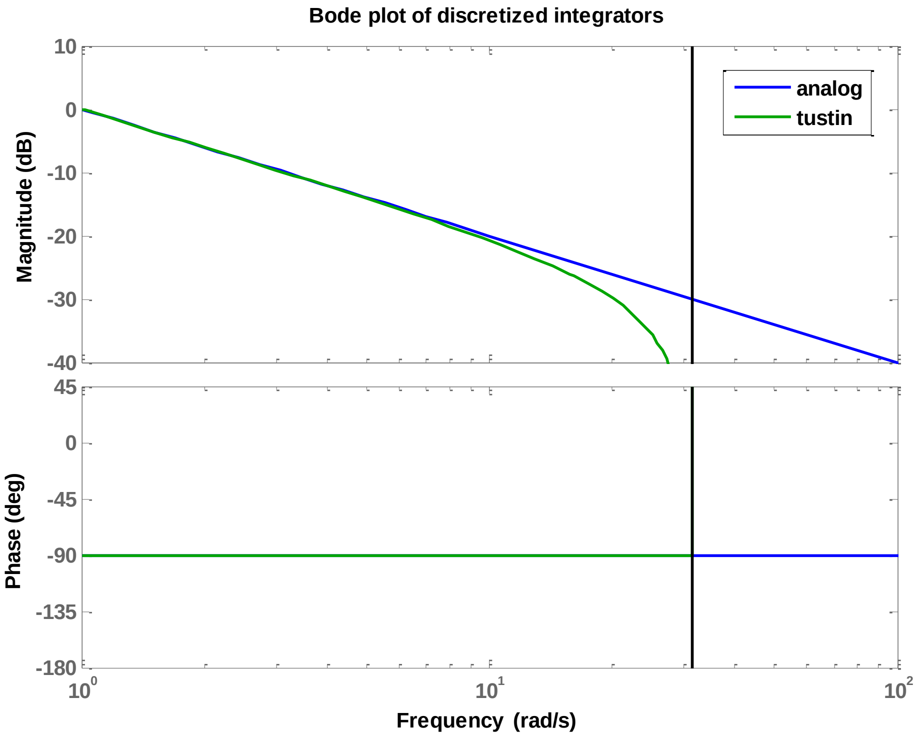
Approximations z <--> s

Näherung	Substitution T konstant	Abbildung $G(s) \rightarrow G(z)$ s-Ebene z-Ebene
Rechteckregel vorwärts (Euler)	$s = \frac{z-1}{T}$ $z = 1 + sT$	
Rechteckregel rückwärts	$s = \frac{1}{T}\frac{z-1}{z}$ $z = \frac{1}{1-sT}$	
Trapezregel (Bilinear-Form, Tustin-Form)	$s = \frac{2}{T}\frac{z-1}{z+1}$ $z = \frac{1+\frac{sT}{2}}{1-\frac{sT}{2}}$	

Source: Theorie der Regelungstechnik, Hugo Gassmann

Bode plot of integrators





How to choose sampling time

- too large -> loss of information
- too small -> loss of precision (numerical issues) / computational overload

- No absolute truth -> rules of thumb:
  - 10x faster than Shannons sampling theorem
  - Fs = 10 – 30x system bandwidth
  - Loss of phase margin not more than 5° -15° compared to the continuous system

Summary

- PI controller for magnet powersupplies is a good choice:
  - can be manually tuned (only two parameters Kp & Ki)
  - good static performance (zero error)
  - reasonable dynamic performance

- Fast enough sampling rate allows to regard the discrete PI controller as a (quasi-)continous controller.

- High frequency behaviour not compensated (output filter resonance)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