An Updated View of Linear Inverter Current Regulation

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Outline

1. Brief History of the Need for Current Regulation
2. Control Strategies for Current Regulation
3. Traditional Regulator Design
4. Effect of Sampling
5. DC Current Regulation with Three Classical Approaches
6. Application to AC Current Regulation
7. Optimized AC Current Regulation
8. Resonant AC Current Regulation
9. Conclusion

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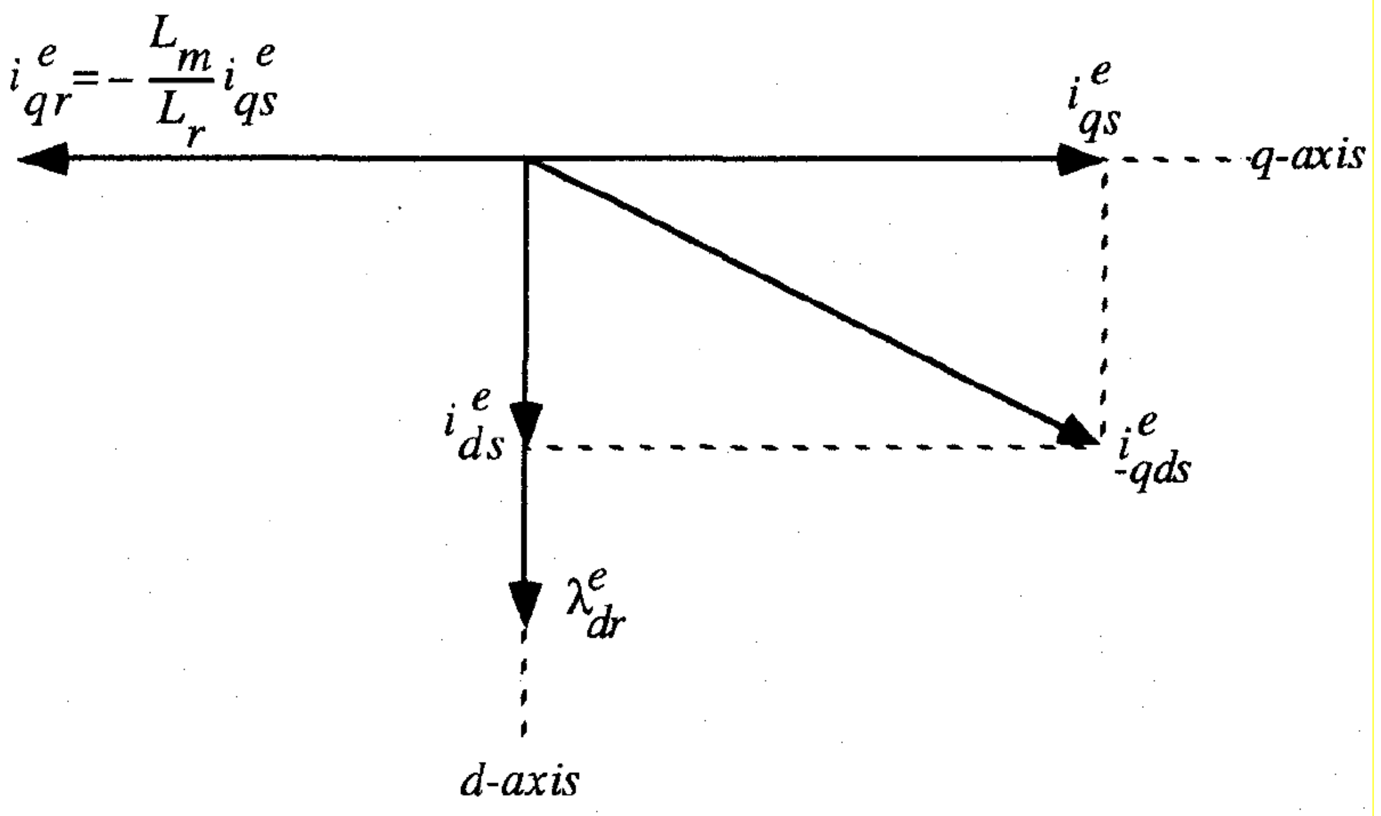
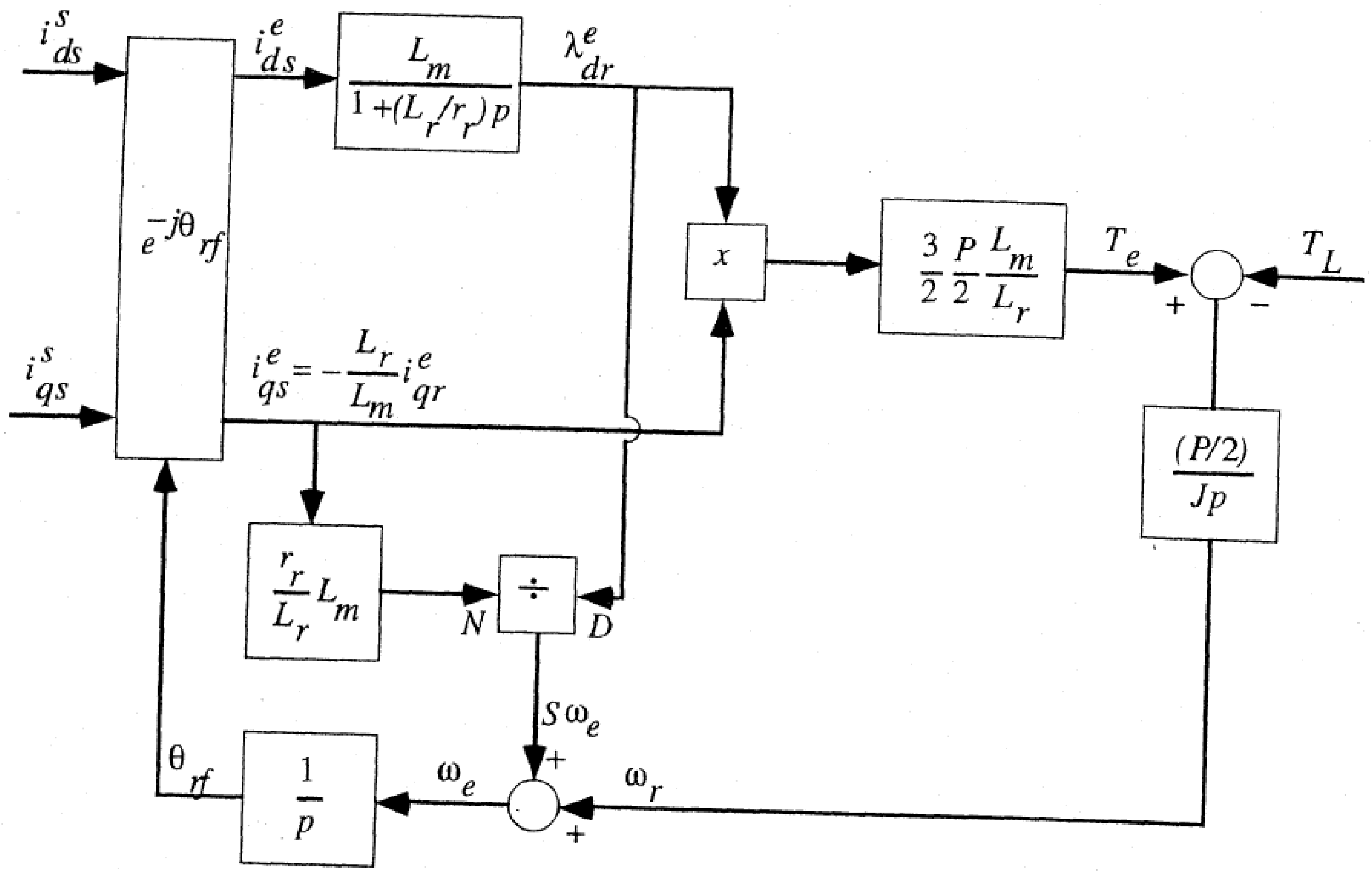
A Bit of History

- Control Prior to 1969
- 1969 – K. Hasse – University of Darmstadt
- 1971 – Felix Blaschke of Siemens – Transvector Control
- 1984 – Dave Brod (UW-MS) and Don Novotny
- 1985/6 – Tim Rowan (UW-PhD) and Russ Kerkman
- ~1990 – Field Oriented Control Takes Off

Field Oriented Control Principle



F.O.C. Block Diagram



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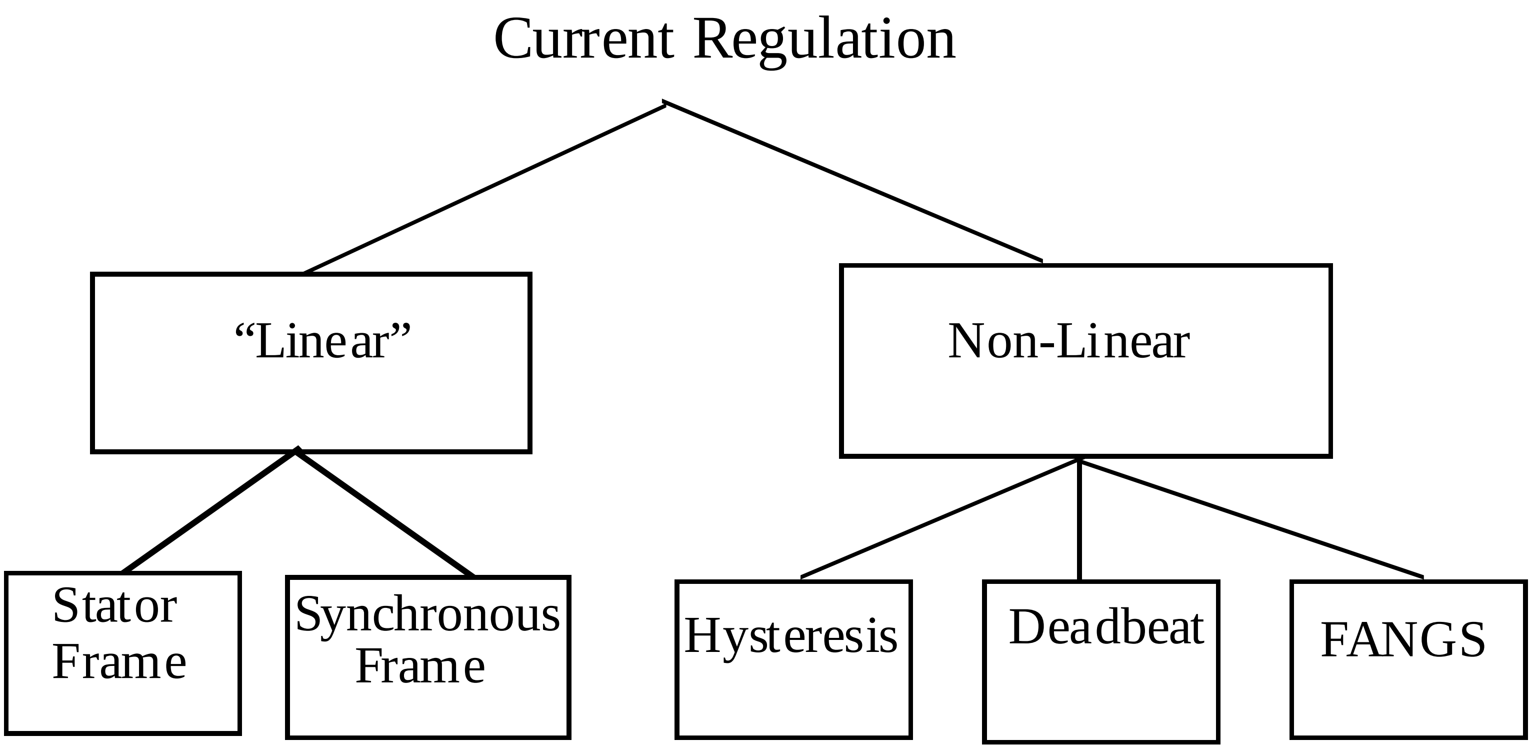
The Family of Current Regulation Techniques



Typical FANGS Paper

"Recurrent Functional-Link-Based Fuzzy-Neural-Network Controlled Induction Generator System Using Improved Particle Swarm Optimization"

IEEE Trans. On Industrial Electronics, May 2009

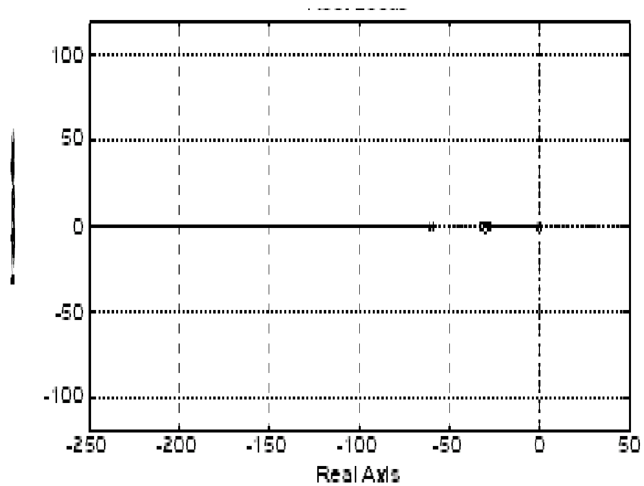
Outline

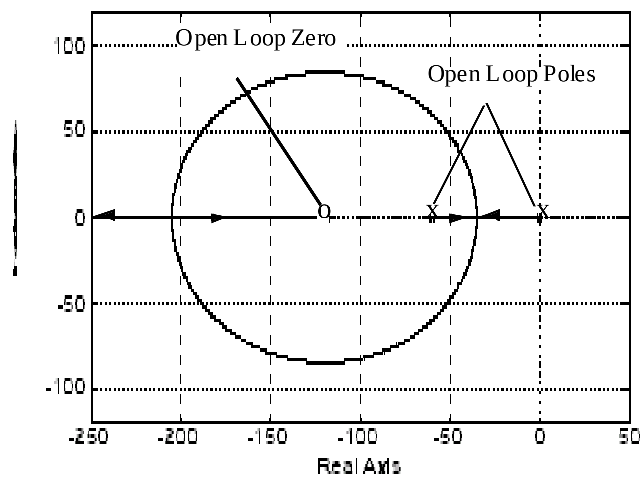
System Parameters

TTest System Circuit Parameters.§

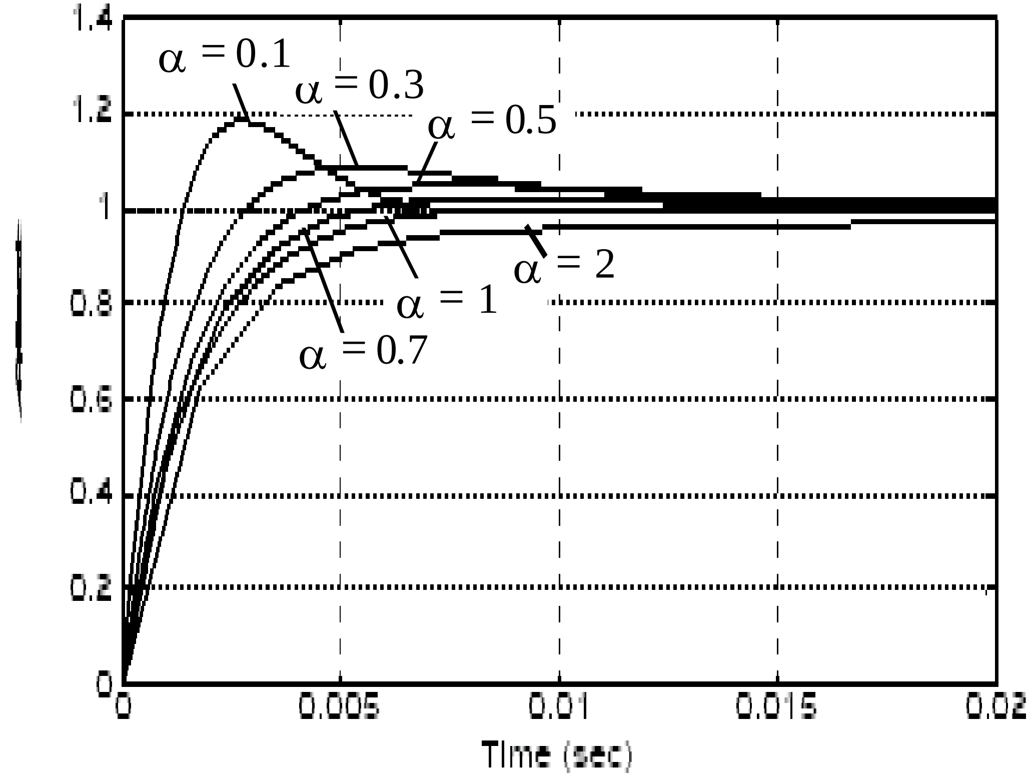
Circuit Parameter§	**Value§**
Plant Resistance R§	1.2 Ω§
Plant Inductance L§	20 mH§
Plant Time Constant T§	16.67 msec§
Controller Sampling Frequency f_s (2 x carrier f_c)§	2000 Hz§
Sampling Delay Time T_d§	0.75 msec§
DC bus voltage V_{dc}§	200 V§

Zero Location and the Root Locus

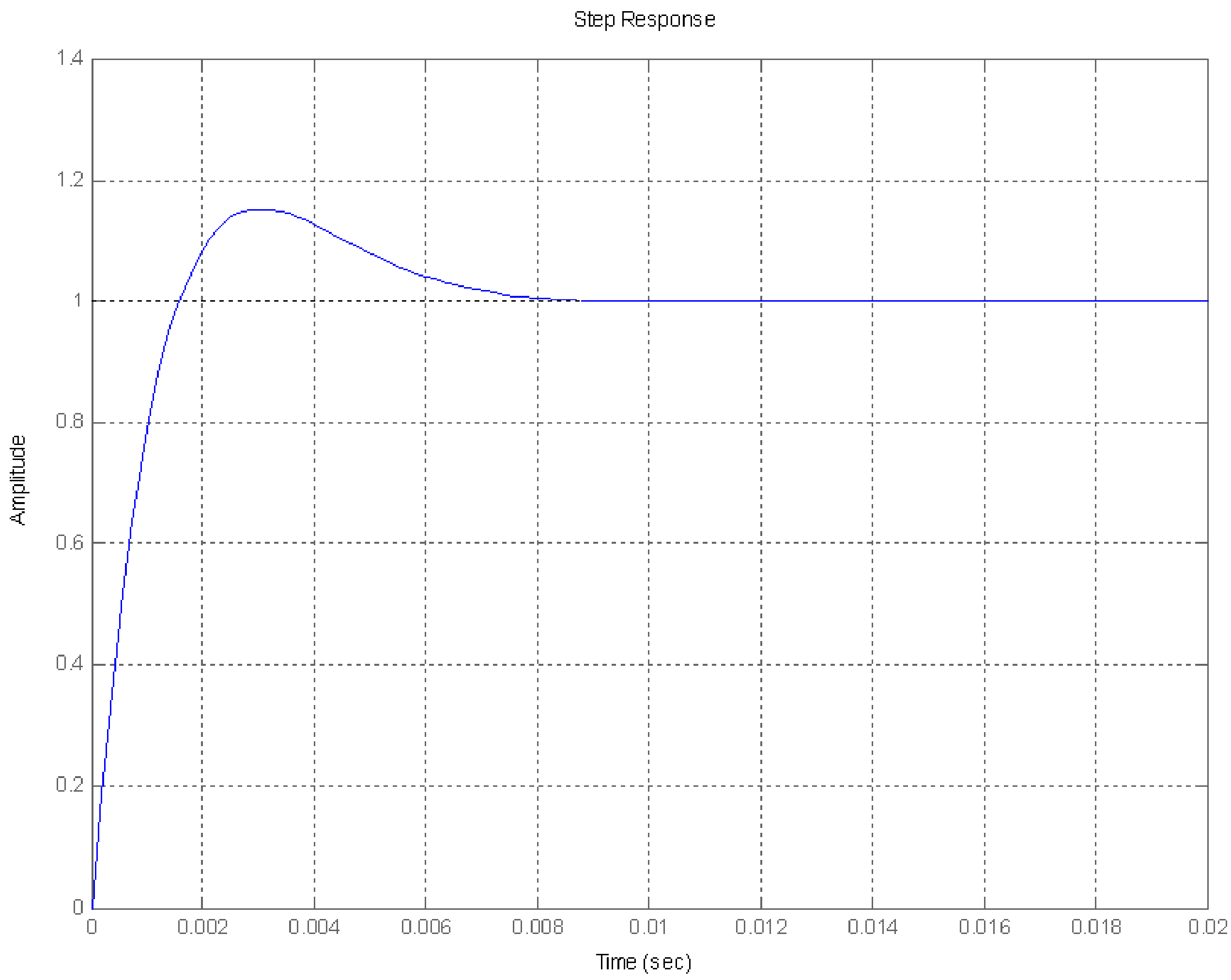




Unit Step Response for 6 Different Zero Locations αz = p, System Pole p = –60 (sec–[1]). Closed Loop Dominant Pole Fixed at –10/T = –600 (sec–[1])



Per unit current step response as a function of time, $k_p = 22.8$, $k_i = 10800$, $a = 0.1267$



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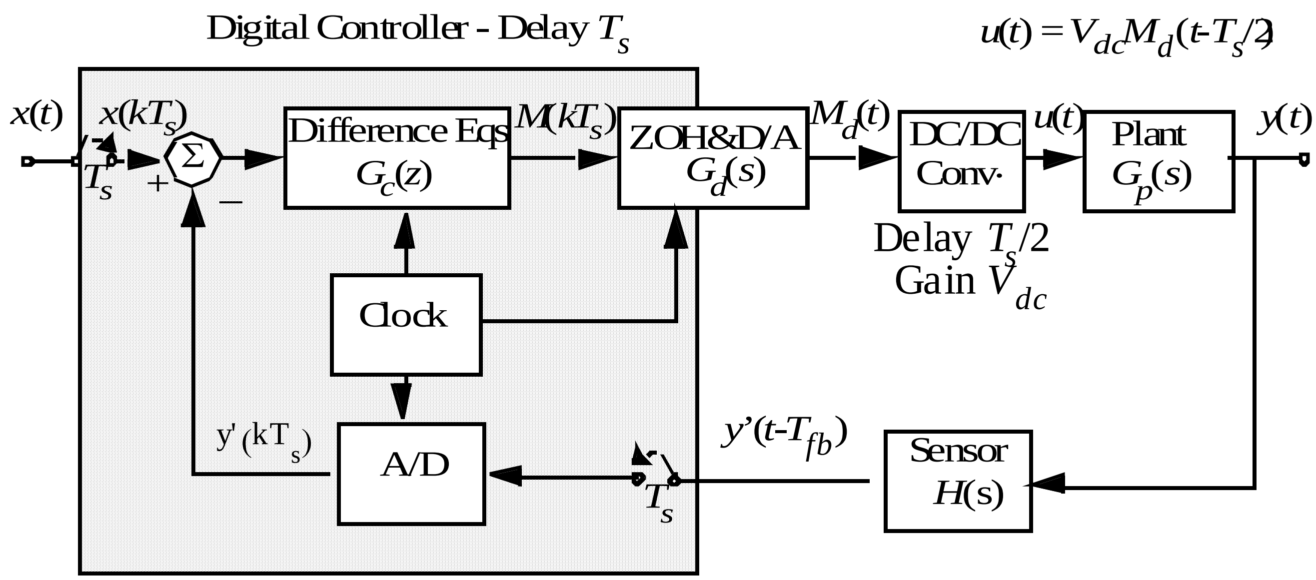
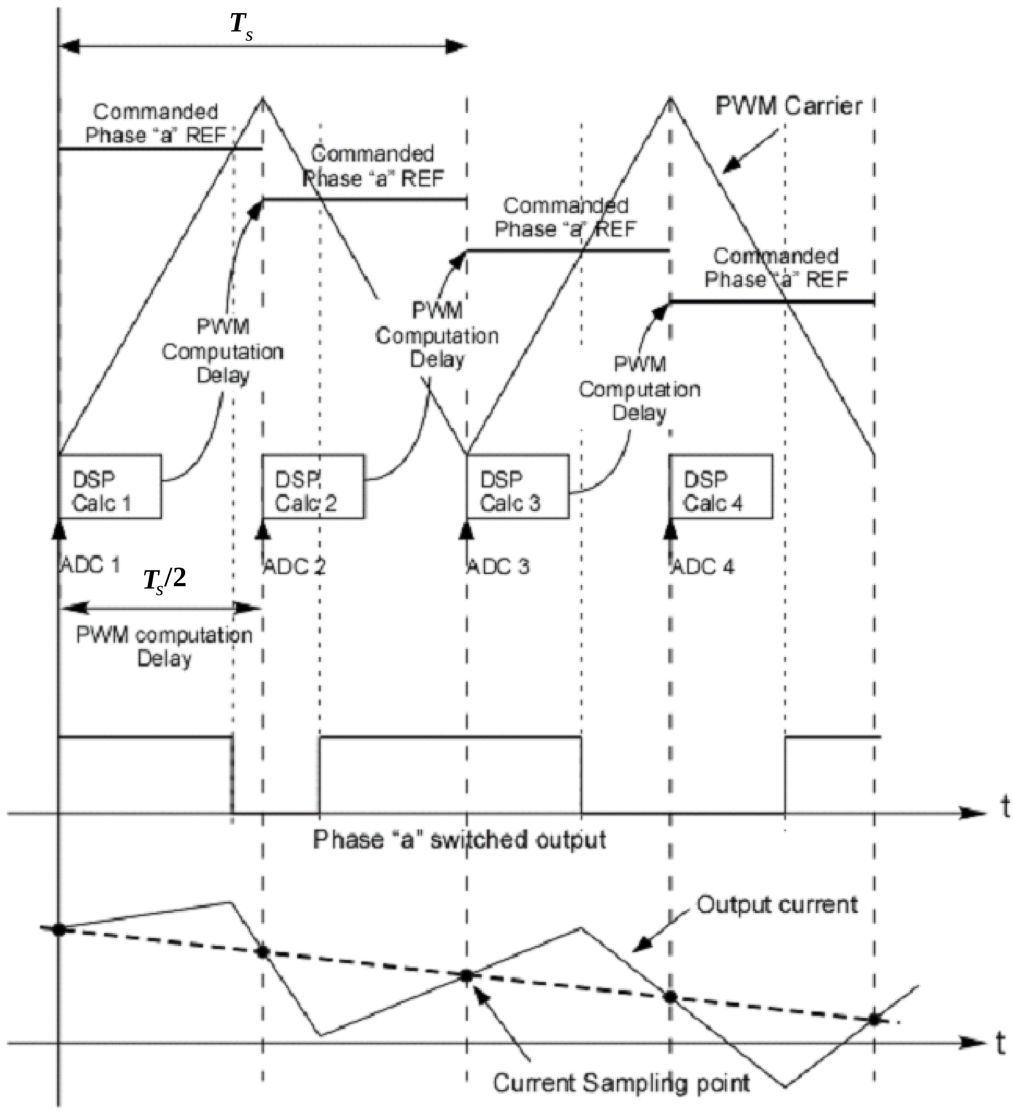
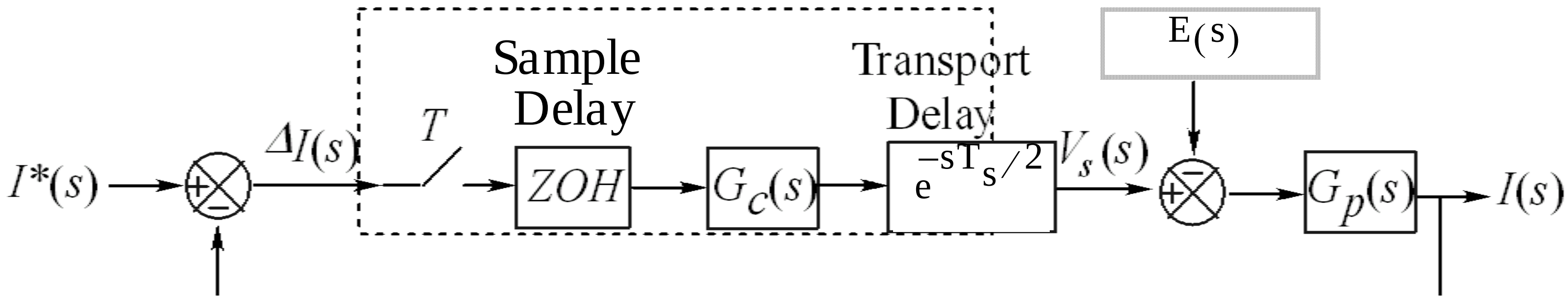
Basic Digital Control System



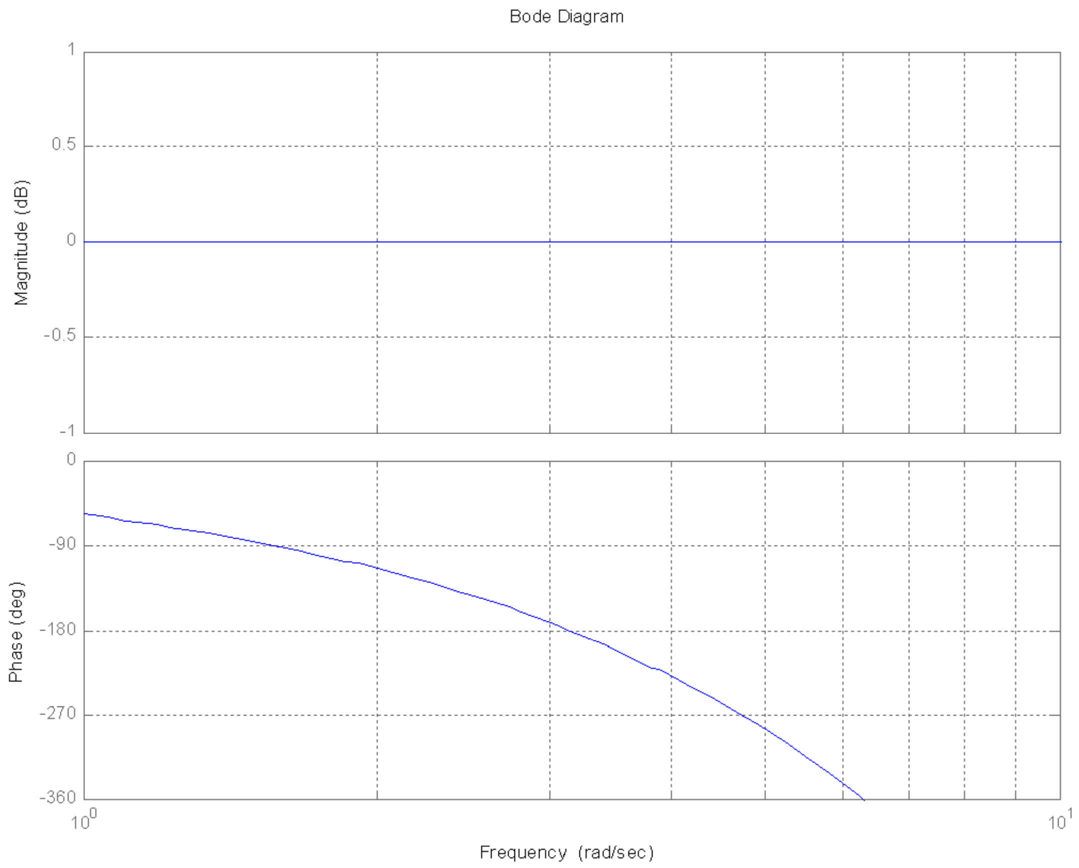
Transport and Sampling Delay Caused by the PWM Process and Digital Controller Sampling/Computation



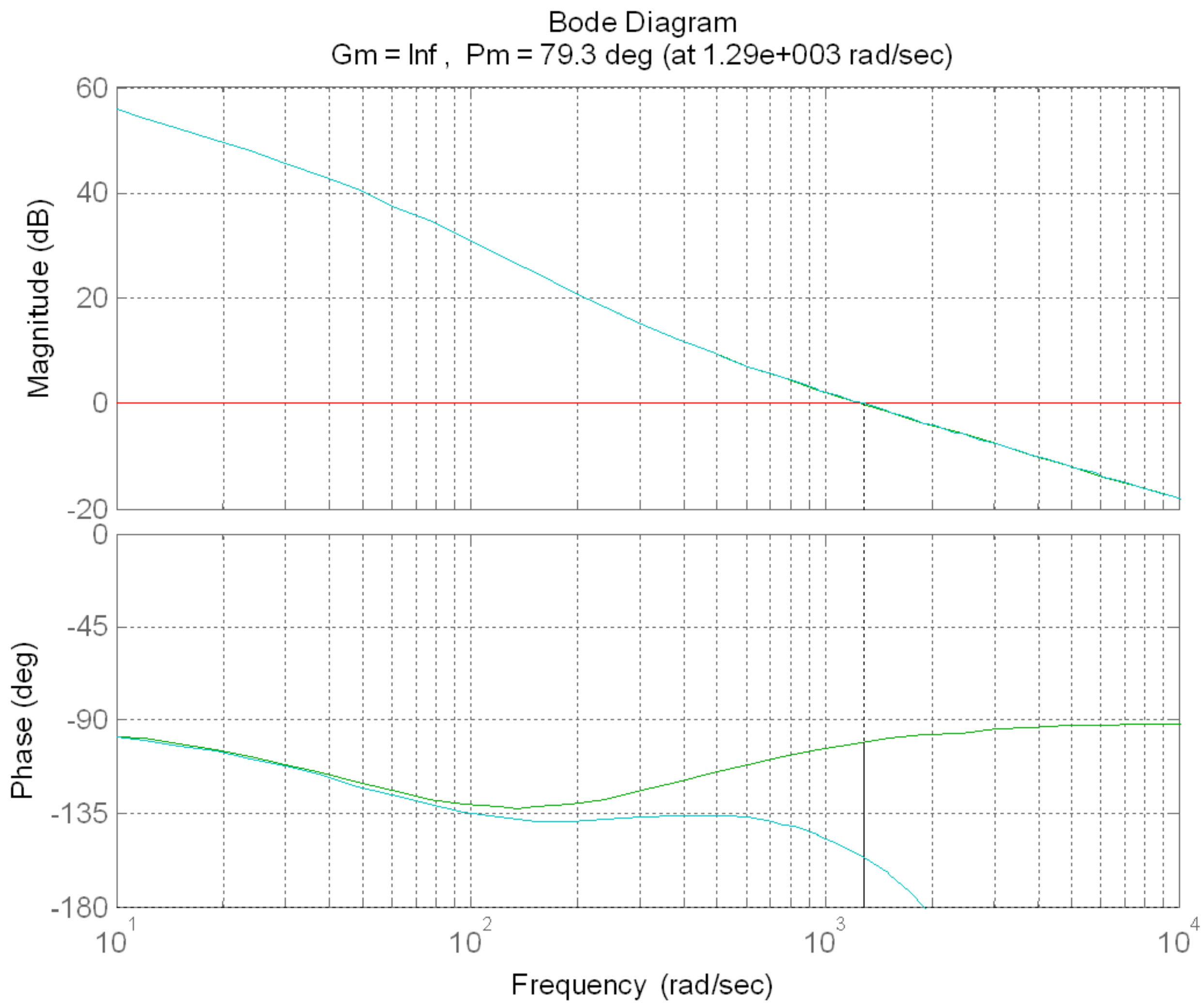
Equivalent Block Diagram



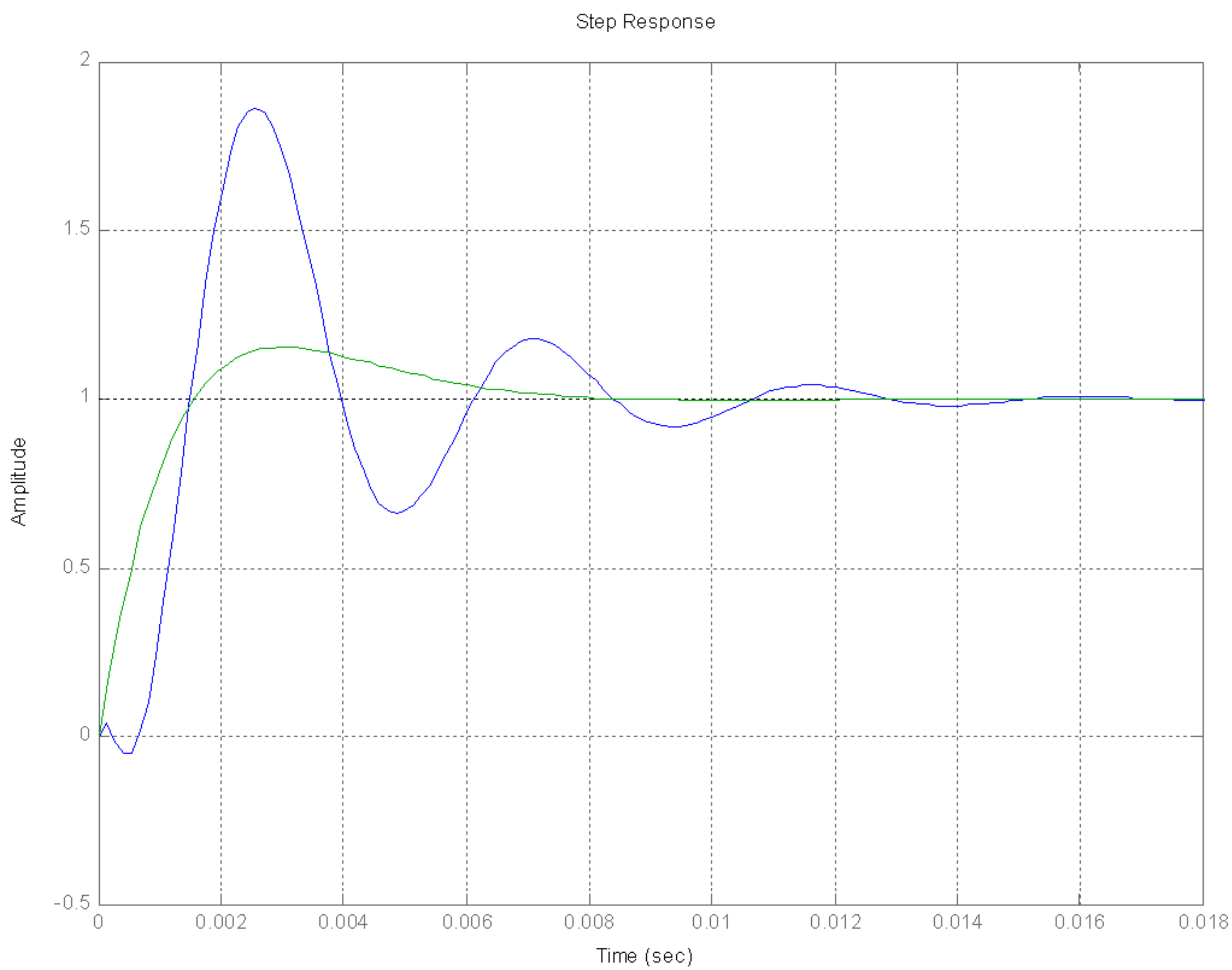
Amplitude and Phase of Sample Delay Effect



Effects of Sampling in Bode Domain



Step Response in Per Unit Showing Effect of Sample Delay, System Pole Moved From *–60 s–¹ to –600 s–¹*



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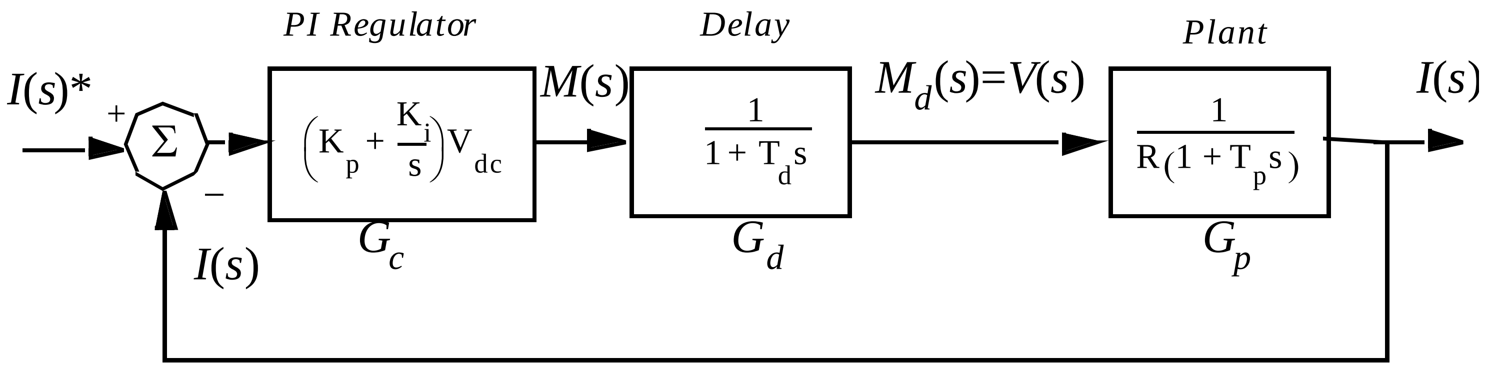
Classical Control Design Methods

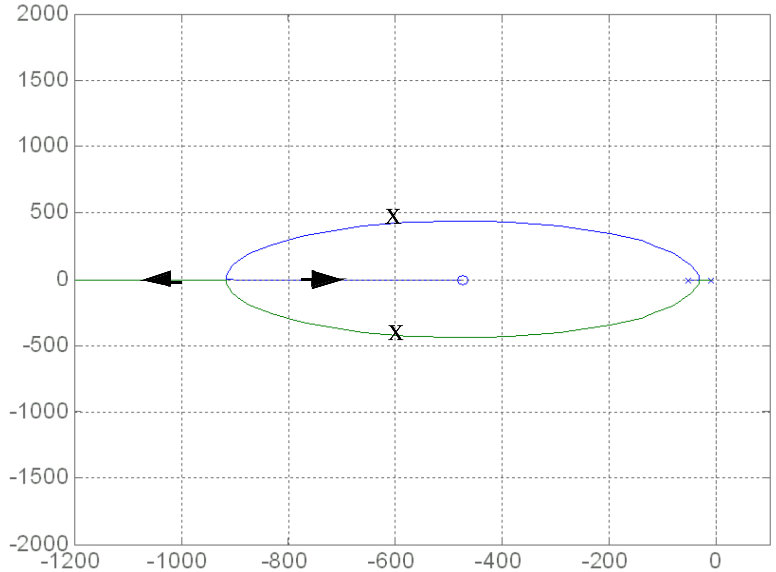
- Root Locus
- Bode Plot
- Symmetrical Optimum

Root Locus

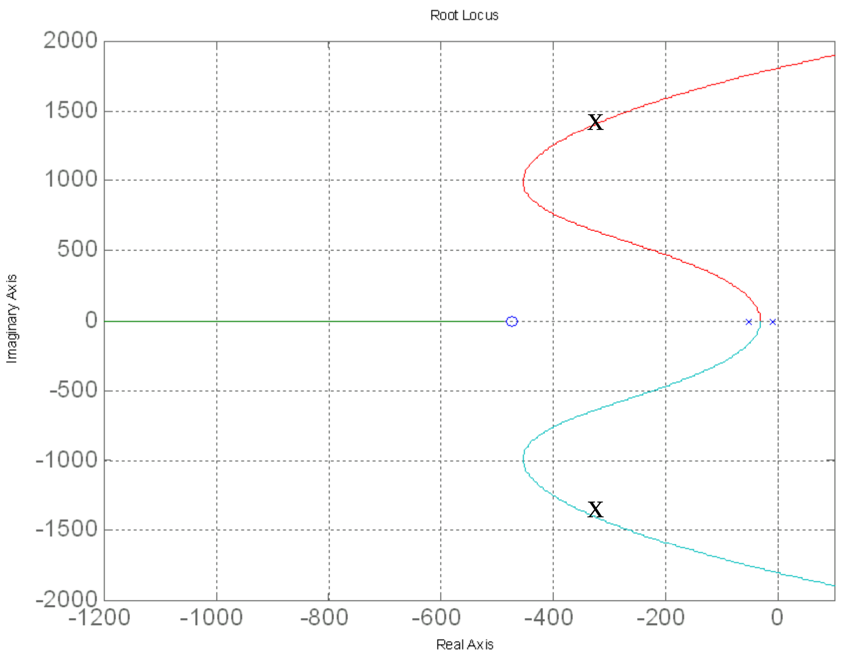
Current Regulator Block Diagram Including Effects of Sampling



Root Locus Plots of System with a PI Controller with Plant Pole at $-1/T = -60\ s^{-1}$, (a) Without Sampling and (b) Including the Effects of Sampling, Closed Loop Poles Denoted by "x"

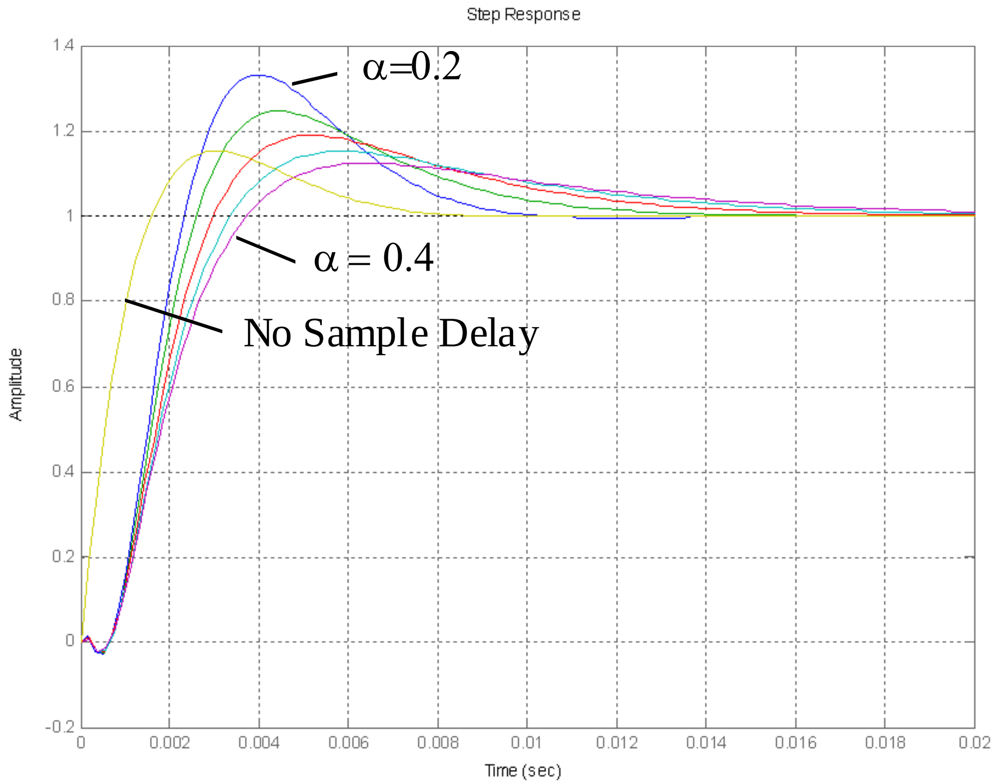


(a)



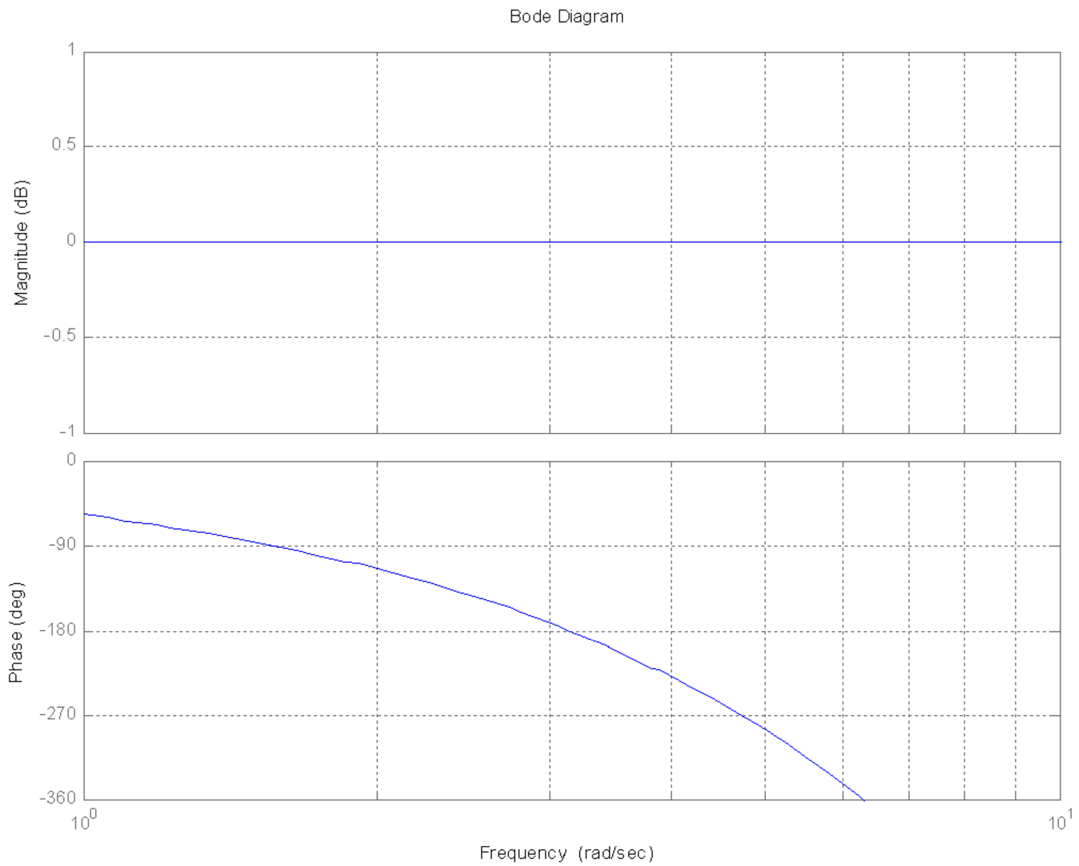
(b)

Step Response for Three Values of Alpha and Gain Which Place the System Pole at –600 s$^{–1}$.

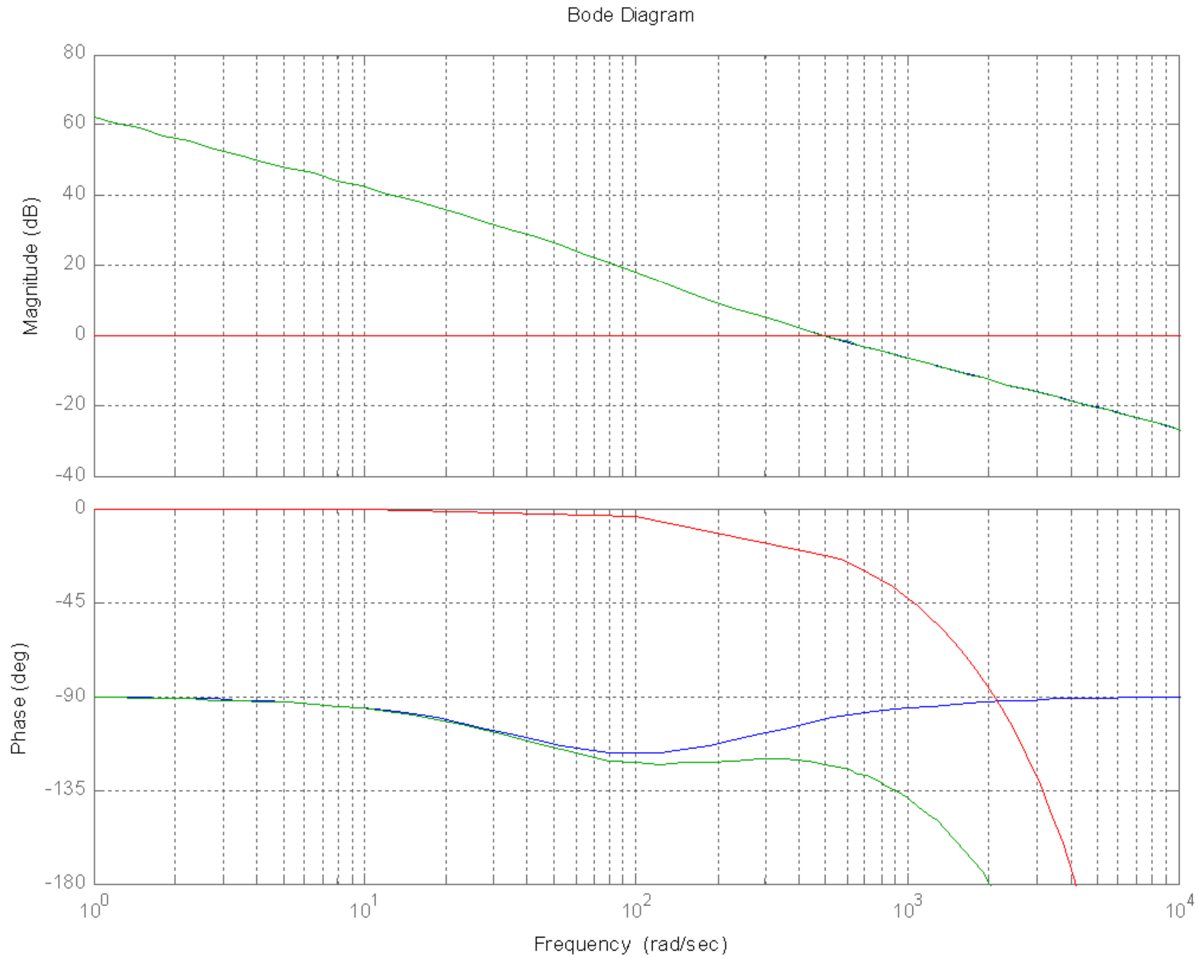


Bode Plot

Amplitude and Phase of Sample Delay Effect



Bode Plot with Controller and With 45 Degree Phase Margin



Symmetrical Optimum

Symmetrical Optimum

The open loop transfer function is

$$G(s) = G_c(s)G_d(s)G_p(s) = \frac{k_i}{R}\frac{\left(1+\frac{k_p}{k_i}s\right)}{s}\left(\frac{1}{1+T_d s}\right)\left(\frac{1}{T_p s}\right)$$

Or

$$G(s) = \frac{k_p}{R}\frac{(1+T_i s)}{T_i s}\left(\frac{1}{1+T_d s}\right)\left(\frac{1}{T_p s}\right)$$

The symmetrical optimum method selects the crossover frequency to be the reciprocal of the geometric average of the controller zero time constant and the faster of the two time constants of the system. To find the crossover frequency ω_c

$$|G_c(j\omega)G_d(j\omega)G_p(j\omega)| = 1$$

Symmetrical Optimum

The geometric average of the two time constants is

$$\omega_c = \frac{1}{\sqrt{T_i T_d}}$$

Define now, also

$$a = \sqrt{\frac{T_i}{T_d}}$$

The open loop transfer function becomes

$$G(s) = \frac{\omega_c^2}{s^2}\left(\frac{\omega_c + as}{a\omega_c + s}\right)$$

This result produces a transfer function whose phase is symmetrical around the frequency $\omega = \omega_c$. The "spread" of the phase around the crossover frequency can be controlled by selecting a. The value of $a = 2$ is often recommended.

Symmetrical Optimum

The closed loop transfer function becomes

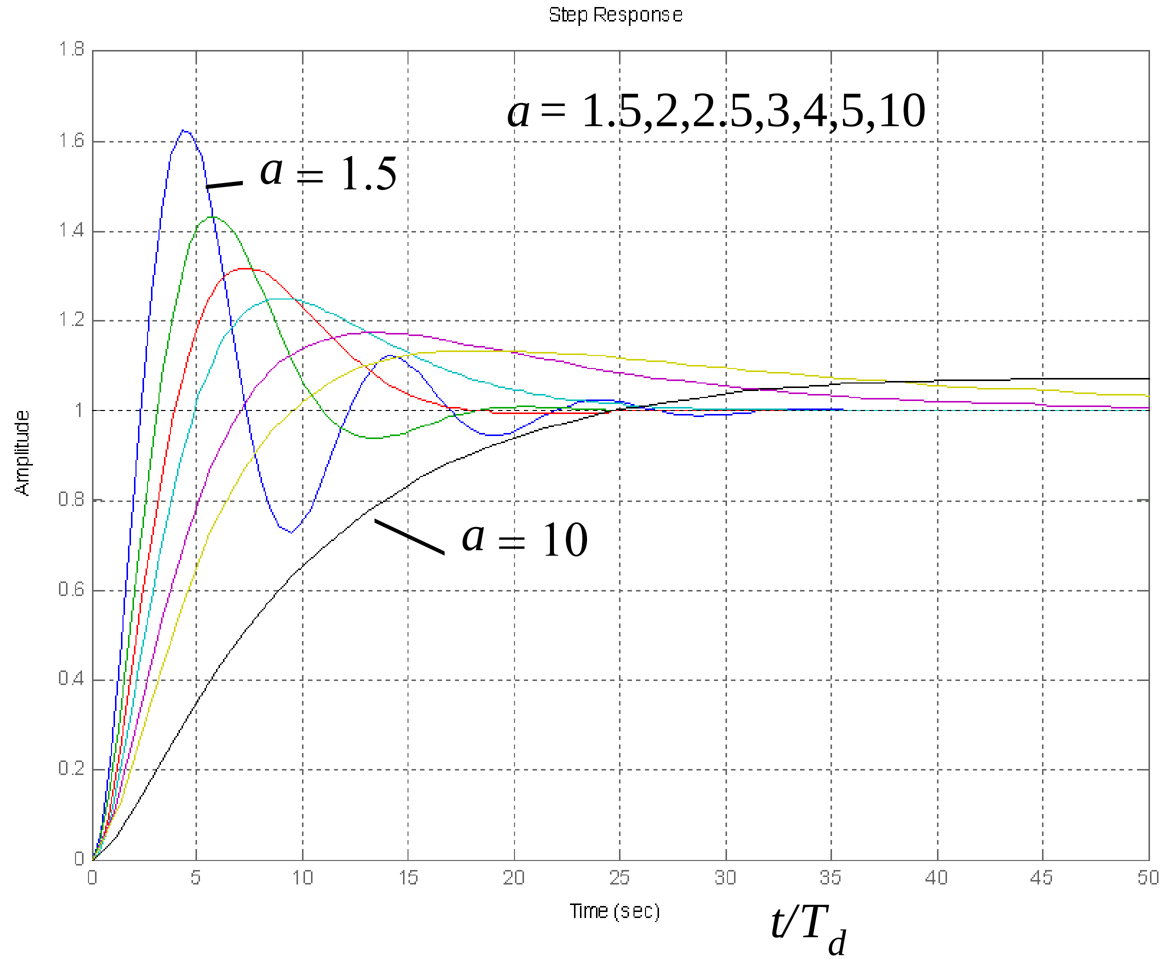
$$\frac{I(s)}{I^*(s)} = \omega_c^2\left(\frac{\omega_c + as}{s^3 + a\omega_c s^2 + a\omega_c^2 s + \omega_c^3}\right)$$

This result can now be factored

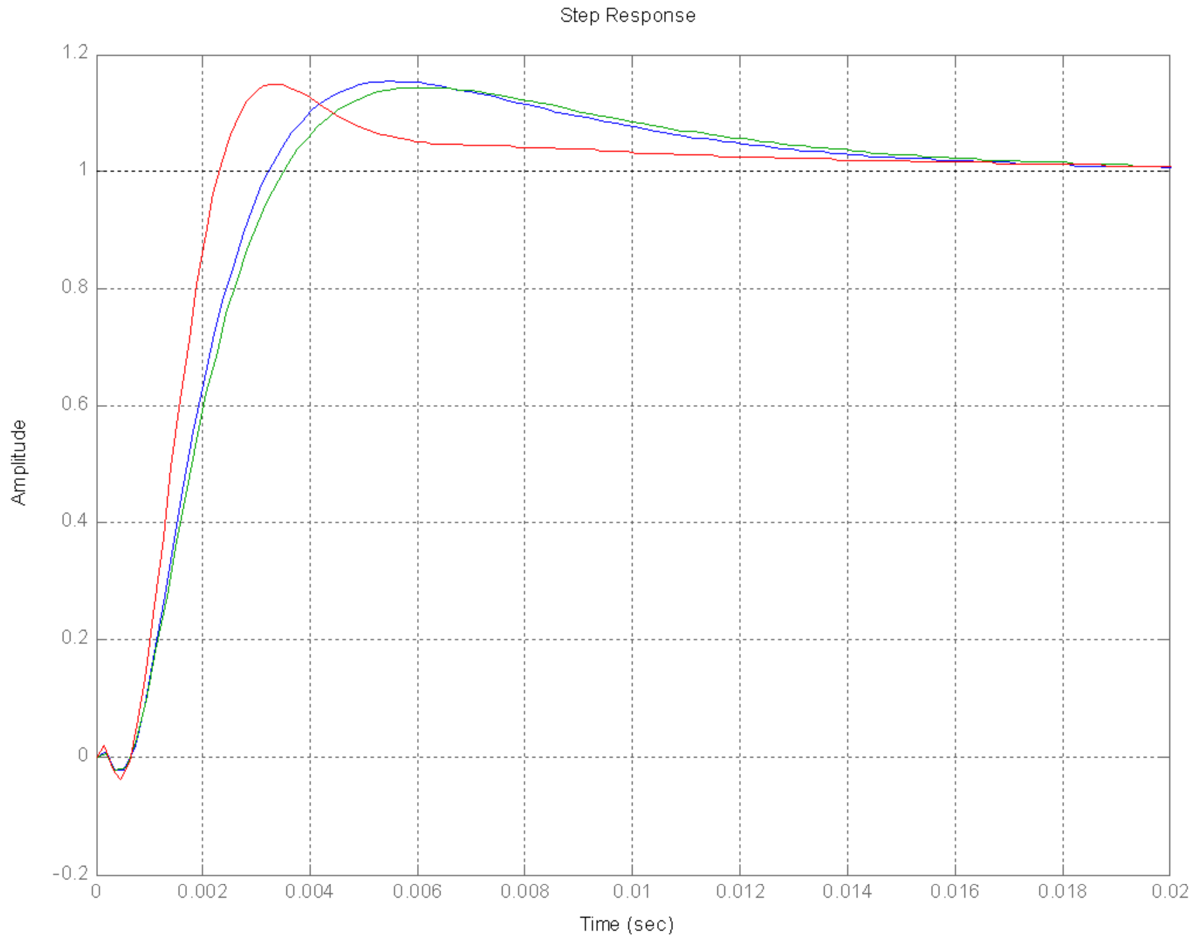
$$\frac{I(s)}{I^*(s)} = \omega_c^2\left(\frac{\omega_c + as}{(s + \omega_c)(s^2 + \omega_c(a-1)s + \omega_c^2)}\right)$$

Having now obtained the solution to the cubic polynomial of the closed loop system, the closed loop poles can be located as a function of ω_c and a.

Step Response for Values of *a*



Step Current Response Using the Three Design Approaches. Peak Overshoot = 15%



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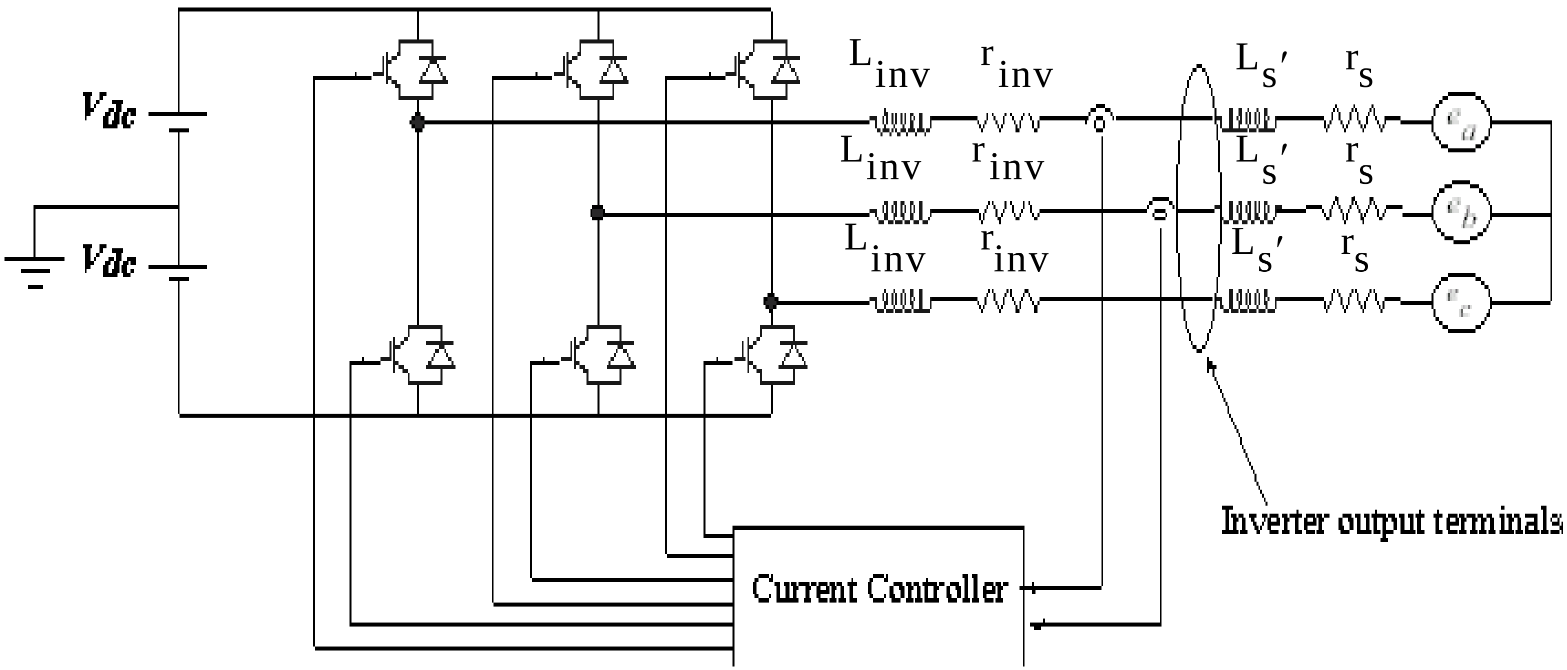
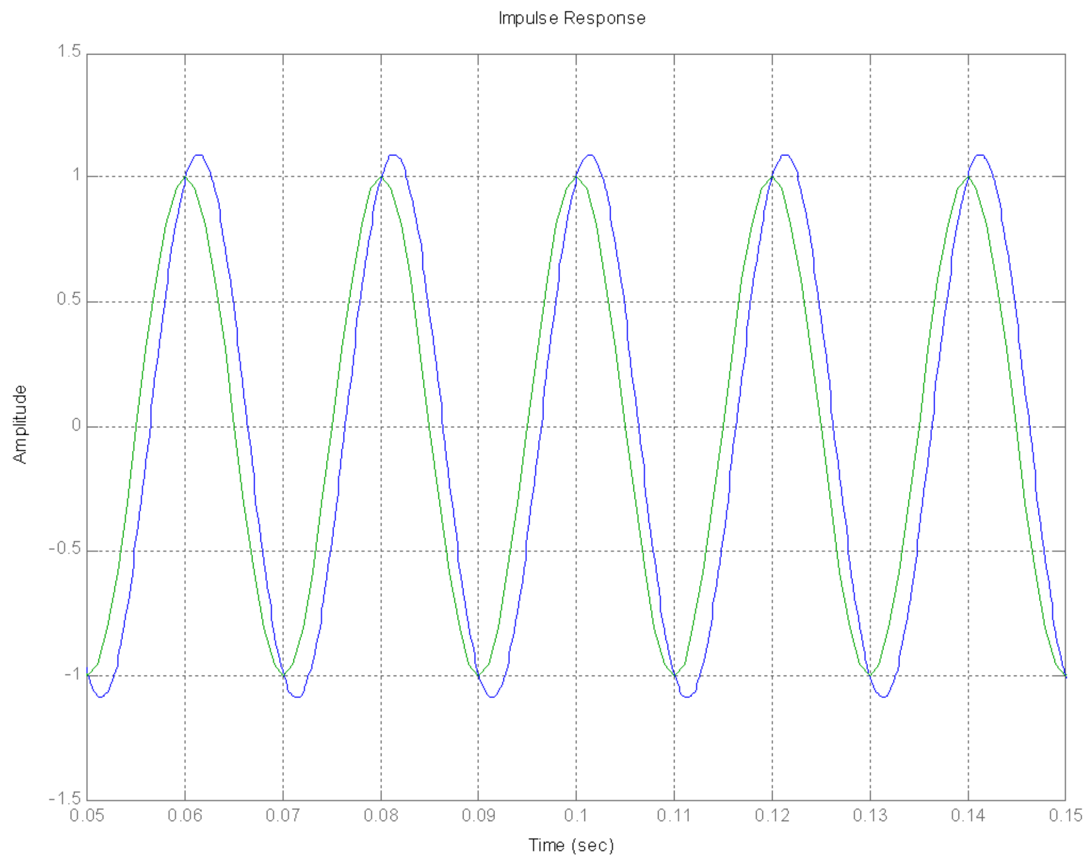
Current Regulated AC System



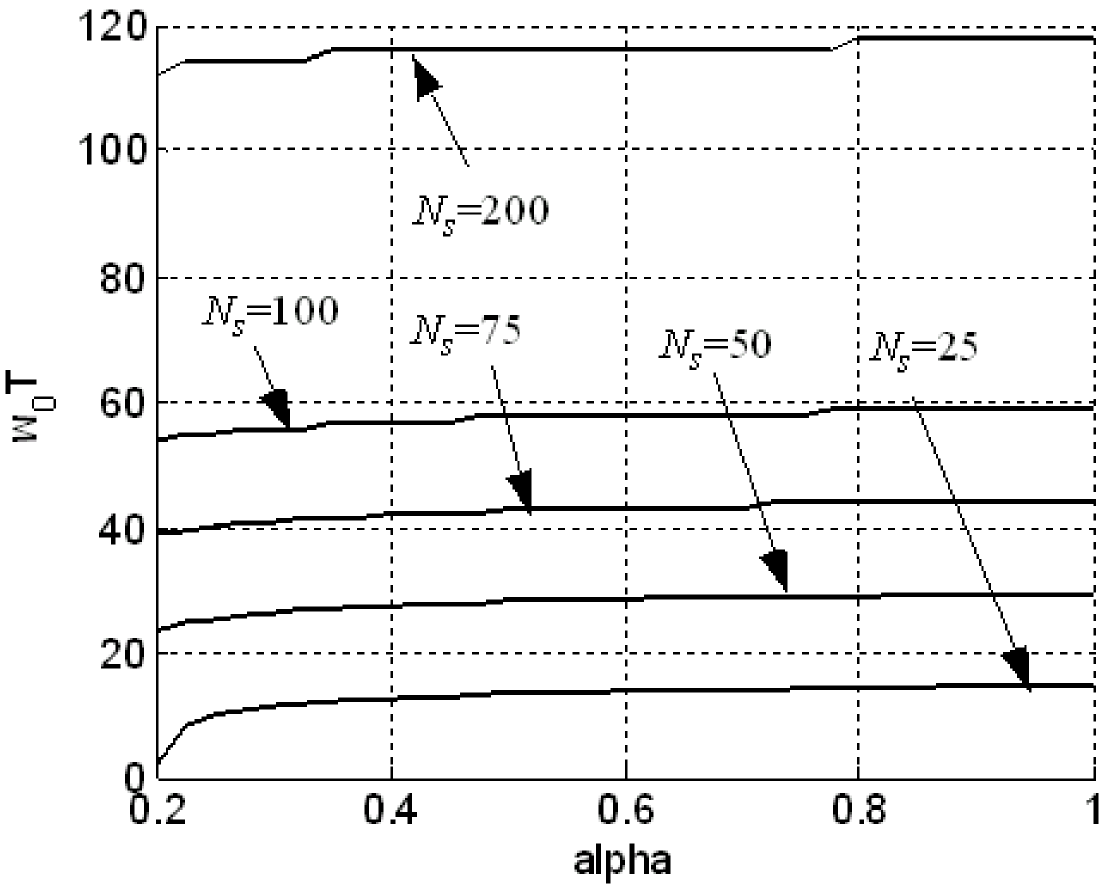
Parameters of AC System

Circuit Parameter	Value
Resistive component of load (r) (Ω)	1.2
Inductive component of load (L_s) (mH)	20
DC bus voltage ($2V_{dc}$) (V)	400
Back EMF voltage (EMF) (V_{rms})	110
Back EMF frequency (f_e) (Hz)	50
Rated current (I) (A_{rms})	10
Switching Frequency (f) (kHz)	5
Sampling update period (T_s) (msec)	0.1
Sample delay period (T_d) (msec)	0.15

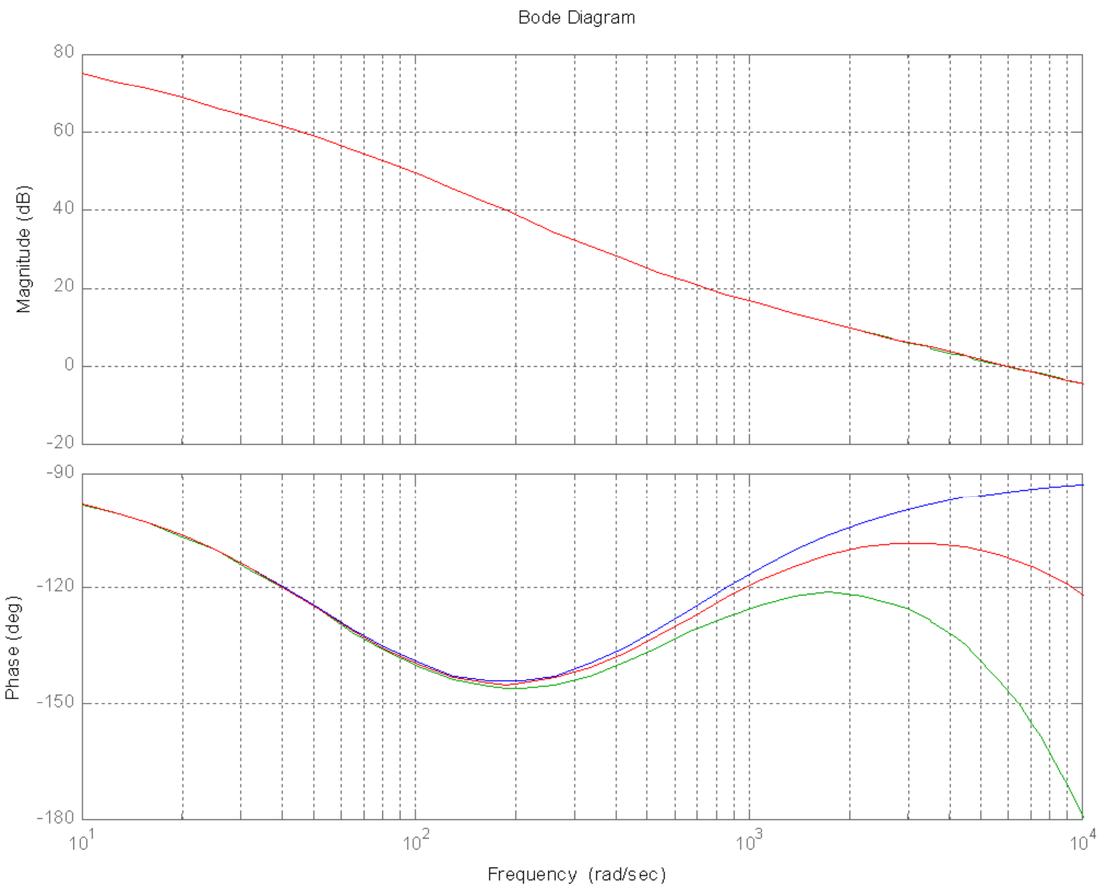
AC Current Regulation – Using PI Gains of the DC System



Per unit Angular Frequency for 40o Phase Margin vs. α and Number of Updates Over Plant Time Constant *R/L*



Effect of Sampling Delay



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Optimal Gain Determination

Representing sampling and transport delay as an e^{-sT_d} time delay, the system open loop gain becomes

$$G_c(s)G_d(s)G_p(s) = \frac{k_p}{RT_i} \cdot \frac{(1+sT_i)e^{-sT_d}}{s(1+sT_p)} \qquad (1)$$

The phase angle of this forward path loop gain at the cross over frequency ω_c is given by (in radians)

$$\angle\{G_c G_d G_p\} = \angle\left\{\frac{k_p}{RT_i} \cdot \frac{(1+j\omega_c T_i)e^{-j\omega_c T_d}}{j\omega_c(1+j\omega_c T_p)}\right\} = -\pi + \phi_m$$

$$= \tan^{-1}(\omega_c T_i) - \pi/2 - \tan^{-1}(\omega_c T_p) - \omega_c T_d$$

Optimal Gain Determination

If the plant time constant T_p is assumed to be substantially larger than T_i, the angular contribution of $\tan^{-1}(\omega_c T_p)$ is approximately $90°$, so that

$$\phi_m \approx \tan^{-1}(\omega_c T_i) - \omega_c T_d$$

The point of inflection for the phase curve can be found by differentiating the with respect to ω_c

$$\frac{d}{d\omega_c}\left(\tan^{-1}(\omega_c T_i) - \omega_c T_d - \phi_m \right) = 0$$

or

$$\frac{T_i}{1 + n(\omega_c T_i)^2} - T_d = 0$$

Optimal Gain Determination

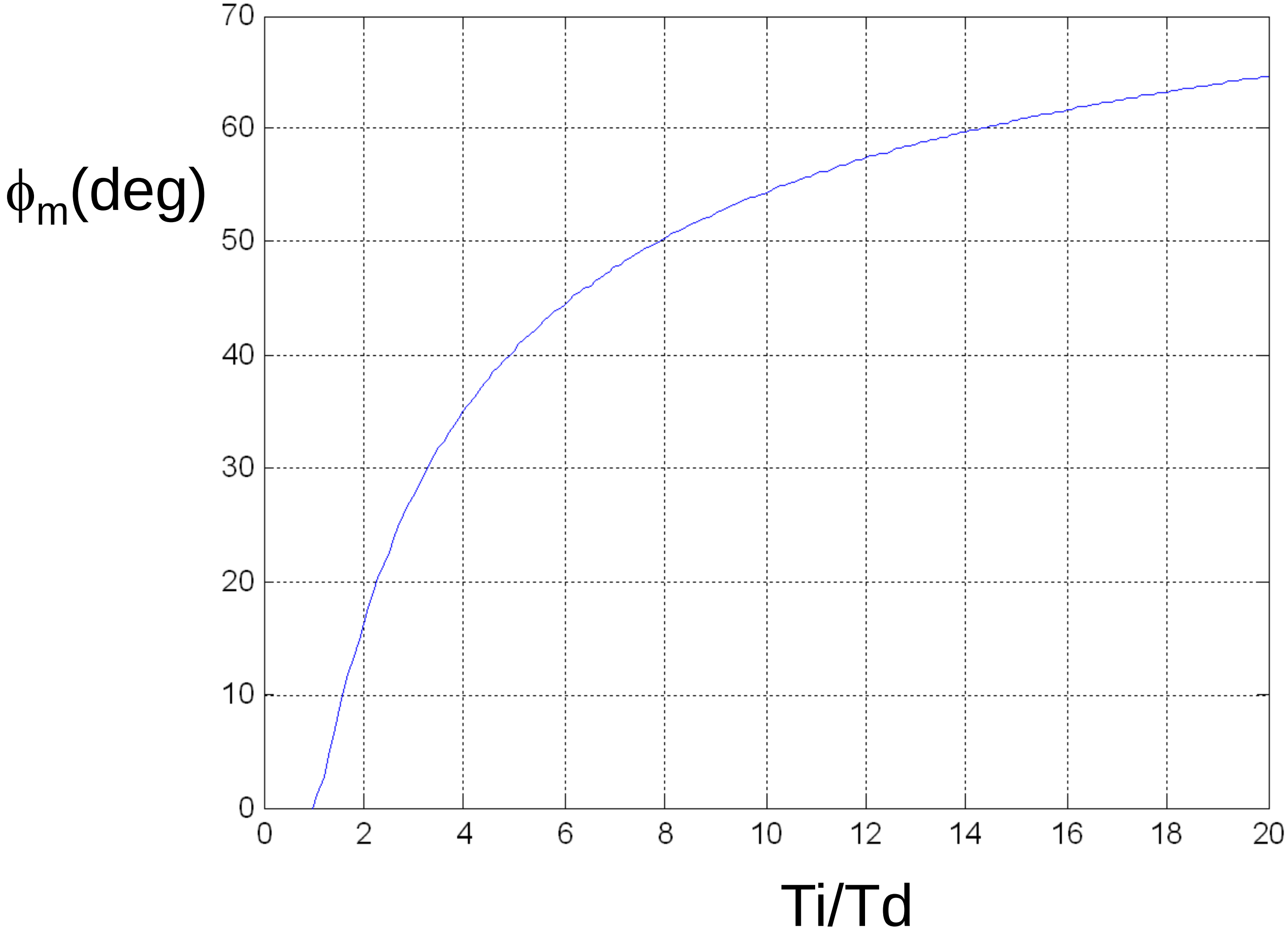
Upon solving for the crossover frequency

$$\omega_c = \frac{1}{T_i}\sqrt{\frac{T_i}{T_d} - 1}$$

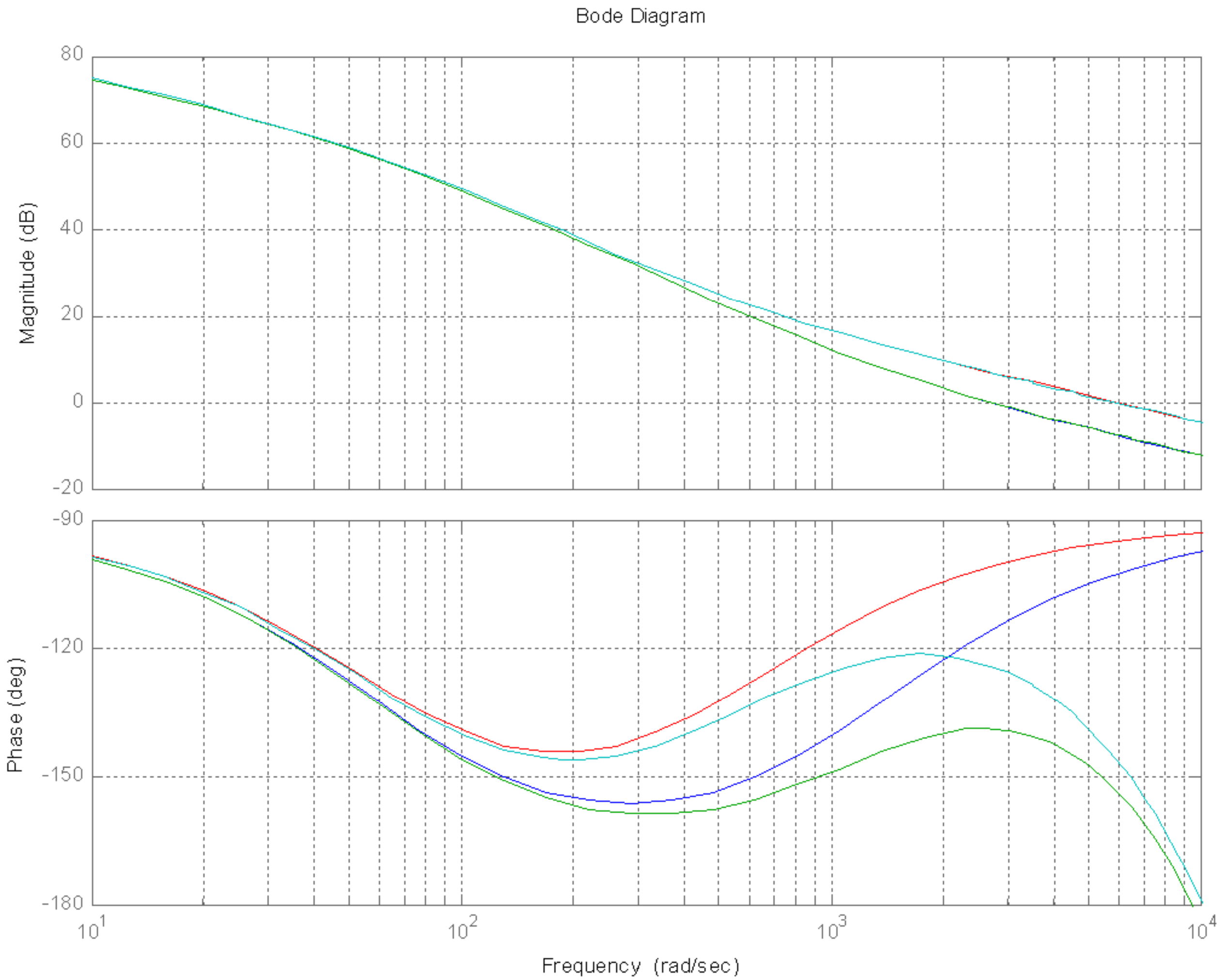
Substituting the back into the expression for $\angle\{G_c G_d G_p\}$ allows T_i to be numerically calculated for any required phase margin using

$$\phi_m = \tan^{-1}\left(\sqrt{\frac{T_i}{T_d} - 1}\right) - \frac{T_d}{T_i}\sqrt{\frac{T_i}{T_d} - 1}$$

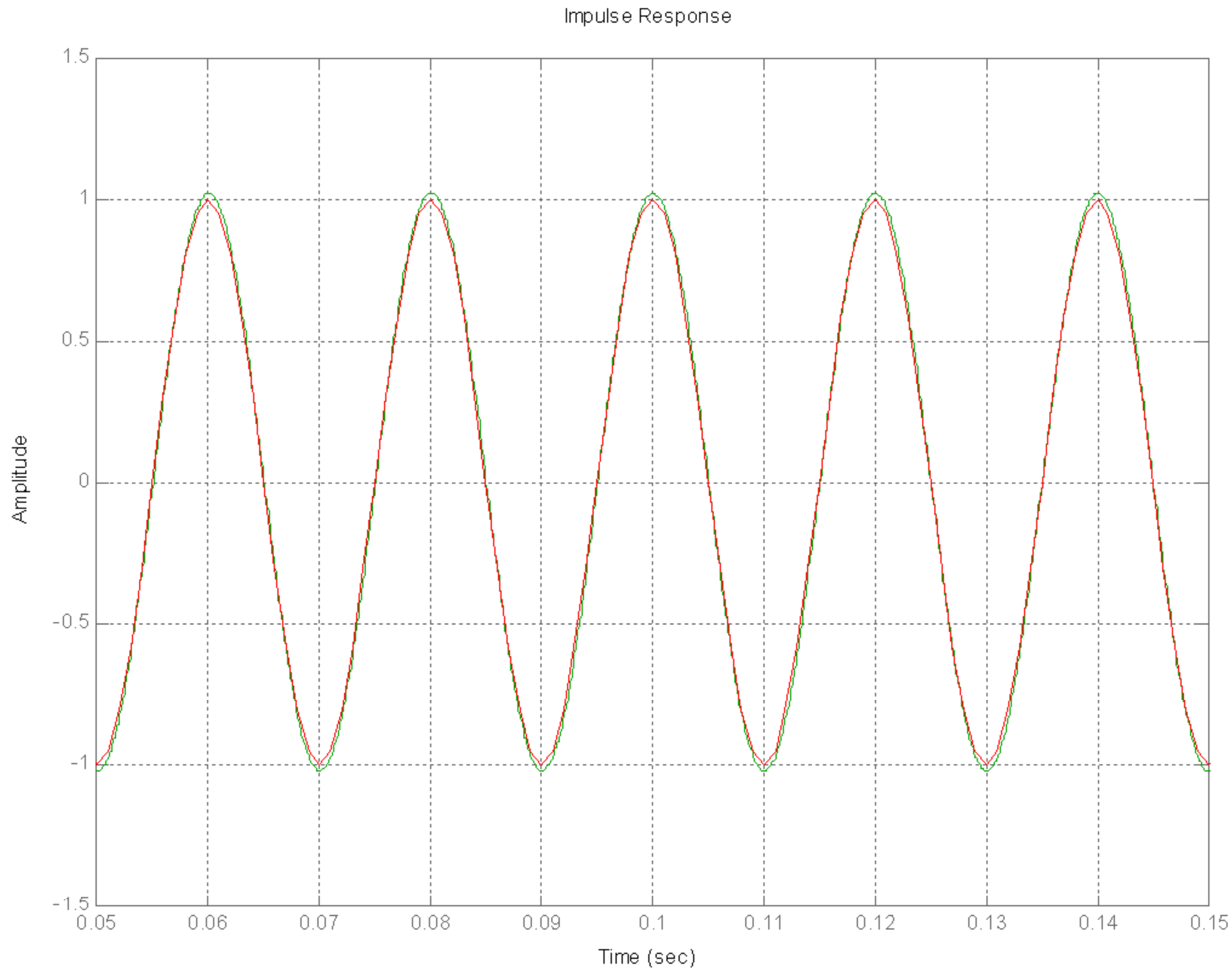
Open Loop Phase Margin at Maximum Inflection Pt. vs. Ti/Td



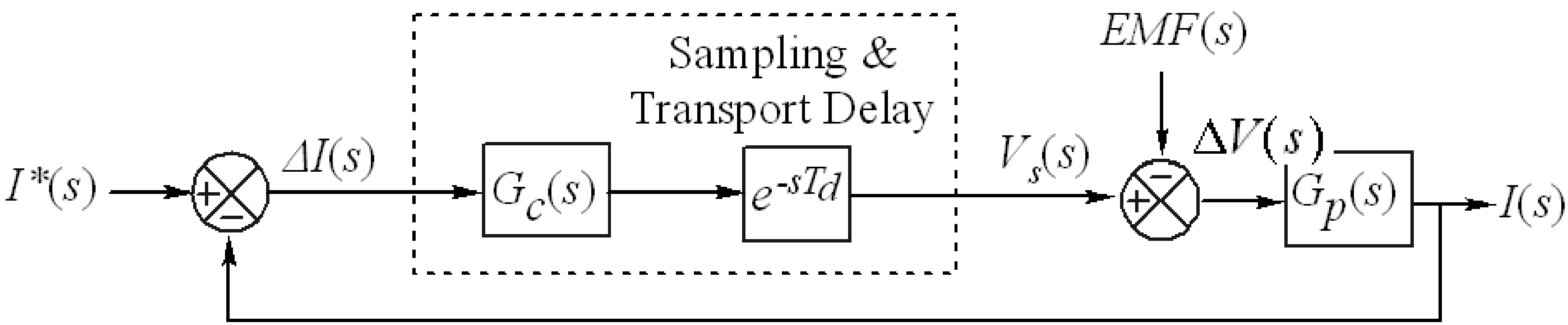
Open Loop Transfer Function for Two Controller Designs



AC Response of the Optimal Value Design ,40 Degree Phase Margin



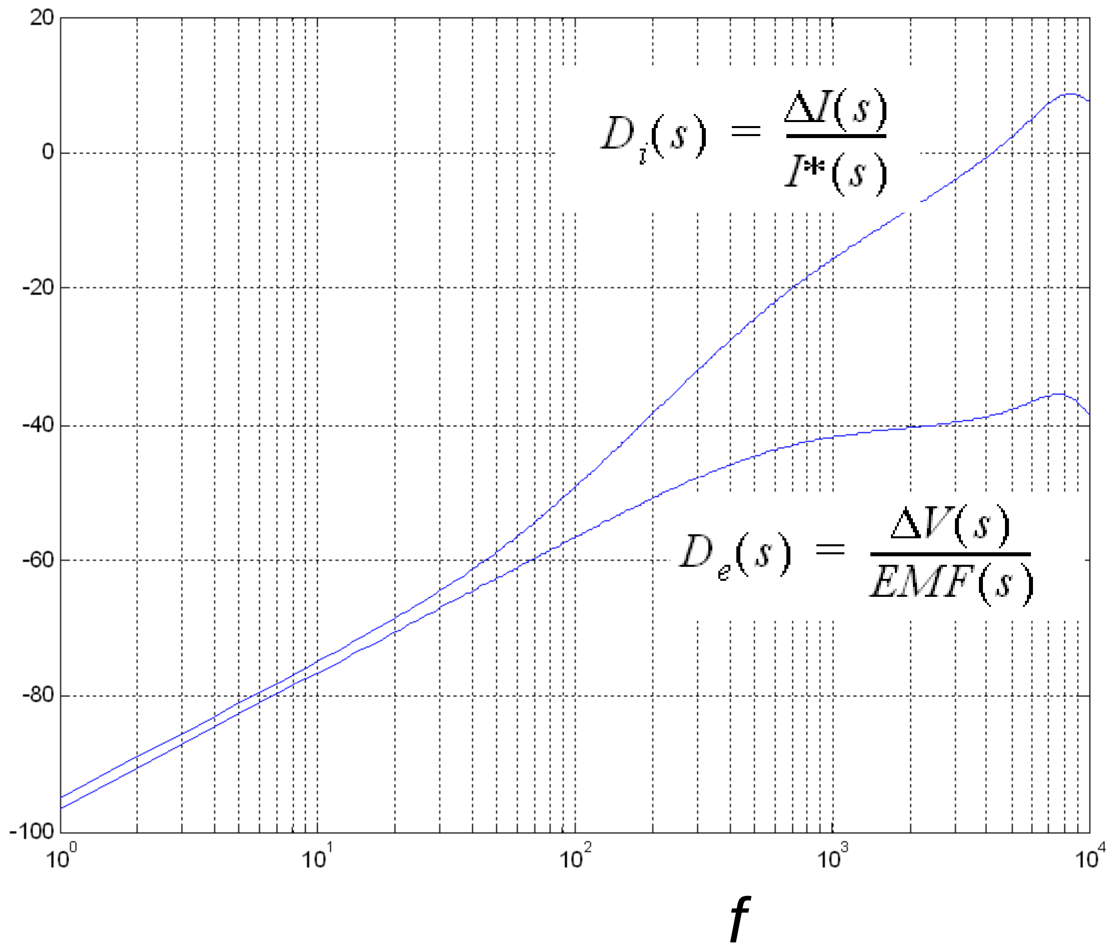
Average value model block diagram
Representation Including the Back EMF



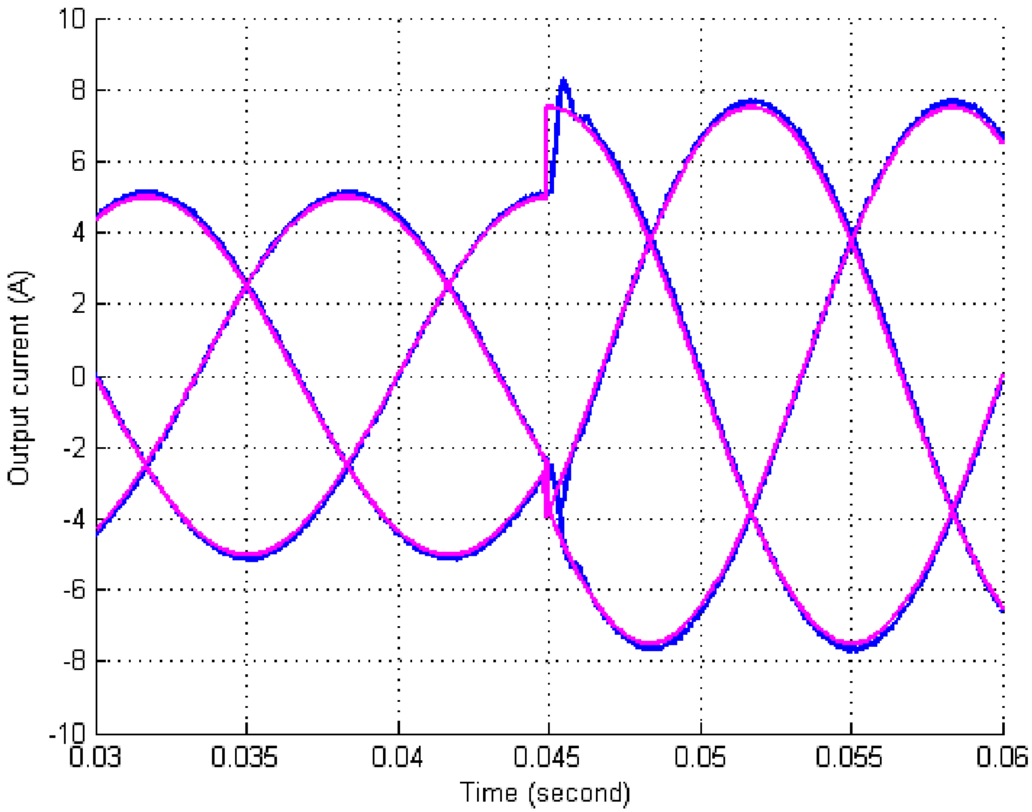
$$D_i(s) = \frac{\Delta I(s)}{I^*(s)}$$

$$D_e(s) = \frac{\Delta V(s)}{EMF(s)}$$

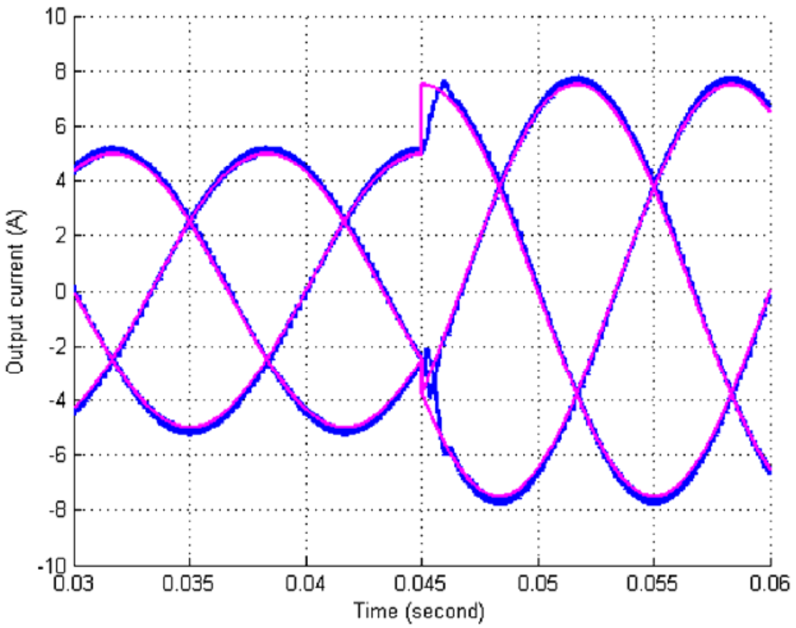
Tracking and Disturbance Error for Optimized PI Stationary Frame Current Regulator

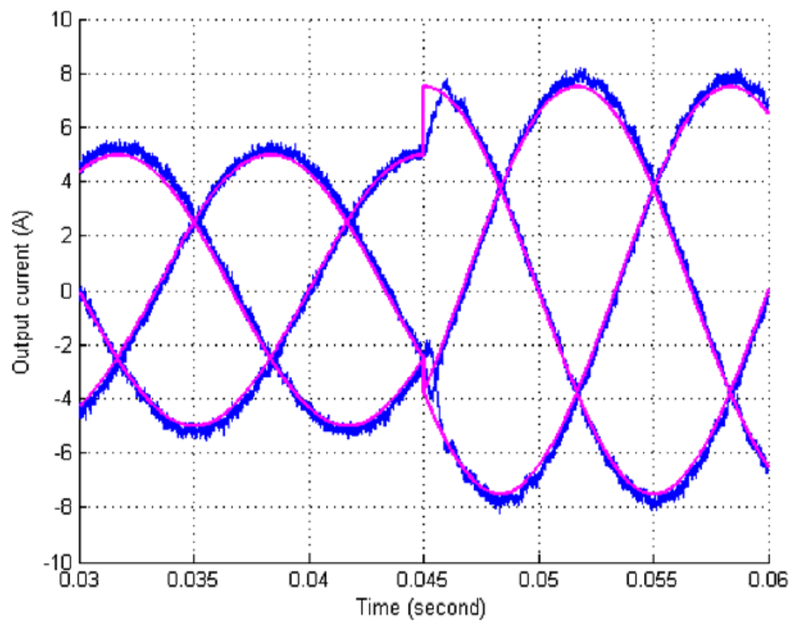


AC Current Regulation Response of Simulated Optimized Stationary Frame PI Current Regulator

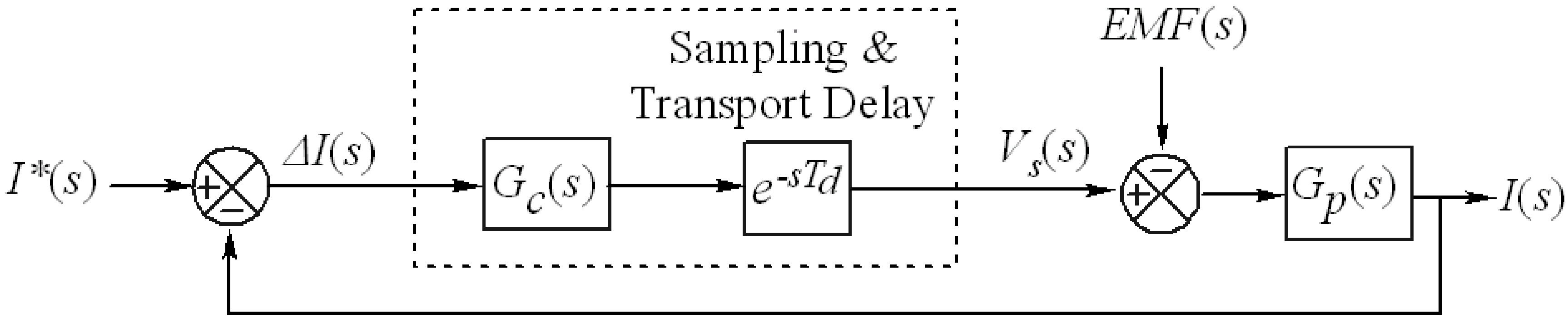


Comparison of Simulated and Experimental Results

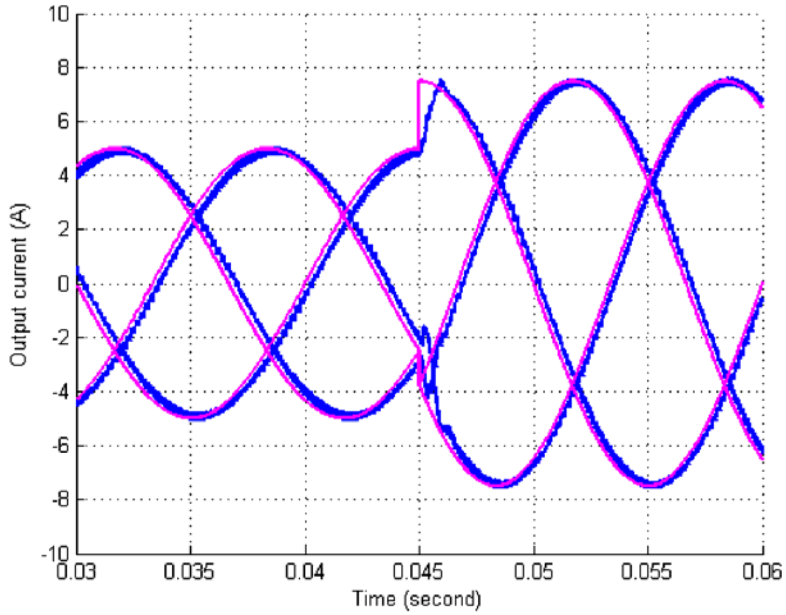


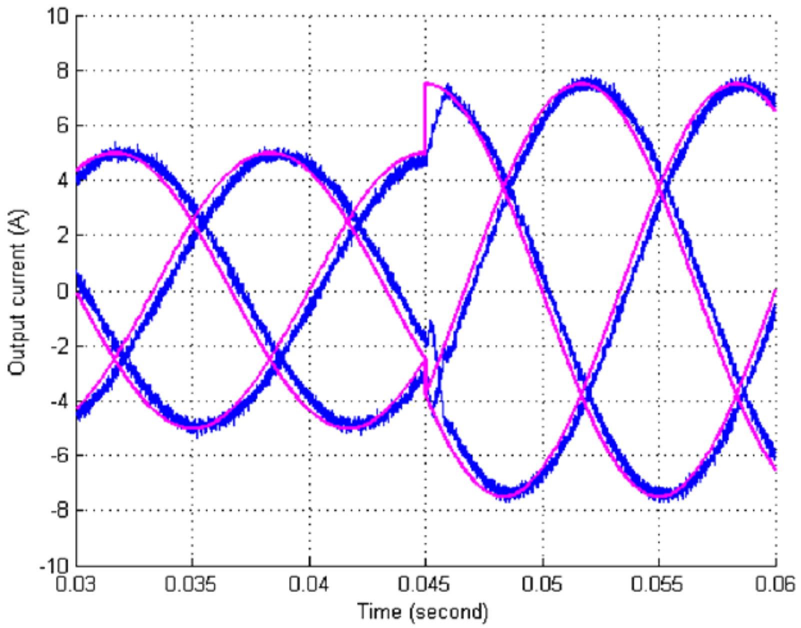


System Block Diagram



Including Back EMF Effects –Simulation and Experimental





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Resonant Current Regulator

The forward gain block $G_r(s)$ of an ideal PR controller is described by the transfer function

$$G_r(s) = k_p\left[1 + \frac{s}{T_i(s^2 + \omega_o^2)}\right]$$

where ω_o is the target reference current frequency. From this expression it can be seen how the $(s^2 + \omega_o^2)$ term in the denominator creates infinite forward controller gain at ω_o.

Resonant Current Regulator

A more practical alternative with damping is

$$G_r(s) = k_p\left[1 + \frac{s}{T_i(s^2 + \omega_r s + \omega_o^2)}\right]$$

This form of controller limits the forward gain at ω_o to

$$G_r(j\omega_o) = k_p[1 + 1/T_i\omega_r]$$

Note that this gain value is independent of the plant time constant!

Resonant Current Regulator

This value of gain can be compared with the gain of a PI controller whose gain at ω_o is

$$G_c(j\omega) = k_p + \frac{k_i}{j\omega_o}$$

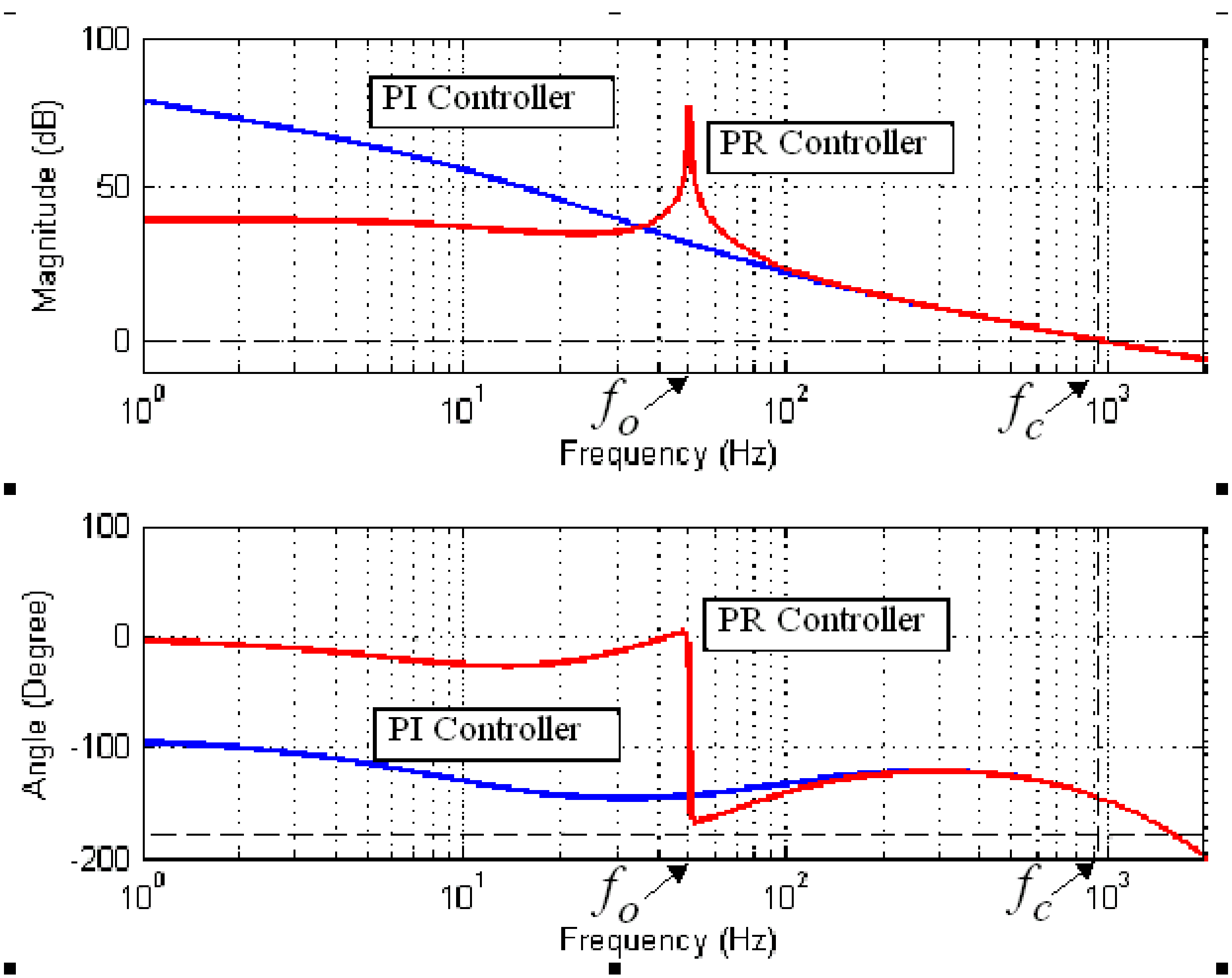
$$= k_p + \frac{k_p}{T_i}\left(\frac{1}{\omega_o}\right)$$

Neglecting k_p which is relatively small compared to k_i the ratio of the two terms is

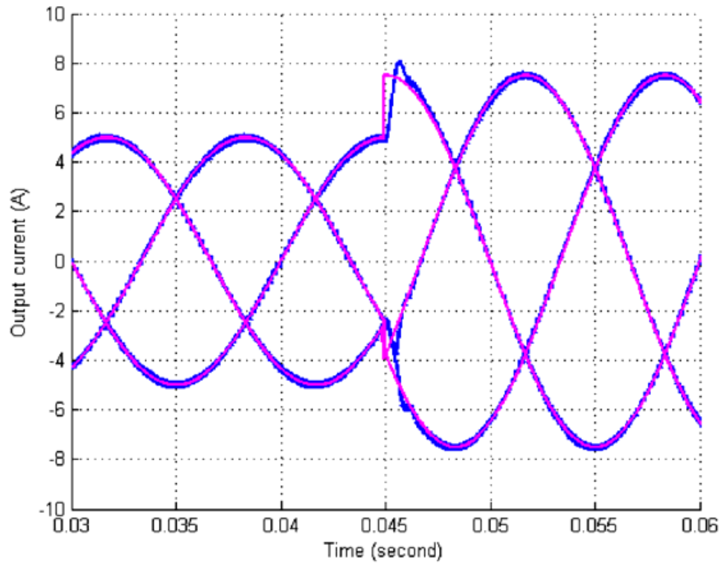
$$\left|\frac{G_r(j\omega)}{G_c(j\omega)}\right| = \frac{\omega_o}{\omega_r}$$

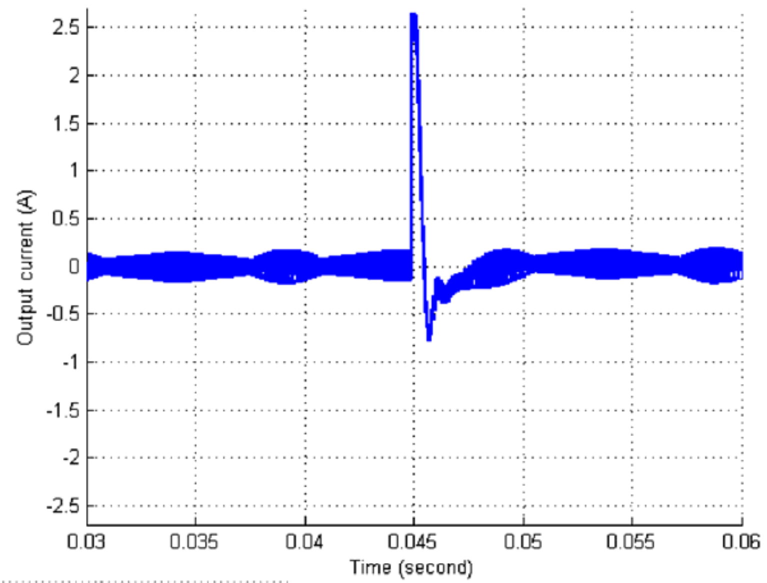
There is a large gain increase compared to the PI controller at the same frequency. In practice, gain increases of 40-60 dB (factor of 100-1000) are readily achievable.

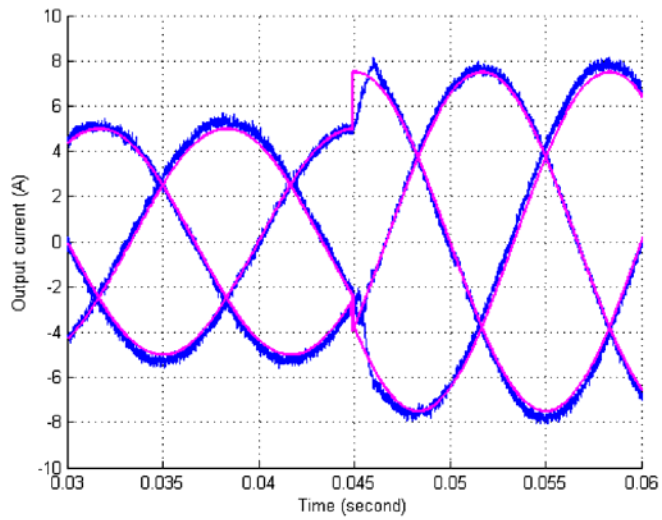
Magnitude and Phase Bode plot of for PI and PR regulators with sampling/transport delay



Simulation and Test Results for Resonant Current Regulator







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Conclusions

- Sampling of the current feedback has a significant effect on regulation
- AC current regulation requires substantially more gain than DC current regulation
- With proper attention to achieving maximum permissible gain, current regulation to 1-2 degree phase shift can be achieved
- Regulation to within a fraction of a degree is possible with a resonant regulator

Benefits of Direct AC Current Regulation

- Approach is the straightforward, least confusing means of control design

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- Optimum gain settings are INDEPENDENT of the plant time constant

- Friendly  Approach - NO FANGS!!


That's all Folks!
A WARNER BROS. CARTOON