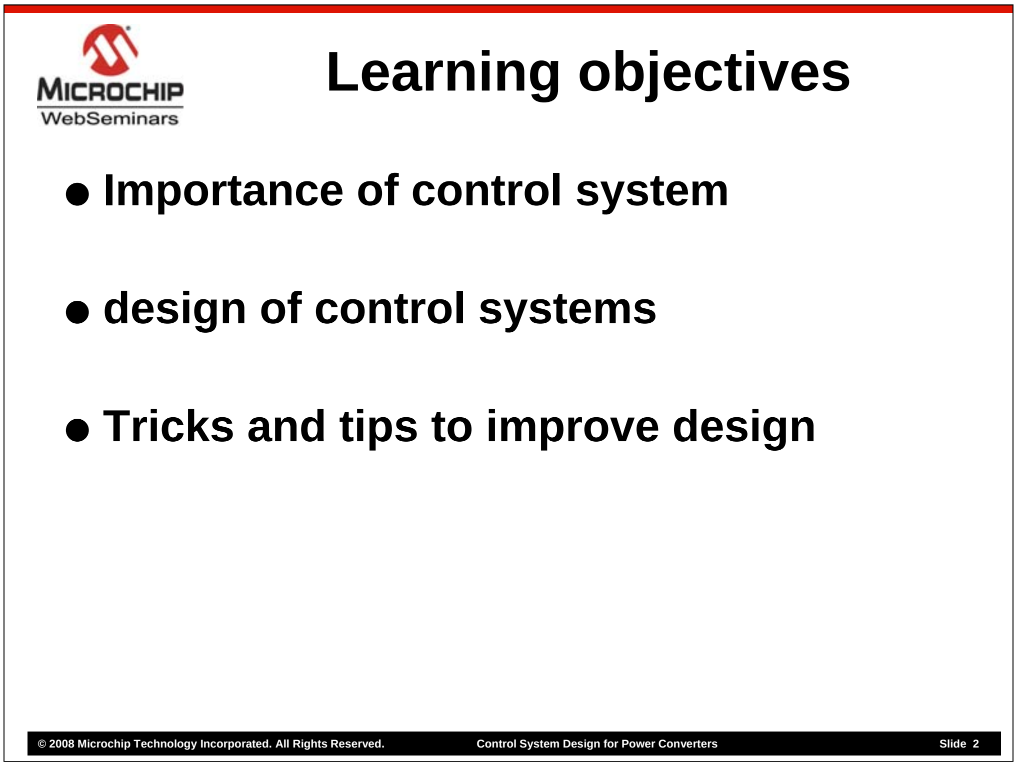
Control System Design for Power Converters



Today we will be talking about basics of control system design for power converters.

The learning objectives are as follows. Importance of control system design , design of control systems and tricks and tips to improve the design

Introduction to Control Systems

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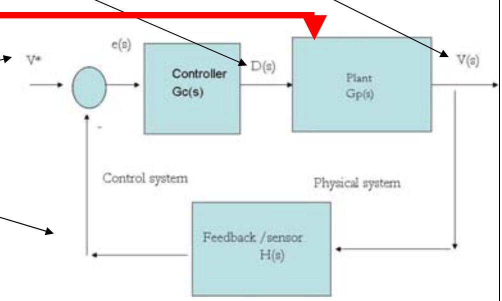
- State variable : physical quantity that needs to be controlled E.g. speed of car
- Manipulated input : A variable whose quantity can be set which controls the state variable. E.g. Pressure on gas pedal
- Load or disturbance : external influence that effects state variable e.g gradient of the road
- Reference : Desired Value of state variable * notation
- Feedback : Actual Value of state variable E.g. speedometer reading



Introduction to control system.

Imagine you are driving a car and want to control the speed of the car. The speed of the car is the state variable

The only thing that can be controlled is the pressure on the gas pedal. The pressure on the gas pedal is the manipulated input The system acts in response to the manipulated input

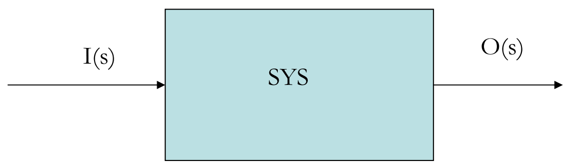
The desired speed is the reference for the system

External factors like road gradient and wind drag are disturbances

The feedback is the measured speed using speedometer

Open loop

- The input command is blindly set "hoping " the system to be at desired value
- Easy to implement
- External variables like load/drift from ideal conditions like payload spoil the party
- Leads to over designed passive components
- Add bulk and cost



One method to control the system is open loop implementation

The manipulated input is blindly set hoping the state variable will be at the desired value

It is easy to implement as no measurement devices of the actual state of the system is required

External factors like wind and gradient and variables like payload spoil the party

To prevent effects of external influences, leads to over designed passive system which adds bulk and cost.

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Closed loop

- Feedback is taken using sensors
- Error between desired value and feedback is used to control the command
- Allows system to respond to external variables

  (isolate state from external influences)
- Reduce passive component size/cost
- Design needs careful consideration

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Feedback is taken from using sensors which measure the desired output variable.

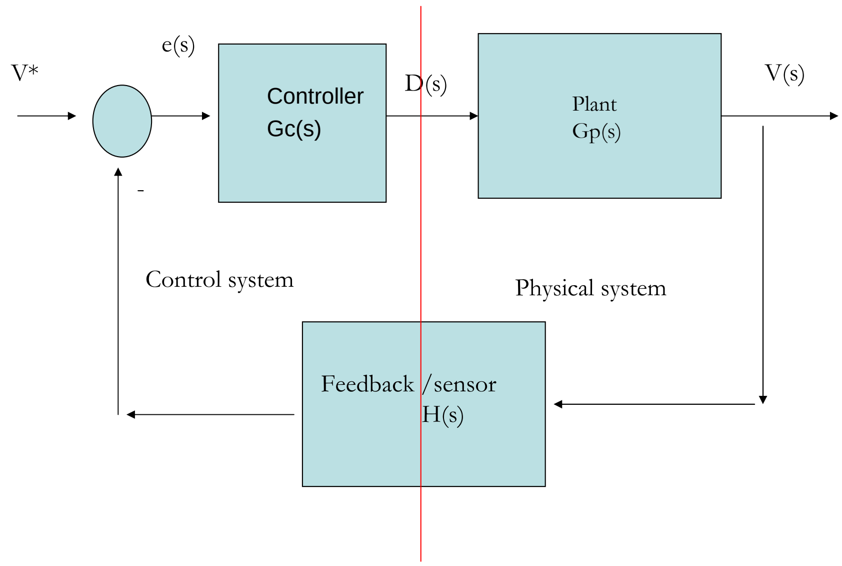
This feedback is used to generate error between the reference. This error is then used to set the drive or the manipulated input. The block that takes in the error as input and generates the drive or the manipulated input is known as the controller.

Closed loop systems can respond to changes in external factors.

They reduce bulk and cost of passive components

Closed loop control system design needs some mathematical analysis.

Closed loop control system



Closed loop control system design objectives

- Given : a system with input commands and output
- Control a physical quantity (state) to a varying desired value within a specified time
- Minimize effect of external influences
- Mitigate effect of measurement errors/noise
- Estimation as sensor replacement

Metrics for evaluation

- Command tracking : Ability of output to respond to varying input reference.
- Disturbance rejection : Ability to isolate output from variation in load
- Line Regulation : Ability to isolate output from variation in input
- Noise rejection : Ability to reject measurement noise/errors

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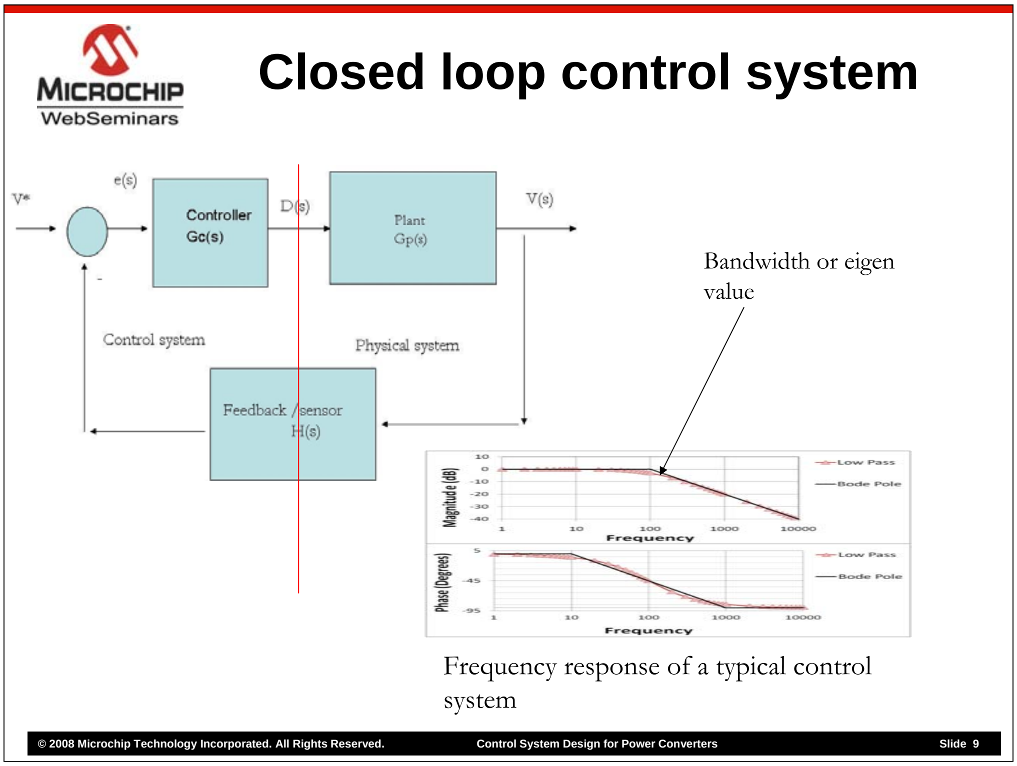
Control system efficacy can be evaluated on 4 metrics

Command tracking : Ability of output to respond to varying input reference.

Disturbance rejection : Ability to isolate output from variation in load

Line Regulation : Ability to isolate output from variation in input

Noise rejection : Ability to reject measurement noise/errors

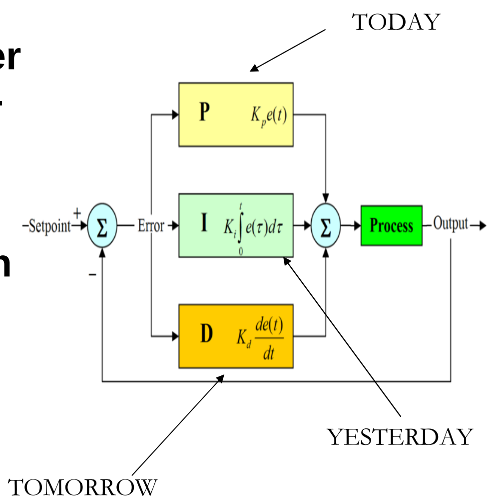


Closed loop control system response is frequency domain is shown here. Typically it looks like a low pass filter.

The cutoff frequency or bandwidth is the frequency over which the controller is not able to track changes in reference

How to control a system

- A polynomial of s is selected for controller
- Typically s.Kd + Kp + Ki/s is used for controller
- Differentiation leads to noise amplification
  Caution
- Estimators may be used for derivative terms



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How Do you Control the system and Why PID??

WHAT DO I HAVE IN HAND . Feed Back . I take the feed back either with amplification or attenuation and do a simple compare (P)

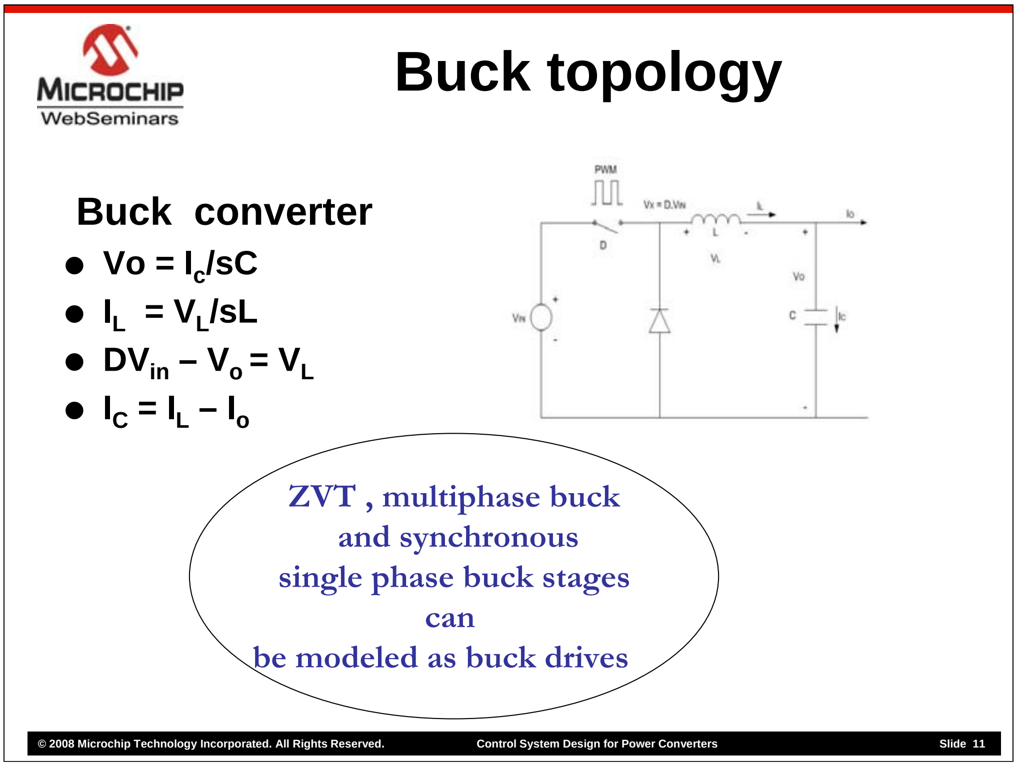
I LOOK AT THE Trend of my feedback with Past set of feedbacks and then control (Integrate)

I look at the rate of change of my feed back and control (Differentiate)

This Control Module is acting upon the system Transfer Function . Which means

Adding Gains to the system

Moving or adding Poles / Zeros for better response and stability



Buck converter

A buck converter is a power converter that converts higher voltage to a lower voltage using switches and inductor and capacitor. The basic algebraic equations are shown in the slide. The capacitor acts like an integrator for the current that flows into it. The output of the integrator is the capacitor voltage. The inductor acts like an integrator for the voltage that gets applied across it. The output of the integrator is the current. The voltage at the point where inductor and switches are connected is D.Vin

The goal is to control the output voltage to desired possibly changing values under varying conditions of line and load

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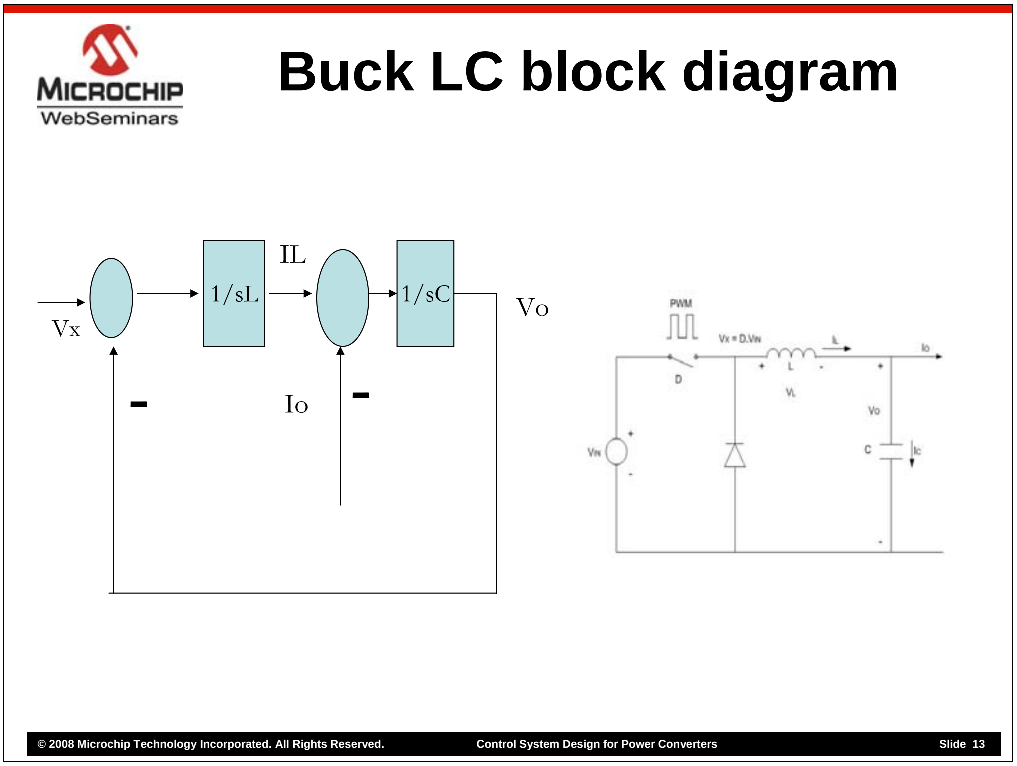
Tricks and tips for insight

- **Represent physical elements as integrations**
- **Natural characteristics of elements**
  - E.g. To control Vo, Ic needs to be 'manipulated' by controller
  - Controller should emulate a current source
  - E.g. To control IL, VL needs to be manipulated by controller
  - Controller should emulate voltage source
- **'information' quantities should be interpreted as having physical units**
- **May lead to more than standard PID and more MATH**
- **Better performance**

Designing control system gets simplified if characteristics of elements and respect for physical quantities



Observing the following rules should make the system design lot easier

Represent physical elements as integrations

Natural characteristics of elements

- E.g. To control Vo, Ic needs to be ‘manipulated’ by controller
- Controller should emulate a current source
- E.g. To control IL, VL needs to be manipulated by controller
- Controller should emulate voltage source

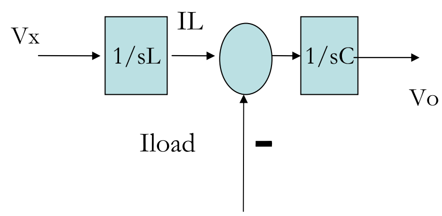
‘information’ quantities should be interpreted as having physical units

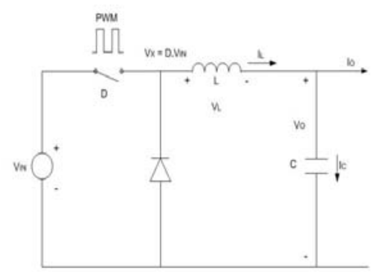
May lead to more than standard PID and more MATH

Better performance

Output voltage decoupling

- The system subtracts Vo from the applied voltage
- The difference is the inductor voltage which determines the current
- The dynamics of current and voltage are cross coupled
- To simplify system dynamics add Vo a priori and then apply new voltage
- Decouples the current and voltage state variables
- Controller output Vx = G(Vo*-Vo) + Vo





The system subtracts Vo from the applied voltage

The difference is the inductor voltage which determines the current

The dynamics of current and voltage are therefore cross coupled

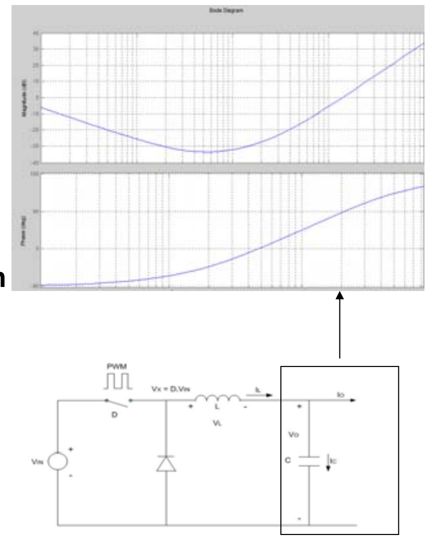
To simplify system dynamics add Vo a priori and then apply new voltage

Decouples the current and voltage state variables

Controller output Vx = G(Vo*-Vo) + Vo

Disturbance rejection/Load regulation

- Changing load causes output to change
- | Io(s)/Vo(s) |, amount of load to cause a unit change in output
- Performance METRIC
- The higher the value the STIFFER the system
- Different regions of the plot are determined by gains and system parameters
- Improves with passive component size → COST
- Load decoupling WILL improve this metric



Changing load causes output to change

| Io(s)/Vo(s) |, amount of load to cause a unit change in output

Performance METRIC

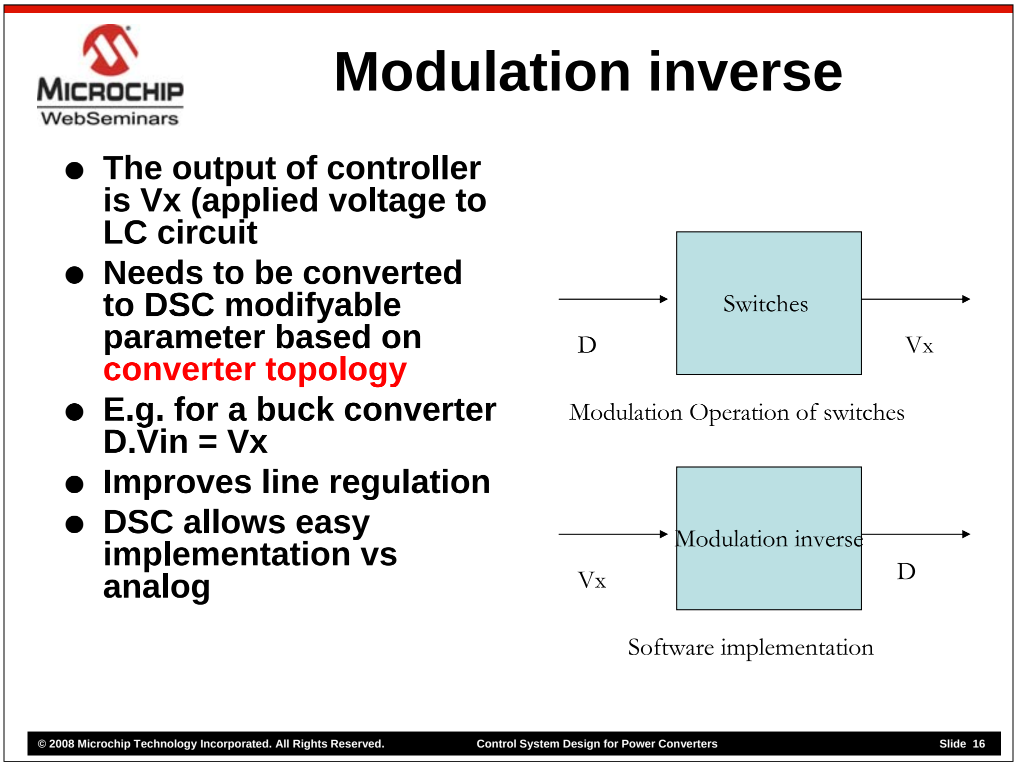
The higher the value the STIFFER the system

Different regions of the plot are determined by gains and system parameters

Higher eigen value in general tends to lift the plot

Improves with passive component size however it leads to more COST

Load decoupling WILL improve this metric



The output of controller is Vx which is the applied voltage to LC circuit

Needs to be converted to DSC modifyable parameter based on converter topology

E.g. for a buck converter D.Vin = Vx

This Improves line regulation

DSC allows easy implementation of divide vs analog which can be implemented at a low frequency

Bandwidths and eigen values

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- **Closed loop system transfer function denominator polynomial**
- **Denominator polynomial in s = characteristic equation**
- **Roots = eigen values / bandwidths**
- **Bandwidths are fixed by choice**
- **Gains are determined by reverse calculation**

Closed loop system transfer function denominator polynomial is called as the characteristic equation

Roots are known as eigen values / bandwidths

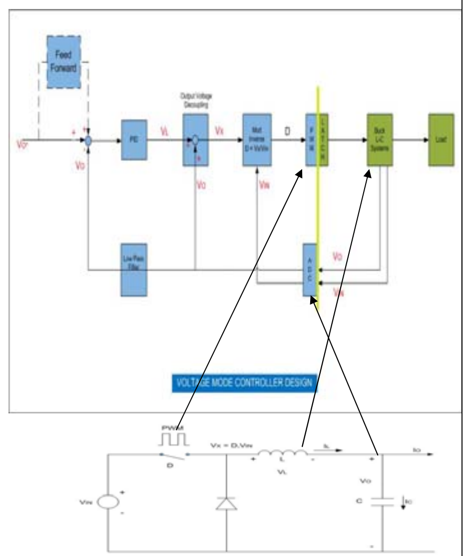
Bandwidths are fixed by choice based on system specs

Gains are determined by reverse calculation

Voltage mode control (VMC)

- Only voltage feedback. No current sensors
- LC oscillatory roots cause poor dynamics
- D term is essential => poor noise rejection
- $|Io/Vo| = (s^2LC + sKd + (Kp + 1) + Ki/s)/sL$
- $Vo/Vo^* = G/(s^2LC + sKd + (Kp + 1) + Ki/s)$

  where G is $sKd + Kp + Ki/s$



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Only voltage feedback is taken

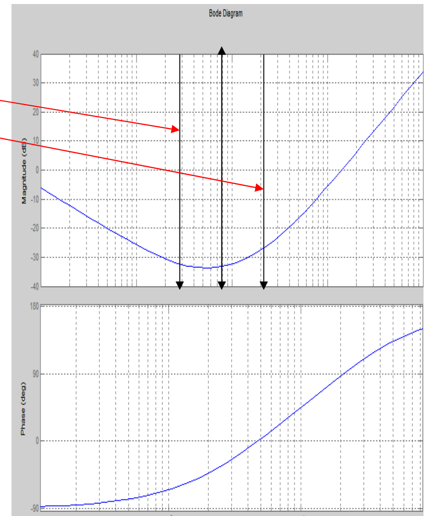
Roots are inherently oscillatory

PID controller is used for VMC to make roots non oscillatory

Typical command tracking and disturbance rejection plots

Bandwidth selection VMC

- f1, > f2, > f3 hz are 3 bandwidths of characteristic equation $(s^2LC + sKd + Kp + Ki/s) = 0$, $-2\pi f1$, $-2\pi f2$, $-2\pi f3$ are its roots
- Bandwidths are separated by a factor of 3 by choice
- f3 is determined by settling time (Ki).
- f2 is primary voltage loop BW (Kp)
- f1 is differentiated voltage loop BW (Kd)
- Determine gains by solving 3 simultaneous eqns



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f1, > f2, > f3 hz are 3 bandwidths of characteristic equation (s2LC + sKd + Kp + Ki/s) = 0 , -2pf1, -2pf2, -2pf3 are its roots

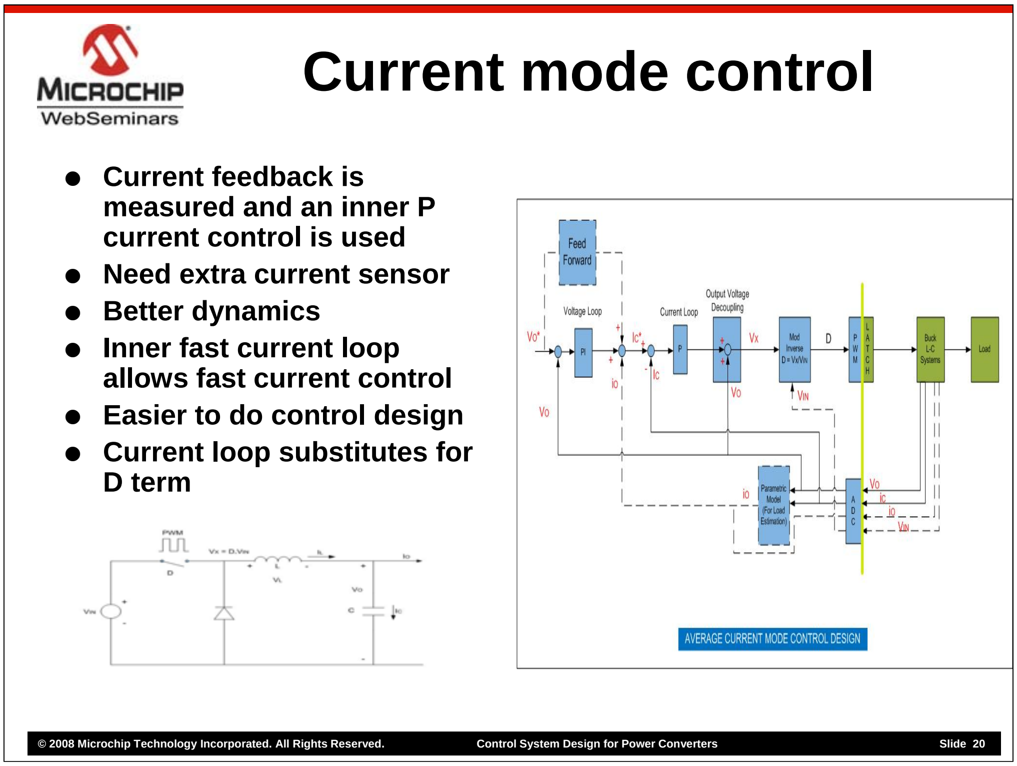
Bandwidths are separated by a factor of 3 by choice

f3 is determined by settling time (Ki).

f2 is primary voltage loop BW (Kp)

f1 is differentiated voltage loop BW (Kd)

determine gains by solving 3 simultaneous eqns



Current feedback is measured and an inner P current control is used

Current loop bandwidth is kept larger

Need extra current sensor

Better dynamics

Inner fast current loop allows fast current control

Easier to do control design

Current loop substitutes for D term

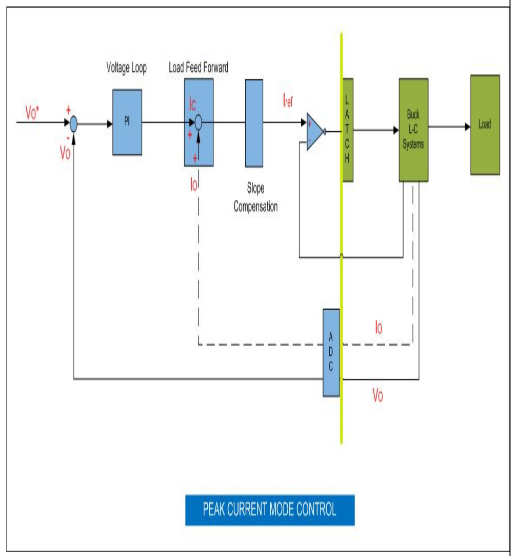
Gains are calculated from bandwidths

Peak current mode control

- Current loop implemented in hardware
- Outer PI voltage loop only sets the peak current reference
- Limits current to the reference
- Approx Ra → inf.

  Vo/Vo* = (Kp + Ki/s)/ (sC + Kp + Ki/s)

  Io(s) / Vo(s) = (sC + Kp + Ki/s)



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Peak current mode control , the current controller is implemented in hardware. Current reference is generated by outer voltage loop. The actual current is cycle by cycle current limited using a comparator to the current reference value.

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digital implementation

- Quantizers, Latches, Difference equations
- Bandwidth < $1/7^{th}$ of sampling freq
- The term Ki/s translates to
  $Ki.Ts.z^{-1}/(1-z^{-1})$
- Ensure, Ki.Ts.e is at least 1 for e> E
- Limitation of 16 bit DSC resolution. (esp . PFC)
- Normalization, Number format and saturation

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Quantizers, Latches, Difference equations need to be taken care of in modeling

Highest Bandwidth should be less than 1/7th of sampling freq

The term Ki/s translates to Ki.Ts.z-1/(1-z-1)

Ensure, Ki.Ts.e may get truncated to 0 for some value of e. If the value of e needs to lower Ts may need to be increased

Limitation of 16 bit DSC resolution. (esp . PFC)

Normalization, Number format and saturation

Thank you!