OCPA2025

POWER SUPPLY

Power Supply Group, SSRF, SARI

SHU KUN

Introduction

Why magnet power supplies?

- Most accelerator magnets are electromagnets.
  - Permanent magnets
    - Hard to change magnetic field dynamically.
    - Sensitive to temperature, external magnetic field, electromagnetic interference, radiation, mechanical shock and vibration …
    - Hard to manufacture, assembly, compensation.
    - High magnetic fields make installation and maintenance difficult.
    - Hard to achieve very high field strength compared to superconducting magnets.
    - Cost, volume, weight …
    - Yet still suitable in certain circumstances: small medical accelerators, insert devices like undulators…

- Transfer electrical energy from the grid to the magnets

Power supplies in daily life

Lab PS ⇨ adjustable current or voltage output

Computer PS ⇨ several fixed voltage

Switching PS ⇨ 1 or 2 fixed voltage

Outdoor PS ⇨ store energy, AC voltage output

Can be used as accelerator PS?

Power, Stability, Reliability

Larger energy

⇩

larger power   Main magnet power: 1 ~ 10kA, 0.1 ~ 2kV   Often dozens of output current / voltage

Orbit stability
Beam quality, brightness,
stability, loss …

VS

⇩

Higher stability   Current stability: $10^{-4} \sim 10^{-5}$ Around 10^{-3} (line regulation)

$MTBF_{single}$ = 10 year

⇩ 1000 devices

Sadly, a power supply failure almost always leads to accelerator failure

$MTBF_{system} = 1/\lambda_{system} = 1/(1000*\lambda_{single}) = 0.01$ year ⇨ System failure: 100 times every year!

More devices ⇨ Higher reliability

Outline

1	History and Classification	A brief history of acclerator magnet power supply
2	Terms and Definition	Key performance indexes and why these matter
3	Priciples of MPS Design	Power electronics devices and PS basic topologies
4	Theory of PS Control	Basic classical control design methods in SMPS
5	Control Hardware and Software	Digital control architecture and key devices
6	Challenges and Developments	Some new techniques in topology, control, ...

We will focus on DC power supplies

History of MPS

Rotary converters and motor-generator sets

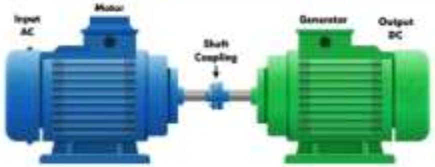
IGBT, MOSFET
Digital Regulation

SiC, GaN
AI-enhanced control

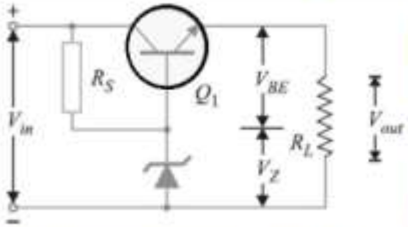
1930 ~ 1950s | **1950 ~ 1960s** | **1970 ~ 1980s** | **1990 ~ 2000s** | **2010 ~ present**

SCRs, Transistorized regulators

Resonant converter
Digital Signal Processor



Cockcroft-Walton accelerator, 1932



SLAC linac, 1966

Femilab Tevatron, 1983

LHC 13kA power converter

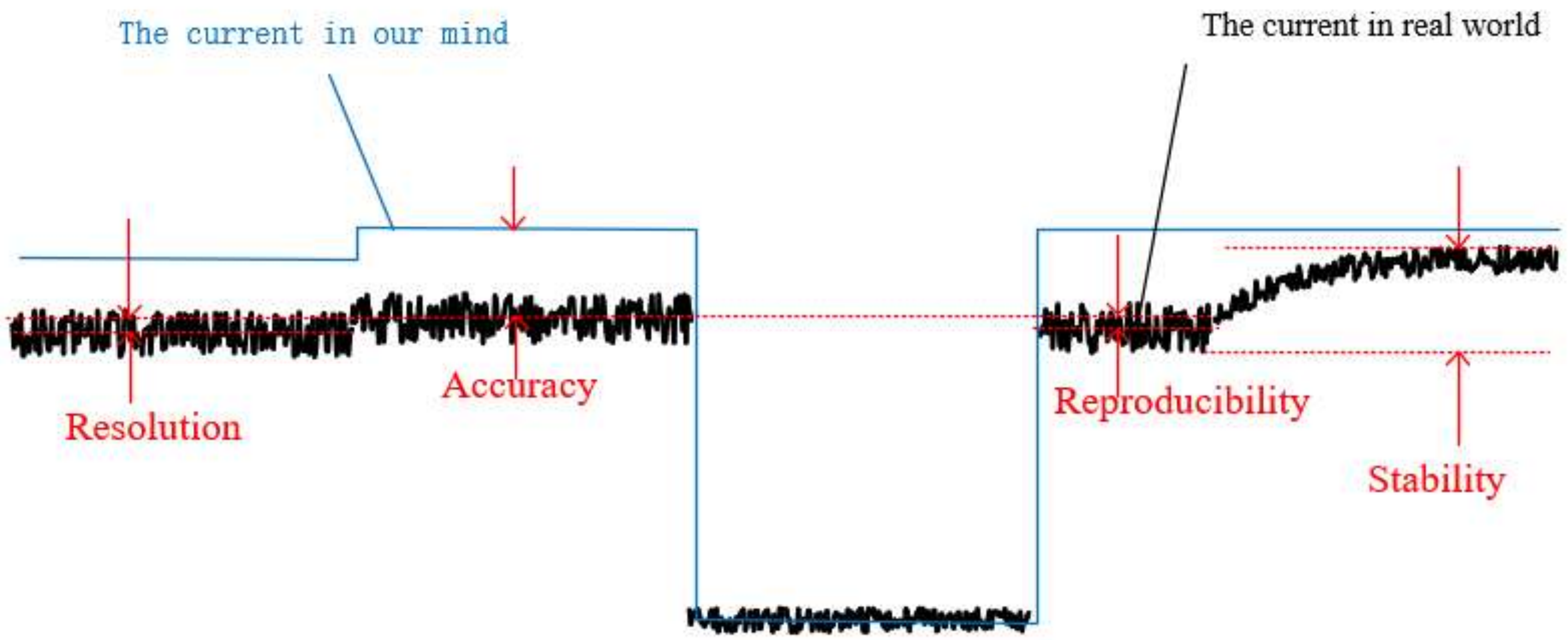
Semiconductors: SCR -> BJT -> MOSFET -> IGBT -> SiC/GaN
Control systems: Analog -> Digital (DSP/FPGA) -> AI-Enhanced

MPS Classifications

- By output current type
  - DC MPS: Stable DC current output for static magnetic field (e.g., transfer line, storage ring)
  - Ramped MPS: Time-varying, waveform output for particle acceleration (e.g., synchrotron cycling, booster ring)
  - Pulsed MPS: Short high-energy pulses (μs-ms) for kicker/septum magnets
- By Power rating
  - Low: <100A, <100V, for correctors, small quadrupoles
  - Medium: 100A-1kA, 100V-1kV, standard dipole/quadrupoles
  - High: 1-10kA, 1-10kV, main magnets in large synchrotrons
  - Ultra-High: >10kA, >10kV, LHC superconducting magnets, fusion device
- By Topology
  - Linear PS: transistor (BJT or MOSFET) acts as a variable resistor
  - Switching-mode PS: transistors (MOSFETs or IGNTs …) act as electronic switches

Terms and Definition

- Precision
  - Accuracy: the absolute bias from the value “in our mind”
  - Stability: the range the value vibrates between
  - Reproducibility: the difference among operations
  - Resolution: the smallest step that makes any difference



- Accuracy

  The closeness of agreement between the measured value and the reference value.
- Stability

  The maximum deviation over a period with no changes in operating conditions.
- Reproducibility

  The uncertainty in returning to a set of previous working values from cycle to cycle of the machines.
- Resolution

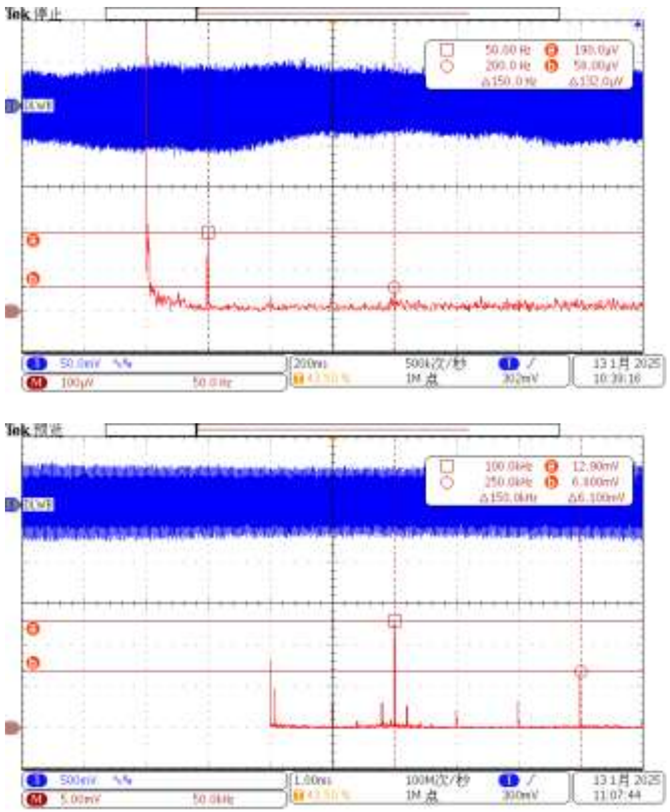
  The smallest increment that can be induced or discerned.

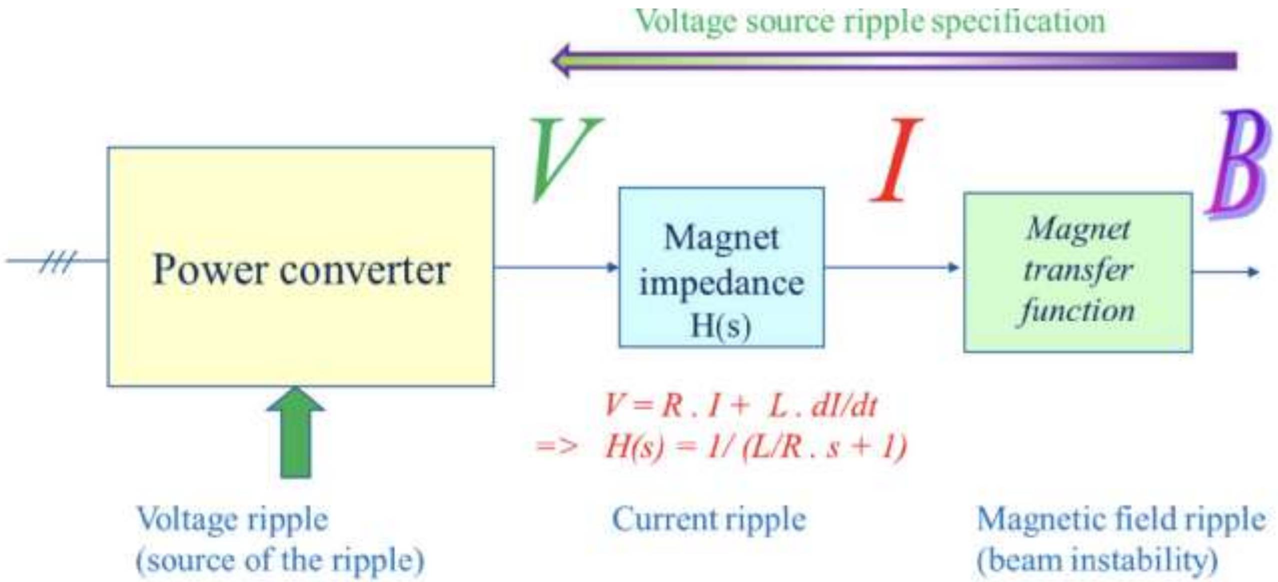
These terms are expressed in ppm of the nominal current.

Part Per Million = $10^{-6} \approx 2^{-20}$ (20 bit)

- Ripples

  Ripple current or voltage refers to the harmonic components in the current or voltage, which can cause variations in their amplitude.





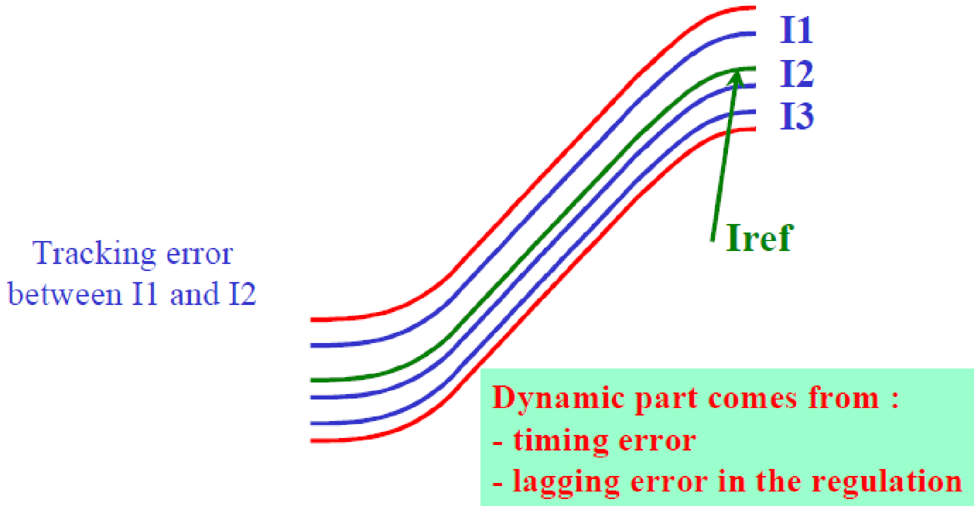
Ripple measurement: direct or indirect $I = \frac{U}{Z} = \frac{U}{2\pi f L + R}$

- Dynamic terms
  - Tracking Error: the maximum deviation in one cycle
  - Total Harmonic Distortion: the percentage of the total harmonic content relative to the fundamental.

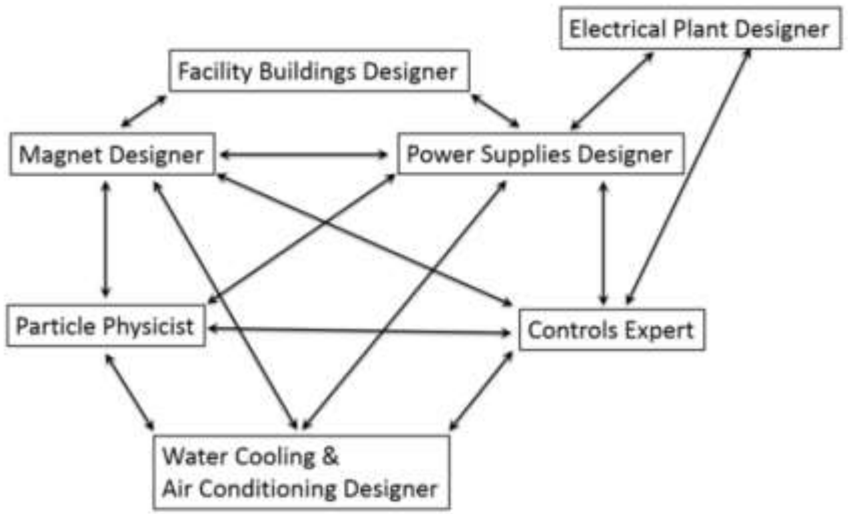
$$THD = \frac{\sqrt{I_1^2+I_2^2+\cdots I_n^2}}{I_0} \times 100\%$$

I_0: the RMS value of the fundamental harmonic

I_n: the RMS value of the n^{th}-order harmonic



A typical magnet power supply specification



Role in the system

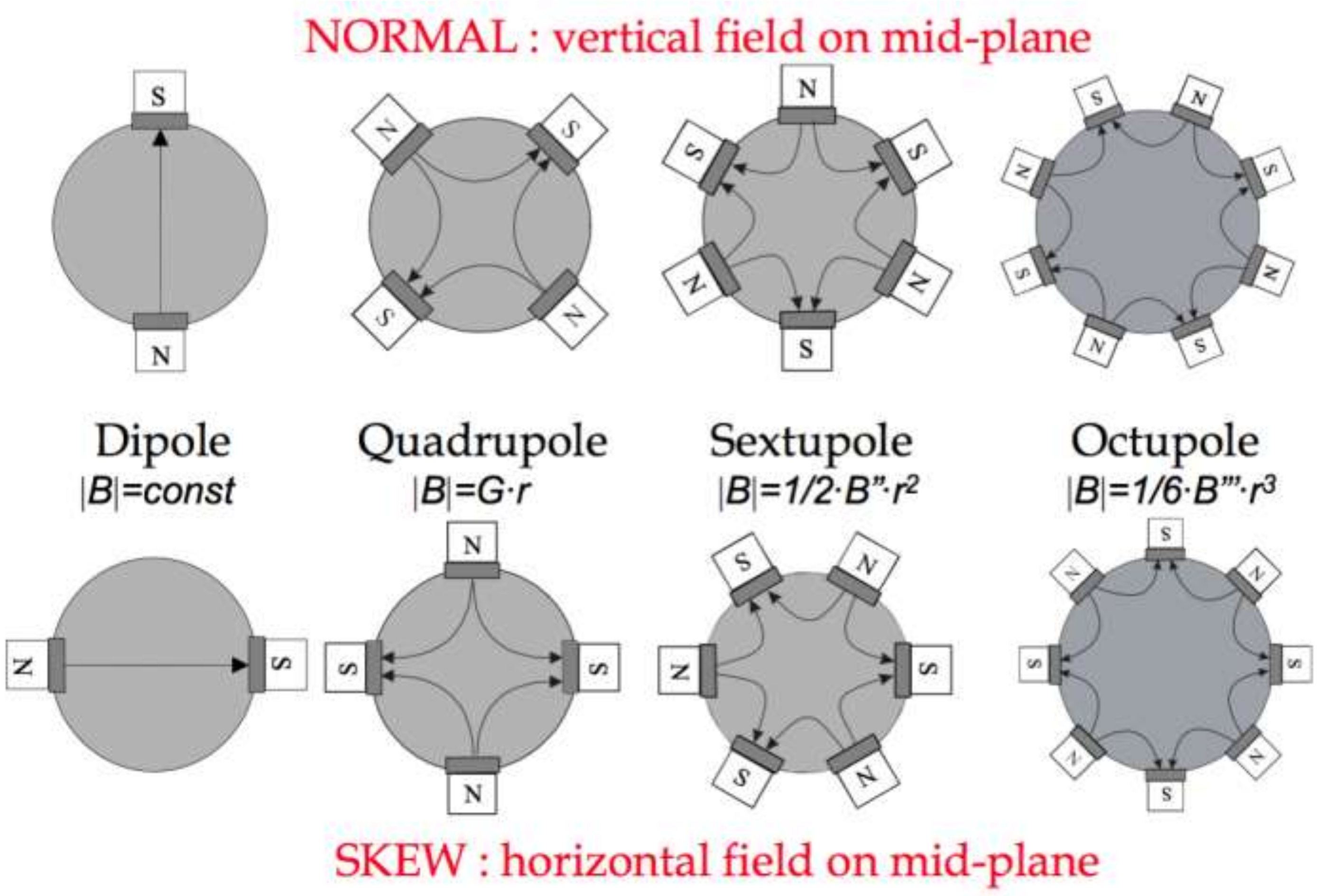
Main Dipole Power Supply Specifications

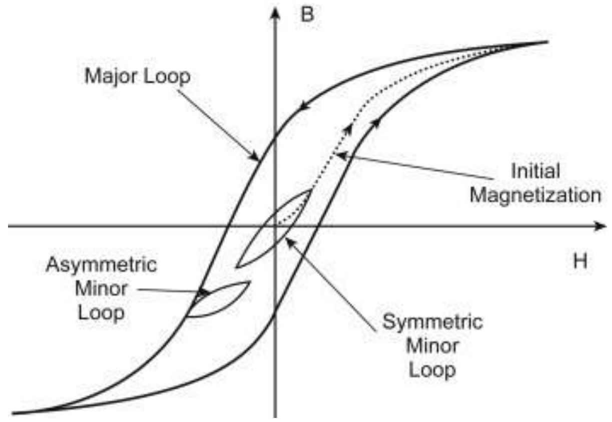
AC input power	3-phase 460 VAC ~683 AAC
DC maximum output current – Imax	450 ADC
DC minimum output current – Imin	~1 ADC
DC output voltage	1100 VDC
operating quadrants	2: (V+, I+) & (V-, I+)
small-signal – 3 db bandwidth	500 Hz
stability (8 h–10 s) – referred to Imax	40 ppm
stability (10s–300 ms) – referred to Imax	20 ppm
stability (300 ms–0 ms) – referred to Imax	10 ppm
absolute accuracy – referred to Imax	100 ppm
reproducibility long term – referred to Imax	50 ppm
current ripple – referred to Imax	5 ppm 60 Hz and greater
resolution of reference current	18 bit ±1 LSB
resolution of current measured – fast sampling	16 bit ±1 LSB at 200 μsec
resolution of current measured – slow sampling	22 bit ±1 LSB at 16.67 msec

From NSLSII

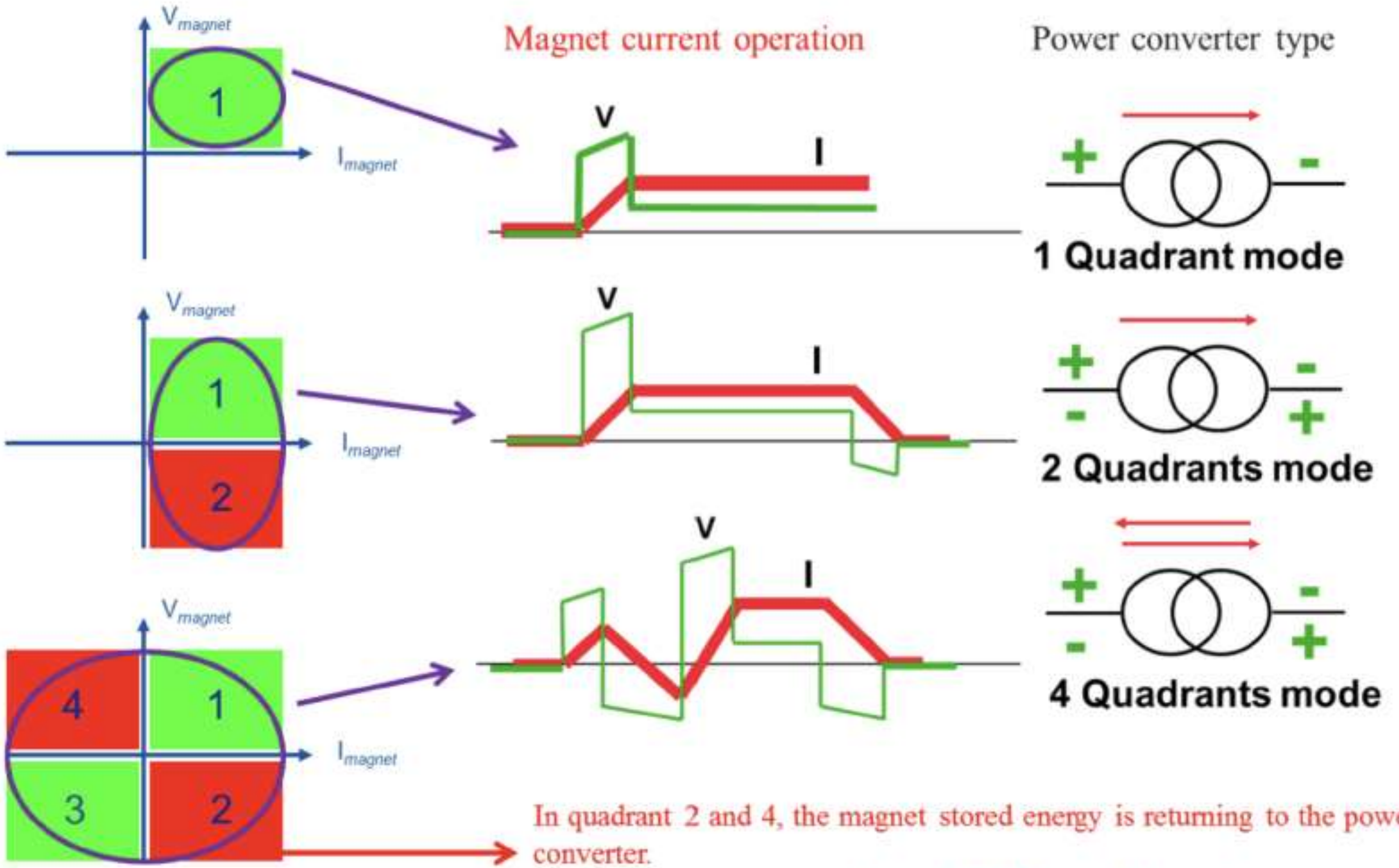
Principles of MPS Design

Load magnets





Operation



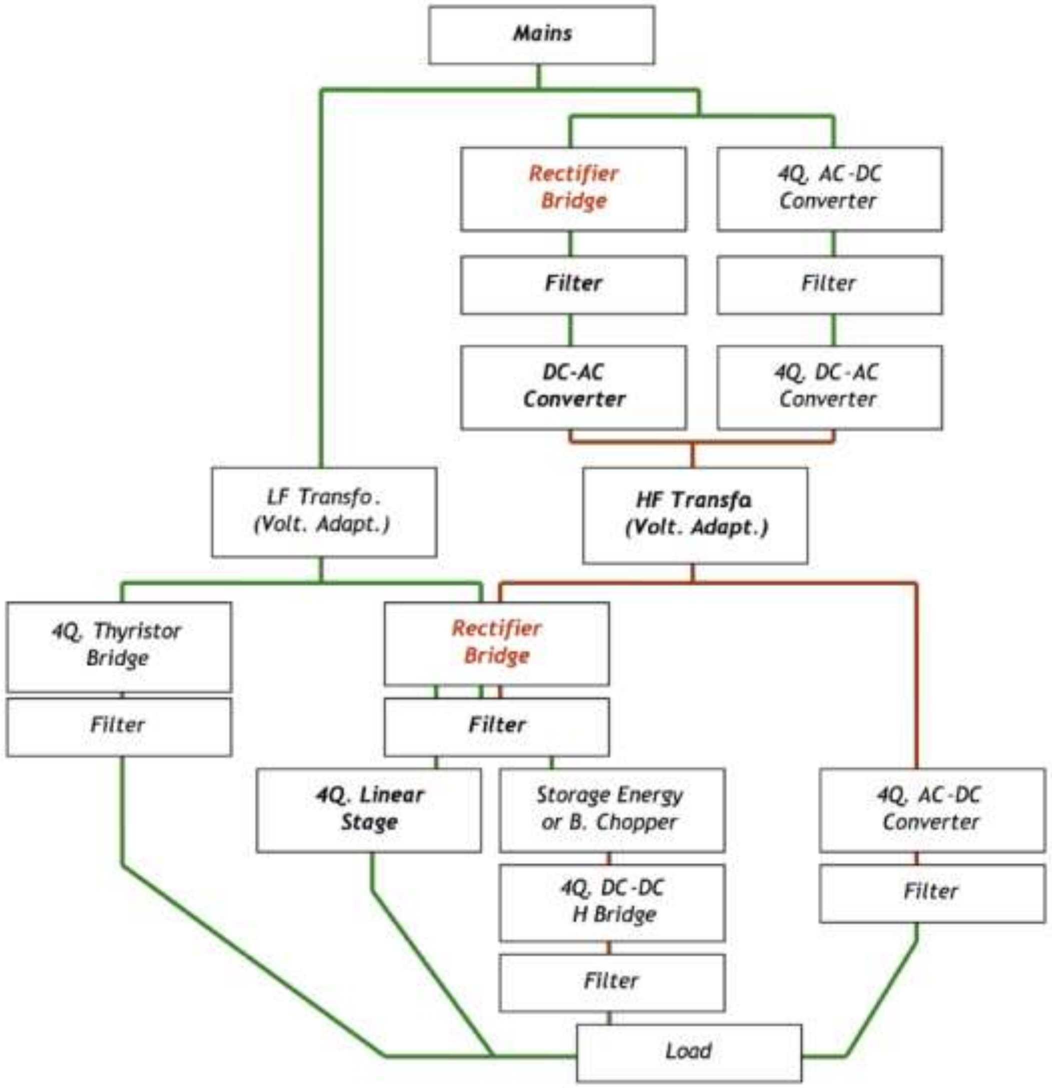
In quadrant 2 and 4, the magnet stored energy is returning to the power converter.

$$E_{magnet} = 0.5 * L_{magnet} * I_{magnet}^2$$

Topology

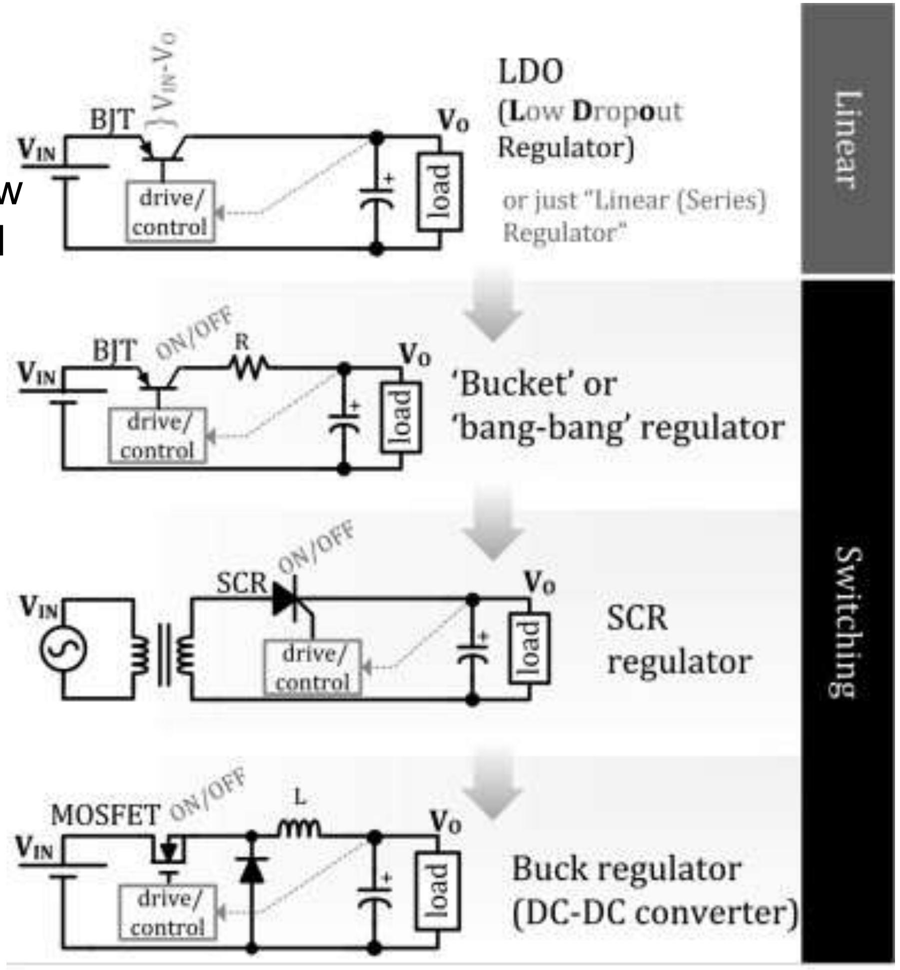
How much voltage and current?
How accurate needed?
Bipolar voltage/current?
How many stages in topology?
Linear or Switching?
A proper topology for each stage

- Buck
- Boost
- Buck-Boost
- Flyback
- LLC
- Full Bridge
- H-Bridge
- Cuk
- SEPIC
- …



Linear and Switching PS

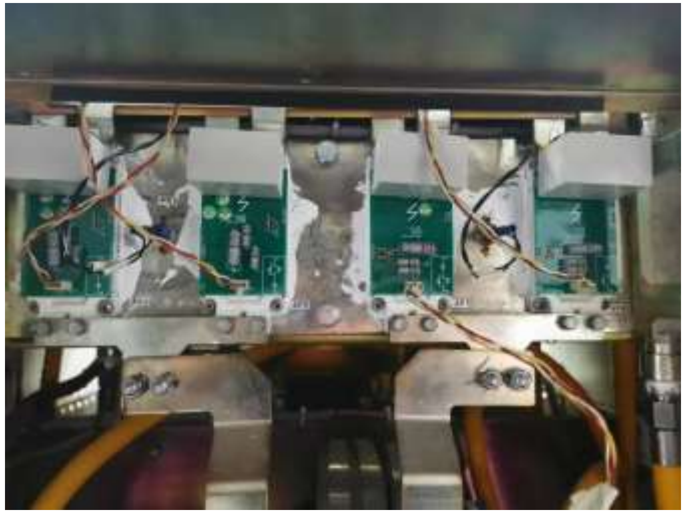
Still good when ultra low noise needed



BJT= Bipolar Junction Transistor
SCR= Silicon-controlled Rectifier
MOSFET= Metal Oxide Semiconductor Field-Effect Transistor

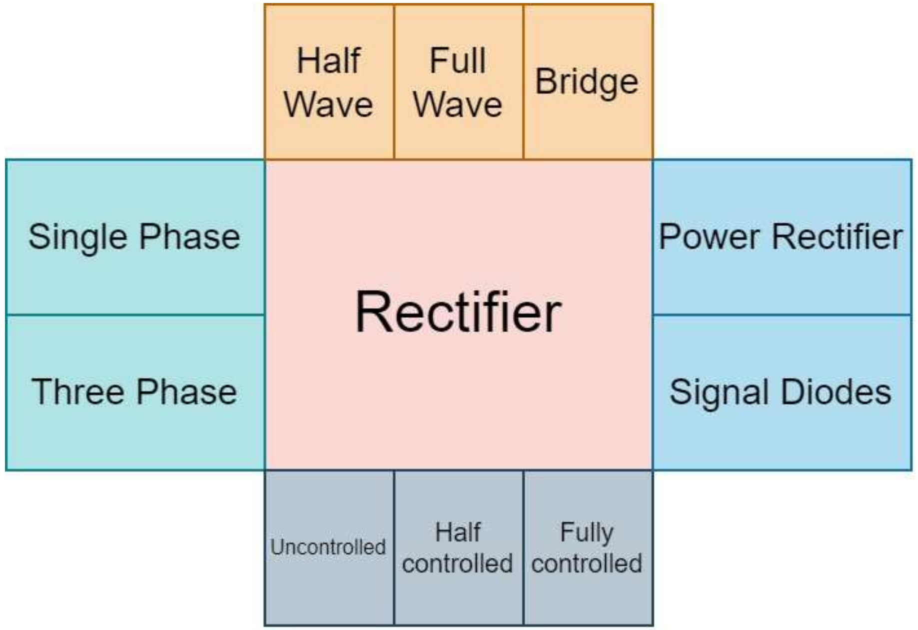
Factor	Linear PS	Switching PS
Efficiency	Low	High
Size/Weight	Large	Compact
Noise/Ripple	Very low	Requires Filtering
Cost	Low	Medium/High
In-Out Isolation	Not supported	Supported

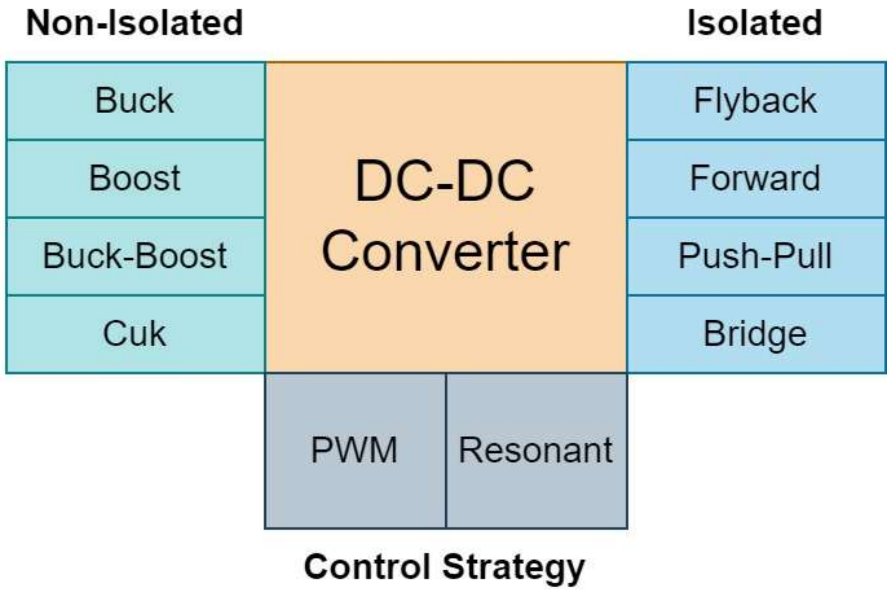
LRTs and heatsink



IGBTs and water-cooling plate

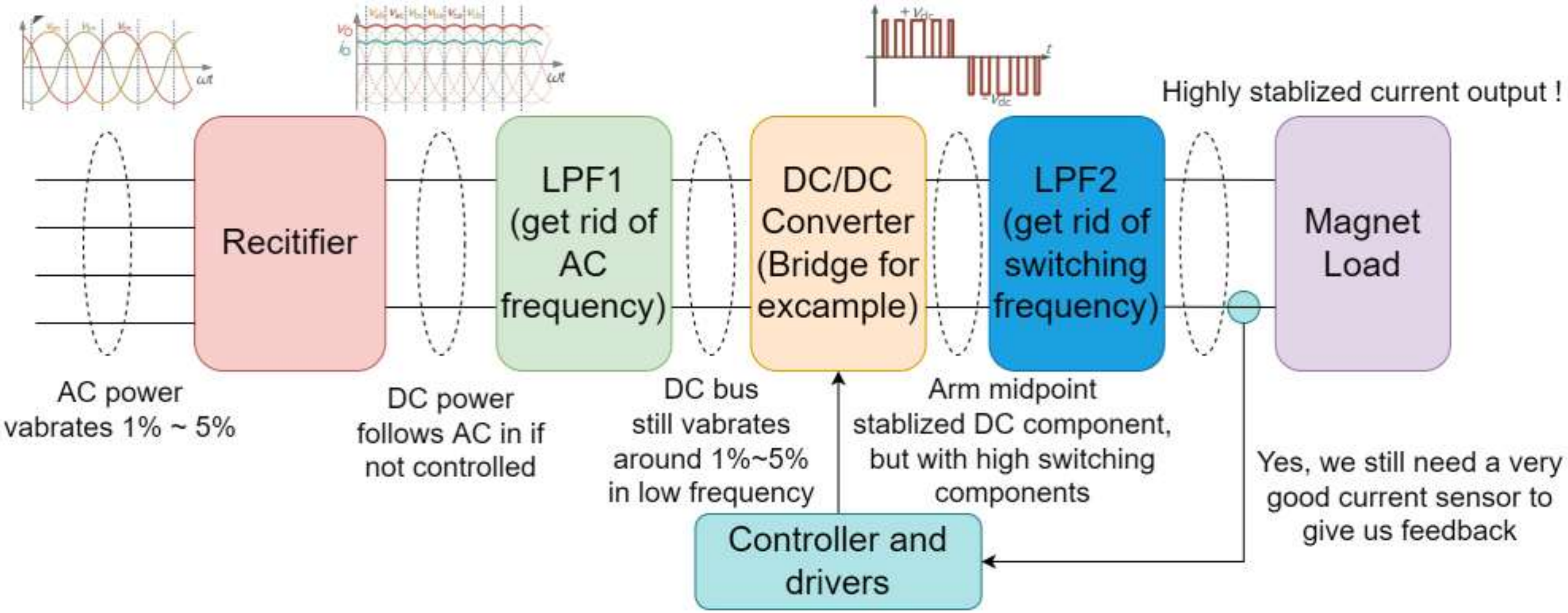
Summary





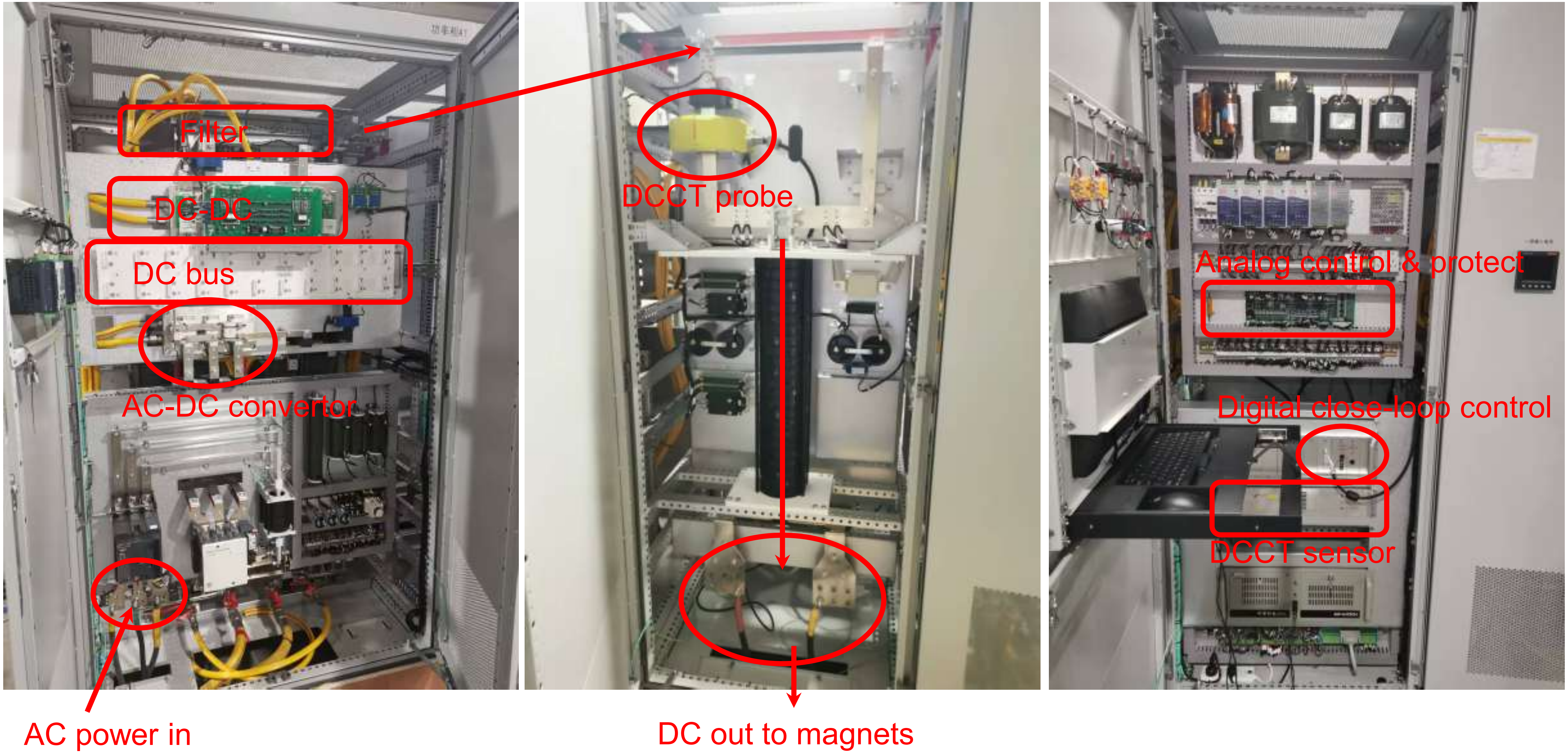
We can choose our design in them according to different specifications.

An Example

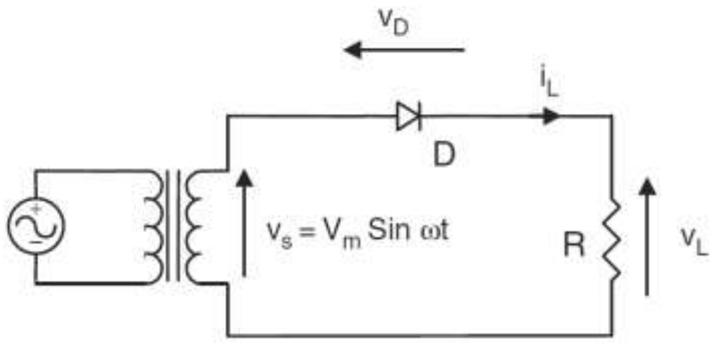


Grid Voltages and Tolerance			
Region	Single-Phase	Three-Phase	Tolerance Range
China	220V	380V	+7/-10%
US	120V	480V	±5% (Class A)
Europe	230V	400V	±10%
Japan	100V	200V	+6%/-10%
Thailand	230V	400V	±5%

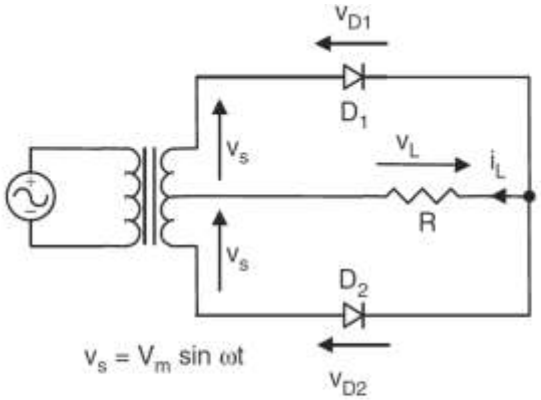
What it may look like



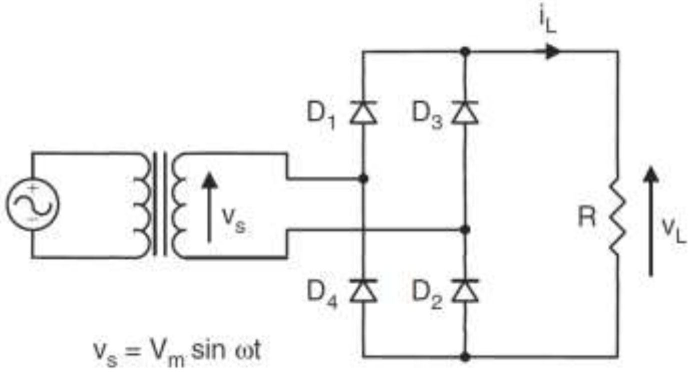
Common AC-DC topology



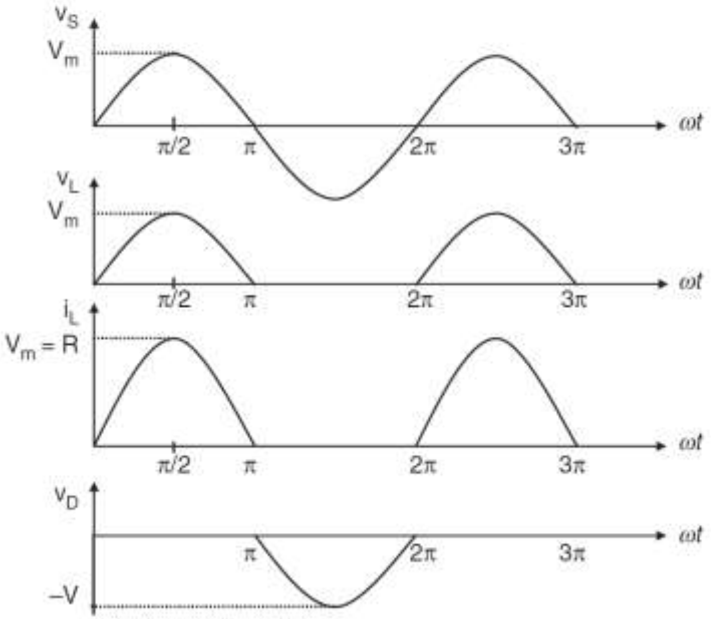
Single-phase, half-wave

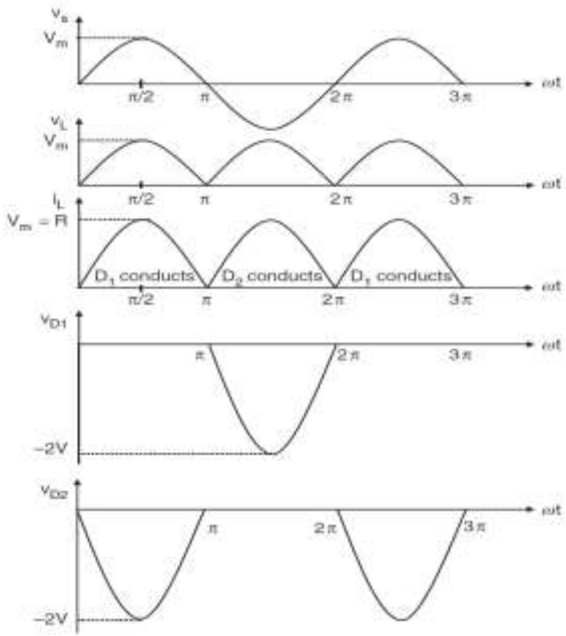


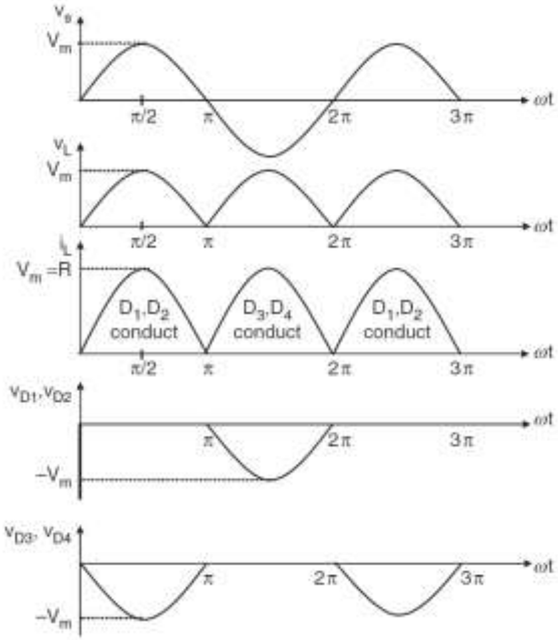
Single-phase, full-wave



Single-phase, bridge



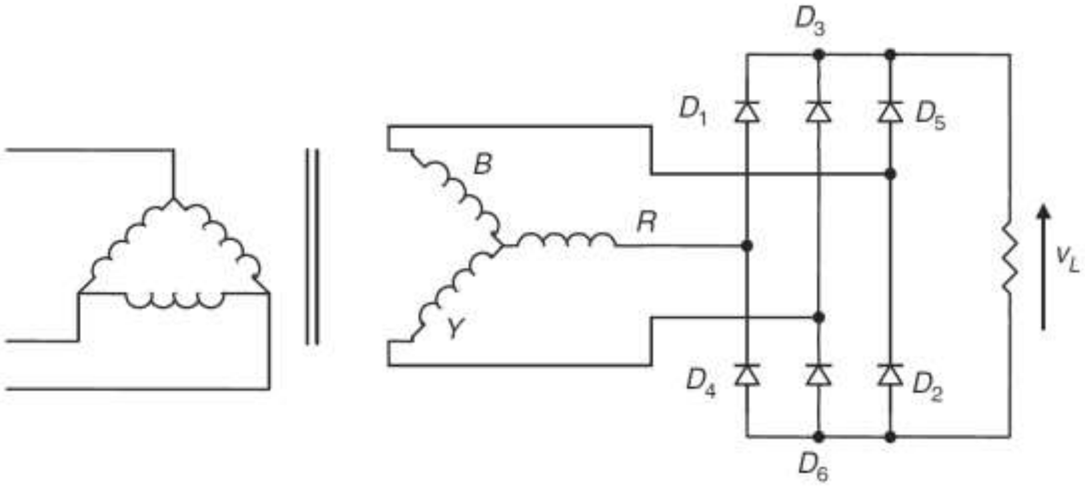


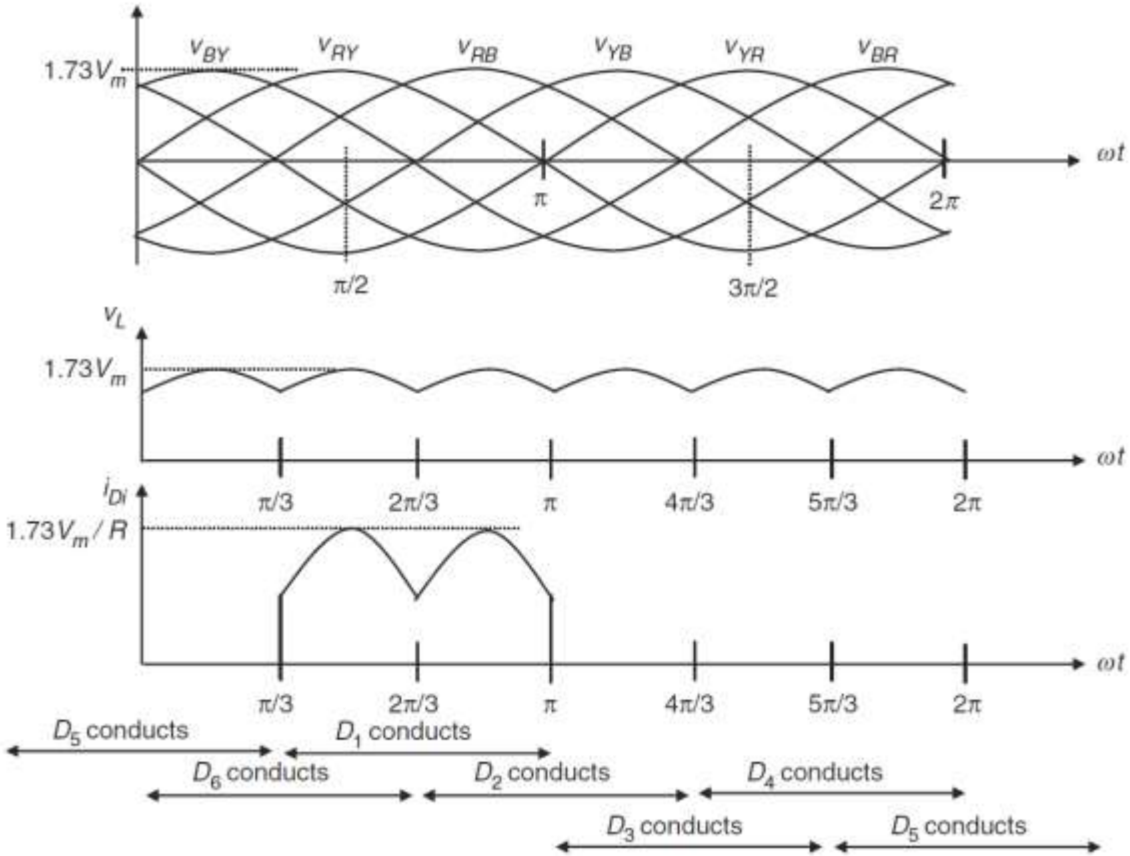


$$V_O = V_{avg} = \frac{1}{2\pi}\int_0^{\pi} V_m \sin(\omega t)\, d(\omega t) = \frac{V_m}{\pi}$$

$$V_O = \frac{1}{\pi}\int_0^{\pi} V_m \sin(\omega t)\, d(\omega t) = \frac{2V_m}{\pi}$$

Common AC-DC topology





Three-phase, bridge

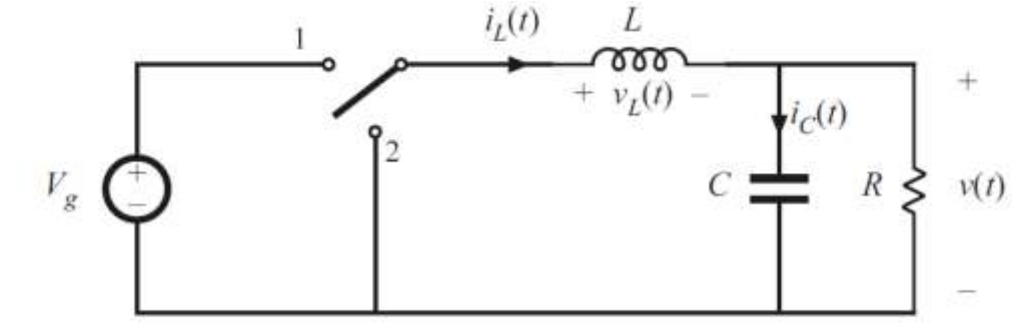
$$V_O = \frac{1}{\pi/3}\int_{\pi/3}^{2\pi/3} \sqrt{3}V_m sin\omega t d(\omega t) = \frac{3\sqrt{3}}{\pi}V_m$$

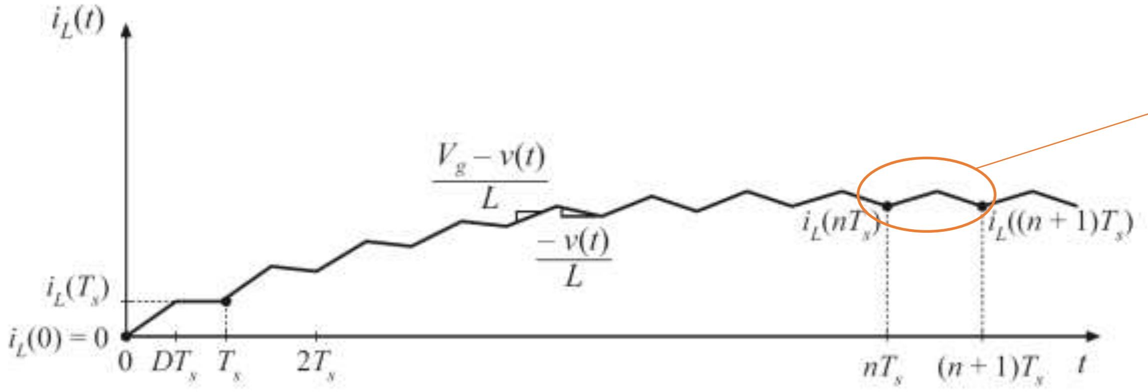
Common AC-DC devices

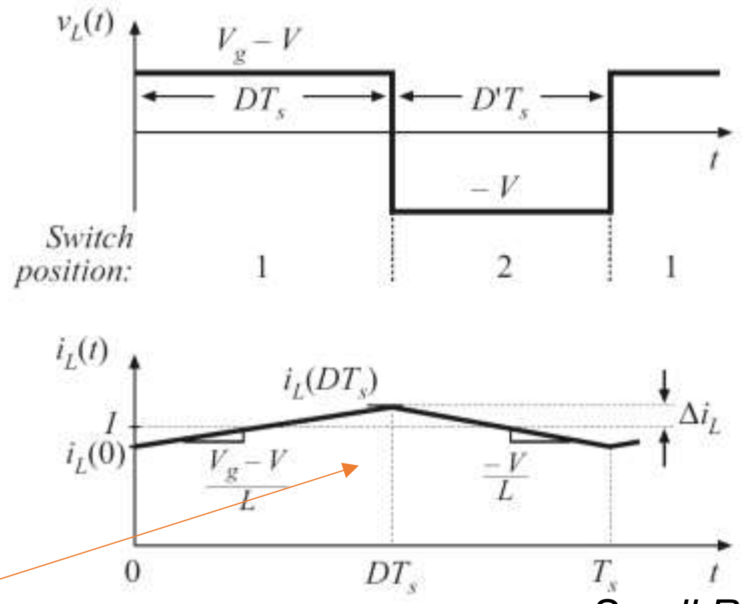
or

Common DC-DC topology

Buck Converter







Small Ripple Assumption

On: $\frac{di_L}{dt} = \frac{V_{g-v(t)}}{L} = \frac{V_g - V}{L}$

Off: $\frac{di_L}{dt} = \frac{-V}{L}$

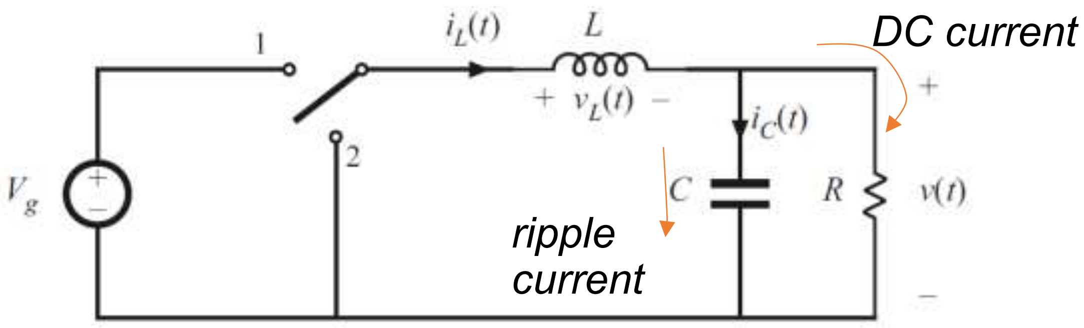
Steady-State Condition: $\frac{V_g - V}{L} \times DT_s = \frac{V}{L} \times (1 - D)T_s$

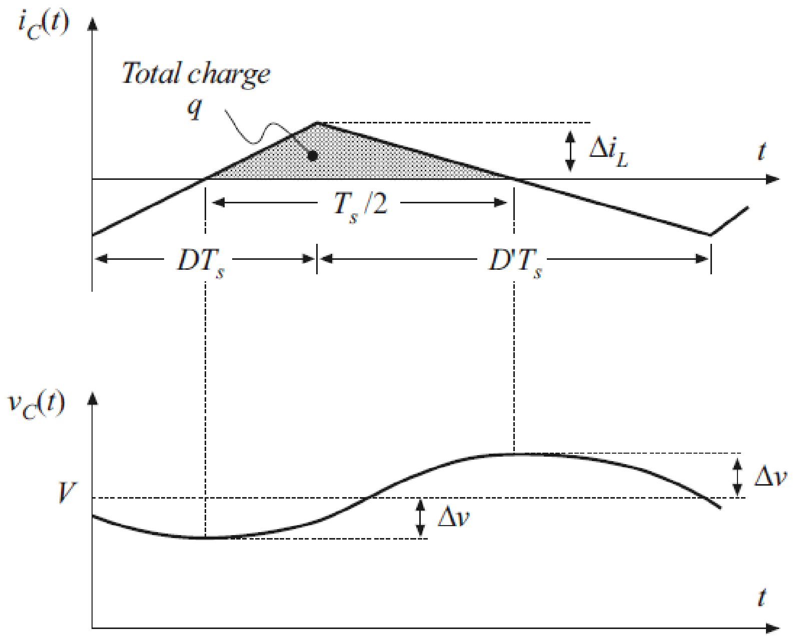
$(V_g - V)DT_s = V(1 - D)T_s$ $\quad \frac{V}{V_g} = D$ *Change D to adjust Vo*

$L = \frac{V_g - V}{\Delta I_L} \times DT_s$ *Choose L to limit current ripple*

Common DC-DC topology

Buck Converter





$$q = \frac{1}{2}\Delta i_L \frac{T_s}{2} = C(2\Delta v)$$

$$\Delta v = \frac{1}{2}\Delta V = \frac{\Delta i_L T_s}{8C} = \frac{\Delta I_L Ts}{16C}$$

Choose C to limit voltage ripple

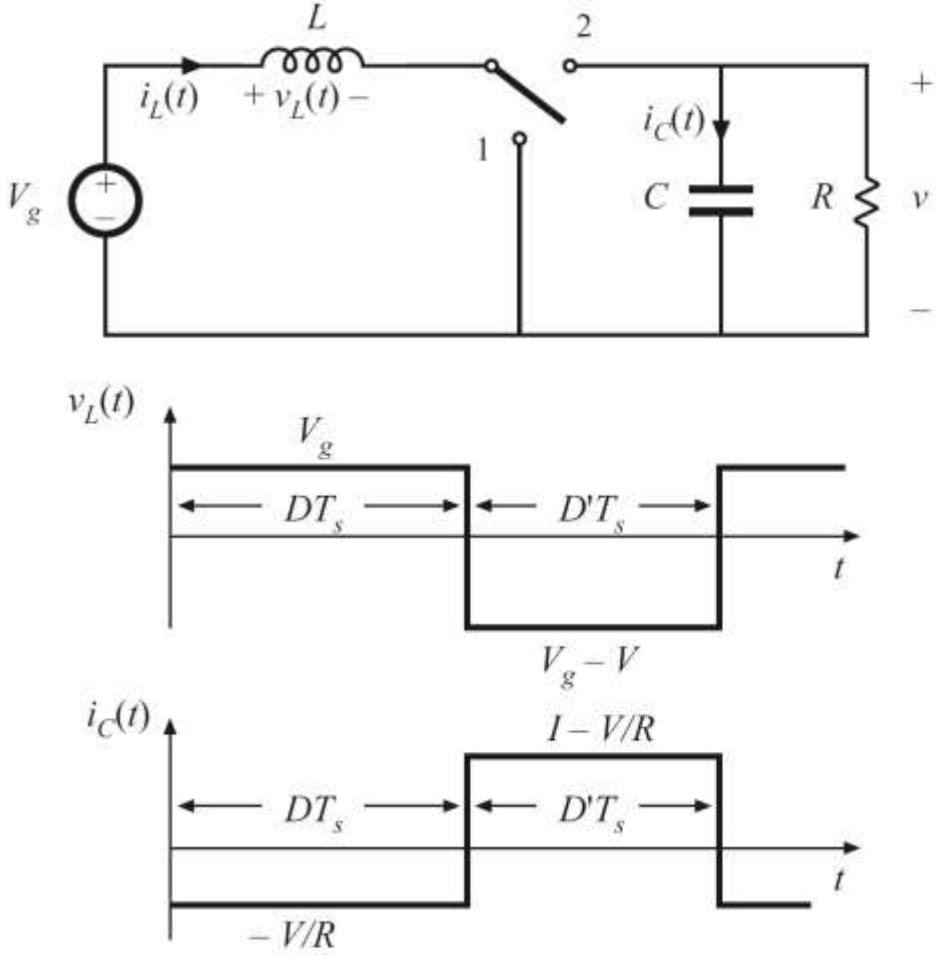
Remember:

1. Low Ripple assumption
   - v(t) can be treated as constant V
   - All the ripple current flows to capacitor, so capacitor current is the same as inductor current without DC component.

2. Steady-State condition
   - $\int_{Tpwm} v_L(t) = 0$
   - $\int_{Tpwm} i_C(t) = 0$

Common DC-DC topology

Boost Converter



On: $v_L(t) = V_g, i_C(t) = -\frac{V}{R}$

Off: $v_L(t) = V_g - V, i_C(t) = i_L(t) - \frac{V}{R} = I - \frac{V}{R}$

Steady-State Condition:

$$V_g \times DT_s = -(V_g - V)D'T_s$$

$$\Rightarrow \frac{V}{V_g} = \frac{1}{D'}$$

$$\frac{V}{R} \times DT_s = \left(I - \frac{V}{R}\right) D'T_s$$

$$\Rightarrow I = \frac{V_g}{R}\frac{1}{D'^2}$$

LC estimation:

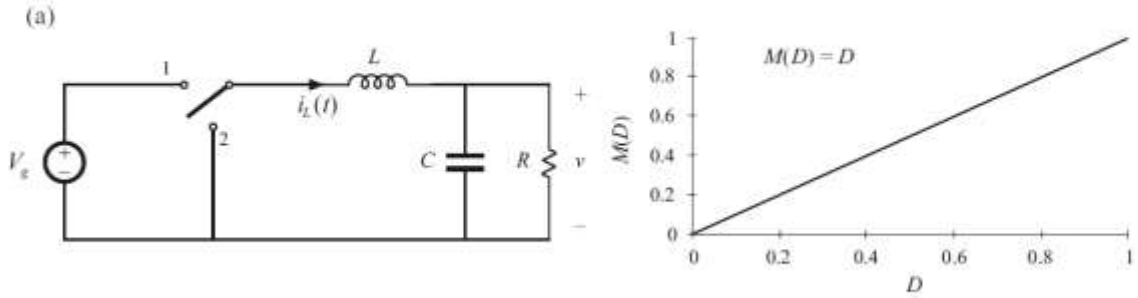
$L = \frac{V_g}{\Delta I_L} DT_s$, ΔI_L : peak-to-peak current ripple

$C = \frac{V}{R\Delta V_C} DT_s, \Delta V_C$: peak-to-peak voltage ripple

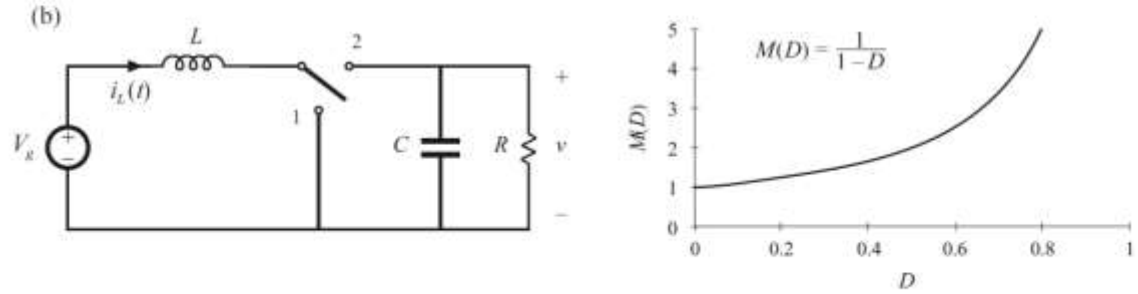
Common DC-DC topology

Basic DC-DC Converters

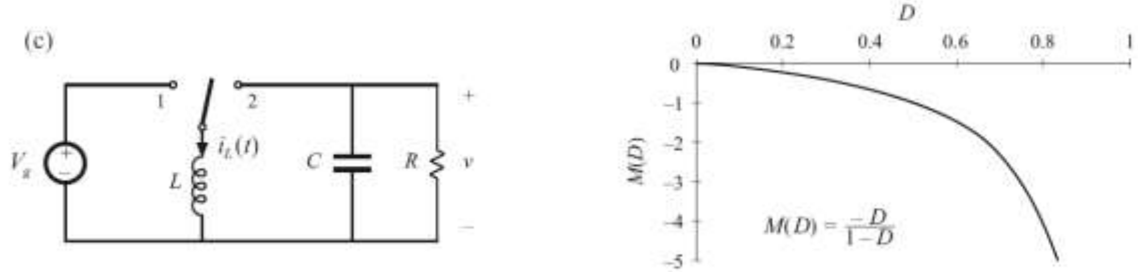
Buck: Vout < Vin



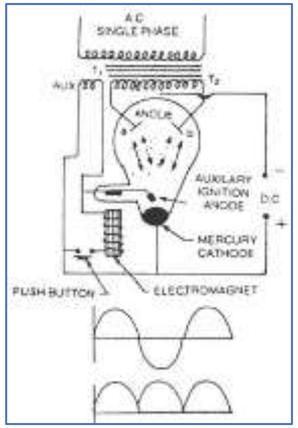
Boost: Vout > Vin



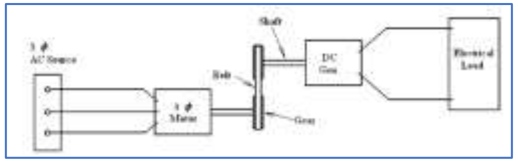
Buck-Boost: Vout < or > Vin



Power Electronic Devices

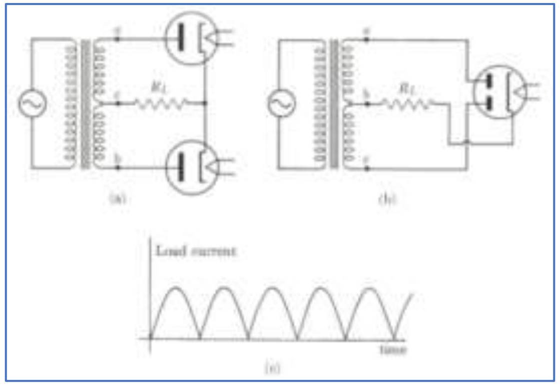


Mercury Arc Rectifier (1902)



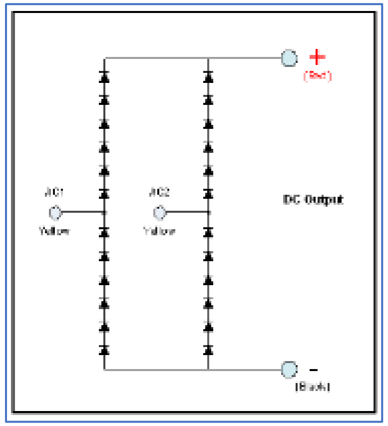
Motor-Generator Sets

(Still used when rugged and robust conversion is required)



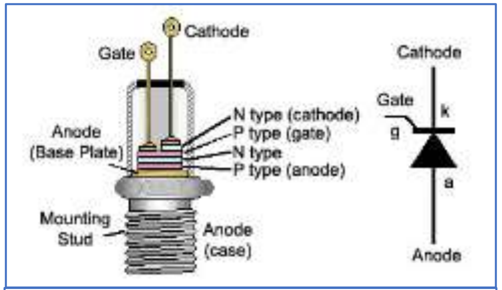
Vacuum Tube Rectifiers

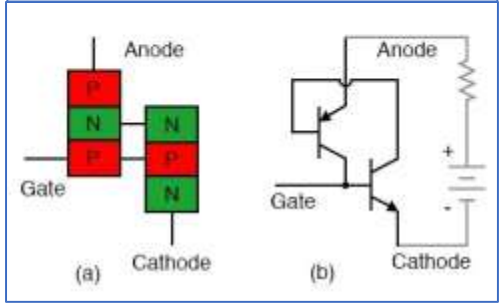
(1920s, Very high voltage capacity)



Selenium Rectifiers

(1930s)





SCR/Thyristor (1957)

IEEE Milestone

Anode: from Greek words, "Way up", positive charge comes in

Cathode: "Way down"

Thyristor: "door" + "transformer" ("Thyri-" ← Greek word "thyreos")

Rectify: to make something right, (Alternating to Direct)

Diode

V_B: Reverse Breakdown Voltage

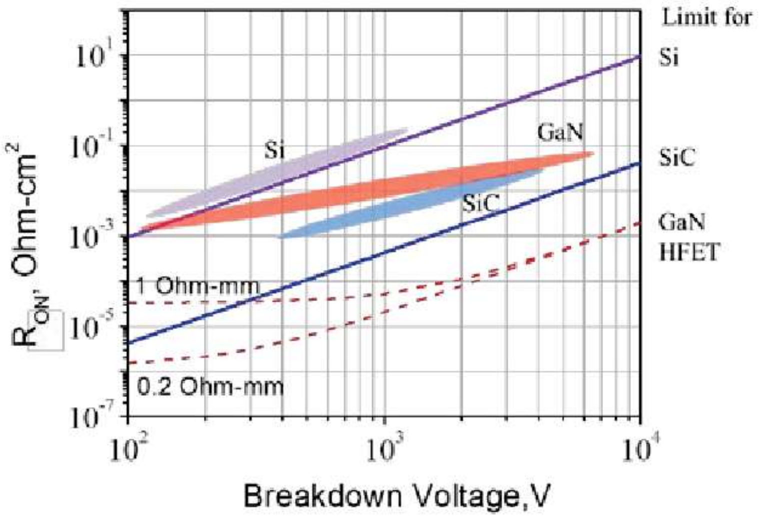
i_R: Reverse (Leakage) Current

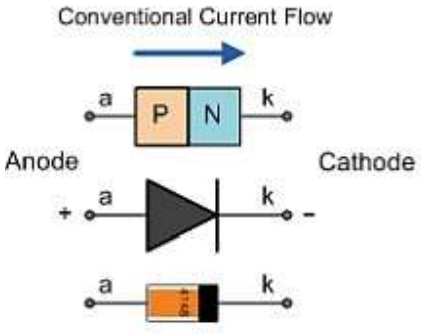
V_F: Forward Voltage Drop

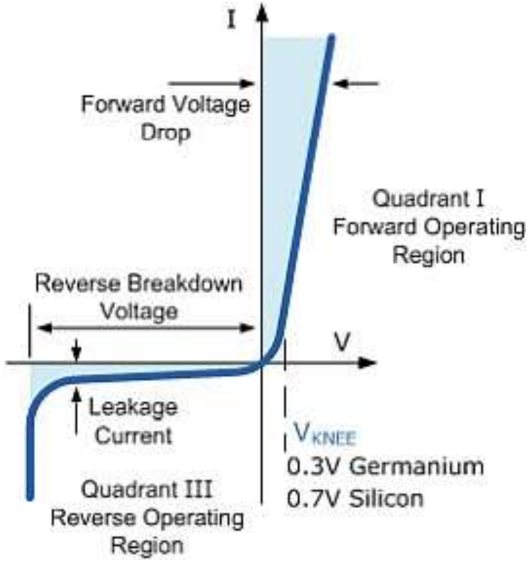
V_{TO}: Threshold Voltage

V_{KNEE}: Knee Voltage

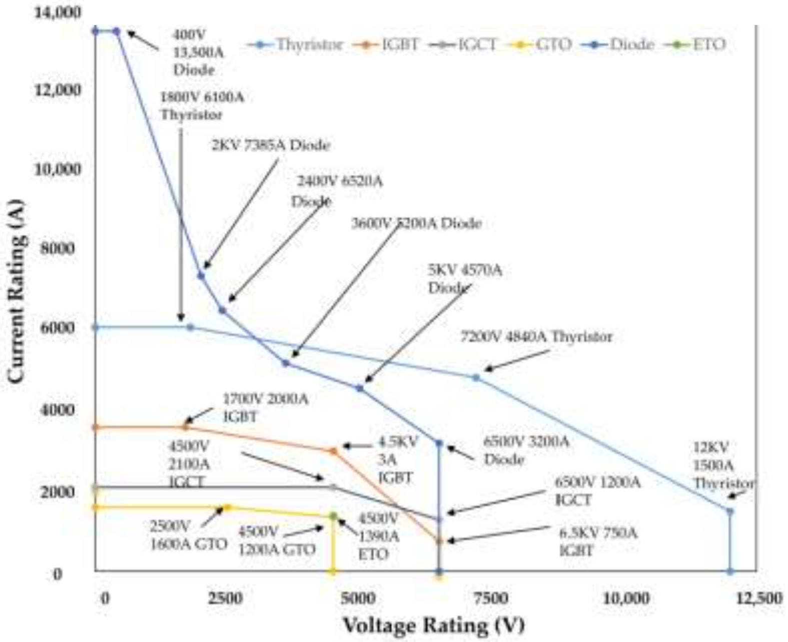
i_F: Forward Current



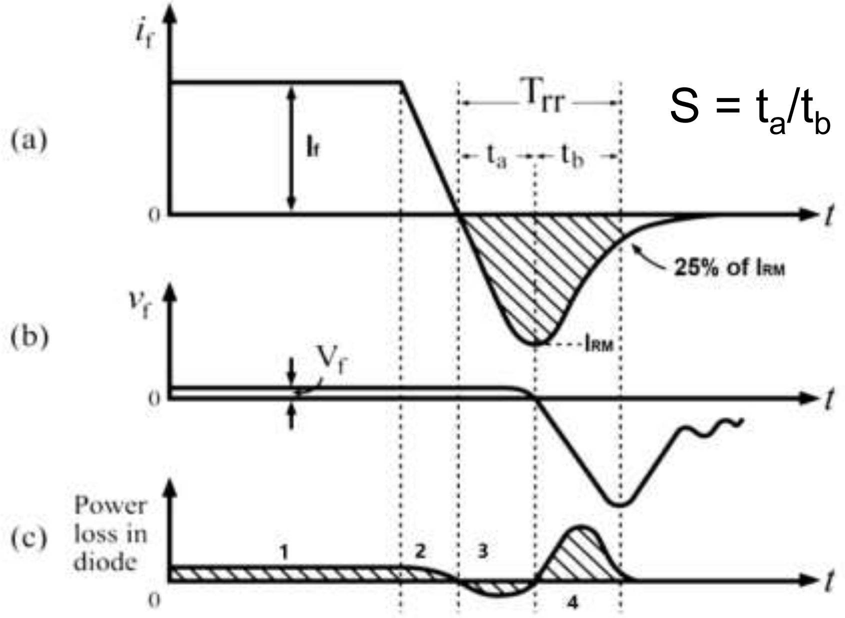




Silicon Diode and its V-I Characteristics



Diode Power Loss



$S = t_a/t_b$

1. Diode is ON

   Loss due to forward current and R_{on}

2. Diode is ON

   Forward current dropping, voltage dropping too (but very little)

3. The charge from the depletion region is removed

   V_f not blocked, until the minority carriers are exhausted at t_a, when the diode reverse-recovery current reaches the negative maximum I_{RM}

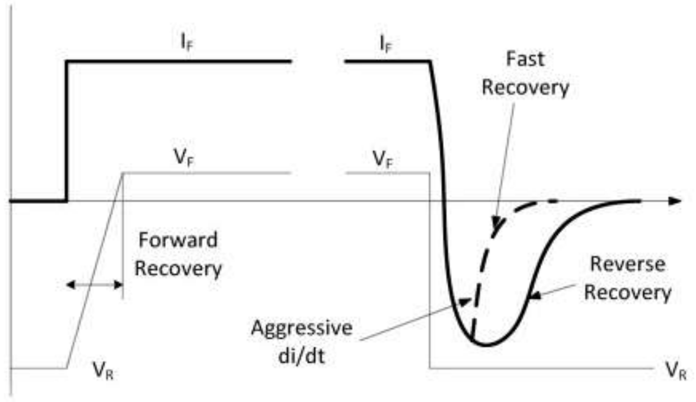
4. The diode blocks negative voltage and the reverse current continues to flow to charge the body diode depletion capacitance.

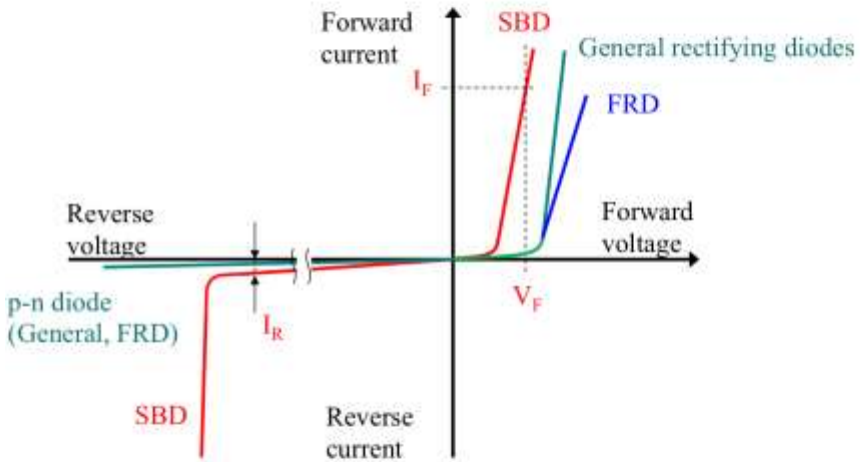
Conduction loss increases with forward current (or “working current”)

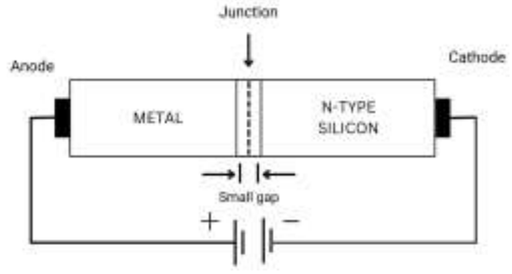
Switching loss increases with switching frequency

How to choose

- Rectifier Diode
  - Normal recovery or soft recovery (S > 1)
  - T_{rr} ~ μs
  - Normally used in rectifier
- Fast Recovery Diode
  - T_{rr} < 1 μs, Super fast recovery diode < 0.1 μs
  - Serves as a freewheeling diode for switching devices, maintaining inductive load operation
- Schottky Barrier Diode
  - Formed by metal-N-type semiconductor junction, only majority carriers participate in conduction
  - No recovery charge
  - Low V_f
  - Limited to low-voltage applications

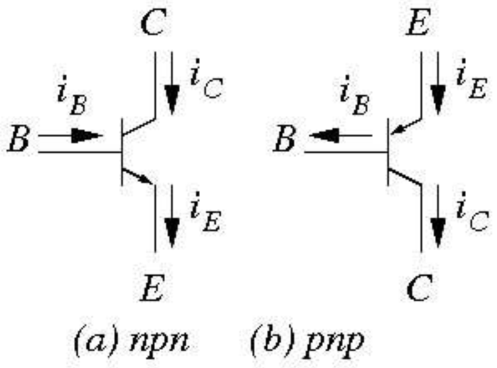






	General Rectifying Diode	Fast Recovery Diode	Schottky Barrier Diode	SiC SBD
VA rating	5000V & 3000A	3000V & 1000A	100V & 300A	1200V & 40A
Reverse Recovery Time	Long	Short	Very Short	Very Short
Shutdown Time	≈ 25μs	≈ 0.1 ~ 5μs	< 10ns	< 15ns
Switching Frequency	Long	Short	Very Short	Very Short
Forward Voltage	0.7 ~ 2.1V	0.8 ~ 1.6V	0.4 ~ 0.6V	1.5 ~ 2.2V

BJT (Bipolar Junction Transistor)



Power BJT always works in saturation and cutoff

i_C: Collector Current

i_B: Base Current

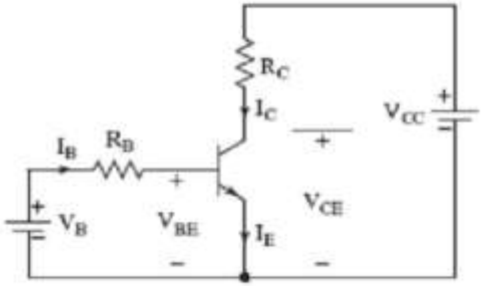
V_{CE}: Collector-Emitter Voltage

V_{BE}: Base-Emitter Voltage

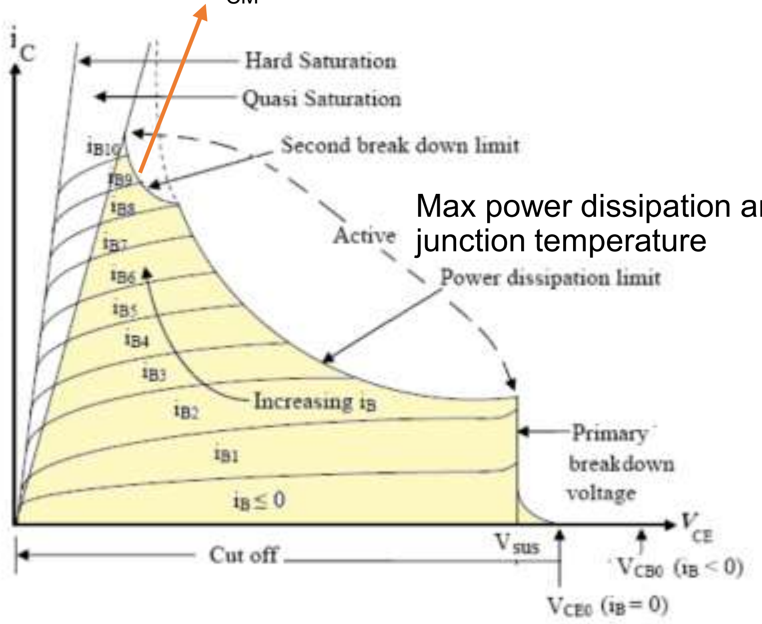
V_{SUS}: Avalanche Breakdown Voltage

V_{CE0}: Breakdown Voltage when $i_B = 0$

V_{CB0}: Breakdown Voltage when $i_B < 0$



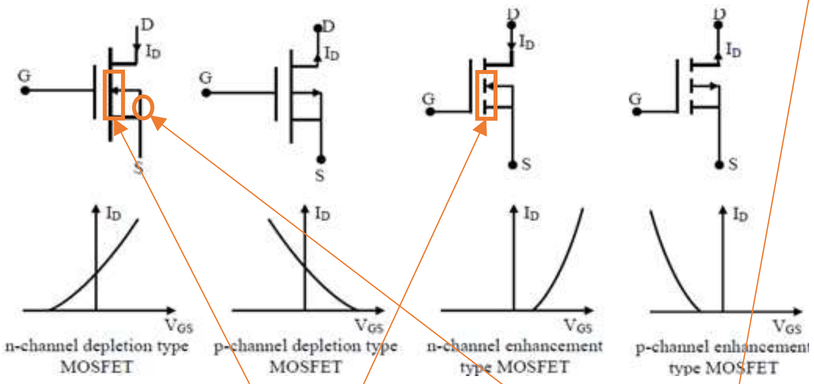
i_{CM}: Max Collector Current

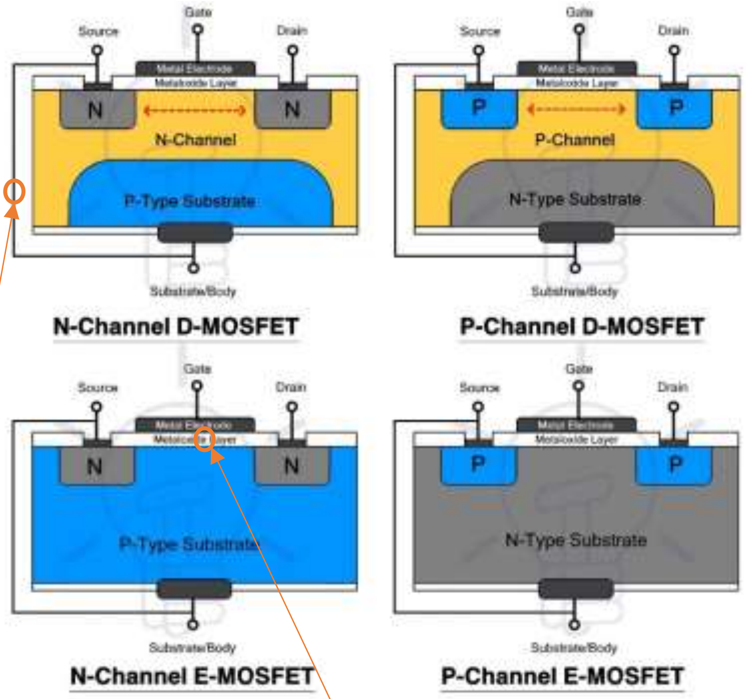


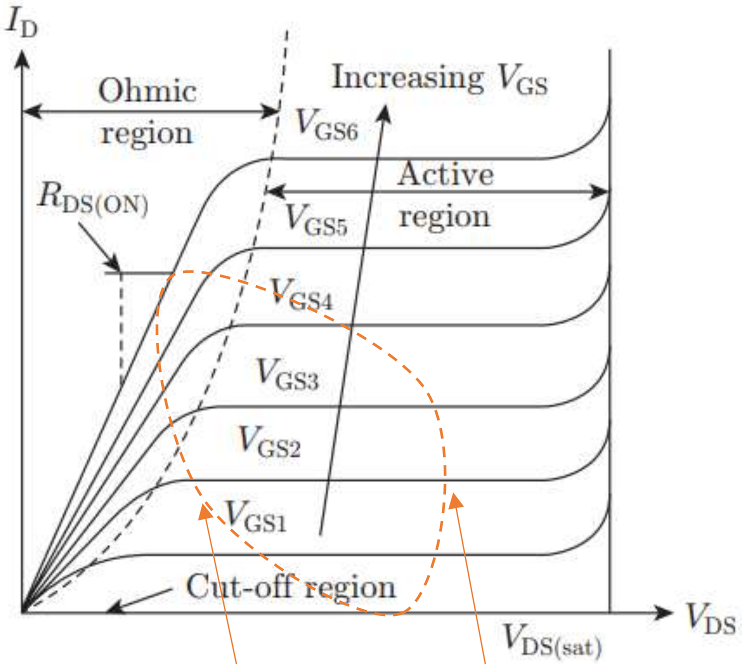
Max power dissipation and junction temperature

- Cutoff
  - $i_C = 0, VCE = VCC$
- Active
  - $i_{C(MAX)} = \frac{V_{CC} - VCE}{R_C} = \beta i_{B(MAX)}$
- Saturation
  - $i_C = \frac{V_{CC}}{R_C}, V_{CE} = 0$

MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor







No direct contact between Gate and Body

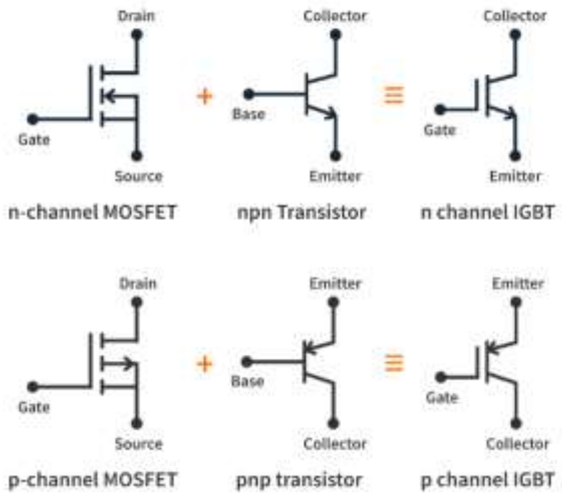
Turn on

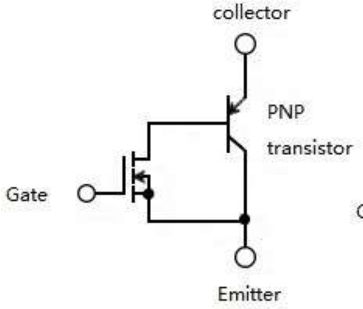
Turn off

The status of default conductive channel

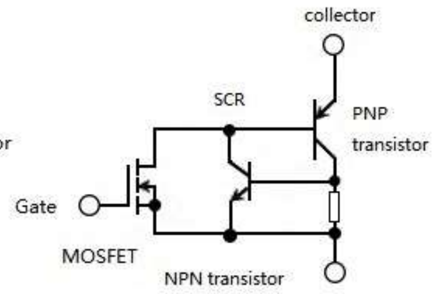
Source is connected to Body

IGBT (Insulated Gate Bipolar Transistor)

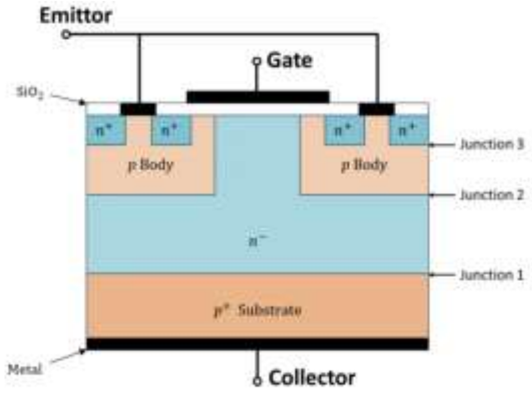




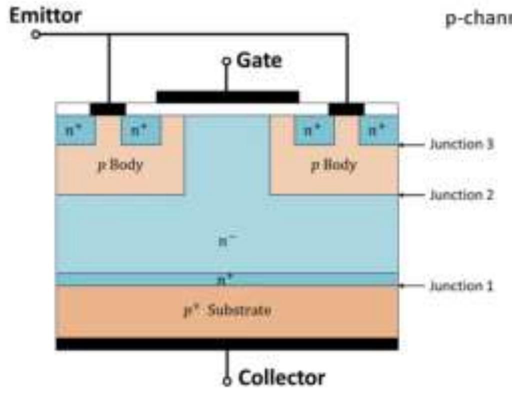
ideal equivalent circuit



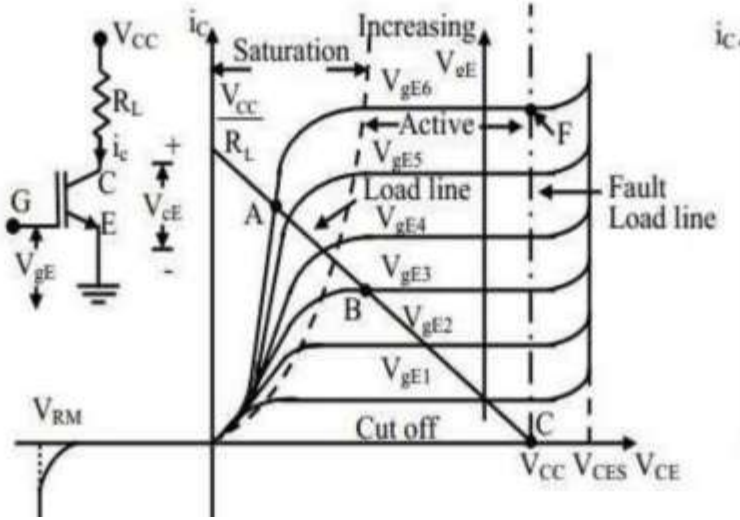
actual equivalent circuit

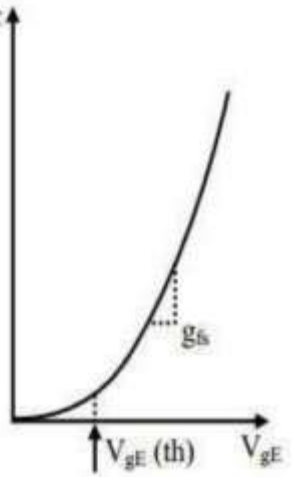


Non Punch Through (NPT) IGBT



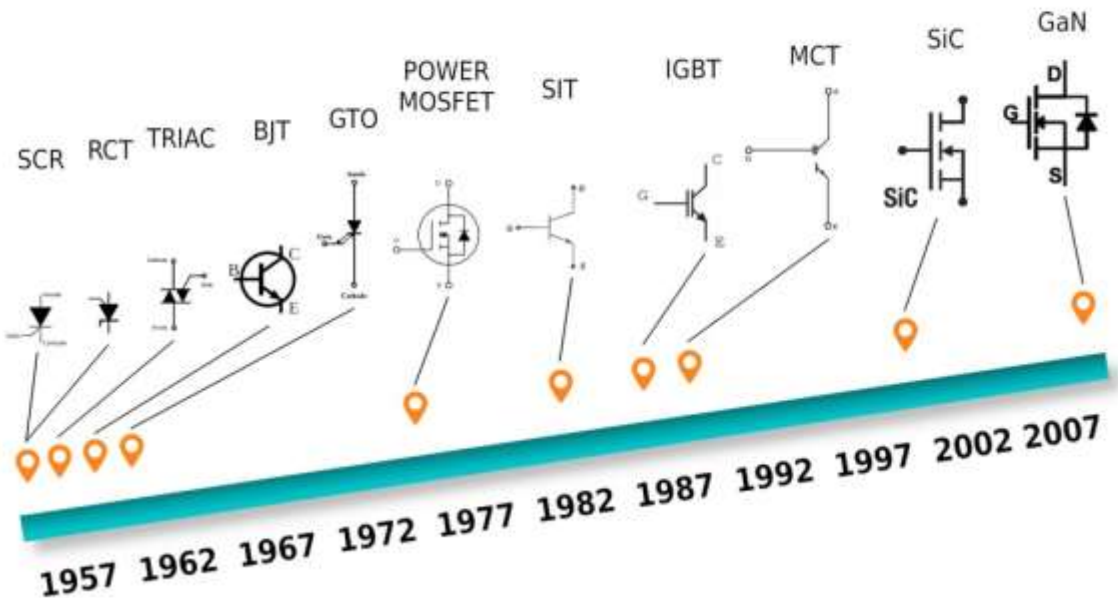
Punch Through (PT) IGBT

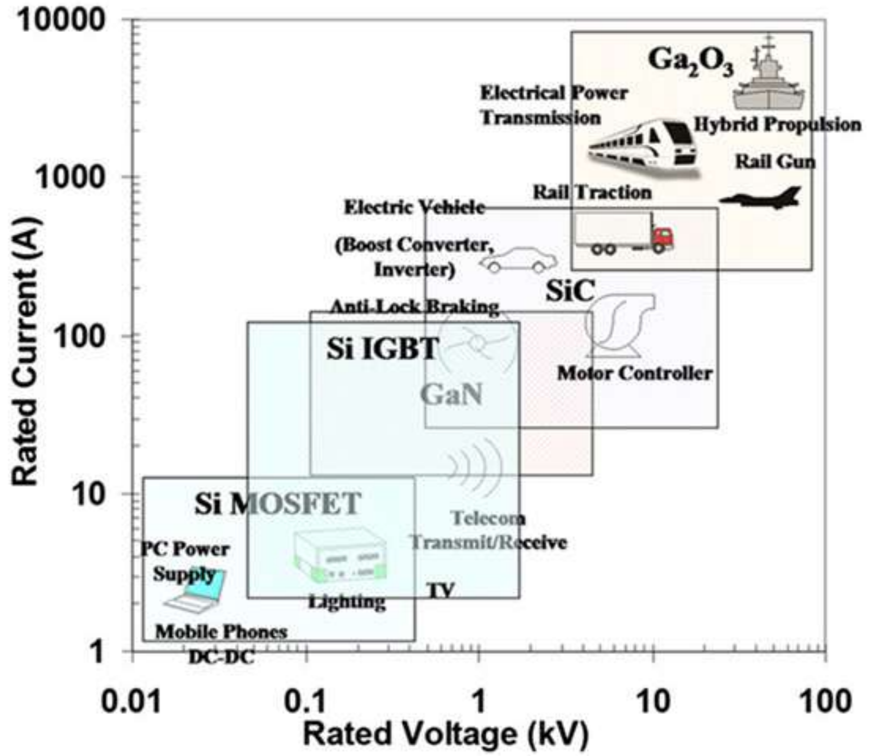


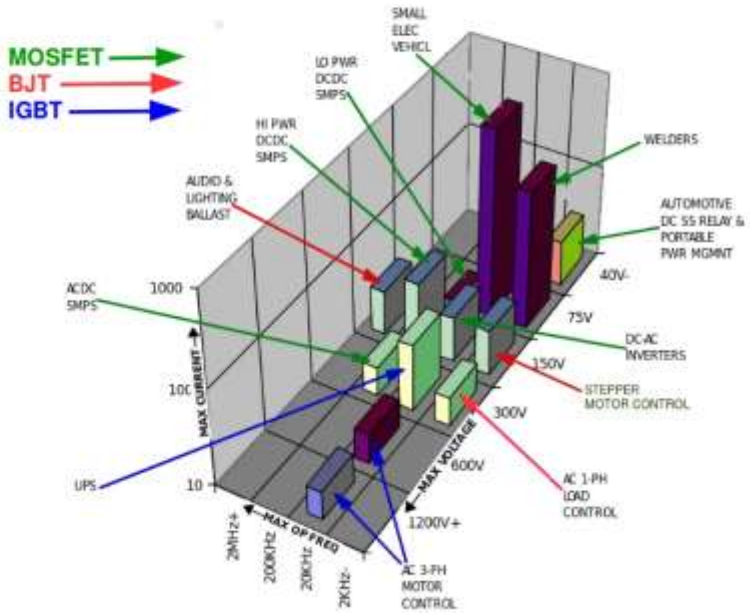


Larger current than MOSFET + smaller loss than BJT ?

Summary







Metric	Development Focus	Traditional Si Devices	Wide-Bandgap Devices (SiC/GaN)
Blocking Voltage	Higher	⩽ 6.5kV (IGBT)	1.2kV (GaN), 10kV (SiC)
Conduction Loss	Reduce RON	VCE ≈ 2V (IGBT)	< 1V
Switching Frequency	Minimize ESW	kHz range (IGBT)	MHz range (GaN)
Temperature Range	Higher	⩽ 175°	⩾ 200°
Power Density	Integrated packaging	Low	High
Reliability	Extend MTTF	High	Improving
Cost	Scale-driven reduction	≈ ＄0.1/W	≈ ＄0.5/W

Machine Protection

MPS Failure Sources:

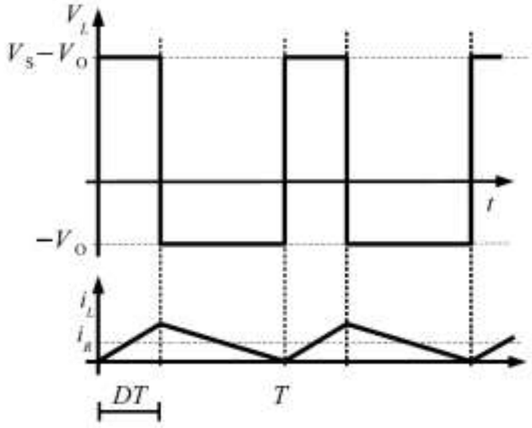
- Heat
  - Resistors
  - Inductors, transformers
  - Capacitors ESR
  - Switches
- OC and OV
  - Driver failure
  - Shoot through
  - Inappropriate deadtime
  - Load or wiring
  - Oscillation
- Water leakage
- Grid fluctuation
  - Phase loss or imbalance
  - Spikes
- External Interlock
  - Load magnets
  - External machine & radiation interlocks

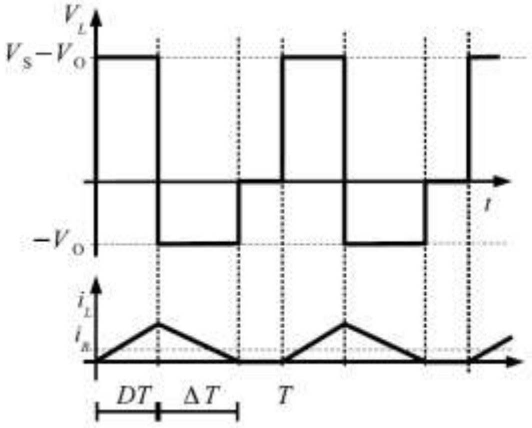
- Carefully thermal design and simulation
- Providing adequate margin in capacitor voltage and ripple current rating, switching devices voltage rating and frequencies.
- Temperature sensors in critical spots
- Full-capacity testing
- Optimize PCB design to reduce drive losses and switching time
- Desing, simulation and optimization of filters and compensation
- Optimize cooling channel to reduce flow resistance
- Design drainage channels in case of leakage
- Hybrid cooling techniques
- Phase-loss relays and snubber circuits
- Hardware protecting circuits for rapid response to interlocks
- ……

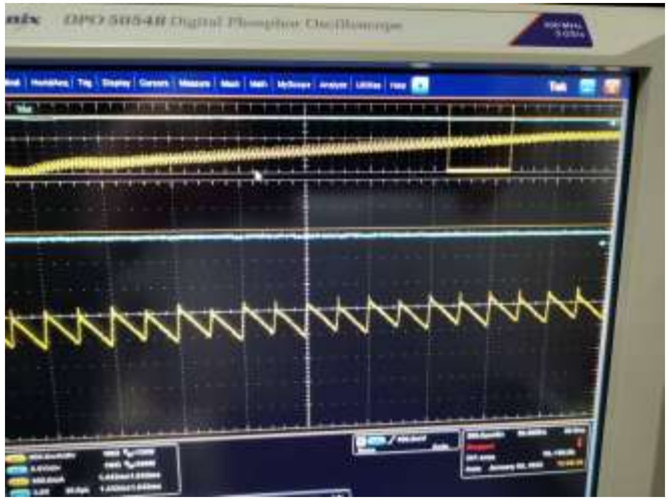
In power electronics, hardware protection is the last line of defense—it must work when everything else fails.

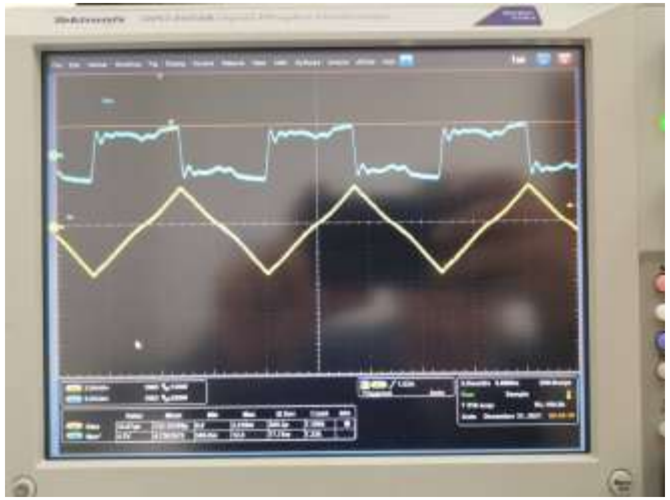
Special Issues about Accelerator MPS

Current discontinuous









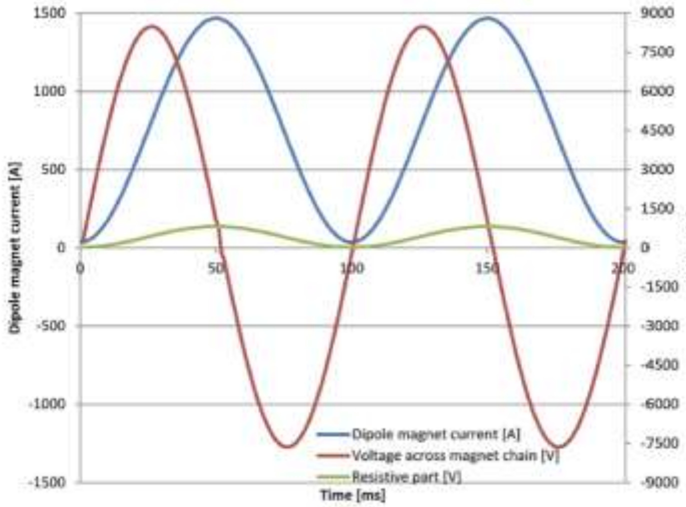
D⬇ or R⬆ → Inductor current reaching zero

Transfer function changes

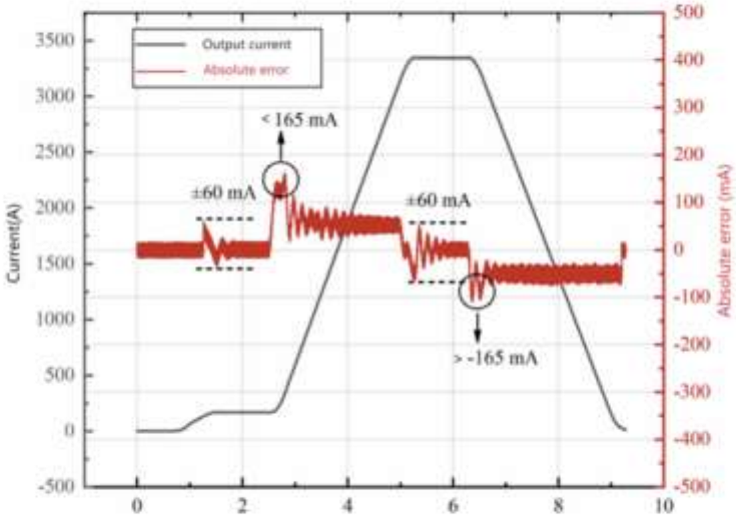
Need consideration when i_L has to pass through zero

Dynamic & Waveform

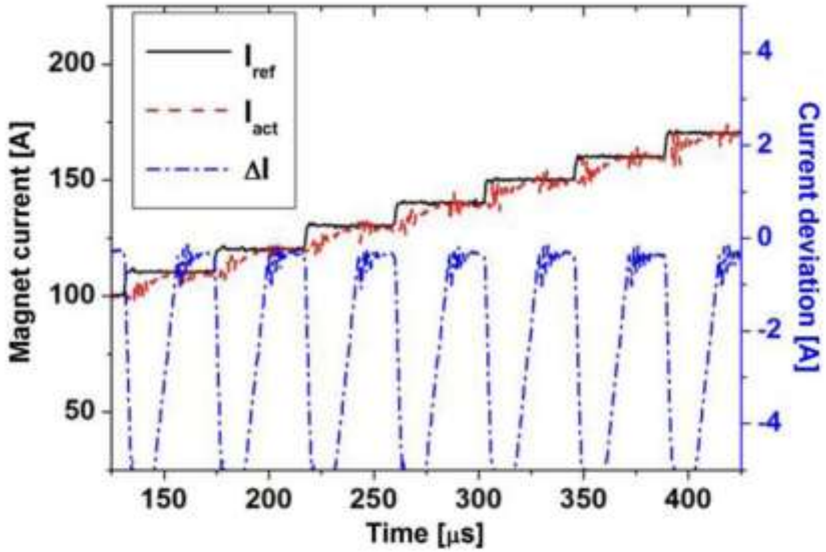
Dynamic current requirements



Booster MPS



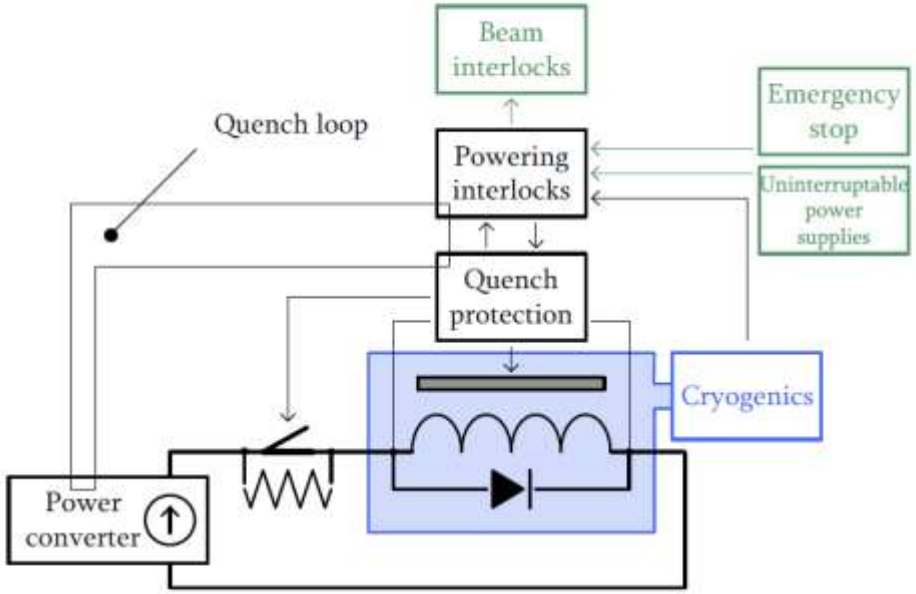
Pulse MPS

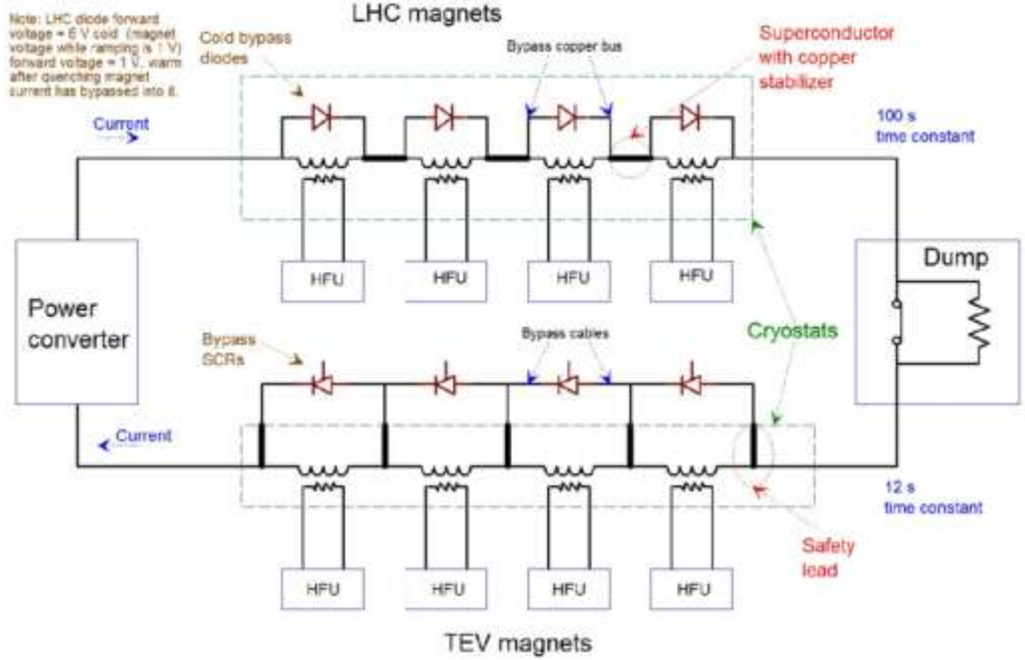


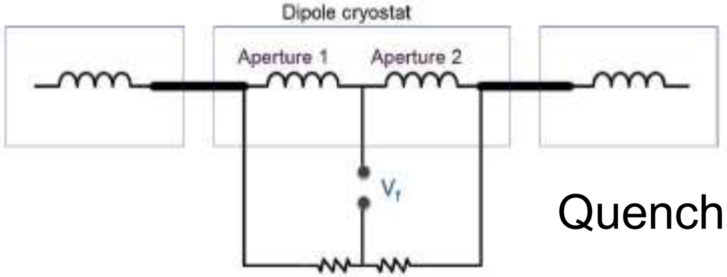
Scanning MPS

Resonant or Digital Controlled Waveform HV + LV architecture

Quench Protection



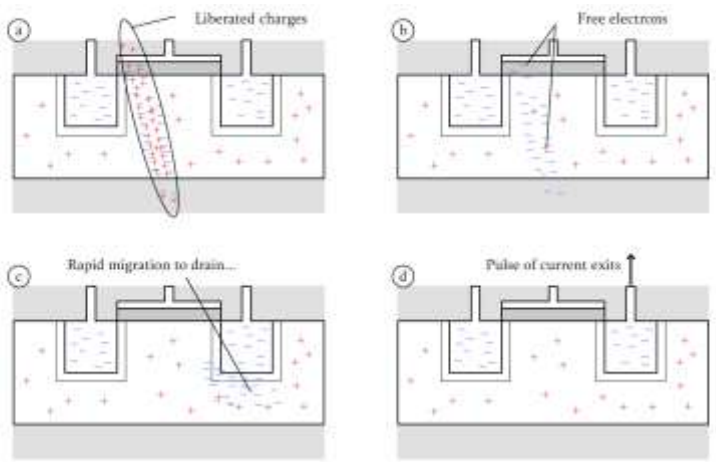




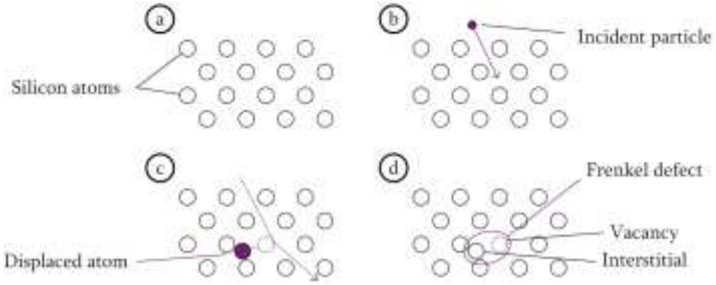
Quench detection: $|V_f| > 0.1V$

Sept. 2008, helium leak caused by “bad solder joint” in copper stabilizer

Radiation



Single event effects



Displacement damage

TABLE II
GAMMA IRRADIATION OF HIGH GAIN NPN TRANSISTOR 2N 3565

TID (krads) at dose rate of 88.23 krads/hr.	Duration of Exposure (Hours/Min.)	Gain before Irradiation of Sample Lot (I)	Gain before Irradiation of Sample Lot (II)	Gain after Irradiation of Sample (I)	Gain after Irradiation of Sample (II)	Average gain after Irradiation of Sample (I) & (II) in (%)
2.94	2 minutes	183	188	179	182	97.3
8.82	6 minutes	170	185	164	178	96.345
25.0	17 minutes	216	208	173	164	79.475
50.0	34 minutes	225	232	157	168	71.095
100.0	68 minutes	236	235	145	127	57.72
300.0	3.24 hours	251	241	83	88	34.805
500.0	5.40 hours	253	254	50	70	23.66
750.0	8.30 hours	269	270	49	51	18.555
4000.0	45.20 hours	325	322	41	47	13.610
6500.0	73.40 hours	209	213	18	10	6.655
10100.0	124.40 hours	305	337	Nil	Nil	0.0

Transistor gain decay

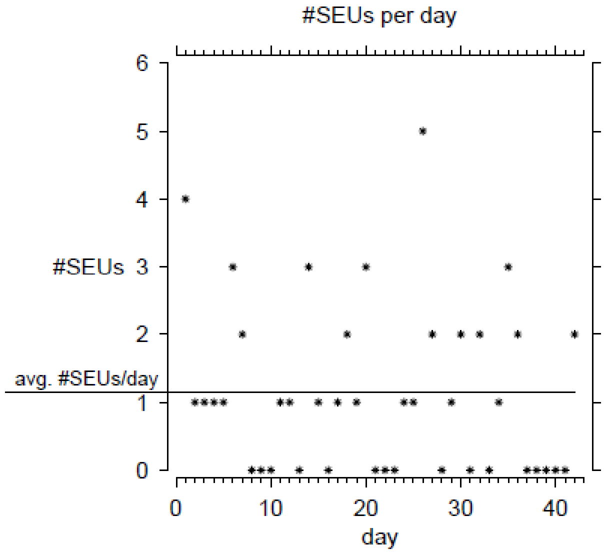
			First phase				Second phase			
Type	Input voltage	Output current	Vout at start of acquisition (V)	Vout at end of first acquisition (V)	N-dose at end of first acquisition (n/cm²)	Output Voltage difference (V)	Vout at start of acquisition (V)	Vout at end of acquisition (V)	N-dose at end of acquisition (n/cm²)	Output Voltage difference (V)
Delta AC/DC 75SX5	230Vac	9.75A	4.9960	5.0093	$0.197\ 10^{12}$	0.0133	5.0103	7.0503	$1.947\ 10^{12}$	2.04
CEA DC/DC C0000071003	48Vdc	4.5A	4.8959	4.8989	$0.197\ 10^{12}$	0.0030	4.9027	4.8932	$1.947\ 10^{12}$	-0.0095
Melcher DC/DC 48IMR-25-05-2	48Vdc	3.75A	4.9724	4.9800	$0.197\ 10^{12}$	0.0076	4.9824	7.6484	$1.947\ 10^{12}$	2.666
Lambda DC/DC RM-30-48-5	48Vdc	4.5	4.9128	4.9101	$0.197\ 10^{12}$	-0.0027	4.9134	6.1780 OVP->Trip	$0.953\ 10^{12}$ Trip N-dose	1.2646
Artesyn DC/DC BXA4048S05SM	48Vdc	6	4.9760	4.9825	$0.197\ 10^{12}$	0.0065	4.9892	6.1899	$1.947\ 10^{12}$	1.2007
Syko DC/DC SRI-U-50-05-60	48Vdc	4.5	5.0899	5.0745	$0.197\ 10^{12}$	-0.0154	5.0754	6.7050	$1.947\ 10^{12}$	1.6296
Traco DC/DC TED 0511	5Vdc	300mA	5.0515	4.9421	$0.197\ 10^{12}$	-0.1094	5.0583	5.5404	$1.947\ 10^{12}$	0.4821

Tests carried out by PH/ESS team (Chris Parkman, Bruno Allongue)

Rectifier output voltage drift

Controller Failure

Figure 4. TESLA Test Facility II tunnel



- Local radiation harden
- Away from high radioactive region
- Distributive PS design
- Hardware watch-dog to reboot CPU
- Controllable control power supply
- Must consider harden if:
  - Total ionizing dose (TID) > 10 Gray/year (1krad(Si)/year)
  - 1MeV equivalent neutron fluency > 10^{11}/cm^2/year

EMC & EMI

CM noise (wire → ground)

- High dv/dt on MOSFETs or IGBTs (can reach 20kV/μs to 50kV/s)
- Parasitic capacitance on transformers/inductors
- Negative impedance: (input voltage drops → input current rises)

DM noise (wire → wire)

- Current ripples in inductors ~ filter capacitors → loop
- Reverse recovery current in rectifier diodes

CM noise (Limitation methods)

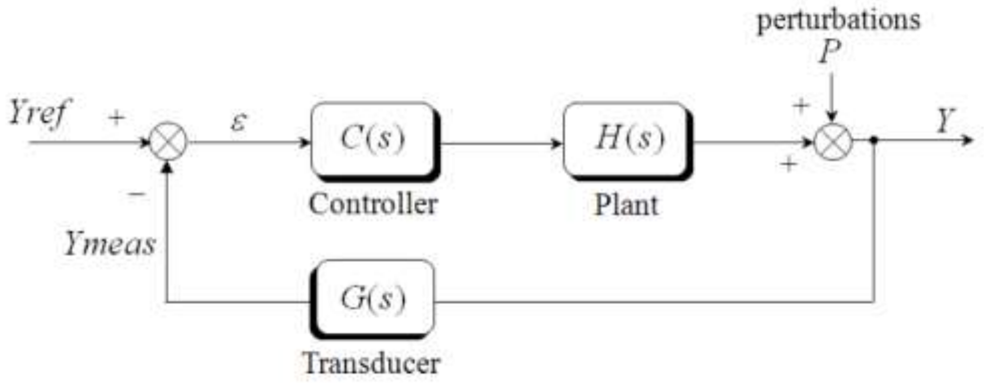
- CM filters in input/output
- Avoid multiple connections between PGND and AGND
- Choose low-parasitic-capacitance switches
- Larger input capacitor and well-designed output filter
- Cable shielding
- Larger grounding area and lower grounding impedance

DM noise

- DM choke
- Smaller loop area
- ZVS/ZCS to reduce switching noise
- Use Schottky diodes if possible (T_{rr} very low)

Theory of PS Control

Basic concept of close-loop



$$TF_{ol} = \frac{Y}{Y_{ref}} = C(s)H(s)$$

$$TF_{cl} = \frac{Y}{Y_{ref}} = \frac{C(s)H(s)}{1 + C(s)H(s)G(s)}$$

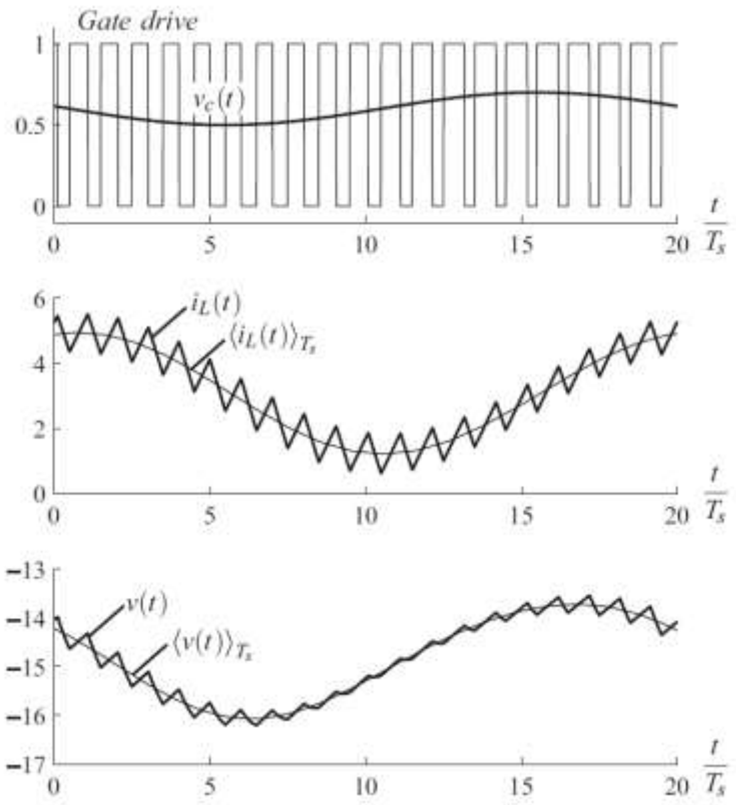
Controller dynamically adjusts its output according to the error between the value we want and the value we see.

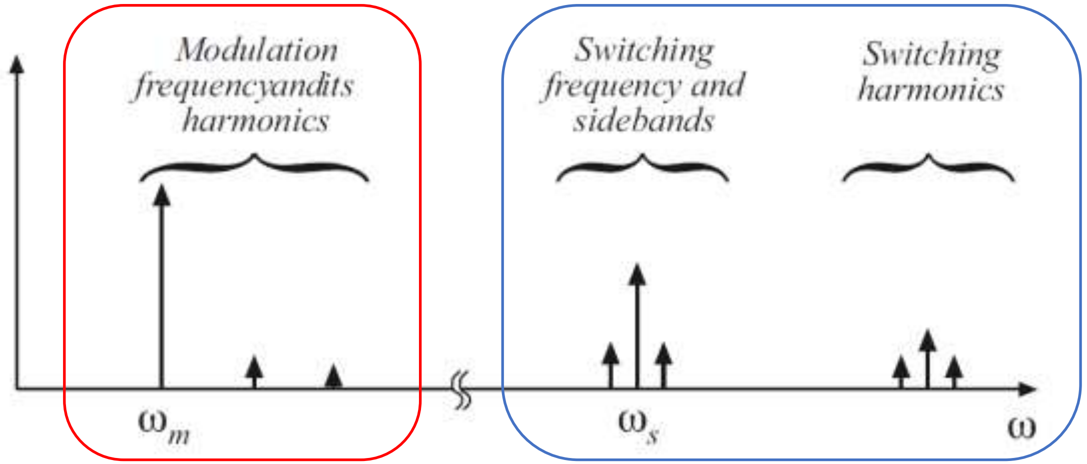
In SMPS (Switching Magnet Power Supply):

- Y_{ref}: the current value given by operators, external systems or controller itself
- Y: the current that excites the magnet
- Y_{meas}: the current measured by transducer (typically a DCCT)
- Controller: An analog or digital arithmetic unit that calculating a control output signal by the error between Y_{ref} and Y_{meas}.
- Plant: several devices that transfer the signal from controller to the current (e.g. Gate drivers transferring the PWM signal to gate voltage, switching devices, filters and magnet loads)
- Transducer: Sensors that measure the current (or voltage and current) and ADC channels
- Perturbations: come from line vibration, rectification harmonics, EM noise, load variations, temperature…

Control Design in MPS – AC small signal modeling

Modeling is a trade-off between insight and complexity



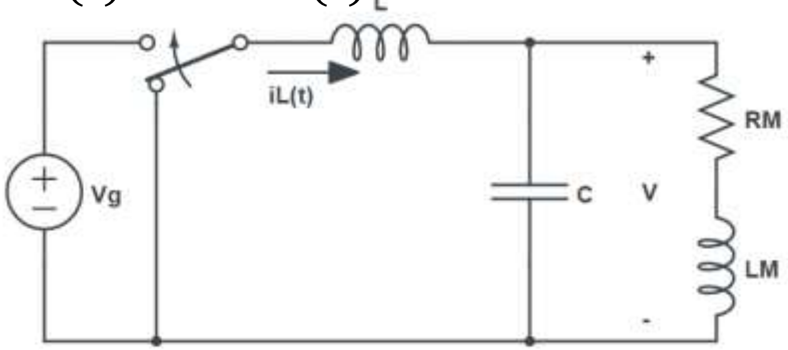


Modeling to predict the low-frequency component

Switching ripples can be neglected

Transfer function

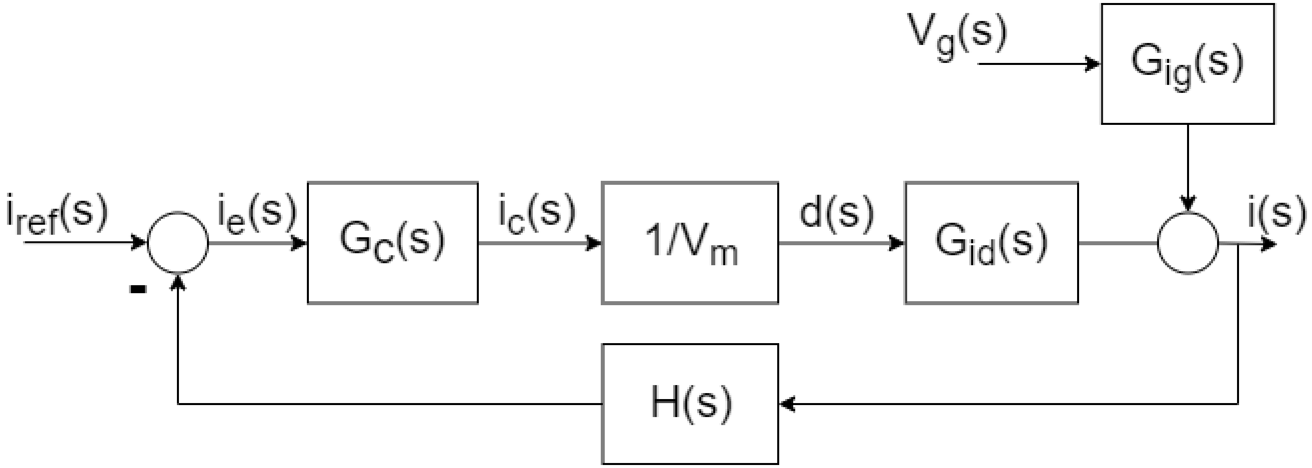
$$D(t) = D + \hat{d}(t)$$



$$V_g(t) = V_g + \hat{v}_g(t)$$

$$\hat{d}(t) = 0 \Rightarrow G_{ig}(s) = \frac{i(s)}{V_g(s)} = \frac{D}{s^3 LCL_M + s^2 LCR_M + s(L + L_M) + R_M}$$

$$\hat{v}_g(t) = 0 \Rightarrow G_{id}(s) = \frac{i(s)}{d(s)} = \frac{V_g}{s^3 LCL_M + s^2 LCR_M + s(L + L_M) + R_M}$$



Now you can plot Bode diagrams to analyze its open-loop behavior and try adding compensation to form Gc, which will be implemented into the controller.

Difficulty in finding roots

Get the roots of n-th order polynomial

$$P(s) = 1 + \alpha_1 s + \alpha_2 s^2 + \cdots + \alpha_n s^n$$

$$\Downarrow$$

$$P(s) = (1 + \tau_1 s)(1 + \tau_2 s) \cdots (1 + \tau_n s)$$

$$\alpha_1 = \tau_1 + \tau_2 + \cdots + \tau_n$$

$$\alpha_2 = \tau_1(\tau_2 + \cdots + \tau_n) + \tau_2(\tau_3 + \cdots + \tau_n) + \cdots$$

$$\alpha_3 = \tau_1\tau_2(\tau_3 + \cdots + \tau_n) + \tau_2\tau_3(\tau_4 + \cdots + \tau_n) + \cdots$$

$$\vdots$$

$$\alpha_n = \tau_1 \tau_2 \cdots \tau_n$$

In a well-designed PS, time constants are well separated.

$$\alpha_1 \approx \tau_1$$

$$\alpha_2 \approx \tau_1\tau_2$$

$$\vdots$$

$$\alpha_n \approx \tau_1\tau_2 \cdots \tau_n$$

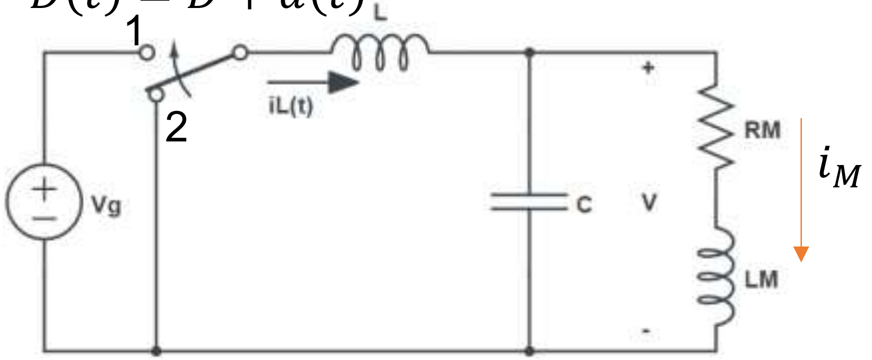
$$P(s) \approx (1 + \alpha_1 s)\left(1 + \frac{\alpha_2}{\alpha_1} s\right) \cdots \left(1 + \frac{\alpha_n}{\alpha_{n-1}} s\right)$$

when $|\alpha_1| \gg \left|\frac{\alpha_2}{\alpha_1}\right| \gg \cdots \gg \left|\frac{\alpha_n}{\alpha_{n-1}}\right|$

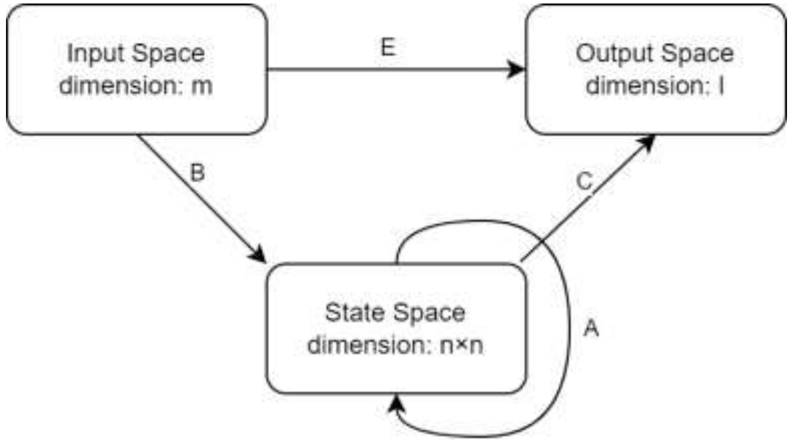
If not, leave the terms in quadratic form

State space approach

$$D(t) = D + \hat{d}(t)$$



$$V_g(t) = V_g + \hat{v}_g(t)$$



1

$$L\frac{di_L}{dt} = V_g - V$$

$$C\frac{dV}{dt} = i_L - i_M$$

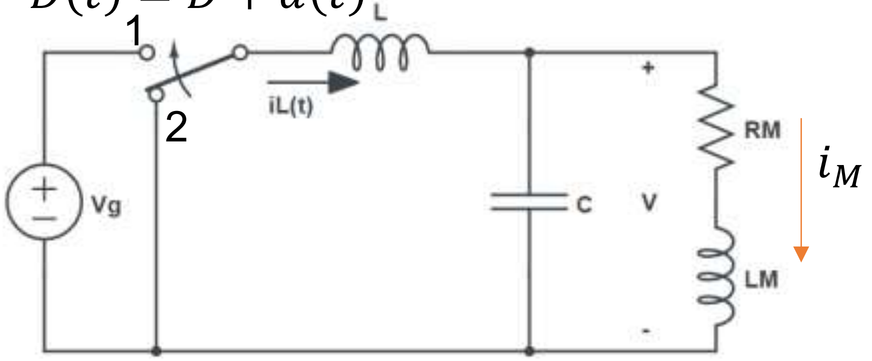
$$L_M\frac{di_M}{dt} = V - i_M R_M$$

$$\overset{X'}{\begin{bmatrix} i_L' \\ V' \\ i_M' \end{bmatrix}} = \overset{A_1}{\boxed{\begin{bmatrix} 0 & -\frac{1}{L} & 0 \\ \frac{1}{C} & 0 & -\frac{1}{C} \\ 0 & \frac{1}{L_M} & -\frac{R_M}{L_M} \end{bmatrix}}} \overset{X}{\begin{bmatrix} i_L \\ V \\ i_M \end{bmatrix}} + \overset{B_1}{\begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix}} \overset{U}{V_g}$$

$$\overset{Y}{i_M} = \overset{C_1}{\begin{bmatrix} 0 & 0 & 1 \end{bmatrix}} \begin{bmatrix} i_L \\ V \\ i_M \end{bmatrix} + \overset{E_1}{\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}} V_g$$

State space approach

$D(t) = D + \hat{d}(t)$



$V_g(t) = V_g + \hat{v}_g(t)$

$\boxed{2}$

$$\begin{bmatrix} i'_L \\ V' \\ i'_M \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} & 0 \\ \frac{1}{C} & 0 & -\frac{1}{C} \\ 0 & \frac{1}{L_M} & -\frac{R_M}{L_M} \end{bmatrix} \begin{bmatrix} i_L \\ V \\ i_M \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} V_g$$

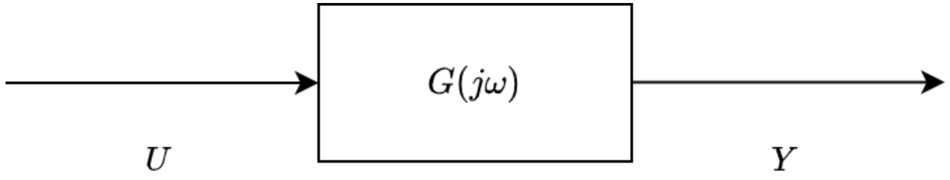
$$i_M = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ V \\ i_M \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} V_g$$

$$A = DA_1 + D'A_2$$
$$B = DB_1 + D'B_2$$
$$C = DC_1 + D'C_2$$
$$E = DE_1 + D'E_2$$

$$\hat{X}' = A\hat{X} + B\hat{U} + [(A_1 - A_2)X + (B_1 - B_2)U]\ \hat{D}$$
$$Y = C\hat{X} + E\hat{U} + [(C_1 - C_2)X + (E_1 - E_2)U]\ \hat{D}$$

The eigen values of matrix A = Roots of transfer function polynomial = Poles of system

Bode diagram – basic concept and a simple example



$$\frac{Y}{U} = G\left(j\omega\right) = \left\|G\left(j\omega\right)\right\|\angle G\left(j\omega\right)$$

$$\|G\|_{\mathrm{dB}} = 20\log_{10}\left(\|G\|\right)$$

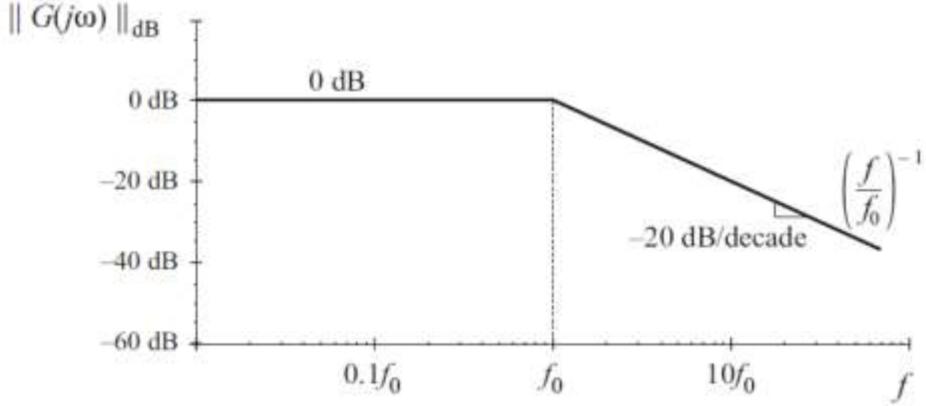
dBV, dBA, dBmA, dBμA, dBΩ, …

$$G(s) = \frac{1}{1+\alpha s}$$

$$G(j\omega) = \frac{1}{1+j\omega\alpha} = \frac{1}{1+j\left(\frac{\omega}{\omega_0}\right)}$$ *assume ω_0 is real*

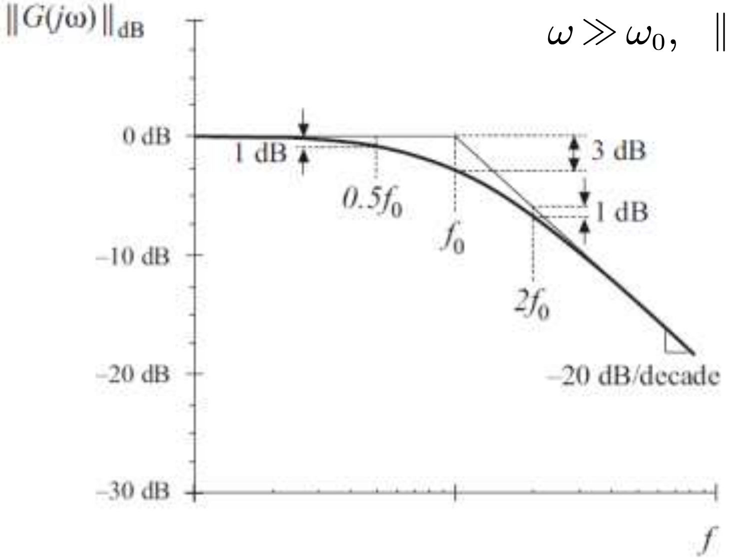
$$\mathrm{Re}\left(G(j\omega)\right) = \frac{1}{1+\left(\frac{\omega}{\omega_0}\right)^2} \qquad \|G(j\omega)\| = \frac{1}{\sqrt{1+\left(\frac{\omega}{\omega_0}\right)^2}}$$

$$\mathrm{Im}\left(G(j\omega)\right) = \frac{-\frac{\omega}{\omega_0}}{1+\left(\frac{\omega}{\omega_0}\right)^2} \qquad \angle G(j\omega) = -\arctan\left(\frac{\omega}{\omega_0}\right)$$



$$\omega \ll \omega_0, \ \|G(j\omega)\| = 1, \ \|G(j\omega)\|_{\mathrm{dB}} = 0$$

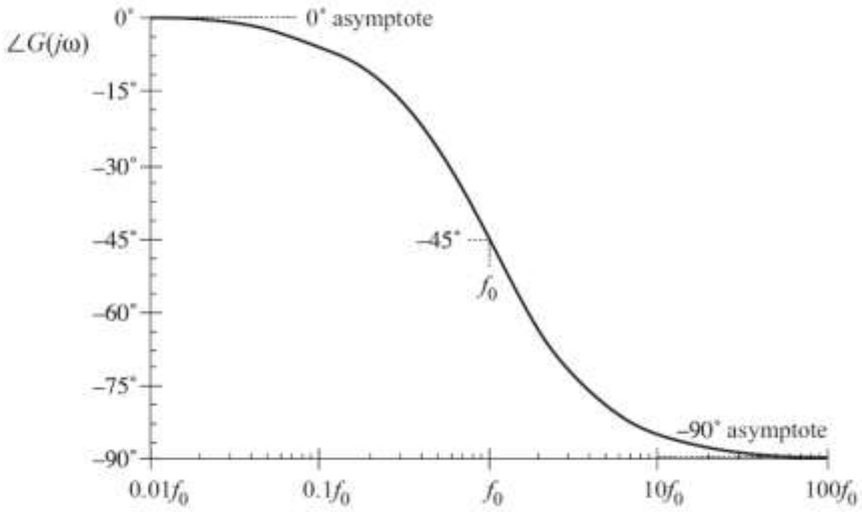
$$\omega \gg \omega_0, \quad \|G(j\omega)\|_{\mathrm{dB}} = -20\log_{10}\left(\frac{\omega}{\omega_0}\right)$$



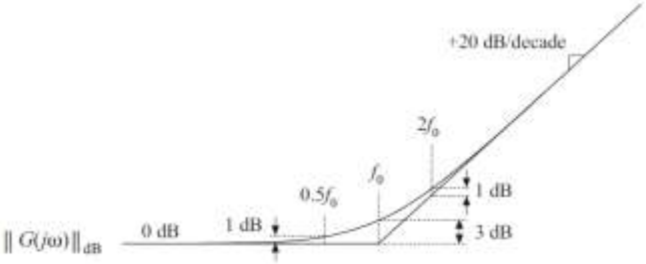
$$\omega = \omega_0, \quad \|G(j\omega)\|_{\mathrm{dB}} = -20\log_{10}\sqrt{2} = -3(\mathrm{dB})$$

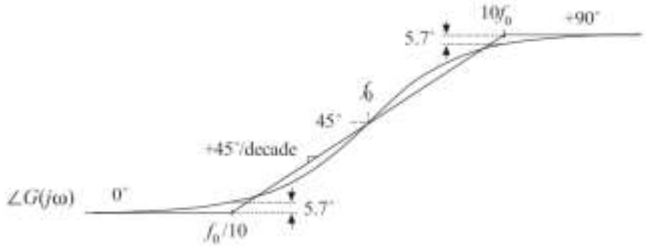
Bode diagram – basic concept and a simple example

$$\angle G(j\omega) = -\arctan\left(\frac{\omega}{\omega_0}\right)$$

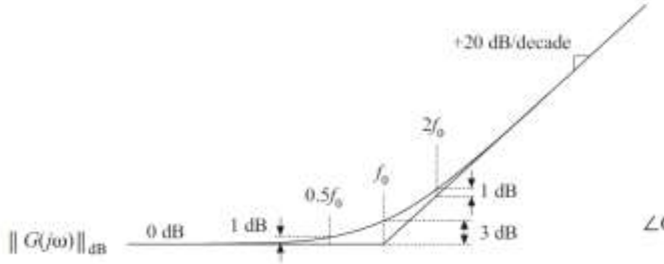


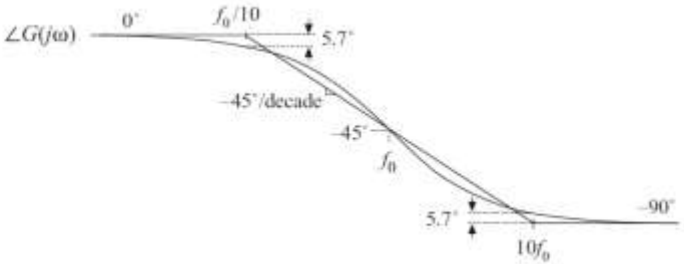
$$G(j\omega) = 1 + j\left(\frac{\omega}{\omega_0}\right) \qquad \angle G(j\omega) = \arctan\left(\frac{\omega}{\omega_0}\right)$$





$$G(j\omega) = 1 - j\left(\frac{\omega}{\omega_0}\right) \qquad \angle G(j\omega) = -\arctan\left(\frac{\omega}{\omega_0}\right)$$





Bode diagram – combination

$$G(j\omega)=\frac{G_0}{\left(1+j\frac{\omega}{\omega_1}\right)\left(1+j\frac{\omega}{\omega_2}\right)}$$

$$(\omega_2 \gg \omega_1)$$

$\omega \ll \omega_1,\ \|G(j\omega)\| = 20\log_{10}|G_0|$

$\omega_1 < \omega < \omega_2,$ similar to one pole

$\omega \gg \omega_2,$ 2 poles function together

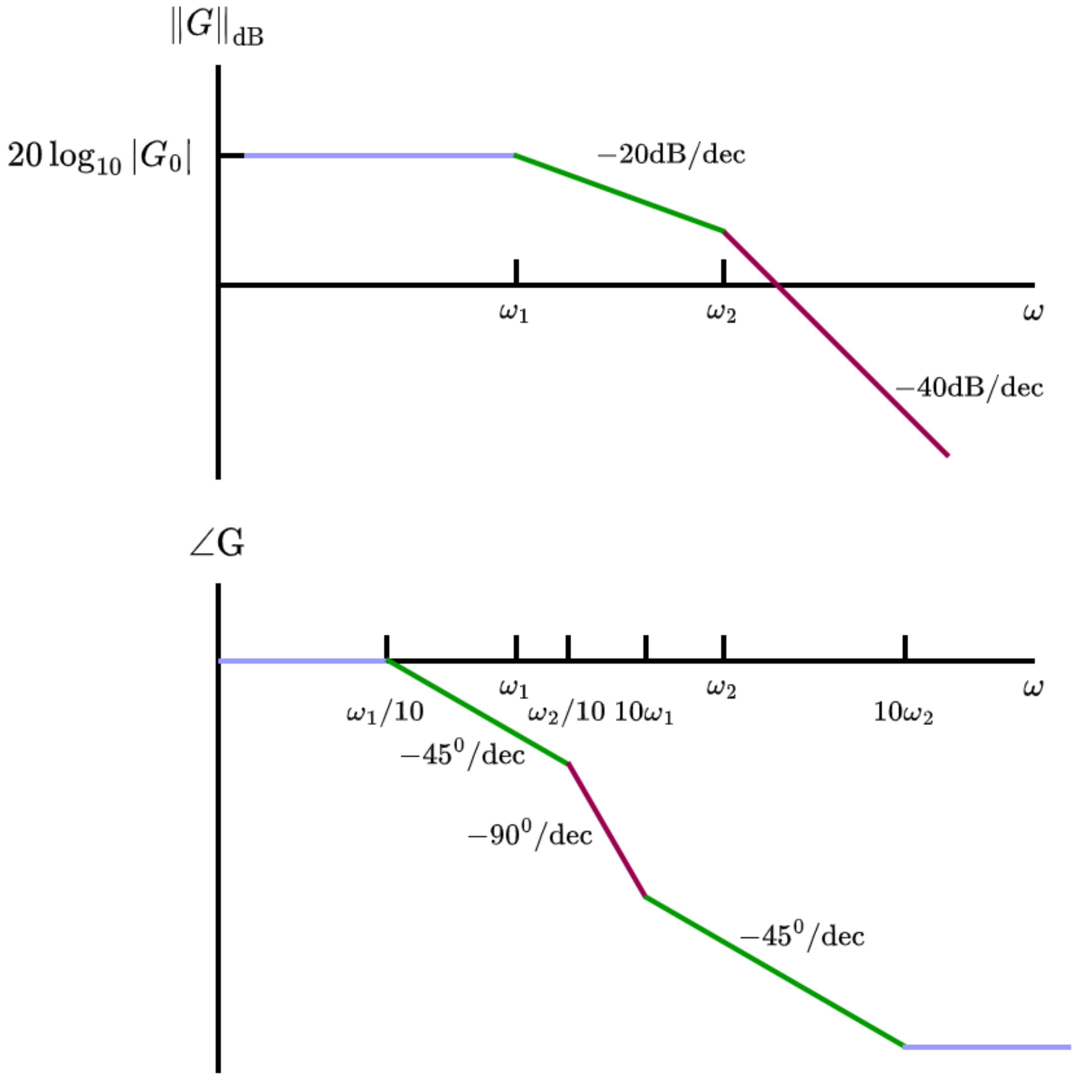
$\omega < 0.1\omega_1,\ \angle G = 0°$

$0.1\omega_1 < \omega < 0.1\omega_2,$ 1st pole functions

$0.1\omega_2 < \omega < 10\omega_1,$ 2 poles function together

$10\omega_1 < \omega < 10\omega_2,$ 2nd pole functions

$\omega > 10\omega_2,$ leaves the pole functioning region



Bode diagram – complex poles

$$G(j\omega) = \frac{1}{1+\alpha_1(j\omega)+\alpha_2(j\omega)^2}$$

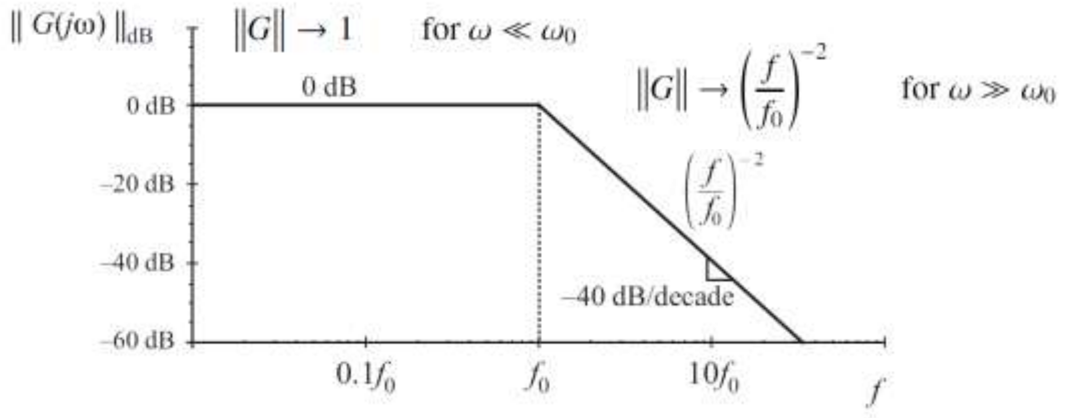
$$\left(\frac{1}{\omega_0}\right)^2 \doteq \alpha_2$$

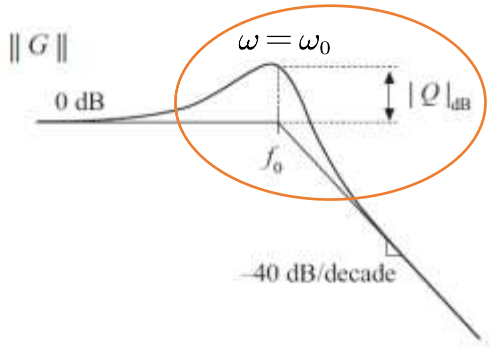
$$\frac{1}{Q\omega_0} \doteq \alpha_1$$

$$G(j\omega) = \frac{1}{1+\frac{1}{Q}\frac{j\omega}{\omega_0}+\left(\frac{j\omega}{\omega_0}\right)^2}$$

$$\|G(j\omega)\| = \frac{1}{\sqrt{\left(1-\left(\frac{\omega}{\omega_0}\right)^2\right)^2+\frac{1}{Q^2}\left(\frac{\omega}{\omega_0}\right)^2}}$$

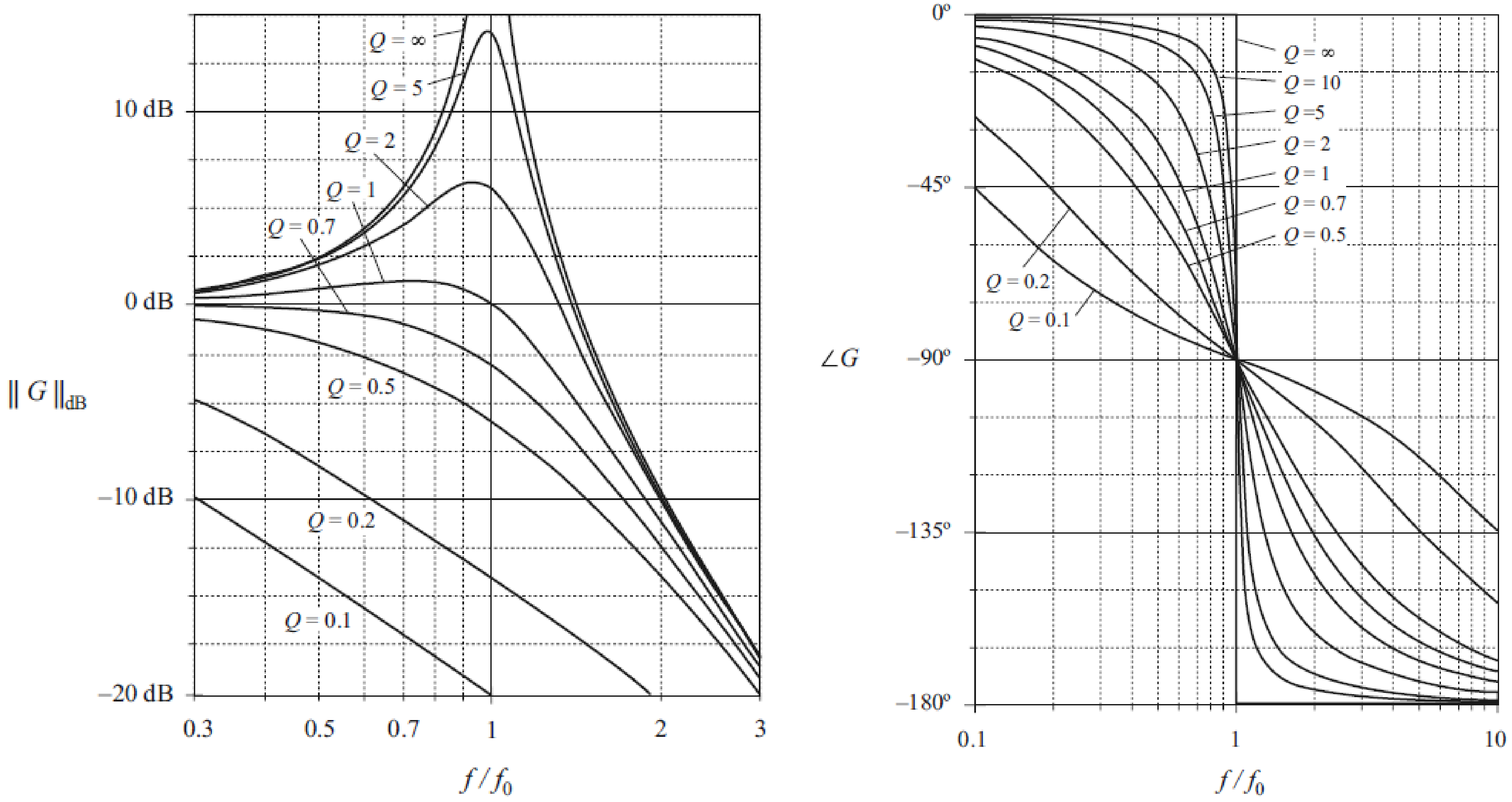
$$\angle G(j\omega) = -\arctan\left(\frac{\frac{1}{Q}\left(\frac{\omega}{\omega_0}\right)}{1-\left(\frac{\omega}{\omega_0}\right)^2}\right)$$



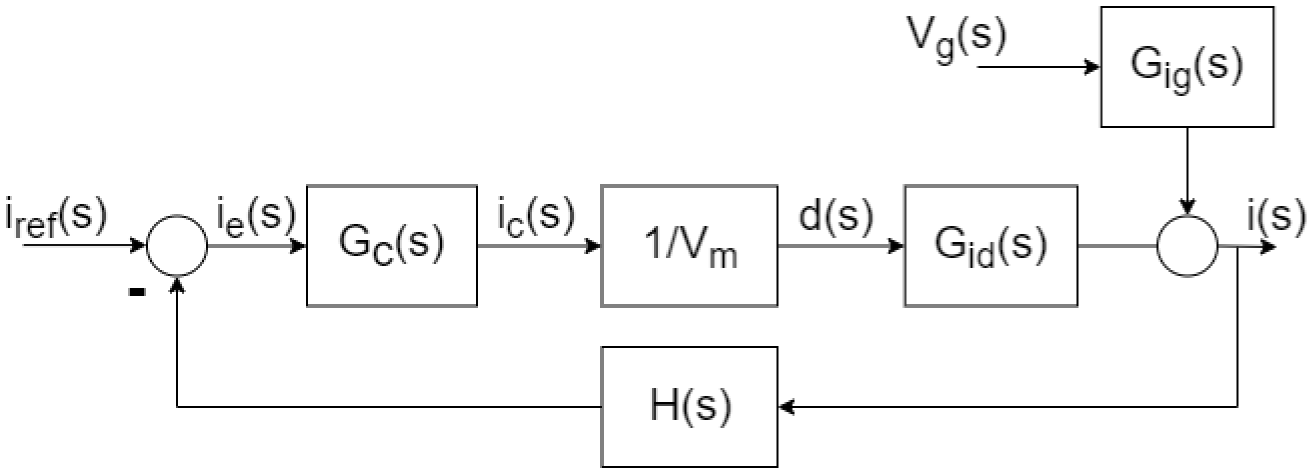


This feature has a profound impact in PS design. If noises came from Vg or D (or other sources), their spectrum in this region, the system will AMPLIFY their power, to form resonant voltage/current in output.

Bode diagram – complex poles



Close-loop



We want:
i(s) not affected by vibration of $V_g(s)$;
i(s) following $i_{ref}(s)$ constantly.

$$T(s) = H(s) G_C(s) G_{id}(s) / V_m$$ *"loop gain"*

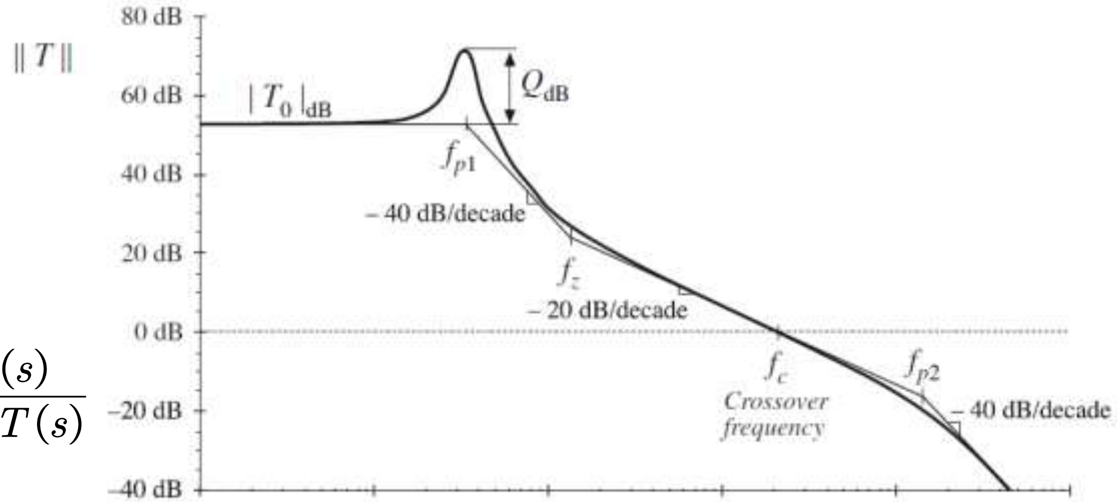
$$G_{ig}(s) = \frac{\hat{i}(s)}{\hat{V}_g(s)} \Big|_{\hat{d}=0} \qquad G_{id}(s) = \frac{\hat{i}(s)}{\hat{d}(s)} \Big|_{\hat{V}_g=0}$$

$$\hat{i}_{ref} = 0 \Rightarrow \frac{\hat{i}(s)}{\hat{V}_g(s)} = \frac{G_{ig}(s)}{1+T(s)}$$ $\hat{V}_g$ *reduced by* $\frac{1}{1+T(s)}$

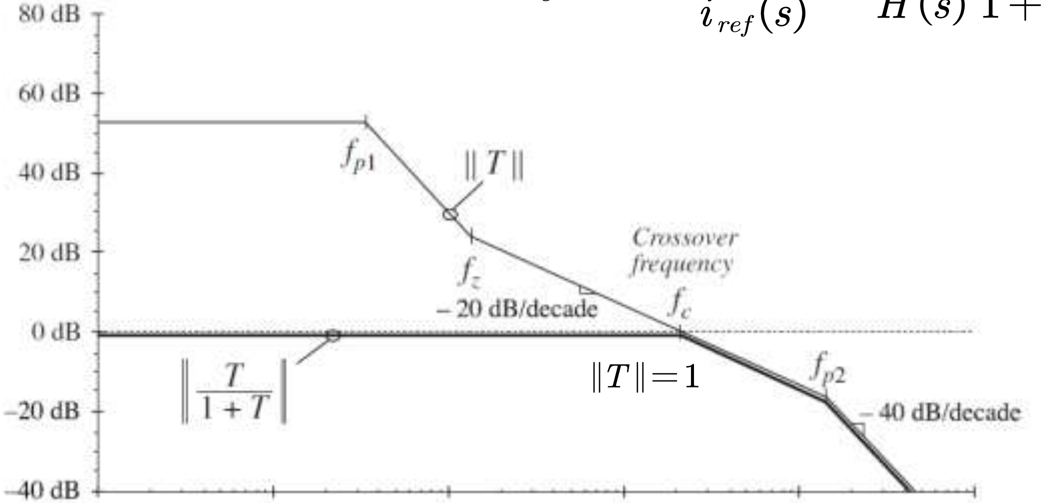
$$\hat{V}_g = 0 \Rightarrow \frac{\hat{i}(s)}{\hat{i}_{ref}(s)} = \frac{1}{H(s)} \frac{T(s)}{1+T(s)}$$ $\frac{\hat{i}(s)}{\hat{i}_{ref}(s)} \Big|_{\mathrm{DC}} \approx \frac{1}{H(0)}$ *i(s) only affected by sensor*

Close-loop

$$T(s) = T_0 \frac{\left(1 + \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{Q\omega_{p1}} + \left(\frac{s}{\omega_{p1}}\right)^2\right)\left(1 + \frac{s}{\omega_{p2}}\right)}$$



$$\hat{V}_g = 0 \Rightarrow \frac{\hat{i}(s)}{\hat{i}_{ref}(s)} = \frac{1}{H(s)} \frac{T(s)}{1 + T(s)}$$



Just by closing loop with unified H(s), the output can follow its reference below the crossover frequency.
Beyond that, the change in reference is damped so the output can not follow.

$$\|T\| \gg 1, \ \frac{\hat{i}(s)}{\hat{i}_{ref}(s)} = \frac{1}{H(s)}$$

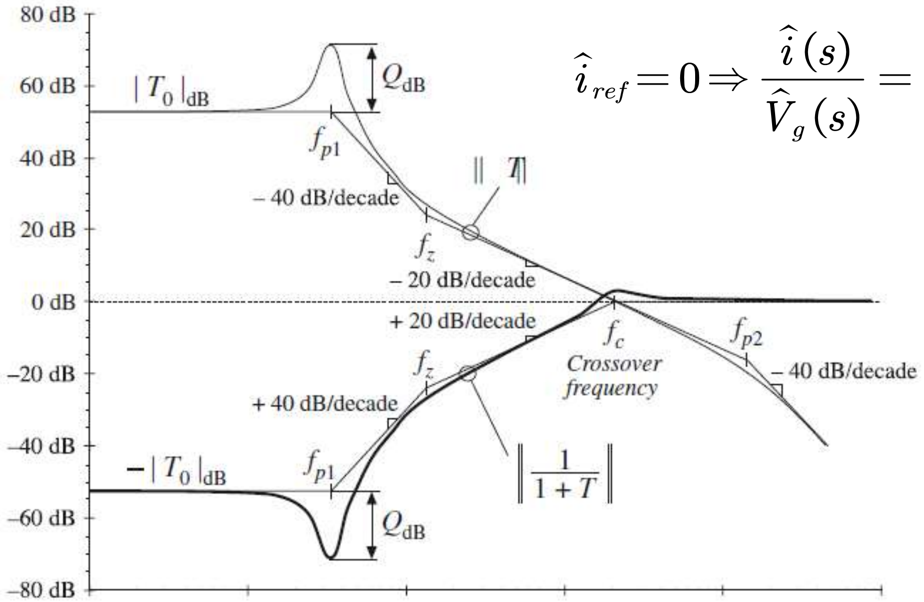
i(s) can follow $i_{ref}(s)$

$$\|T\| \ll 1, \ \frac{\hat{i}(s)}{\hat{i}_{ref}(s)} = \frac{T(s)}{H(s)} = G_C(s) G_{id}(s) / V_m$$

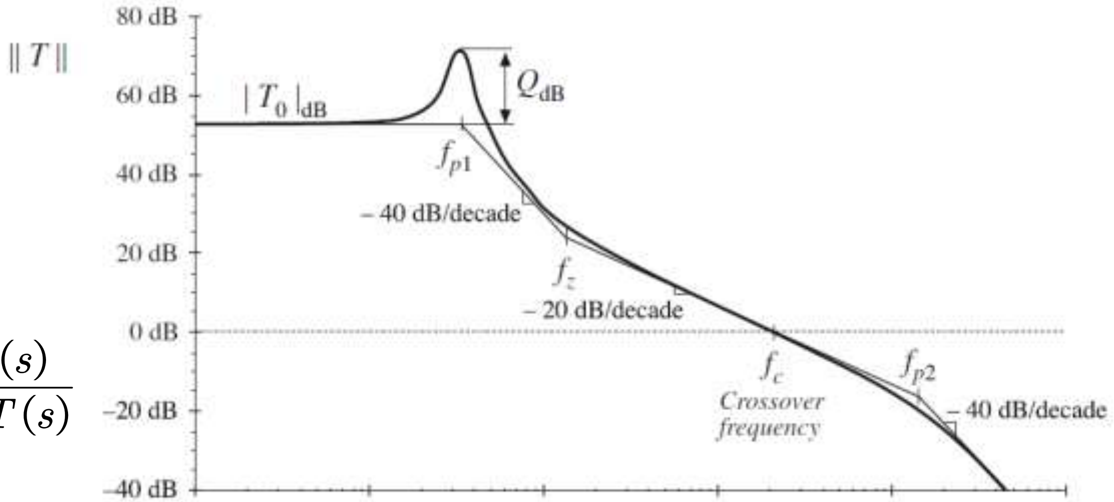
Can not

Close-loop

$$T(s) = T_0 \frac{\left(1 + \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{Q\omega_{p1}} + \left(\frac{s}{\omega_{p1}}\right)^2\right)\left(1 + \frac{s}{\omega_{p2}}\right)}$$



$$\hat{i}_{ref} = 0 \Rightarrow \frac{\hat{i}(s)}{\hat{V}_g(s)} = \frac{G_{ig}(s)}{1 + T(s)}$$

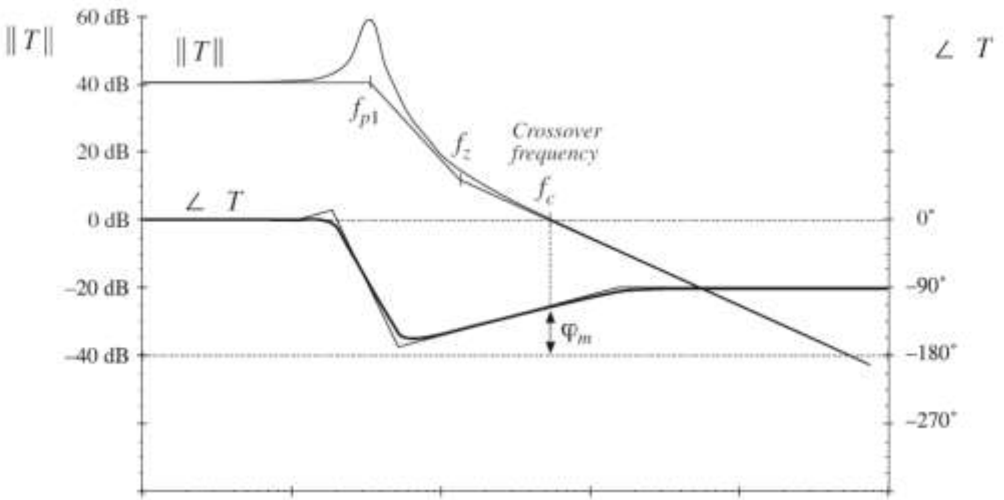


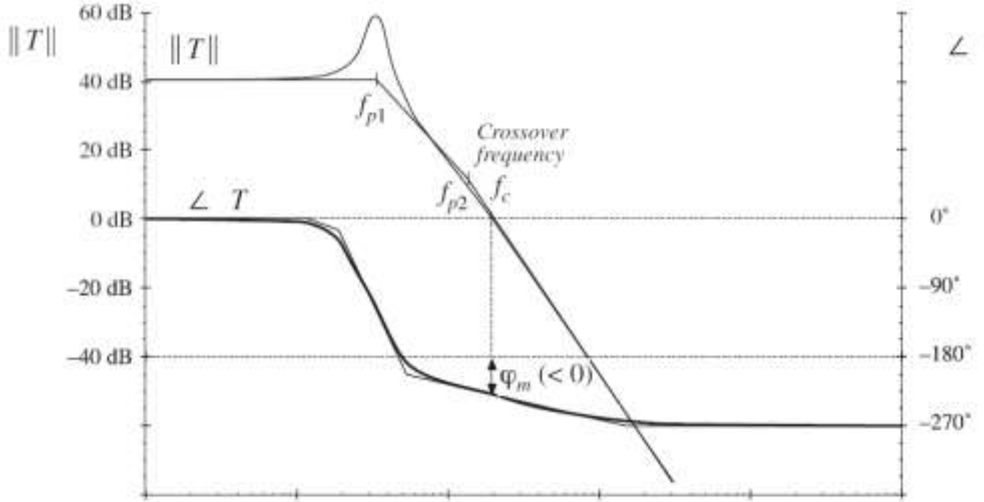
By closing loop, vibrations under frequency f_c are reduced, but high frequency vibrations just go though without damping.

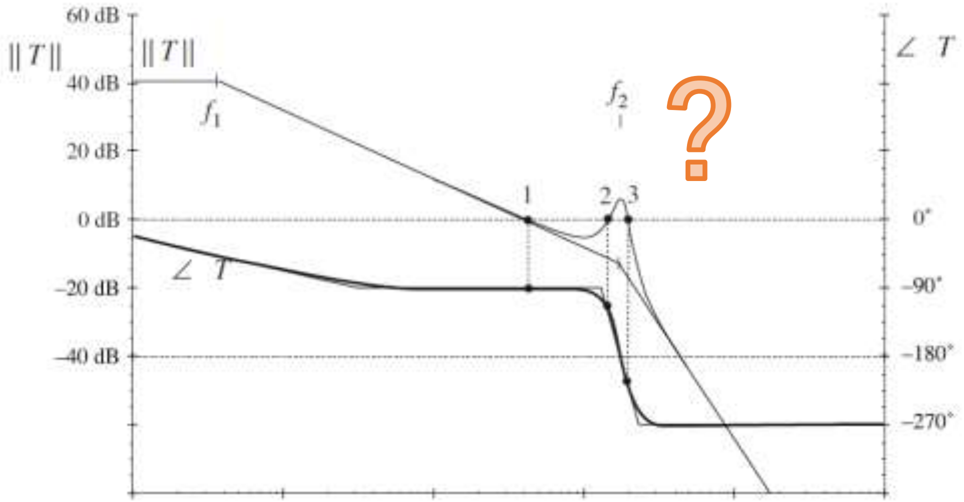
$$\|T\| \gg 1, \ \frac{\hat{i}(s)}{\hat{V}_g(s)} = \frac{1}{T(s)} G_{ig}(s)$$ *Vibration in V_g damped*

$$\|T\| \ll 1, \ \frac{\hat{i}(s)}{\hat{V}_g(s)} = G_{ig}(s)$$ *No damping*

Stability – phase margin





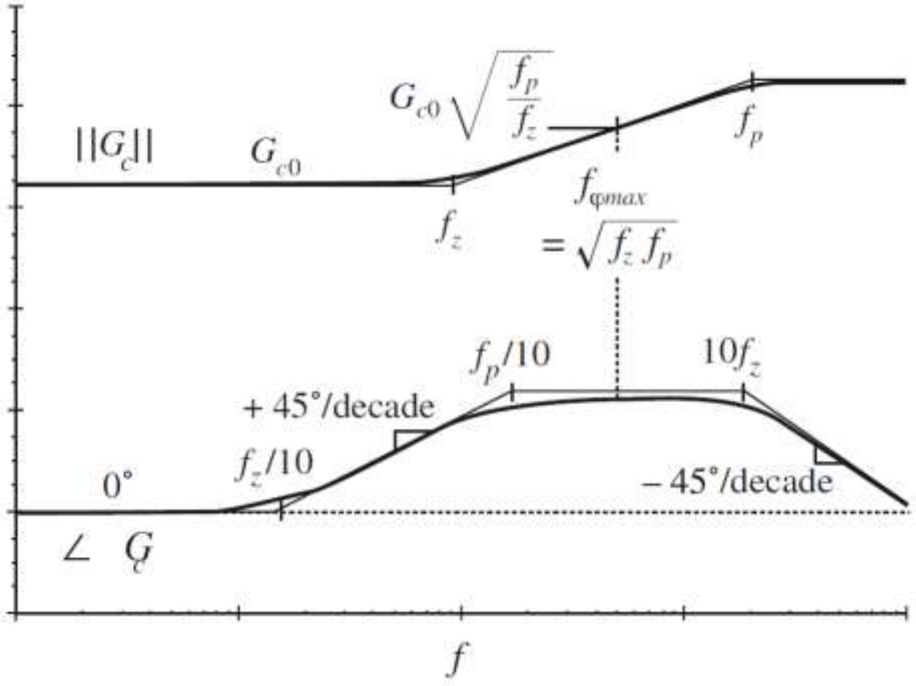


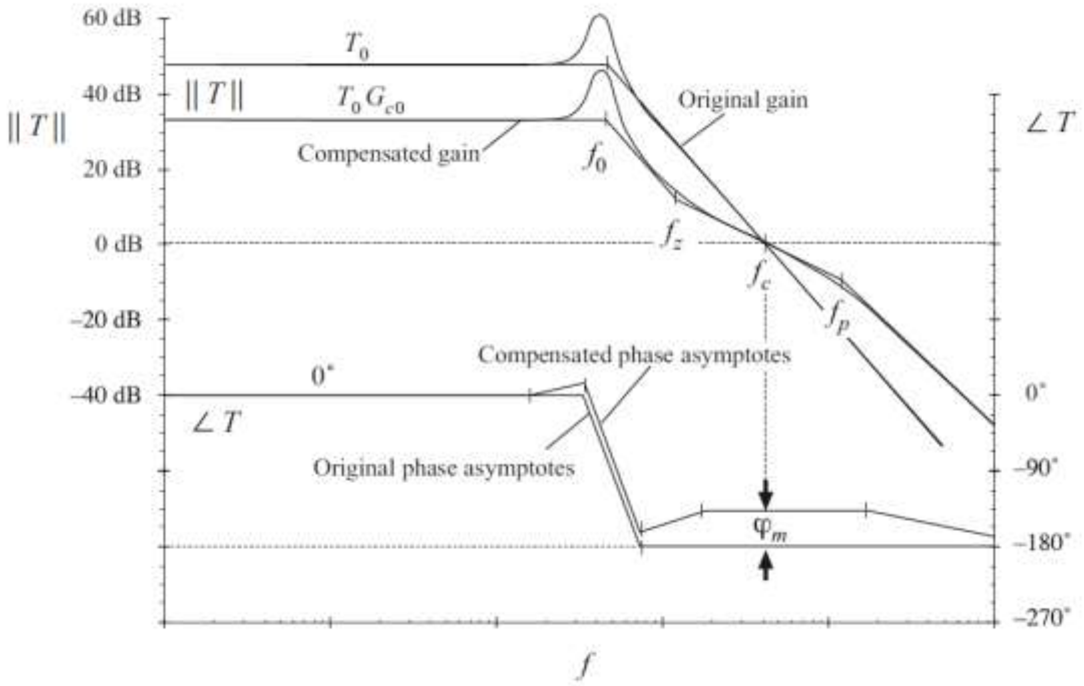
Go to Nyquist criterion

Only apply phase margin when:
No multiple crossovers;
No poles at origin.

Regulation – PD in Gc

$$G_c(s) = G_{c0}\frac{\left(1+\frac{s}{\omega_z}\right)}{\left(1+\frac{s}{\omega_p}\right)}$$



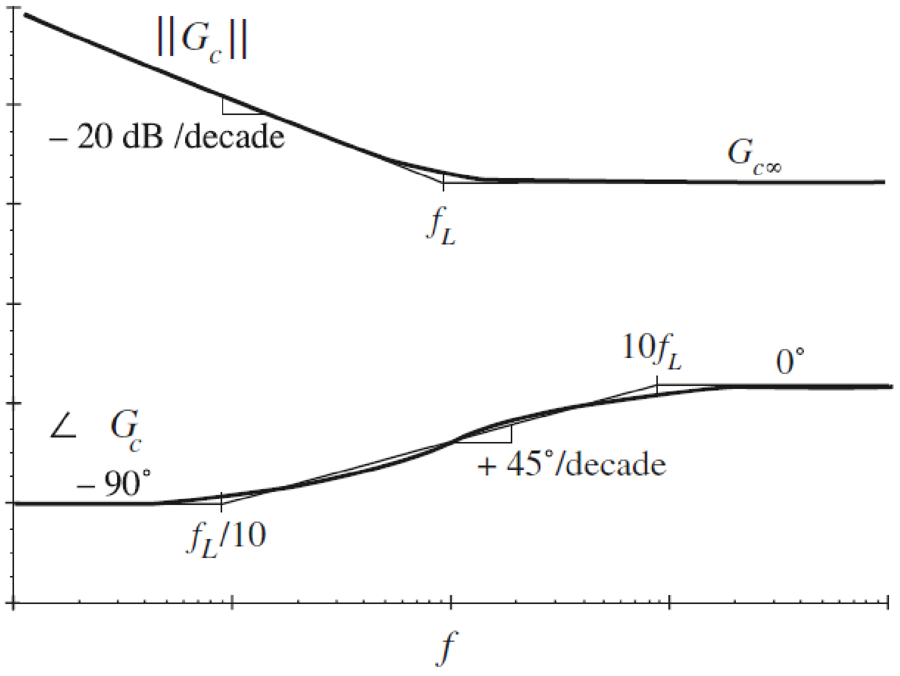


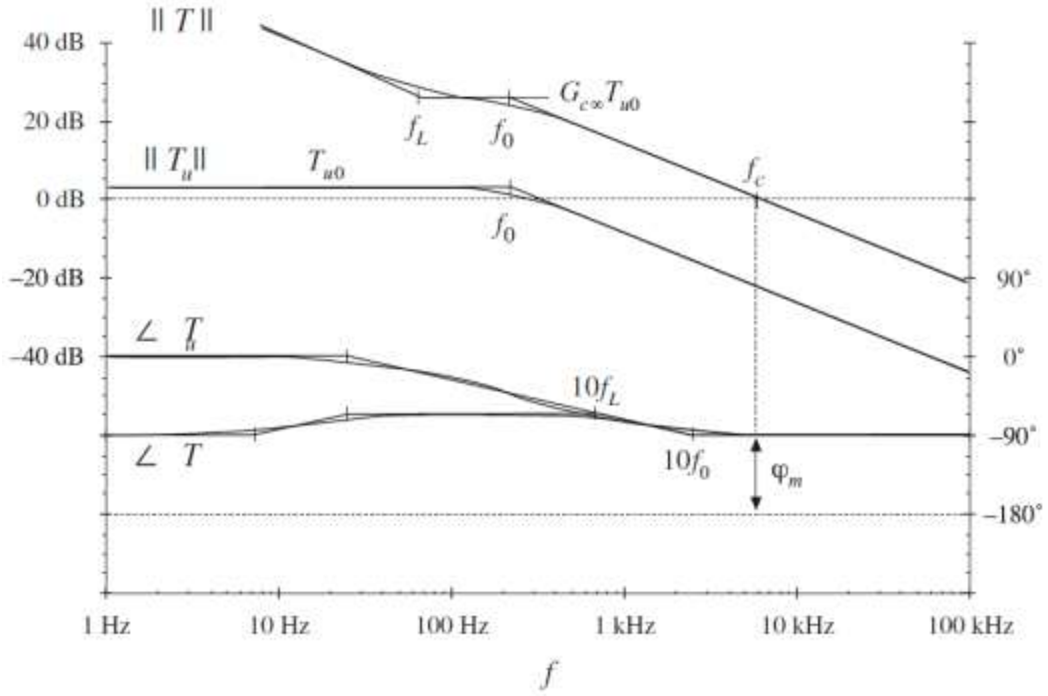
Increase phase margin;
Reduce tracking error.

Make system more sensitive to high frequency noises;
Reduce low frequency gain.

Regulation – PI for Gc

$$G_c(s) = G_{c\infty}\left(1 + \frac{\omega_L}{s}\right)$$





Reduce/eliminate DC and low-frequency error.

Enlarge overshoot;
Reduce phase margin;
Wind-up.

Summary

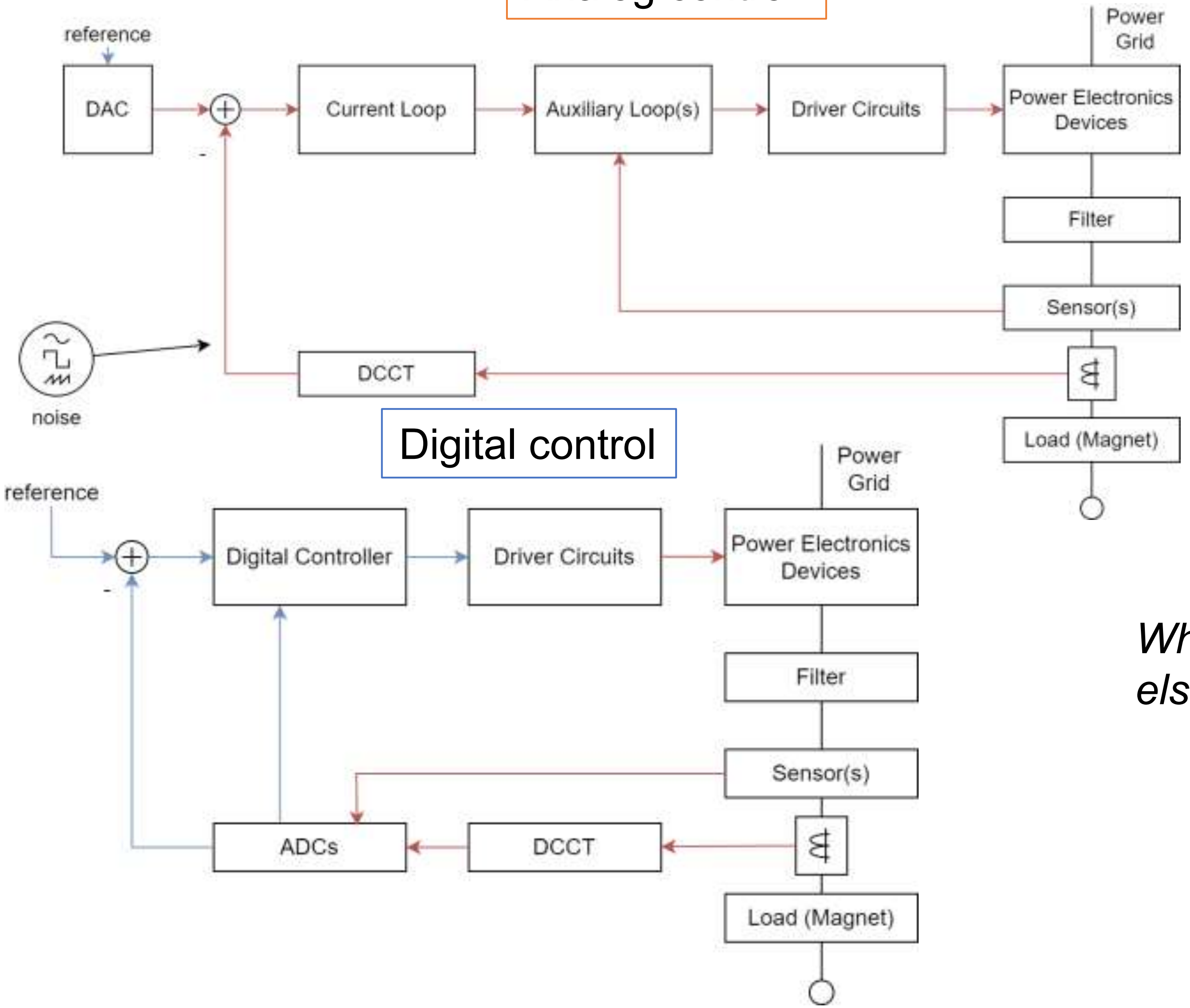
- AC small signal modeling
  - Out-to-Vg-TF;
  - Out-to-D-TF.
- TF analysis
  - Draw gain-loop bode diagram
  - Analyze the low-frequency gain, crossover frequency and phase margin, and high frequency gain…
  - Implant proper regulators as Gc to compensate the above diagram
- Evaluation
  - Simulation and examine the results

Control Hardware and Software

Analog vs Digital

Analog control

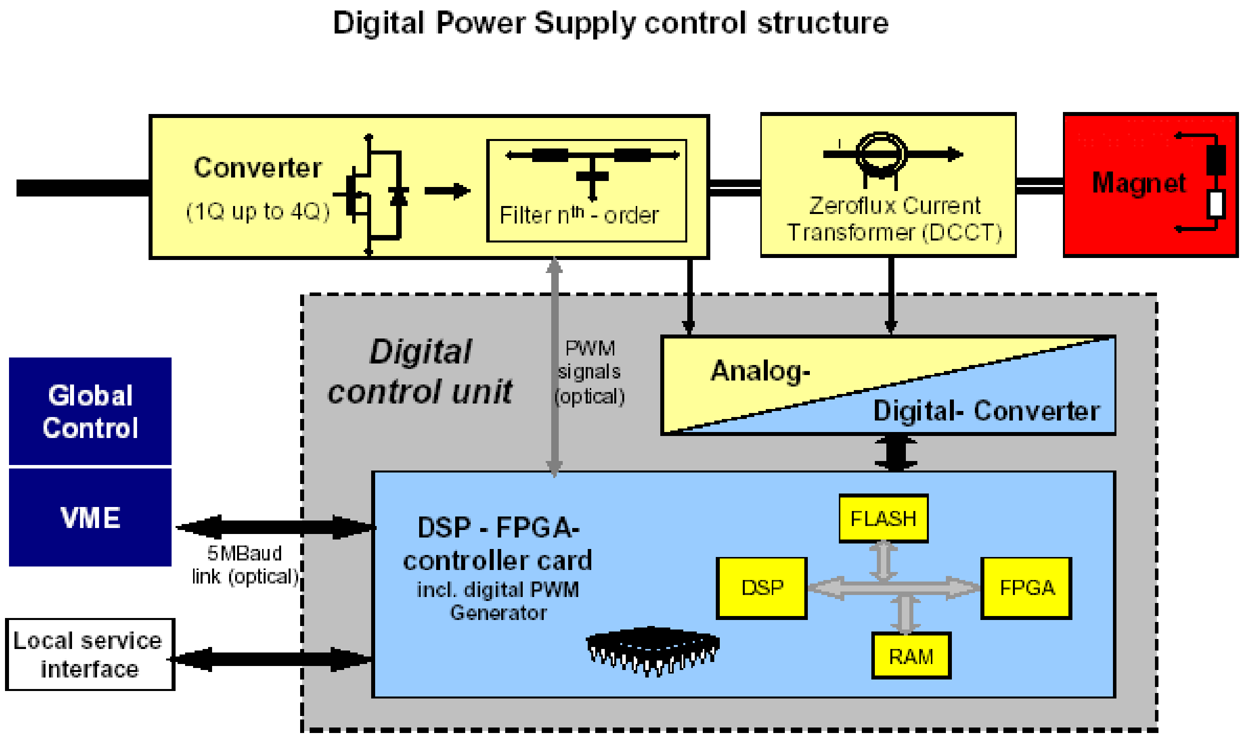
Digital control



- Noise preventing
- Simplicity
- Adjustability
- Versatility
- Maintenance
- Flexibility
- Speed

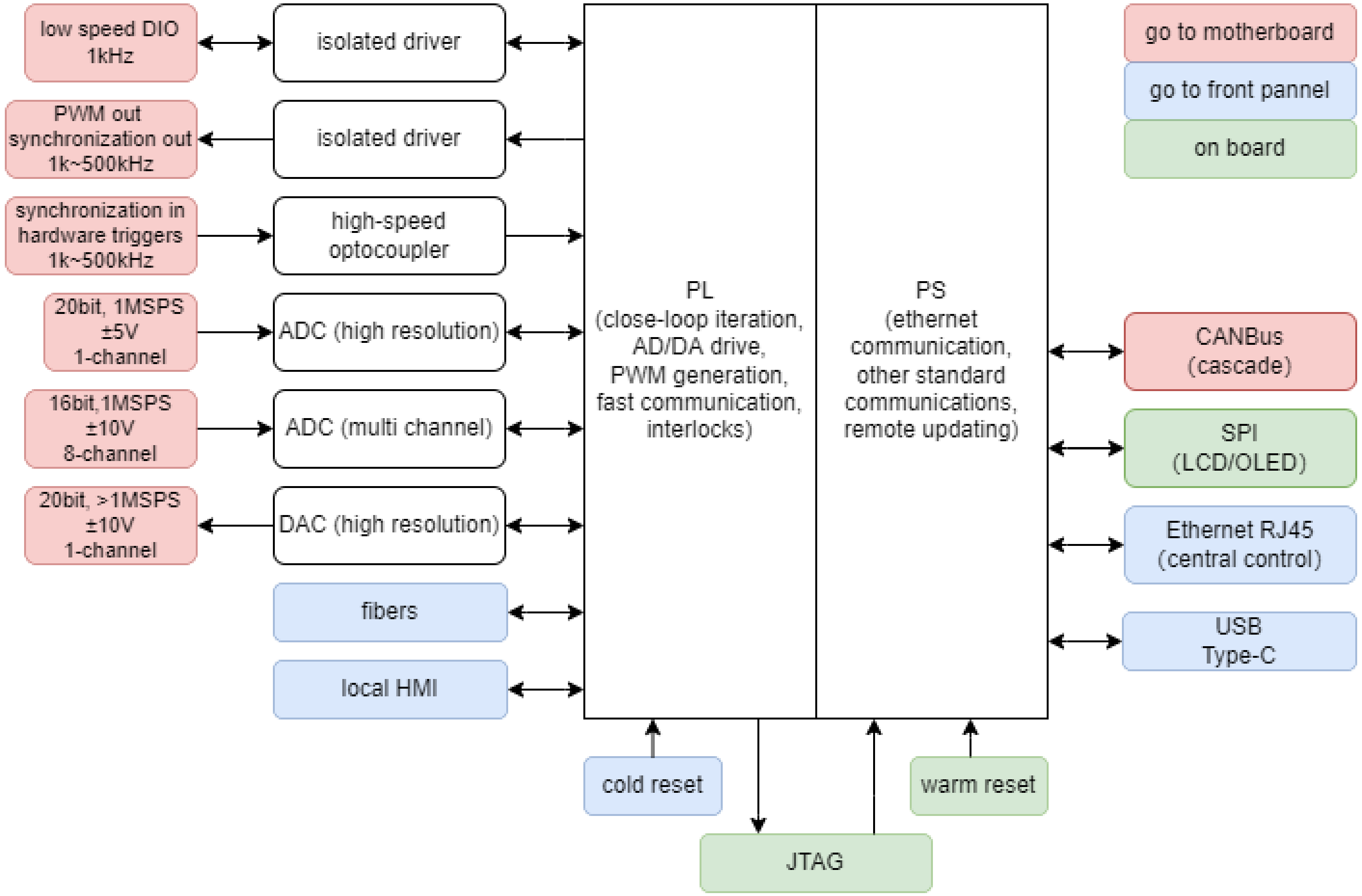
While digital controlling exceeds in everything else, analog controlling is good at SPEED.

Digital Controller Structure

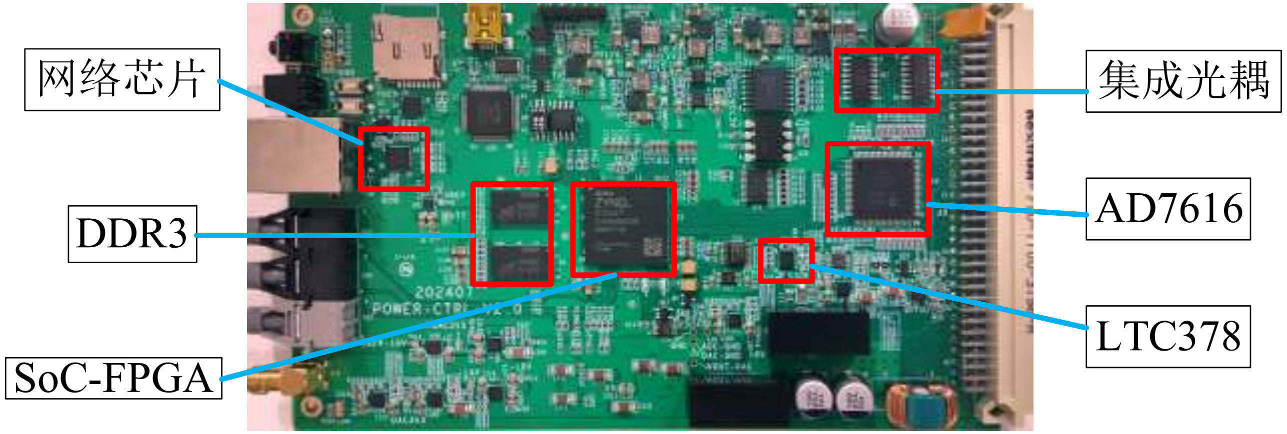


- Memory control
- IO control
- PWM generator
- Local and remote interface
- Analog to digital control
- Close-loop control

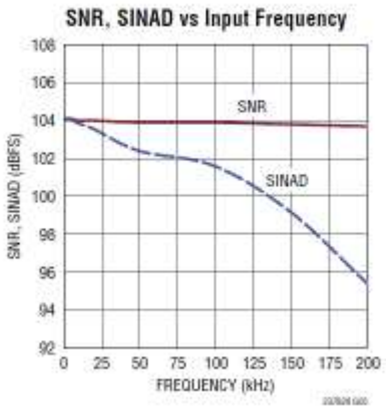
Processor and Peripherals



Key Devices



- High resolution AD
  - 1ppm => 10^{-20}
  - Switching freq. 100kHz => Controller DUC >100kHz => Sample rate > 200kHz (approx.)



$$\mathrm{ENOB} = \frac{\mathrm{SINAD_{dB}} - 1.76}{6.02} \approx 16.8\ \mathrm{bit}$$

$$\mathrm{RR@20k} = 2^{-16.8} \times \mathrm{FS_{AD}} = 8.76 \times 10^{-5}\,(\mathrm{V})$$

Bandwidth > 10kHz, Stability < 20ppm

⇩

There is a sine wave of 10kHz within 20ppm/FS_{PS}, you need to recognize it.

By properly choosing DCCT and I/V transmission, FS_{PS} ~ FS_{AD} (±5V).

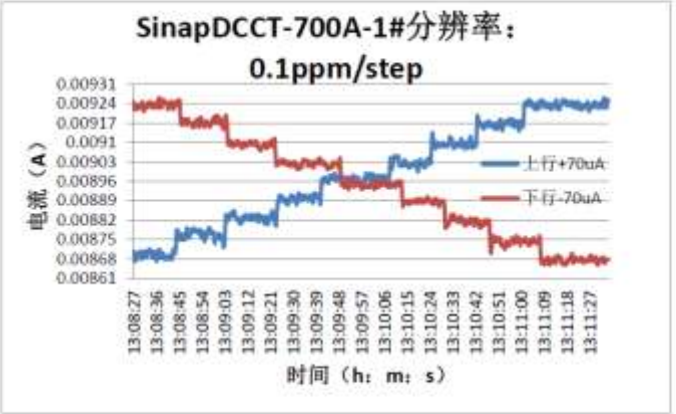
⇩

At 20kHz, AD must have a real resolution better than 10×10^{-5}V.

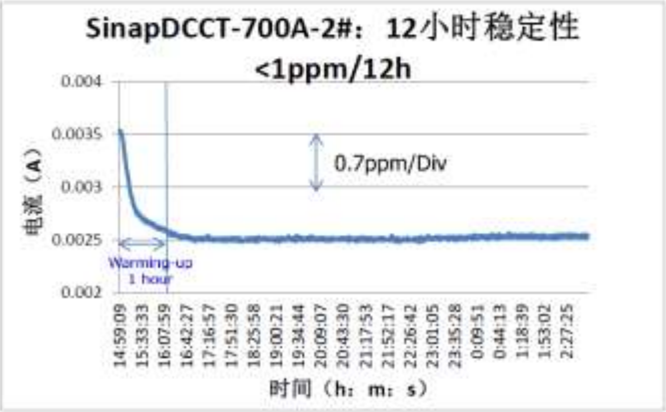
If not, try another ADC or over sampling techniques

Key Devices

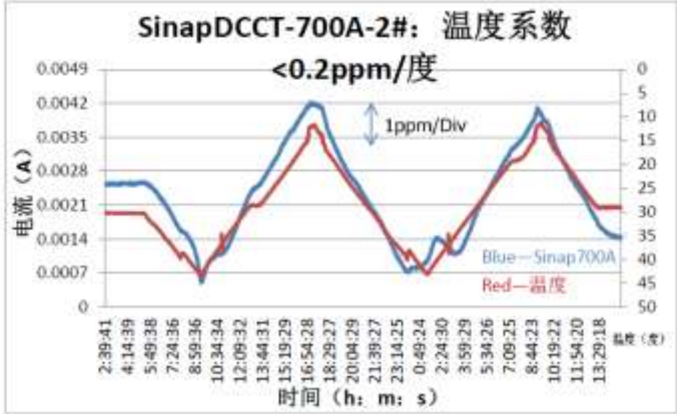
Resolution



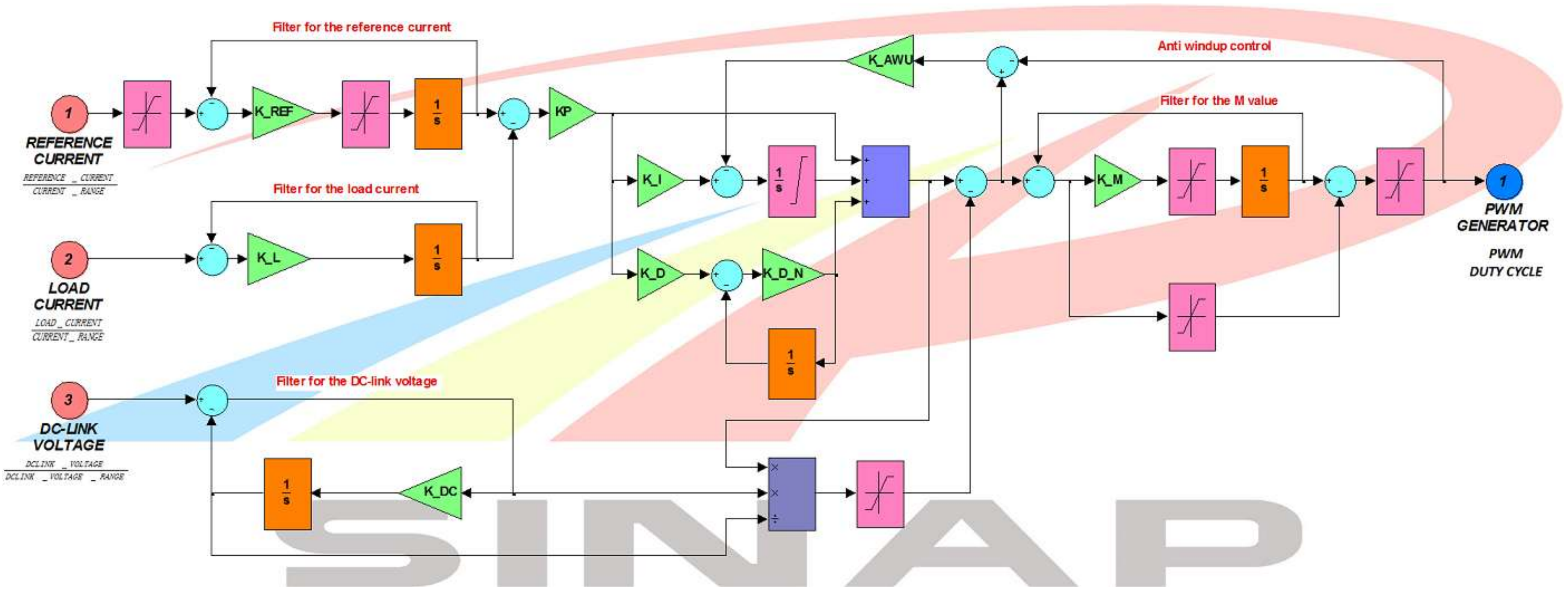
Stability



Temperature coefficient

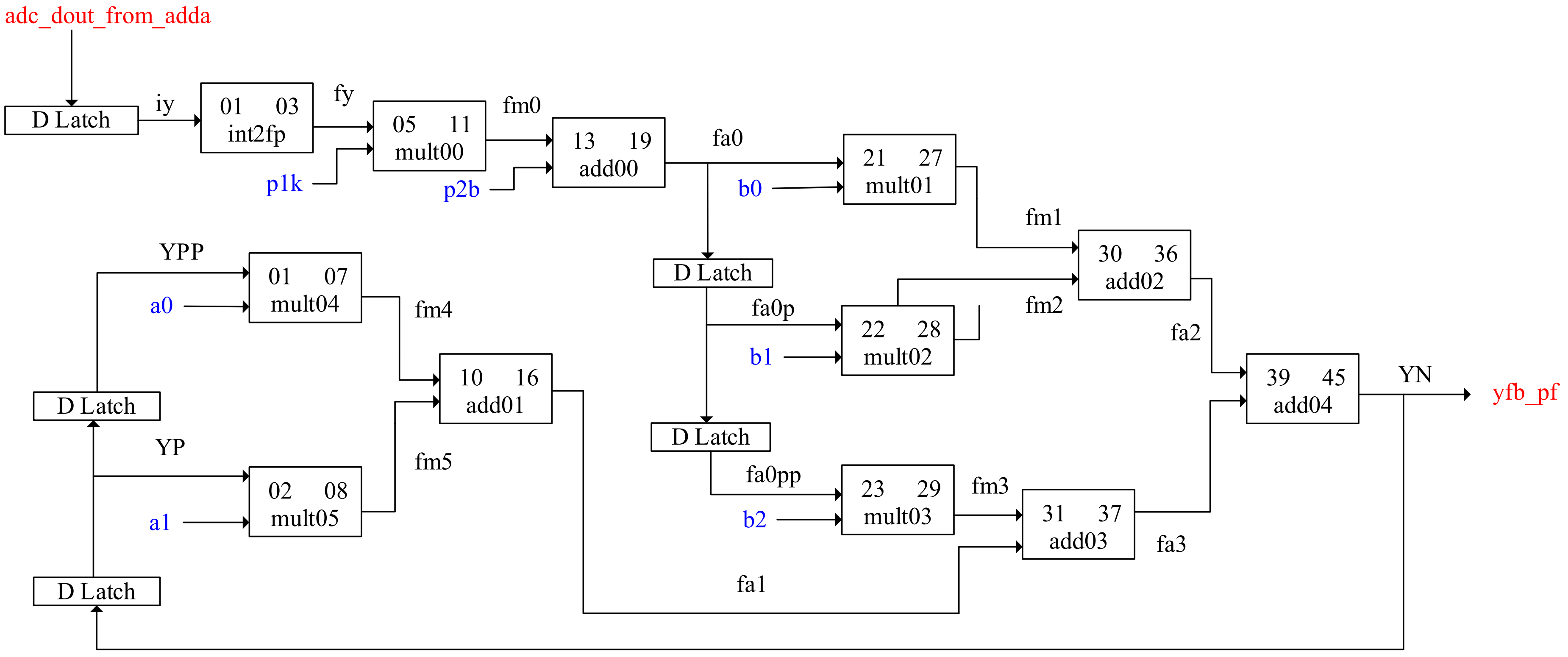


Close Loop Architecture

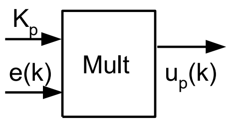


HDL of Difference Equations

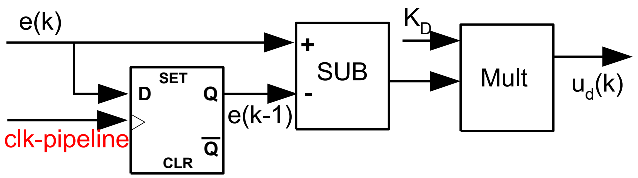
$$y(n) = b_0x(n) + b_1x(n-1) + b_2x(n-2) - a_1y(n-1) - a_2y(n-2)$$



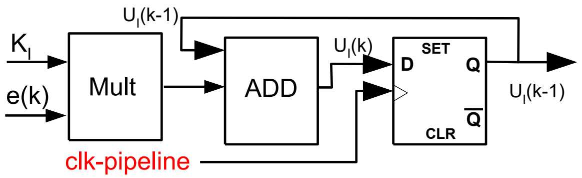
HDL of PID



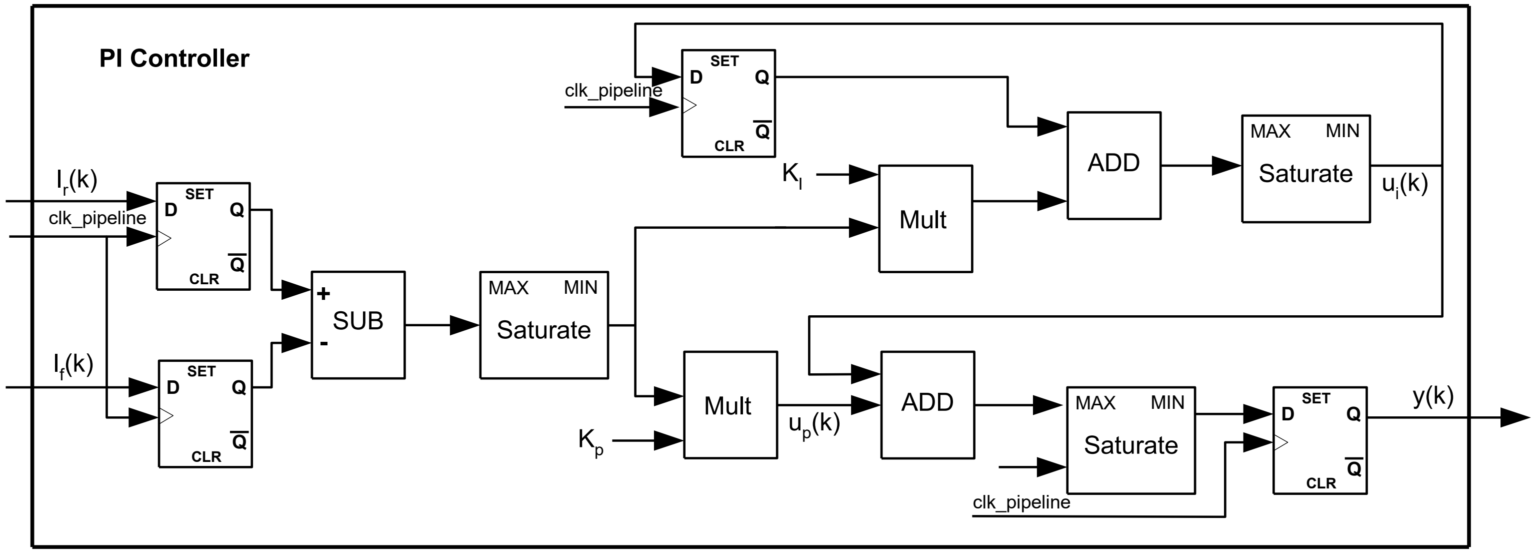
P



D



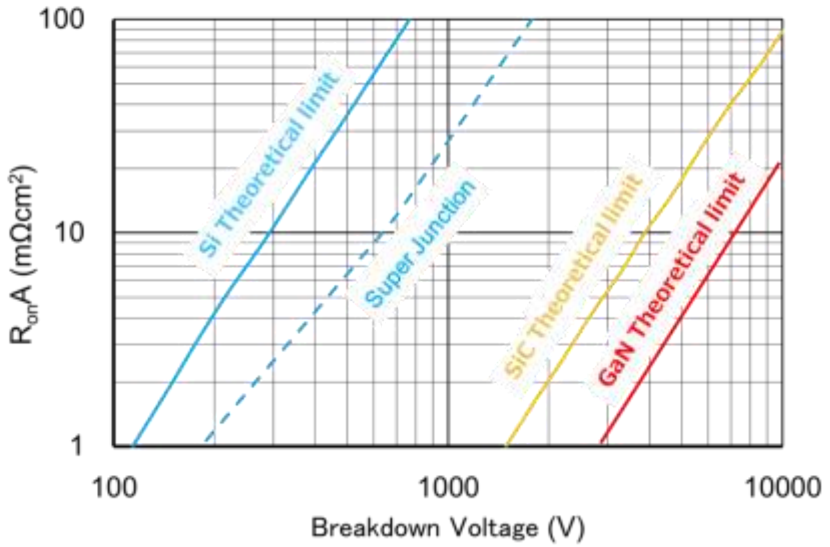
I

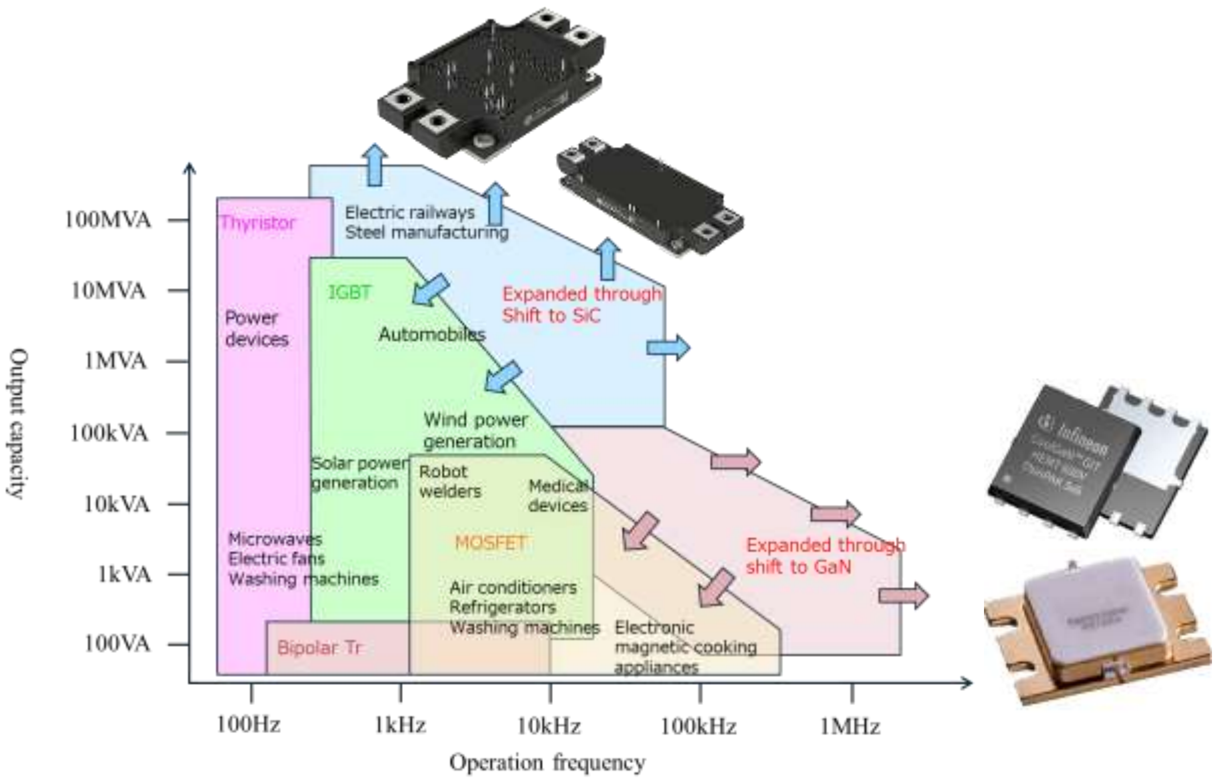


Challenges and Developments

Power Electronics Devices

Wide band gap semiconductors like SiC, GaN



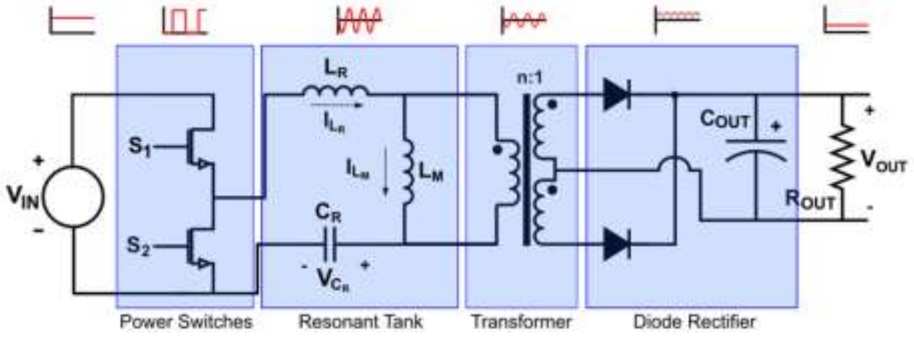


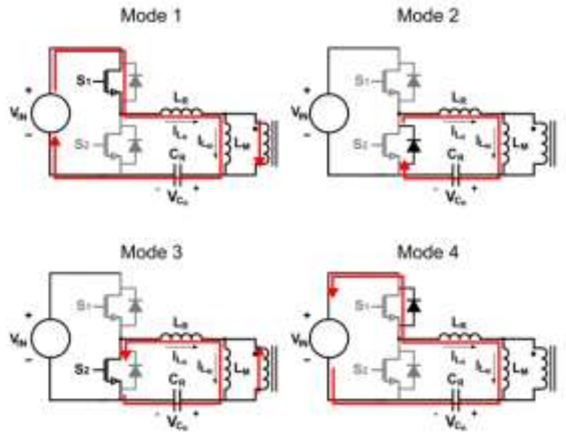
Lower Ron => lower loss

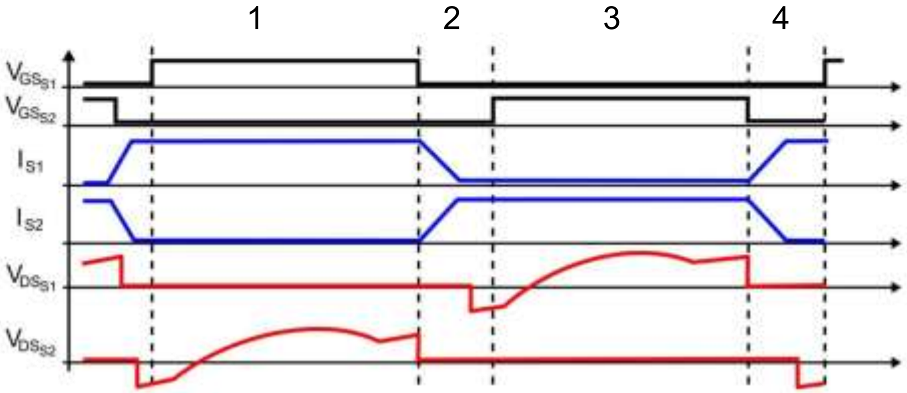
Higher thermal conductivity => more heat withstand

Topology

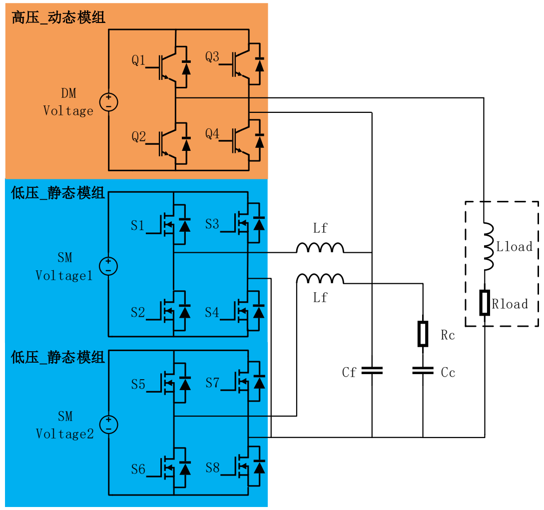
Soft-switching technique,
LLC resonant converter

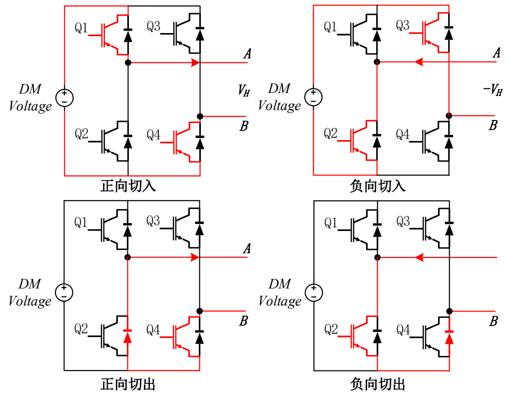


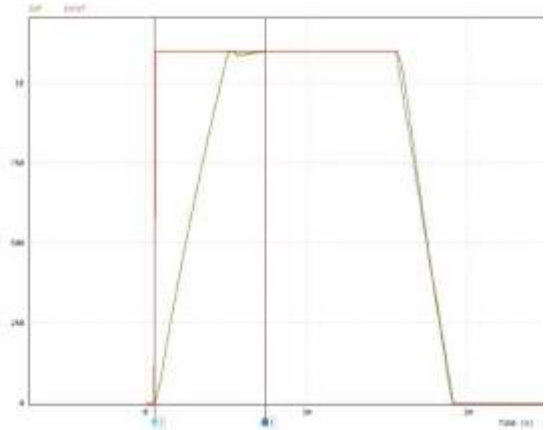




Super-fast scanner

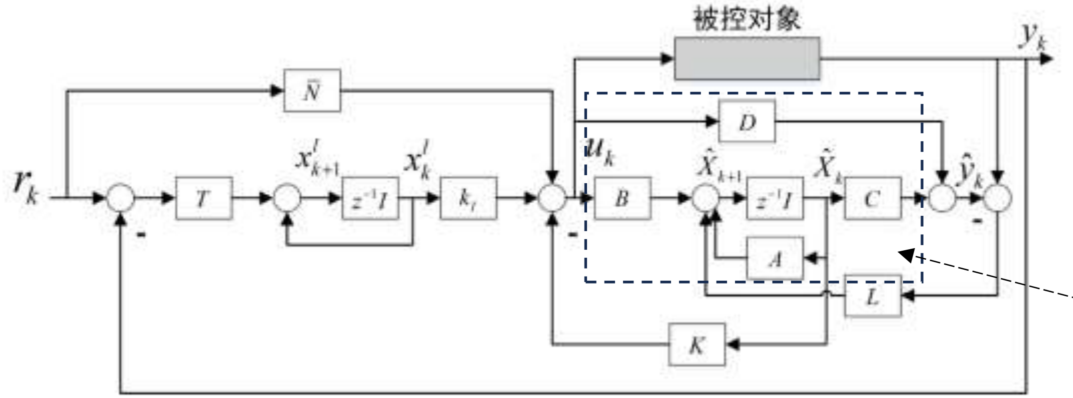


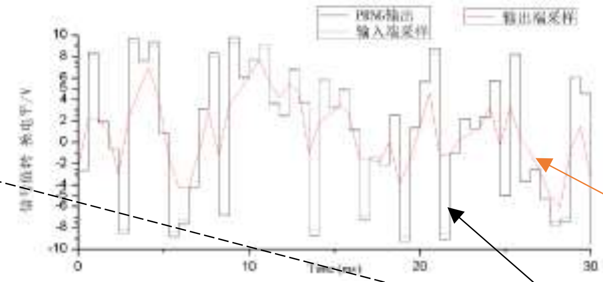


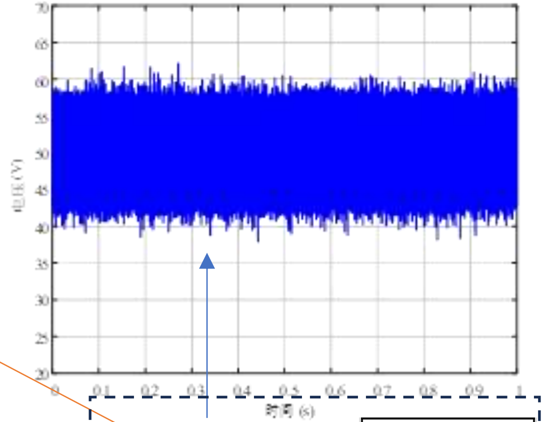


Modeling and Control Algorithm

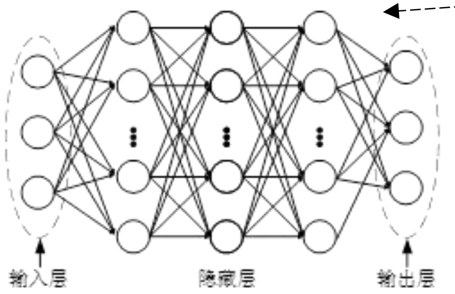
State space feedback and
observer identification

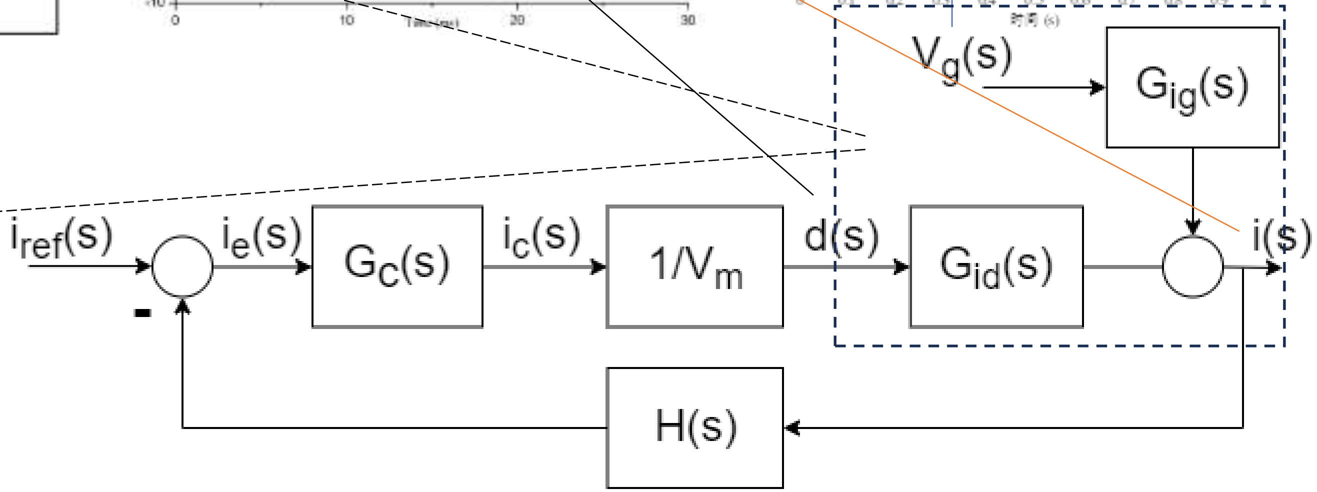






Self-adaptive
Non-linear
MIMO





Digital Intelligence

Intelligence in:

- Design
  - Unified auto-design and simulation scheme
- Modeling
  - “white box” + “black box” => closer circuit modeling to actual devices + better insight of data-based models.
- Controlling
  - State space feedback + observer
  - Optimal control
  - Non-linear control
- Running
  - On-line identification + on-board digital-twin
  - Failure snapshot + source locating + life forecasting
  - High-level AI-assisted evaluation + distributive analysis

THANKS FOR LISTENING

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