# Power Supply for accelerator

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# Content

- Power components;
- Power supply classification;
- Power supply parameters definitions;
- Regulation Loop;
- CSNS PS system;

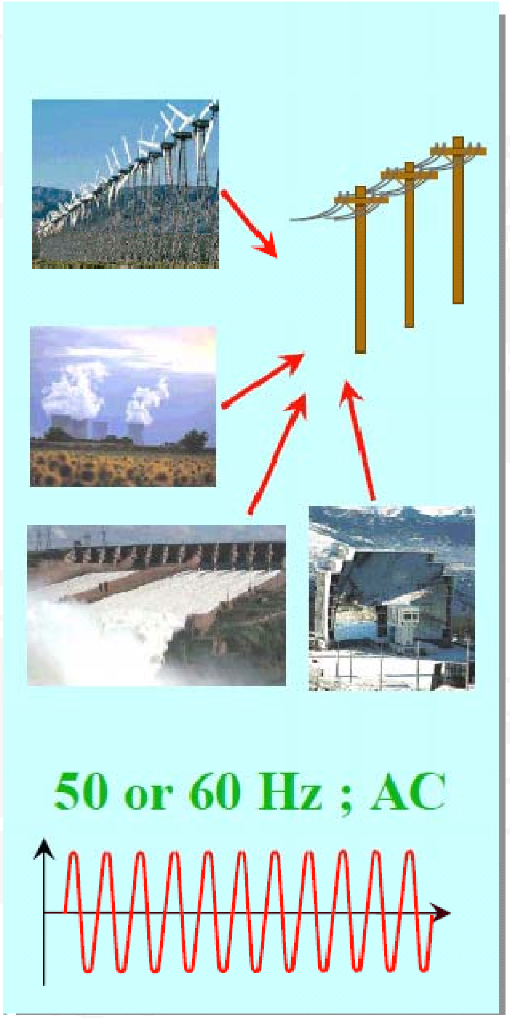
# Power electronics needs the knowledge of :

- Power electronic devices;
- Regulation theory;
- High precision measurement;
- Analog circuit technology;
- Digital circuit technology;
- Mechanical capabilities;
- Cooling technology;
- Control system;
- Databases;
- Programming, internet, FPGAs, DPSs, PLCs……;
- Simulation tools.

# Content

- Power components;
- Power supply classification;
- Power supply parameters definitions;
- Regulation Loop;
- CSNS PS system;

# Energy source → Applications




## Power supply (Power converter)

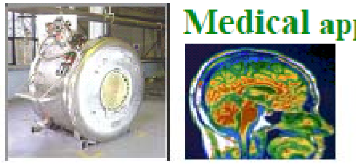
**The task for a PS is to process and control the flow of electric energy by voltages and currents in a form that is optimally suited for user loads**

↑

**control**

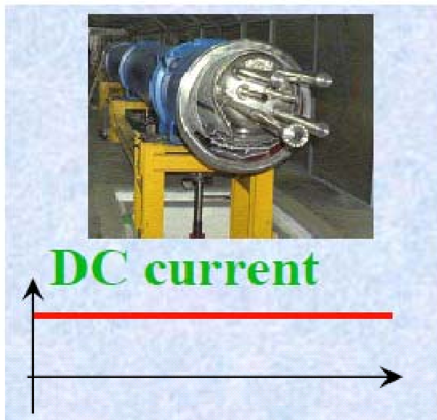
Traction and auxiliary

Domestic Appliance



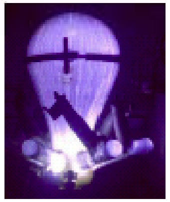
Medical applications

Indutrial applications, Welding, Induction Heating, ….



# Evolution of Power semiconductors

From mercury arc rectifier, grid-controlled vacuum-tube rectifier, inignitron ,….



# Power Electronics

## From 1960

Power Diode and Thyristor

or SCR (Silicon-Controlled Rectifier )

Link to frequency of the electrical network 50 Hz (60 Hz)

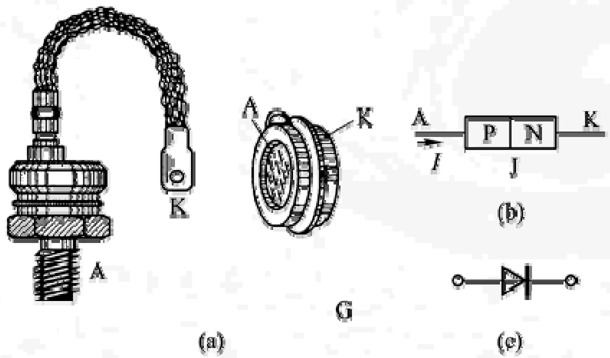
## From 1985

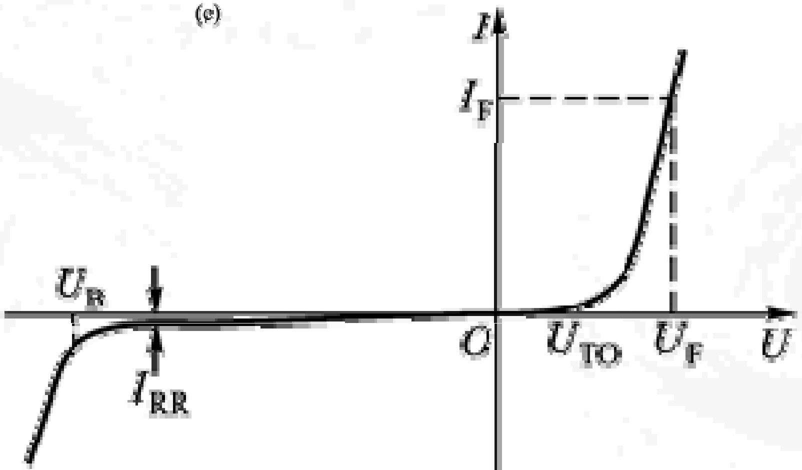
High frequency power semiconductors :

MosFet, IGBTs , GTOs, MCTs,….

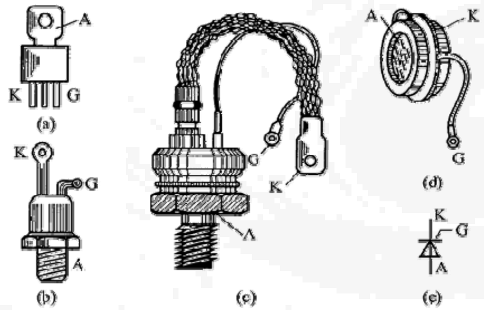
High frequency => high performances (ripple, bandwidth, perturbation rejection,...)
small magnetic (volume, weight)

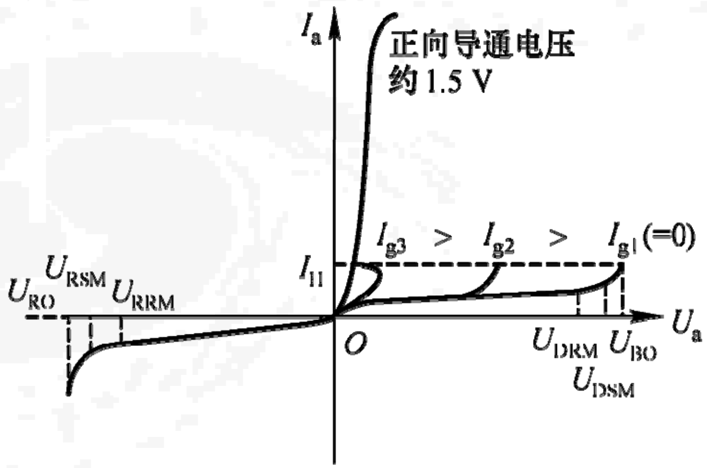
# Power Diode



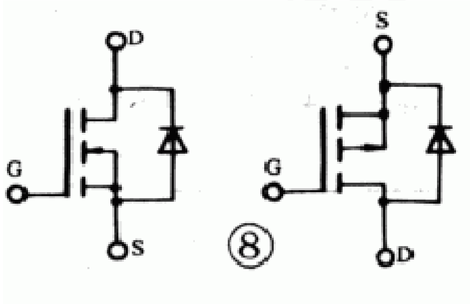



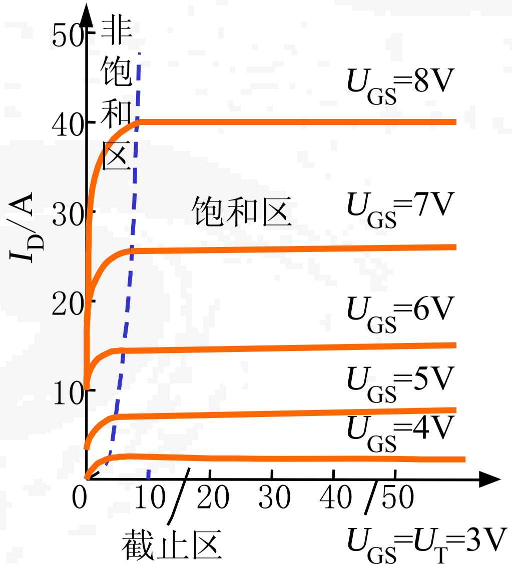
# Thyristor


A
K
G
(a)
(b)
(c)
(d)
(e)


正向导通电压
约 1.5 V
I_a
I_g3 > I_g2 > I_g1 (=0)
I_H
U_RSM
U_RO
U_RRM
O
U_DRM
U_BO
U_DSM
U_a

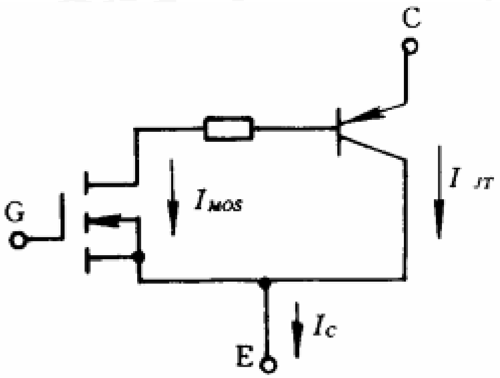
# MOSFET (MetalOxide Semicoductor Field Effect Transistor )



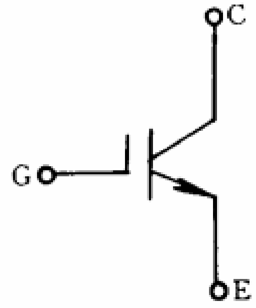





# IGBT (Insulated Gate Bipolar Transistor)

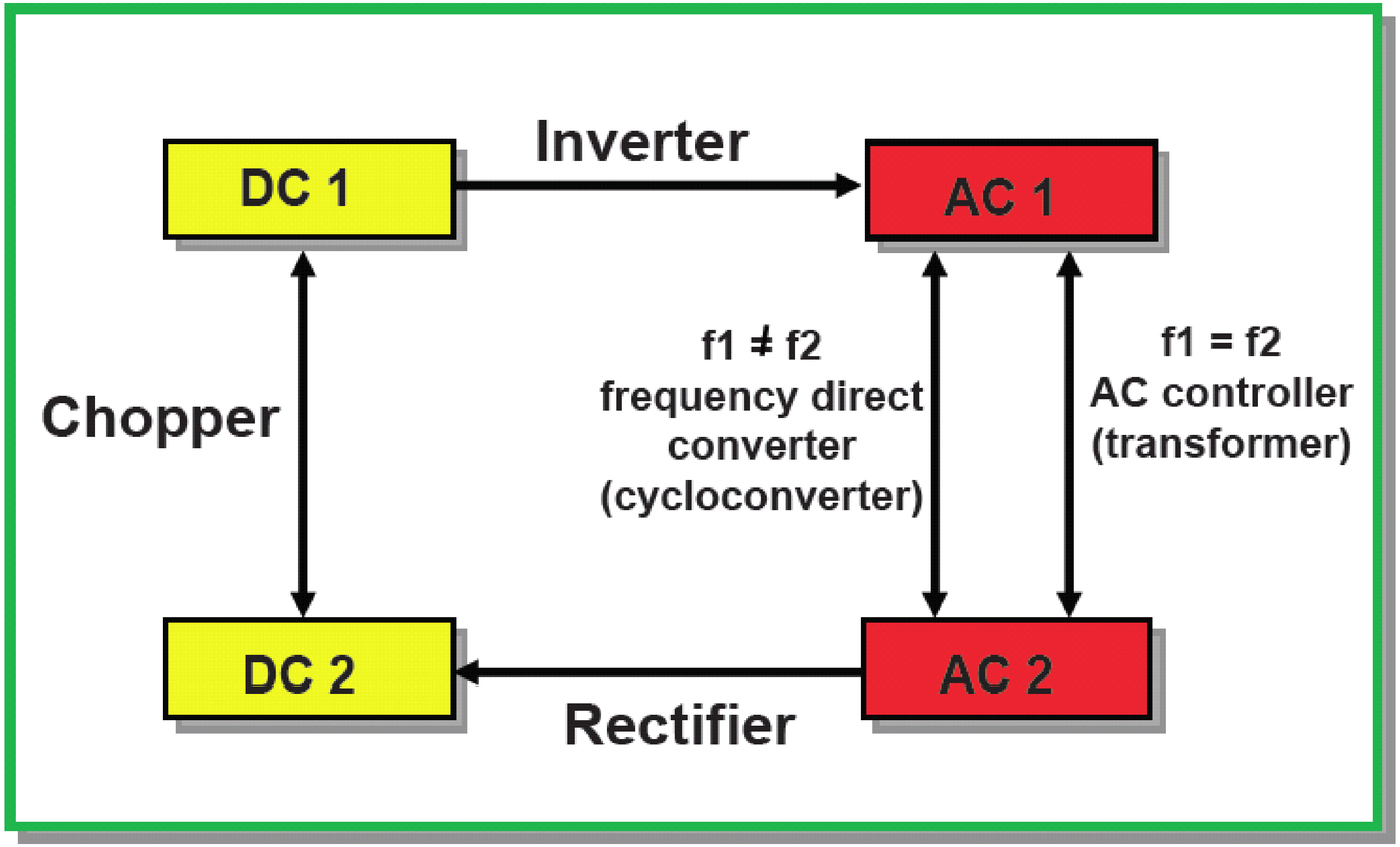


(a)



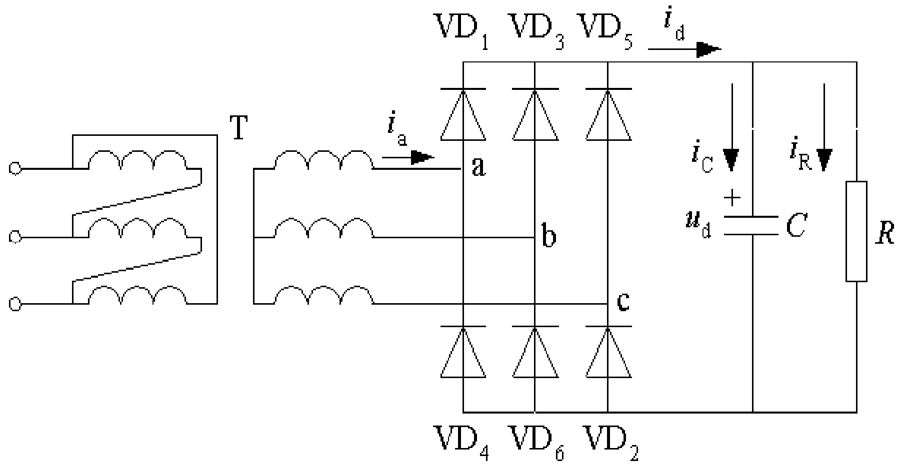
(b)

- Power components;
- **Power supply classification;**
- Power supply parameters definitions;
- Regulation Loop;
- CSNS PS system;

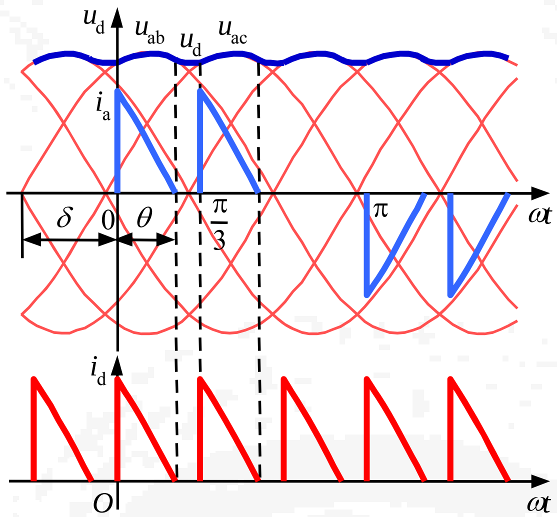



# Power Supply classification

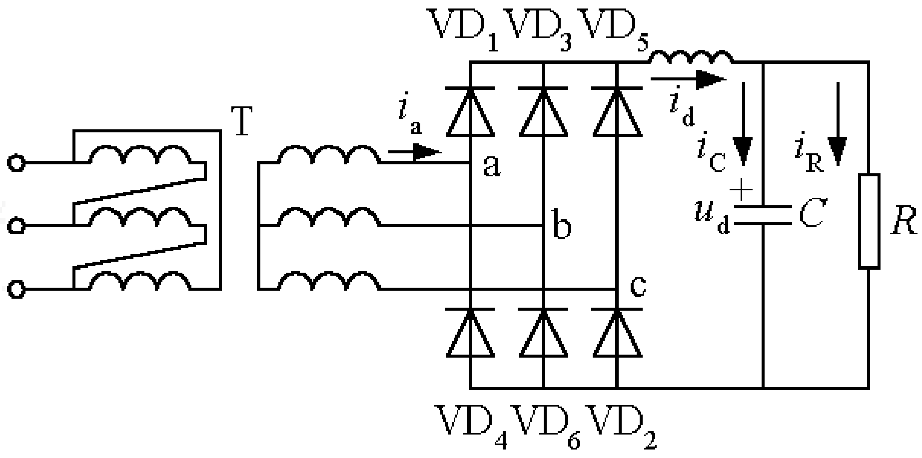
# Diode Rectifier



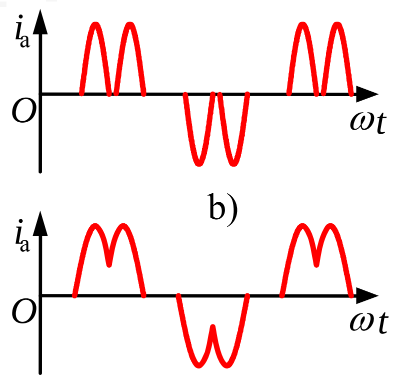

a)




b)




a)




b)

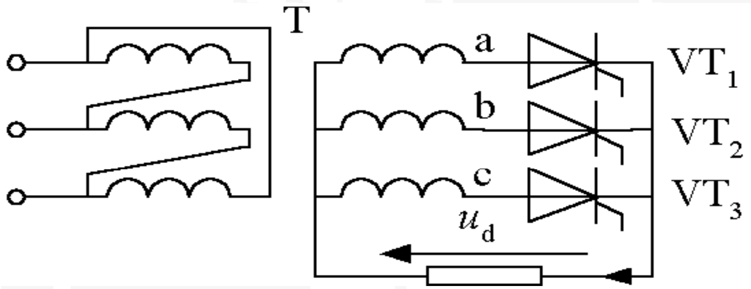
c)

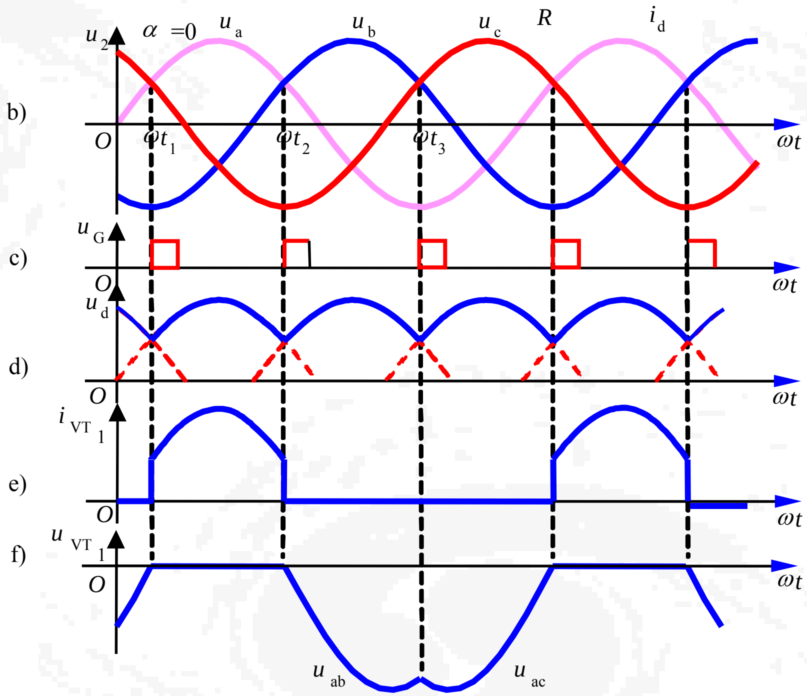
$$U_d = (2.34 \sim 2.45U)$$

$$I_R = U_d / R$$

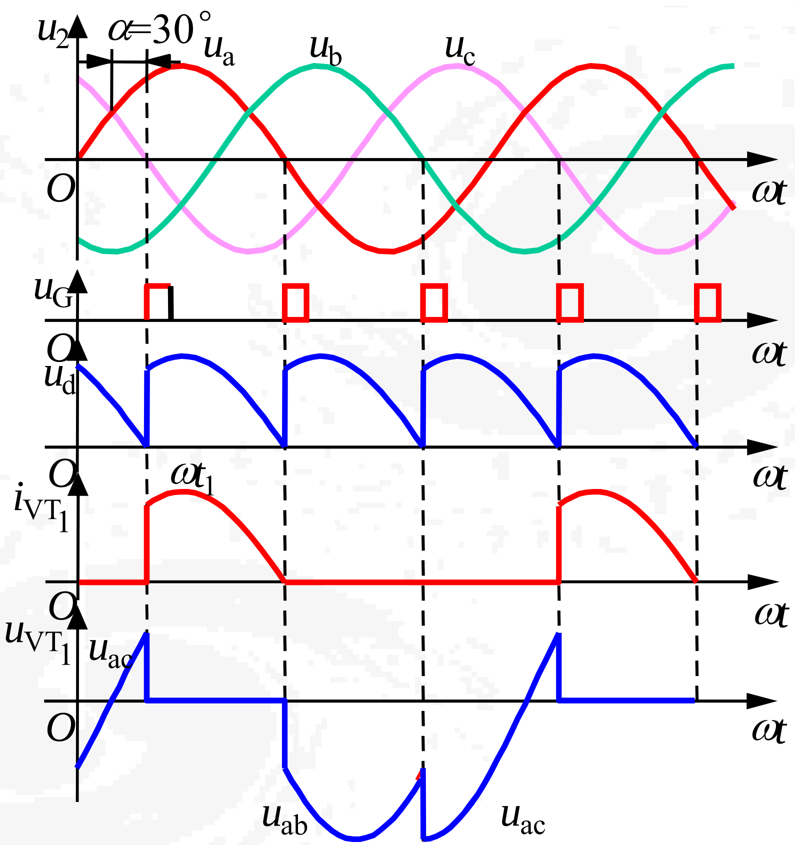
$$I_D = I_d / 3 = I_R / 3$$

# SCR (Silicon Controlled Rectifier)

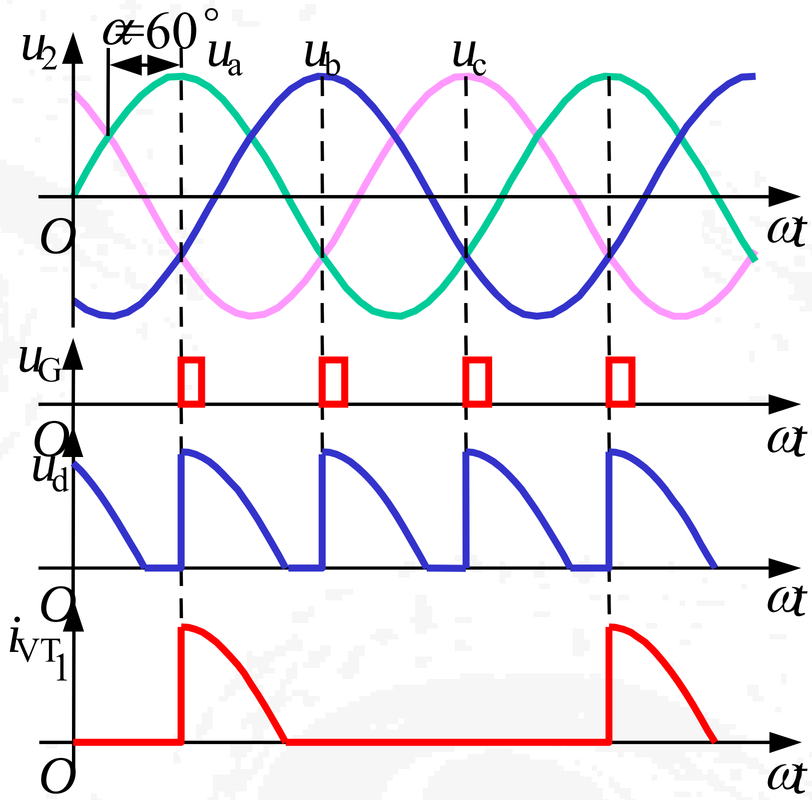



## Half wave SCR



u2
α=30°
ua
ub
uc
O
ωt
uG
O
ωt
ud
O
ωt
ωt1
iVT1
O
ωt
uVT1
uac
O
ωt
uab
uac

u2
α=60°
ua
ub
uc
O
ωt
uG
O
ωt
ud
O
ωt
iVT1
O
ωt

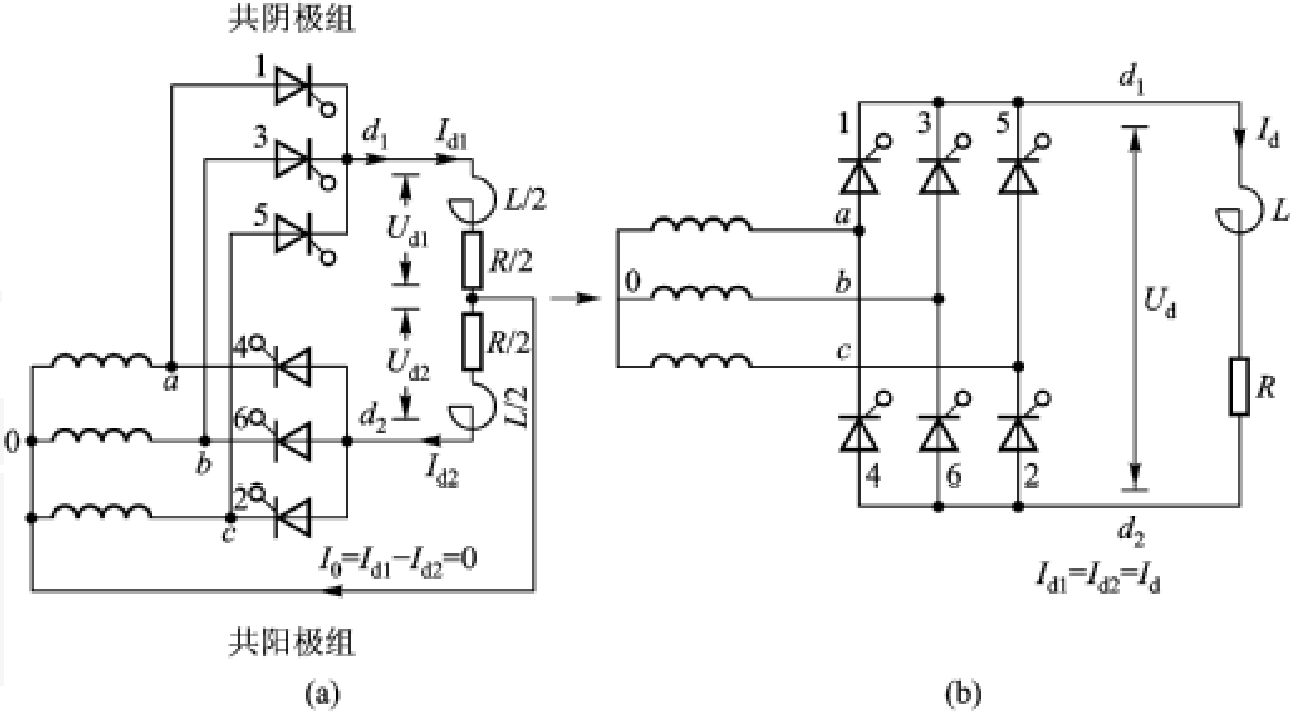
a≤30°

$$U_d = \frac{1}{\frac{2\pi}{3}} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} \sqrt{2}U_2 \sin \omega t d(\omega t) = \frac{3\sqrt{6}}{2\pi} U_2 \cos\alpha = 1.17 U_2 \cos\alpha$$

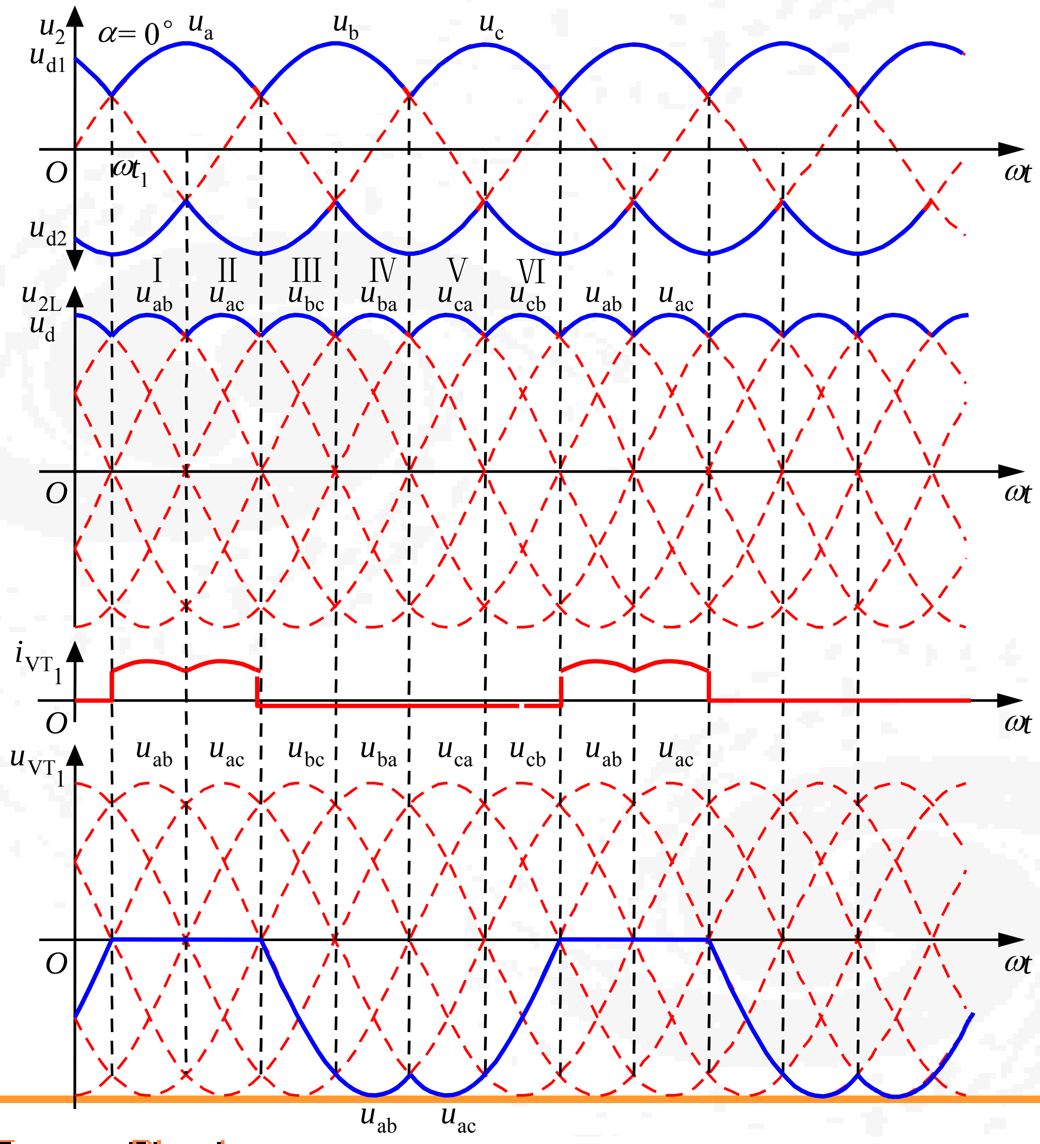
a>30°

$$U_d = \frac{1}{\frac{2\pi}{3}} \int_{\frac{\pi}{6}+\alpha}^{\pi} \sqrt{2}U_2 \sin \omega t d(\omega t) = \frac{3\sqrt{2}}{2\pi} U_2 \left[1 + \cos(\frac{\pi}{6} + \alpha)\right] = 0.675 \left[1 + \cos(\frac{\pi}{6} + \alpha)\right]$$

# Full Bridge SCR

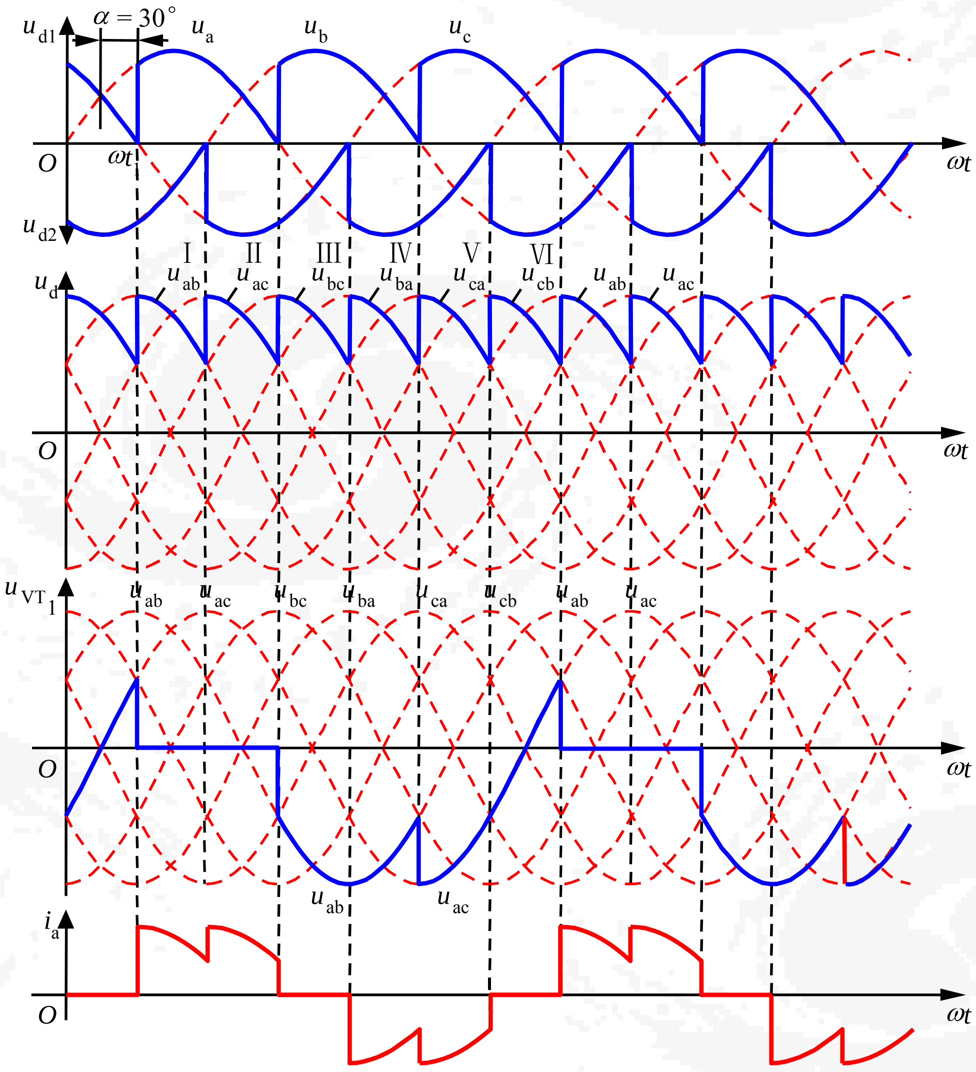


# α=0°



u2
ud1
α= 0°
ua
ub
uc
O
ωt1
ωt
ud2
I
II
III
IV
V
VI
u2L
ud
uab
uac
ubc
uba
uca
ucb
iVT1
uVT1

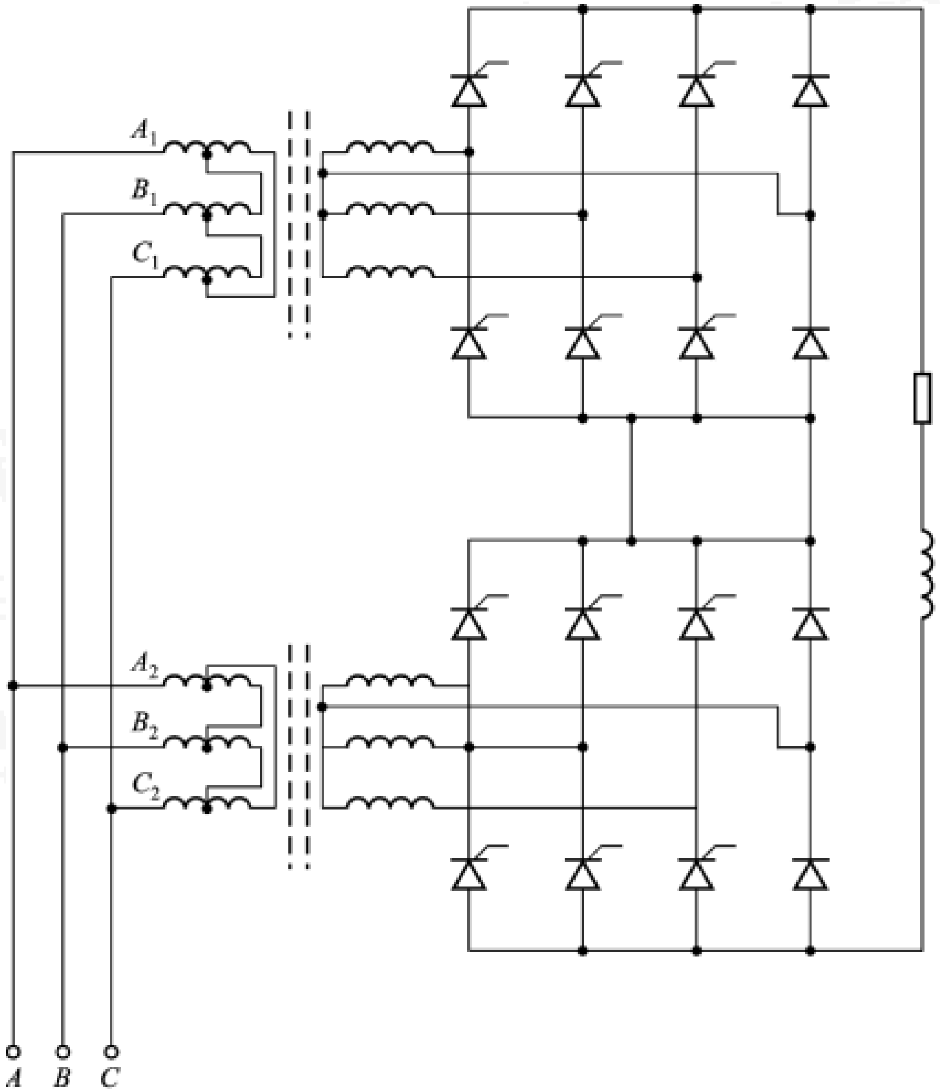
# α=30°


$u_{d1}$
$\alpha = 30°$
$u_a$
$u_b$
$u_c$
O
ωt
ωt
$u_{d2}$
I
II
III
IV
V
VI
$u_{ab}$ $u_{ac}$ $u_{bc}$ $u_{ba}$ $u_{ca}$ $u_{cb}$ $u_{ab}$ $u_{ac}$
$u_d$
O
ωt
$u_{VT_1}$
$u_{ab}$ $u_{ac}$ $u_{bc}$ $u_{ba}$ $u_{ca}$ $u_{cb}$ $u_{ab}$ $u_{ac}$
O
ωt
$u_{ab}$
$u_{ac}$
$i_a$
O
ωt

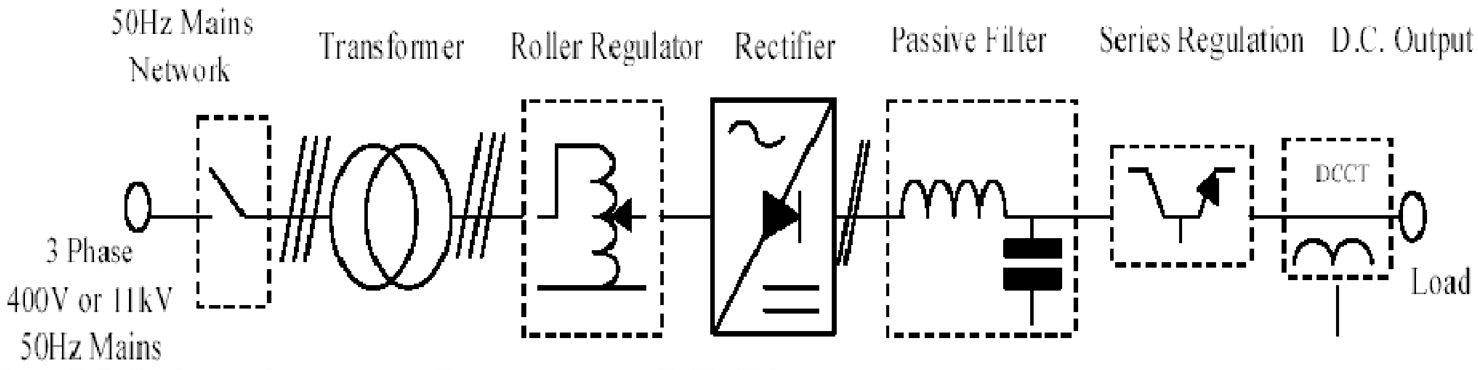
***a*≤60°**

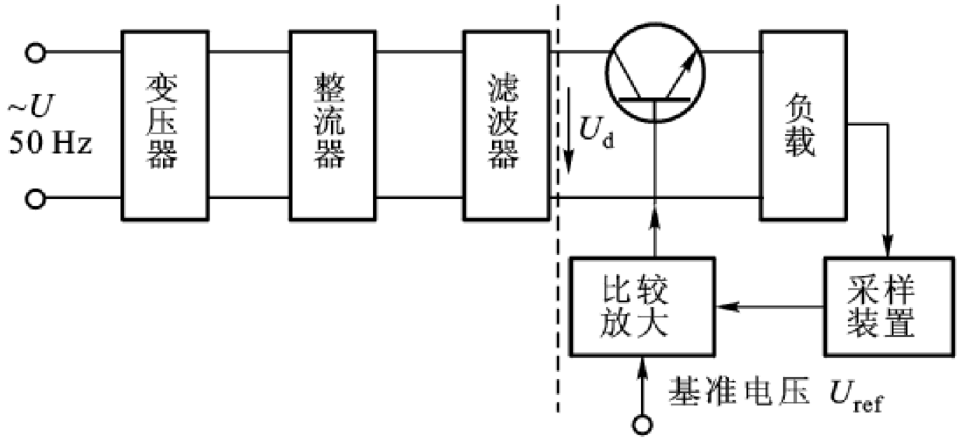
$$U_d = \frac{1}{\frac{\pi}{3}} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} \sqrt{6}U_2 \sin \omega t d(\omega t) = 2.34 U_2 \cos \alpha$$

$$I_d = U_d / R$$


A1
B1
C1
A2
B2
C2
A
B
C

# Line Regulation Power Supply

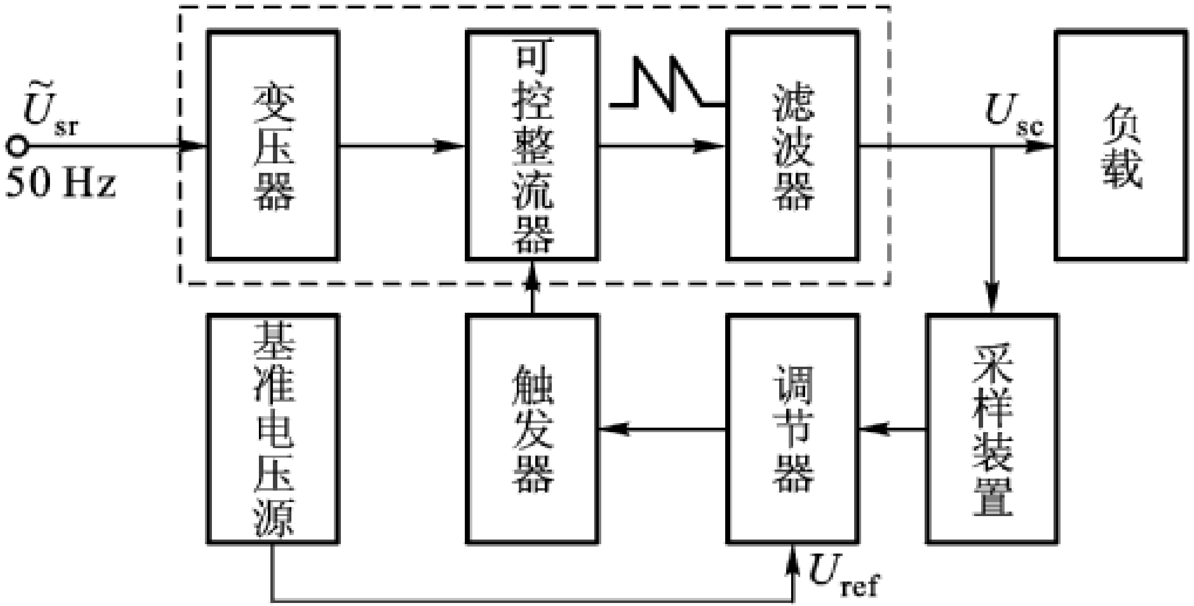


# characteristic

- **Advantage**
  - **Main circuit is simple;**
  - **Fast dynamic;**
  - **Low ripple;**
  - **Low noise;**
- **Disadvantage**
  - **Low efficient;**
  - **Large value and weight;**

# SCR Power Supply



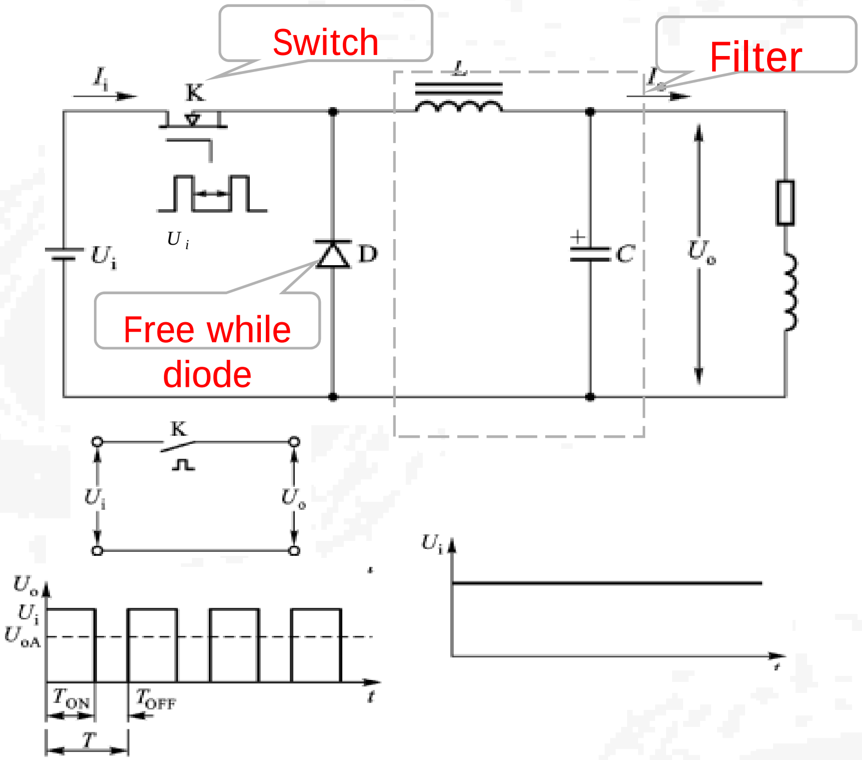
# characteristic

- **Advantage**
  - **Main circuit is simple;**
  - **Big power ratio;**
  - **Noise;**
  - **efficient;**
- **Disadvantage**
  - **Large value and weight;**
  - **High ripple;**
  - **DC;**

# Switch Mode Power Supply

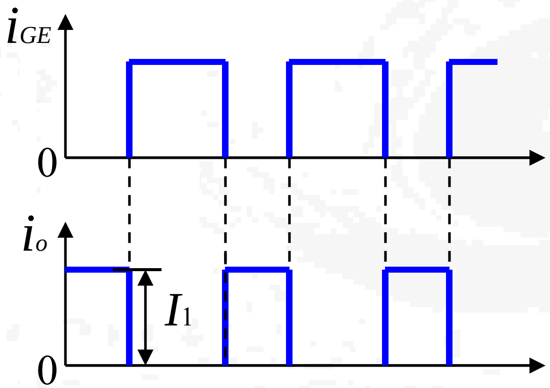
- **PWM : Pulse Width Modulation;**
- **IGBT, MOSFET…;**

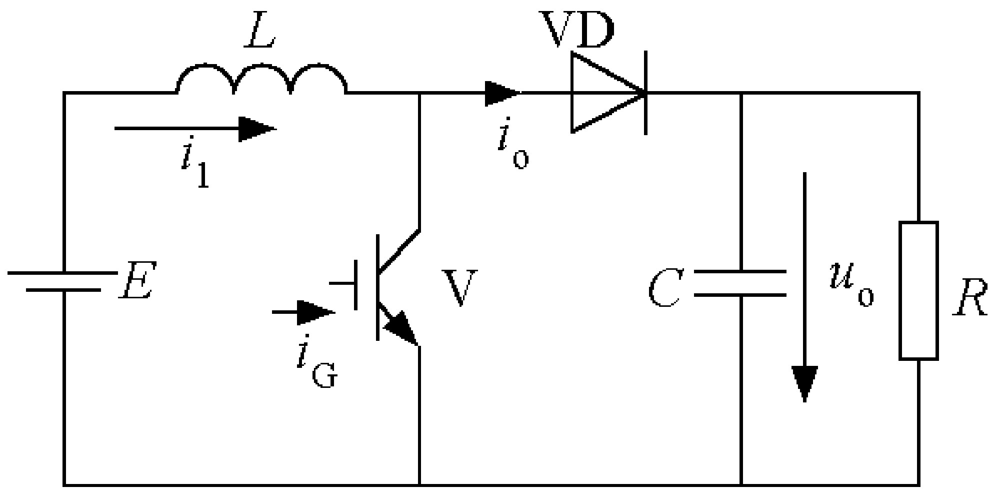
# Buck




$$U_o = \frac{t_{on}}{t_{on} + t_{off}} E = \frac{t_{on}}{T} E = \alpha E$$

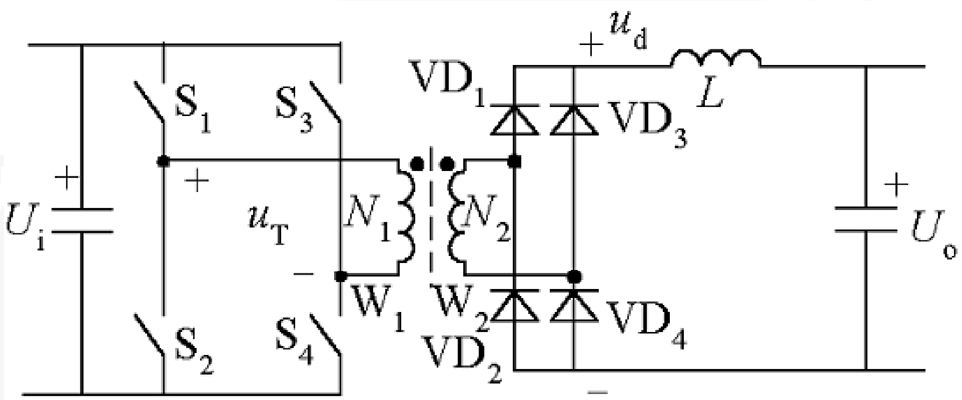
# Booster



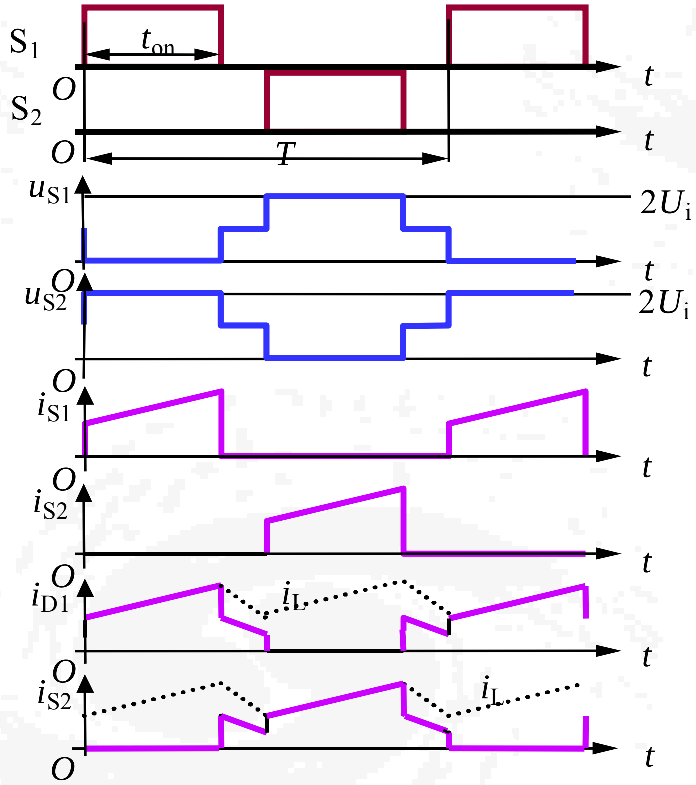




$$U_o = \frac{t_{on} + t_{off}}{t_{off}} E = \frac{T}{t_{off}} E$$

# Full Bridge



$u_d$
VD1
VD3
L
S1
S3
Ui
uT
N1
N2
Uo
W1
W2
VD4
S2
S4
VD2

S1
ton
S2
T
uS1
2Ui
uS2
2Ui
iS1
iS2
iD1
iL
iS2
iL
O
t

# Characteristic

- **Advantage**
  - **High efficiency;**
  - **Small value and weigh;**
  - **Low ripple;**
  - **Fast dynamic;**
- **Disadvantage**
  - **EMI;**
  - **High price;**

# Soft switch

- Why soft switch

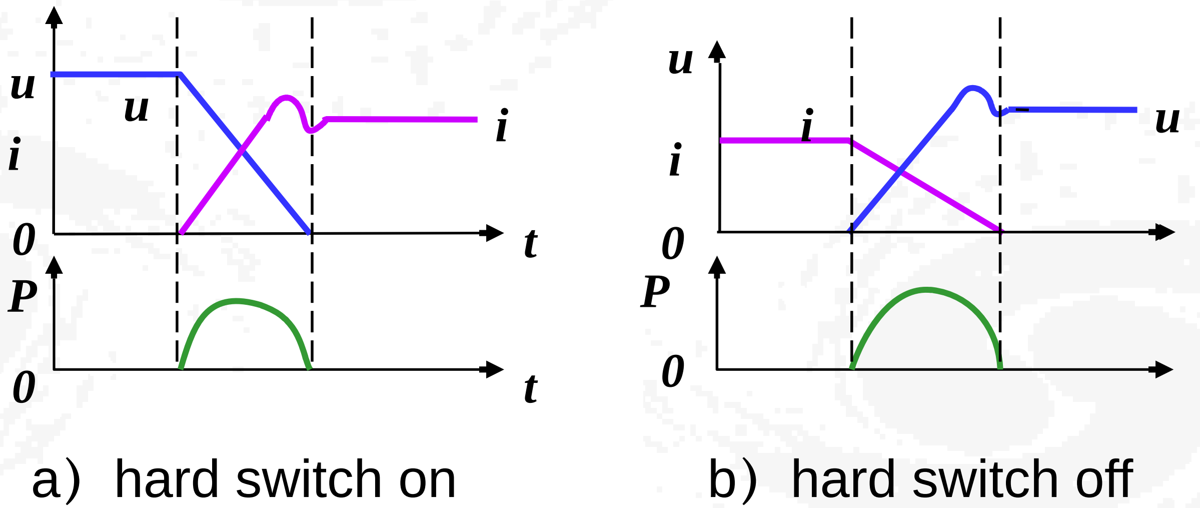
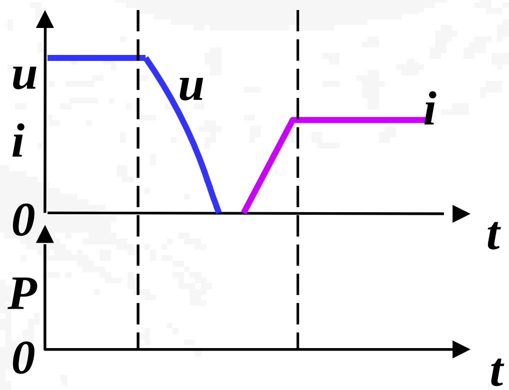
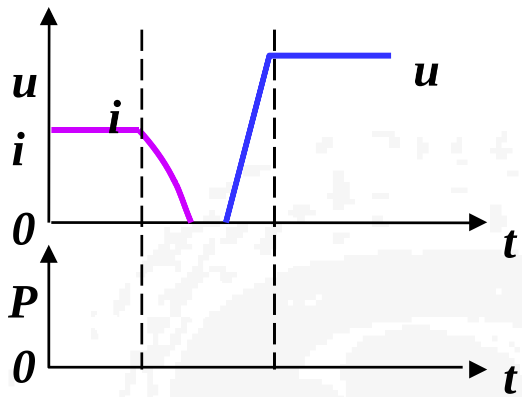



图7－1 硬开关的开关过程

## ➢ Zero voltage Switch and Zero current Switch

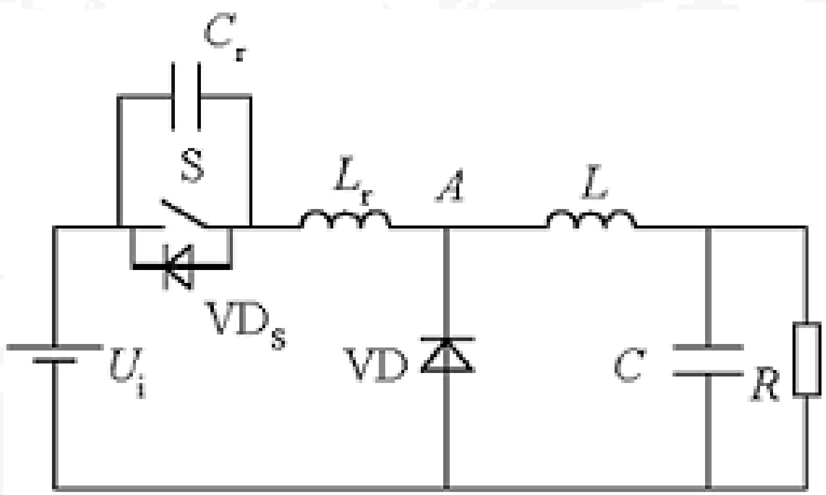


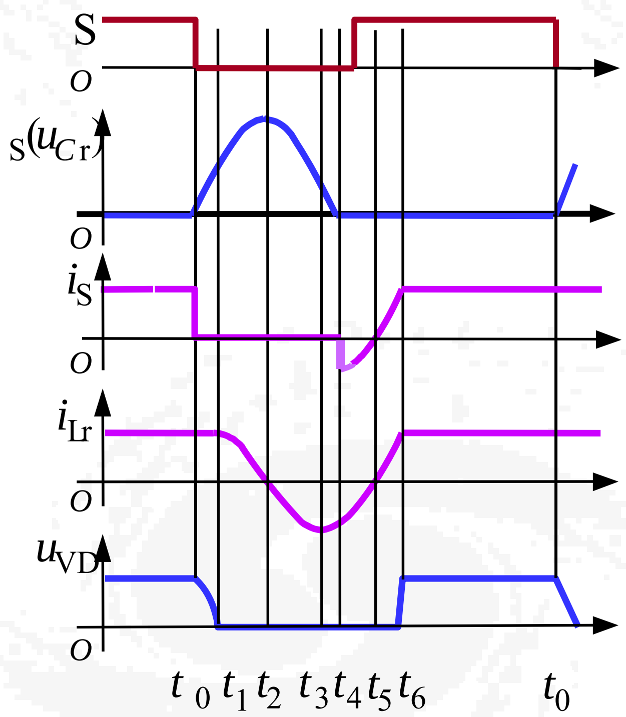

a） Soft switch on




b） soft switch off

# Zero Voltage Switch



- Power components;
- Power supply classification;
- **Power supply parameters definitions;**
- Regulation Loop;
- CSNS PS system;

# Some definitions

- **PPM: Part Per Million=$10^{-6}$=$2^{-20}$(20 bits);**
- **Nominal value ($I_{Nominal}$): Normal maximum value;**
- **ppm of nominal: $10^{-6} \times I_{Nominal}$(Amp);**

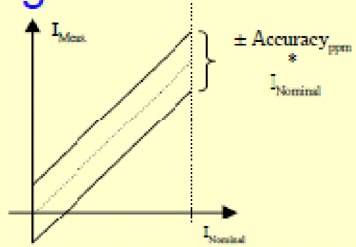
**Example: $I_{nominal}$=1000A, 1ppm of nominal=1mA.**

**Precision**

## – Accuracy

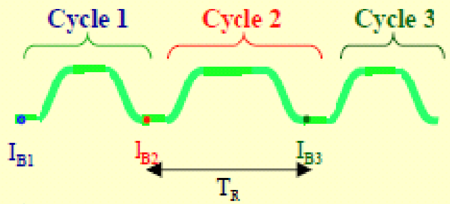
Long term setting or measuring uncertainty taking into consideration the full range of permissible changes* of operating and environmental conditions.

* requires definition



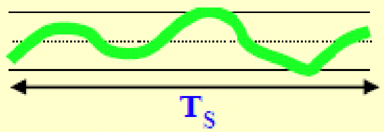

## – Reproducibility

Uncertainty in returning to a set of previous working values from cycle to cycle of the machine.




## – Stability

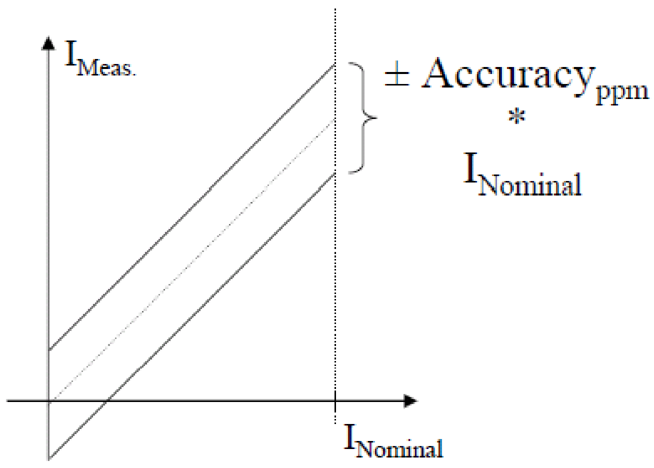
Maximum deviation over a period with no changes in operating conditions.




Accuracy, reproducibility and stability are defined for a given period

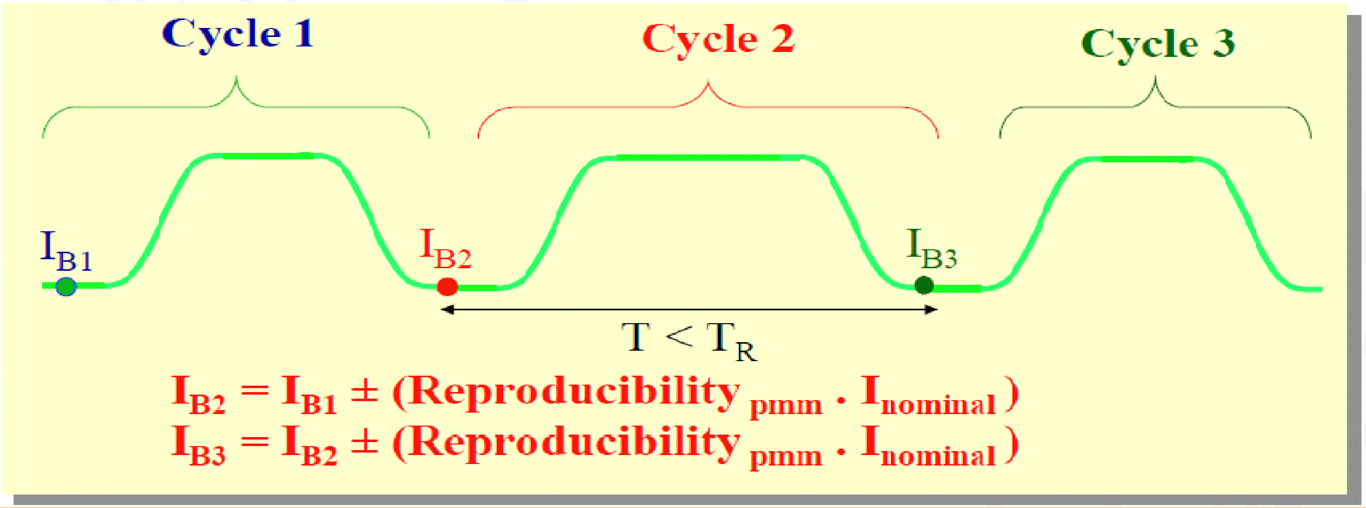
# Accuracy

- Long term setting or measuring, uncertainty talking into consideration the full range of permissible change in operating and environmental conditions;
- Requires definition: Electrical distribution system perturbation, temperature variation,…
- The accuracy is defined by default for a defined period, such as one year, one month, 24 hours…
- The accuracy is expreeed in ppm of $I_{Nominal}$.
- If the define period is too large, a calibration process should be executed more often.



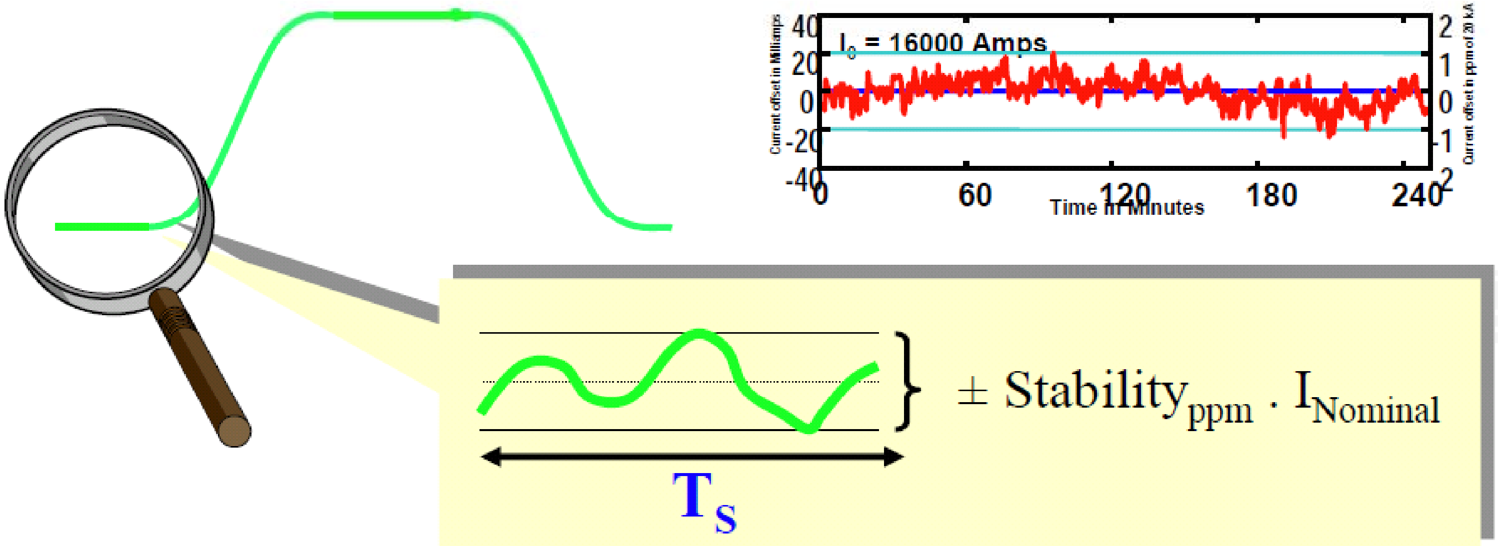
# Reproducibility

- **Uncertainty in returning to a set of previous working values from cycle to cycle of the machine;**
- **The reproducibility is defined by default for a period of time Tr without any intervention affecting the calibrated parts (DCCT, ADC……)**
- **The reproducibility is expressed in ppm if $I_{Nominal.}$**



# Stability

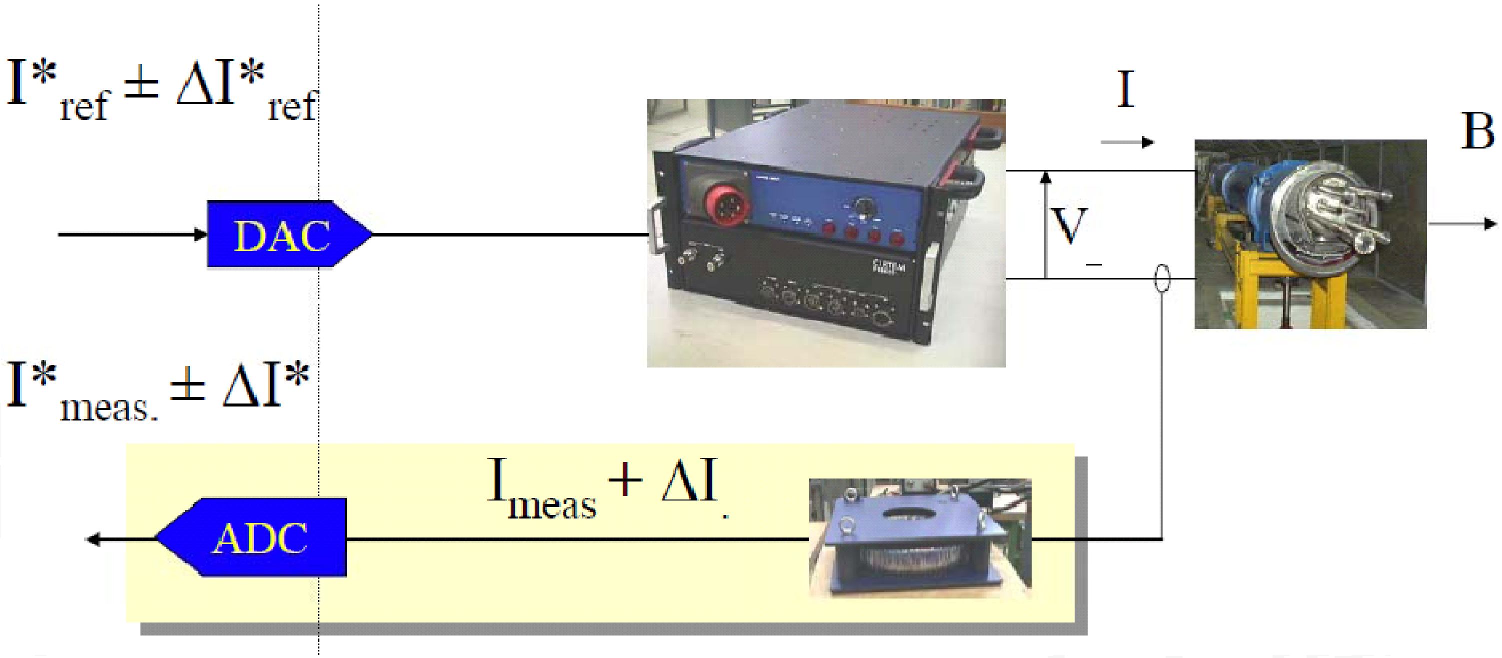
- Maximum deviation over a period with no changes in operating conditions;
- The stability is defined by default for a period of time Ts
- The stability is expressed in ppm of $I_{Nominal}$



# Resolution

**Smallest increment that can be induced or discerned.**

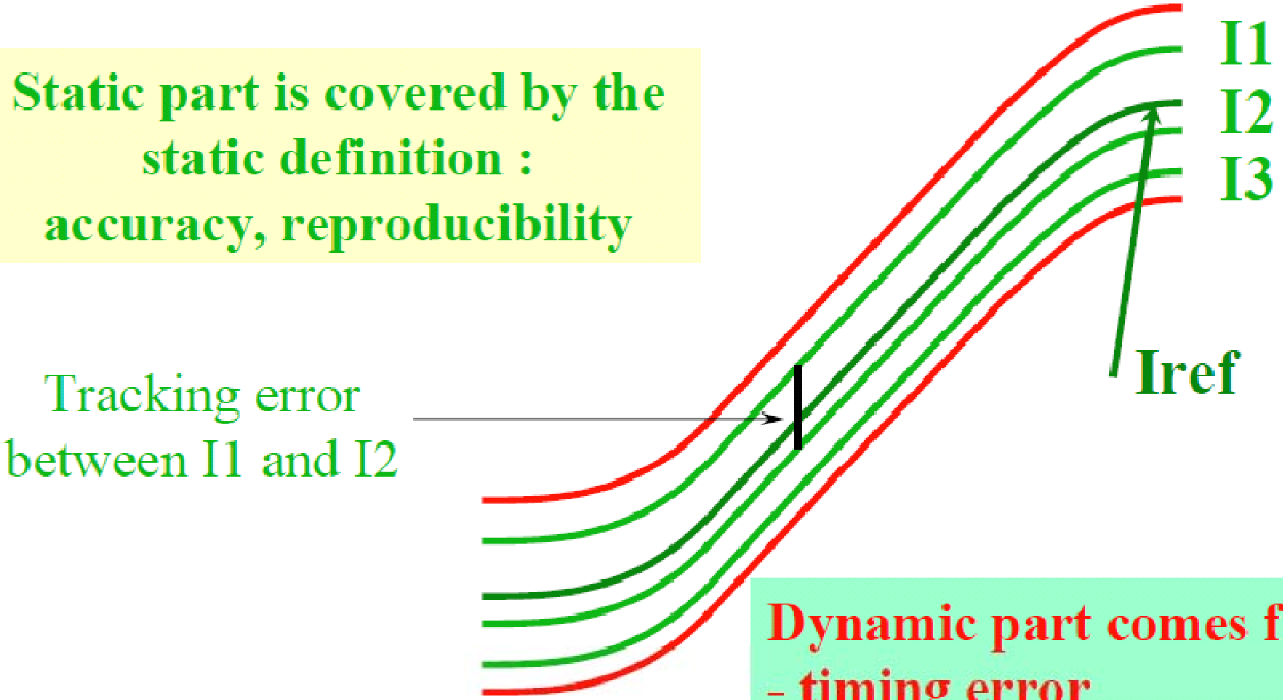
**The resolution is expressed in ppm of $I_{Nominal}$.**
**Resolution is directly linked to A/D system**



# Tracking

- **Ability of the power supply to follow the reference function (static, dynamics);**

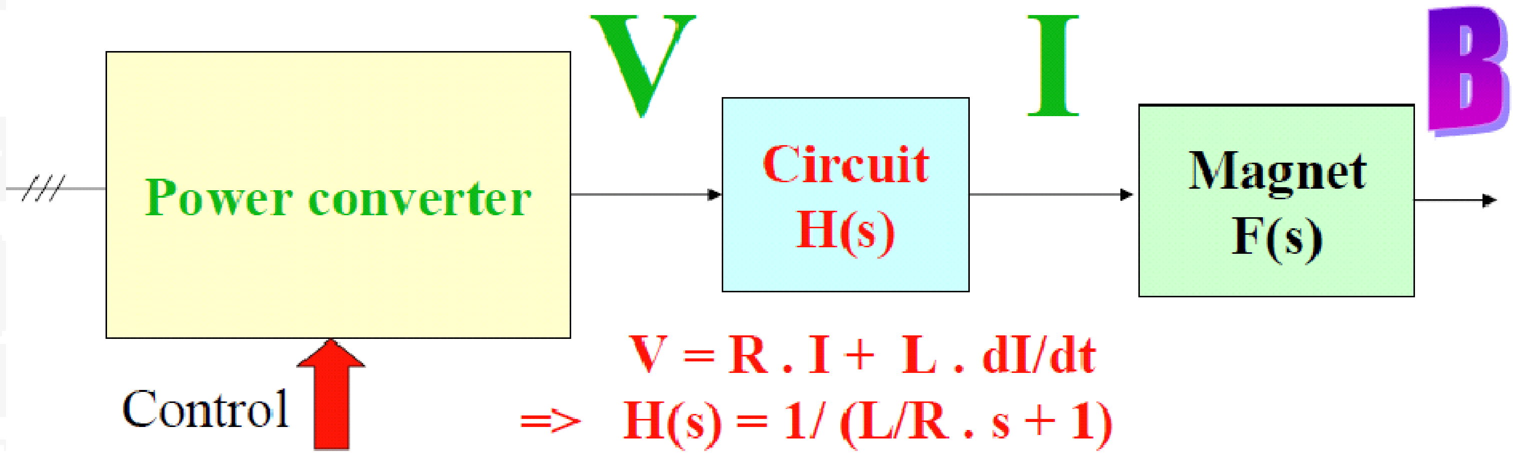
**Static part is covered by the static definition : accuracy, reproducibility**

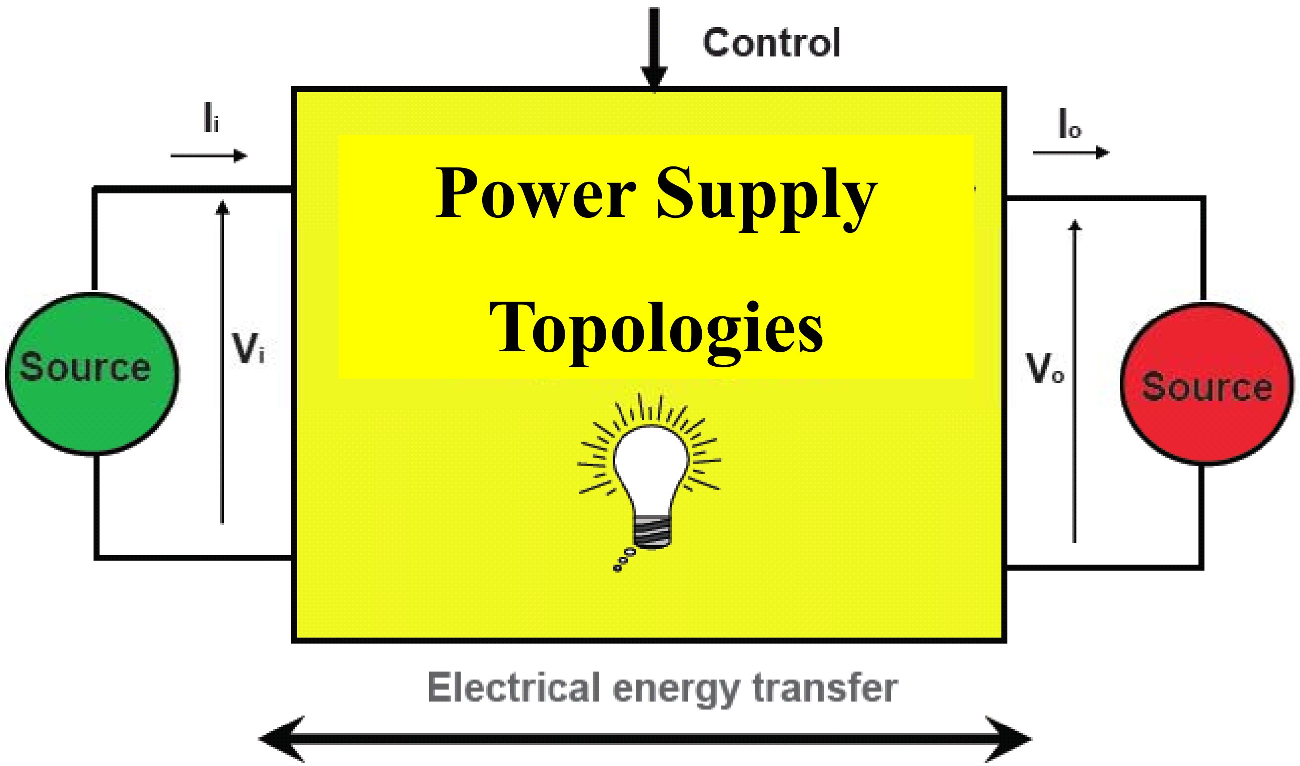



**Dynamic part comes from :**
**- timing error**
**- lagging error in the regulation**

# Ripple

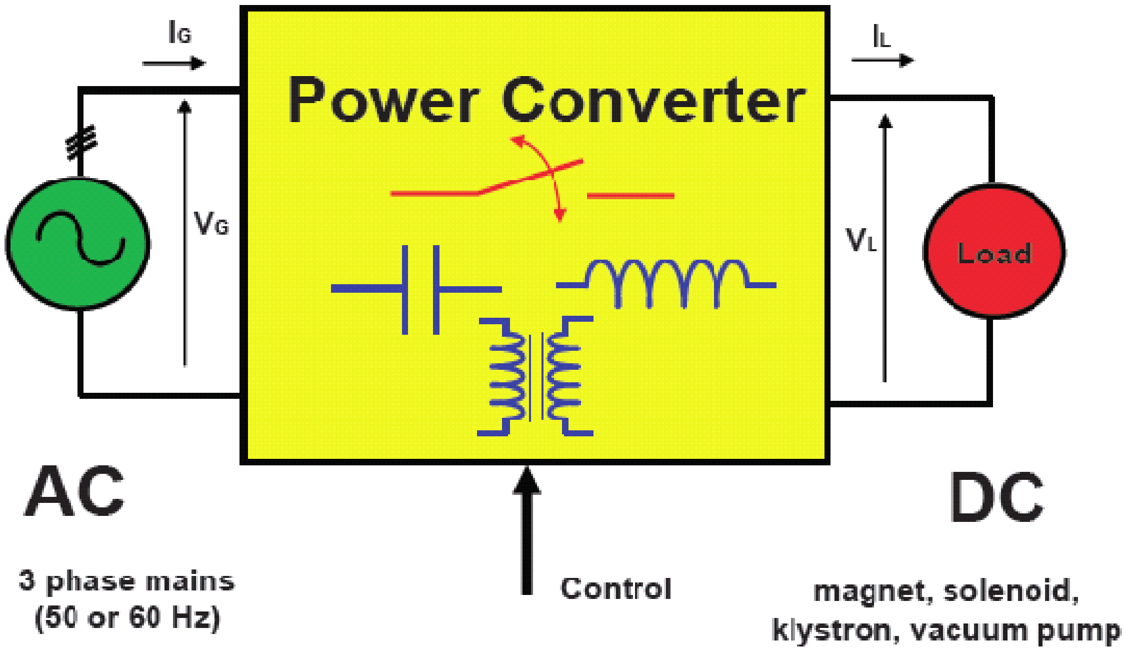
- **Voltage ripple is defined by power supply;**
- **Current ripple: load transfer function ( cable, magnet inductance,…)**






**Power Converter**

- performance
- efficiency
- reliability, repairability, availability
- low cost
- effect on environment (RFI, noise,...)




- low mains harmonic distortion
- power factor (closest to 1)

- low ripple (current)
- reproducibility (short and long term)
- rejection of mains disturbance
- dynamic response

Achieving high performance : **COMPROMISE**

# How do the stability and the accuracy of the Power Supplies affect the accelerator?

- **Accuracy of the energy of the beams: dipoles;**

$$E_0 = \rho s * e * c * B0$$

- **Modify the turns of the machine: quadrupoles;**

$$\Delta \upsilon = -\frac{1}{4\pi} \beta_n \Delta K \Delta S$$

- **Perturb the closed orbit of the machine: field errors/fluctuations.**

**The stability and the accuracy of the power supplies is one of the key ingredients to ensure the expected performance of the machine!**

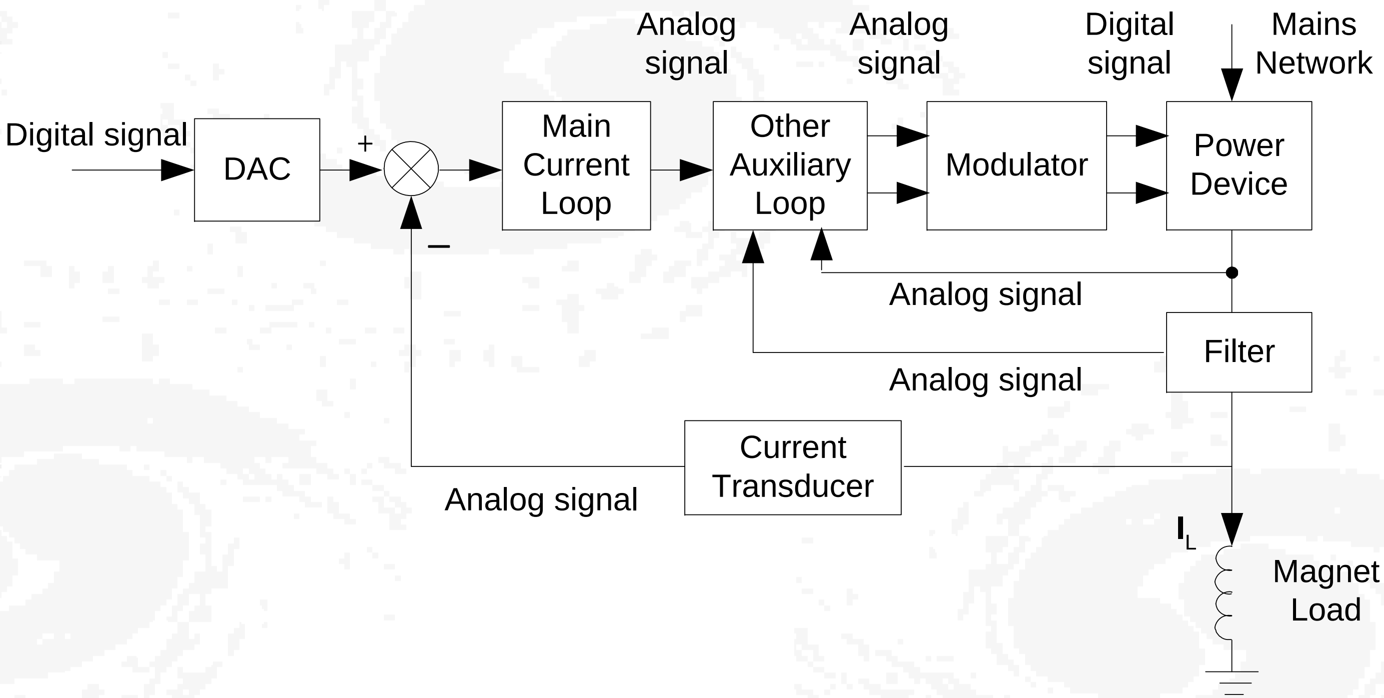
- Power components;
- Power supply classification;
- Power supply parameters definitions;
- **Regulation Loop;**
- CSNS PS system;

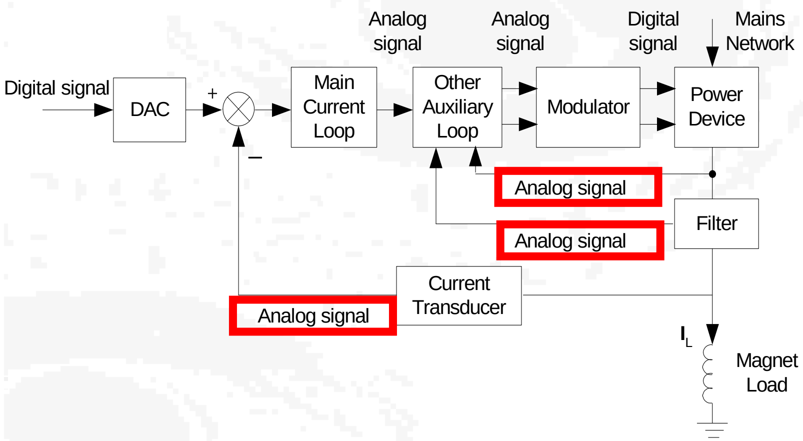
# Controller Design

## In order to design and tune a controller:

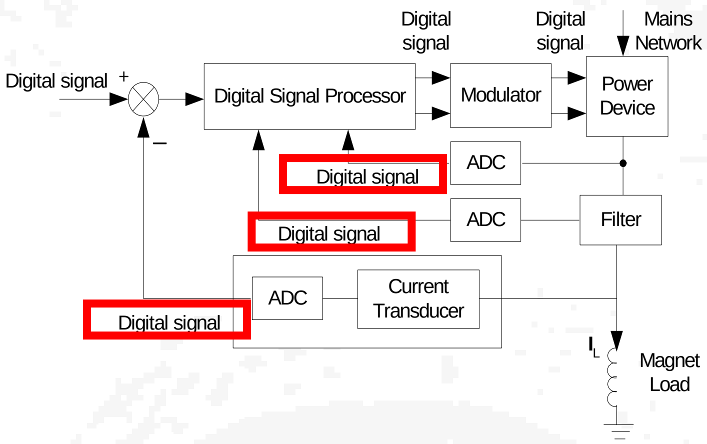
- To specify the desired closed control loop performance:
  - Regulation and tracking: rise time and max overshoot or bandwidth and resonance
- To choose a suitable controller design method
- To know the dynamic model of the plant to be controlled → control model

# Control Loop



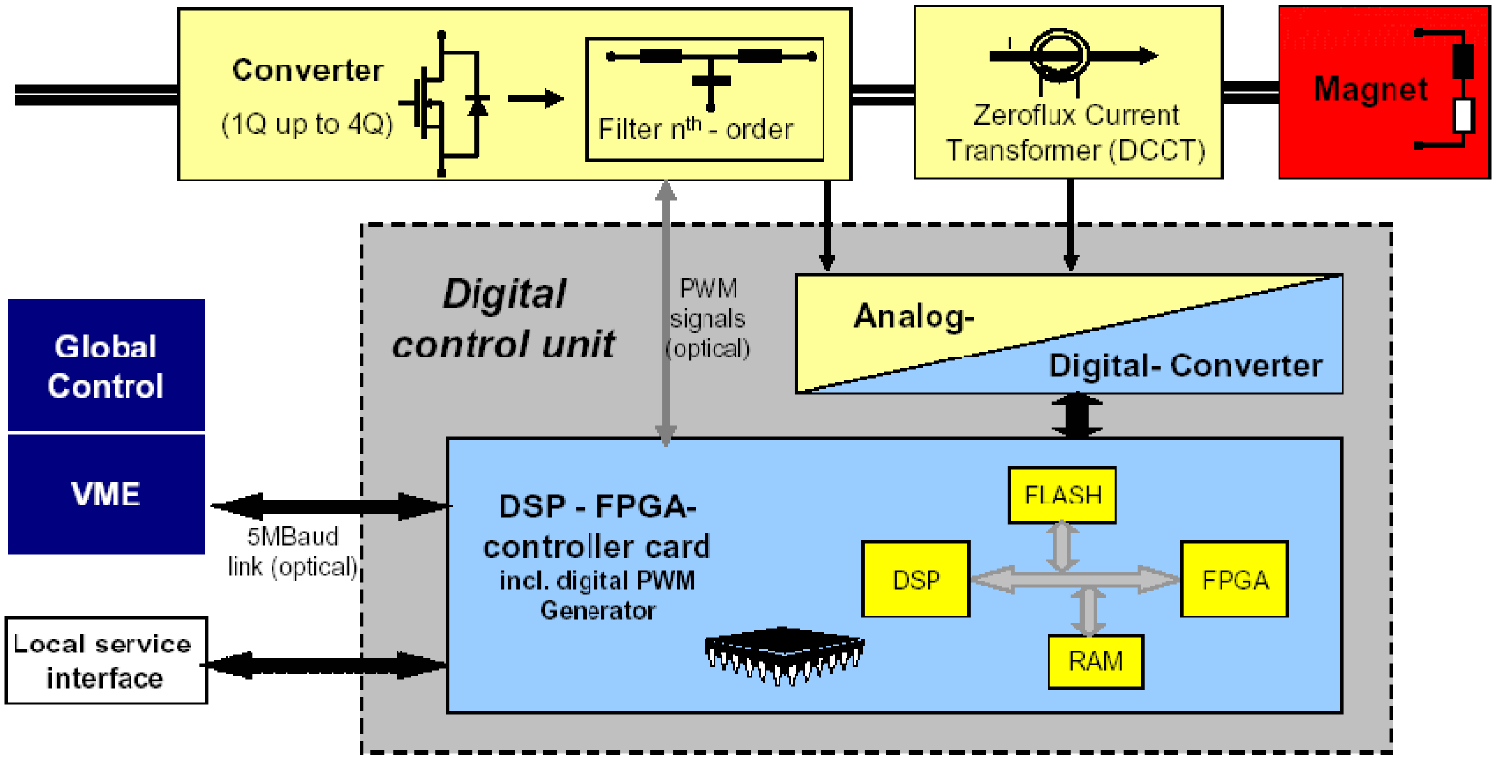



Anlog control loop



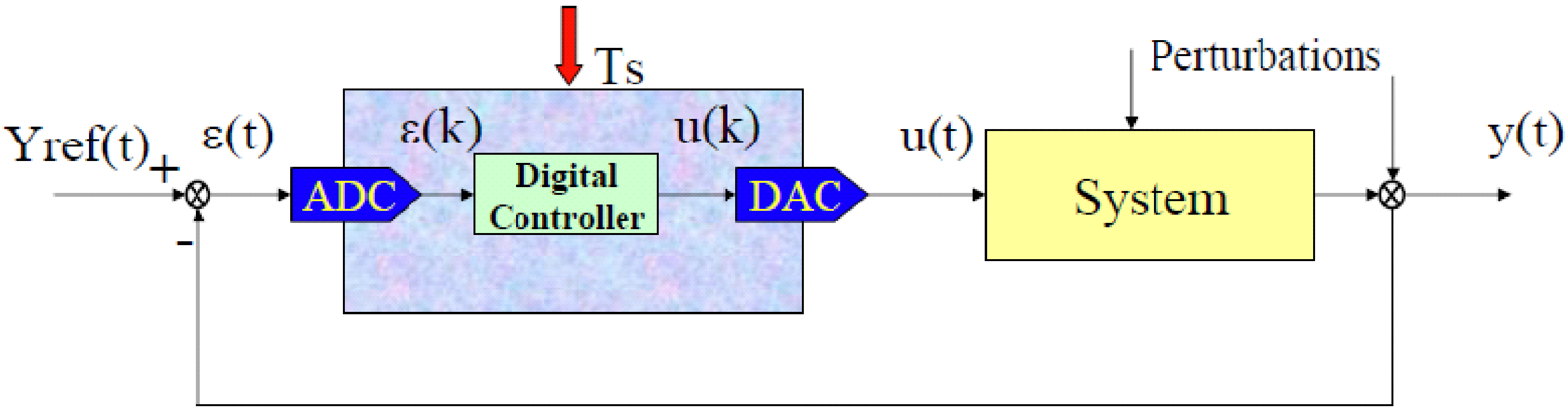

Digital control loop

# SLS Digital controller

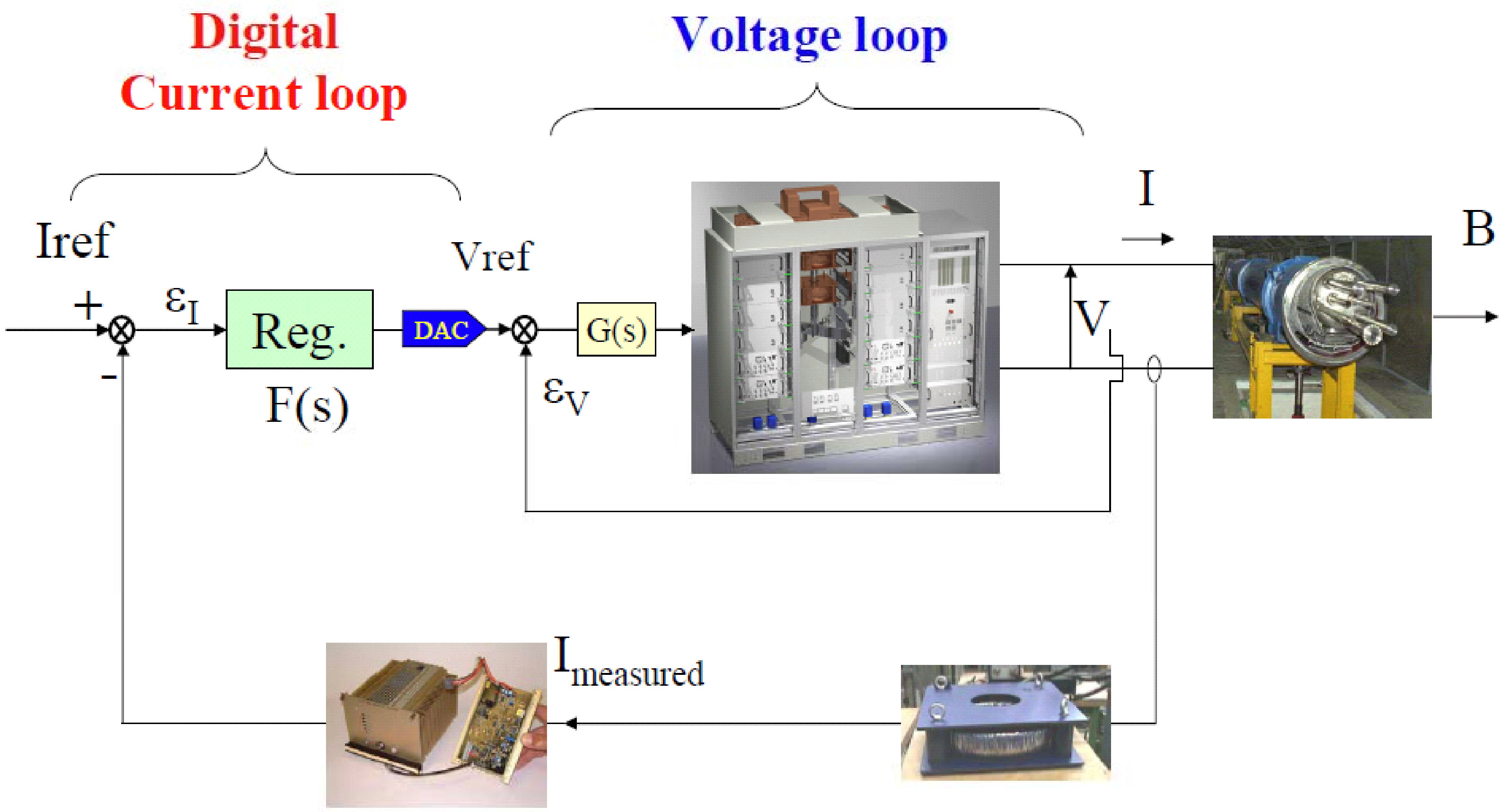


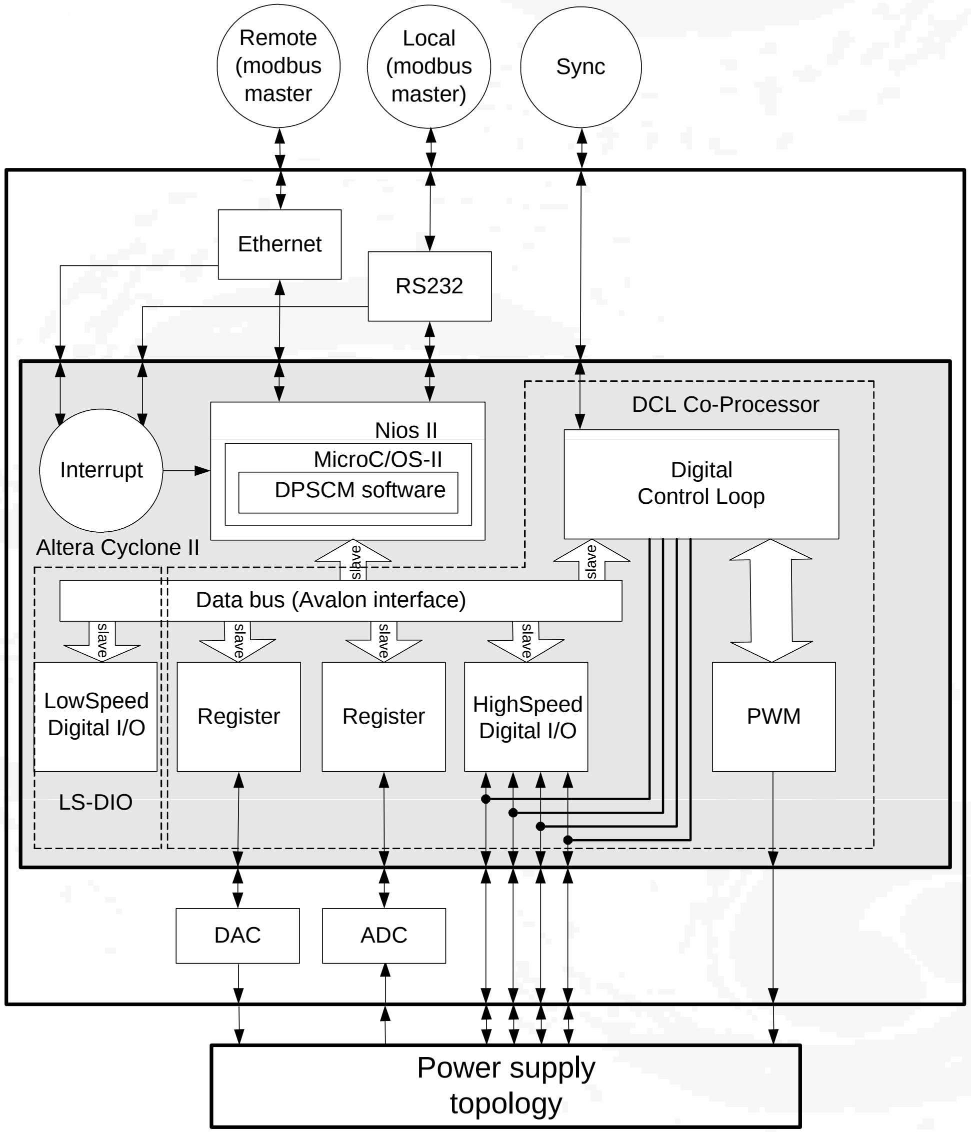
# LHC

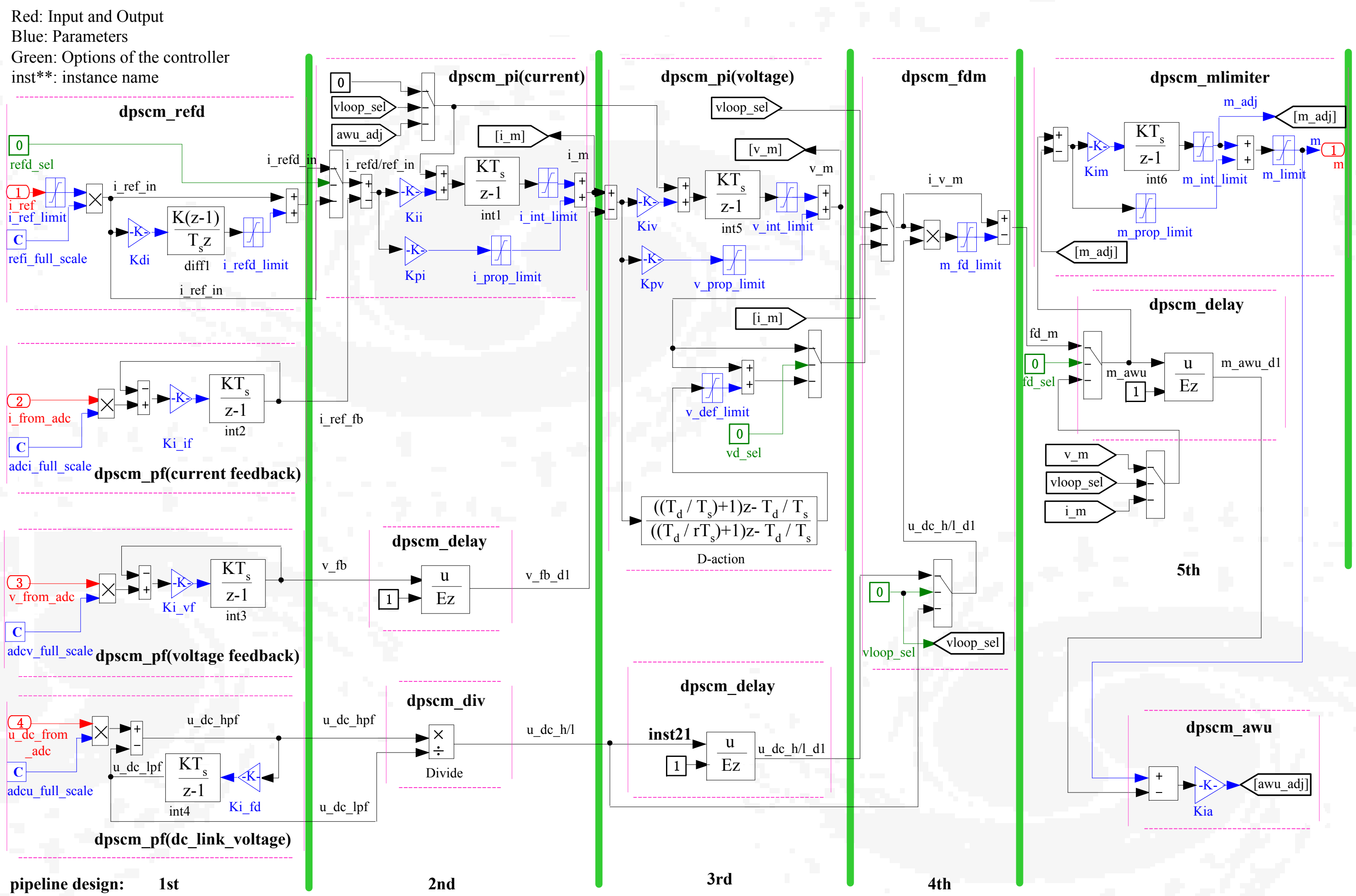
*Digital realisation of an "analogue type" controller*



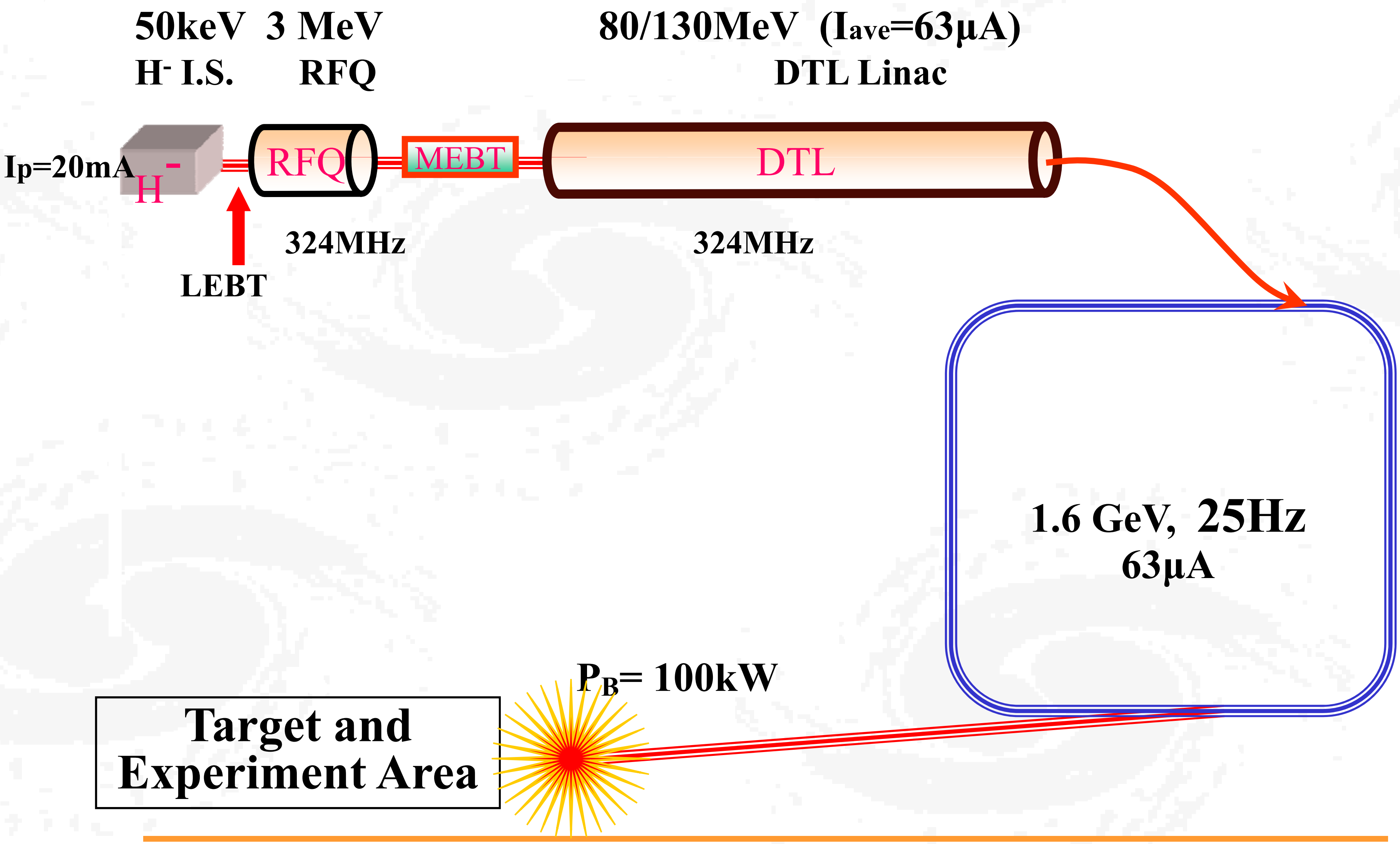

**ADC- Digital controller - DAC** should behave the same as an analogue controller (e.g. PID type), which implies **the use of a high sampling frequency** (the algorithm implemented is very simple)


Digital
Current loop
Voltage loop
Iref
+
-
εI
Reg.
F(s)
DAC
Vref
εV
G(s)
I
V
B
Imeasured


Remote (modbus master
Local (modbus master)
Sync
Ethernet
RS232
DCL Co-Processor
Nios II
MicroC/OS-II
DPSCM software
Interrupt
Digital Control Loop
Altera Cyclone II
slave
Data bus (Avalon interface)
LowSpeed Digital I/O
Register
Register
HighSpeed Digital I/O
PWM
LS-DIO
DAC
ADC
Power supply topology


Red: Input and Output
Blue: Parameters
Green: Options of the controller
inst**: instance name
dpscm_refd
dpscm_pi(current)
dpscm_pi(voltage)
dpscm_fdm
dpscm_mlimiter
dpscm_pf(current feedback)
dpscm_delay
dpscm_pf(voltage feedback)
dpscm_div
dpscm_pf(dc_link_voltage)
dpscm_awu
refd_sel
i_ref
i_ref_limit
refi_full_scale
Kdi
diff1
i_refd_limit
i_ref_in
i_refd_in
i_refd/ref_in
Kii
int1
i_int_limit
Kpi
i_prop_limit
[i_m]
i_m
vloop_sel
awu_adj
Kiv
int5
v_int_limit
Kpv
v_prop_limit
[v_m]
v_m
v_def_limit
vd_sel
D-action
$\frac{((T_d/T_s)+1)z - T_d/T_s}{((T_d/rT_s)+1)z - T_d/T_s}$
i_v_m
m_fd_limit
u_dc_h/l_d1
Kim
int6
m_int_limit
m_limit
m_prop_limit
[m_adj]
m_adj
m
fd_m
fd_sel
m_awu
m_awu_d1
i_from_adc
adci_full_scale
Ki_if
int2
i_ref_fb
v_from_adc
adcv_full_scale
Ki_vf
int3
v_fb
v_fb_d1
u_dc_from_adc
adcu_full_scale
u_dc_hpf
u_dc_lpf
int4
Ki_fd
Divide
u_dc_h/l
inst21
Kia
[awu_adj]
pipeline design:
1st
2nd
3rd
4th
5th

- Power components;
- Power supply classification;
- Power supply parameters definitions;
- Regulation Loop;
- **CSNS PS system;**


50keV 3 MeV
80/130MeV (Iave=63μA)
H- I.S. RFQ
DTL Linac
Ip=20mA
H-
RFQ
MEBT
DTL
324MHz
324MHz
LEBT
1.6 GeV, 25Hz
63μA
PB= 100kW
Target and
Experiment Area

- **RCS:**
  - **Multi-mesh White circuit:**

    **One dipole power supply**

    **5 quadrupole power supplies**
  - **Large dynamical system**

    **Total input power rating:**

    **BMPS 3.2MW, QMPS 4.5MW**
  - **Repeating rate:**

    **25HZ, DC biased sine waveform**
- **Others: DC Power Supplies.**

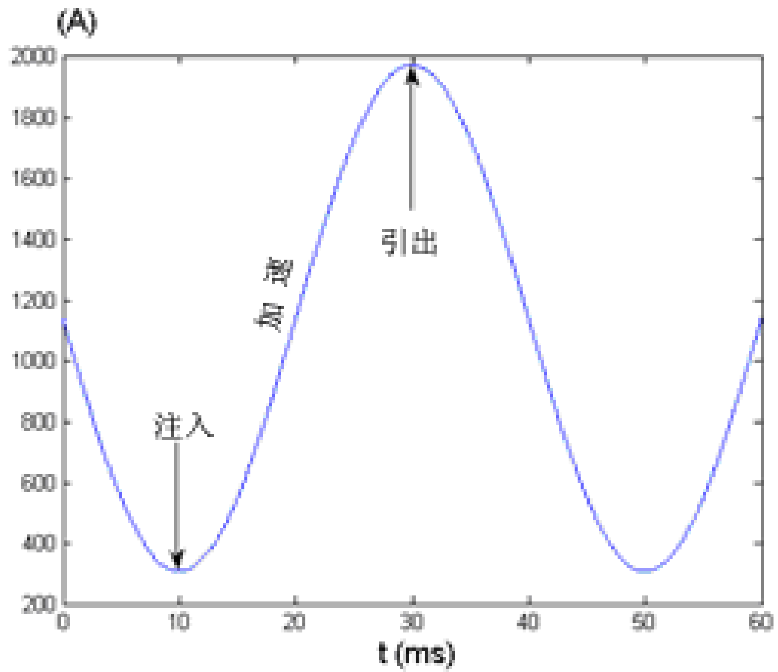
# White circuit parameters

- **Magnet current:** $I_m = I_{DC} - I_{AC}\sin(\omega t)$
- **Magnet voltage:** $V_m = R_m I_m - \omega I_{AC} L_m \cos(\omega t)$
- **Choke inductance:**

  $L_{ch} = L_m$
- **Choke current:**

  $I_{ch} = I_{DC} + I_{AC} * \sin(\omega t)$
- **Peak magnet energy:**

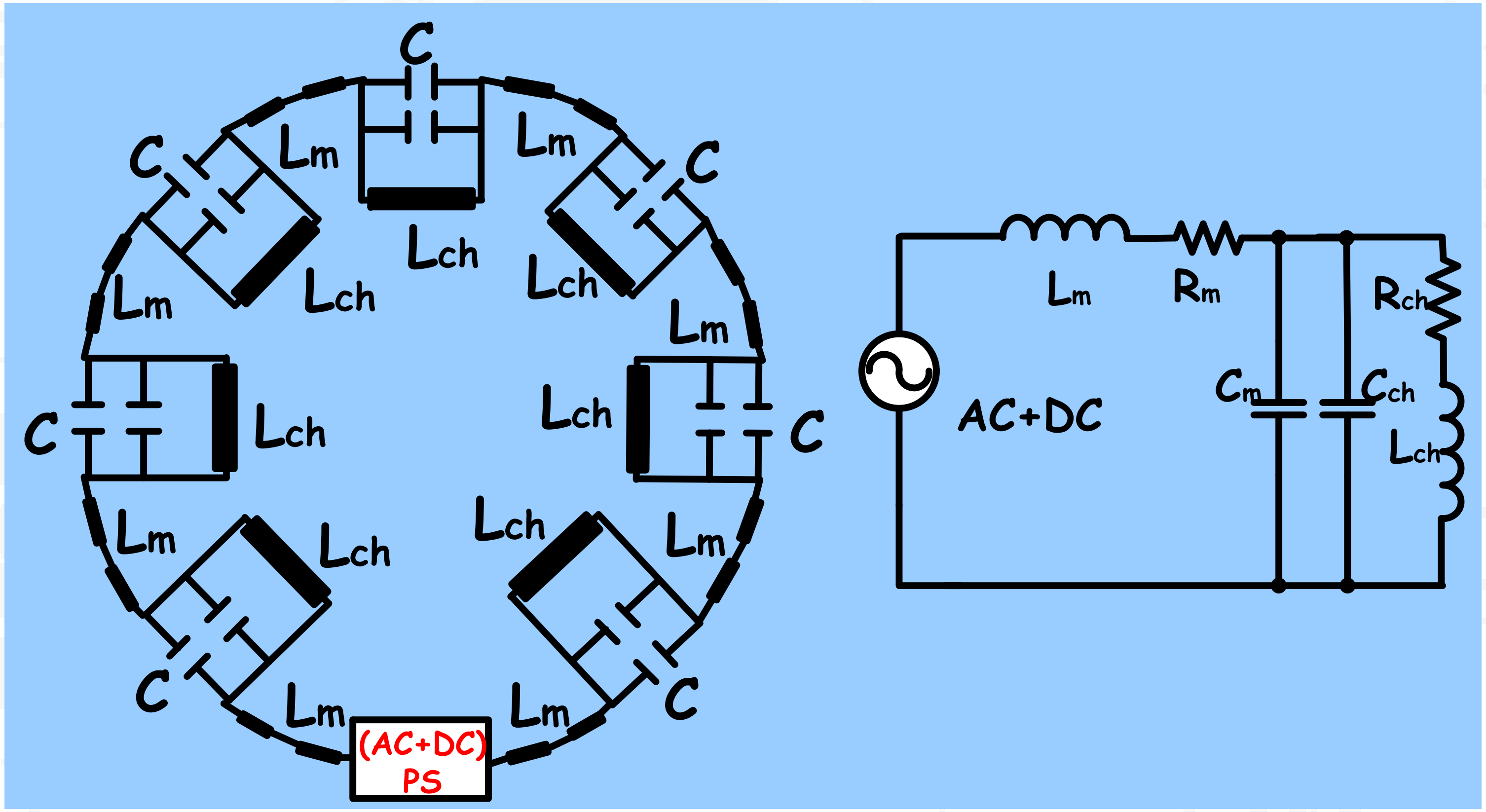
  $E_m = (1/2) L_m (I_{DC} + I_{AC})^2$



# Main Power Supply of RCS/CSNS

| Power Supply | | $I_N$ (A) | $V_N$ (V) | $P_{avr}$ (kW) | | magnet |
|---|---|---|---|---|---|---|
| RCS-BPS | 1 | 2200 | 6000 | 3108 | 160B | 24 |
| RCS-QPS1 | 1 | 1393 | 828 | 598 | 206Q | 8 |
| RCS-QPS2 | 1 | 1484 | 3700 | 2036 | 265Q | 16 |
| RCS-QPS3 | 1 | 1393 | 828 | 598 | 206Q | 8 |
| RCS-QPS4 | 1 | 1226 | 800 | 484 | 222Q | 8 |
| RCS-QPS5 | 1 | 1419 | 1400 | 754 | 253Q | 8 |

# Serial resonant network



# Resonant Component parameter

| | BPS | QPS1 | QPS2 | QPS3 | QPS4 | QPS5 |
|---|---|---|---|---|---|---|
| Magnet | 24 | 8 | 16 | 8 | 8 | 8 |
| Magnet No./cell | 2 | 8 | 4 | 8 | 8 | 8 |
| Cell No. | 12 | 1 | 4 | 1 | 1 | 1 |
| $L_{MAGNET}$ (mH) | 38.8 | 8.69 | 24.88 | 8.69 | 9.33 | 17.33 |
| Cm (μF) | 1045.6 | 1167.1 | 815.3 | 1167.1 | 1087.1 | 585.3 |
| $L_{CH}$(mH) | 77.6 | 69.52 | 99.52 | 69.52 | 74.64 | 138.64 |
| $Voltage_{p-p}$(V) | 10624 | 6327 | 9651 | 6327 | 5976 | 12856 |

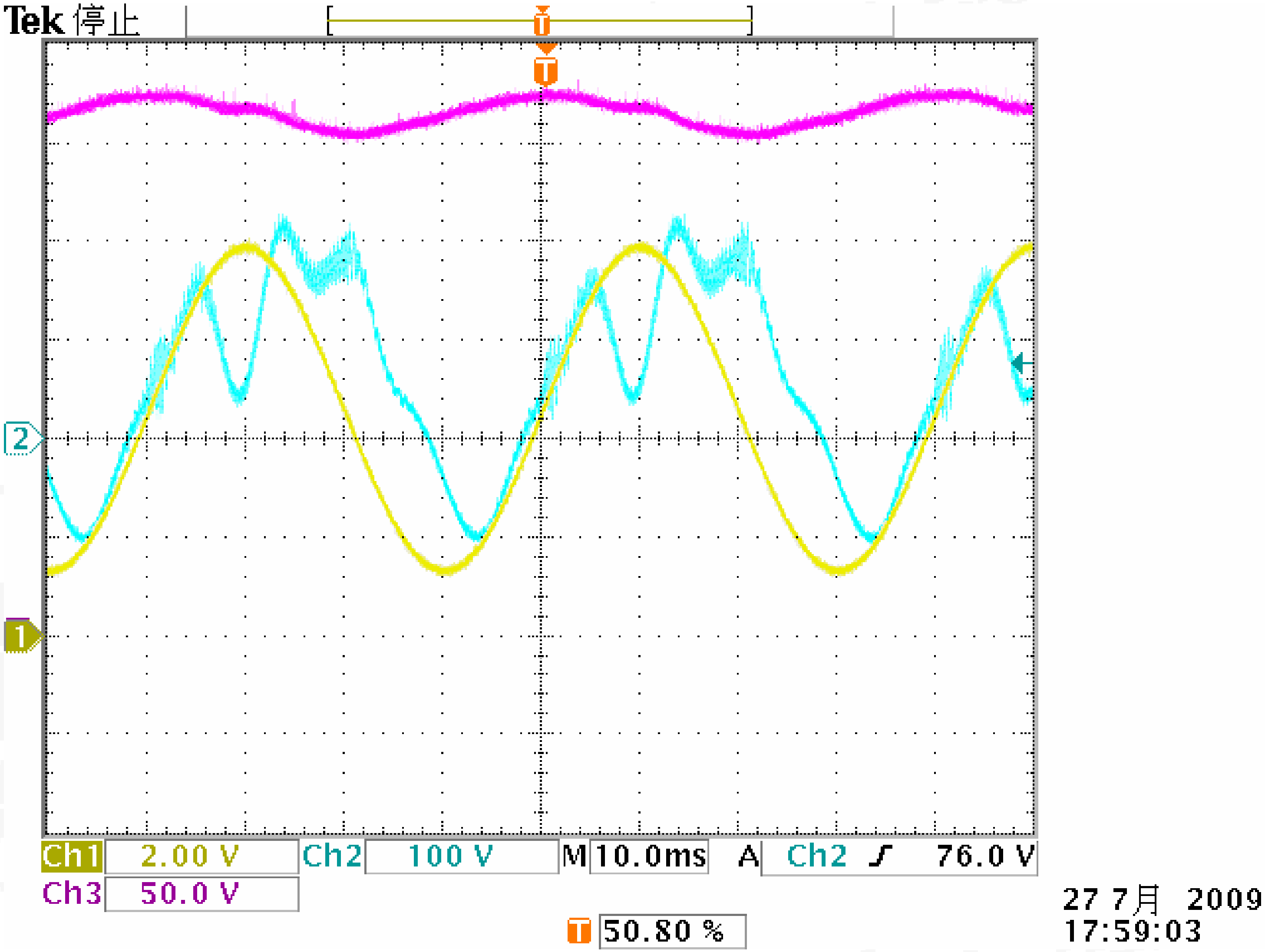

12/17/2007

# Choke





2007/12/18


Tek 停止
2
1
Ch1 2.00 V
Ch2 100 V
M 10.0ms
A Ch2 76.0 V
Ch3 50.0 V
50.80 %
27 7月 2009
17:59:03

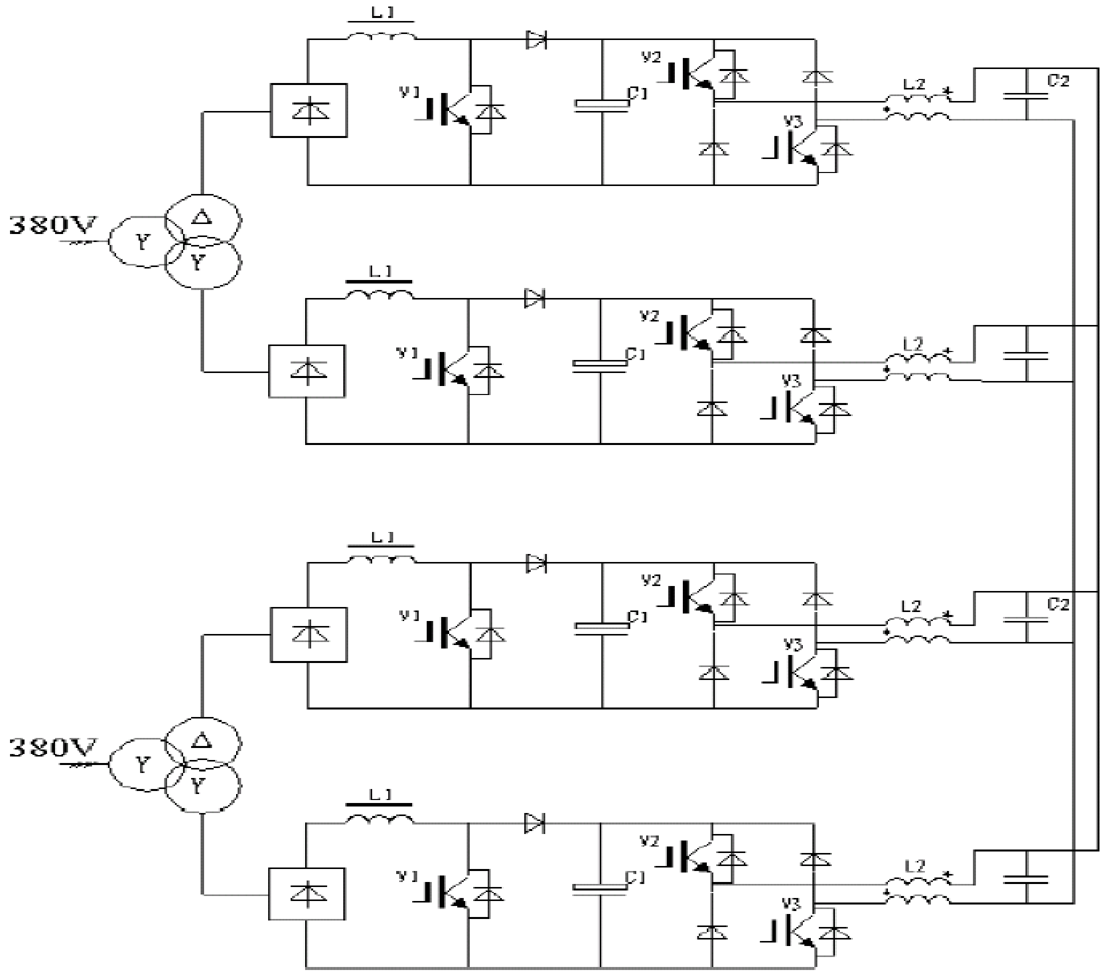
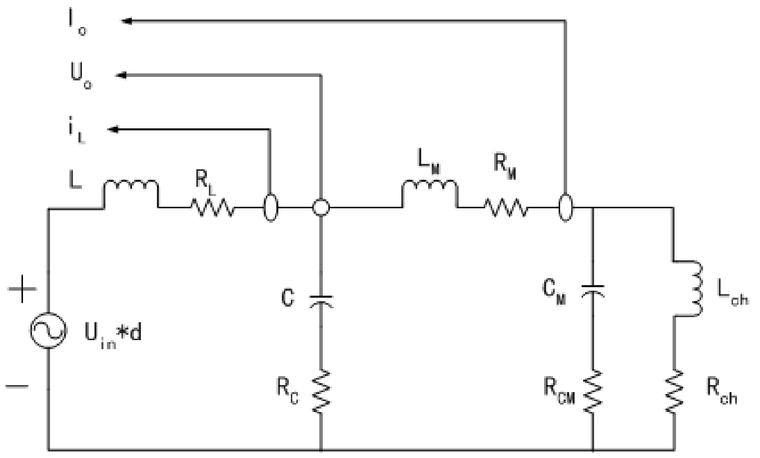
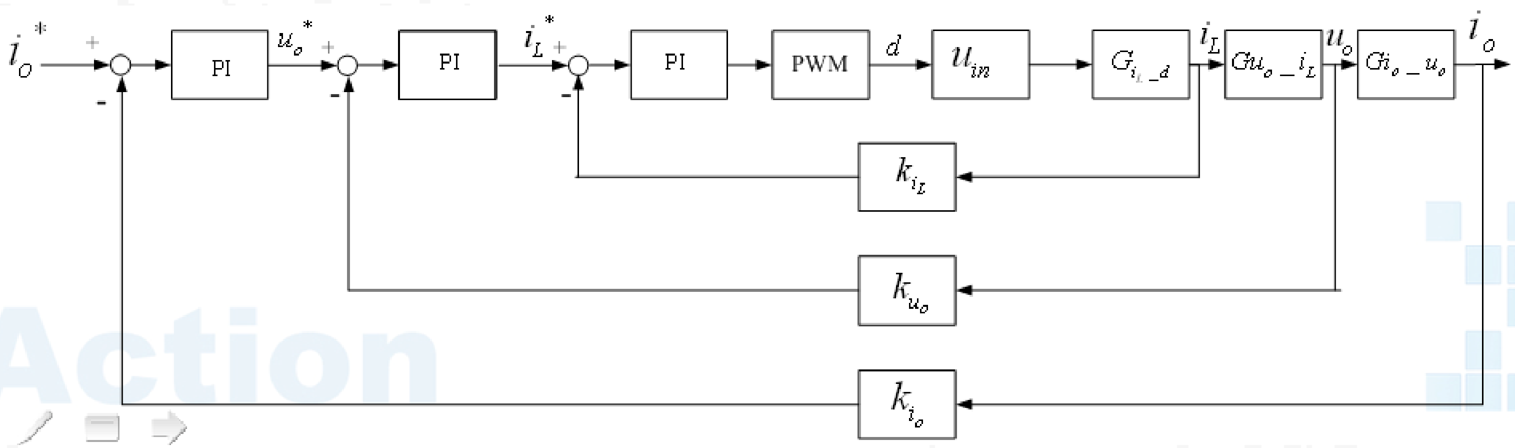
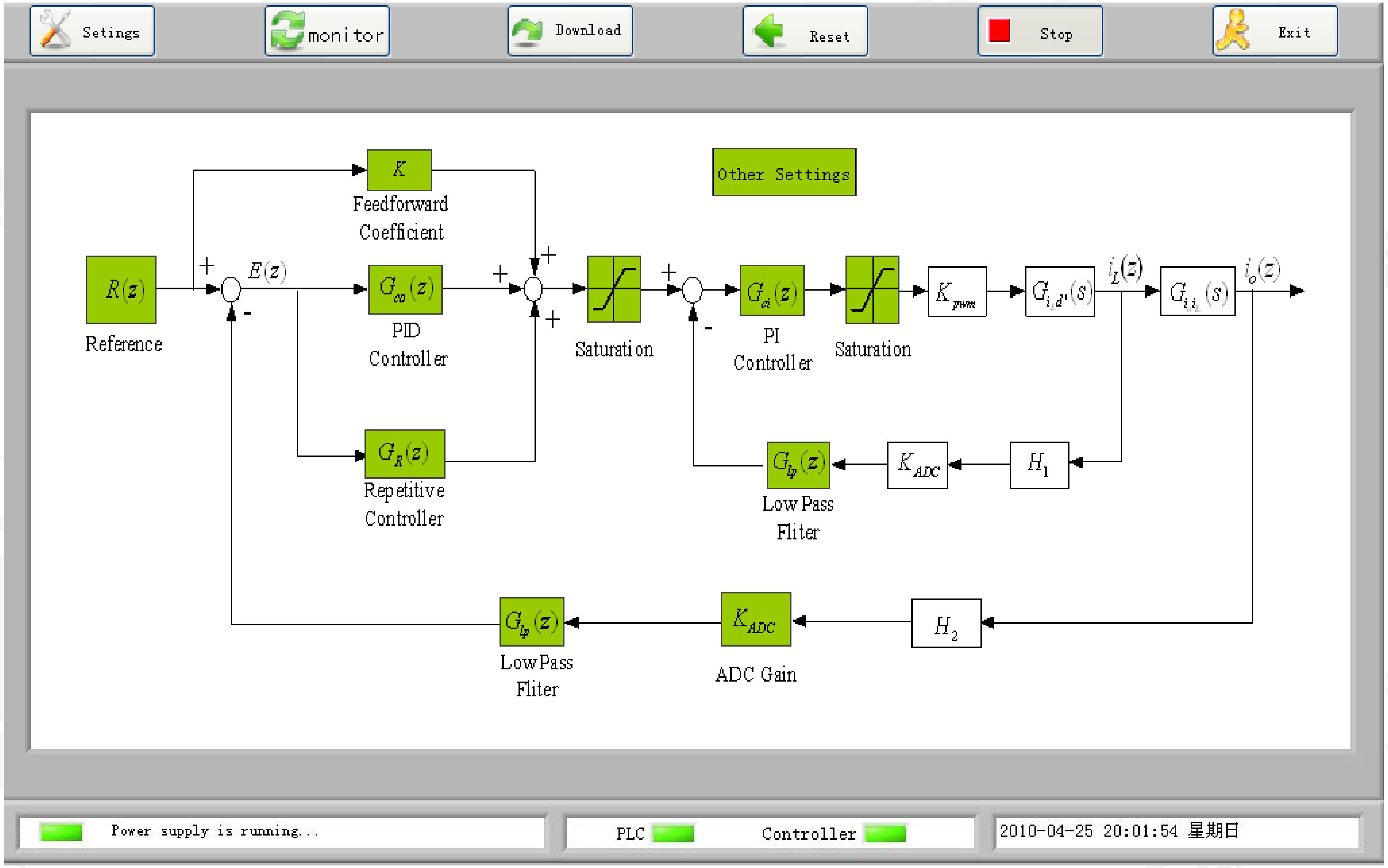


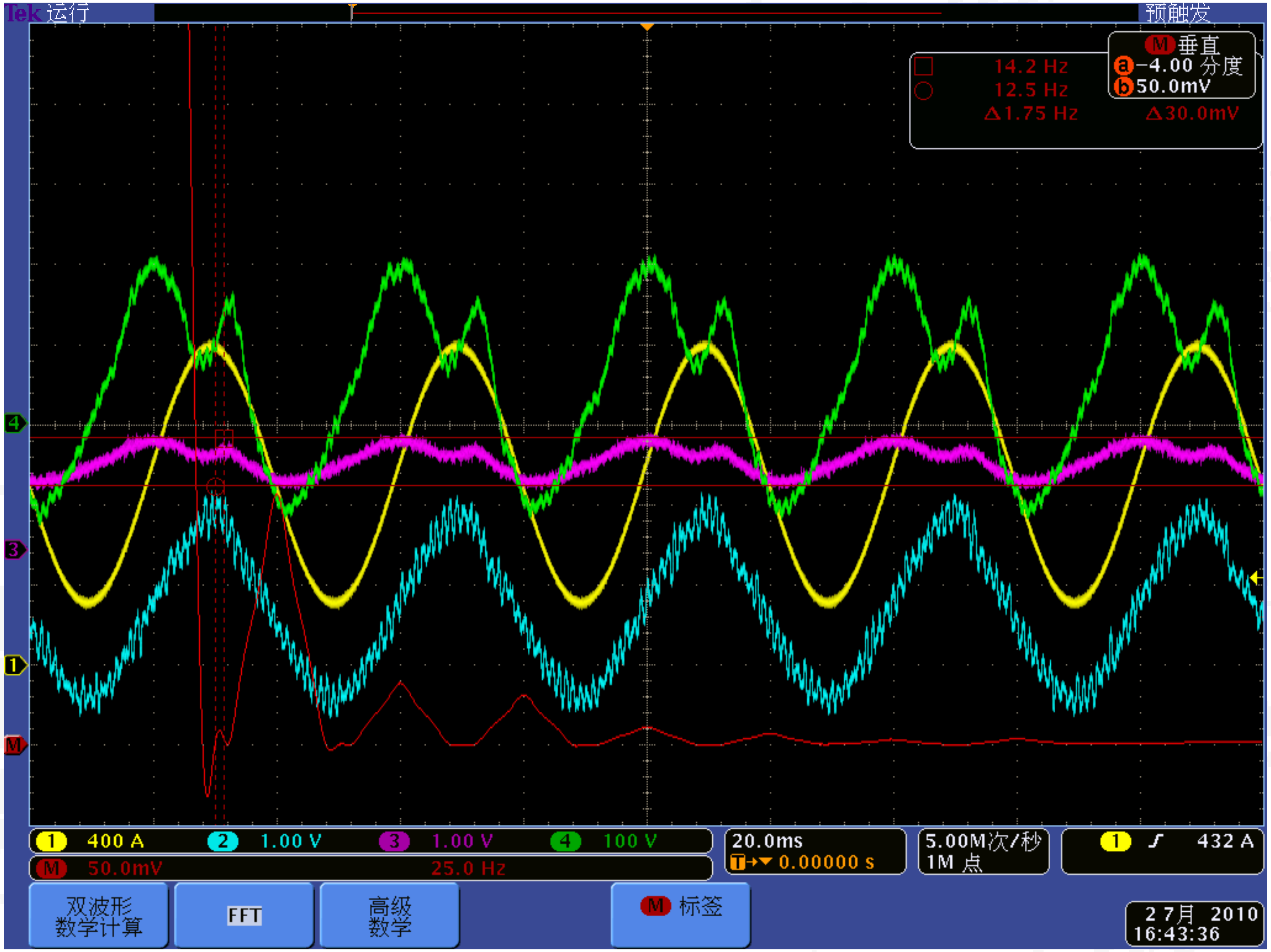

图 1 主电路结构示意图


05/19/2010


I o
U o
i L
L
R L
L M
R M
C
C M
L ch
U in *d
R C
R CM
R ch
+
−


PI
PI
PI
PWM
d
u in
+
-


Setings
monitor
Download
Reset
Stop
Exit
K
Feedforward Coefficient
Other Settings
R(z)
Reference
E(z)
G_co(z)
PID Controller
Saturation
G_ci(z)
PI Controller
Saturation
K_pwm
G_iLd'(s)
i_L(z)
G_ioiL(s)
i_o(z)
G_R(z)
Repetitive Controller
G_lp(z)
Low Pass Fliter
K_ADC
H_1
G_lp(z)
LowPass Fliter
K_ADC
ADC Gain
H_2
Power supply is running...
PLC
Controller
2010-04-25 20:01:54 星期日


Tek 运行
预触发
M 垂直
a -4.00 分度
b 50.0mV
14.2 Hz
12.5 Hz
Δ1.75 Hz
Δ30.0mV
1 400 A
2 1.00 V
3 1.00 V
4 100 V
M 50.0mV
25.0 Hz
20.0ms
0.00000 s
5.00M次/秒
1M 点
1 432 A
双波形
数学计算
FFT
高级
数学
M 标签
2 7月 2010
16:43:36

- Thanks for your attention!