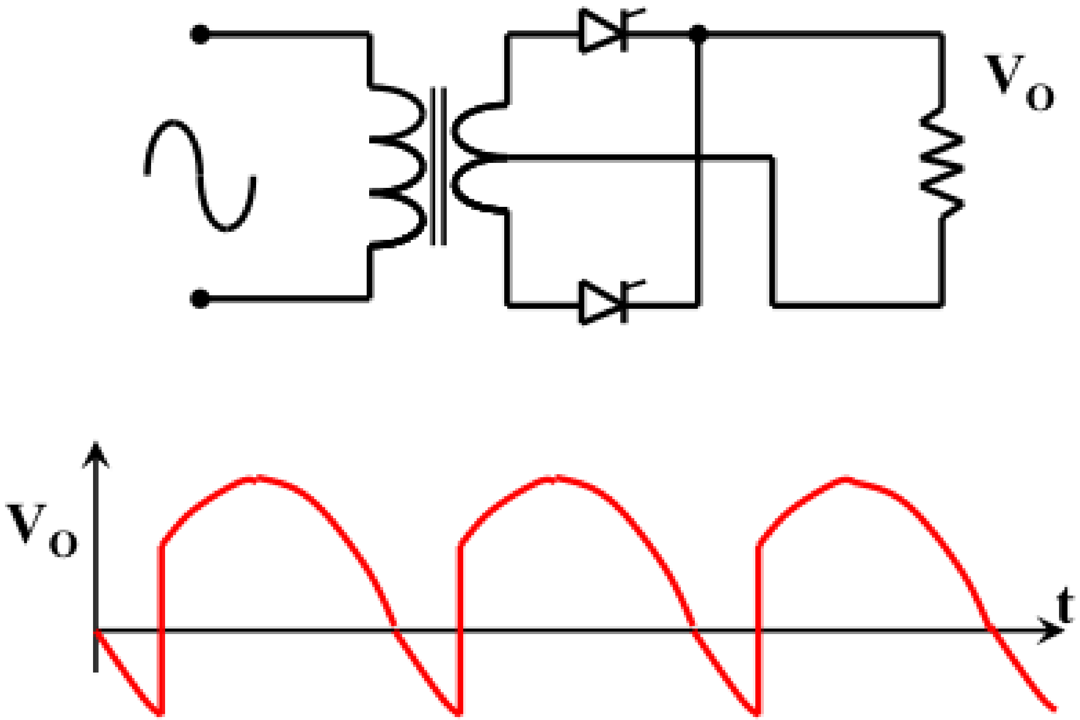
Switched Mode Power Conversion

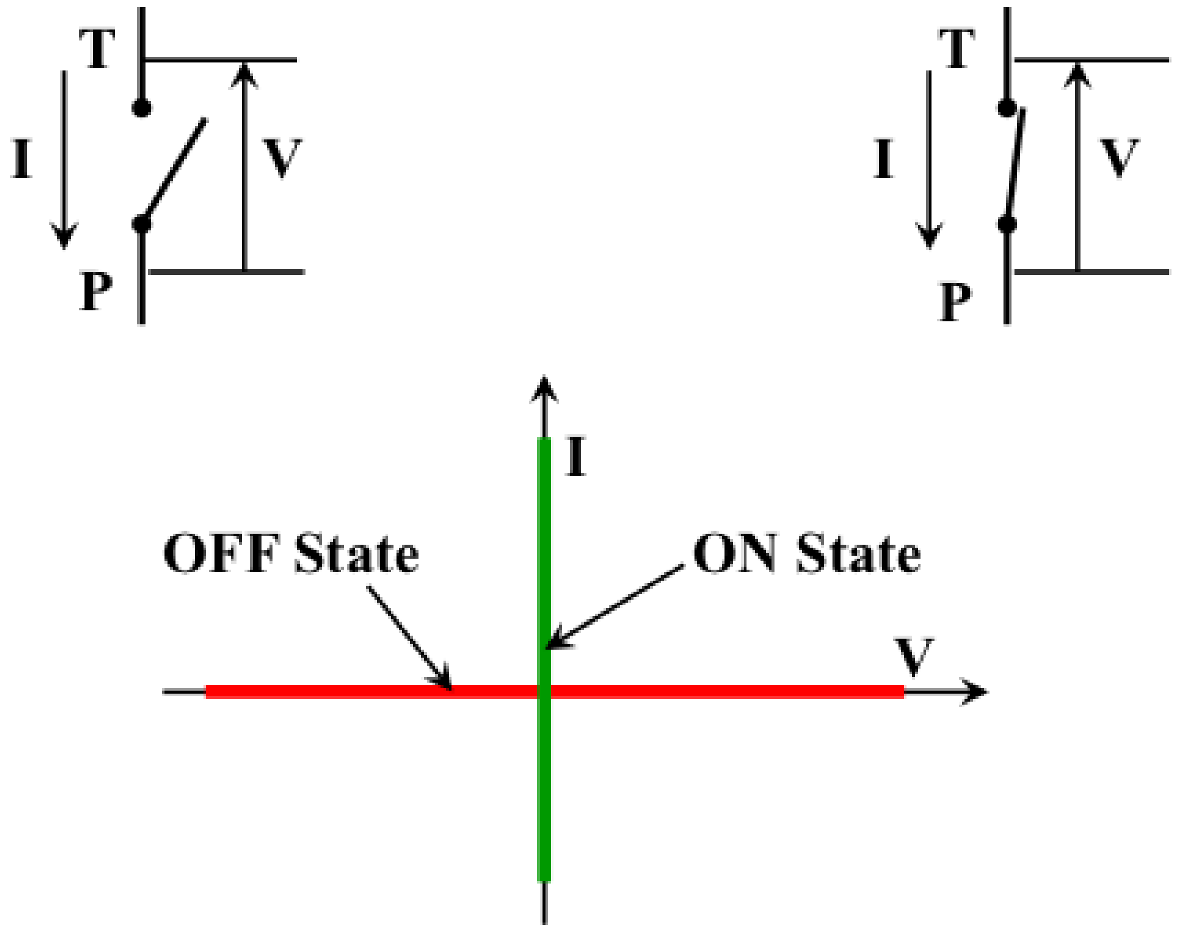
SCR – A Simple Application



Controlled AC/DC Rectifier

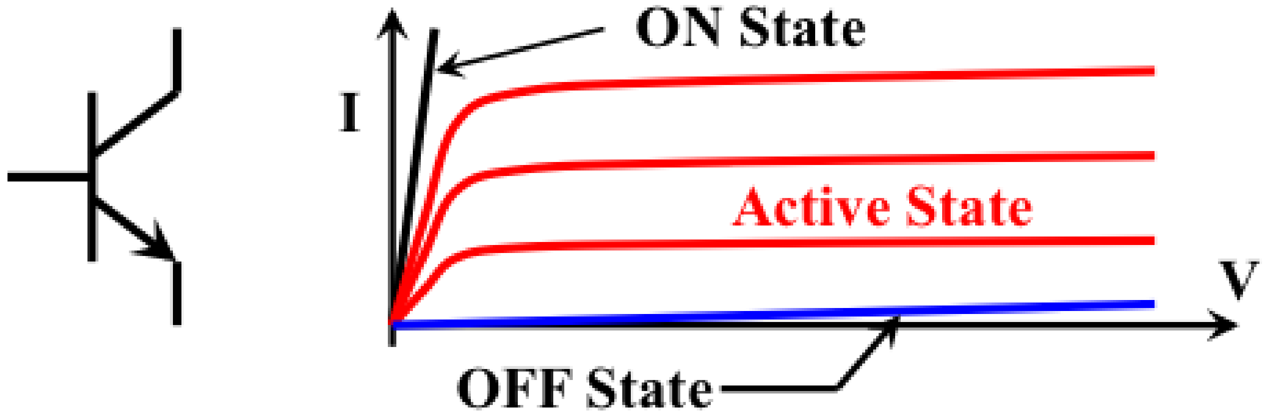
Switched Mode Power Conversion

Ideal Switch – In the VI Plane



Switched Mode Power Conversion

A Fully Controlled Switch – BJT



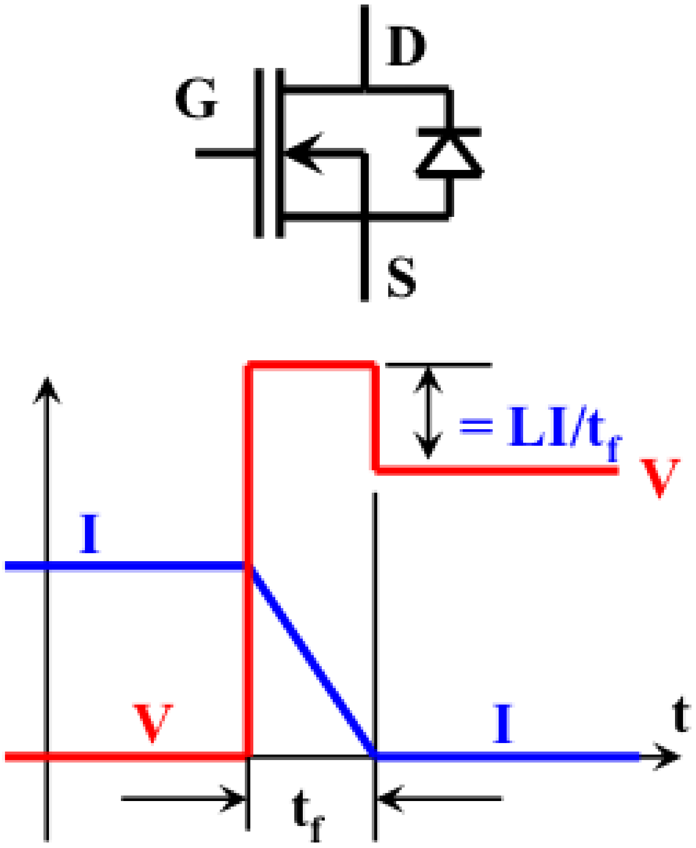
BJT

ON Switch for I > 0

OFF Switch for V > 0

Switched Mode Power Conversion

Switching Characteristics

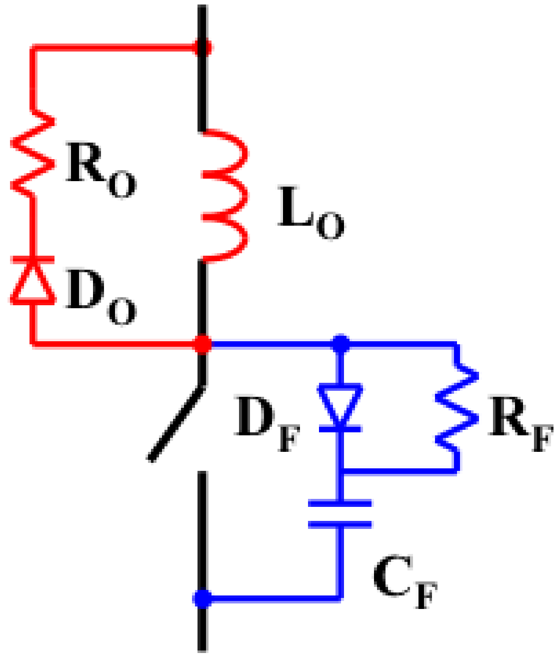


Turn-Off of Inductive Load

Over-voltage in Turn-Off

Switched Mode Power Conversion

Switching Aid Circuit



Strategy for Reducing Switching Stress

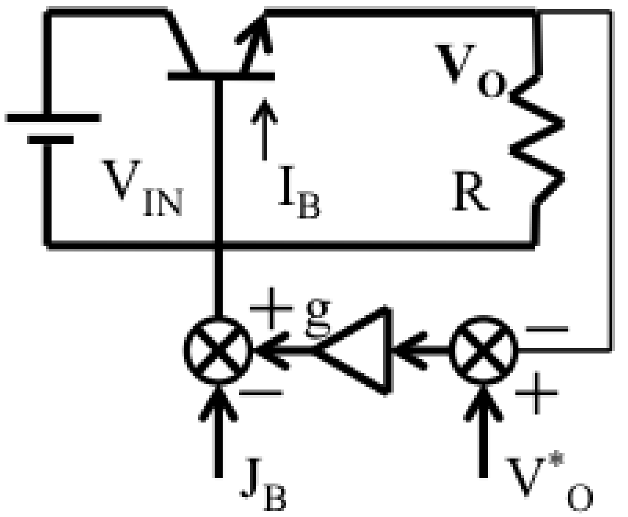
L_O, R_O, D_O, form Turn-On Aid Circuit

L_F, R_F, D_F, form Turn-Off Aid Circuit

Prior Art

Output Voltage

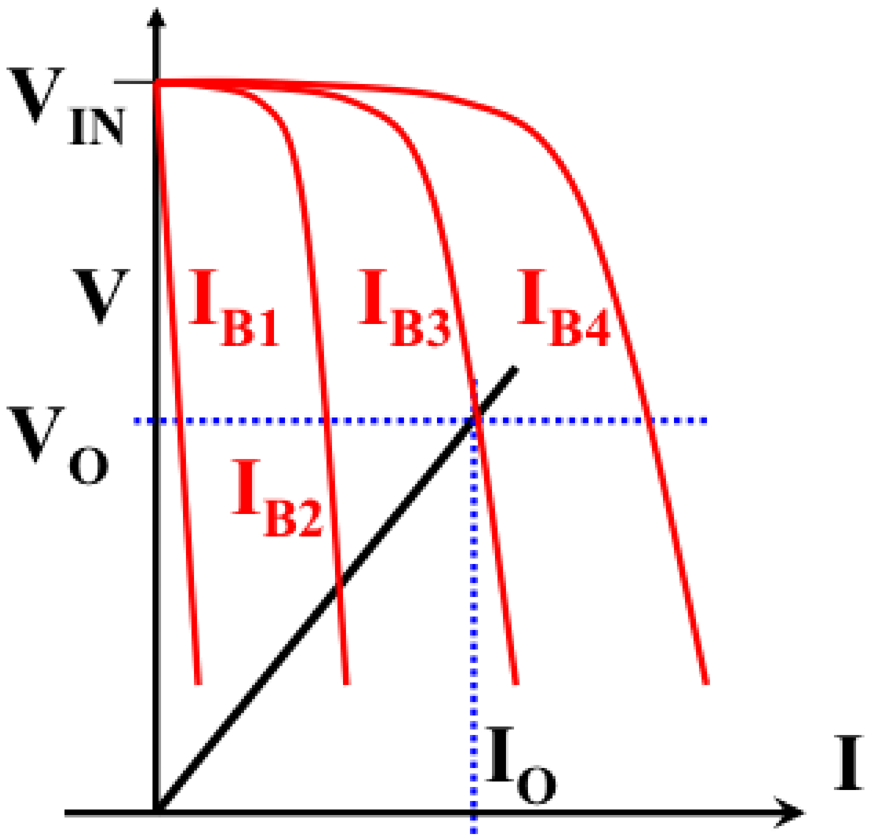
Series Controlled Converter



$$\left(g(V_O^* - V_O) - J_B\right)\beta R = V_O$$

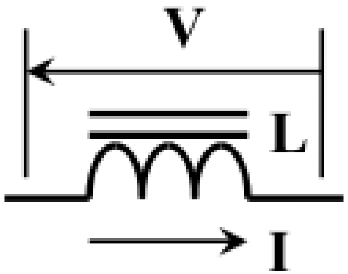
$$V_O = V_O^* \frac{g\beta R}{1 + g\beta R} + J_B \frac{\beta R}{1 + g\beta R}$$

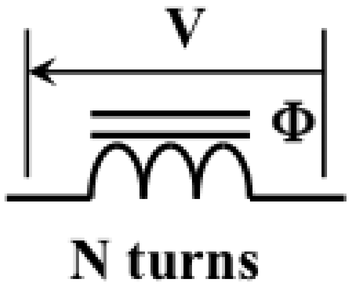
$$V_O \approx V_O^* \quad \text{for } g >>> 1$$



Switched Mode Power Conversion

Inductors





$$V = L\frac{dI}{dt} \qquad L\,I = N\,\Phi \qquad V = N\frac{d\Phi}{dt}$$

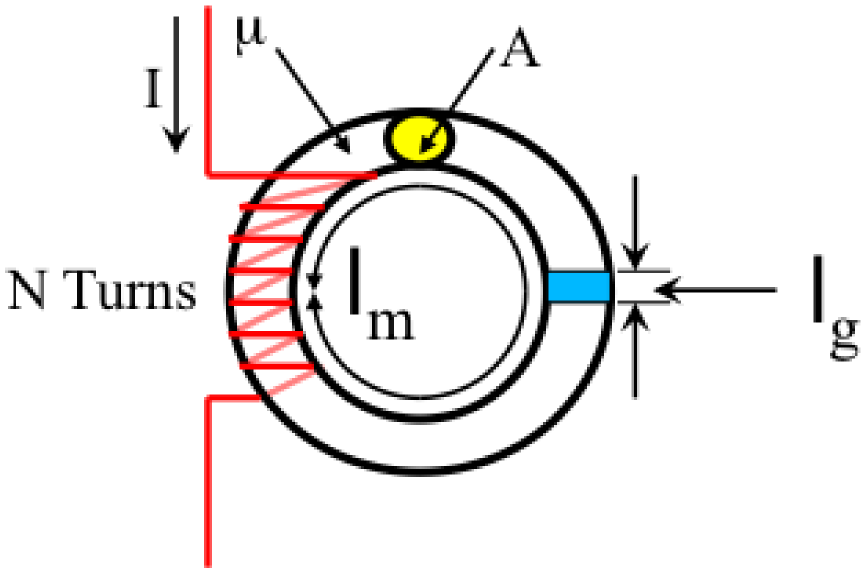
How to Relate the Electrical Circuit V, L, I

and

The Magnetic Circuit of the Inductor N, Φ, I & R

Switched Mode Power Conversion

Practical Design of an Inductor



$$L = \frac{N\Phi}{I} = \frac{N^2}{\left({}^{l_m}\!/\!_{A\mu_o\mu_m} + {}^{l_g}\!/\!_{A\mu_o} \right)} \cong \frac{N^2 A\mu_o}{l_g}$$

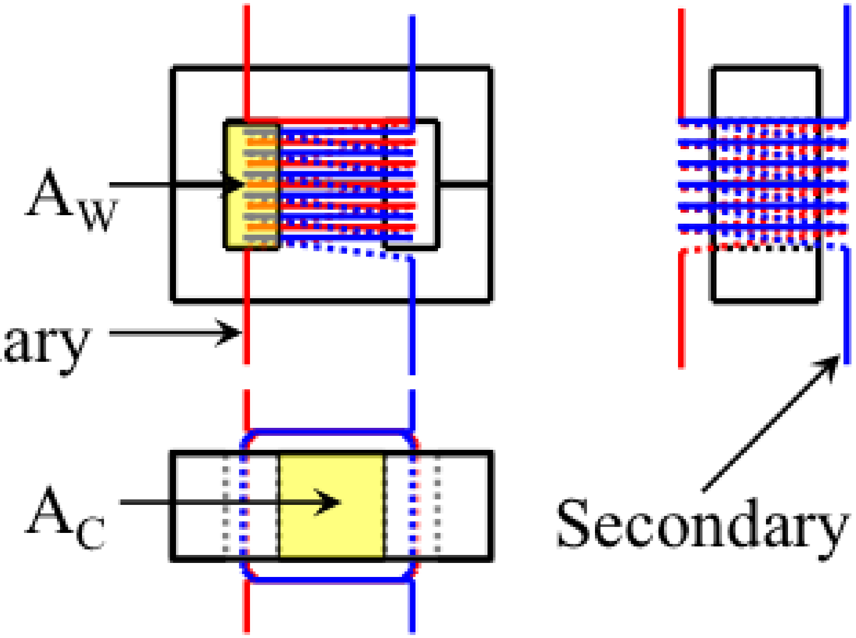
Inductance is Independent of Core Material (μ)

Inductance is Independent of Core Shape (l_m)

Switched Mode Power Conversion

Transformers

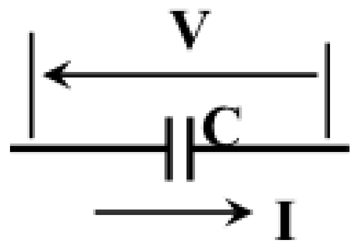
Voltage Equation



$$V_1 = N_1 \frac{d\Phi}{dt}; V_2 = N_2 \frac{d\Phi}{dt}$$

Switched Mode Power Conversion

Capacitors



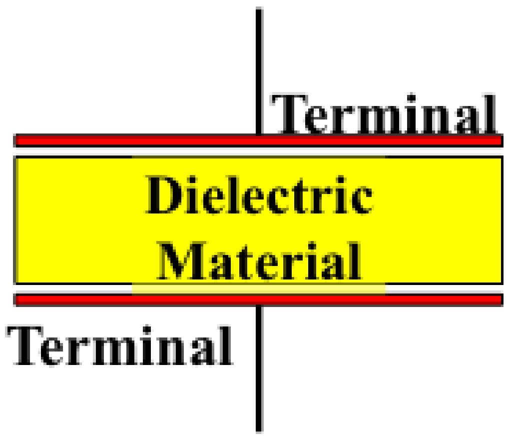
$$I = C\frac{dV}{dt}\ ;\ V(t) = V_I + \frac{1}{C}\int_0^t I\,dt$$

Electrical Circuit Element Equation

V, C, I are Electrical Circuit Quantities

Switched Mode Power Conversion

Capacitors – Stored Energy



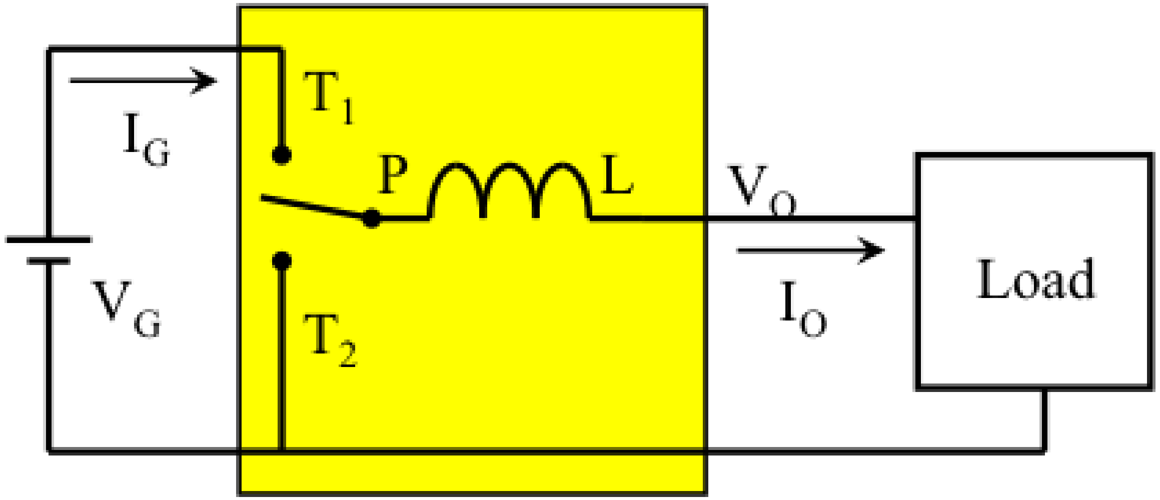
$$E = \int_0^V Q\,dV = \int_0^V CV\,dV = \frac{1}{2}CV^2$$

Energy is Work Done to Separate the Charge Through a Potential of V

Switched Mode Power Conversion

Primitive Converters

Primitive Voltage to Current Converter

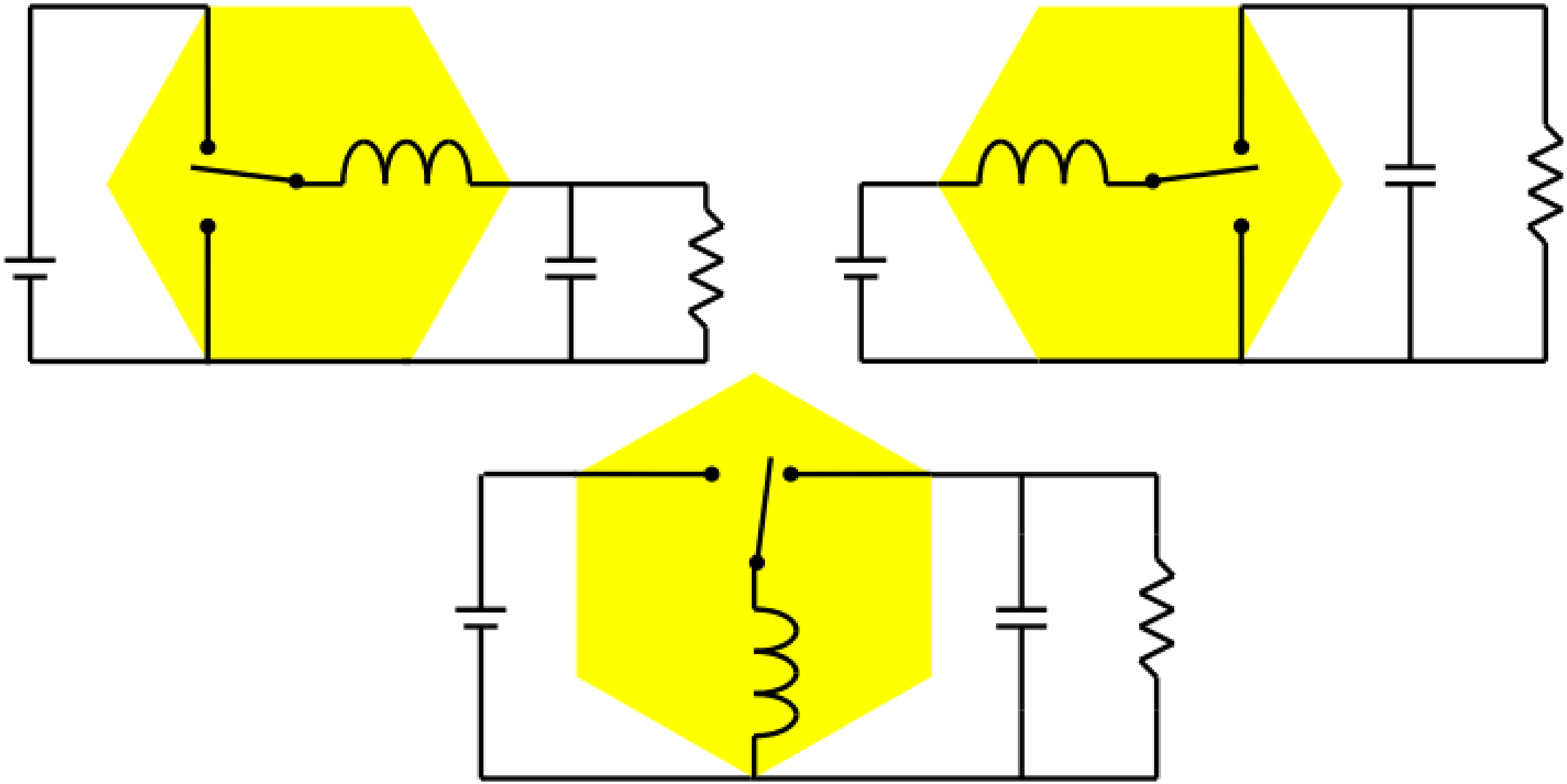


Input average quanities: V_G and I_G

Output average quantities: I_O and V_O

Switched Mode Power Conversion

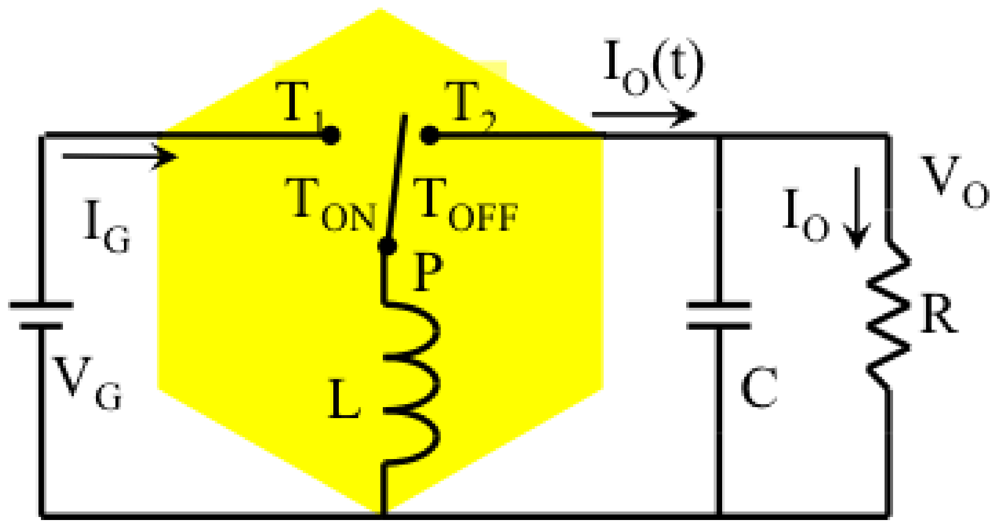
Basic Power Converters



Buck, Boost & Buck-Boost Variants

Switched Mode Power Conversion

Flyback Converter

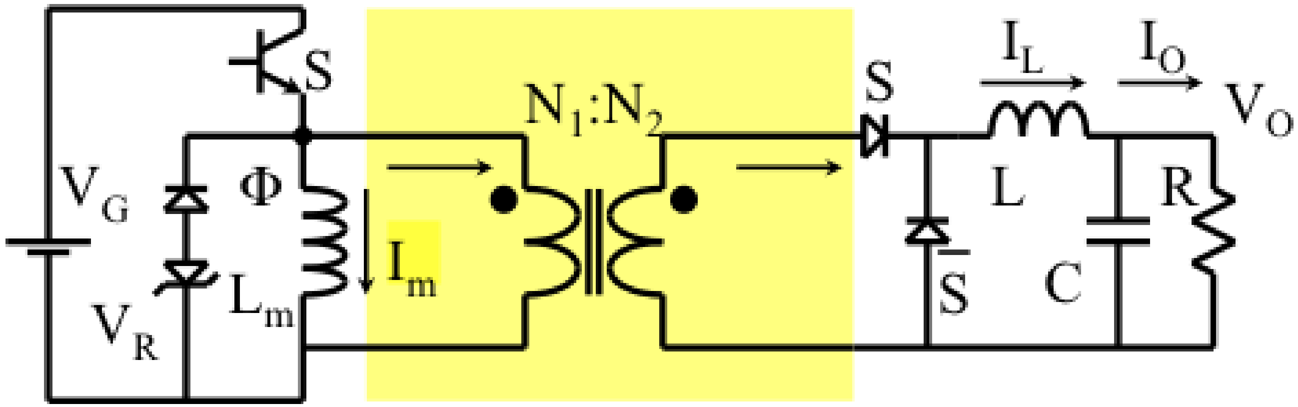


$$\frac{V_O}{V_G}\frac{I_O}{I_G} = \frac{D}{1-D}\,\frac{1-D}{D} = 1$$

Ideal Efficiency is Unity

Switched Mode Power Conversion

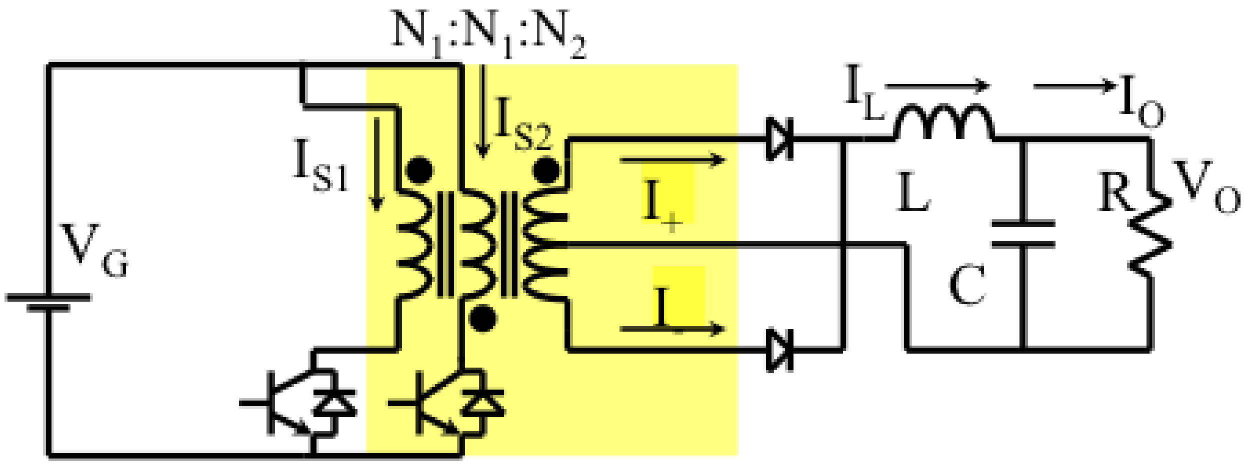
Forward Converter



Forward Converter – Circuit Realisation

Switched Mode Power Conversion

Push-Pull Converter



Switches turn-on with PWM in alternate half cycles

Flux resetting is done in Complementary Fashion

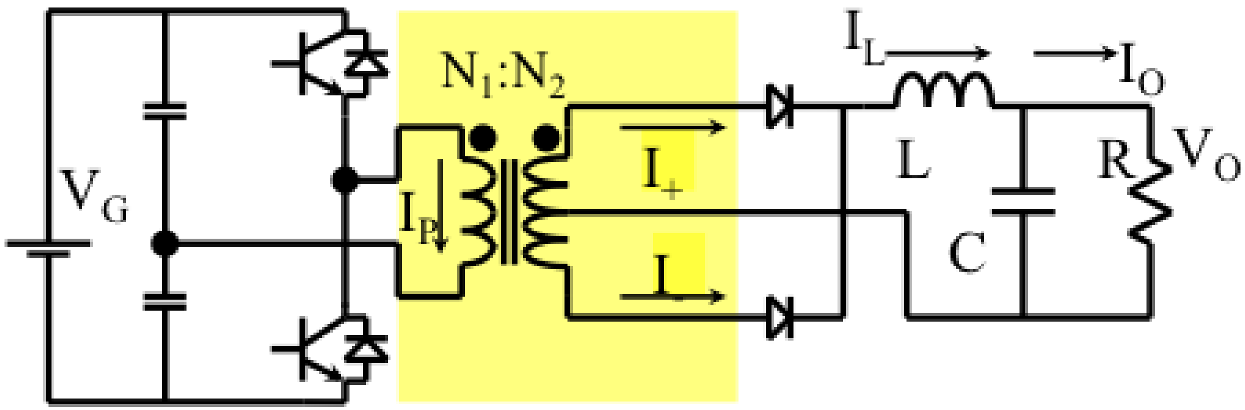
Duty ratio of primary switches < 50%

Secondary duty ratio < 100%

Back-to-Back Forward Converters

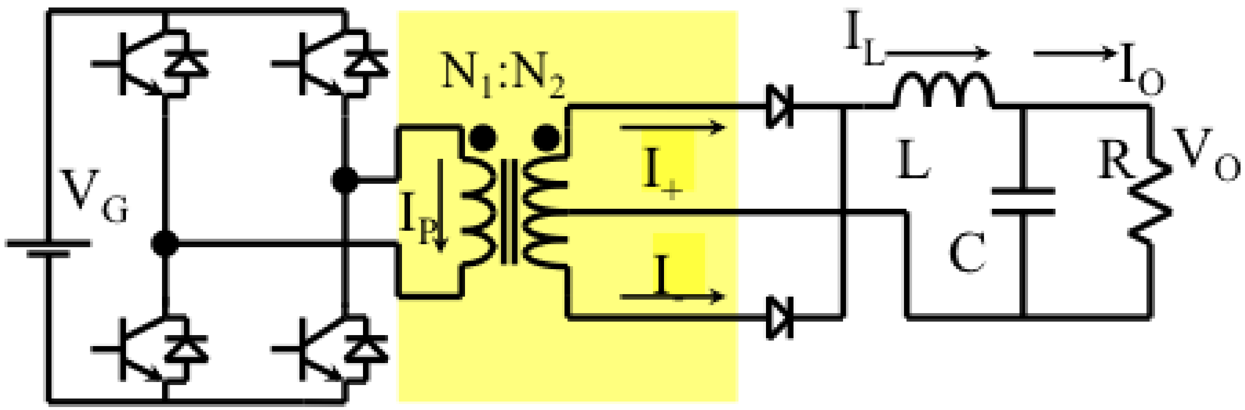
Switched Mode Power Conversion

Half Bridge Converters



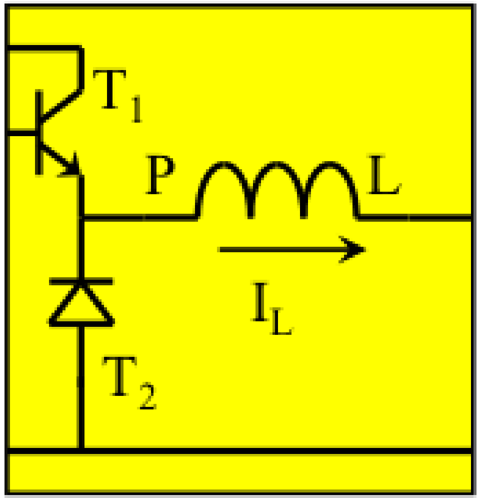
Switched Mode Power Conversion

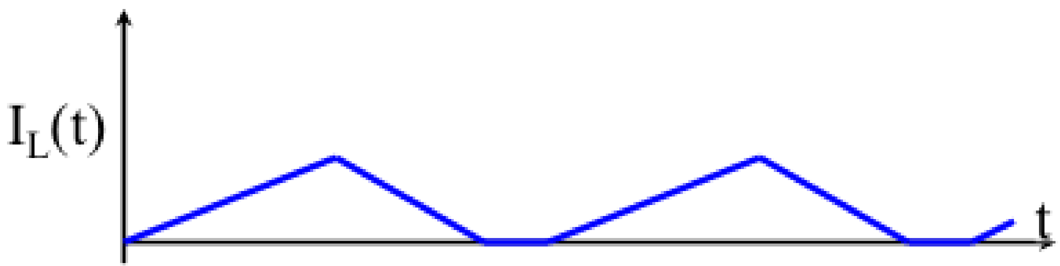
Full Bridge Converters



Switched Mode Power Conversion

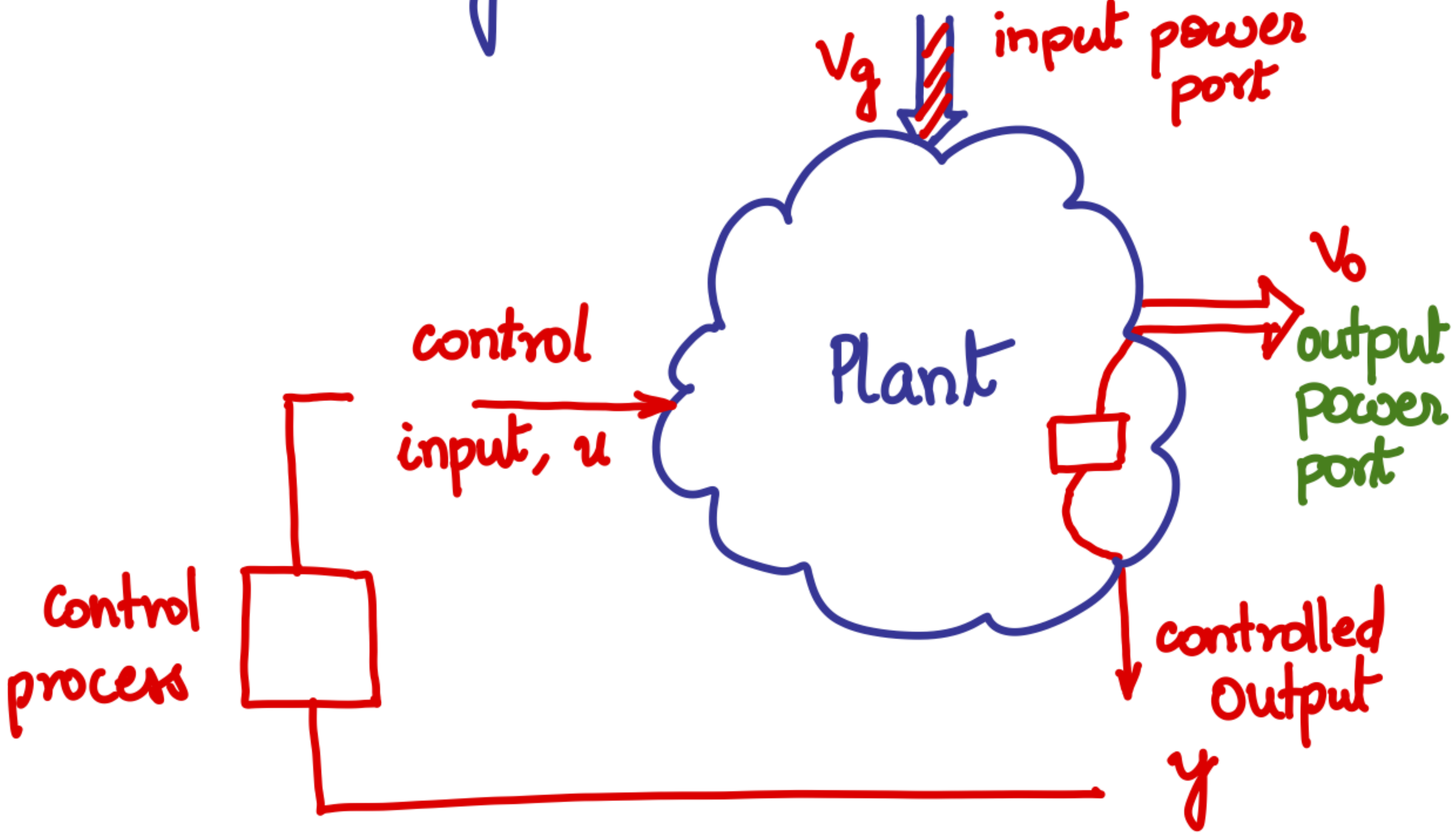
Buck Converter – DCM

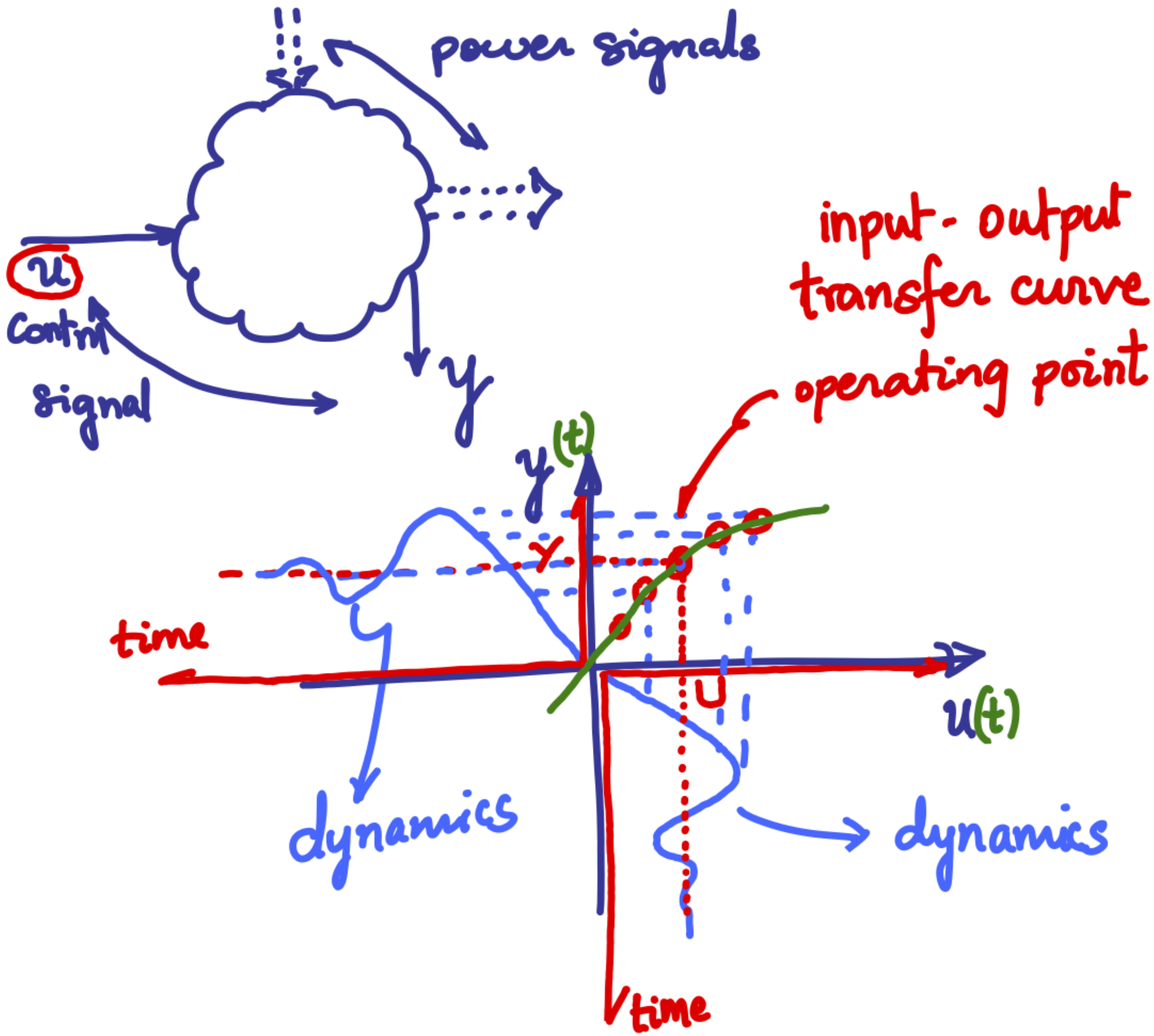




Third State: Transistor & Diode Both are OFF

Modeling Basics




power signals
input-output
transfer curve
operating point
u
control
signal
y
y(t)
Y
time
U
u(t)
dynamics
dynamics
time

$$\left\{\begin{aligned} \dot{x} &= \mathbb{A}x + \mathbb{B}u \\ y &= \mathbb{C}x + \mathbb{D}u \end{aligned}\right. \quad \Bigg\|$$

state space representation

State Equation

Output Equation

STANDARD

$$\frac{di_L}{dt} = -\left(\frac{R_1}{L}\right)(i_L) - \left(\frac{1}{L}\right)(v_c) + \left(\frac{1}{L}\right) v_g$$

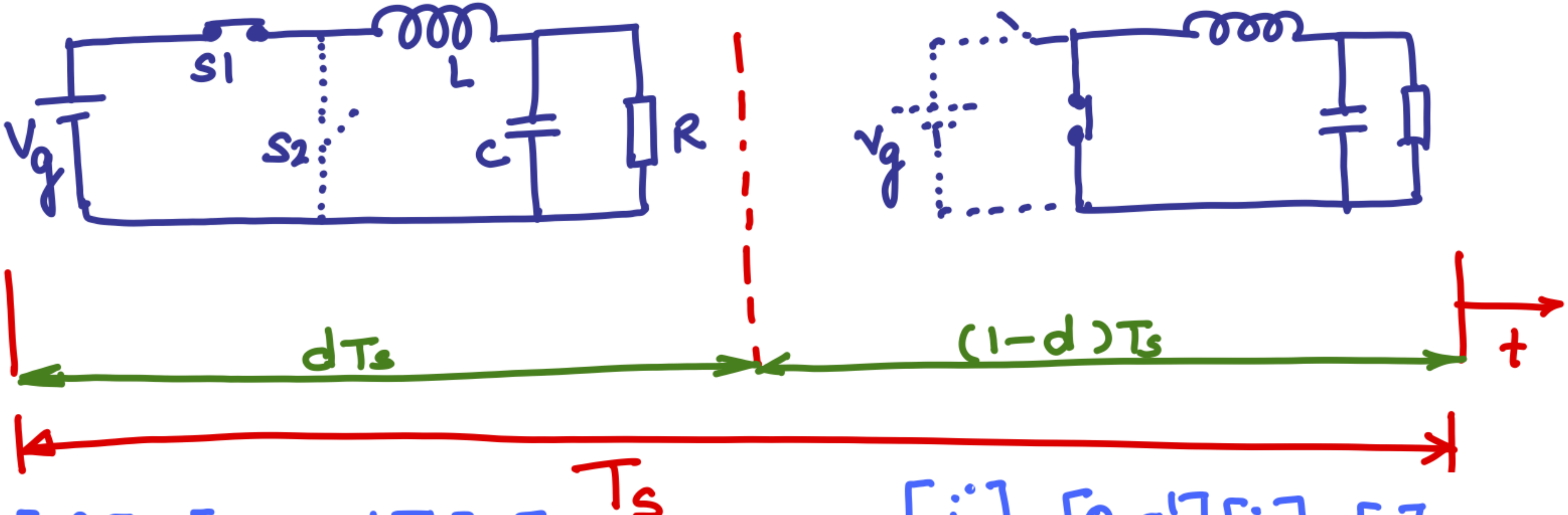
$$\frac{dv_c}{dt} = \underbrace{\left(\frac{1}{C}\right) i_L - \left(\frac{1}{R_2 C}\right) v_c}\; + \underbrace{0\; v_g}$$

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_c \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{R_1}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{R_2 C} \end{bmatrix}} \begin{bmatrix} i_L \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \begin{bmatrix} v_g \end{bmatrix}$$

$$\dot{x} = \mathbb{A} \cdot x \qquad \mathbb{B} \cdot u$$

STATE EQUATION

Circuit Averaging Method



$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} [v_g]$$

$$v_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + [0][v_g]$$

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} [v_g]$$

$$v_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + [0] v_g$$

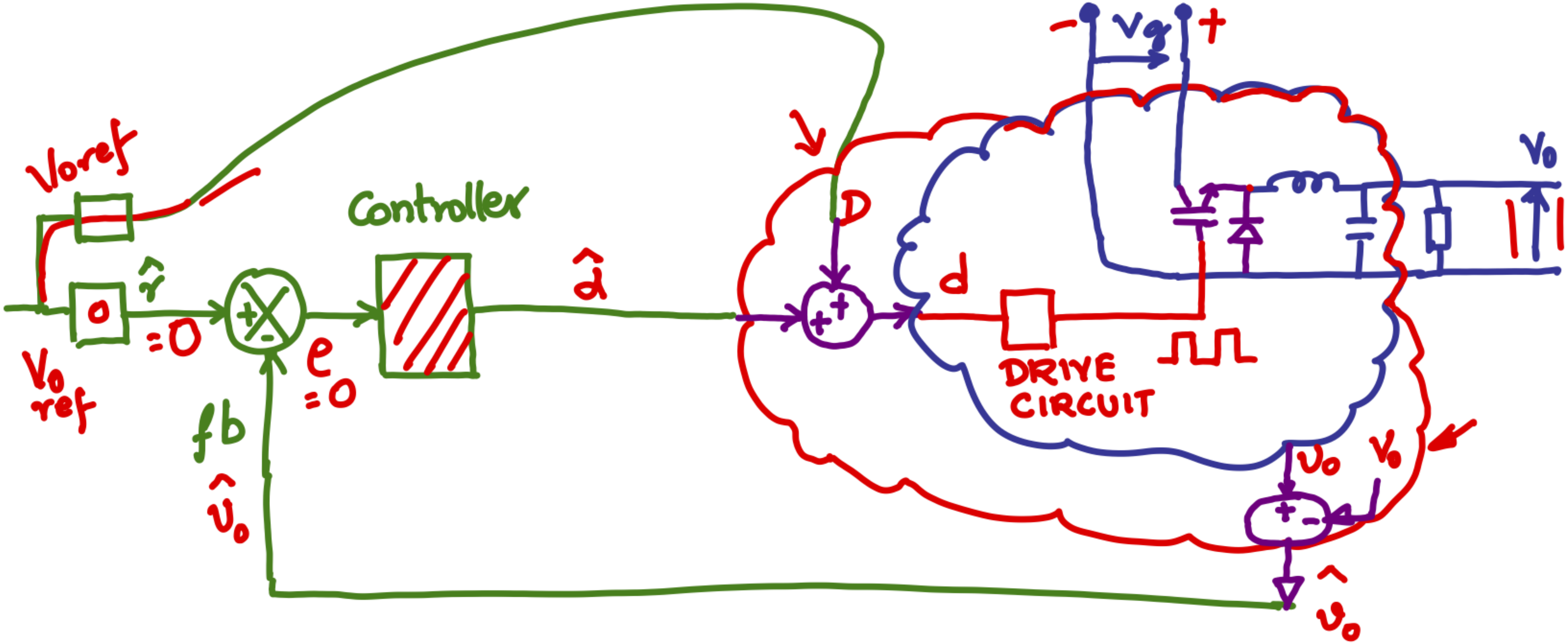
Large signal : $\dot{x} = \mathbb{A}x + \mathbb{B}u$ | actual system

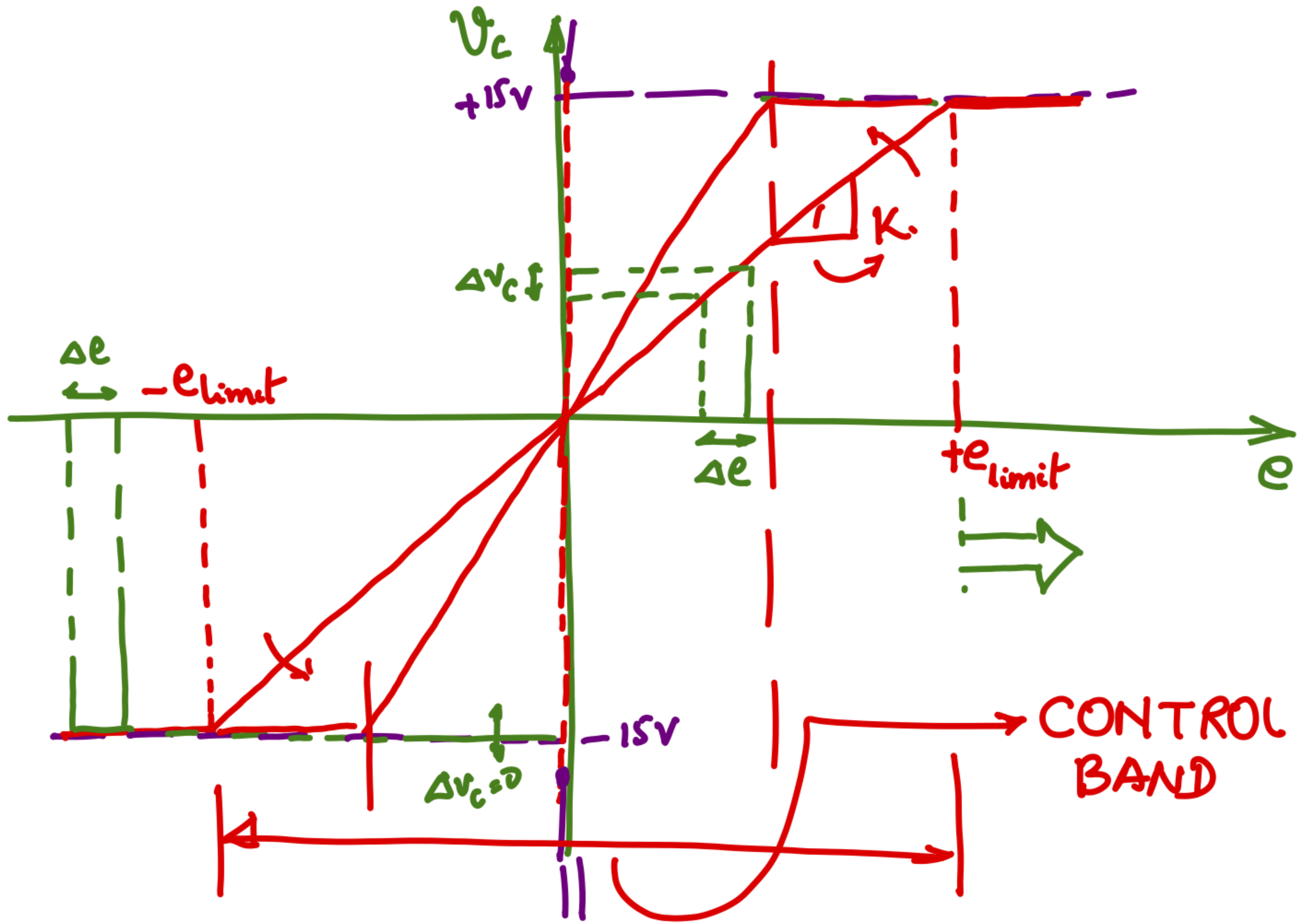
Steady State : $\dot{X} = 0 = \mathbb{A}X + \mathbb{B}U$ | Equilibrium

DESIGN of converter

Small signal : $$\underbrace{\dot{\hat{x}} = \mathbb{A}\hat{x} + \mathbb{B}\hat{u}}_{\text{dynamics variations about OPERATING POINT}}$$ || CONTROLLER DESIGN

linear model


Voref
Controller
$\hat{r}$
$\hat{d}$
=0
e
=0
V_o ref
fb
$\hat{v}_o$
D
d
V_g
V_o
DRIVE CIRCUIT
v_o
V_o
$\hat{v}_o$

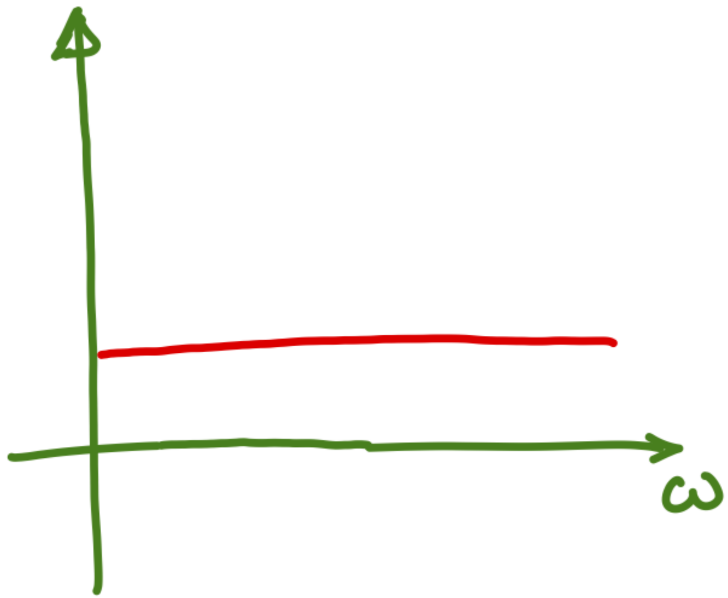


v_c
+15V
Δv_c
Δe
$-e_{limit}$
K.
1
Δe
$+e_{limit}$
e
-15V
$\Delta v_c = 0$
CONTROL BAND

Proportional

$$K_p$$

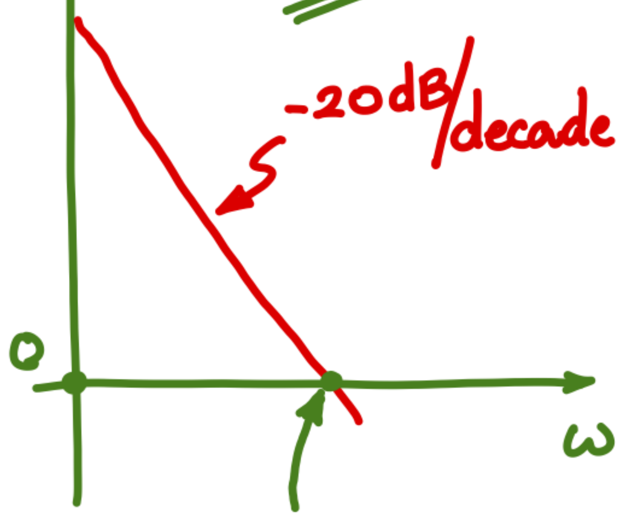
$$dB = 20\log_{10} K_p$$



Integrator

$$\frac{K_i}{s}$$

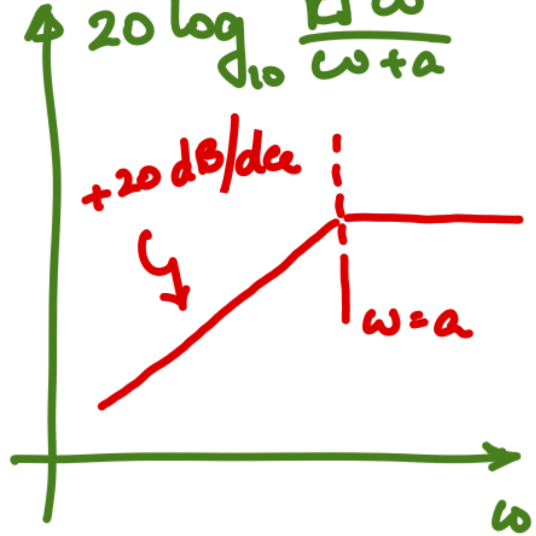
$$20\log_{10}\left(\frac{K_i}{\omega}\right)$$

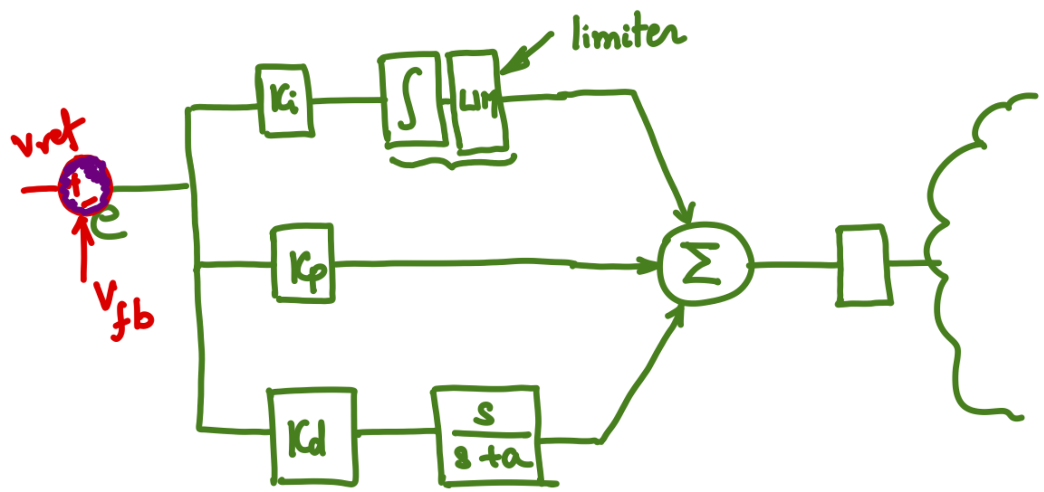


Derivative

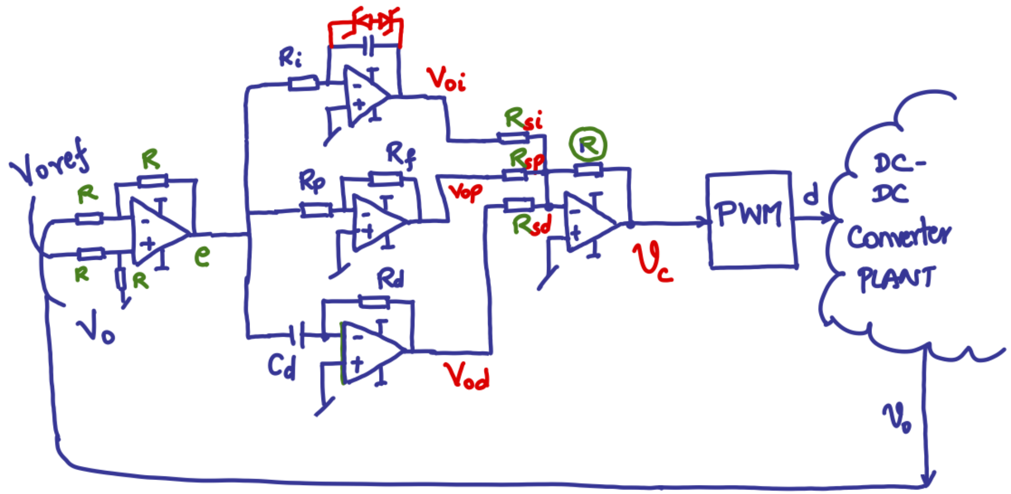
$$\frac{K_d\, s}{s+a}$$

$$20\log_{10}\frac{K_d\,\omega}{\omega+a}$$

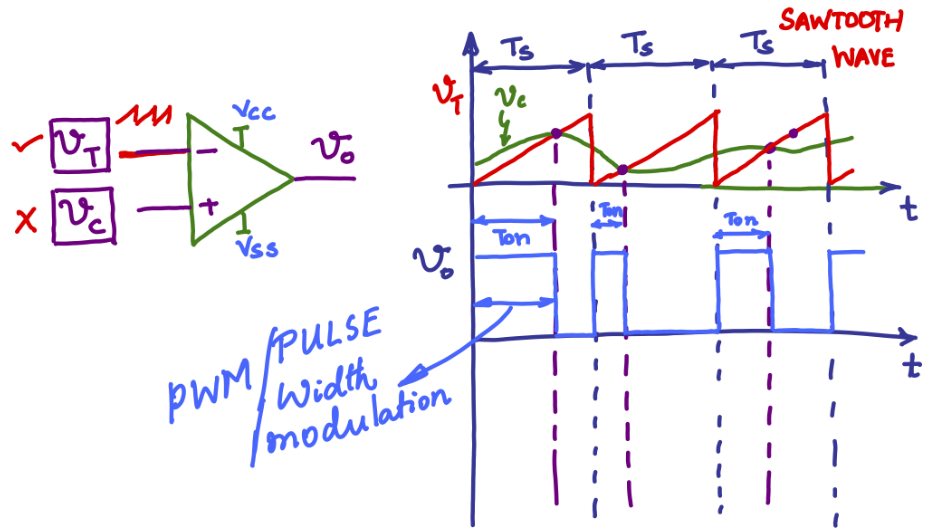




limiter
Vref
+
-
e
Vfb
Ki
∫
LIM
Kp
Σ
Kd
s
s+a



Voref
R
R
R
R
e
Vo
Ri
Voi
Rp
Rf
Vop
Cd
Rd
Vod
Rsi
Rsp
Rsd
R
Vc
PWM
d
DC-
DC
Converter
PLANT
Vo

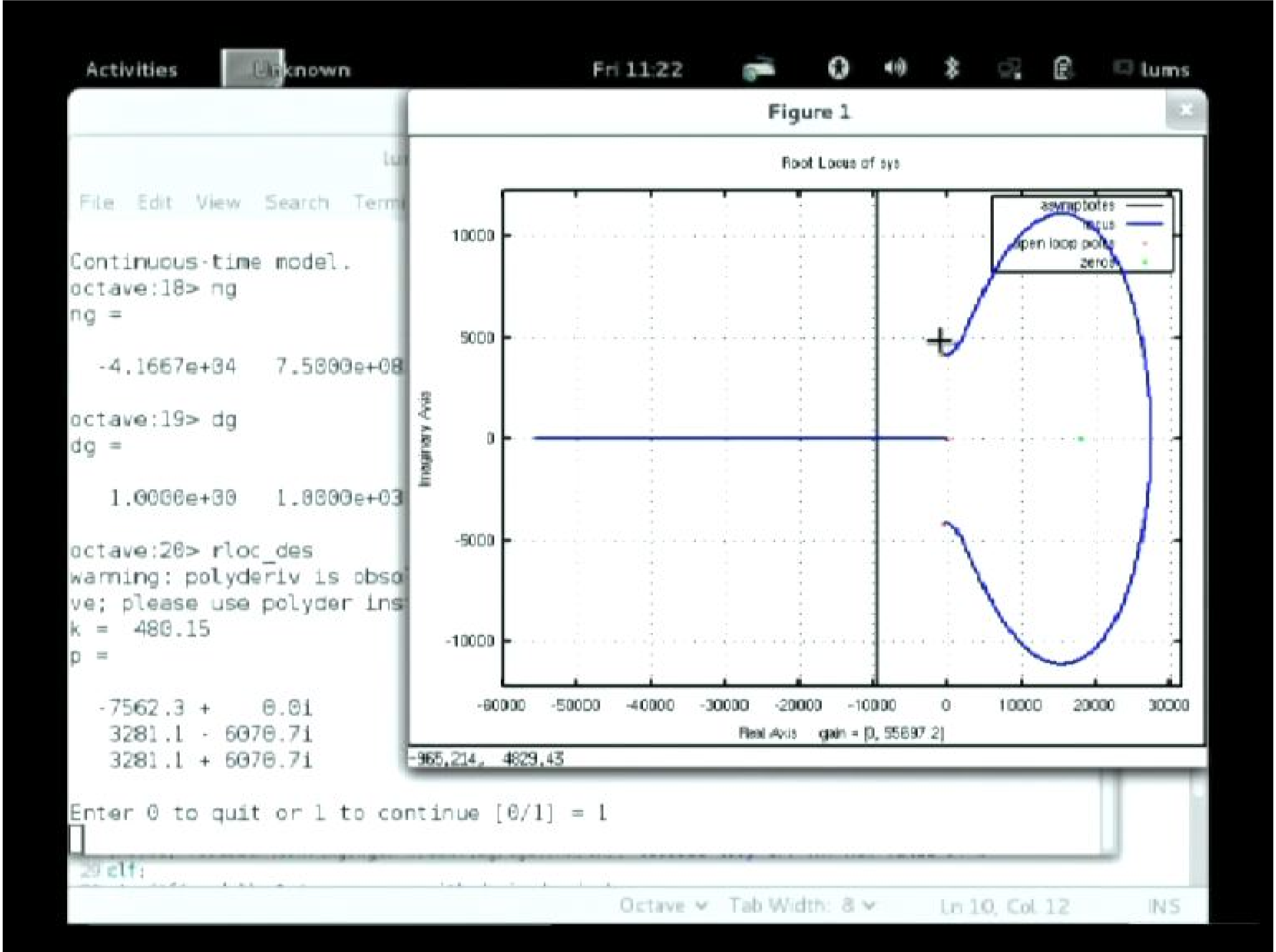


v_T
v_c
Vcc
Vss
v_o
T_s
T_s
T_s
SAWTOOTH WAVE
v_T
v_c
t
Ton
Ton
Ton
v_o
t
PWM
PULSE Width modulation

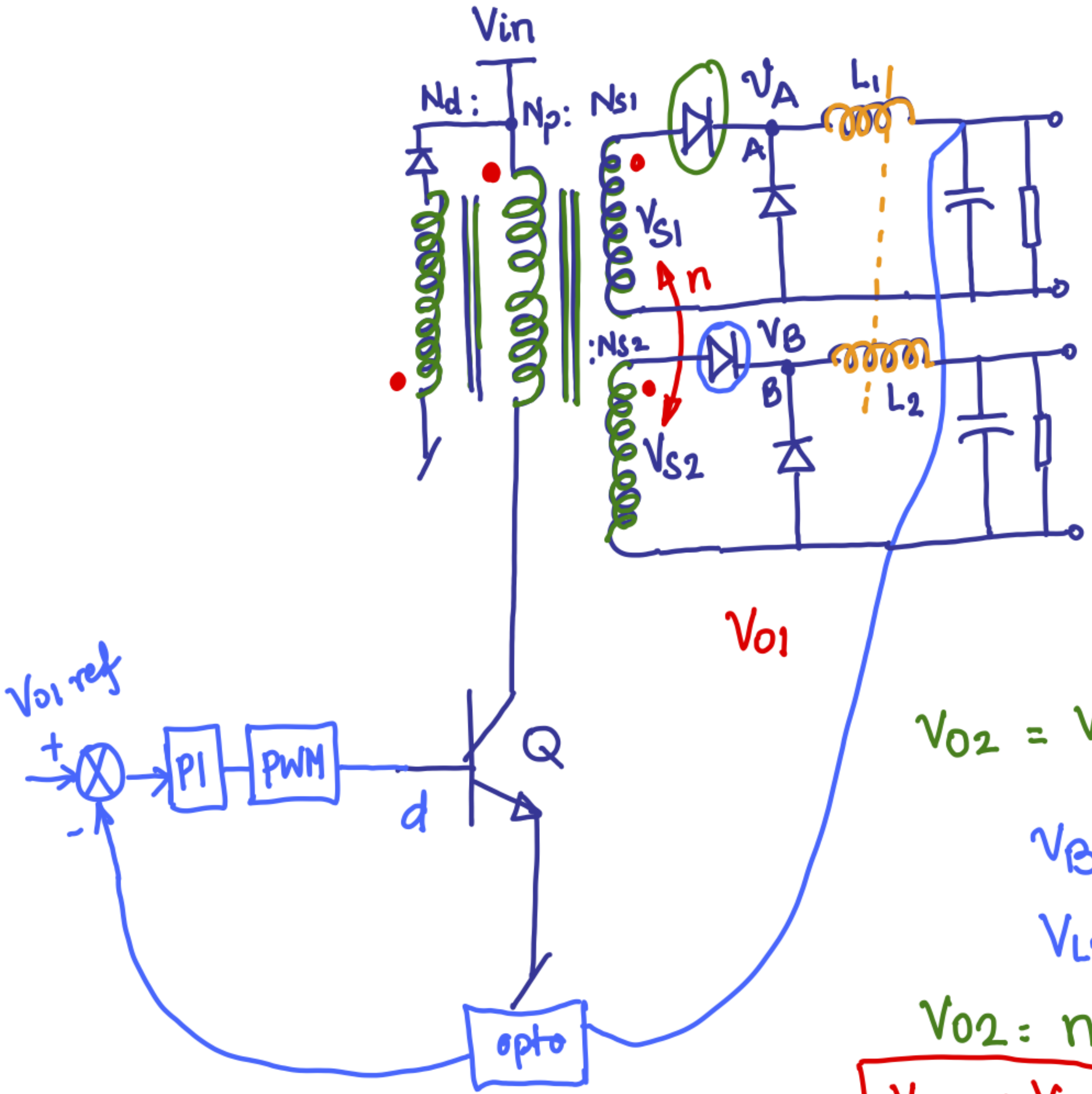
CONTROLLER
DESIGN

TUNING
CONTROLLER
DIRECTLY
on system (HW)
or simulation.

MODEL
$\downarrow$
root locus
technique
$\downarrow$
controller params
$\downarrow$
included in HW
or simulation platform


Activities
Unknown
Fri 11:22
lums
Figure 1
File Edit View Search Term
Continuous-time model.
octave:18> ng
ng =
-4.1667e+34 7.5000e+08
octave:19> dg
dg =
1.0000e+30 1.8000e+03
octave:20> rloc_des
warning: polyderiv is obso
ve; please use polyder ins
k = 480.15
p =
-7562.3 + 0.0i
3281.1 - 6070.7i
3281.1 + 6070.7i
Enter 0 to quit or 1 to continue [0/1] = 1
Root Locus of sys
asymptotes
locus
open loop poles
zeros
10000
5000
0
-5000
-10000
Imaginary Axis
-60000
-50000
-40000
-30000
-20000
-10000
0
10000
20000
30000
Real Axis gain = [0, 55697.2]
-965.214, 4829.43
Octave
Tab Width: 8
Ln 10, Col 12
INS

COUPLED INDUCTOR METHOD



$V_{01} = V_A - V_{L1}$

$\dfrac{V_{S2}}{V_{S1}} = \underline{\underline{n}} = \dfrac{N_{S2}}{N_{S1}}$

$\underline{\underline{n}} = \dfrac{N_{L2}}{N_{L1}}$

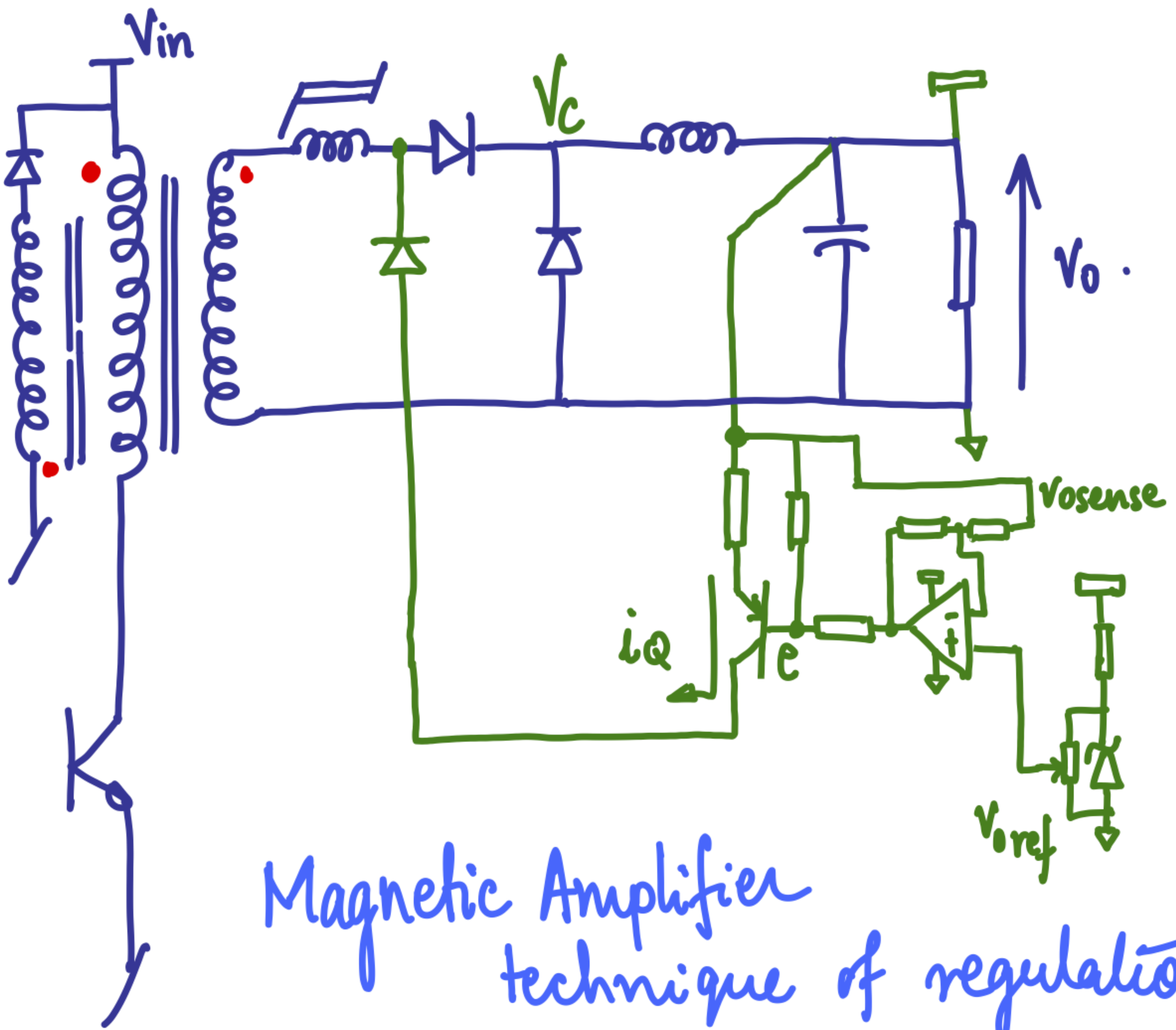
$V_{02} = \underline{V_B - v_{L2}}$

$V_B = n\,V_A \quad \because \; V_{S2} = n\,V_{S1}$

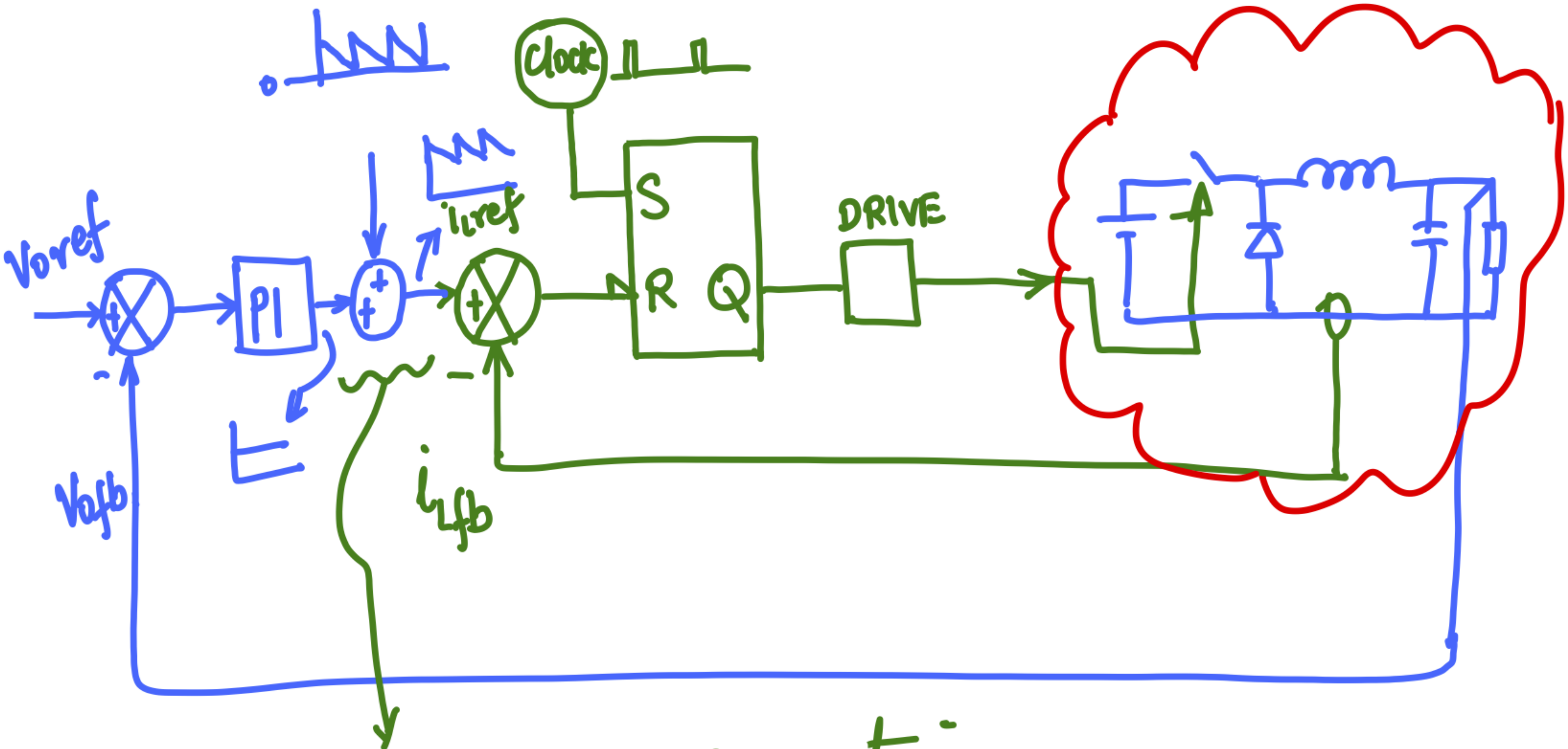
$V_{L2} = n\,V_{L1}$

$V_{02} = nV_A - nV_{L1} = n\underbrace{(V_A - V_{L1})}_{V_{01}}$

$\boxed{V_{02} = nV_{01}}$



Magnetic Amplifier technique of regulation



slope compensation

FARADAY EQN.

AMPERE'S RULE

Electric

Magnetic.

$v = N\dfrac{d\phi}{dt}$

$Ni = mmf$

mmf

i

$\dfrac{d\phi}{dt}$

N

Number of turns of the winding.

$$Ni = \int H \cdot dl$$

$$Ni = H \cdot l_m$$

$$\boxed{H = \frac{Ni}{l_m}}$$

FULL BRIDGE FORWARD CONVERTER.