Switched Mode Power Conversion

SCR – A Simple Application

Controlled AC/DC Rectifier
Switched Mode Power Conversion

Ideal Switch – In the VI Plane

OFF State

ON State
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

\[
(g(V_0^* - V_o) - J_B) \beta R = V_o
\]

\[
V_o = V_0^* \frac{g \beta R}{1 + g \beta R} + J_B \frac{\beta R}{1 + g \beta R}
\]

\[
V_o \approx V_0^* \text{ for } g \gg 1
\]
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Inductors

\[ V = L \frac{dI}{dt} \quad \text{LI} = N \Phi \quad V = N \frac{d\Phi}{dt} \]

How to Relate the Electrical Circuit V, L, I and The Magnetic Circuit of the Inductor N, \( \Phi \), I & R
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Practical Design of an Inductor

\[ L = \frac{N \Phi}{I} = \frac{N^2}{\left( \frac{l_m}{A \mu_o \mu_m} + \frac{l_g}{A \mu_o} \right)} \approx \frac{N^2 A \mu_o}{l_g} \]

Inductance is Independent of Core Material (\( \mu \))
Inductance is Independent of Core Shape (\( l_m \))
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Transformers

Voltage Equation

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

\[ \frac{V}{C} \]

\[ I = C \frac{dV}{dt} \]

\[ V(t) = V_i + \frac{1}{C} \int_0^t I \, dt \]

Electrical Circuit Element Equation

V, C, I are Electrical Circuit Quantities
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Capacitors – Stored Energy

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

$$E = \int_{0}^{V} Q \, dV = \int_{0}^{V} CV \, dV = \frac{1}{2} CV^2$$
Switched Mode Power Conversion

Primitive Converters

Primitive Voltage to Current Converter

Input average quantities: $V_G$ and $I_G$
Output average quantities: $I_O$ and $V_O$
Switched Mode Power Conversion

Basic Power Converters

Buck, Boost & Buck-Boost 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

- **Input Power Port**: \( v_g \)
- **Output Power Port**: \( v_o \)
- **Controlled Output**: \( y \)
- **Control Process**: \( u \)

Diagram:
- **Plant**
- **Input, \( u \)**
- **Control**
input-output transfer curve
operating point

dynamics

time

control signal

power signals

y(t)

u(t)

y
\[
\begin{aligned}
\dot{x} &= Ax + Bu \\
y &= Cx + Du
\end{aligned}
\]

**State Equation**

**Output Equation**

**State space representation**

**STANDARD**
\[
\begin{align*}
\frac{di_L}{dt} &= -\left(\frac{R_1}{L}\right)i_L - \left(\frac{1}{L}\right)v_c + \left(\frac{1}{L}\right)v_q \\
\frac{dv_c}{dt} &= \left(\frac{1}{C}\right)i_L - \left(\frac{1}{R_2 C}\right)v_c + 0v_q \\
\begin{bmatrix}
\dot{i}_L \\
\dot{v}_c
\end{bmatrix} &= \begin{bmatrix}
-\frac{R_1}{L} & -\frac{1}{L} \\
\frac{1}{C} & -\frac{1}{R_2 C}
\end{bmatrix}
\begin{bmatrix}
i_L \\
v_c
\end{bmatrix} + \begin{bmatrix}
\frac{1}{L} \\
0
\end{bmatrix}
v_q \\
\dot{x} &= A \cdot x + B \cdot u
\end{align*}
\]

STATE EQUATION
Circuit Averaging Method

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

\[
v_0 =
\begin{bmatrix}
0 & 1
\end{bmatrix}
\begin{bmatrix}
i_L \\
v_C
\end{bmatrix} +
\begin{bmatrix}
0
\end{bmatrix} [v_g]
\]
Large signal: \( \dot{x} = Ax + Bu \) | actual system

Steady State: \( \dot{X} = 0 = AX + BU \) | Equilibrium design of converter

Small signal: \( \dot{\hat{x}} = A\hat{x} + B\hat{u} \) | Controller design

linear model

dynamics variations about operating point
Proportional $K_p$

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

Integrator $\frac{K_i}{S}$

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

$-20 \text{dB/decade}$

Derivative $\frac{K_d S}{S + a}$

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

$+20 \text{dB/dec}$
PWM/PULSE Width modulation

SAWTOOTH WAVE

\[ V_T \]

\[ V_C \]

\[ V_S \]

\[ V_O \]

\[ T_S \]

\[ T_{on} \]

\[ T_{off} \]
Controller Design

- Tuning Controller:
  - Directly on system (HW) or simulation.

- Model:
  - Root locus technique
  - Controller params included in HW or simulation platform.
Continuous-time model.

octave:18> ng
ng =
-4.1667e+04 7.5000e+08

octave:19> dg
dg =
1.0000e+30 1.0000e+03

octave:20> rlocus
warning: polyderiv is obsolete; please use polyder instead

k = 488.15
p =
-7562.3 + 0.01
3281.1 - 6070.71
3281.1 + 6070.71

Enter 0 to quit or 1 to continue [0/1] = 1
Coupled Inductor Method

\[ V_{01} = V_A - V_{L1} \]

\[ \frac{V_{S2}}{V_{S1}} = n = \frac{N_{S2}}{N_{S1}} \]

\[ n = \frac{N_{L2}}{N_{L1}} \]

\[ V_{02} = V_B - V_{L2} \]

\[ V_B = nV_A \]

\[ V_{L2} = nV_{L1} \]

\[ V_{02} = nV_A - nV_{L1} = n \left( \frac{V_A - V_{L1}}{V_{01}} \right) \]

\[ V_{02} = nV_{01} \]
Magnetic Amplifier technique of regulation
slop compensation

Voref

VoFB

i_ref

Clock

SRQ

DRIVE

Diagram of a control system with components labeled and connections indicated.
FARADAY EQN.

AMPERE'S RULE

Electric

\[ V = \frac{Nd\phi}{dt} \]

Magnetic.

\[ Ni = mmf \]

\[ mmf \]

\[ Ni = \int H \cdot dl \]

\[ Ni = H \cdot \text{lm} \]

Number of turns of the winding.

\[ H = \frac{Ni}{\text{lm}} \]
FULL BRIDGE FORWARD CONVERTER.