Switched Mode Power Conversion

Switches

Devices for Efficient Power Conversion

Switches
Inductors
Transformers
Capacitors
Switched Mode Power Conversion

Switches

Switch is a Bistable Circuit Element

OFF State
&
ON State
Switched Mode Power Conversion

Switches

Simple Switch has Two Terminals

Pole
&
Throw
Switched Mode Power Conversion

Switches

In the OFF State

Pole & Throw are Isolated from Each Other
Switched Mode Power Conversion

Switches

In the ON State

Pole & Throw are Connected to Each Other
Switched Mode Power Conversion

Switches

In the OFF State

Current through the Switch is Zero
Switched Mode Power Conversion

Switches

In the ON State

Voltage Across the Switch is Zero

\[ V_{ON} = 0 \]
Switched Mode Power Conversion

Switch – Primary Characteristics

In the OFF State: \( I_{OFF} = 0 \)

In the ON State: \( V_{ON} = 0 \)
Switched Mode Power Conversion

Switch

In the OFF State: $V_{OFF} = ?$

In the ON State: $I_{ON} = ?$
Switched Mode Power Conversion

Switch – OFF State

In the OFF State: $I_{OFF} = 0$

In the OFF State: $V_{OFF} = V_G$
Switched Mode Power Conversion

Switch – ON State

In the ON State: $V_{ON} = 0$

In the ON State: $I_{ON} = V_G/R$
Switched Mode Power Conversion

Switch – Ideal Performance

In the OFF State:
\[ I_{OFF} = 0 \]; \[ V_{OFF} \] by External Circuit

In the ON State:
\[ V_{ON} = 0 \]; \[ I_{ON} \] by External Circuit
Switched Mode Power Conversion

Ideal Switch – In the VI Plane

OFF State

ON State
Switched Mode Power Conversion

Ideal Switch – Power Loss

Power Loss in the Ideal Switch

Conduction Loss = $V_{ON} \times I_{ON} = 0$

Blocking Loss = $V_{OFF} \times I_{OFF} = 0$
Switched Mode Power Conversion

Ideal Switch – Switching Performance

How Does the Switch Perform in Switching?
- Time Taken to Switch!
- Energy Needed to Switch!
- Dependence on Environment!
Switched Mode Power Conversion

Ideal Switch – Switching Performance

How Does the Switch Perform in Switching?

Energy Required to Remain On = \( E_{ON} = 0 \)
Energy Required to Remain Off = \( E_{OFF} = 0 \)
Switched Mode Power Conversion

Ideal Switch – Switching Performance

How Does the Switch Perform in Switching?

Time Taken to Turn On = $T_{OFF/ON} = 0$
Time Taken to Turn Off = $T_{ON/OFF} = 0$
Switched Mode Power Conversion

Ideal Switch – Switching Performance

How Does the Switch Perform in Switching?

Energy Consumed to Turn On = $E_{OFF/ON} = 0$
Energy Consumed to Turn Off = $E_{ON/OFF} = 0$
Switched Mode Power Conversion

Ideal Switch – Dependence on Ambient

Switch Performance

is

Independent of Ambient Conditions
Switched Mode Power Conversion

Compound Switch

Example: Single Pole Double Throw Switch
Made-up of Two Single Pole Single Throw Switches

Multiple Pole Multiple Throw Switches are Common
Switched Mode Power Conversion

Real Switch

In the OFF State: \( I_{OFF} \neq 0 \)

In the ON State: \( V_{ON} \neq 0 \)
Switched Mode Power Conversion
Real Switch – Power Loss

Power Loss in the Real Switch

Conduction Loss = $V_{ON} \cdot I_{ON} \neq 0$

Blocking Loss = $V_{OFF} \cdot I_{OFF} \neq 0$
Switched Mode Power Conversion

Real Switch – In the VI Plane

OFF State

ON State
Switched Mode Power Conversion

A Sample Real Switch – Diode

Diode
ON Switch for $I > 0$

OFF Switch for $V < 0$
Switched Mode Power Conversion

A Sample Real Switch – Diode

Single Quadrant Switch

Uncontrolled Switch
Switched Mode Power Conversion

Diode – Typical Datasheet

20ETS Diodes
Switched Mode Power Conversion

Diode – Percentage Loss

Conduction Loss: \( (1.1V/20A) \) 22 W @ 25 °C

Blocking Loss: \( (0.1mA/800V) \) 0.8 W @ 25 °C

Blocking Loss is Invariably Negligible

True for All Switching Devices
Switched Mode Power Conversion

Diode – Temperature Co-efficient of $V_{ON}$

Conduction Drop

1.0V/10A @ 25°C ; 0.9V/10A @ 150°C

20ETS Diodes

Caution is Required in Parallel Operation
Switched Mode Power Conversion
Dioded – A Simple Application

AC/DC Rectifier
Switched Mode Power Conversion

Another Real Switch – SCR

ON Switch for $I > 0$

OFF Switch for $V < 0$ ; $V > 0$
Switched Mode Power Conversion

Another Real Switch – SCR

Forward Conduction

Reverse Blocking

Forward Blocking

SCRTwo Quadrant Switch

Semicontrolled Switch
Switched Mode Power Conversion

SCR – Data Sheet

Reverse Blocking  Forward Conduction

Forward Blocking

SCR
Switched Mode Power Conversion

SCR – Data Sheet

Conduction Loss : (1.7V/32A) 54 W @ 25 ºC
Blocking Loss : (2 mA/400V) 0.8 W @ 25 ºC

Blocking Losses or Invariably Negligible
True for All Switching Devices
Switched Mode Power Conversion

SCR – A Simple Application

Controlled AC/DC Rectifier
Switched Mode Power Conversion
Diode & SCR – Short Circuit Protection

20ETS Diodes          SCR

For Satisfactory Protection
Fuse $I^2t < $ Device $I^2t$
Switched Mode Power Conversion
Power Device – Thermal Protection

20ETS Diodes  SCR

Device is Mounted on a Case C

\[ R_{TH(JC)} \times P = \Theta_J - \Theta_C \]

\( R_{TH(JC)} \) : Thermal Resistance
\( P \) : Power Dissipation in Device
\( \Theta_J \) : Junction Temperature
\( \Theta_C \) : Case Temperature
Switched Mode Power Conversion
Thermal Protection – An Example

\[ R_{\text{TH(JC)}} \times P = \Theta_J - \Theta_C \]

20ETS Diodes
Device is Mounted on a Case C

\[ R_{\text{TH(JC)}} : 1.3 \, ^\circ \text{C/W} \]
\[ P : 22 \, \text{W} \]
\[ \Theta_J : 125 \, ^\circ \text{C} \]
\[ \Theta_C : ? = 96.4 \, ^\circ \text{C} \]
Switched Mode Power Conversion

Diode – Dynamic Performance

\[ I_{RM} = t_A \times \frac{dI_F}{dt} = 5 \, \text{A} \]
Switched Mode Power Conversion
A Fully Controlled Switch – BJT

BJT
ON Switch for $I > 0$

OFF Switch for $V > 0$
Switched Mode Power Conversion

A Fully Controlled Switch – BJT

BJT

Single Quadrant Switch

Fully Controlled Switch

Current Controlled Switch
Switched Mode Power Conversion

BJT – Data Sheet

BJT

$V_{CE(sat)} : 1.5 \text{ V @ } I_C = 10 \text{ A, } I_B = 2 \text{ A}$

$R_{TH(JC)} : 1^\circ\text{C/W}$

$I_{CEX} : 2 \text{ mA}$
Switched Mode Power Conversion
A Fully Controlled Switch – MOSFET

MOSFET
ON Switch for $I > 0$ & $I < 0$

OFF Switch for $V > 0$
Switched Mode Power Conversion
A Fully Controlled Switch – MOSFET

MOSFET
Two Quadrant Switch
Fully Controlled Switch
Voltage Controlled Switch
Switched Mode Power Conversion

MOSFET – Data Sheet

MOSFET

\[ R_{DS(on)} : 0.05 \, \Omega \quad @ \quad I_D = 16 \, A, \quad V_{GS} = 10 \, V \]

\[ R_{TH(JC)} : 1.6^\circ C/W \]

\[ I_{CEX} : 250 \, \mu A \]
Switched Mode Power Conversion
A Fully Controlled Switch – IGBT

IGBT
ON Switch for $I > 0 \& I < 0$

OFF Switch for $V > 0$
Switched Mode Power Conversion

A Fully Controlled Switch – IGBT

IGBT

Two Quadrant Switch
Fully Controlled Switch
Voltage Controlled Switch
Switched Mode Power Conversion

IGBT – Data Sheet

IGBT

\[ V_{CE(sat)} : 3.5 \, V \text{ @ } I_C = 30 \, A, \, V_{GE} = 15 \, V \]

\[ R_{TH(JC)} : 0.6^\circ\text{C/W} \]

\[ I_{CEX} : 4 \, mA \]
Switched Mode Power Conversion

Compound Switches

OFF State

ON State

Anti-parallel SCRs

Four Quadrant Switch

Semiconcontrolled Switch

Pulse Triggered Switch
Switched Mode Power Conversion

Compound Switches

Anti-parallel MOSFET/IGBTs

Four Quadrant Switch

Fully Controlled Switch

Voltage Controlled Switch
Switched Mode Power Conversion
Switching Characteristics – Controlled Switch

MOSFET – Turn-On

Turn-on delay time ($t_d$)
Rise time ($t_r$)
In time $t_r$, Switch voltage drops linearly to zero
Switched Mode Power Conversion
Switching Characteristics – Controlled Switch

MOSFET – Turn-Off

Turn-off delay time \((t_d)\)
Fall time \((t_f)\)

In time \(t_f\), Switch current drops linearly to zero
Switched Mode Power Conversion

Switching Characteristics – Controlled Switch

MOSFET – Turn-On – Resistive Load
Switched Mode Power Conversion

Switching Characteristics – Controlled Switch

MOSFET – Turn-Off – Resistive Load
Switched Mode Power Conversion
Switching Characteristics – Data Sheet

MOSFET
Switched Mode Power Conversion

Switching Characteristics

Turn-On of Capacitive Load

Over-current in Turn-On
Switched Mode Power Conversion
Switching Characteristics

Turn-Off of Inductive Load
Over-voltage in Turn-Off

\[ V = \frac{L I}{t_f} \]
Switched Mode Power Conversion

Switching Stress

Preferred Load
Inductive Turn-On & Capacitive Turn-Off
Switching-Aid Circuits
(Snubber Circuits)
Exploit this Feature
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
Switched Mode Power Conversion

Switching V-I Characteristic
Switched Mode Power Conversion
Other Fully Controlled Switches – Data Sheet

BJT  MOSFET  IGBT
Switched Mode Power Conversion
Switching Aid Circuit – Sample Design

Switching Voltage & Current
400 V, 15 A

Switching Time
400 ns
Switched Mode Power Conversion
Switching Aid Circuit – Sample Design

\[ \text{Apparent Switching Loss} \]

\[ 400 \times 15 \times 0.4 \, \mu\text{J} \]

\[ 2.4 \, \text{mJ per switching} \]
Switched Mode Power Conversion

Turn-On Snubber Design

\[ t = 0.4\mu s \]

\[ 400V \]

\[ 15A \]

\[ 4A \]
Switched Mode Power Conversion

Turn-On Snubber Design

\[ L_O = \frac{(0.5 \times 400 \times 0.4 \mu s)}{4} = 20 \mu H \]

Switching loss = \( \frac{(400 \times 4 \times 0.4 \mu s)}{12} \)

0.053 mJ per switching

Select \( L_O/R_O \) to be much less than \( T_{ON} \)
Switched Mode Power Conversion
Switching Aid Circuit – Sample Design

Switching Voltage & Current
400 V, 15 A
Switching Time
800 ns
Switched Mode Power Conversion

Switching Aid Circuit – Sample Design

\[ 400 \times 15 \times 0.8 \, \mu J \]

\[ 4.8 \, mJ \text{ per switching} \]
Switched Mode Power Conversion

Turn-Off Snubber Design

\[ V = 100V \]

\[ t = 0.8\mu s \]

\[ L_O \]

\[ R_O \]

\[ D_O \]

\[ D_F \]

\[ R_F \]

\[ C_F \]

\[ 15A \]

\[ 400V \]
Switched Mode Power Conversion

Turn-Off Snubber Design

\[ C_O = \frac{(0.5 \ 15 \ 0.8 \mu s)}{100} = 0.06 \mu F \]

Switching loss = \( \frac{(15 \ 100 \ 0.8 \mu s)}{12} \)

0.01 mJ per switching

Select \( C_F R_F \) to be much less than \( T_{OFF} \)
Switched Mode Power Conversion

Switches – Summary

Ideal Switch
Lossless Operation
Instantaneous Operation
Four Quadrant Operation
Switched Mode Power Conversion

Switches – Summary

Ideal Switch
Lossless, Instantaneous, Four Quadrant

Real Switches
Uncontrolled Switch – Diode
Semicontrolled Switch – SCR
Controlled Switch – BJT, MOSFET, IGBT

Single & Multiquadrant Switches
Losses & Thermal Design
Switched Mode Power Conversion

Switches – Summary

Ideal Switch
Lossless, Instantaneous

Real Switches
Diode, SCR, BJT, MOSFET, IGBT

Single & Multiquadrant Switches

Losses & Thermal Design
Protection
Fuse Protection – Diodes & SCRs
Through Driver – BJT, MOSFET, IGBT
Switched Mode Power Conversion

Switches – Summary

Ideal Switch
Lossless, Instantaneous
Real Switches
Diode, SCR, BJT, MOSFET, IGBT
Single & Multiquadrant Switches
Losses & Thermal Design
Protection
Fuse Protection – Diodes & SCRs
Through Driver – BJT, MOSFET, IGBT
Switching Transients
Switching Aid Circuit