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

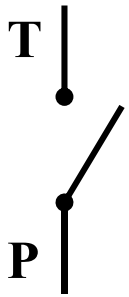
OFF State

&

ON State

Switched Mode Power Conversion

Switches



Simple Switch has Two Terminals

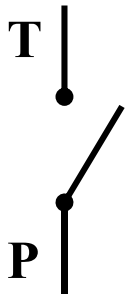
Pole

&

Throw

Switched Mode Power Conversion

Switches



In the OFF State

Pole & Throw are Isolated from Each Other

Switched Mode Power Conversion

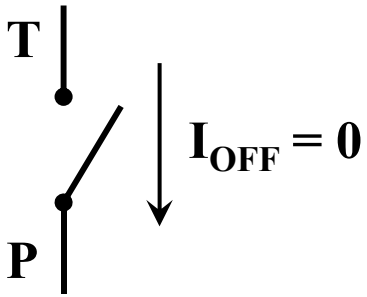
Switches

In the ON State

Pole & Throw are Connected to Each Other

Switched Mode Power Conversion

Switches

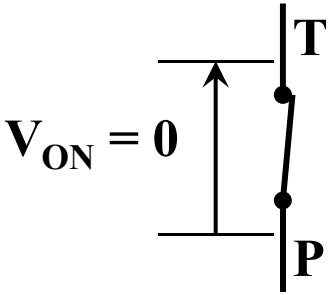


In the OFF State

Current through the Switch is Zero

Switched Mode Power Conversion

Switches

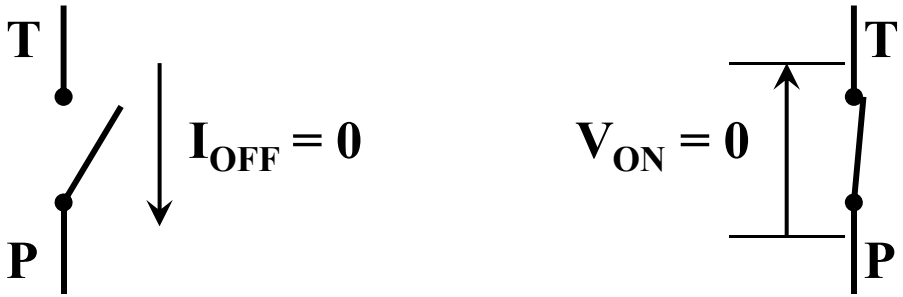


In the ON State

Voltage Across the Switch is Zero

Switched Mode Power Conversion

Switch – Primary Characteristics

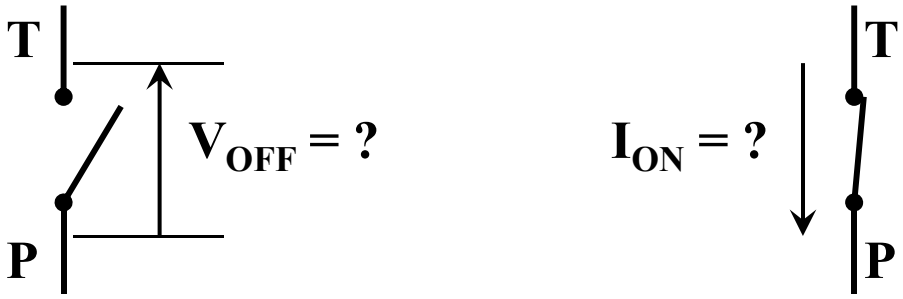


In the OFF State: $I_{OFF} = 0$

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

Switched Mode Power Conversion

Switch

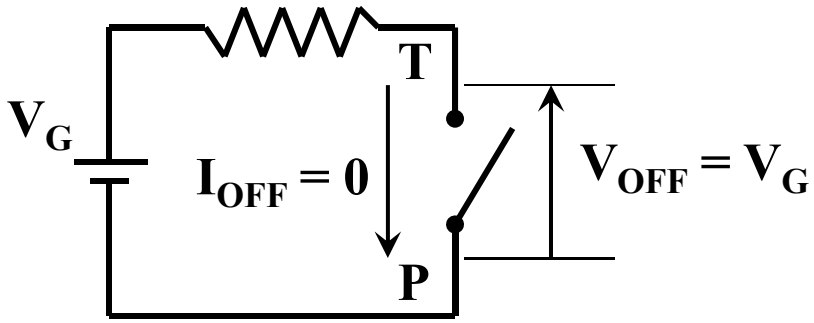


In the OFF State: V_{OFF} = ?

In the ON State: I_{ON} = ?

Switched Mode Power Conversion

Switch – OFF State

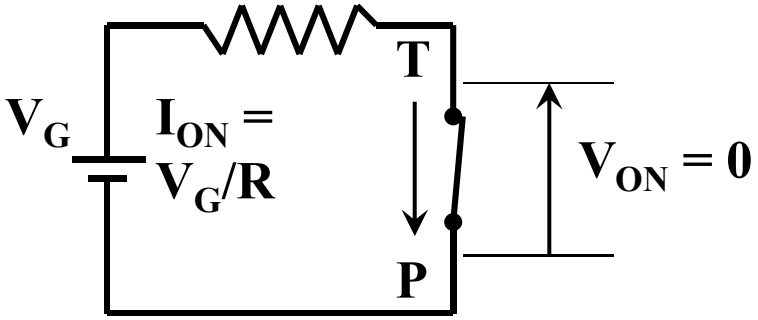


In the OFF State: $I_{OFF} = 0$

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

Switched Mode Power Conversion

Switch – ON State

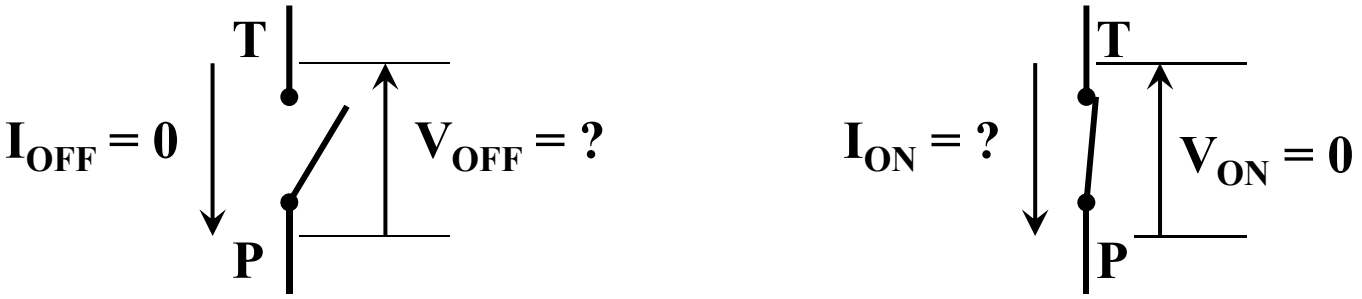


In the ON State: $V_{ON} = 0$

In the ON State: $I_{ON} = V_G/R$

Switched Mode Power Conversion

Switch – Ideal Performance



In the OFF State:

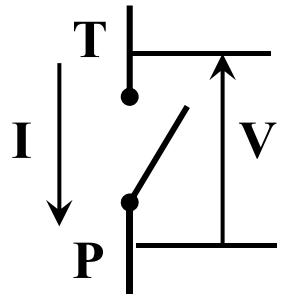
$I_{OFF} = 0$; V_{OFF} by External Circuit

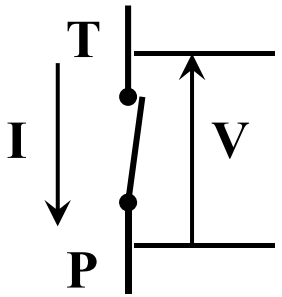
In the ON State:

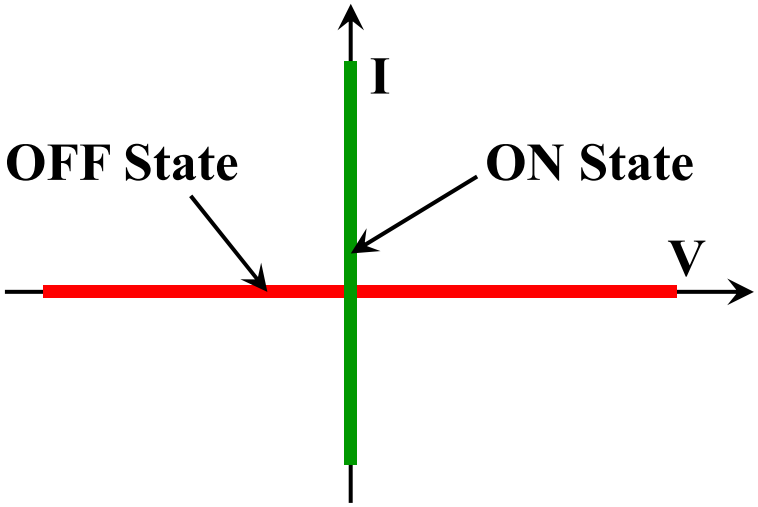
$V_{ON} = 0$; I_{ON} by External Circuit

Switched Mode Power Conversion

Ideal Switch – In the VI Plane







Switched Mode Power Conversion

Ideal Switch – Power Loss

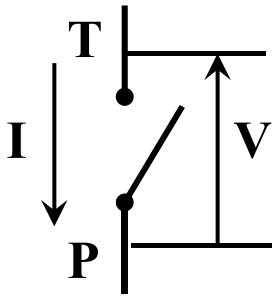
Power Loss in the Ideal Switch

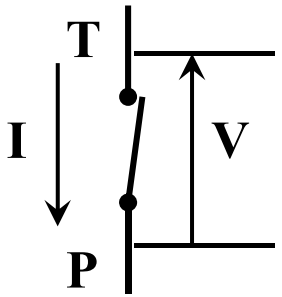
$$\text{Conduction Loss} = V_{ON} * I_{ON} = 0$$

$$\text{Blocking Loss} = V_{OFF} * I_{OFF} = 0$$

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

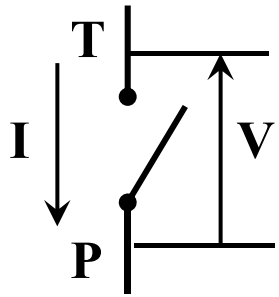
How Does the Switch Perform in Switching?

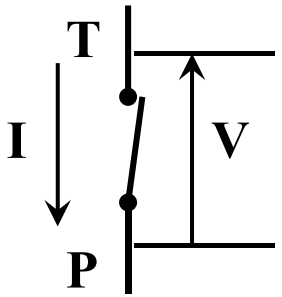
Energy Consumed to Turn On = $E_{OFF/ON} = 0$

Energy Consumed to Turn Off = $E_{ON/OFF} = 0$

Switched Mode Power Conversion

Ideal Switch – Dependence on Ambient





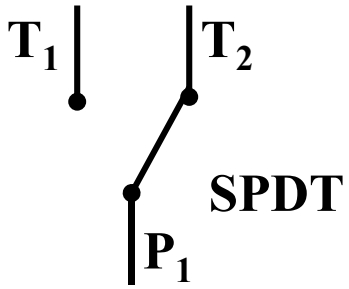
Switch Performance

is

Independent of Ambient Conditions

Switched Mode Power Conversion

Compound Switch



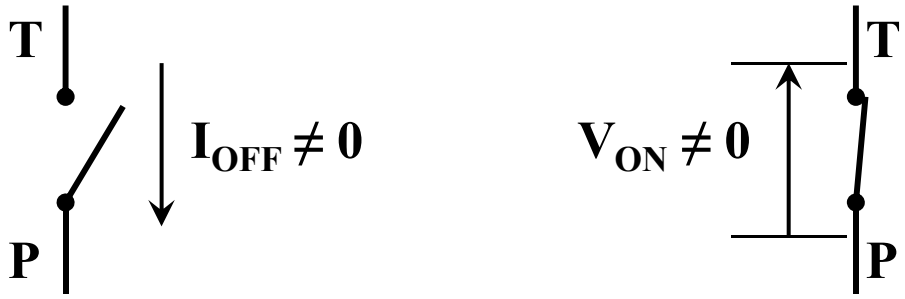
Example: Single Pole Double Throw Switch

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

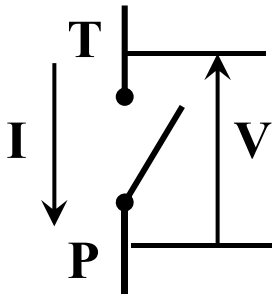
Power Loss in the Real Switch

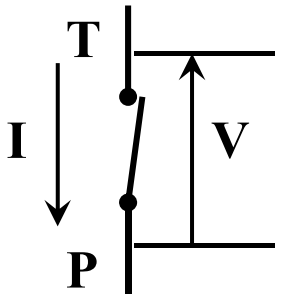
$$\text{Conduction Loss} = V_{ON} * I_{ON} \neq 0$$

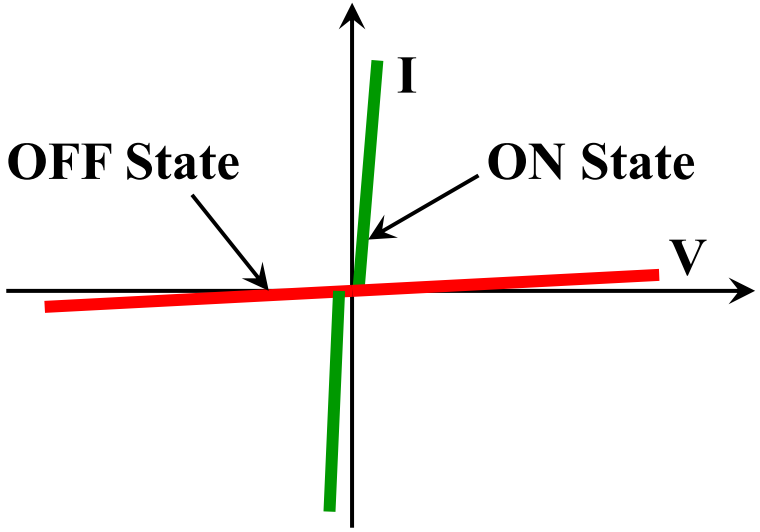
$$\text{Blocking Loss} = V_{OFF} * I_{OFF} \neq 0$$

Switched Mode Power Conversion

Real Switch – In the VI Plane

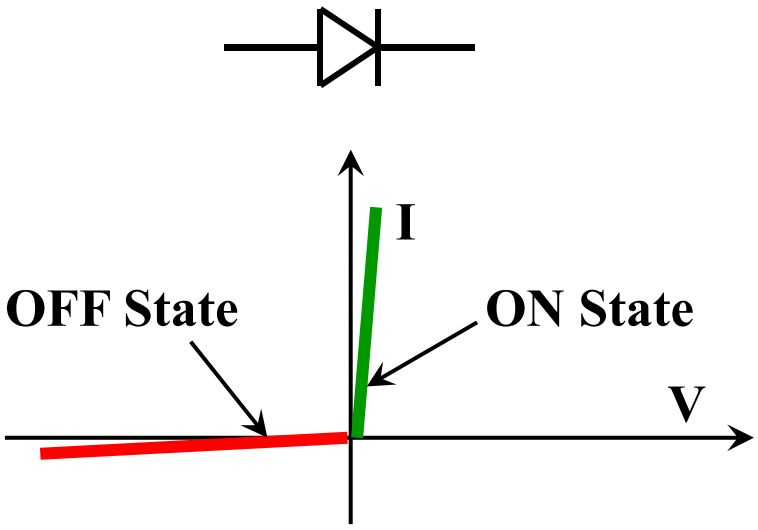






Switched Mode Power Conversion

A Sample Real Switch – Diode



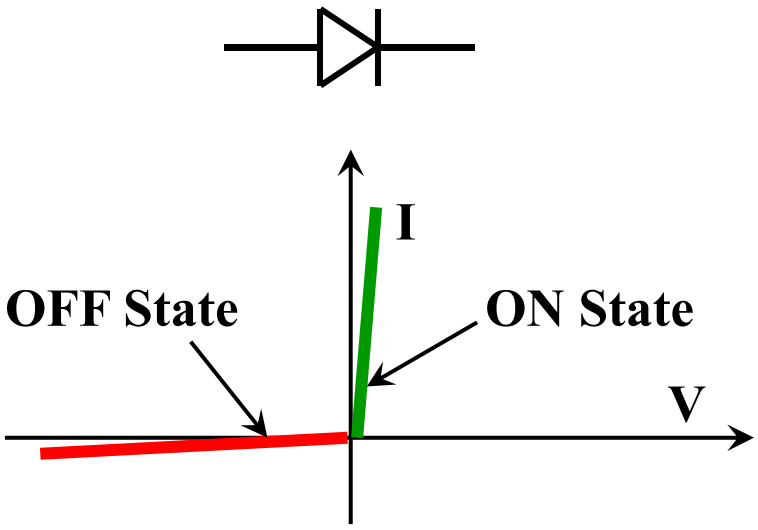
Diode

ON Switch for I > 0

OFF Switch for V < 0

Switched Mode Power Conversion

A Sample Real Switch – Diode

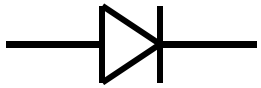


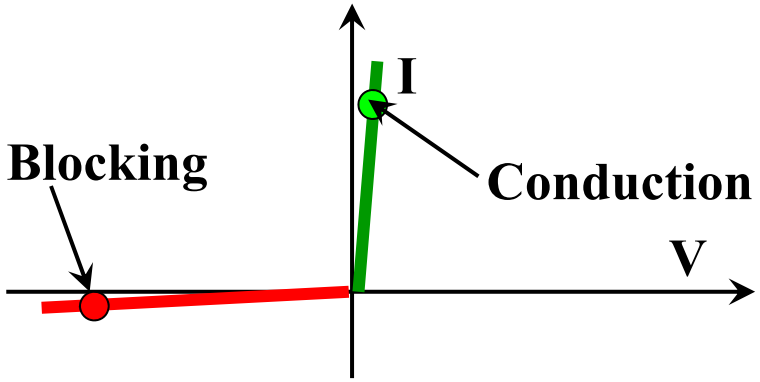
Single Quadrant Switch

Uncontrolled Switch

Switched Mode Power Conversion

Diode – Typical Datasheet

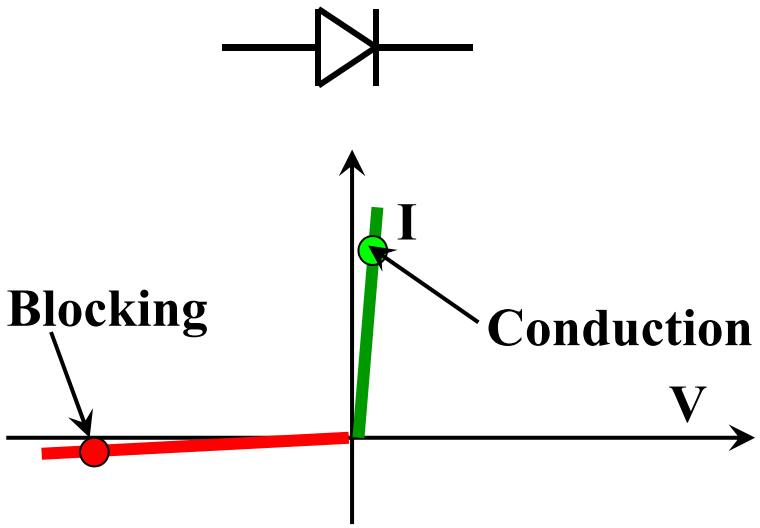




20ETS Diodes

Switched Mode Power Conversion

Diode – Percentage Loss



Conduction Loss : (1.1V/20A) 22 W @ 25 ºC

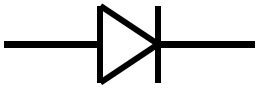
Blocking Loss : (0.1mA/800V) 0.8 W @ 25 ºC

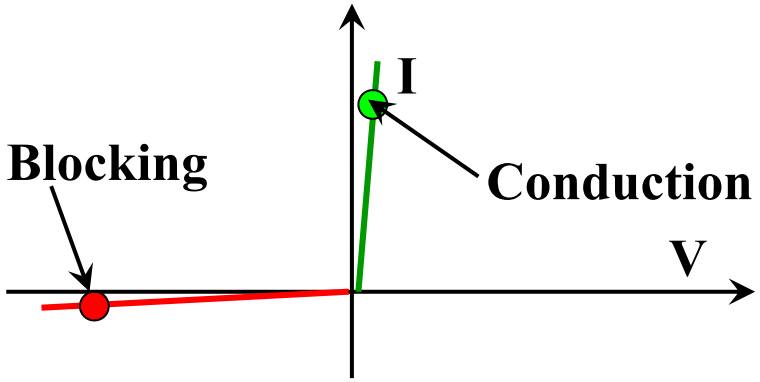
Blocking Loss is Invariably Negligible

True for All Switching Devices

Switched Mode Power Conversion

Diode – Temperature Co-efficient of V_{ON}





Conduction Drop

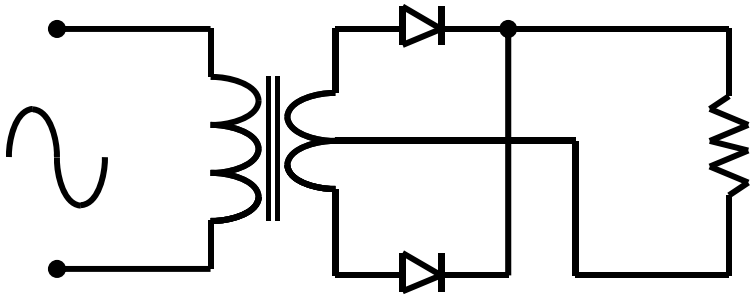
1.0V/10A @ 25ºC ; 0.9V/10A @ 150ºC

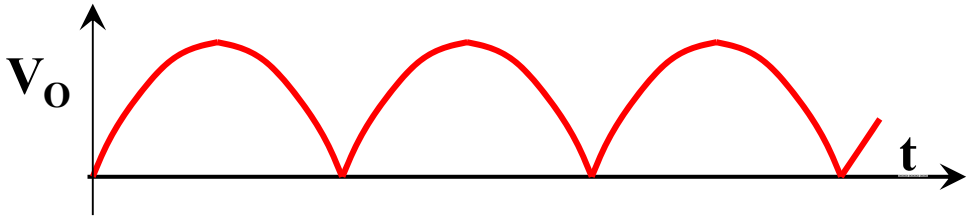
20ETS Diodes

Caution is Required in Parallel Operation

Switched Mode Power Conversion

Diode – A Simple Application

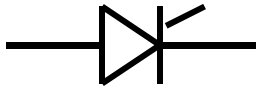


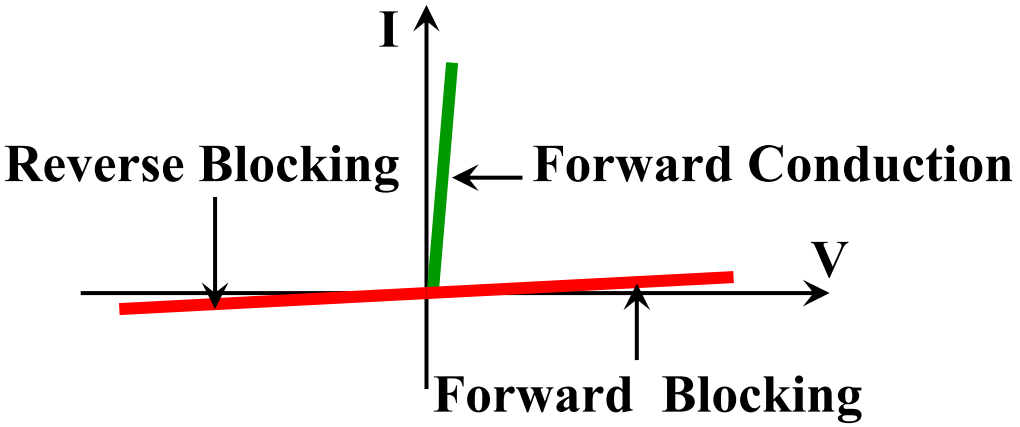


AC/DC Rectifier

Switched Mode Power Conversion

Another Real Switch – SCR





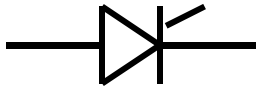
SCR

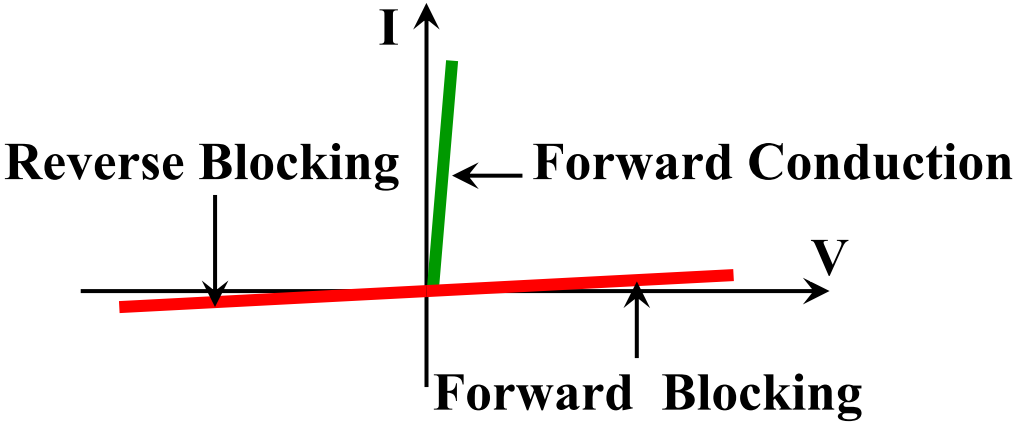
ON Switch for I > 0

OFF Switch for V < 0 ; V > 0

Switched Mode Power Conversion

Another Real Switch – SCR





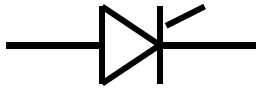
SCR

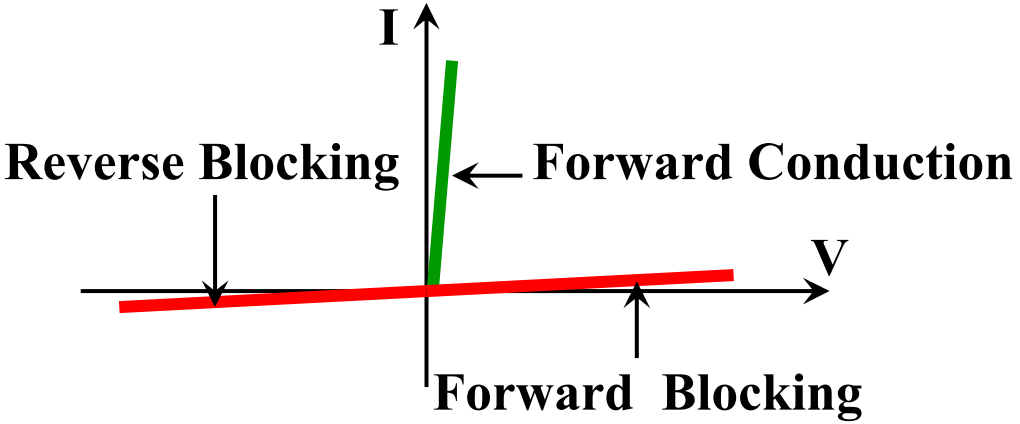
Two Quadrant Switch

Semicontrolled Switch

Switched Mode Power Conversion

SCR – Data Sheet

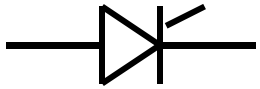


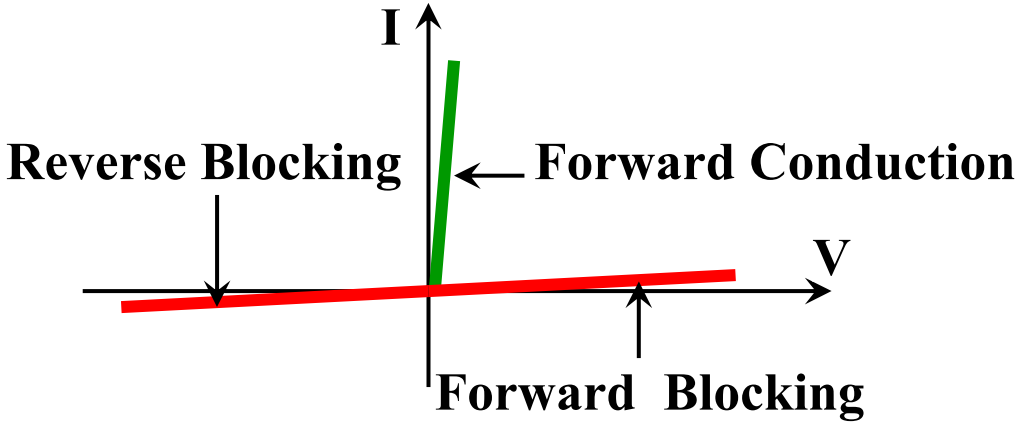


SCR

Switched Mode Power Conversion

SCR – Data Sheet





Conduction Loss : (1.7V/32A) 54 W @ 25 ºC

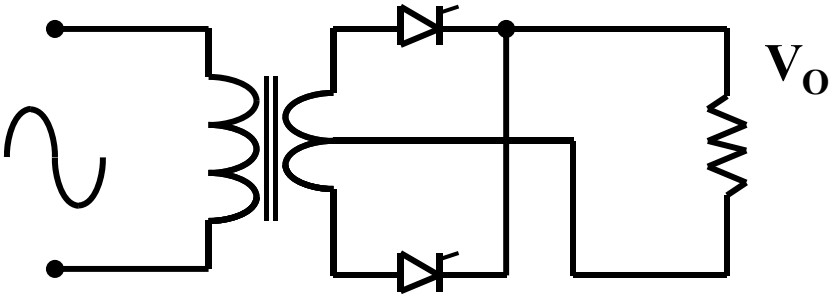
Blocking Loss : (2 mA/400V) 0.8 W @ 25 ºC

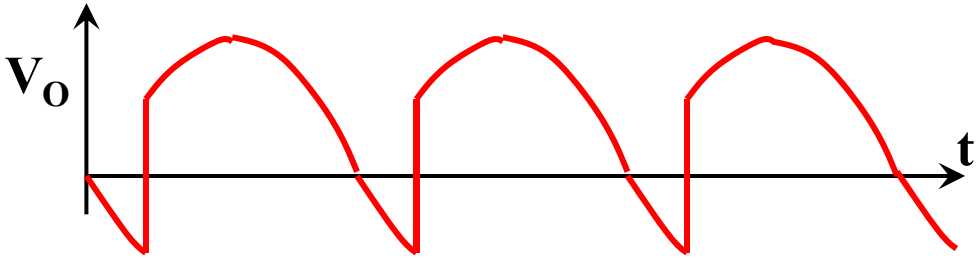
Blocking Losses or Invariably Negligible

True for All Switching Devices

Switched Mode Power Conversion

SCR – A Simple Application





Controlled AC/DC Rectifier

Switched Mode Power Conversion

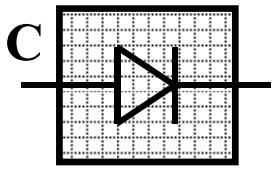
Diode & SCR – Short Circuit Protection

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

$$R_{TH}(JC)*P = \Theta_J - \Theta_C$$

$R_{TH}(JC)$: Thermal Resistance

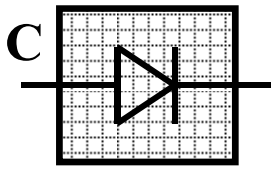
P : Power Dissipation in Device

Θ_J : Junction Temperature

Θ_C : Case Temperature

Switched Mode Power Conversion

Thermal Protection – An Example



20ETS Diodes

Device is Mounted on a Case C

$$R_{TH}(JC)*P = \Theta_J - \Theta_C$$

$R_{TH}(JC)$: 1.3 ºC/W

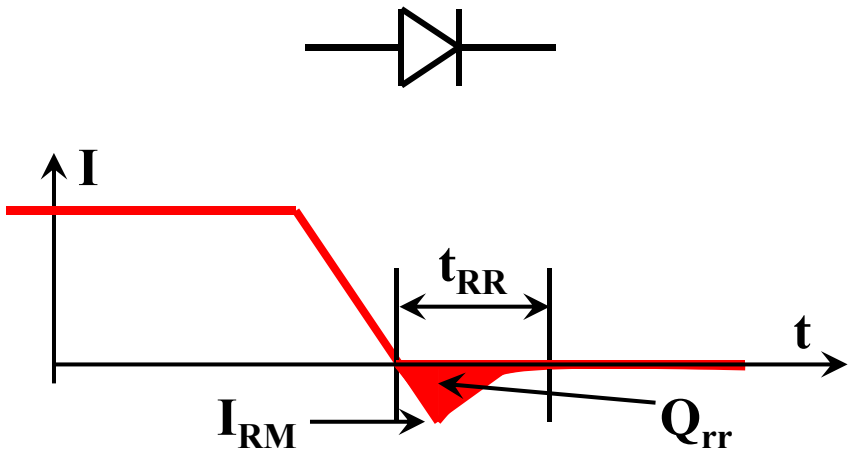
P : 22 W

Θ_J : 125 ºC

Θ_C : ? = 96.4 ºC

Switched Mode Power Conversion

Diode – Dynamic Performance

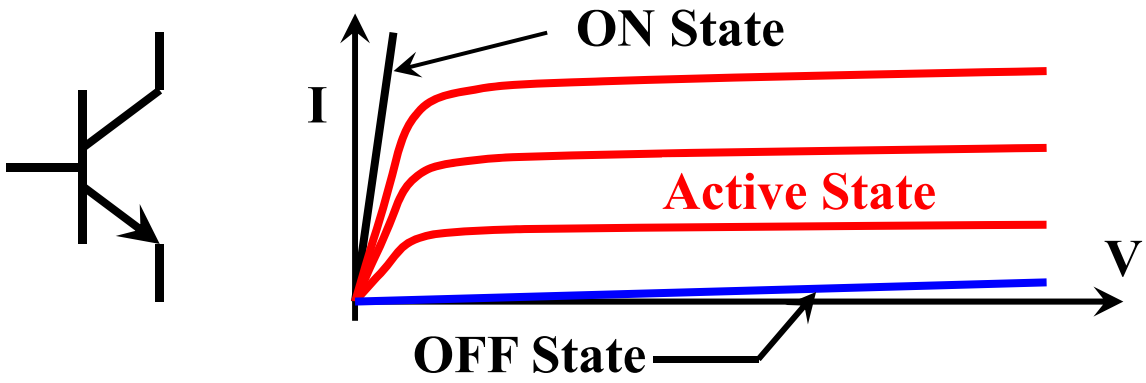


RHRG

$$I_{RM} = t_A * dI_F/dt = 5\ A$$

Switched Mode Power Conversion

A Fully Controlled Switch – BJT



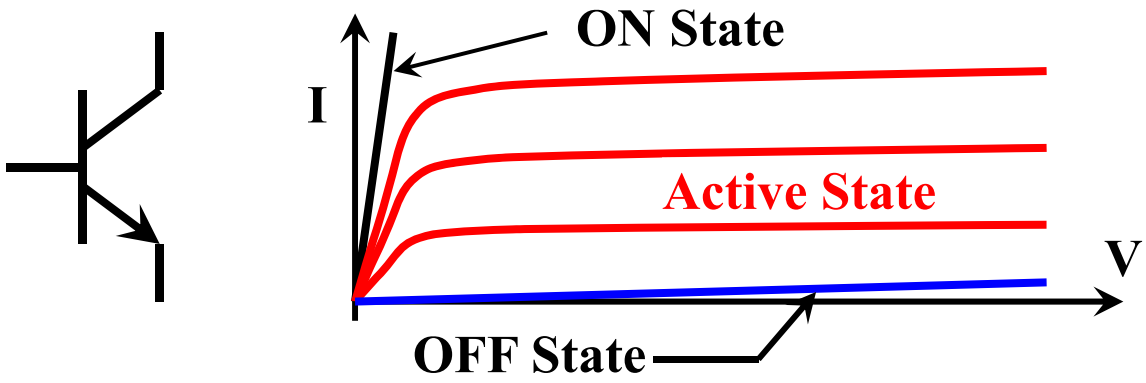
BJT

ON Switch for I > 0

OFF Switch for V > 0

Switched Mode Power Conversion

A Fully Controlled Switch – BJT



BJT

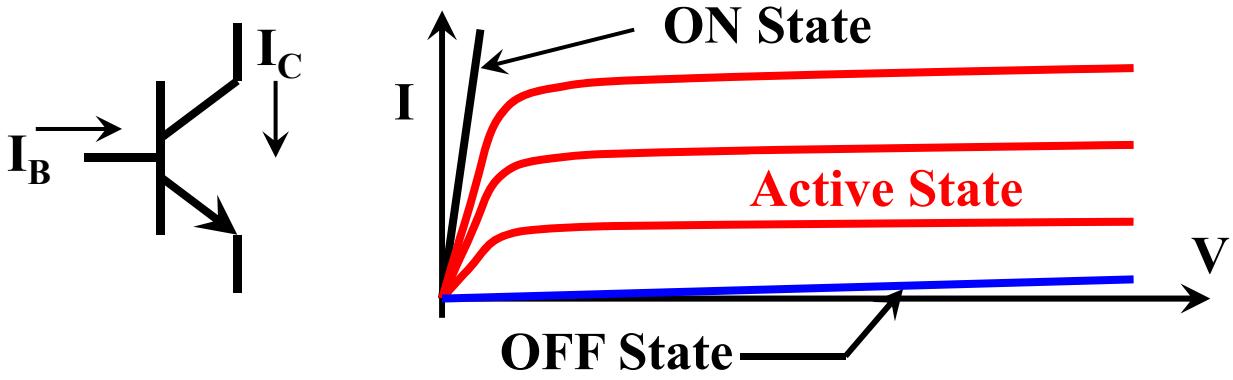
Single Quadrant Switch

Fully Controlled Switch

Current Controlled Switch

Switched Mode Power Conversion

BJT – Data Sheet



BJT

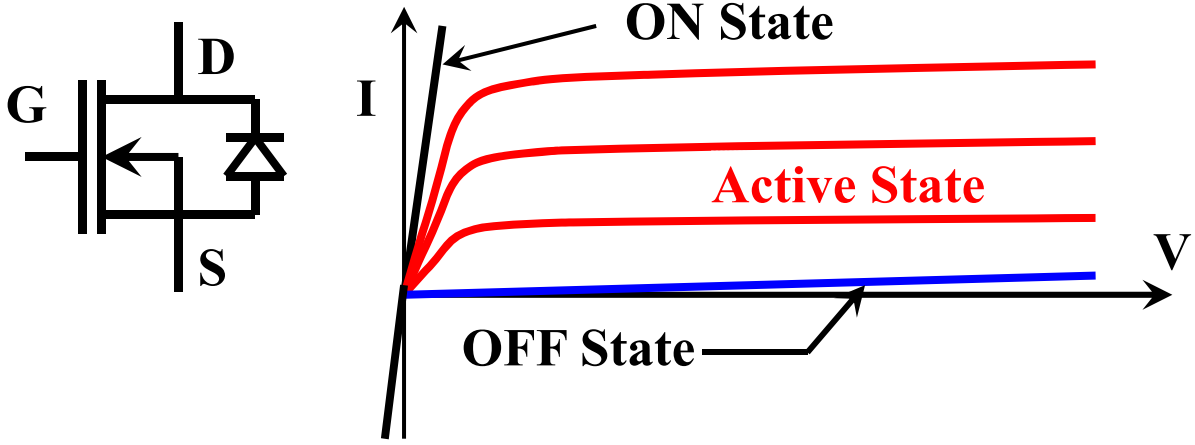
$V_{CE}(sat)$: 1.5 V @ I_C = 10 A, I_B = 2 A

$R_{TH}(JC)$: 1°C/W

I_{CEX} : 2 mA

Switched Mode Power Conversion

A Fully Controlled Switch – MOSFET



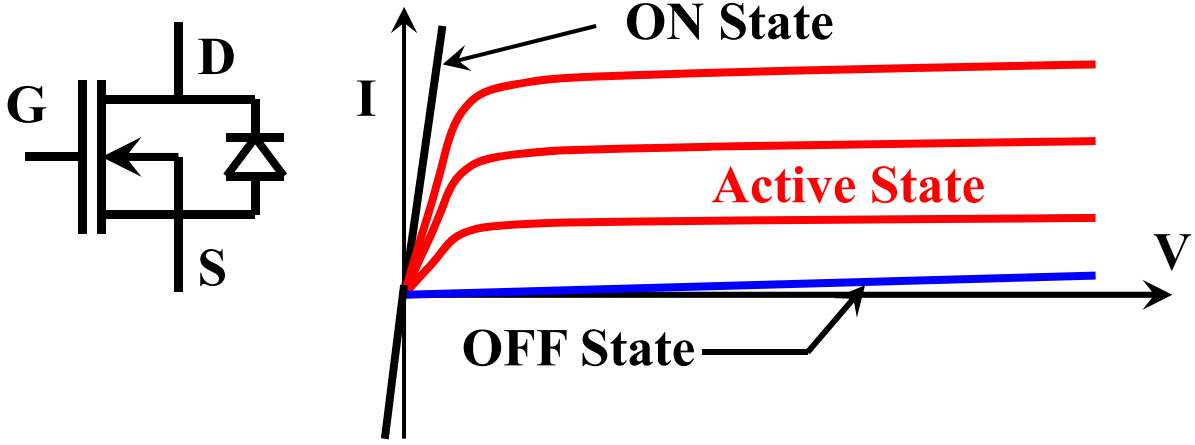
MOSFET

ON Switch for I > 0 & I < 0

OFF Switch for V > 0

Switched Mode Power Conversion

A Fully Controlled Switch – MOSFET



MOSFET

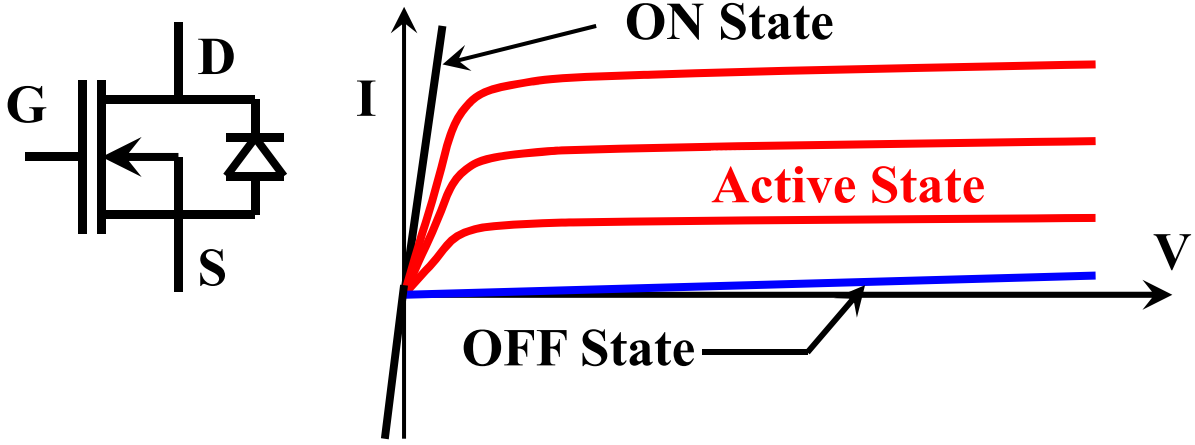
Two Quadrant Switch

Fully Controlled Switch

Voltage Controlled Switch

Switched Mode Power Conversion

MOSFET – Data Sheet



MOSFET

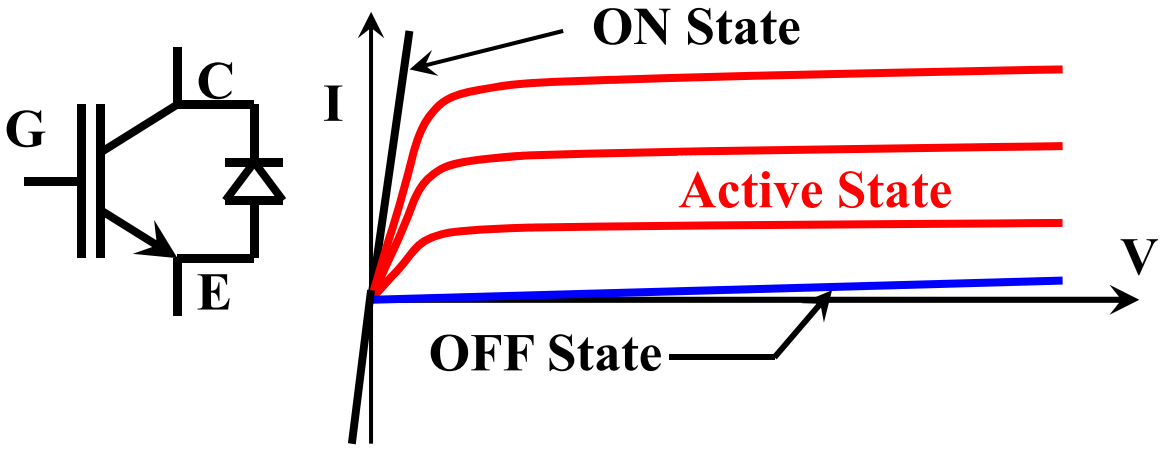
$R_{DS}(on)$: 0.05 Ω @ I_D = 16 A, V_{GS} = 10 V

$R_{TH}(JC)$: 1.6°C/W

I_{CEX} : 250 µA

Switched Mode Power Conversion

A Fully Controlled Switch – IGBT



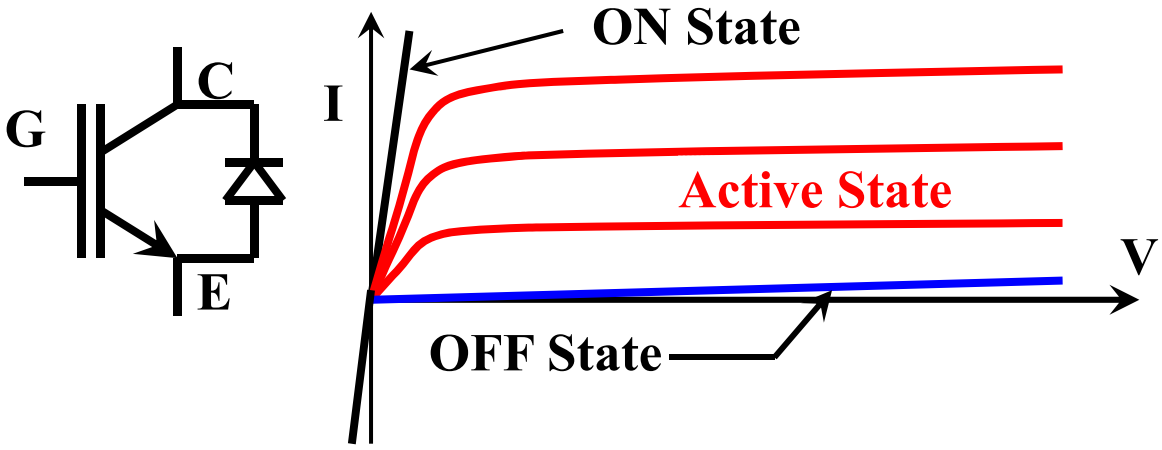
IGBT

ON Switch for I > 0 & I < 0

OFF Switch for V > 0

Switched Mode Power Conversion

A Fully Controlled Switch – IGBT



IGBT

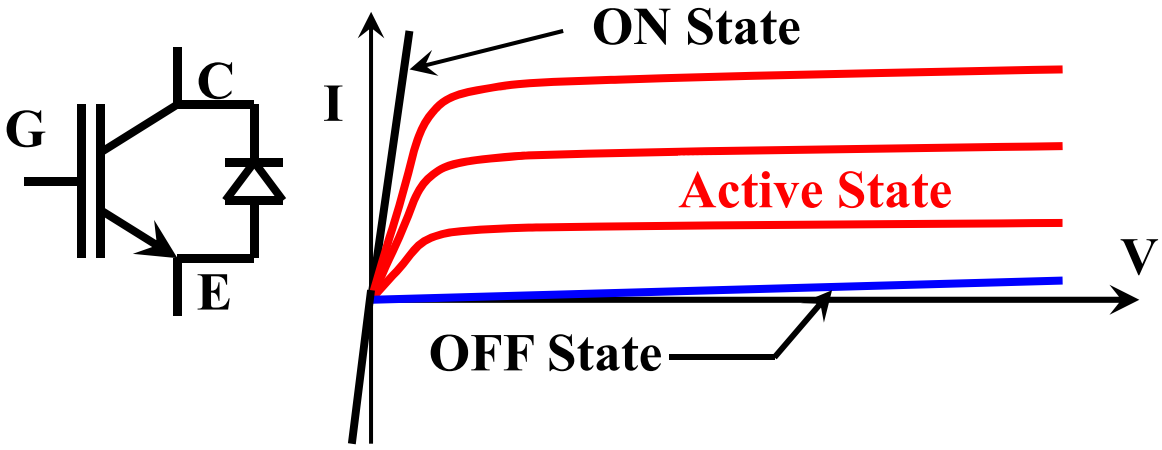
Two Quadrant Switch

Fully Controlled Switch

Voltage Controlled Switch

Switched Mode Power Conversion

IGBT – Data Sheet



IGBT

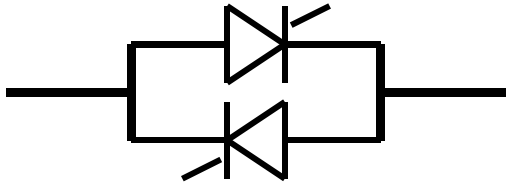
$V_{CE}(sat)$: 3.5 V @ I_C = 30 A, V_{GE} = 15 V

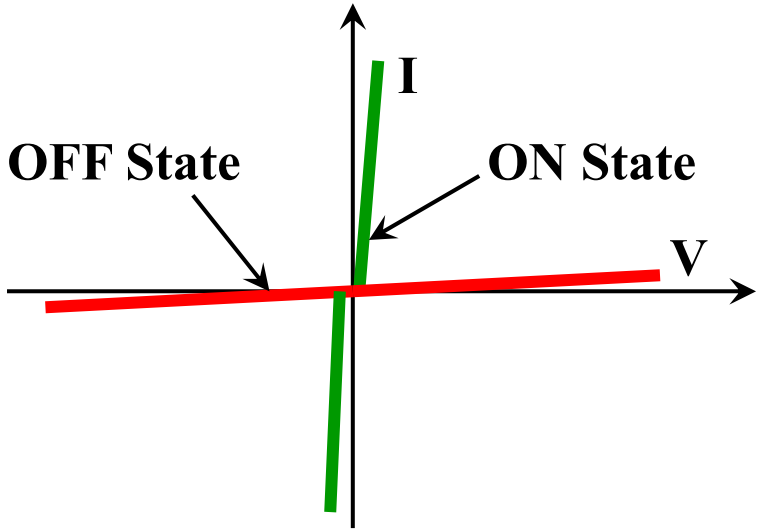
$R_{TH}(JC)$: 0.6°C/W

I_{CEX} : 4 mA

Switched Mode Power Conversion

Compound Switches





Anti-parallel SCRs

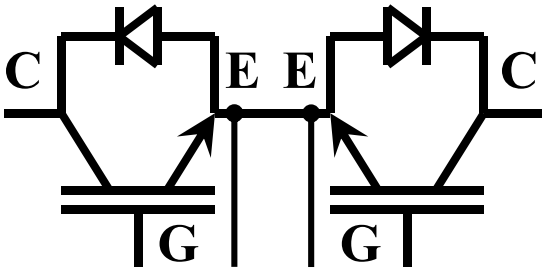
Four Quadrant Switch

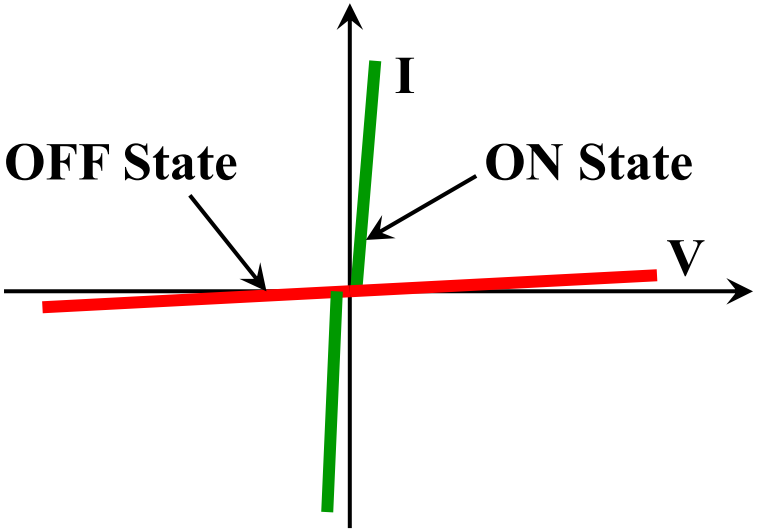
Semicontrolled Switch

Pulse Triggered Switch

Switched Mode Power Conversion

Compound Switches





Anti-parallel MOSFET/IGBTs

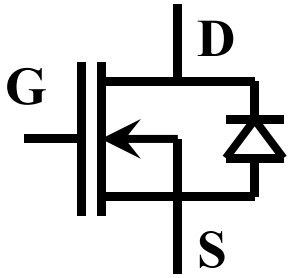
Four Quadrant Switch

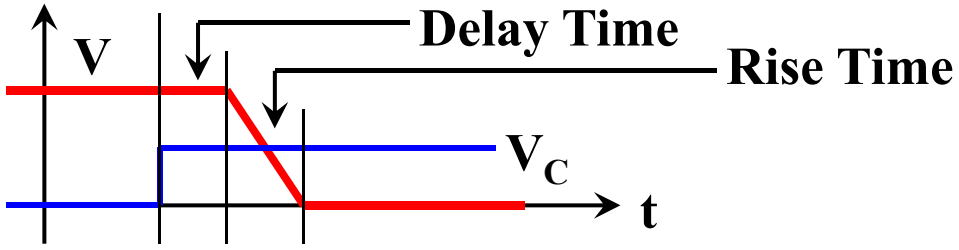
Fully Controlled Switch

Voltage Controlled Switch

Switched Mode Power Conversion

Switching Characteristics – Controlled Switch





MOSFET – Turn-On

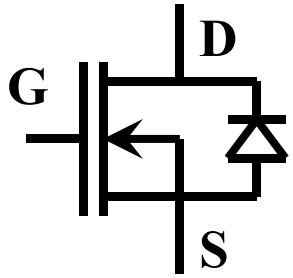
Turn-on delay time (t_d)

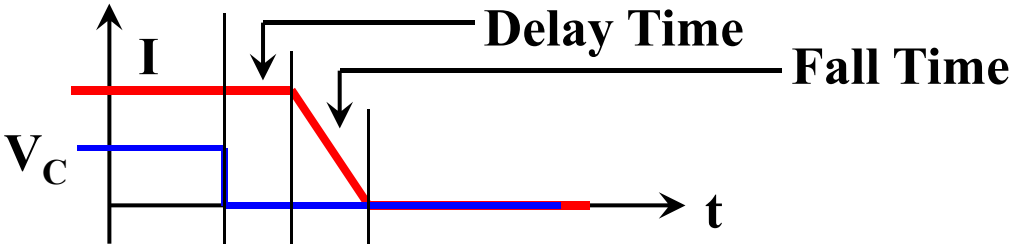
Rise time (t_r)

In time t_r, Switch voltage drops linearly to zero

Switched Mode Power Conversion

Switching Characteristics – Controlled Switch





MOSFET – Turn-Off

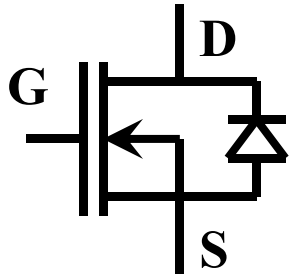
Turn-off delay time (t_d)

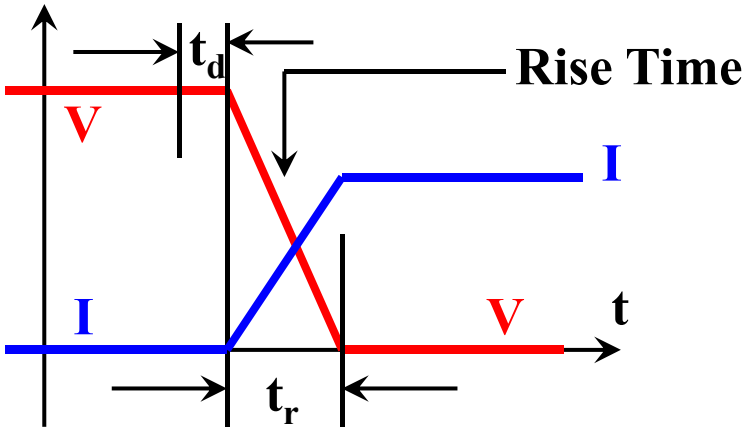
Fall time (t_f)

In time t_f, Switch current drops linearly to zero

Switched Mode Power Conversion

Switching Characteristics – Controlled Switch

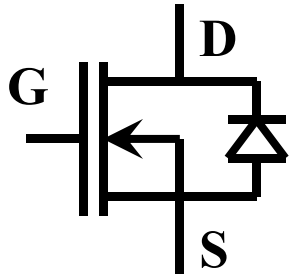


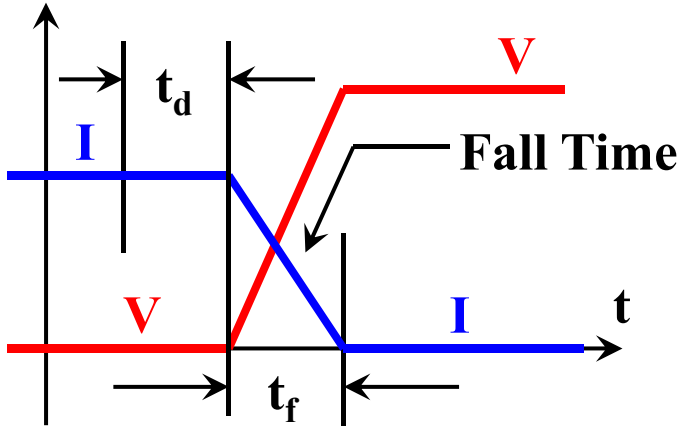


MOSFET – Turn-On – Resistive Load

Switched Mode Power Conversion

Switching Characteristics – Controlled Switch

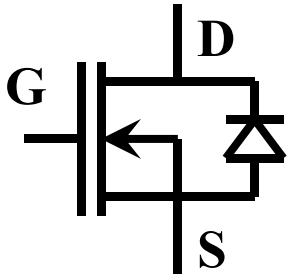


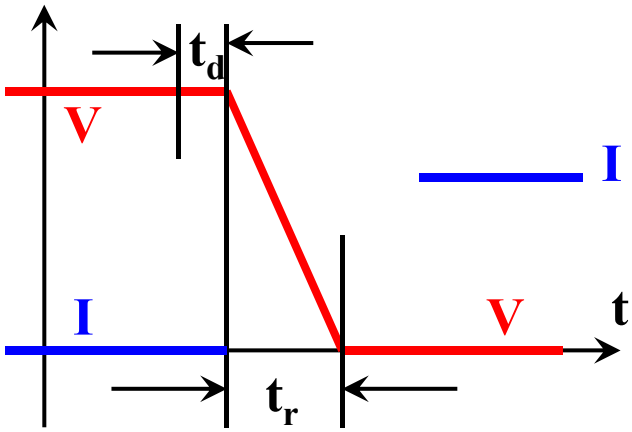


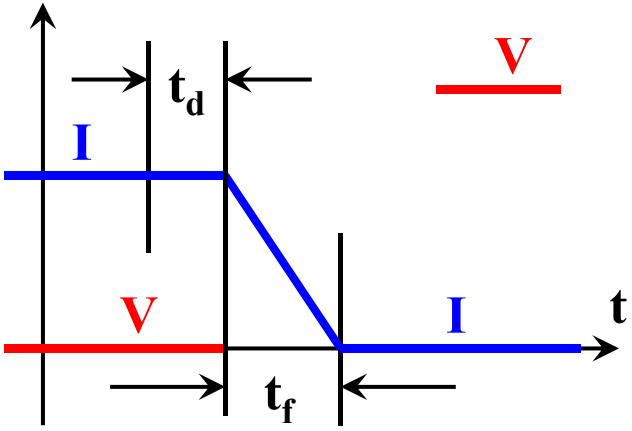
MOSFET – Turn-Off – Resistive Load

Switched Mode Power Conversion

Switching Characteristics – Data Sheet



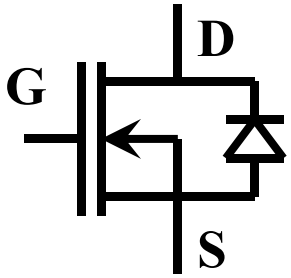


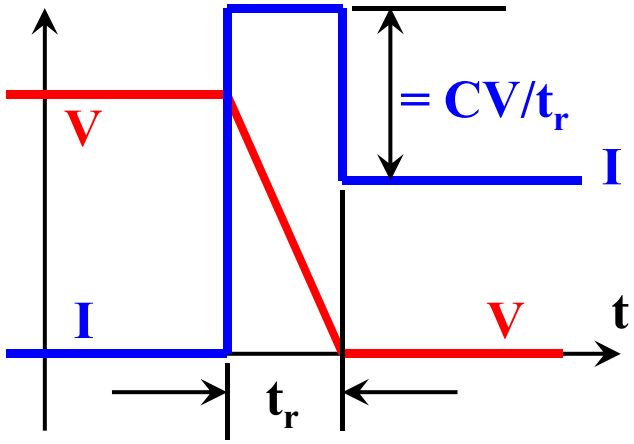


MOSFET

Switched Mode Power Conversion

Switching Characteristics



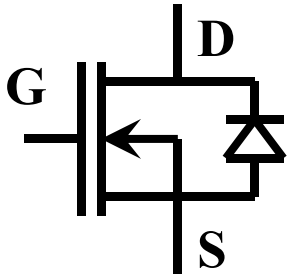


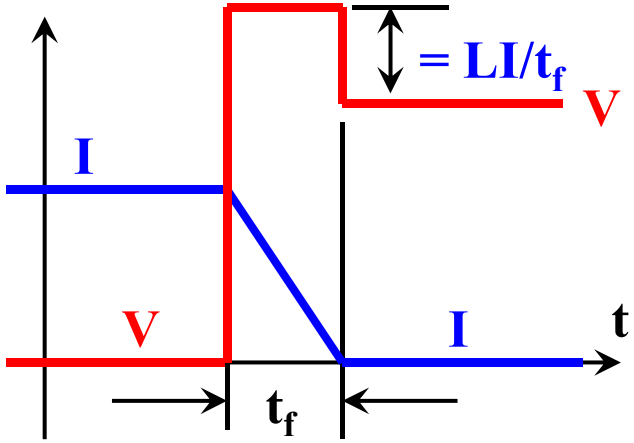
Turn-On of Capacitive Load

Over-current in Turn-On

Switched Mode Power Conversion

Switching Characteristics



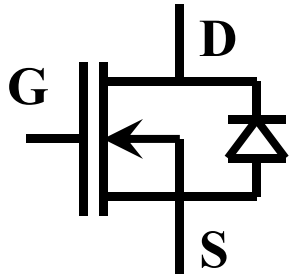


Turn-Off of Inductive Load

Over-voltage in Turn-Off

Switched Mode Power Conversion

Switching Stress



Preferred Load

Inductive Turn-On & Capacitive Turn-Off

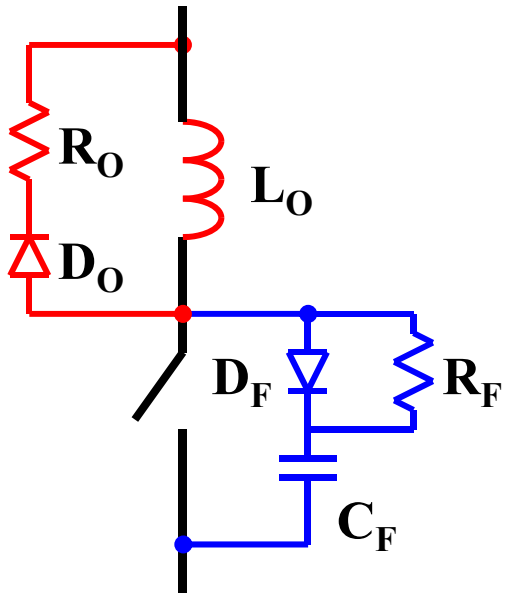
Switching-Aid Circuits

(Snubber Circuits)

Exploit this Feature

Switched Mode Power Conversion

Switching Aid Circuit



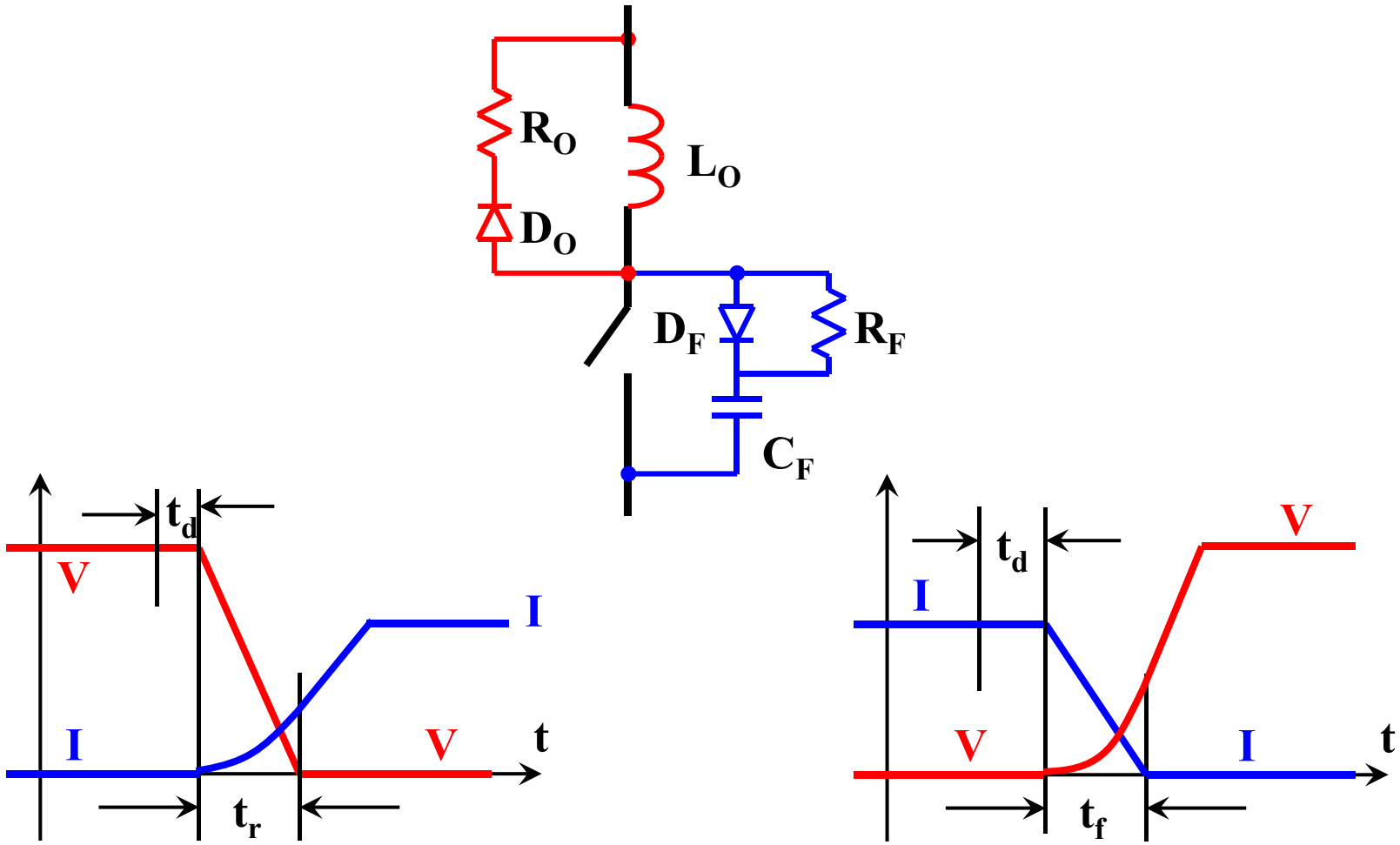
Strategy for Reducing Switching Stress

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

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

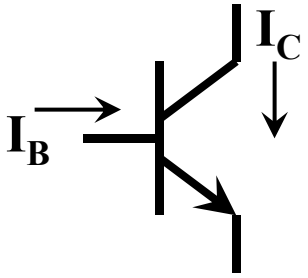
Switched Mode Power Conversion

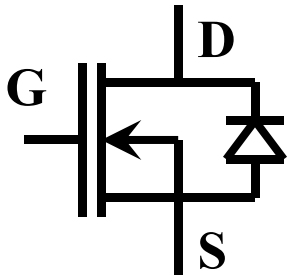
Switching V-I Characteristice

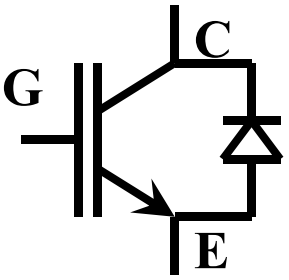


Switched Mode Power Conversion

Other Fully Controlled Switches – Data Sheet



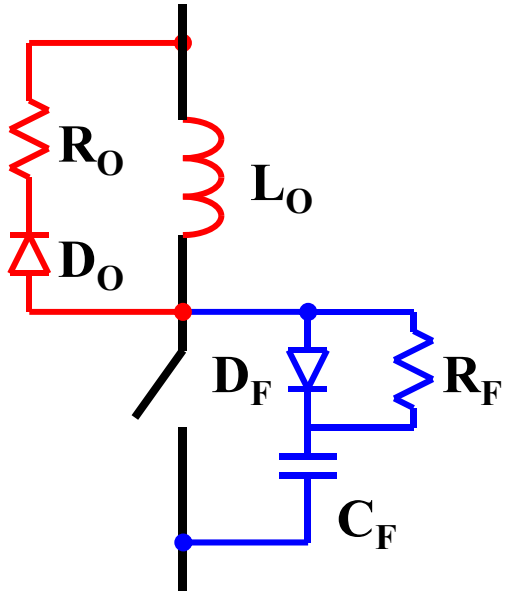




BJT MOSFET IGBT

Switched Mode Power Conversion

Switching Aid Circuit – Sample Design



Switching Voltage & Current

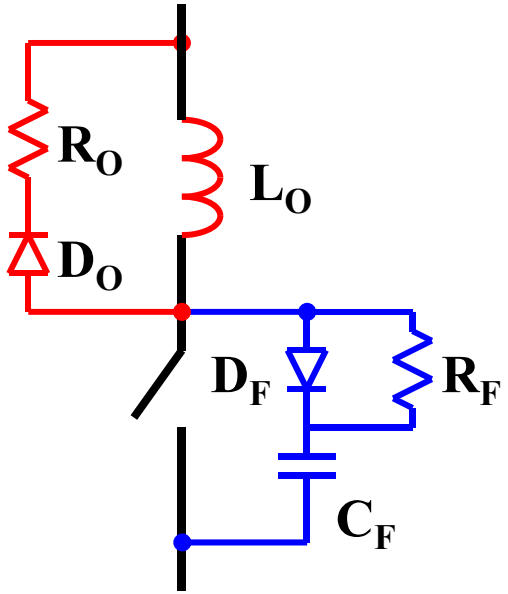
400 V, 15 A

Switching Time

400 ns

Switched Mode Power Conversion

Switching Aid Circuit – Sample Design



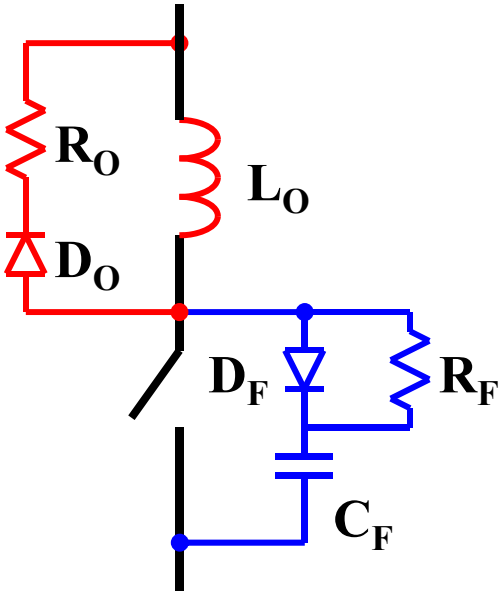
Apparent Switching Loss

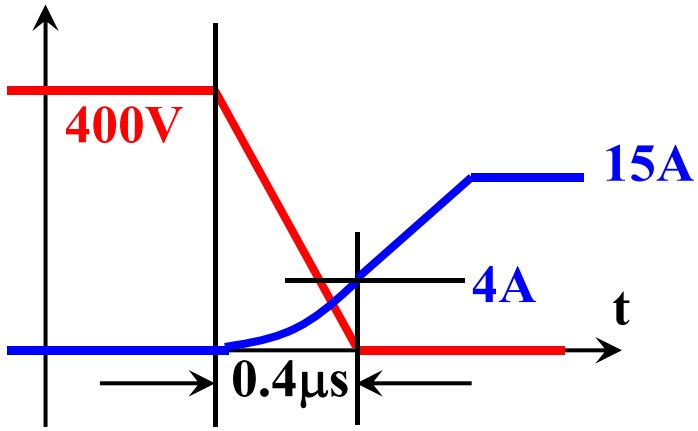
400*15*0.4 μJ

2.4 mJ per switching

Switched Mode Power Conversion

Turn-On Snubber Design





Switched Mode Power Conversion

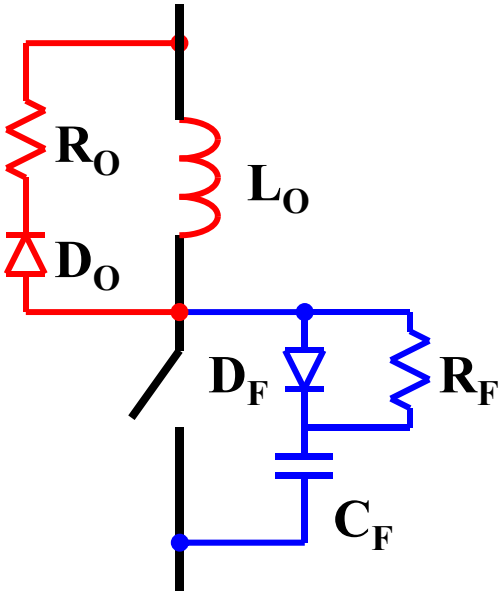
Turn-On Snubber Design

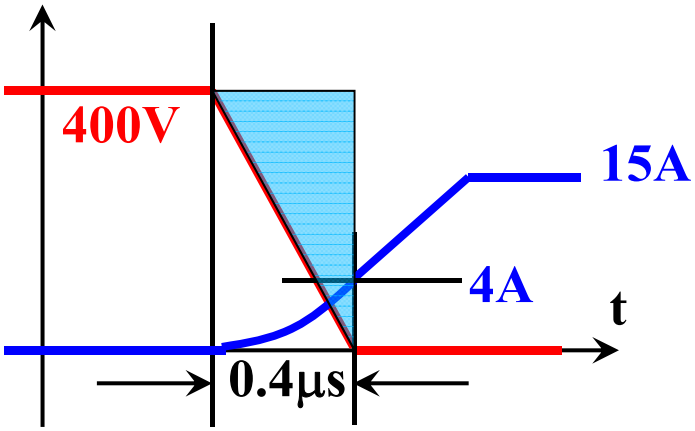
$L_O = (0.5\ 400\ 0.4\mu s)/4 = 20\ \mu H$

Switching loss = (400 4 0.4 μs)/12

0.053 mJ per switching

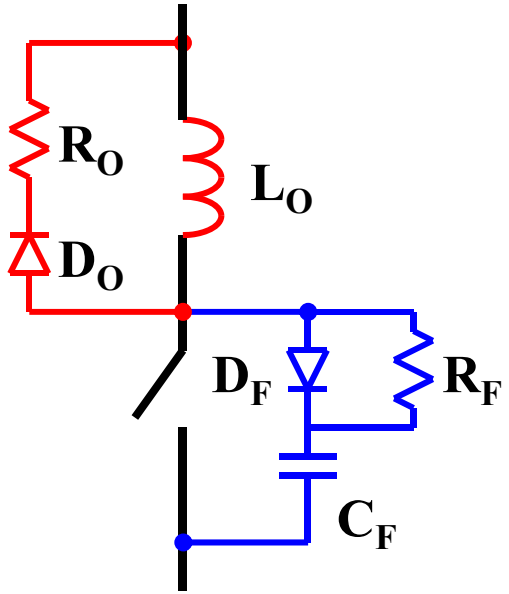
Select L_O/R_O to be much less than T_{ON}





Switched Mode Power Conversion

Switching Aid Circuit – Sample Design



Switching Voltage & Current

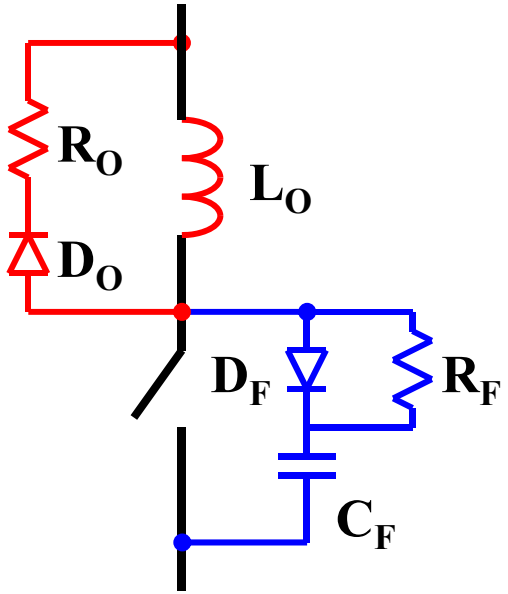
400 V, 15 A

Switching Time

800 ns

Switched Mode Power Conversion

Switching Aid Circuit – Sample Design



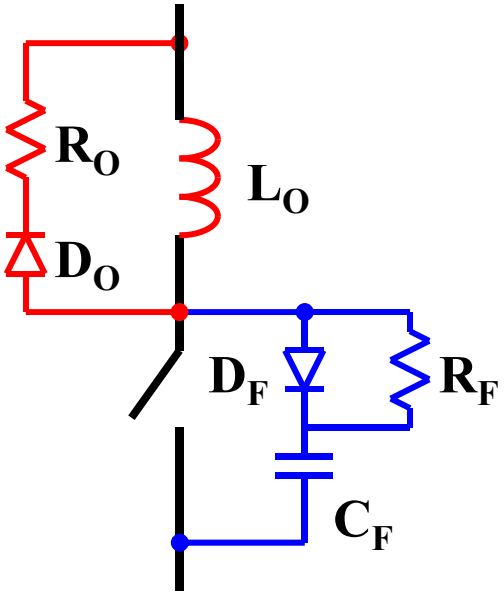
Apparent Switching Loss

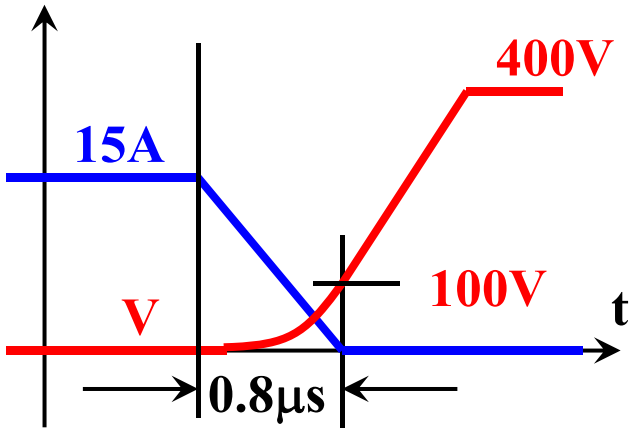
400*15*0.8 μJ

4.8 mJ per switching

Switched Mode Power Conversion

Turn-Off Snubber Design





Switched Mode Power Conversion

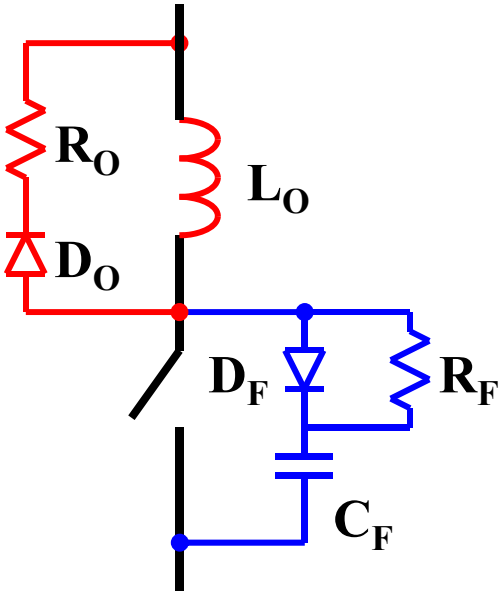
Turn-Off Snubber Design

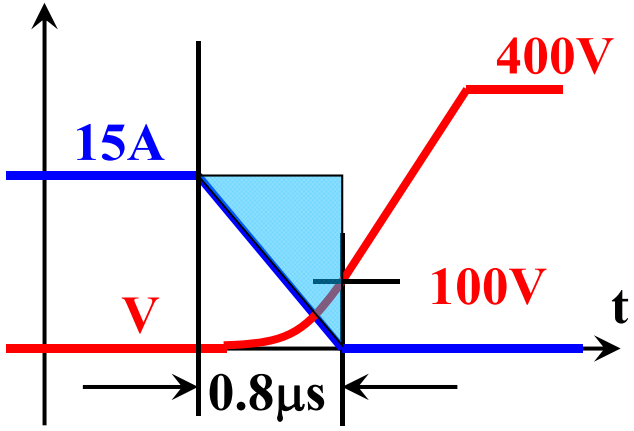
$C_O = (0.5\ 15\ 0.8\mu s)/100 = 0.06\ \mu F$

Switching loss = (15 100 0.8 μs)/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