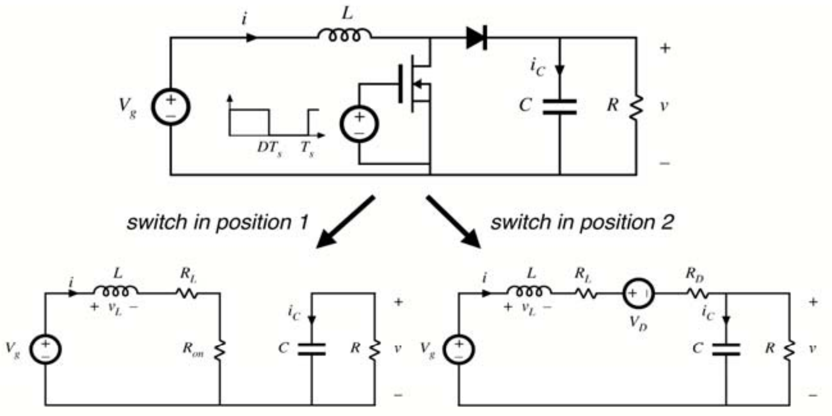
Lecture 5: Semiconductor Device Implementation

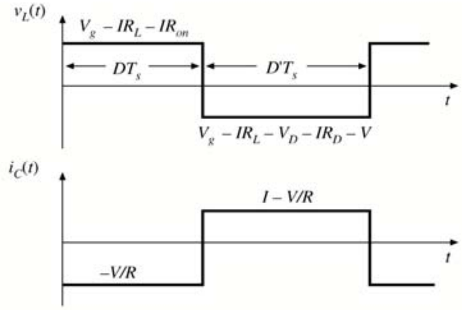
ECE 481: Power Electronics

Prof. Daniel Costinett
Department of Electrical Engineering and Computer Science
University of Tennessee Knoxville
Fall 2013

Boost converter example: circuits during subintervals 1 and 2



Average inductor voltage and capacitor current

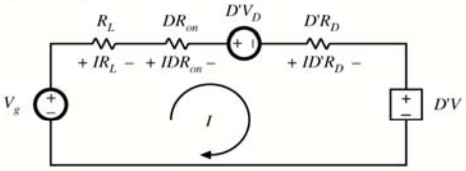


$$\langle v_L \rangle = D(V_g - IR_L - IR_{on}) + D'(V_g - IR_L - V_D - IR_D - V) = 0$$

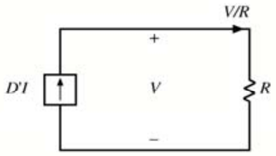
$$\langle i_C \rangle = D(-V/R) + D'(I - V/R) = 0$$

Construction of equivalent circuits

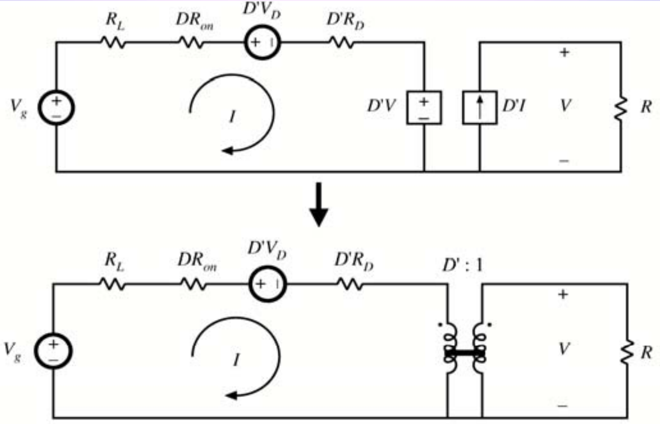
$$V_g - IR_L - IDR_{on} - D'V_D - ID'R_D - D'V = 0$$



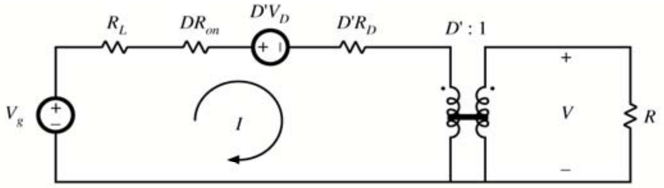
$$D'I - V/R = 0$$



Complete equivalent circuit



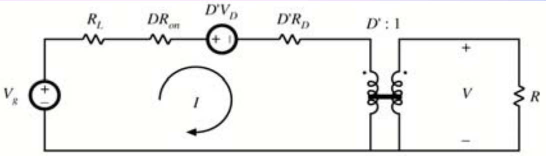
Solution for output voltage



$$V = \left(\frac{1}{D'}\right)\left(V_g - D'V_D\right)\left(\frac{D'^2 R}{D'^2 R + R_L + DR_{on} + D'R_D}\right)$$

$$\frac{V}{V_g} = \left(\frac{1}{D'}\right)\left(1 - \frac{D'V_D}{V_g}\right)\left(\frac{1}{1 + \dfrac{R_L + DR_{on} + D'R_D}{D'^2 R}}\right)$$

Solution for converter efficiency



$$P_{in} = (V_g)\,(I)$$

$$P_{out} = (V)\,(D'I)$$

$$\eta = D'\,\frac{V}{V_g} = \frac{\left(1 - \frac{D'V_D}{V_g}\right)}{\left(1 + \frac{R_L + DR_{on} + D'R_D}{D'^2 R}\right)}$$

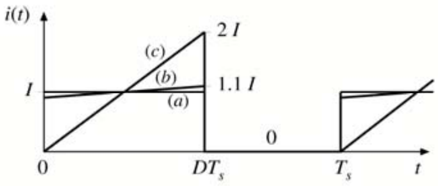
Conditions for high efficiency:

$$V_g/D' \gg V_D$$
$$D'^2 R \gg R_L + DR_{on} + D'R_D$$

Accuracy of the averaged equivalent circuit in prediction of losses

- Model uses average currents and voltages
- To correctly predict power loss in a resistor, use rms values
- Result is the same, provided ripple is small

MOSFET current waveforms, for various ripple magnitudes:



Inductor current ripple	*MOSFET rms current*	*Average power loss in R_{on}*
(a) $\Delta i = 0$	$I\sqrt{D}$	$D\,I^2\,R_{on}$
(b) $\Delta i = 0.1\,I$	$(1.00167)\,I\sqrt{D}$	$(1.0033)\,D\,I^2\,R_{on}$
(c) $\Delta i = I$	$(1.155)\,I\sqrt{D}$	$(1.3333)\,D\,I^2\,R_{on}$

Summary of chapter 3

1. The dc transformer model represents the primary functions of any dc-dc converter: transformation of dc voltage and current levels, ideally with 100% efficiency, and control of the conversion ratio M via the duty cycle D. This model can be easily manipulated and solved using familiar techniques of conventional circuit analysis.
2. The model can be refined to account for loss elements such as inductor winding resistance and semiconductor on-resistances and forward voltage drops. The refined model predicts the voltages, currents, and efficiency of practical nonideal converters.
3. In general, the dc equivalent circuit for a converter can be derived from the inductor volt-second balance and capacitor charge balance equations. Equivalent circuits are constructed whose loop and node equations coincide with the volt-second and charge balance equations. In converters having a pulsating input current, an additional equation is needed to model the converter input port; this equation may be obtained by averaging the converter input current.

Chapter 4. Switch Realization

4.1. Switch applications

Single-, two-, and four-quadrant switches. Synchronous rectifiers

4.2. A brief survey of power semiconductor devices

Power diodes, MOSFETs, BJTs, IGBTs, and thyristors

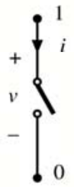
4.3. Switching loss

Transistor switching with clamped inductive load. Diode recovered charge. Stray capacitances and inductances, and ringing. Efficiency vs. switching frequency.

4.4. Summary of key points

SPST (single-pole single-throw) switches

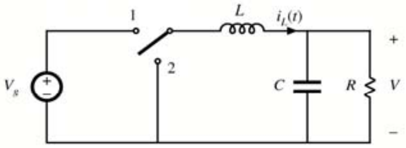
SPST switch, with voltage and current polarities defined



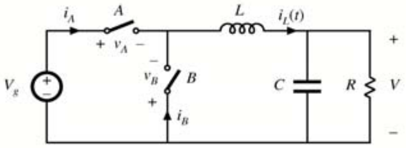
All power semiconductor devices function as SPST switches.

Buck converter

with SPDT switch:



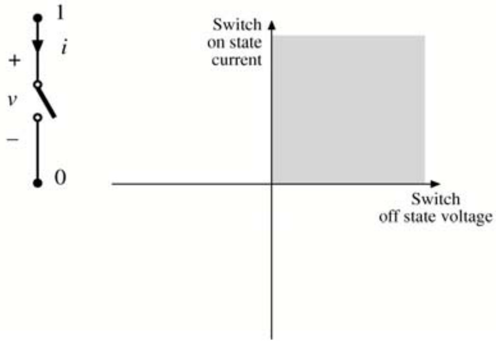
with two SPST switches:



Realization of SPDT switch using two SPST switches

- A nontrivial step: two SPST switches are not exactly equivalent to one SPDT switch
- It is possible for both SPST switches to be simultaneously ON or OFF
- Behavior of converter is then significantly modified
—discontinuous conduction modes (chapter 5)
- Conducting state of SPST switch may depend on applied voltage or current —for example: diode

Quadrants of SPST switch operation

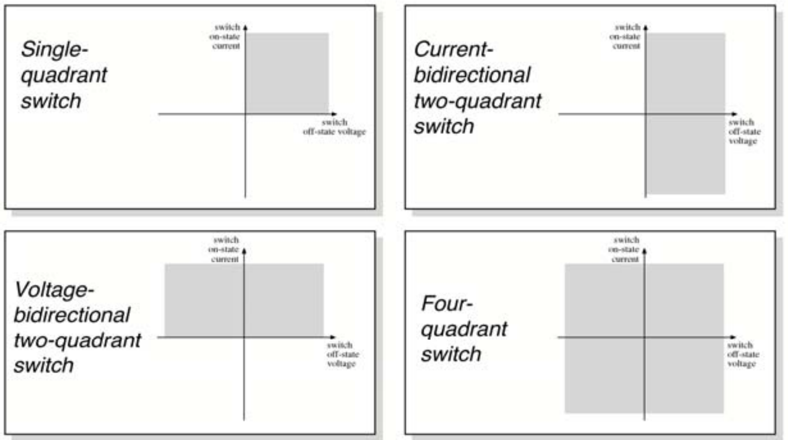


A single-quadrant switch example:

ON-state: $i > 0$

OFF-state: $v > 0$

Some basic switch applications



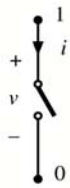
Single-quadrant switch

Current-bidirectional two-quadrant switch

Voltage-bidirectional two-quadrant switch

Four-quadrant switch

4.1.1. Single-quadrant switches



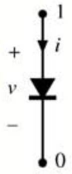
Active switch: Switch state is controlled exclusively by a third terminal (control terminal).

Passive switch: Switch state is controlled by the applied current and/or voltage at terminals 1 and 2.

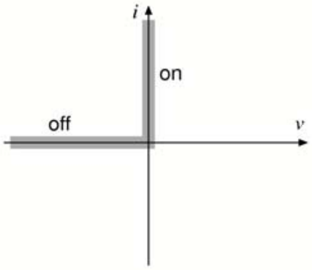
SCR: A special case — turn-on transition is active, while turn-off transition is passive.

Single-quadrant switch: on-state $i(t)$ and off-state $v(t)$ are unipolar.

The diode



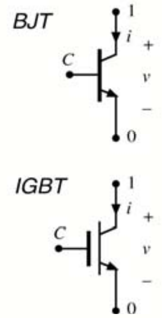
Symbol

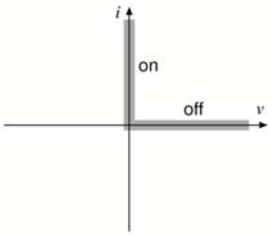


instantaneous i-v characteristic

- *A passive switch*
- *Single-quadrant switch:*
- *can conduct positive on-state current*
- *can block negative off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the diode i-v characteristic, then switch can be realized using a diode*

The Bipolar Junction Transistor (BJT) and the Insulated Gate Bipolar Transistor (IGBT)

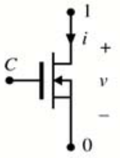




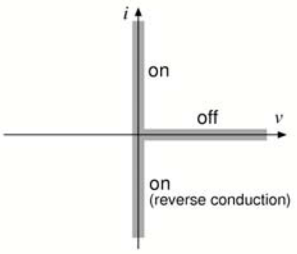
instantaneous i-v characteristic

- *An active switch, controlled by terminal C*
- *Single-quadrant switch:*
- *can conduct positive on-state current*
- *can block positive off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the transistor i-v characteristic, then switch can be realized using a BJT or IGBT*

The Metal-Oxide Semiconductor Field Effect Transistor (MOSFET)



Symbol

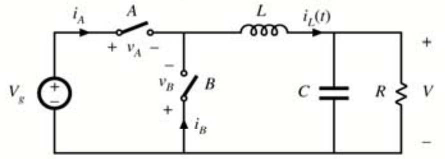


instantaneous i-v characteristic

- *An active switch, controlled by terminal C*
- *Normally operated as single-quadrant switch:*
- *can conduct positive on-state current (can also conduct negative current in some circumstances)*
- *can block positive off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the MOSFET i-v characteristic, then switch can be realized using a MOSFET*

Realization of switch using transistors and diodes

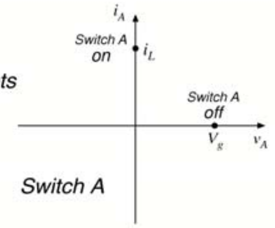
Buck converter example



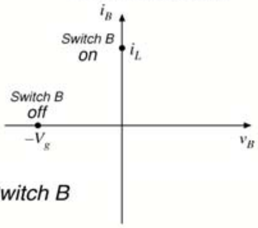
Switch A: transistor

Switch B: diode

SPST switch operating points

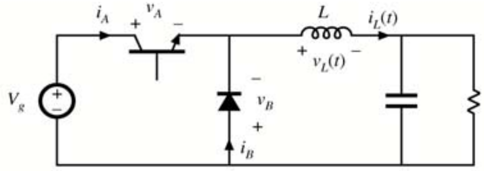


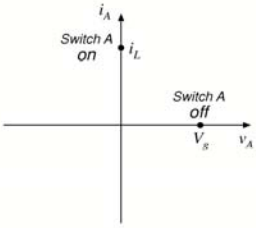
Switch A

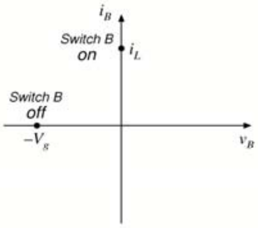


Switch B

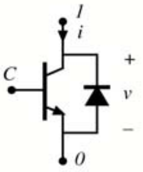
Realization of buck converter using single-quadrant switches



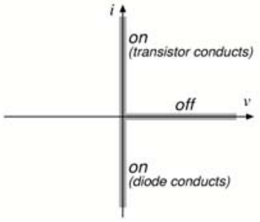




4.1.2. Current-bidirectional two-quadrant switches



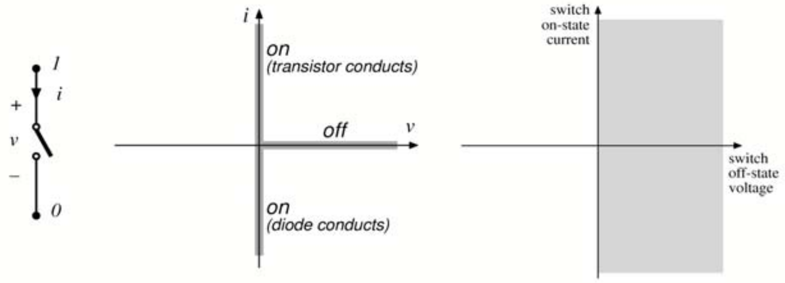
BJT / anti-parallel diode realization



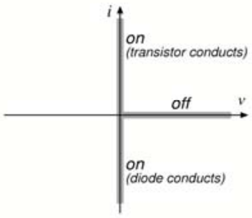
instantaneous i-v characteristic

- *Usually an active switch, controlled by terminal C*
- *Normally operated as two-quadrant switch:*
- *can conduct positive or negative on-state current*
- *can block positive off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the composite i-v characteristic, then switch can be realized as shown*

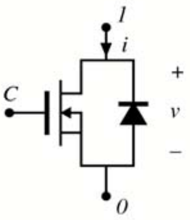
Two quadrant switches



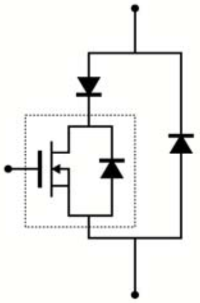
MOSFET body diode



Power MOSFET characteristics

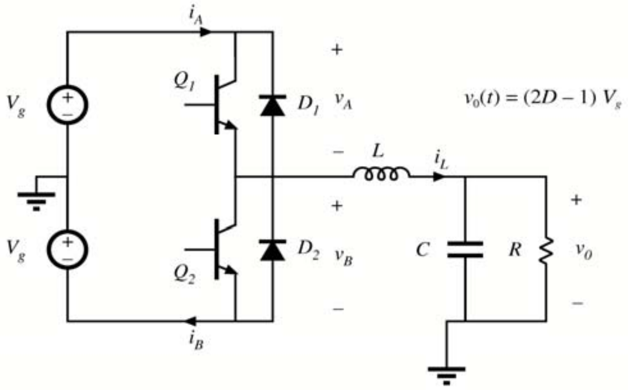


Power MOSFET, and its integral body diode



Use of external diodes to prevent conduction of body diode

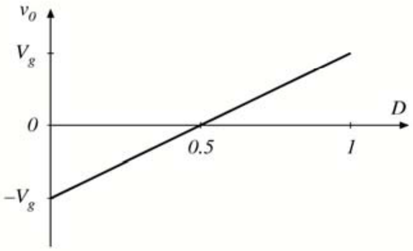
A simple inverter



$v_0(t) = (2D - 1)\, V_g$

Inverter: sinusoidal modulation of D

$$v_0(t) = (2D-1)\,V_g$$



Sinusoidal modulation to produce ac output:

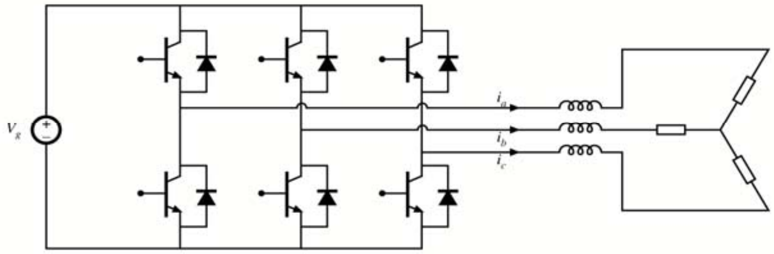
$$D(t) = 0.5 + D_m \sin(\omega t)$$

The resulting inductor current variation is also sinusoidal:

$$i_L(t) = \frac{v_0(t)}{R} = (2D-1)\frac{V_g}{R}$$

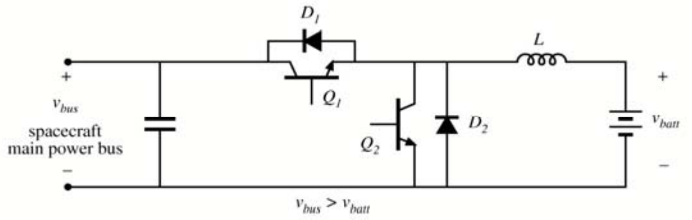
Hence, current-bidirectional two-quadrant switches are required.

The dc-3øac voltage source inverter (VSI)



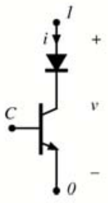
Switches must block dc input voltage, and conduct ac load current.

Bidirectional battery charger/discharger

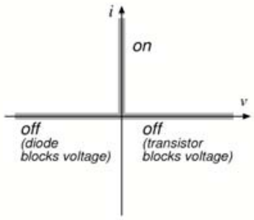


A dc-dc converter with bidirectional power flow.

4.1.3. Voltage-bidirectional two-quadrant switches



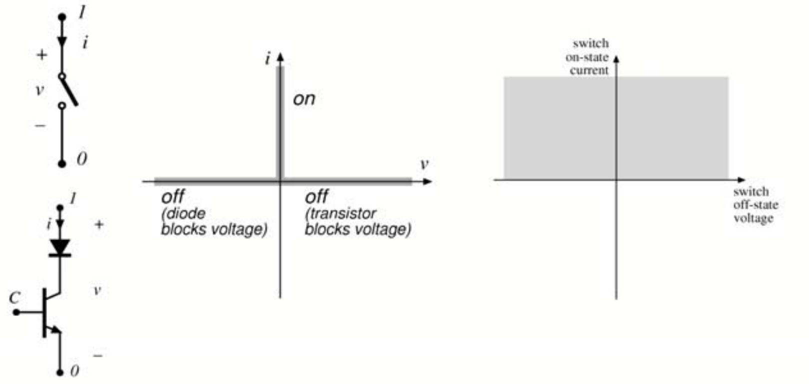
BJT / series diode realization



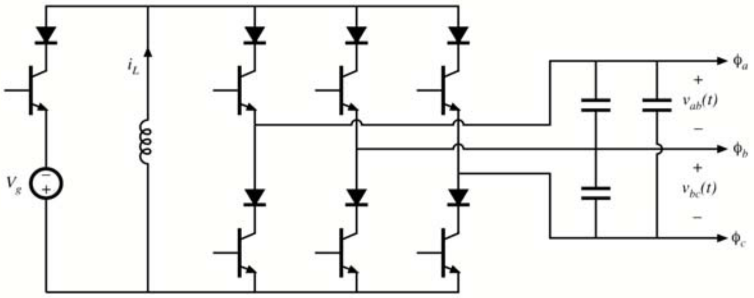
instantaneous i-v characteristic

- *Usually an active switch, controlled by terminal C*
- *Normally operated as two-quadrant switch:*
- *can conduct positive on-state current*
- *can block positive or negative off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the composite i-v characteristic, then switch can be realized as shown*
- *The SCR is such a device, without controlled turn-off*

Two-quadrant switches



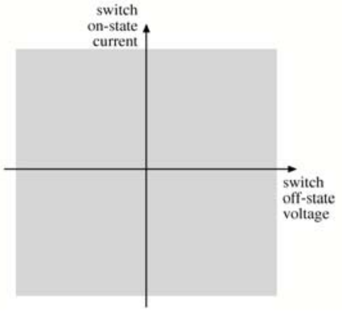
A dc-3øac buck-boost inverter



Requires voltage-bidirectional two-quadrant switches.

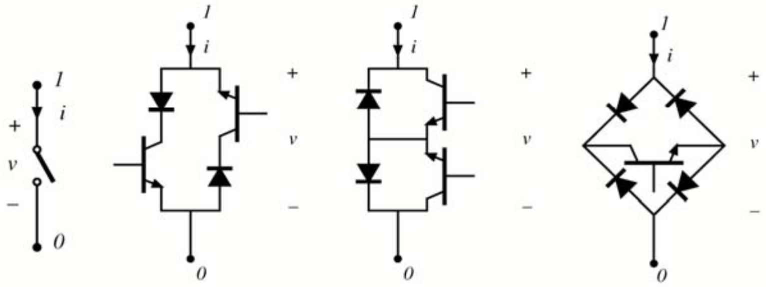
Another example: boost-type inverter, or current-source inverter (CSI).

4.1.4. Four-quadrant switches

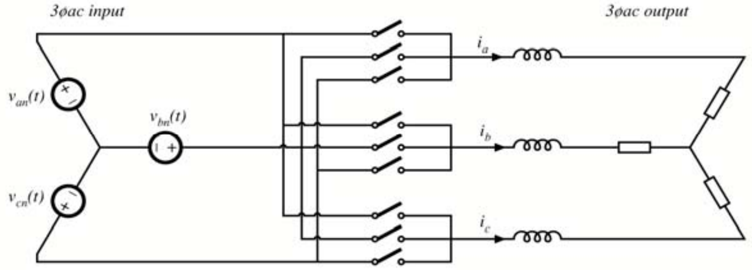


- *Usually an active switch, controlled by terminal C*
- *can conduct positive or negative on-state current*
- *can block positive or negative off-state voltage*

Three ways to realize a four-quadrant switch



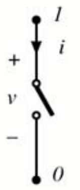
A 3øac-3øac matrix converter



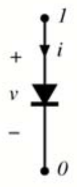
- All voltages and currents are ac; hence, four-quadrant switches are required.
- Requires nine four-quadrant switches

4.1.5. Synchronous rectifiers

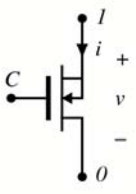
Replacement of diode with a backwards-connected MOSFET,
to obtain reduced conduction loss



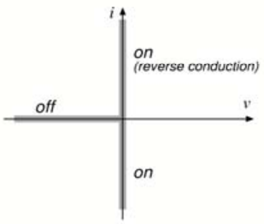
ideal switch



conventional diode rectifier

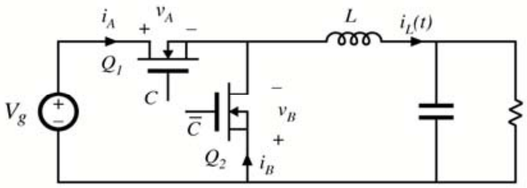


MOSFET as synchronous rectifier



instantaneous i-v characteristic

Buck converter with synchronous rectifier



- MOSFET Q_2 is controlled to turn on when diode would normally conduct
- Semiconductor conduction loss can be made arbitrarily small, by reduction of MOSFET on-resistances
- Useful in low-voltage high-current applications