EEE118: Electronic Devices and Circuits

Lecture XII

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Review

- Discussed an ideal switch
- Considered the non-idealities of a switch
- Looked at three classes of 'switch'
- Considered how the switching action of a transistor is represented on the output characteristics.
- Introduced the idea of a 'load line'
- Considered power dissipation in the "on" state
- Provided design equations for MOS and BJT switches

Outline

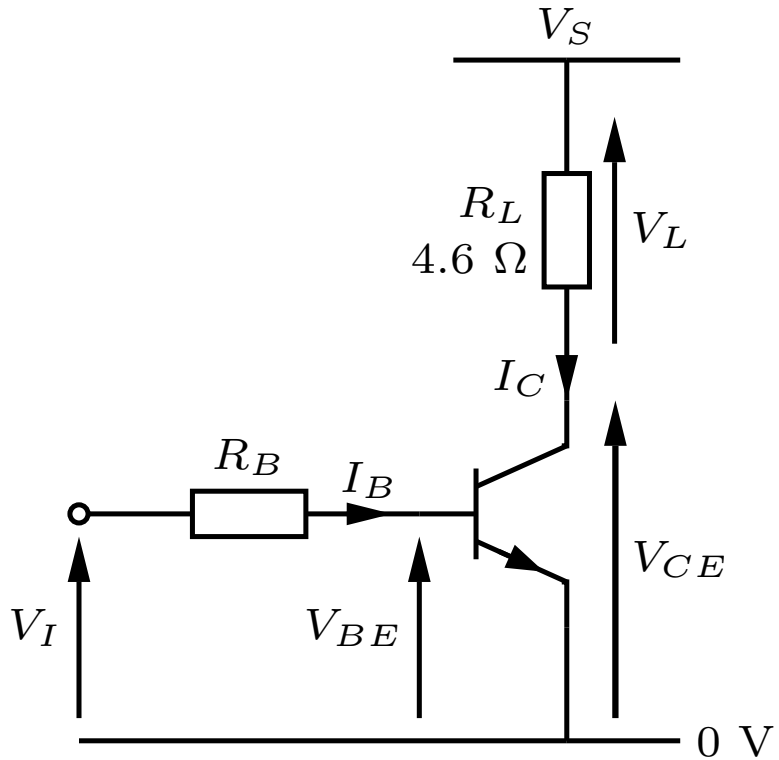
1. Switching Transistor Example
2. Alternating Current Circuits for Switching Transistors
   - Half Wave
   - Full Wave
   - Full Wave Bridge
3. H-Bridge
4. Switching Inductive Loads
   - Single Transistor Switch with Inductive Load
   - H Bridge with Inductive Load
5. Review
6. Bear

Switching Transistor Example: Part One

For the following BJT switching circuit find the,

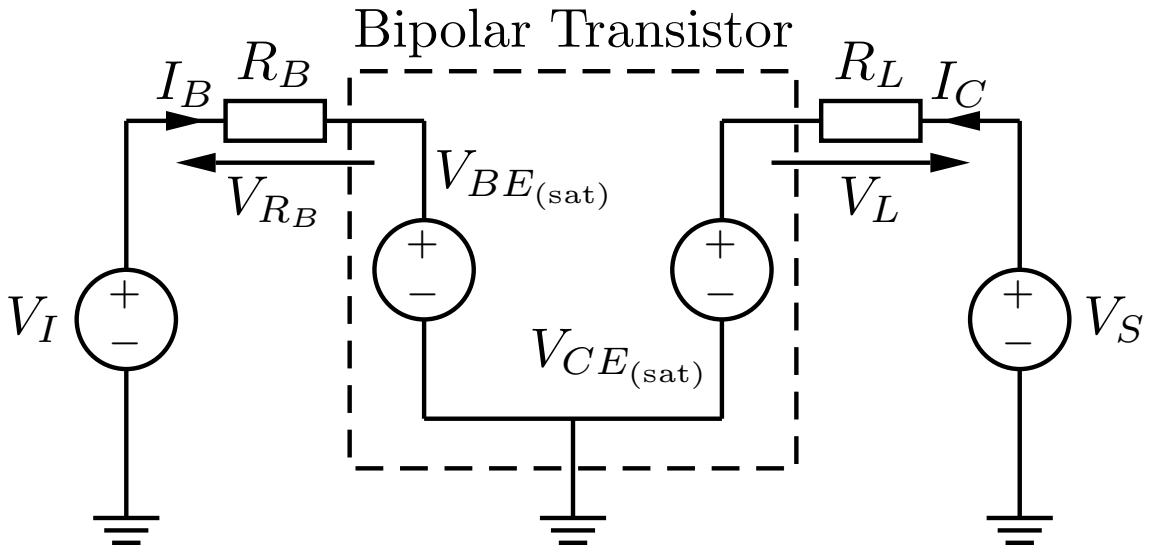
- collector current
- load power
- switch "on" state power loss
- range of possible base currents
- maximum value of R_B

$V_S = 48$ V, $h_{FE} = 35 - 170$,
$V_{CE(sat)} = 0.21$ V, $V_{BE(sat)} = 0.7$ V,
$V_I = 10$ V.



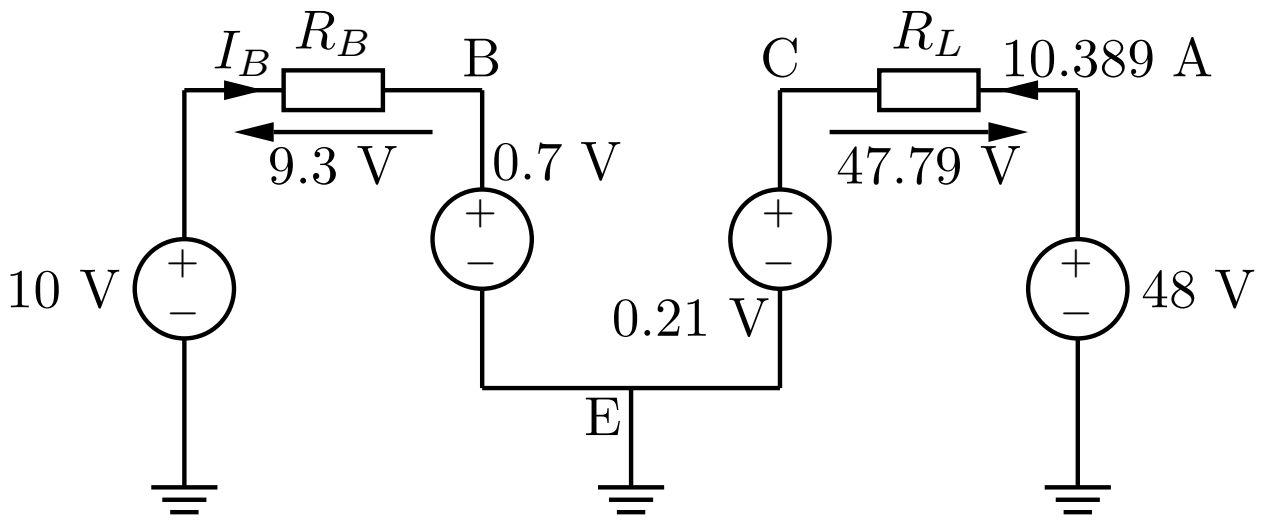
Solution

The "on" state or "saturation" large signal model can be drawn (if necessary)



For the collector current, apply Ohm's law to the collector circuit:

$$I_C = \frac{V_S - V_{CE(\text{sat})}}{R_L} = \frac{48 - 0.21}{4.6} = 10.389 \text{ A} \qquad (1)$$



For the load power,

$$P_L = \frac{V_L^2}{R_L} = \frac{(48 - 0.21)^2}{4.6} = 496.49 \text{ W} \tag{2}$$

For the transistor on state power loss,

$$P_T = V_{CE(sat)} \cdot I_C = 0.21 \cdot 10.389 = 2.182 \text{ W} \tag{3}$$

For the minimum I_B (need to use max h_{FE}),

$$I_B = \frac{I_C}{h_{FE(\max)}} = \frac{10.389}{170} = 61.11 \text{ mA} \tag{4}$$

For the maximum I_B (need to use min h_{FE}),

$$I_B = \frac{I_C}{h_{FE(\min)}} = \frac{10.389}{35} = 296.82 \text{ mA} \tag{5}$$

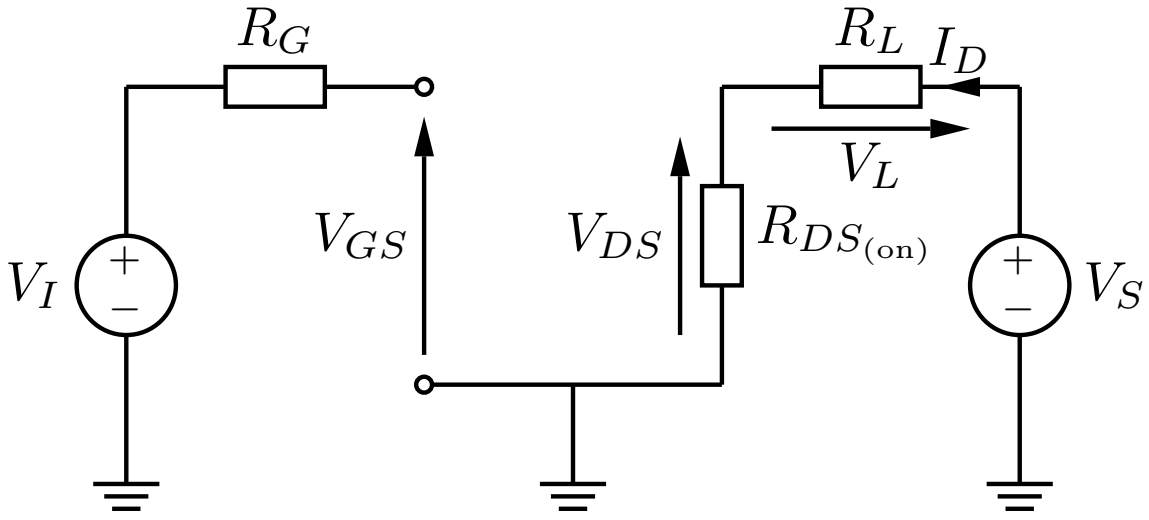
For the max permissible value of R_B (use $I_{B(max)}$),

$$R_B = \frac{V_I - V_{BE(sat)}}{I_{B(max)}} = \frac{10 - 0.7}{296.82 \times 10^{-3}} = 31.33 \ \Omega. \tag{6}$$

Always assume worst case h_{FE} in a switching problem.

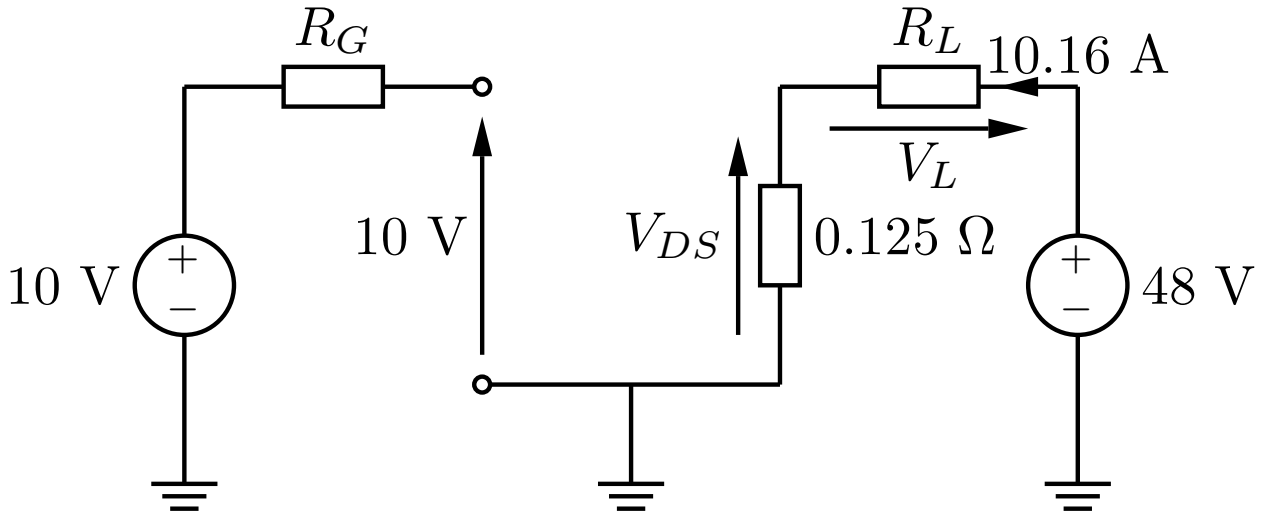
Switching Transistor Example: Part Two

What would the new load power and transistor power be if the BJT was replaced with a MOSFET where $R_{DS(on)} = 0.125\ \Omega$?



For the drain current,

$$I_D = \frac{V_S}{R_{DS(on)} + R_L} = \frac{48}{0.125 + 4.6} = 10.158\ \text{A} \tag{7}$$



The power in the load resistance,

$$P_L = \frac{V_L^2}{R_L} = \frac{\left(V_S - \left(R_{DS(on)}\, I_D\right)\right)^2}{R_L} \tag{8}$$

$$= \frac{\left(48 - \left(0.125 \cdot 10.158\right)\right)^2}{4.6} = 474.72 \text{ W} \tag{9}$$

The power loss in the FET is,

$$P_T = I_D^2 \, R_{DS(on)} = 10.158^2 \cdot 0.125 = 12.9 \text{ W} \tag{10}$$

What value of $R_{DS(on)}$ for the MOSFET would yield the same on state loss as the BJT in part one?

Use the *BJT* current and power loss figures to find an equivalent resistance value

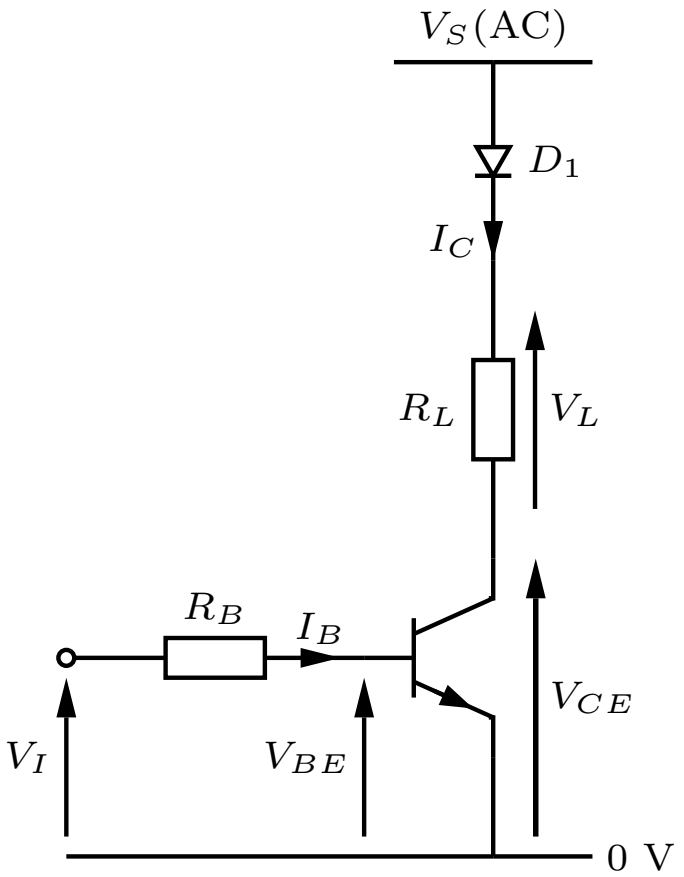
$$P_T = 2.181 \text{ W} \tag{11}$$

$$I_D = 10.398 \text{ A} \tag{12}$$

$$R_{DS(on)} = \frac{P_T}{I_D^2} = \frac{2.181}{10.389^2} = 0.0202 \ \Omega \tag{13}$$

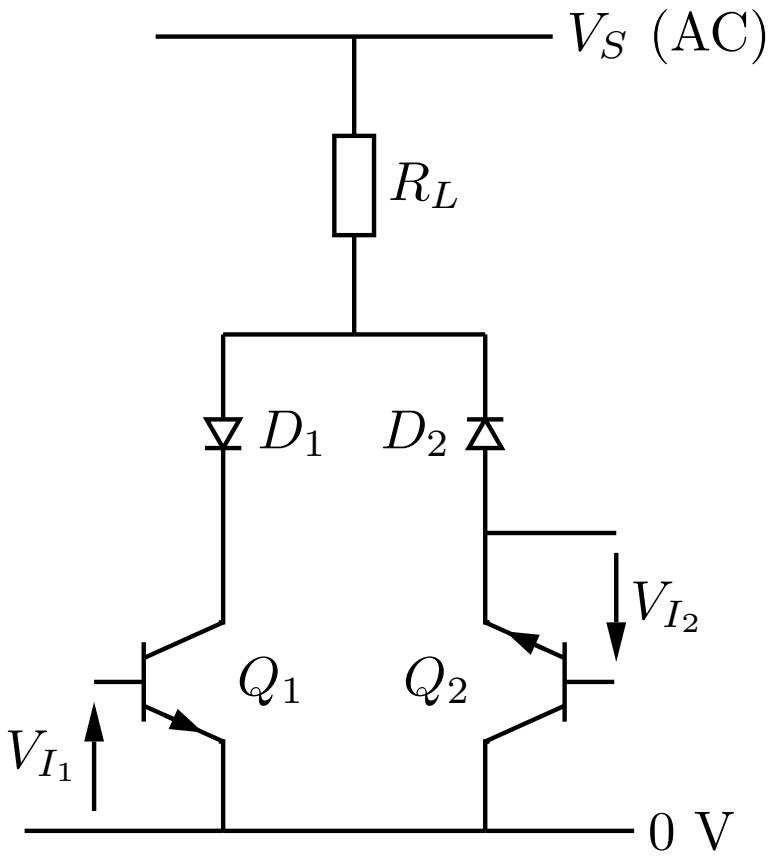
AC Transistor Switching Circuits

The NPN BJT and N-Ch MOSFET should only be operated with conventional current flowing from collector to emitter and drain to source. What about switching voltages that have both positive and negative values?



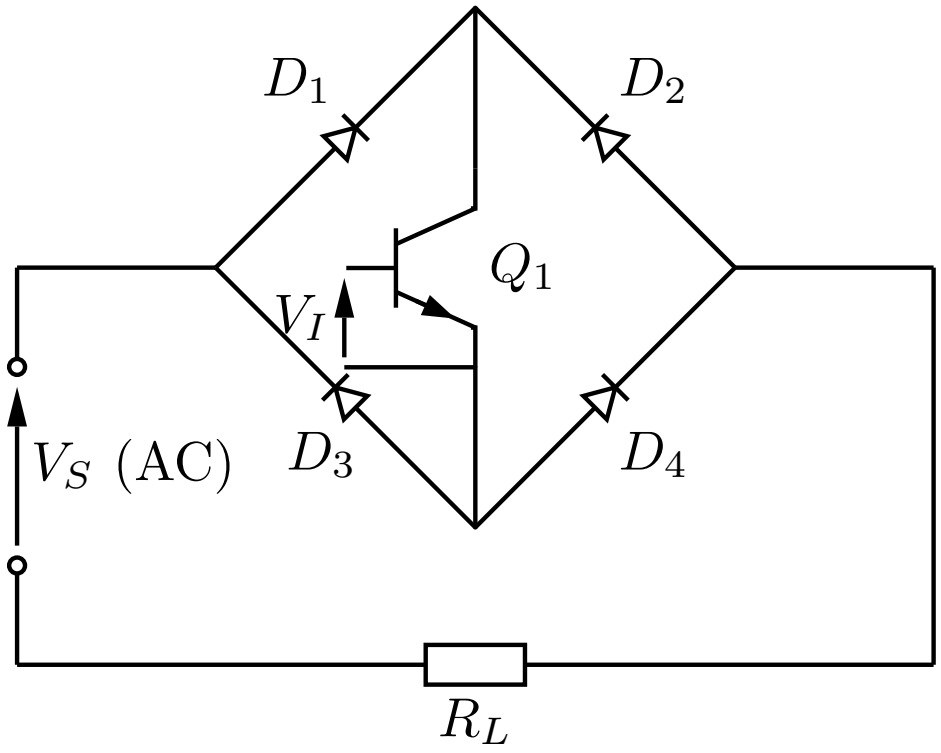
- One option is to include a diode in series with the load.
- When V_S falls below 0 V the diode is reverse biased.
- Only provides half wave rectification.
- On state diode power loss is $0.7 \cdot I_C$

To produce a full wave rectifying AC transistor switching circuit, two NPN transistors can be used together each dealing with one half of the AC cycle.



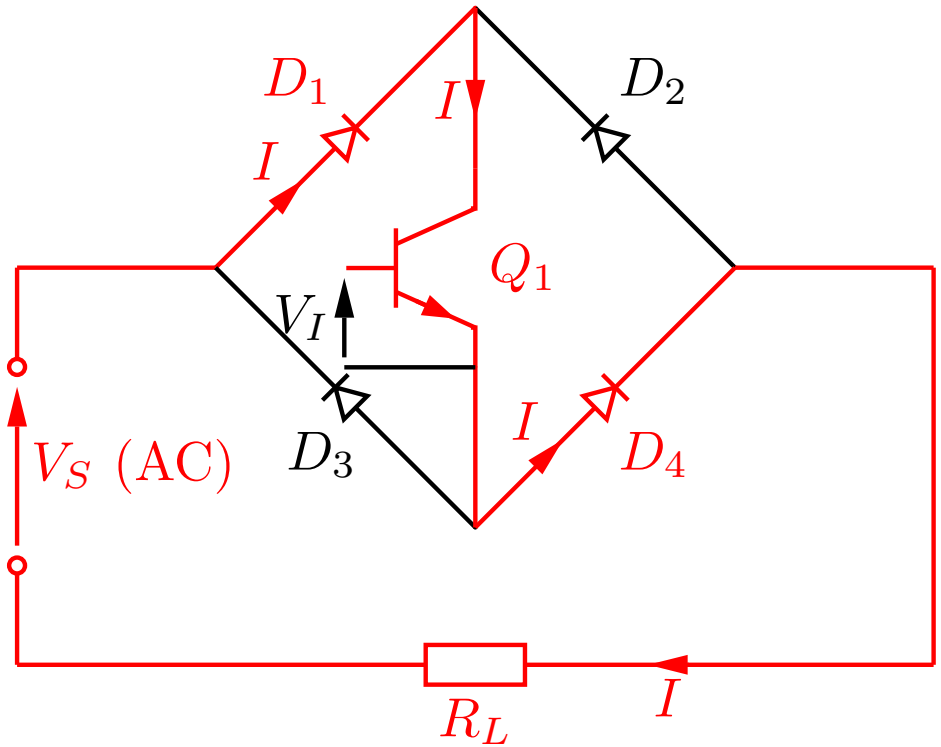
- Q_1 and D_1 are responsible for the current in R_L while $V_S > 0\ V$
- Q_2 and D_2 are responsible for the current in R_L while $V_S < 0\ V$
- The control input for Q_2 is a little inconvenient but it can easily be overcome in practice.

To produce an AC transistor switching circuit with only one switch,



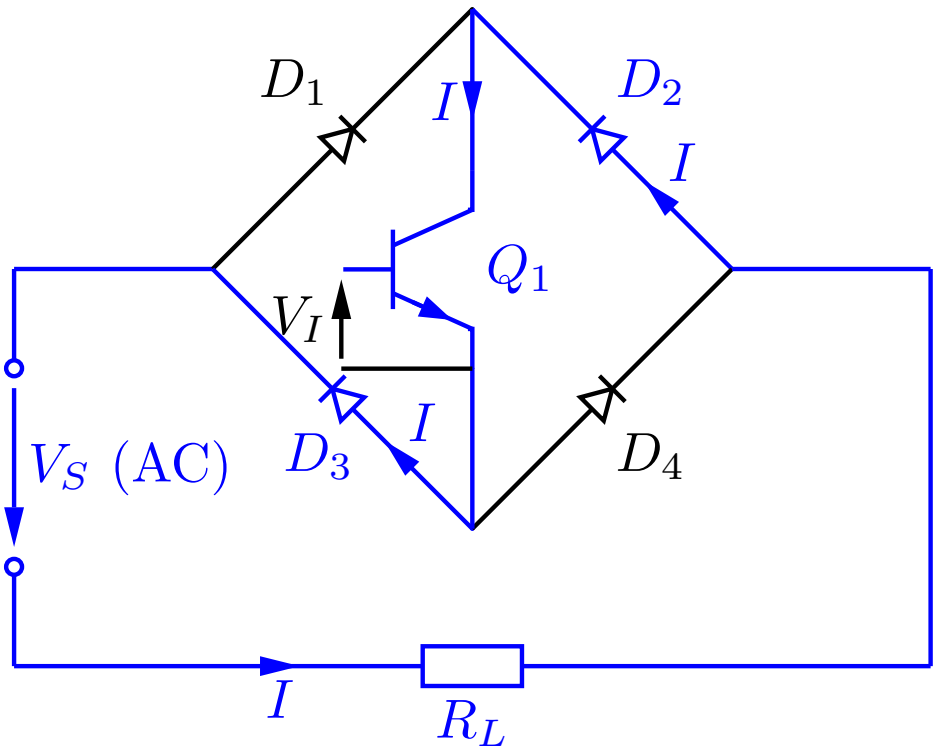
The control voltage is still referenced to a tricky location, but it is not too troublesome.

For one half cycle,



Note that the transistor current is DC, but the load current is AC.

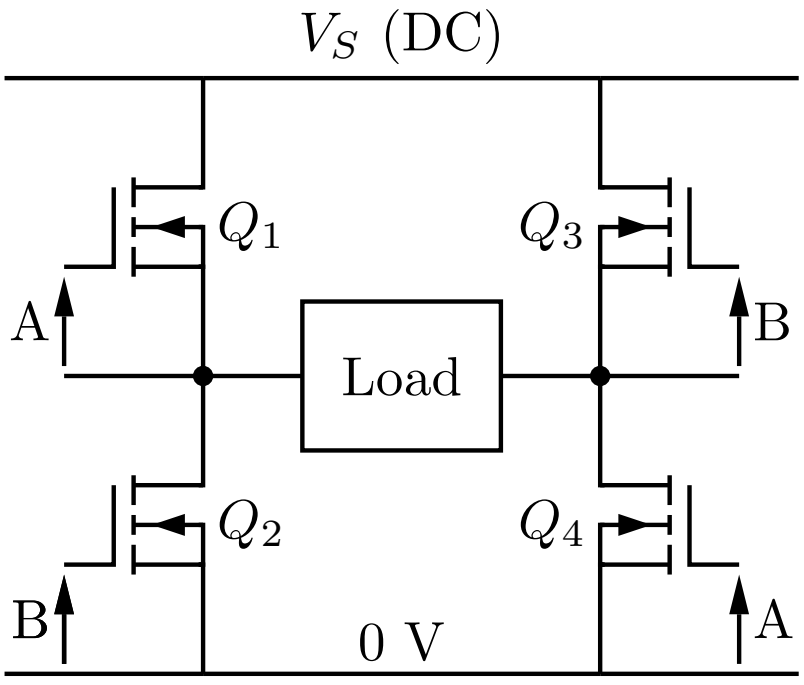
For one the other half cycle,



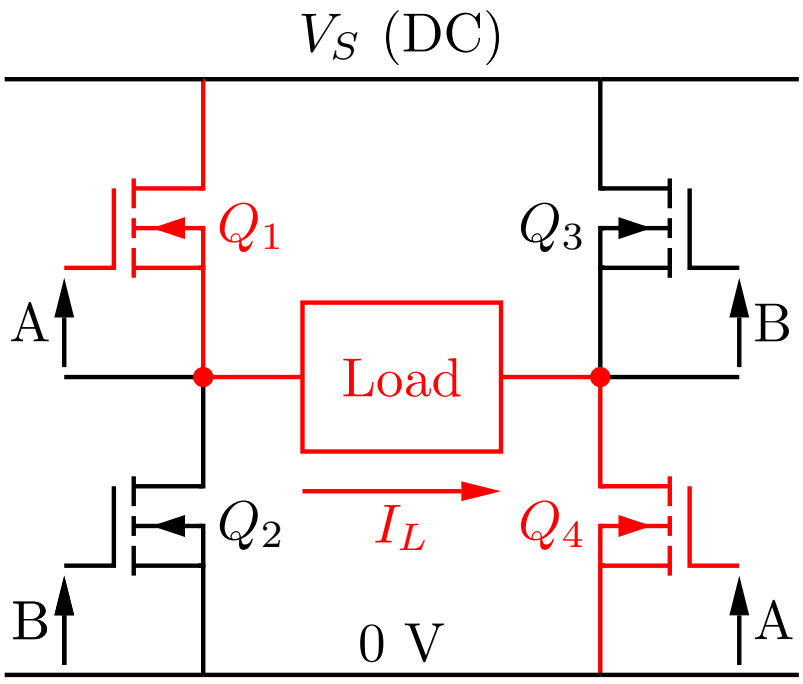
Whatever happens to V_S, I_C is always flowing into the collector.

H Bridge

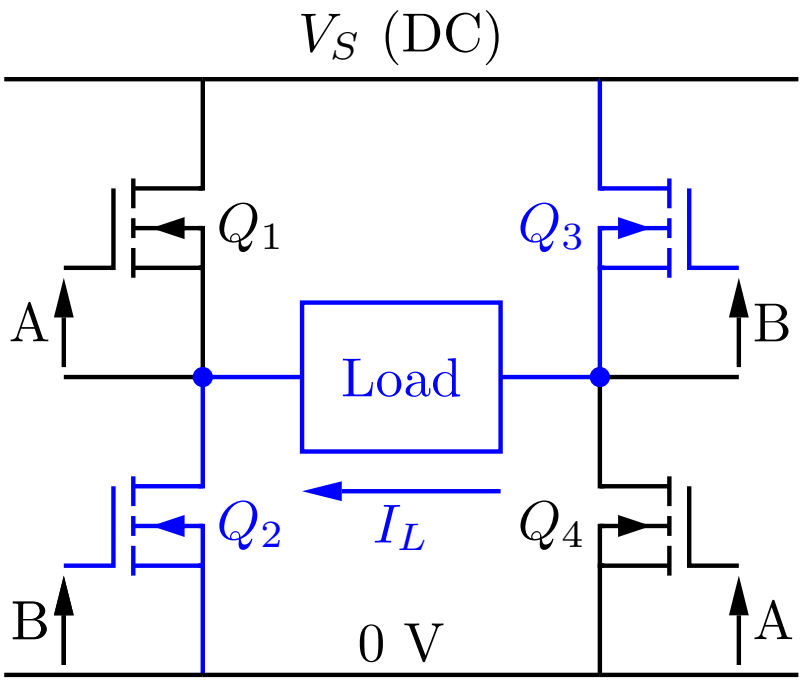
Often used for motor control from a DC supply.



- Four switches in an "H" shape. The load is the cross bar.
- For Toyota Prius $V_S \approx 220\ V$, $I \approx 110\ A$
- By controlling the switches current can flow in either direction.
- DC motors can run in both directions.
- Average power can also be controlled.



"A" switches on
"B" switches off



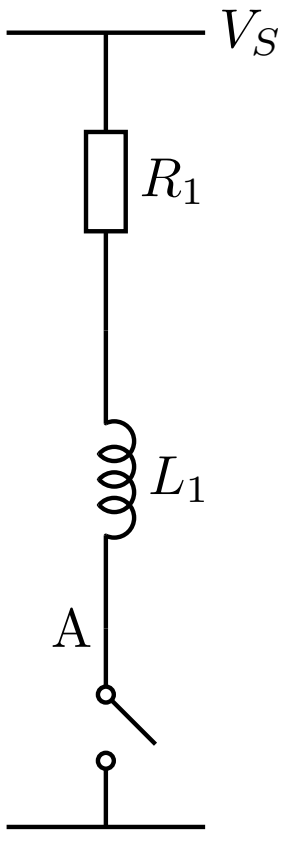
"B" switches on
"A" switches off

If both "A" and "B" are on together a large 'shoot through' current results, usually destroying the switches. Both "A" and "B" can be time varying which modulates the load current, dissipating a predetermined average power in the load.

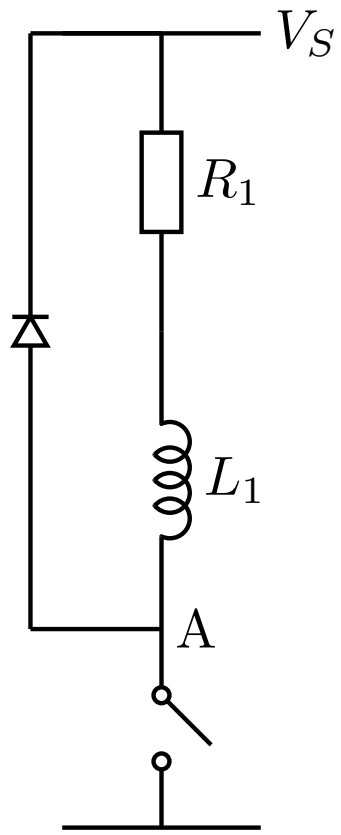
Switching Inductive Loads

Inductors always try to keep current flowing. $V = L\frac{\mathrm{d}I}{\mathrm{d}t}$. If a switch is opened its current falls to zero very rapidly and $\frac{\mathrm{d}I}{\mathrm{d}t} \to \infty$. Consequently $V_{L_1} \to \infty$ too.

- When the switch is "on", a current $\frac{V_S}{R_1}$ flows.
- When the switch turns "off", L_1 attempts to maintain the prior "on" current by increasing the voltage across its terminals.
- The charge attempting to leave the inductor as its magnetic field collapses appears at node A, but has no where to go thereafter

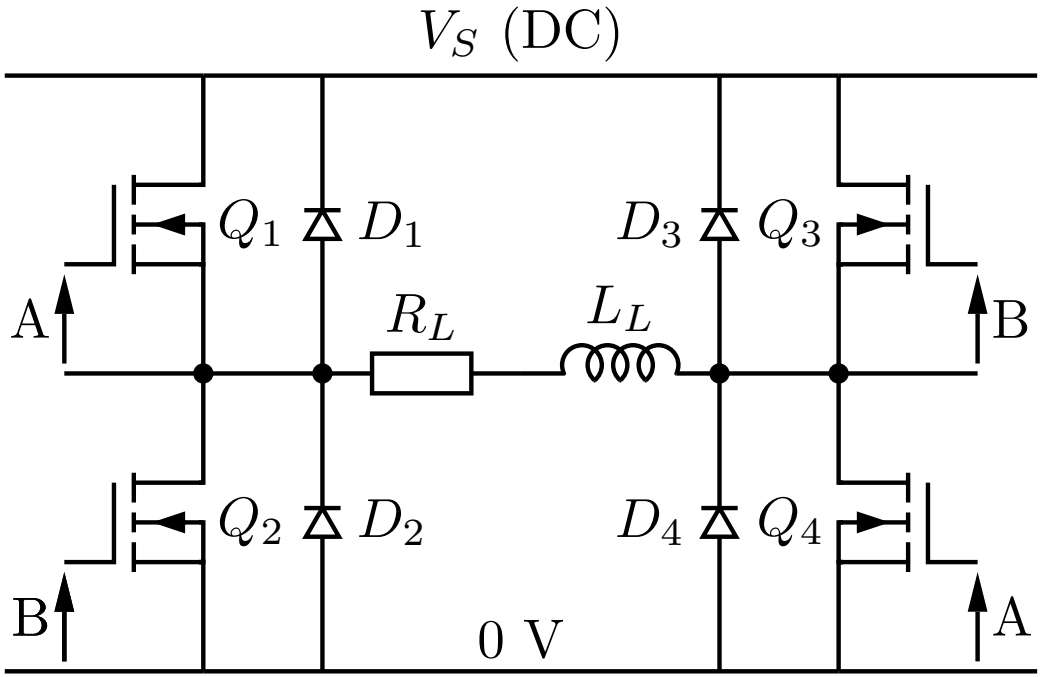


- Node A has some small stray parasitic capacitance due to its physical dimensions.
- The charge arriving on node A charges this stray capacitance according to $Q = C\,V$.
- Since C is small, V must become very large to accommodate even a modest charge, Q.
- The very high voltage spikes which occur may damage any semiconductor switches in the circuit.
- The solution is to provide another path for the charge leaving the inductor to escape from node A.
- The diode is reverse biased under normal circumstances. If $V_A > (V_S + 0.7)$ the diode will conduct any charge on A back into the power supply.



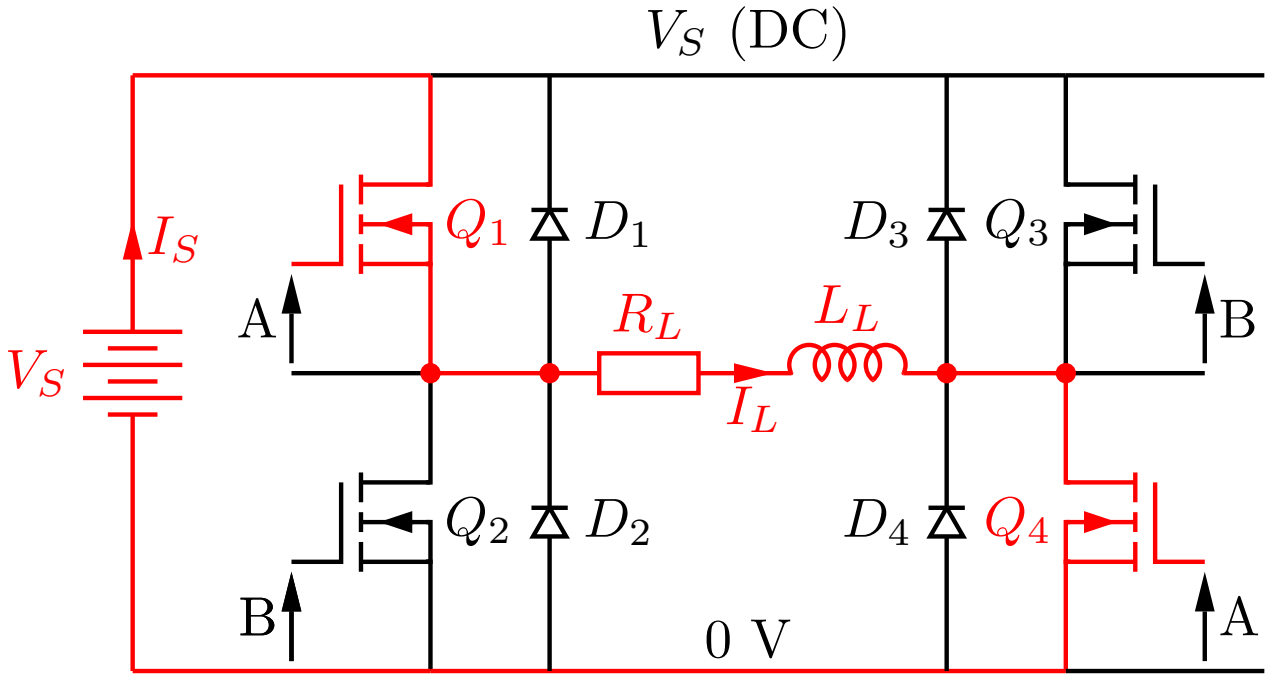
- Just after the switch off event, the diode current is equal to the on state inductor current
- After switch off this current falls exponentially with a time constant of $\frac{L_1}{R_T}$ where R_T is the total resistance of the return or "free wheeling" pathway.
- In some applications the "inductive kick" is desirable for example, "boost" and "flyback" converters (types of Switched Mode Power Converter). Also in CRT power supplies and in internal combustion engine ignition systems. Often though, it is highly undesirable and methods to control it are used.

The energy stored in the inductor drives the "back EMF" process. The situation is similar for electrical machines (motors & generators).



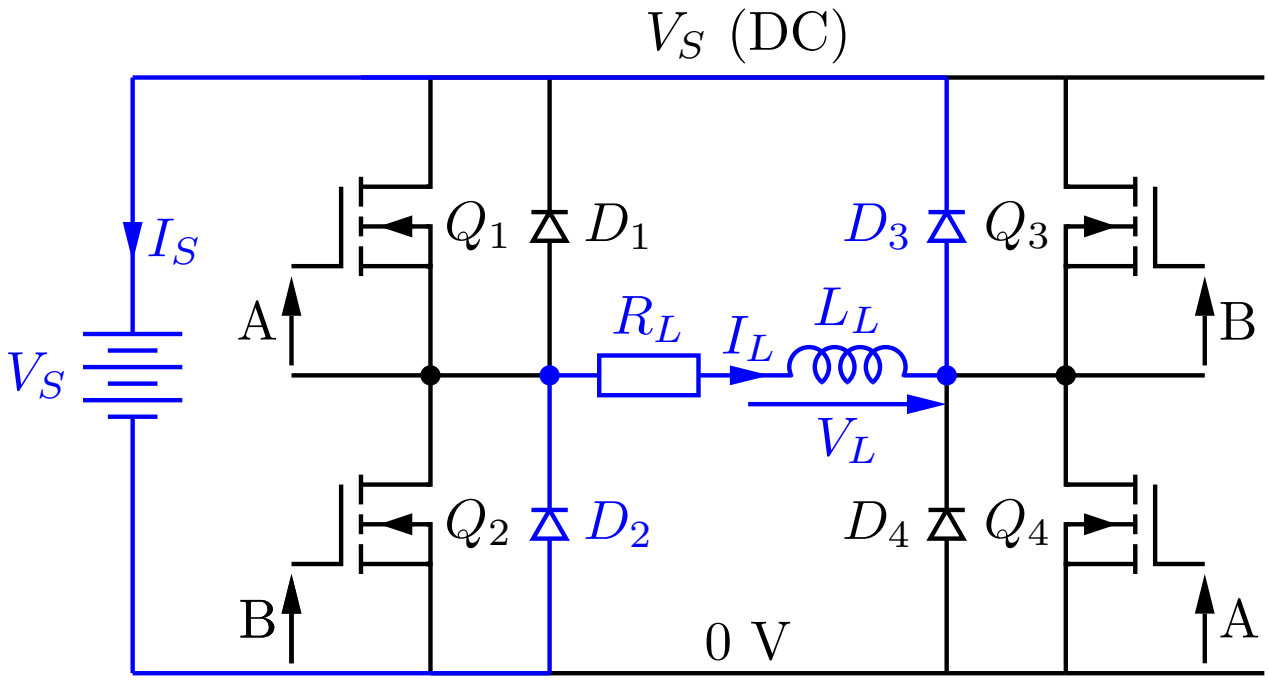
- Operation is as before, Q_1 and Q_4 operate together as do Q_2 and Q_3.
- Now the energy stored in the inductor must be considered.
- As soon as the switches turn off the inductor current must continue.
- There are six interesting states in total, but only four are considered here.

H Bridge with Inductive Load - A switches "on"



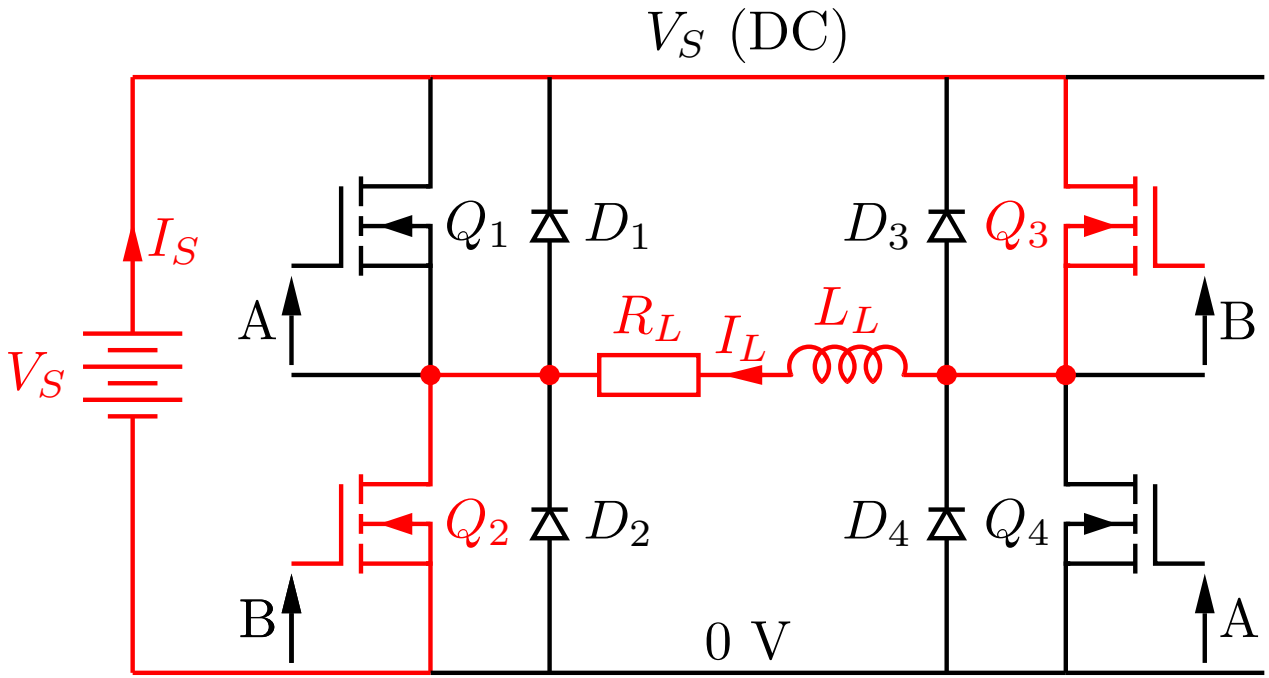
- "A" switches have been on for a long time.
- I_L is constant and flows out of the battery.
- The machine is drawing electrical power from the supply and converting it to mechanical power.

H Bridge with Inductive Load - A switches "off"



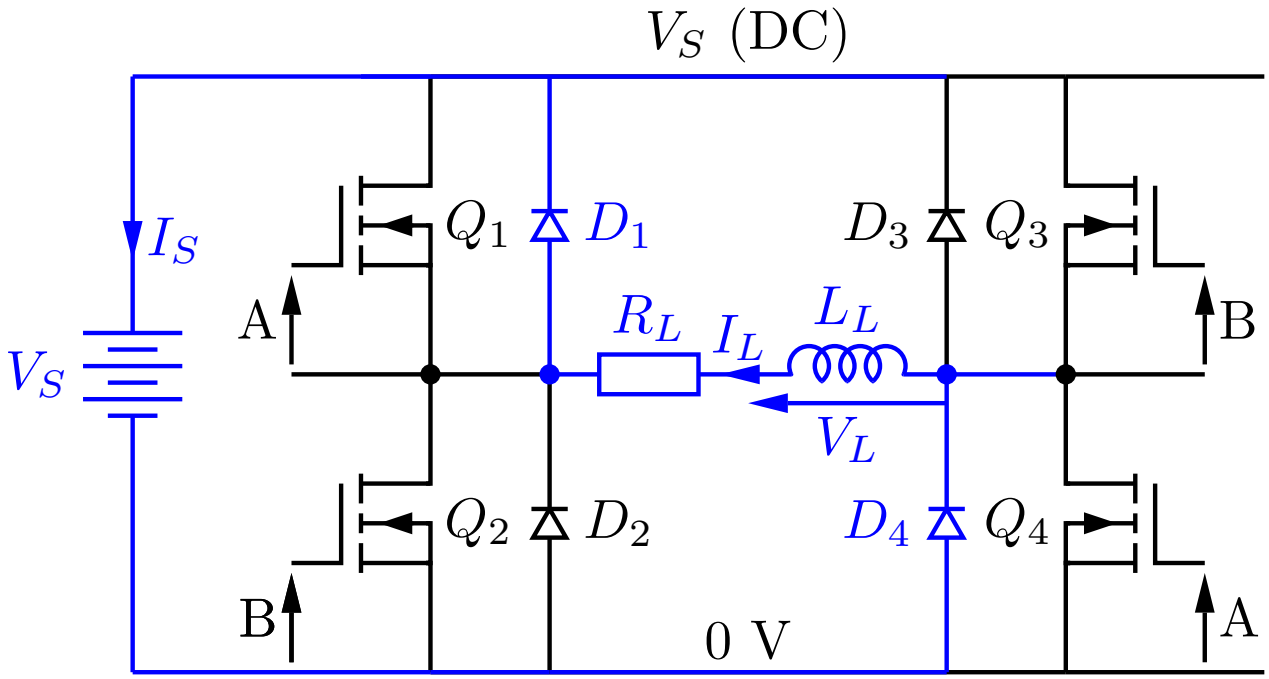
- "A" switches, having been on for a long time, switch off.
- I_L has not yet changed due to the inductive load, note the direction of V_L, I_L and I_S. From a circuit perspective L_L is now a generator.
- The machine is returning electrical power stored in it's inductance to the battery.

H Bridge with Inductive Load - B switches "on"



- "B" switches have been on for a long time.
- I_L is constant and flows out of the battery.
- The machine is drawing electrical power from the supply and converting it to mechanical power (rotating in opposite direction).

H Bridge with Inductive Load - B switches "off"



- "B" switches, having been on for a long time, switch off.
- I_L has not yet changed due to the inductive load, note the direction of V_L, I_L and I_S. From a circuit perspective L_L is now a generator.
- The machine is returning electrical power stored in it's inductance to the battery.

Review

- Performed switching circuit example calculation (exam/tutorial sheet style)
- Considered several transistor switching circuits for AC including,
  - Half wave single transistor switch
  - Full wave two transistor switch
  - Bridge full wave single transistor switch
- Introduced the H-bridge as a circuit commonly used to drive electrical machines from a DC supply.
- Considered the effects of inductance in the load of a transistor switch in terms of rate of change of current and provided a diode as an alternate current pathway.
- Applied the parallel diode approach to the H bridge and considered four states of operation.