EE 366
POWER ELECTRONICS

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Course Objectives

- Provide an introduction to the technology of Power Electronics at a level suitable for BSc Electrical and Electronic Engineering students
- Demonstrate the key concepts using examples from relatively low current applications (e.g. Electronic Power Supplies)
- Cover the following specific topics:
  - Methods of analysis for power electronic circuits
  - Introduction to power semiconductor devices and their use
  - Power supplies for electronic equipment - requirements
  - Linear and switching regulators
  - Single phase diode rectifiers
  - Three phase thyristor rectifiers
  - Voltage source inverters
  - DC-DC converters
  - AC voltage regulators, etc.

Books

- There are no essential books for this course. However, the following books are excellent and cover most of the material in this course.
  - POWER ELECTRONICS: Converters, Applications and Design by Mohan, Underland and Robbins, Wiley publishing, 2003
  - High Power Converters and AC Drives, 2nd Edition by Bin Wu and M. Narimani, Wiley, 2017
  - P. T. Krein, Elements of Power Electronics. New York and Oxford: Oxford University Press, 1998.

Unit 1
Introduction to Power Electronics

What is Power Electronics?

SIMPLE DEFINITION:

CONTROL/PROCESSING OF ELECTRICAL ENERGY USING SEMICONDUCTOR SWITCHES AND ENERGY STORAGE ELEMENTS (Inductors and Capacitors)

- Power Electronics is an ENABLING technology – it enables other technologies to function:
  - ❖ Computers and Communications
  - ❖ Energy networks – smart grids – smart homes – renewable energies, etc.
  - ❖ Electric and hybrid road transport
  - ❖ More Electric Airplanes (e.g. Boeing 787)
  - ❖ All Electric Ships
  - ❖ Electric Motor Drives
- Power Electronics has a vital role to play in energy efficiency

Power Electronics Applications

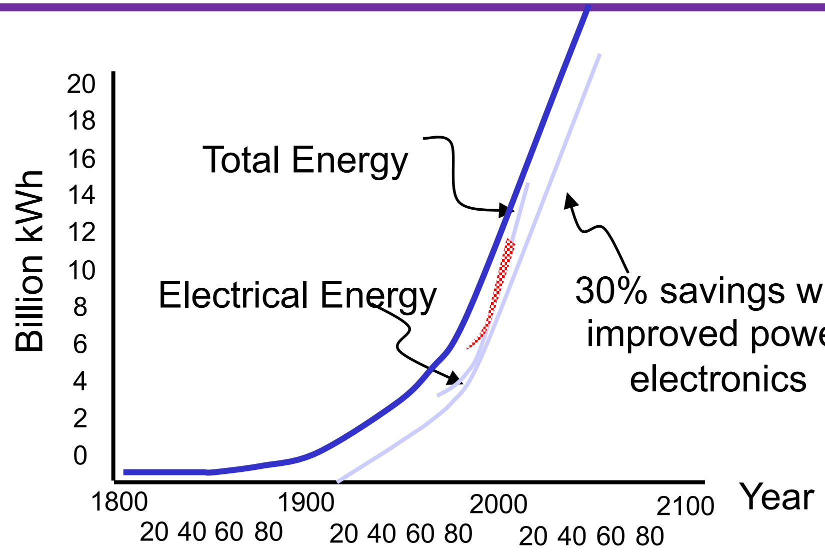
Why Power Electronics?

- Power electronics is an essential technology in all future sustainable energy scenarios
- Underpins the low-carbon economy
- It is the only technology that can deliver efficient and flexible control of electrical energy
- Share of electrical energy which will be controlled by power electronics is expected to increase from 40% in 2000 to 80% in 2020 and beyond

Growth areas for Power Electronics

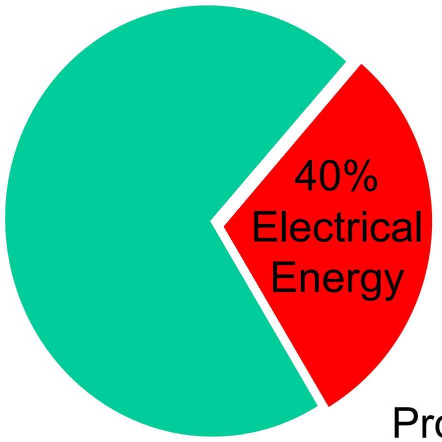
- Connection of **renewable energy sources** to power grids is not possible without power electronics.
- **Future electricity networks** must incorporate power electronics.
- **Transport:** electric and hybrid drive trains are only possible with efficient and intelligent power electronics. Weight savings through power electronics will reduce fuel demand.
- **Power supplies:** new concepts can improve overall efficiency by 2-4%.
- **Motor drives:** use 50-60% of all electrical energy consumed in the developed world: a potential reduction in energy consumption of 20-30% is achievable.
- **Home appliances:** electronic thermostats for refrigerators and freezers can yield 23% energy saving: an additional 20% can be saved by using power electronics to control compressor motors (with 3-phase PMDC motors).
- **Lighting:** power electronics can improve the efficiency of fluorescent and HID ballasts by a minimum of 20%.

Energy and Power Electronics



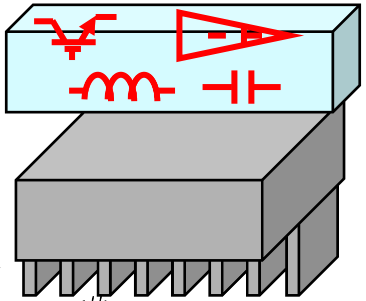
* Output of 840 power plants

Total Energy



1997: 40%
2015: 80%
Processed by Power Electronics

Power Electronics



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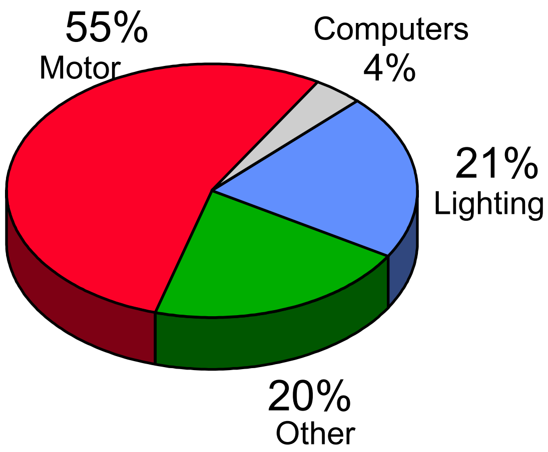
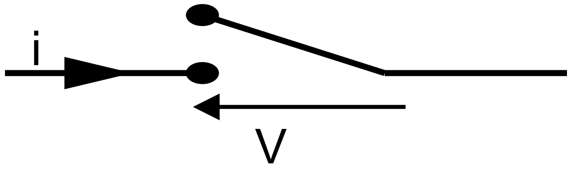
Electrical Energy



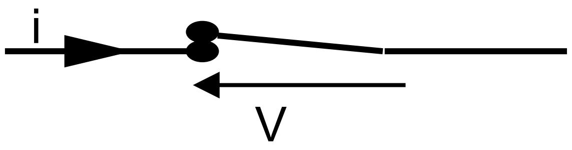
* EPRI

Why use Switching?



Open Switch: i = 0, V = ? (depends on rest of circuit)

Power Dissipation = Vi = 0

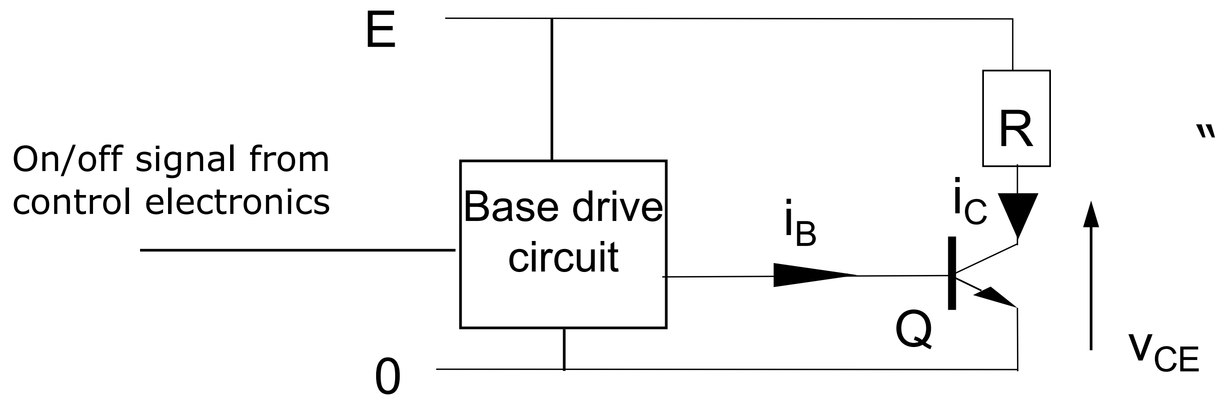


Closed Switch: V = 0, i = ? (depends on rest of circuit)

Power Dissipation = Vi = 0

- "Switching" means that power electronic converters are *theoretically* 100% efficient
- Switching on and off gives pulsed energy flow – that's why we need energy storage elements as well to give "smooth" control of power flow
- Energy storage elements smooth power flow:
  - Inductors smooth current – they don't like you trying to change their current since Energy=$\frac{1}{2}Li^2$
  - Capacitors smooth voltage - they don't like you trying to change their voltage since Energy=$\frac{1}{2}Cv^2$

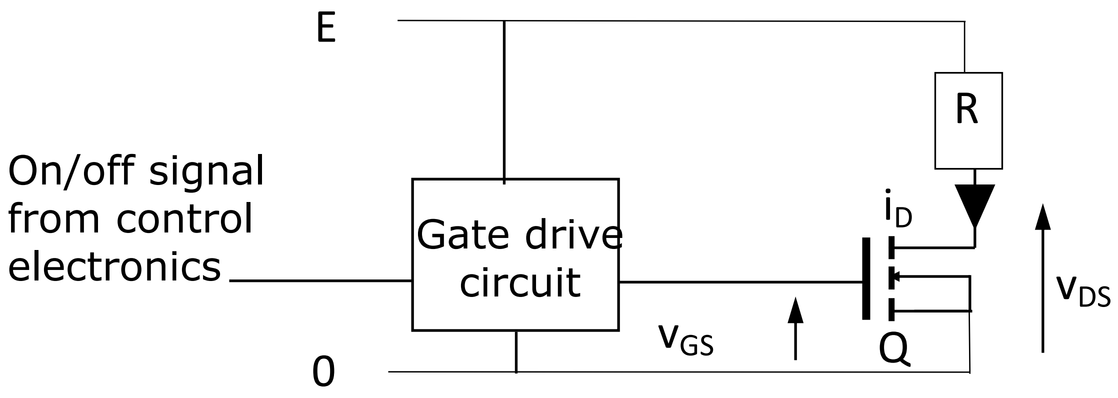
BJT as a switch



Base drive circuit "boosts" on/off logic signal to form required to drive Transistor

- OFF state
  - $i_B = 0$, $i_C = 0$, $v_{CE} = E$ $\Rightarrow$ Q behaves like an open switch
- Linear region
  - $i_B > 0$, $i_C = \beta i_B$, $v_{CE} = E - I_C R$ $\Rightarrow$ Q has high power dissipation
- ON (saturated) state
  - increase i_B until i_C approaches E/R and hence v_{CE} approaches 0. Further increase in i_B beyond this value ($i_B = E/\beta R$) results in no further increase in i_C - this is the saturated state $\Rightarrow$ Q behaves like a closed switch ($v_{CE} \approx 0$)
- Only ON and OFF states are used in Power Electronics

MOSFET as a switch

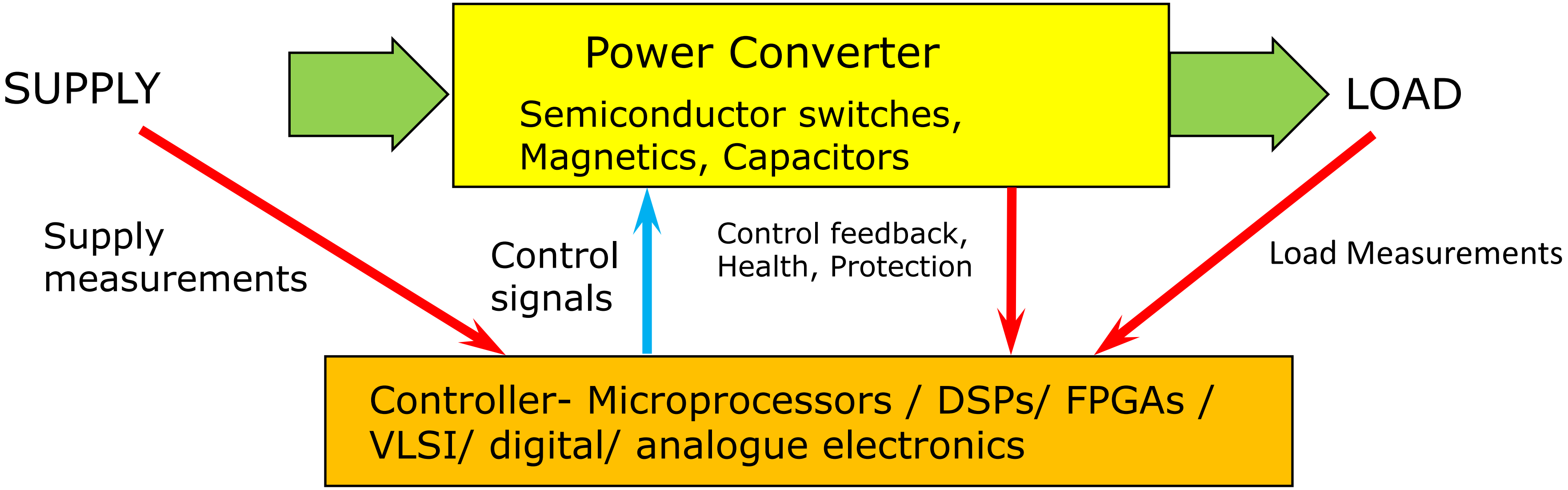


Gate drive circuit "boosts" on/off logic signal to form required to drive MOSFET

- OFF state
  - $v_{GS} = 0$, $i_D = 0$, $v_{DS} = E \Rightarrow$ Q behaves like an open switch
- Linear region
  - $v_{GS} > v_T$, $i_D \approx g_m(v_{GS} - v_T)$, $v_{DS} = E - I_D R \Rightarrow$ Q has high power dissipation

    Approx for power device
- ON state
  - increase v_{GS} until i_D approaches E/R and hence v_{DS} approaches 0. Further increase in v_{GS} beyond this value results in no further increase in i_D - this is the ON state $\Rightarrow$ Q behaves like a closed switch ($v_{DS} \approx 0$)
- Only ON and OFF states are used in Power Electronics

Power Electronic Systems



- Power converter matches "supply" characteristics to the "load" characteristics
- An appropriate power converter exists for all load and supply types (AC, DC, single phase, polyphase, fixed freq, variable freq, fixed voltage, variable voltage etc)
- Power flow may be bidirectional (supply $\Leftrightarrow$ load) or unidirectional (supply $\Rightarrow$ load)
- Switching technology gives very efficient power conversion
- Digital control gives sophisticated functionality, monitoring and protection capability for many systems

Power Electronic Applications

- Applications are vast spanning a huge power range – some examples are given below.
- **< 1kW**
  - Small electronic power supplies (eg PCs)
  - White goods (e.g. washing machines etc)
  - Lighting
- **1kW to 100kW** *(a 2 litre car engine is about 100kW)*
  - Industrial motor drives (pumps, fans, robots etc)
  - Lifts
  - Transportation (e.g. electric vehicles)
  - Uninterruptible power supplies (UPS)

Power Electronic Applications

- **100kW to 1MW**
  - Larger motor drives (paper mills, steel mills etc)
  - Transportation (Trolleybuses, trams etc)
- **1MW to 10MW**
  - Very large industrial motor drives
  - Industrial processes (furnaces etc)
  - Transportation (e.g. Railway locomotives)
- **10MW to 1000+MW**
  - Transportation (e.g. ships - Frigate (20MW))
  - Control of electricity distribution - High Voltage DC links (HVDC) – e.g. UK-France link (2000MW at ± 270kV DC)

Analysis of Power Electronic Circuits

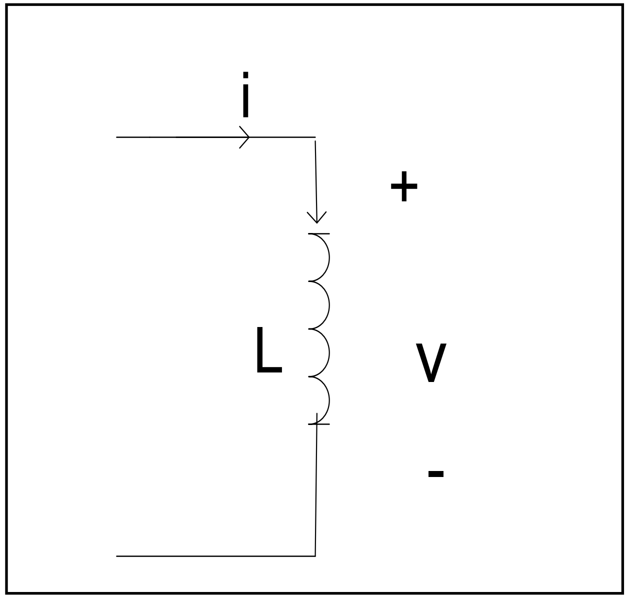
ASSUMPTIONS FOR ANALYSIS

- All semiconductor switches are treated as "IDEAL" switches
  - No forward voltage drop when they are conducting (ON)
  - No leakage current when they are blocking (OFF)
  - Instantaneous switching between the ON and OFF states
- Inductors are treated as "IDEAL"
  - Zero resistance in the winding(s)
  - No power loss in the magnetic material (Zero eddy current loss and hysteresis loss)
- Capacitors are treated as "IDEAL"
  - Zero series resistance in the capacitor
  - Zero power loss in the dielectric

Inductors and Capacitors

- It is **ESSENTIAL** to think about inductors and capacitors as energy storage elements when trying to understand power electronic circuits
- The abstract notion of inductors and capacitors as impedances ($j\omega L$ and $1/j\omega C$) is often **USELESS** in the analysis of power electronic circuits
- Impedance is a concept of “Phasor Analysis”. “Phasor Analysis” relates to “steady state” sinusoidal (AC) conditions. These conditions are not applicable to most power electronic circuits
- Phasor analysis is a **“Frequency Domain”** method where we analyse how a (linear) circuit operates at different frequencies for sinusoidal inputs
- To understand power electronic circuits, we need to look at the waveforms as a function of time – we need a **“Time Domain”** analysis
- This means differential equations for the energy storage components

Inductors



$$V_L(t) = L\frac{di(t)}{dt}$$

Often this is more usefully stated in the integral form

$$i(t_2) - i(t_1) = \frac{1}{L}\int_{t_1}^{t_2} V_L(t)\,dt$$

This leads to the "Voltage–time area rule"

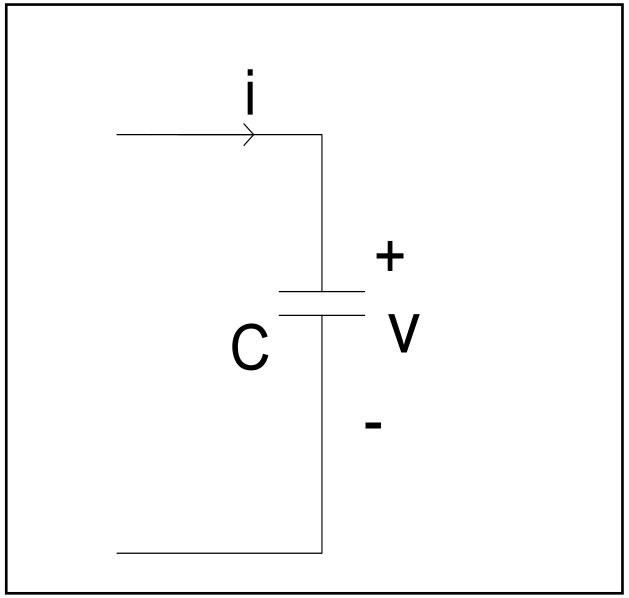
Change in current = (area under voltage versus time curve)/Inductance

$$\Delta I = \frac{VTA}{L}$$

Shorthand for Voltage-Time-Area

We will use this "rule" extensively in analysing power electronic circuits

Capacitors



$$i_C(t) = C\frac{dv(t)}{dt}$$

Often this is more usefully stated in the integral form

$$v(t_2) - v(t_1) = \frac{1}{C}\int_{t_1}^{t_2} i_C(t)dt$$

This leads to the "Current–time area rule"

Change in voltage = (area under current versus time curve)/capacitance

$$\Delta V = \frac{ITA}{C}$$

Shorthand for current-Time-Area

We will use this "rule" extensively in analysing power electronic circuits

Inductors: Special Case

From before for an inductor we had:

$$i(t_2) - i(t_1) = \frac{1}{L}\int_{t_1}^{t_2} V_L(t)dt$$

If the current at t_2 is equal to the current at t_1 then:

$$i(t_2) - i(t_1) = 0 = \frac{1}{L}\int_{t_1}^{t_2} V_L(t)dt$$

Hence in this case the area under the voltage waveform between t_1 and t_2 is zero and consequently the **average voltage** across the inductor between t_1 and t_2 is zero.

This situation is very common in power electronic circuits where the inductor current varies periodically and is identical in shape from one period to the next. Under such conditions, the average voltage across the inductor taken over one period is zero.

This is an **IMPORTANT RESULT** which we will use again and again.

Capacitors: Special Case

From before for an capacitor we had:

$$v(t_2) - v(t_1) = \frac{1}{C}\int_{t_1}^{t_2} i_C(t)dt$$

If the voltage at t_2 is equal to the voltage at t_1 then:

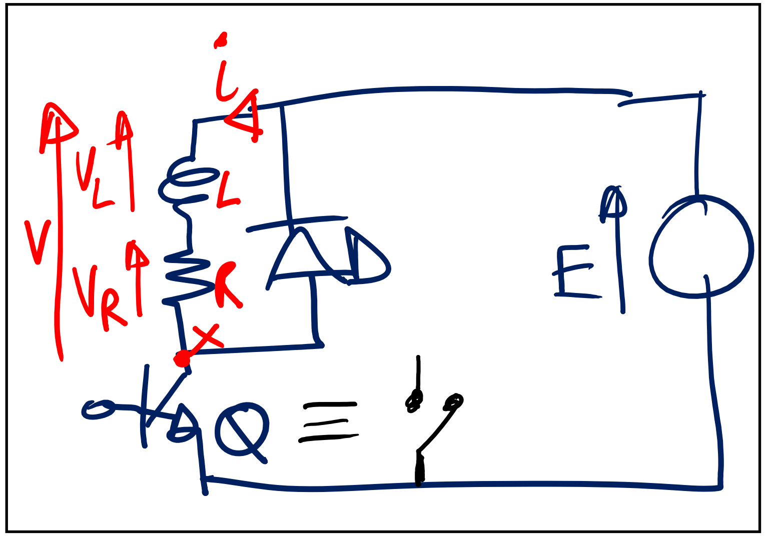
$$v(t_2) - v(t_1) = 0 = \frac{1}{C}\int_{t_1}^{t_2} i_C(t)dt$$

Hence in this case the area under the current waveform between t_1 and t_2 is zero and consequently the **average current** through the capacitor between t_1 and t_2 is zero.

This situation is very common in power electronic circuits where the capacitor voltage varies periodically and is identical in shape from one period to the next. Under such conditions, the average current through the capacitor taken over one period is zero.

This is an **IMPORTANT RESULT** which we will use again and again.

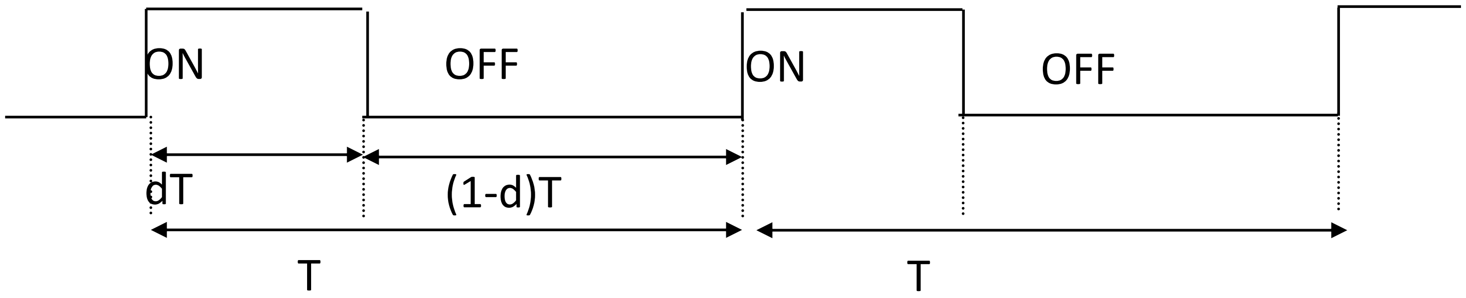
Commutation(1)



Consider a simple circuit

Note: The “base drive circuit” is not shown, but we assume that such a circuit is there to turn the transistor ON and OFF upon command from a control circuit of some kind (also not shown).

Q is operated as follows:



$T \rightarrow$ Switching period, $1/T \rightarrow$ Switching frequency

$d \rightarrow$ Duty cycle ($0 \leq d \leq 1$) – often quoted as a %

Normally T is kept constant and d is varied by the controller to control the current in R and L (representing a load of some sort)

Commutation(2)

CIRCUIT OPERATION

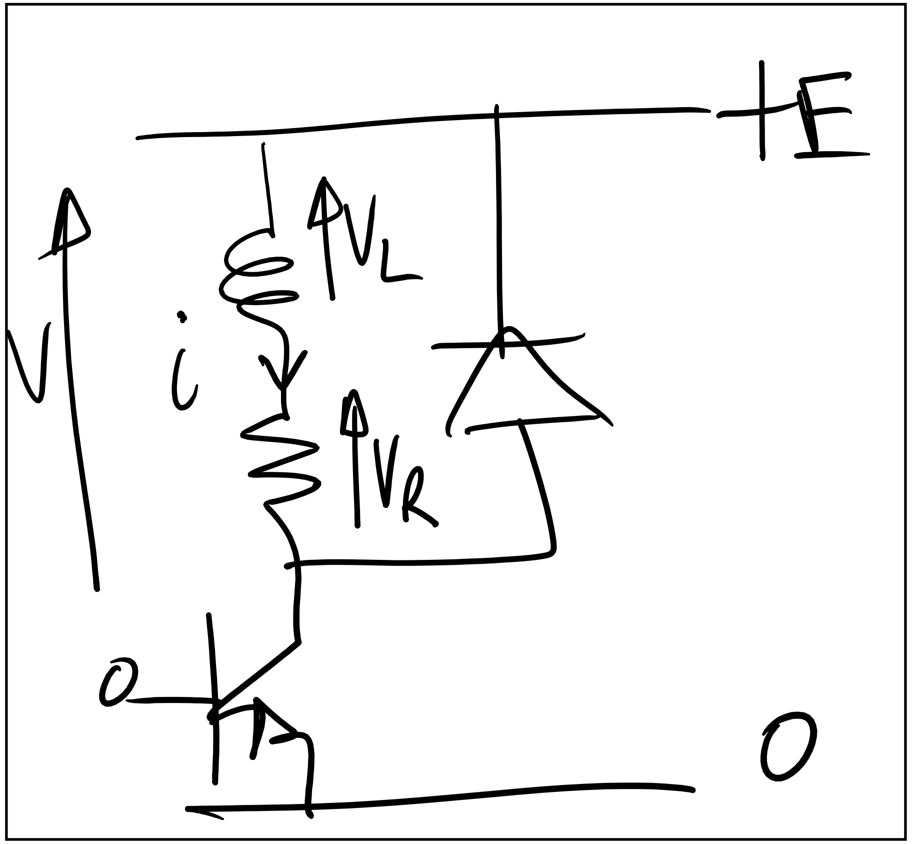
- Assume initially i = 0
- When Q is first turned ON, V = E and i increases exponentially (with time constant L/R)
- When Q is turned OFF i tries to decay
- The voltage across the inductor reverses polarity (remember V=Ldi/dt and di/dt is now negative)
- If there was no diode in the circuit, the voltage across the inductor would reach a very large value and so would the voltage at point X
  - then either Q blows up, or L blows up
- With the diode in the circuit, the voltage at point X rises to E then D turns ON, “clamping” the voltage at X to E
- Current now flows through R, L and D
- We say the current has **commutated** from Q to D

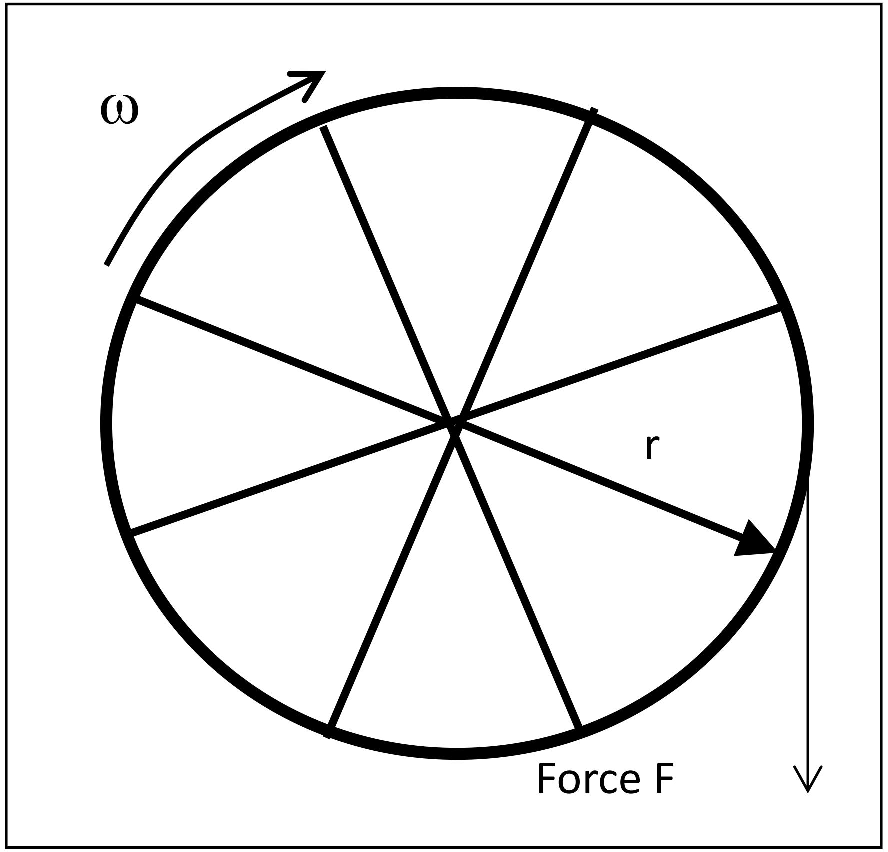
Commutation(3)

CIRCUIT OPERATION Cont

- Current flows through R, L and D driven by the ENERGY STORED IN L
  - This is called "**freewheeling**" (analogy between inductors and flywheels) - D is called a "**freewheel diode**"
- Current amplitude decays exponentially as the energy in the inductor is used up (dissipated in R)
- Assume Q is turned back ON before the current decays completely to zero
- When Q is turned ON again, the current transfers back to Q (commutates) and the process repeats
- Commutation takes place very quickly (typically 10ns for low power devices to 10μs for very large devices)
- We will assume commutation is instantaneous for analysing circuits.

Freewheeling: Mechanical Analogy (1)

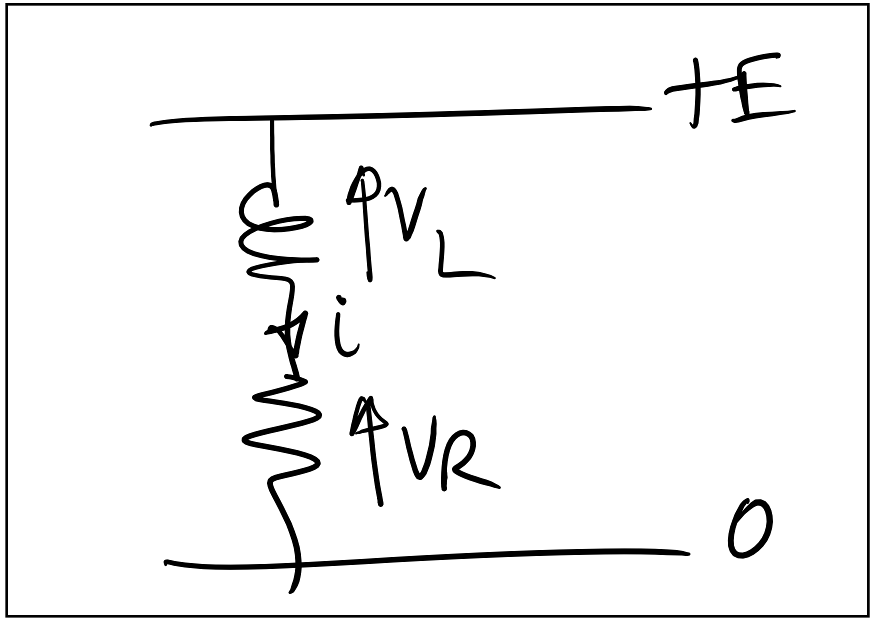




- Power Electronic Circuit
- Assume ideal Q and D

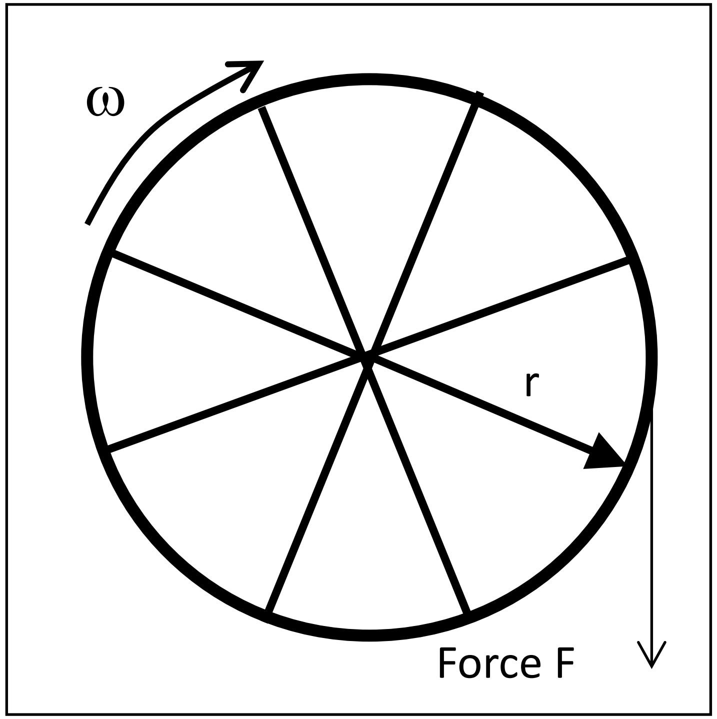
- Bicycle wheel
- Inertia J
- Friction B
- Torque T = F*r
- Angular velocity ω

Freewheeling: Mechanical Analogy (2)



- Q ON, D OFF
- Equivalent circuit
- Equation

$$E = L\frac{di}{dt} + Ri$$

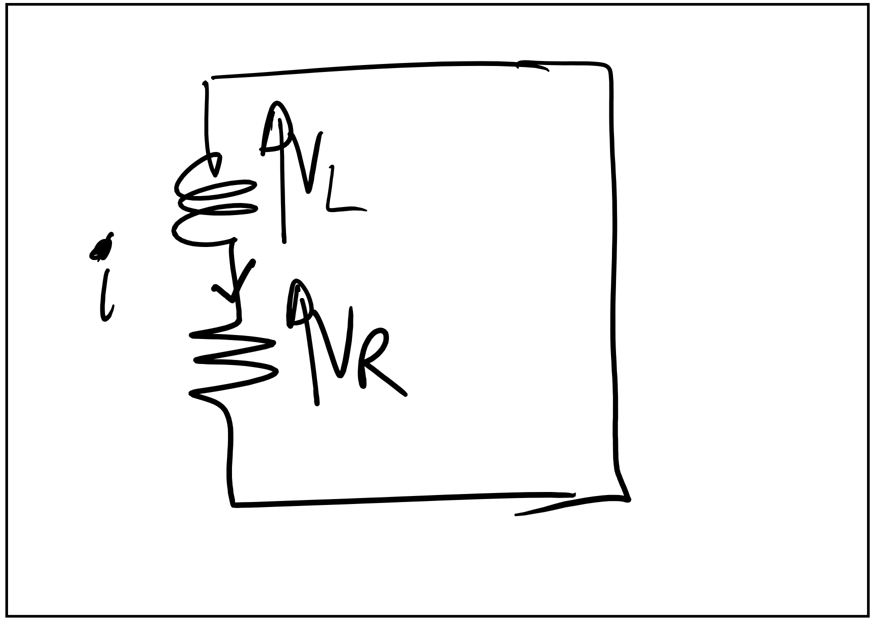


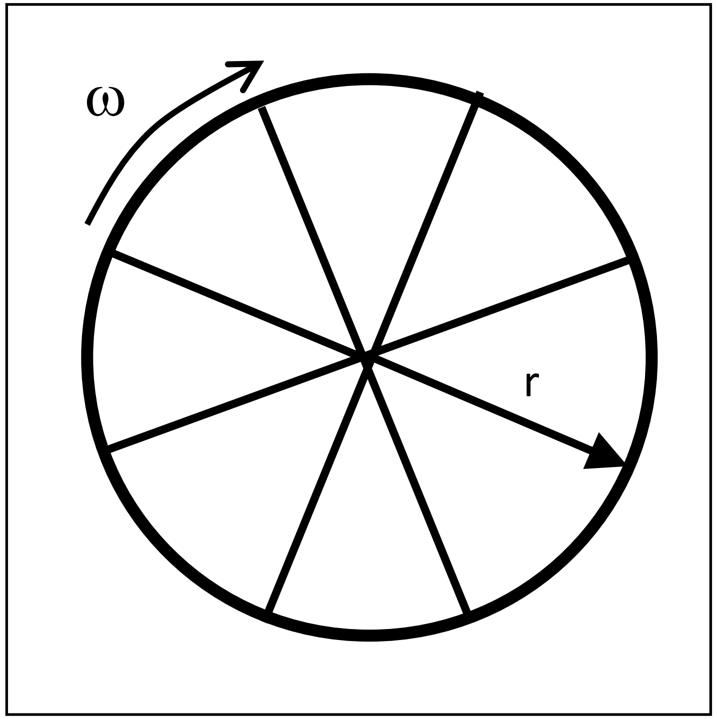
- Wheel with force applied
- Equation

$$\text{Torque} = J\frac{d\omega}{dt} + B\omega$$

$$L \equiv J \quad B \equiv R$$
$$i \equiv \omega \quad E \equiv \text{TORQUE}$$

Freewheeling: Mechanical Analogy (3)





- Q OFF, D ON
- Equivalent circuit
- Equation

$$0 = L\,di/dt + Ri$$

- Wheel with no force applied (freewheeling)
- Equation

$$0 = J\frac{d\omega}{dt} + B\omega$$

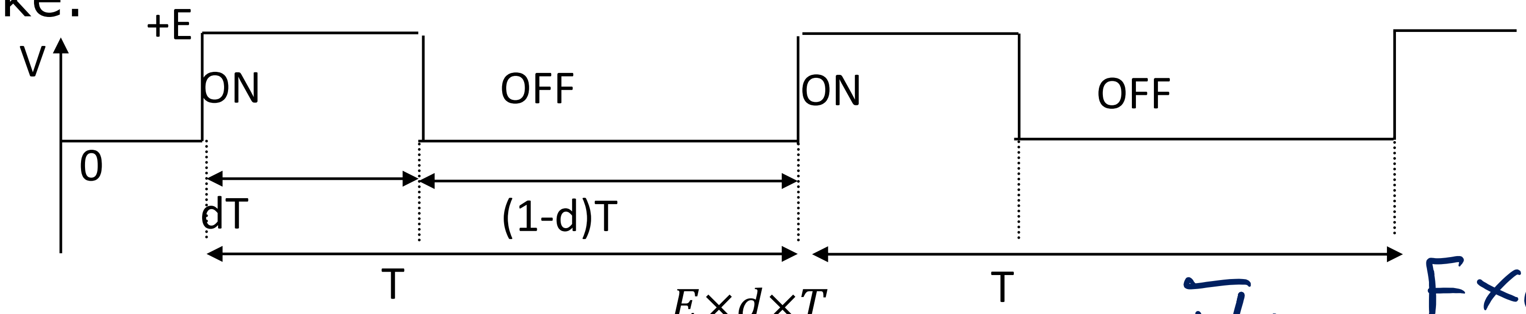
Freewheeling: Mechanical Analogy (4)

- Bicycle Wheel
  - Apply force $\rightarrow \omega$ increases
  - Energy is stored in the wheel's rotation = $1/2J\ \omega^2$
  - Remove force – wheel "freewheels"
  - Wheel continues to rotate because of stored kinetic energy
  - Speed reduces due to energy loss due to friction
  - If no further force is applied eventually it will stop
- Our Power Electronic Circuit
  - Turn ON Q $\rightarrow$ apply voltage to load $\rightarrow$ current increases
  - Energy is stored in the magnetic field in the inductor = $1/2Li^2$
  - Turn Q OFF – D turns ON $\rightarrow$ zero voltage across load
  - Current continues to flow because of stored energy in L
  - Current reduces due to the energy being lost in the resistor
  - If Q is not turned ON again, eventually the current will fall to zero

Steady state operation (1)

In the previous circuit the voltage across the load (R and L) will look like:

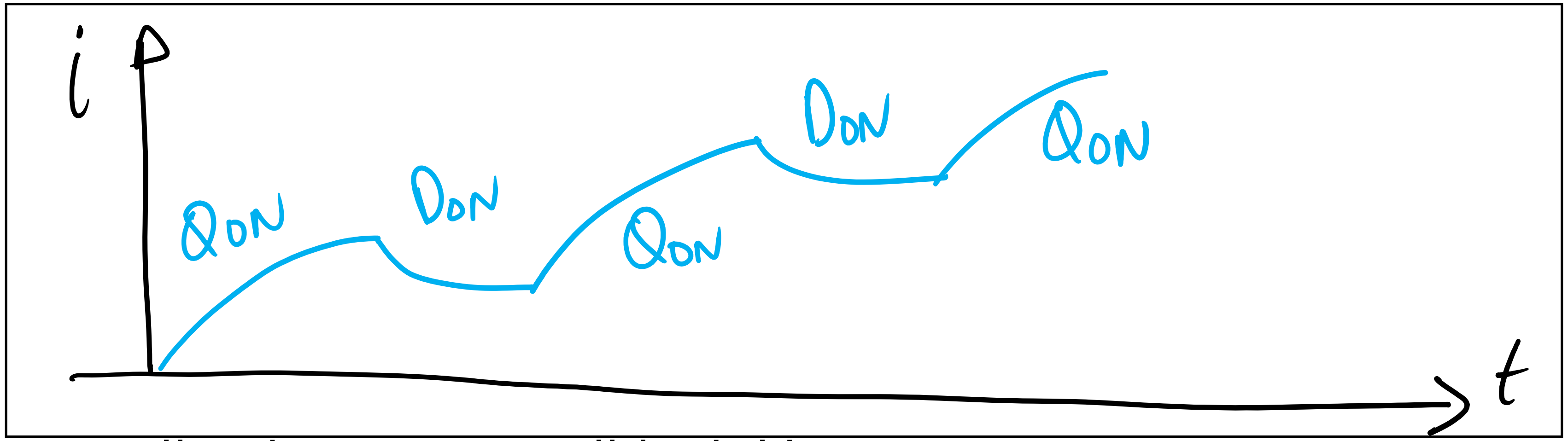
V



$$AVERAGE = AREA/PERIOD \Rightarrow \bar{V} = \frac{E\times d\times T}{T} = Ed$$

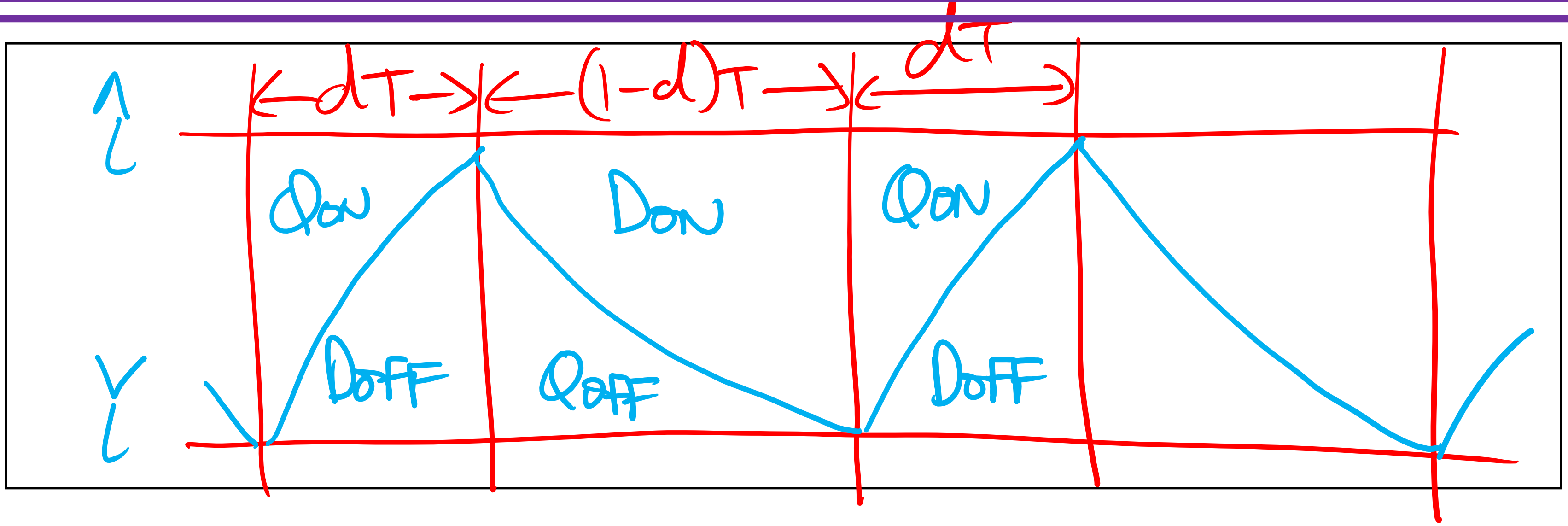
$$\bar{V} = \frac{E\times d\times T}{T} = Ed$$

Its just a bigger (assuming E is big) version of the base drive waveform. The current will look something like:



Eventually, the current will look like..................

Steady state operation (2)



Eventually, the current falls into a regular pattern where the energy stored in the inductor when Q is ON exactly matches the energy lost when D is ON

$\hat{i} \equiv$ "i HAT" $\qquad \check{i} \equiv$ "i TROUGH"

This is what we call **STEADY STATE OPERATION** for this type of circuit. Note that the inductor current returns to the same value at the start of each switching period – therefore the **AVERAGE VALUE OF THE INDUCTOR VOLTAGE IS ZERO**

Steady state operation (3)

Can we calculate the average value of the load current in the previous circuit in the steady state?

Hard way → find equations defining the current trajectories + lots of pages of algebra!!

Easy way → use the fact that the average voltage across the inductor is zero:

$$V(t) = V_L(t) + V_R(t) \quad \rightarrow \quad \overline{V} = \overline{V_L} + \overline{V_R} \rightarrow \overline{V_R} = \overline{V}$$

$$\rightarrow \bar{i} = \overline{V_R} / R = \overline{V} / R$$

We know the waveform of *V(t)* and can find its average easily:

$$\overline{V} = dET / T = dE \rightarrow \bar{i} = dE / R$$

With this simple circuit we can control the current in an inductive load by varying the duty cycle and there is no power loss (except in the load!)

Exactly the same idea is used, for example, in many electric railway locomotives, disc drive motor controllers and many other applications.

Steady state operation (4)

Definition of steady state operation for any circuit with a periodic switching action

- For any inductor in the circuit, the value of the **current** in that inductor will be the same at the start of each and every switching cycle
- For any capacitor in the circuit, the value of the **voltage** across that capacitor will be the same at the start of each and every switching cycle

HENCE IN THE STEADY STATE

- The **average voltage** across every inductor in the circuit is **zero**
- The **average current** through every capacitor in the circuit is **zero**

IN THIS COURSE WE WILL ONLY DEAL WITH CIRCUITS IN THE STEADY STATE (USING THE ABOVE DEFINITION)

Four “Rules”

From the previous discussion, we will apply the following 4 rules to circuits that we analyse:

- ΔI = voltage time area/inductance (VTA/L)
- ΔV = current time area/capacitance (ITA/C)

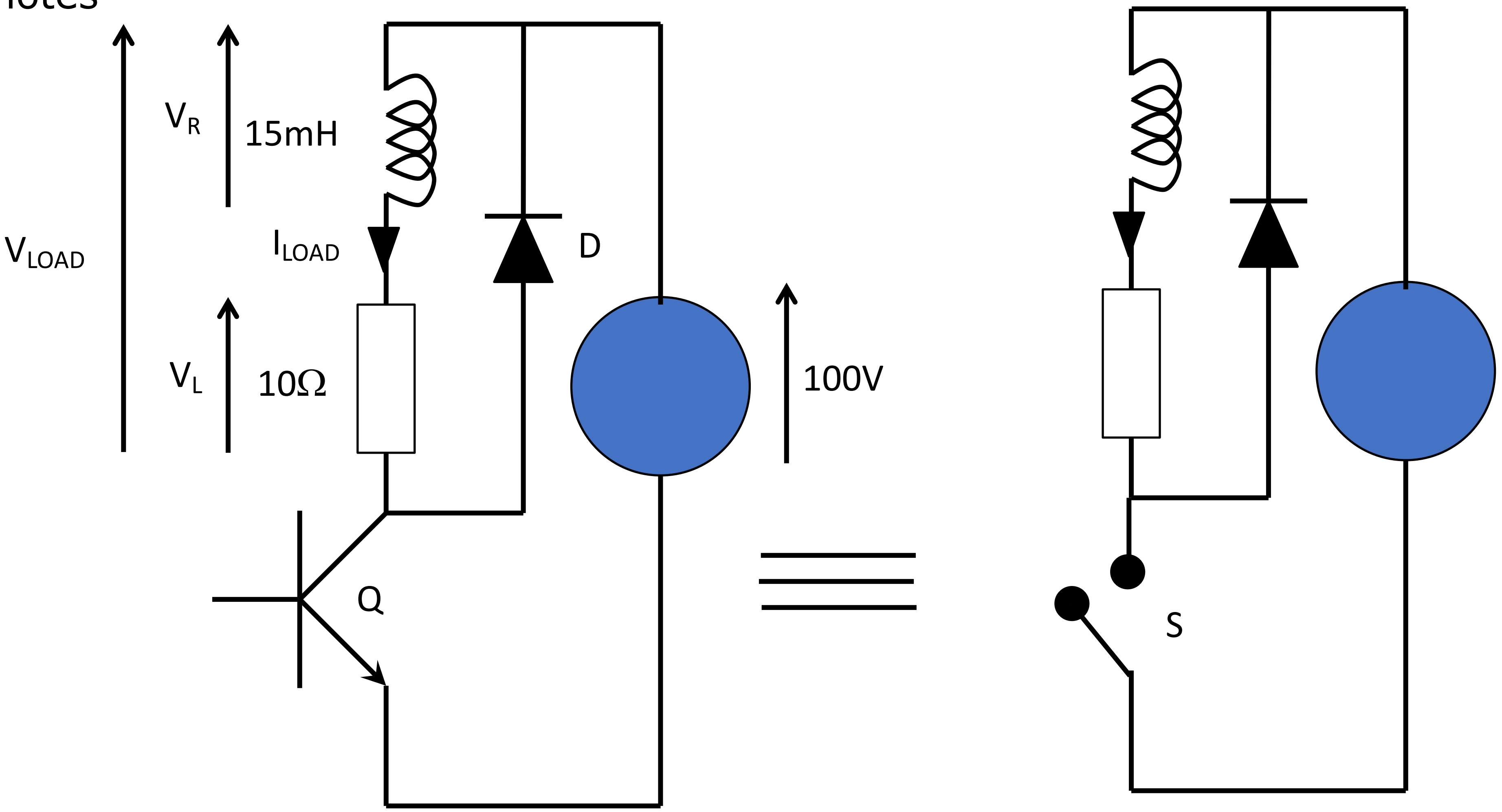
and for a circuit with a periodic switching action (most circuits we look at)

- Average voltage across all inductors (taken over a period) = zero
- Average current through all capacitors (taken over a period) = zero

You **MUST** understand and remember what is on this page!!

Example Circuit – more explanation

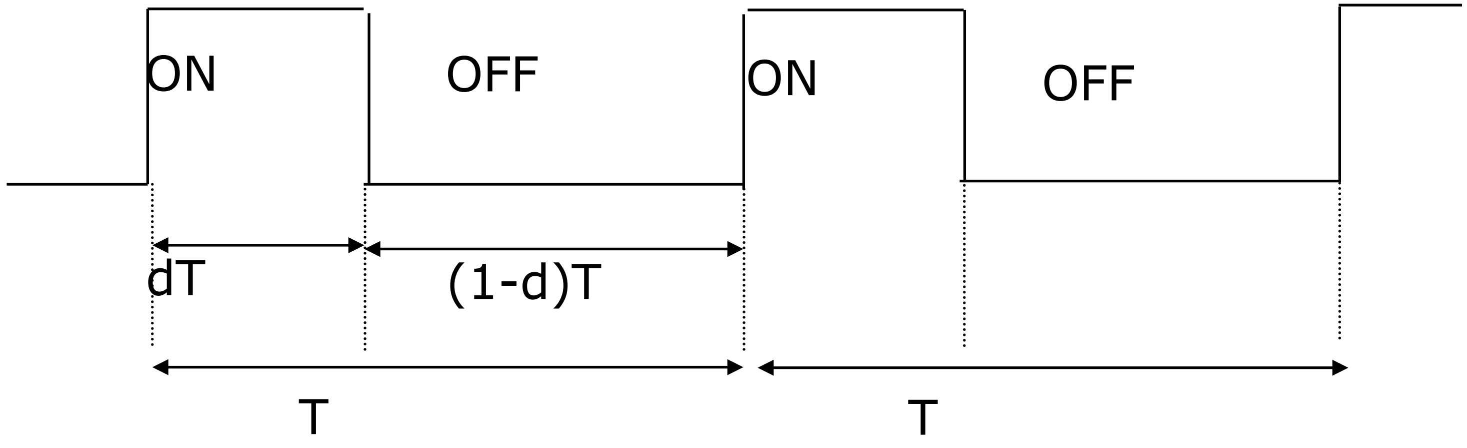
Consider a specific example of the circuit we looked at in the introductory notes



Purpose of the circuit is to control the average current in the load by switching Q

Example Circuit

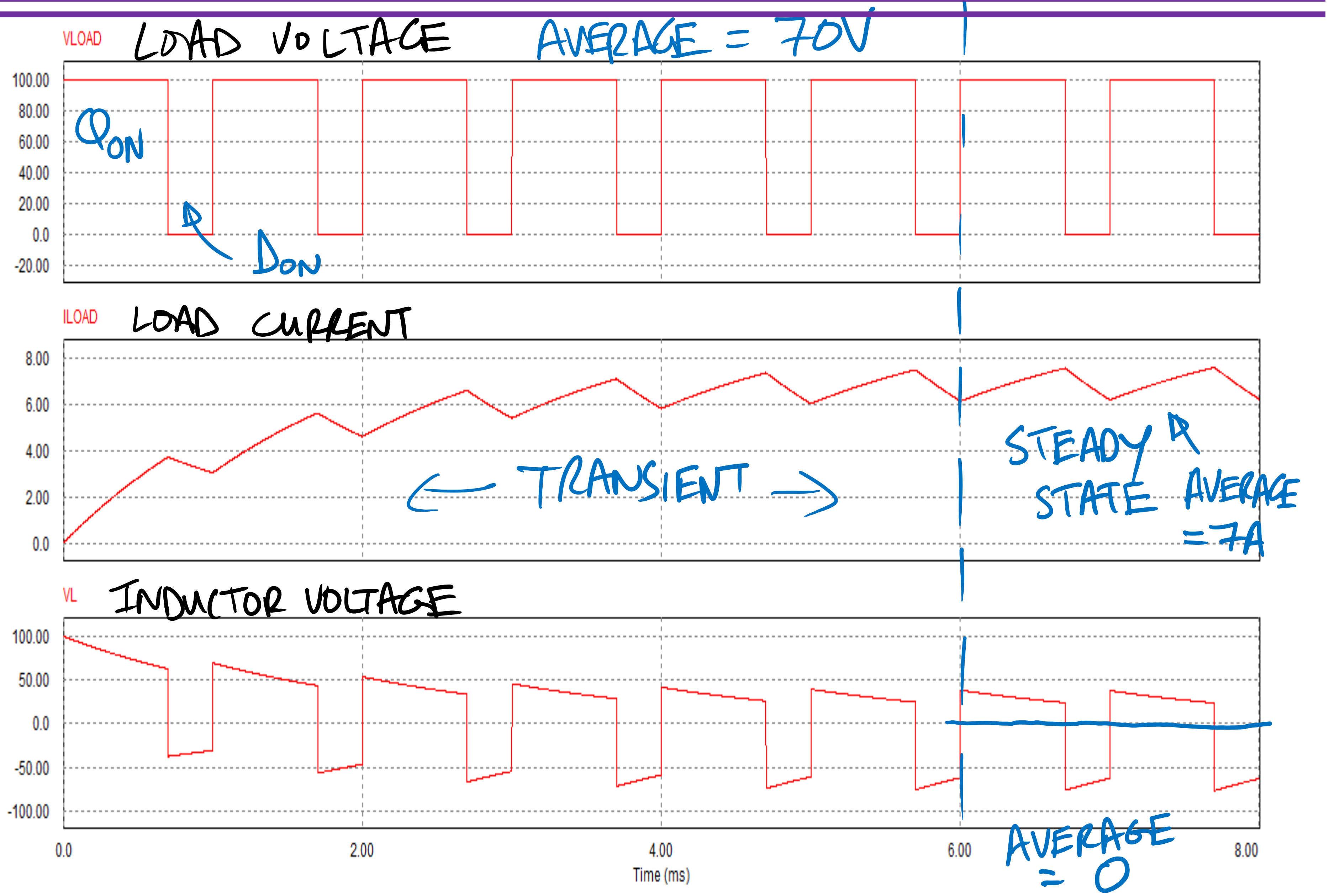
In order to control the current, Q is switched at a constant frequency and with variable duty cycle (d) as we discussed before



In the simulation results that follow, T is set to 1ms (f = 1kHz)

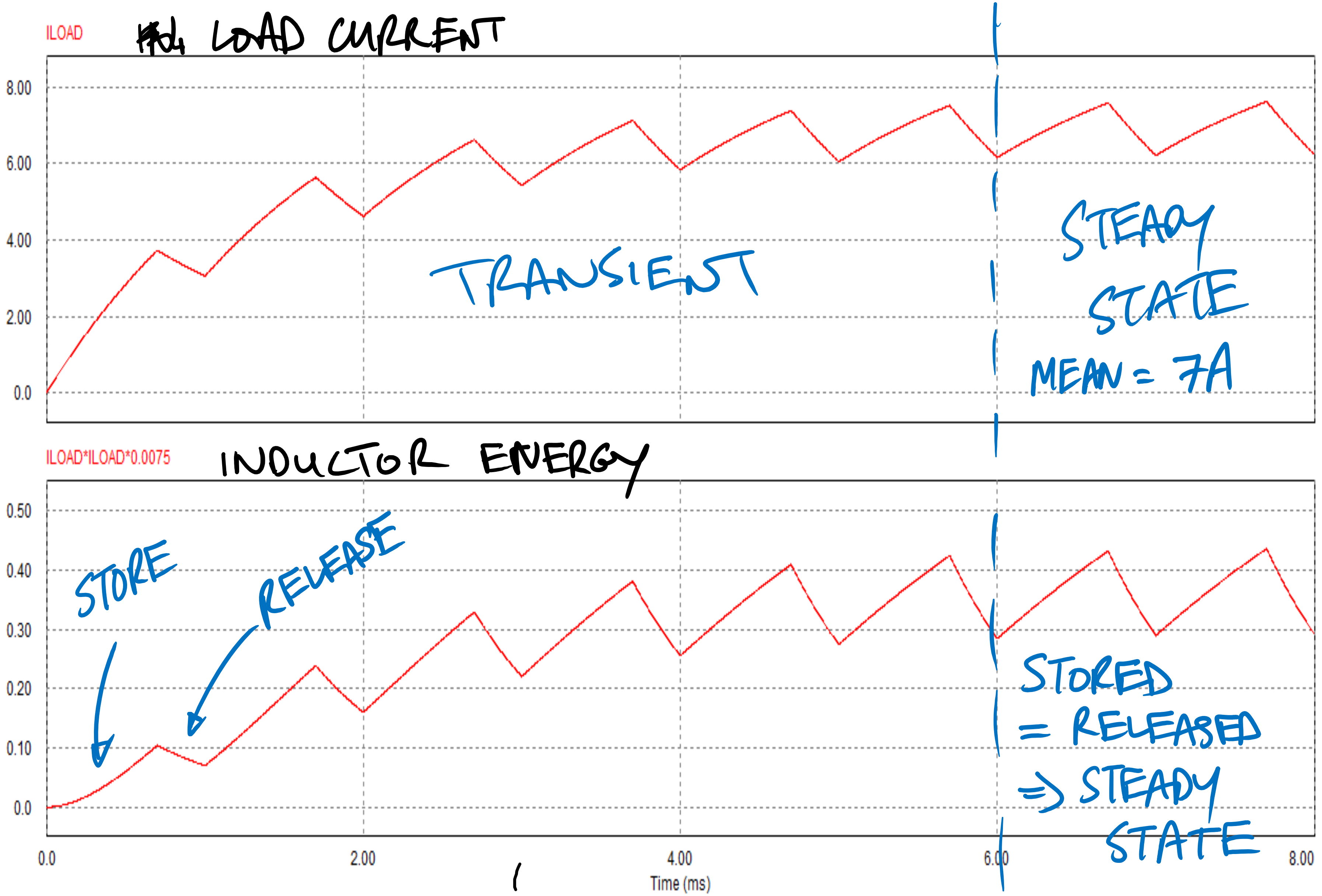
d is set to 0.7 (70%) for the first set of results and to 0.3 (30%) for the second set

Sim

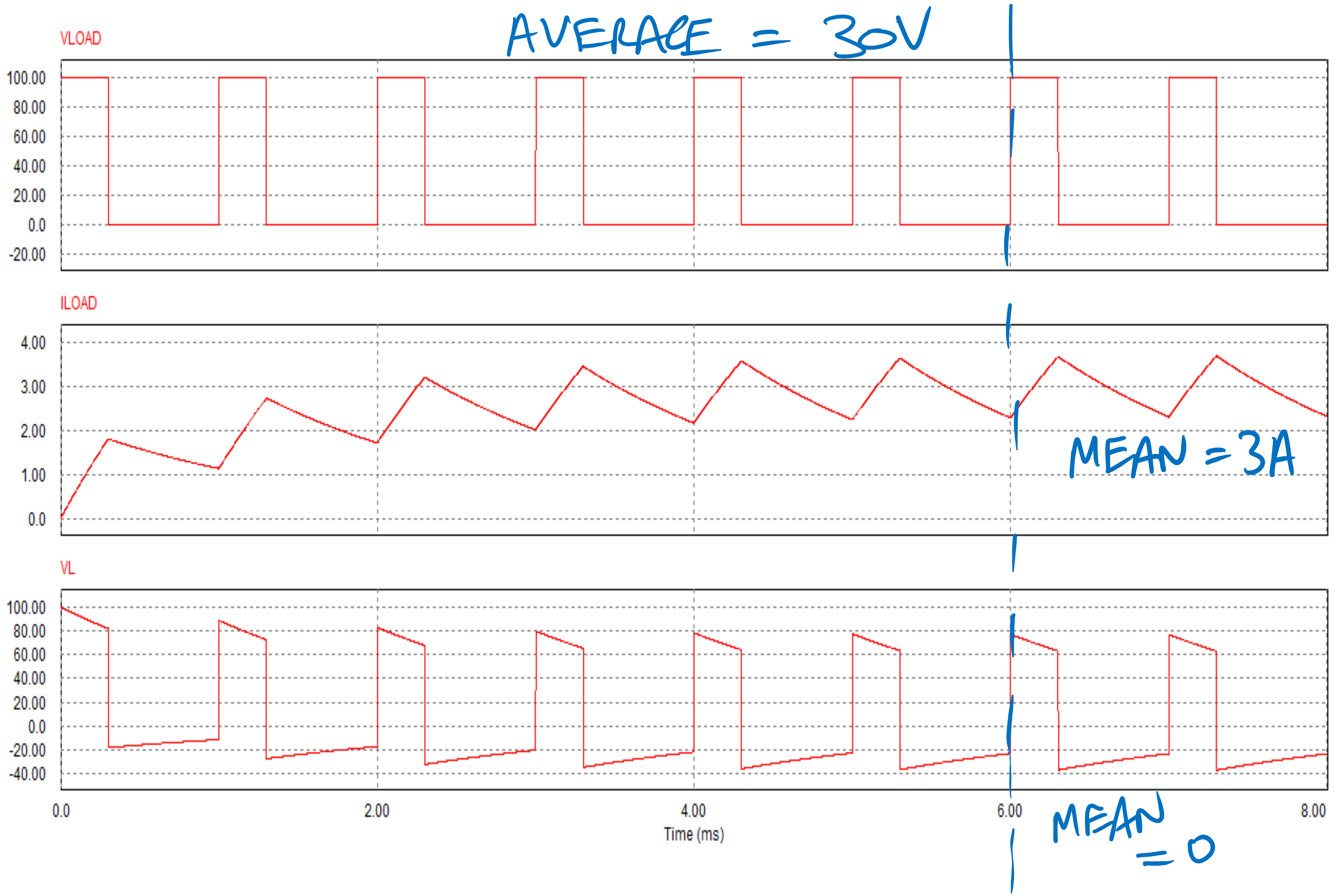


VLOAD
LOAD VOLTAGE
AVERAGE = 70V
100.00
80.00
60.00
40.00
20.00
0.0
-20.00
Q_{ON}
D_{ON}
ILOAD
LOAD CURRENT
8.00
6.00
4.00
2.00
0.0
← TRANSIENT →
STEADY STATE
AVERAGE = 7A
VL
INDUCTOR VOLTAGE
100.00
50.00
0.0
-50.00
-100.00
0.0
2.00
4.00
6.00
8.00
Time (ms)
AVERAGE = 0

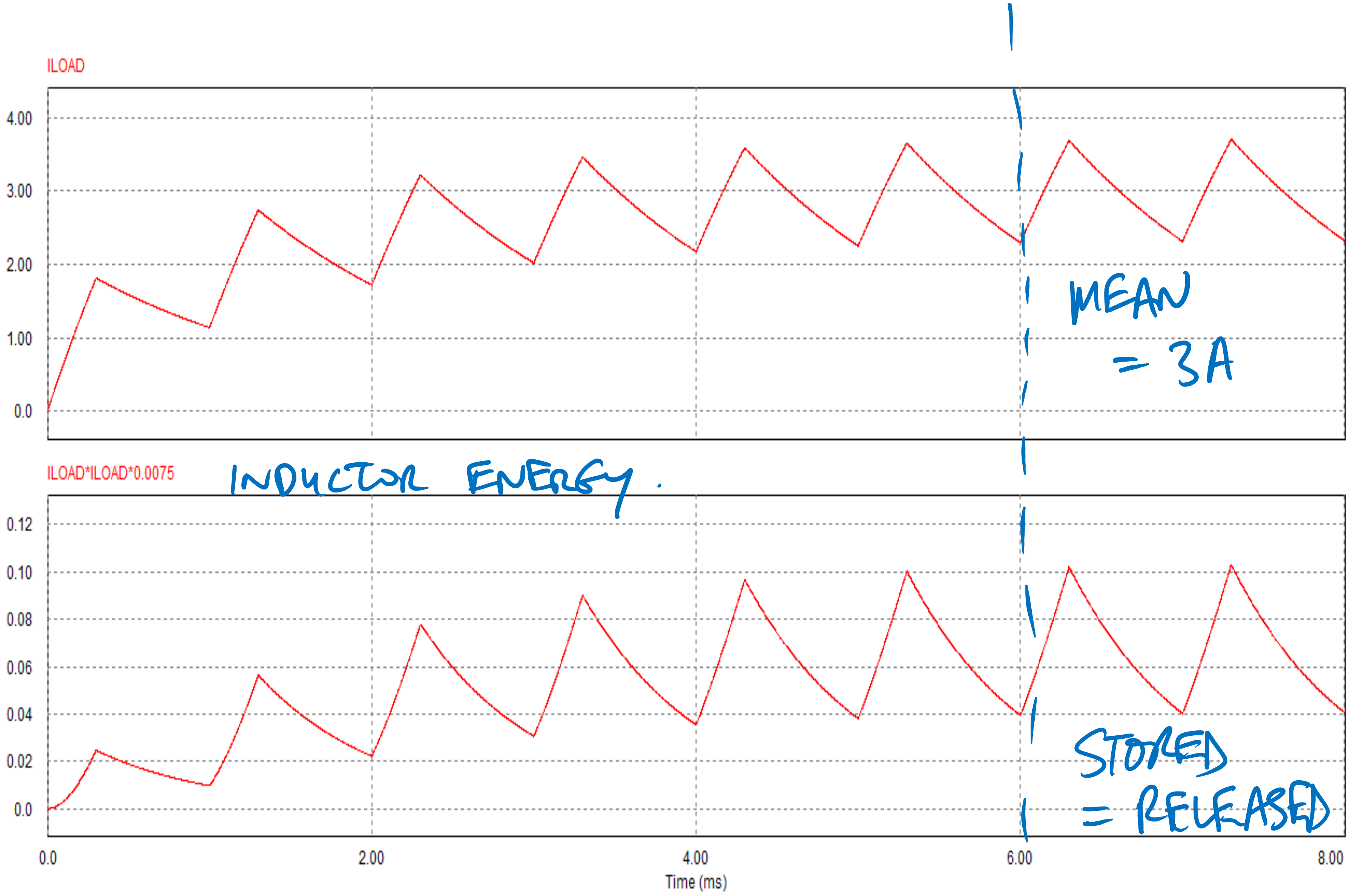
Simulation Results: d=0.7



Simulation Results: d=0.3



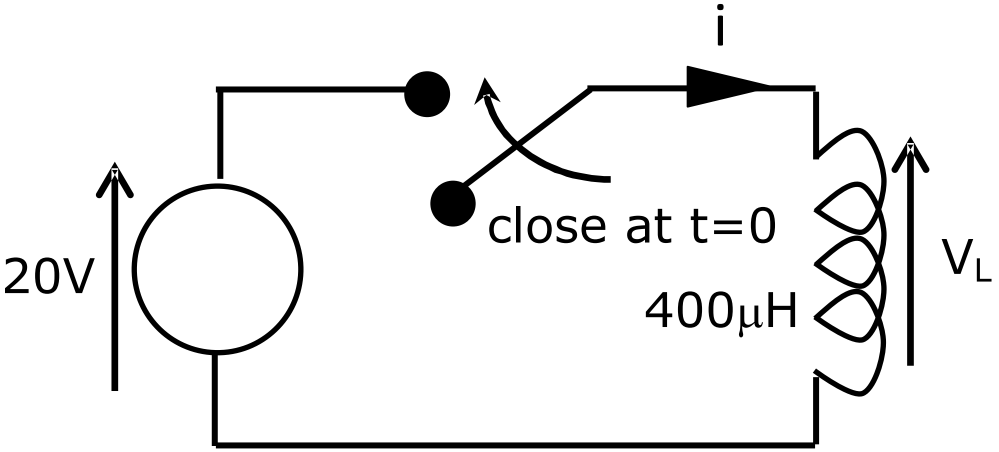
Simulation Results: d=0.3



Comments on simulation results

- In each case the current starts at zero and gradually builds up until the energy stored in the inductor when Q is ON balances the energy lost from the inductor when Q is OFF – this is the equilibrium condition (or steady state condition)
- When we get to the steady state condition, the average voltage across the inductor is zero in each cycle and the current has a regular pattern (i.e. it is the same in every cycle)
- The duty cycle determines the average current when we reach the steady state
  - When d = 0.7, the average current is 7A
  - When d = 0.3, the average current is 3A
  - These values agree with what we expect from the analysis in the introduction
- Even though we did not prove it – the efficiency is 100% - the only power loss in the circuit is in the load
- In this course – for the future – we will only be interested in the steady state operation of the circuits we look at.

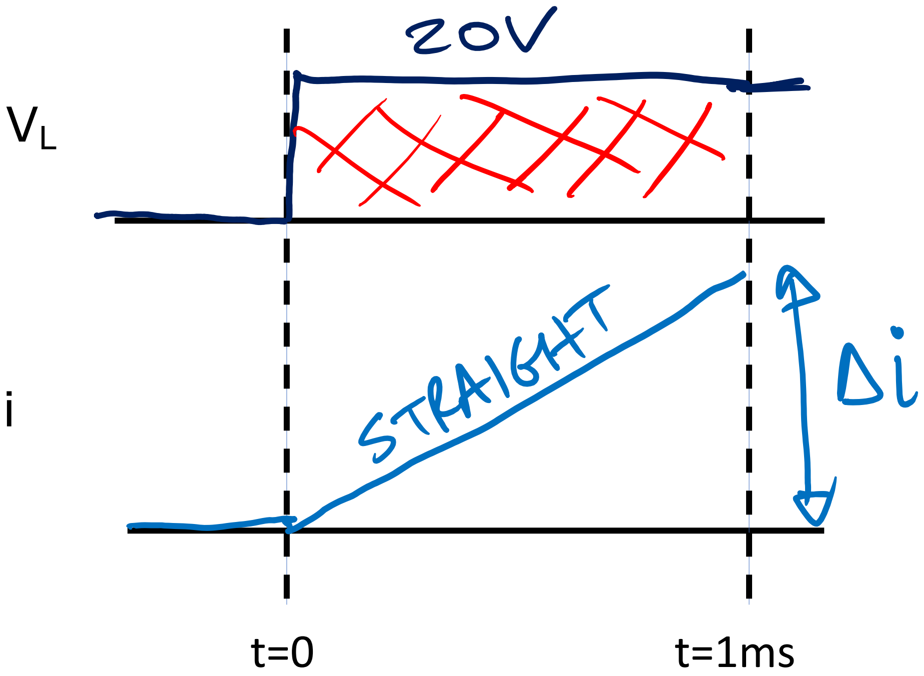
Example 1



$i(0) = 0$

Sketch V_L and i for $0 < t < 1ms$

Determine i (1ms)

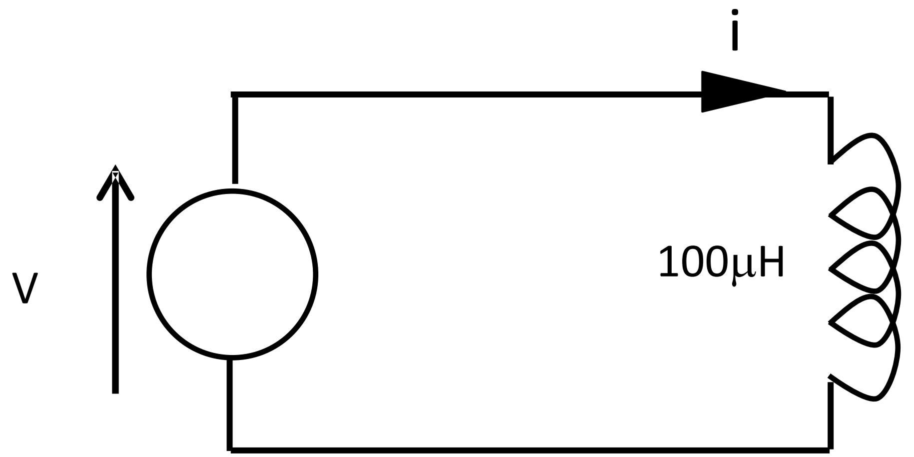


$$\Delta i = \frac{V \Delta T}{L} = \frac{\square}{L}$$

$$= \frac{1000\,\mu s \times 20V}{400\,\mu H}$$

$$= \underline{\underline{50A}} = i(1ms)$$

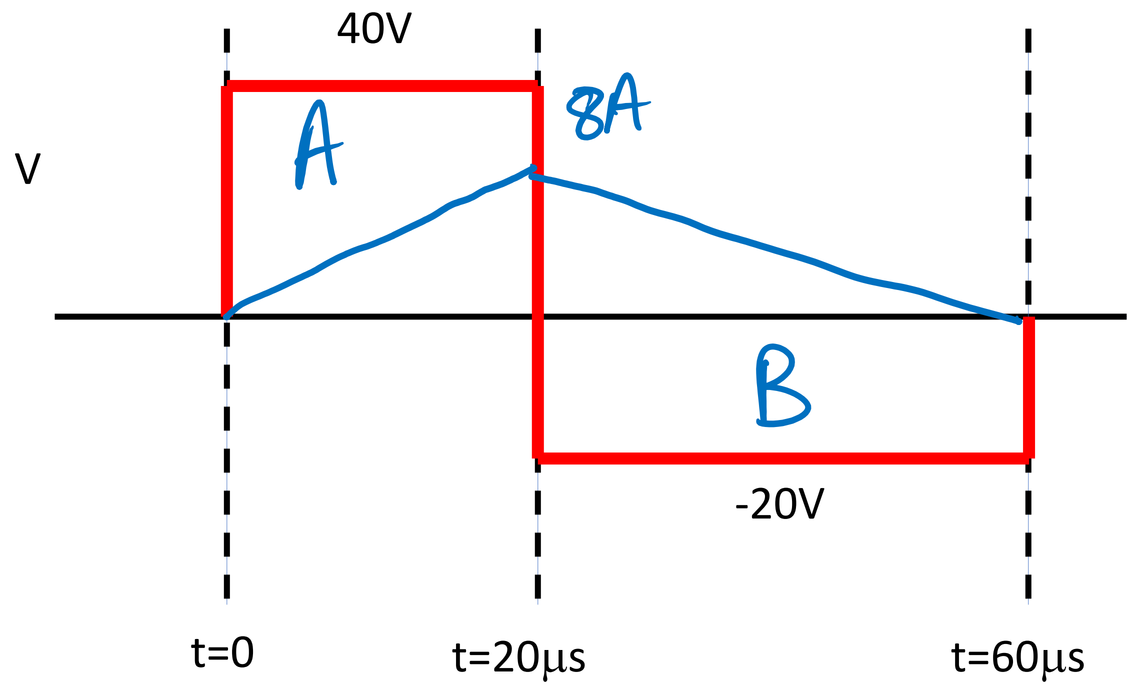
Example 2



$i(0) = 0$

Determine i at t=20μs and i at t=60μs

Sketch i for $0 < t < 60\mu s$



Example 2

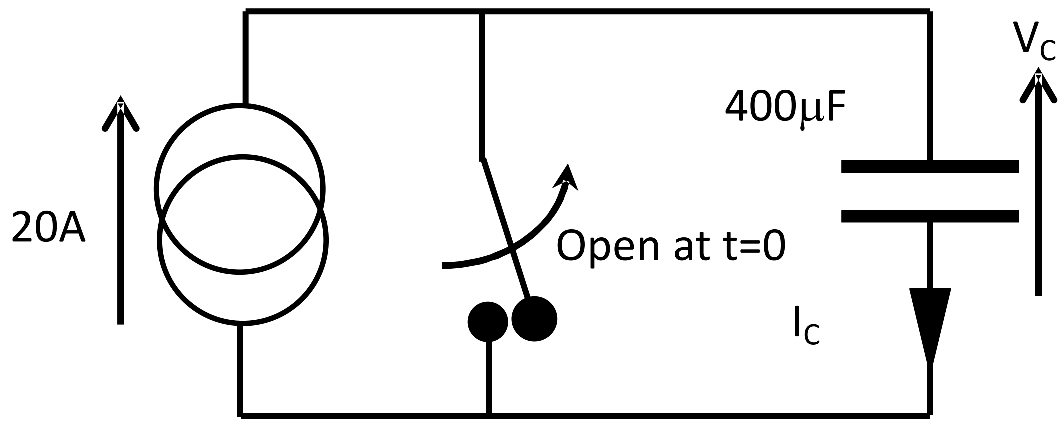
$$i(20\mu s) = \frac{Area\ A}{L} = \frac{40\times 20\mu s}{100\mu H} = 8\ A$$

$$i(60\mu s) = 8A + \frac{Area\ B}{L} = 8 + (-20)\times\frac{40\mu s}{100\mu H} = 8 - 8 = 0\ A$$

Current returns to zero because Area A + Area B = 0

Note $\bar{V}_L = \frac{Area\ A + Area\ B}{60\mu s} = 0$

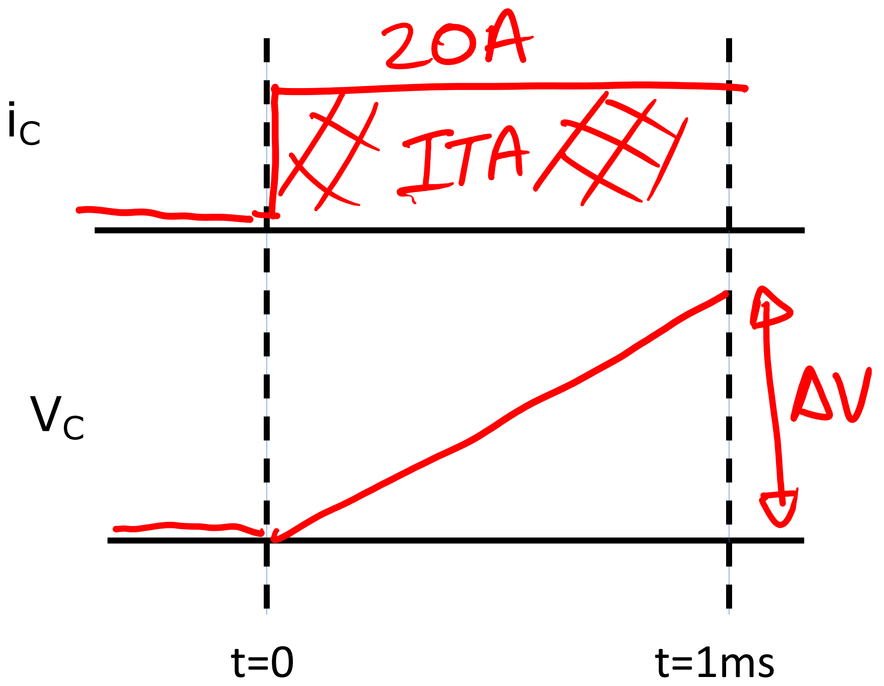
Example 3



$V_C(0) = 0$

Sketch i_C and V_C for $0 < t < 1ms$

Determine V_C (1ms)

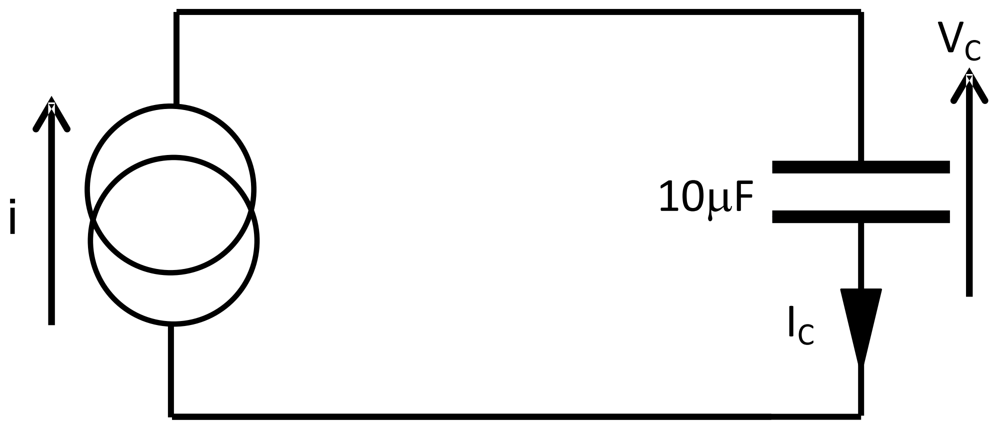


$$\Delta V = \frac{ITA}{C} = \frac{\boxed{\text{XX}}}{C}$$

$$= \frac{1000\,\mu s \times 20A}{400\,\mu F}$$

$$= 50V$$

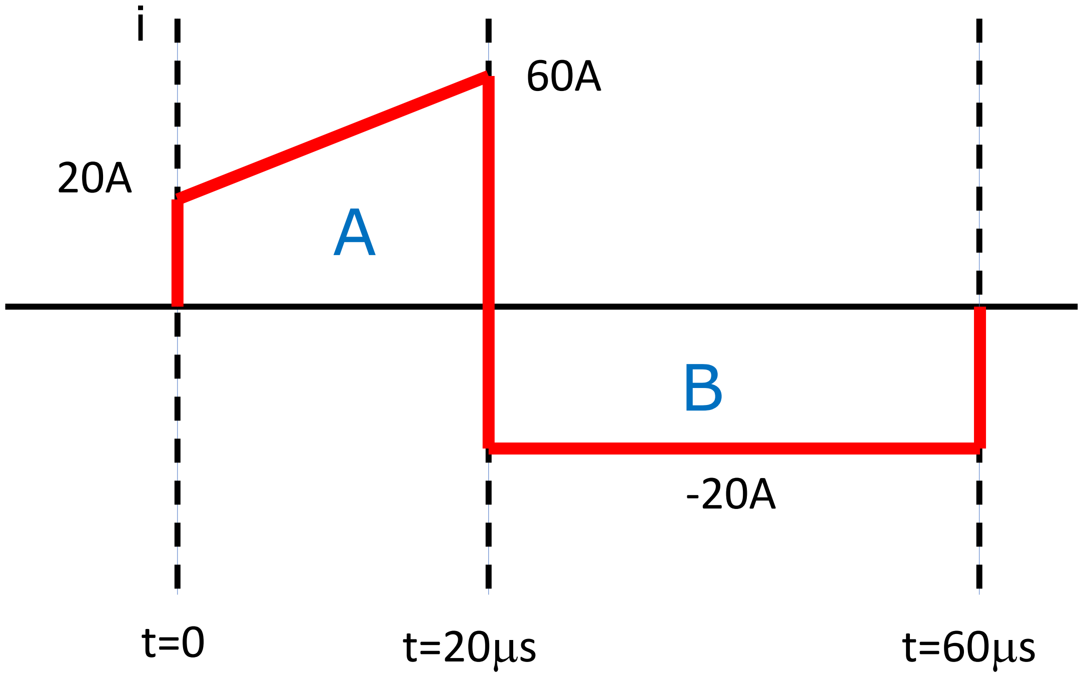
Example 4



$V_C(0) = 0$

Determine V_C at $t=20\mu s$ and V_C at $t=60\mu s$

Sketch V_C for $0 < t < 60\mu s$

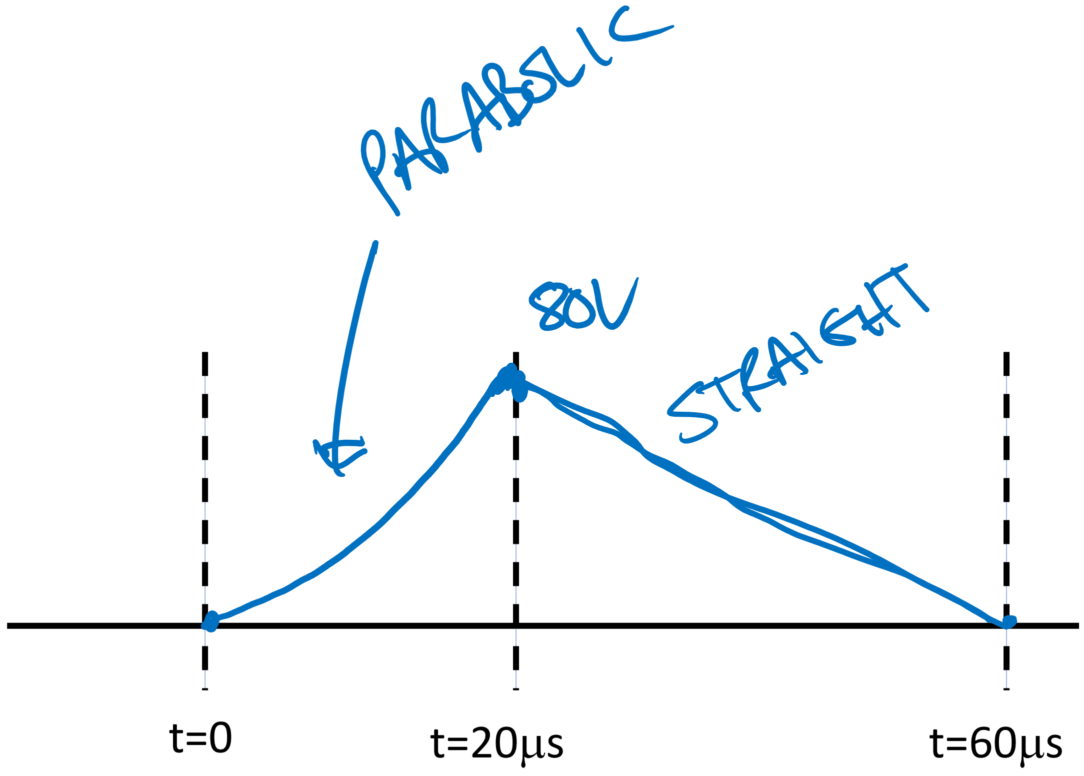


Example 4

$$V(20\mu s) = \frac{\text{Area A}}{C} = \left(\frac{20+60}{2}\right) \times \frac{20\mu s}{10\mu F} = 80V$$

$$V(60\mu s) = V(20\mu s) + \frac{\text{Area B}}{C} = 80 - \frac{20 \times 40\mu s}{10\mu F}$$

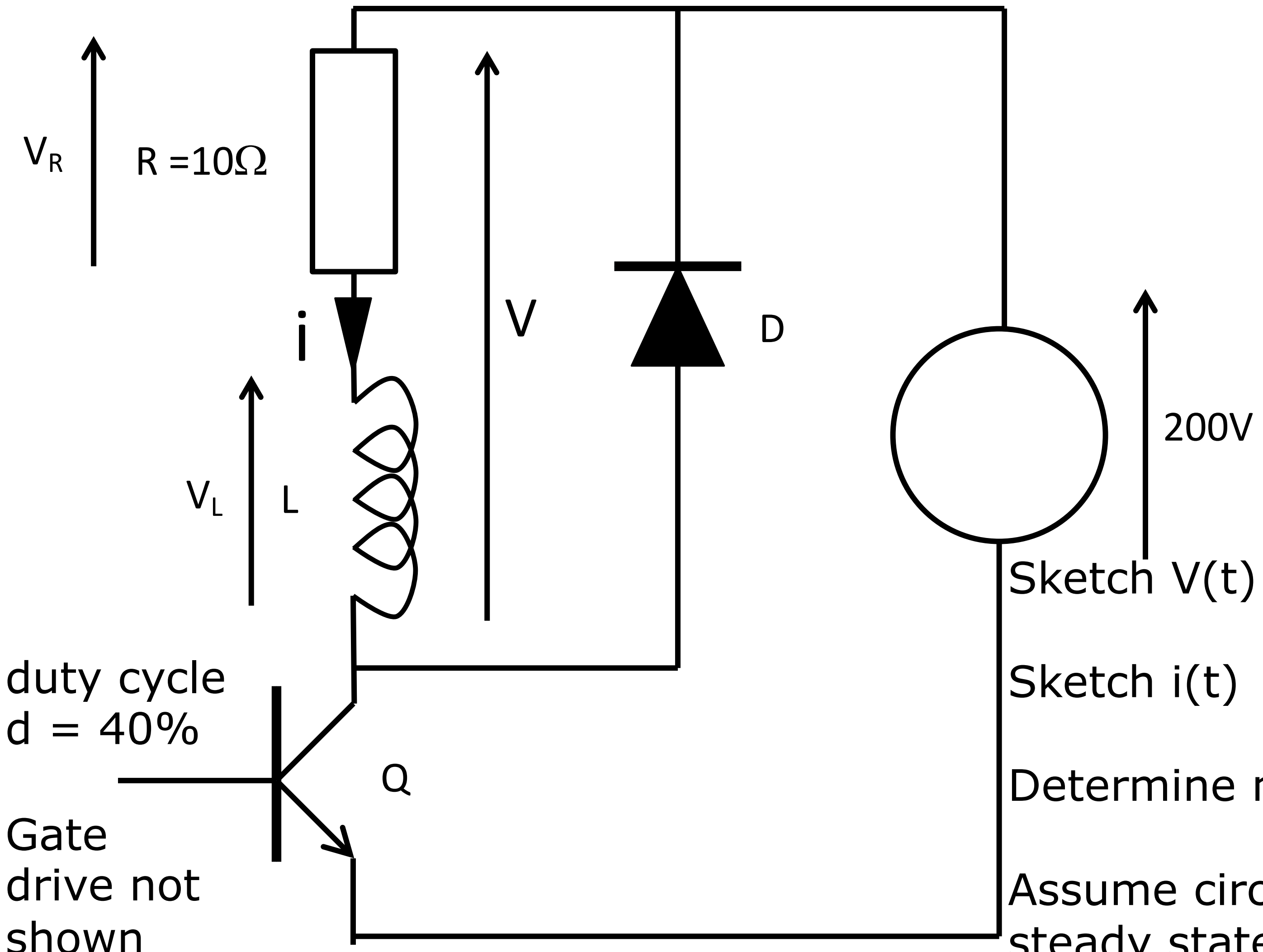
$$= 80 - 80 = \underline{\underline{0V}}$$



$$\text{Area A} + \text{Area B} = 0$$

$$\Rightarrow I = 0$$

Example 5



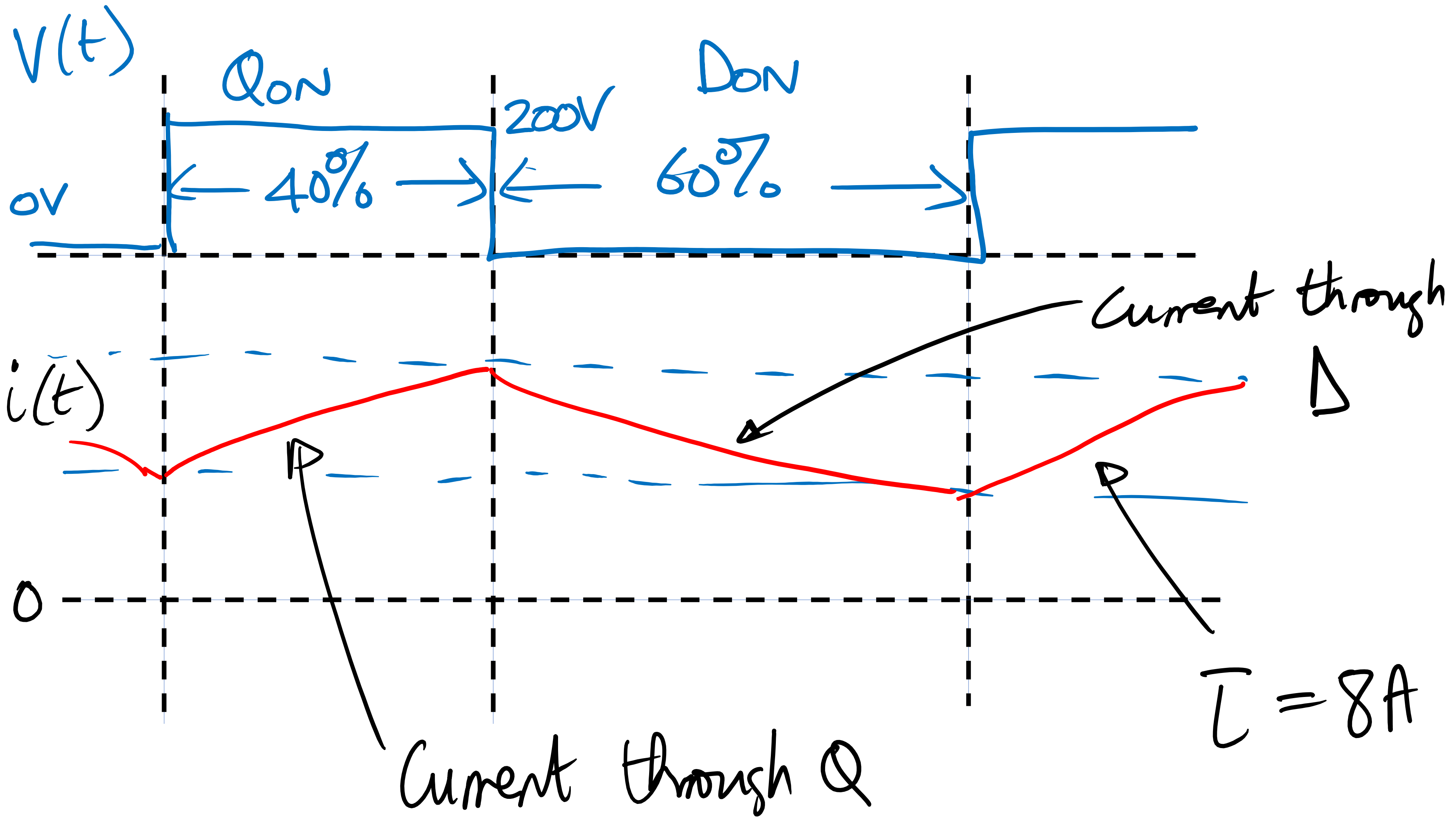
Sketch V(t)

Sketch i(t)

Determine mean value of i

Assume circuit has reached steady state

Example 5



V(t)
Q ON
D ON
200V
0V
40%
60%
i(t)
0
Current through D
Current through Q
I = 8A

Example 5

$$V(t) = V_L(t) + V_R(t)$$

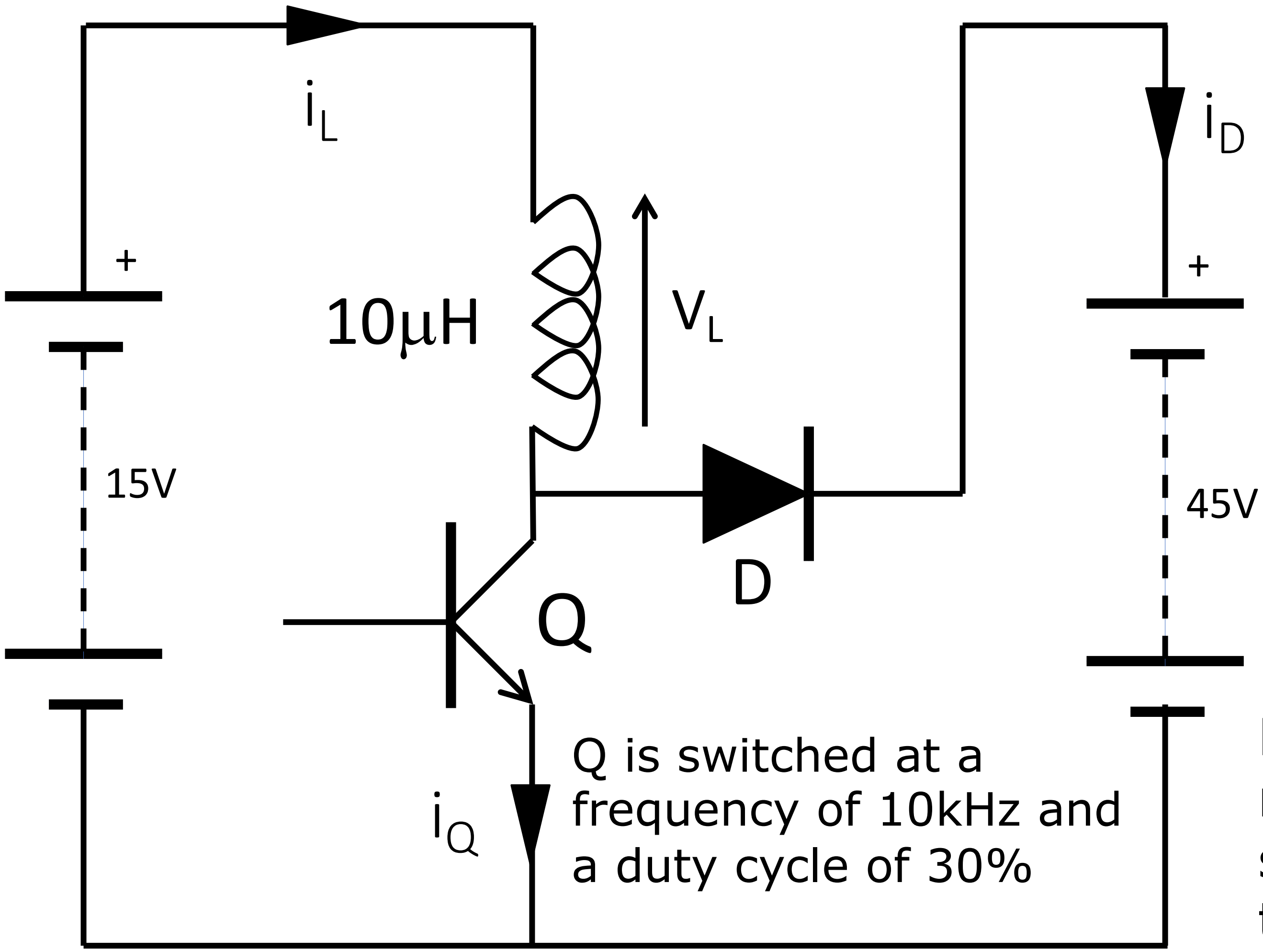
$$\bar{V}(t) = \overline{V_L}(t) + \overline{V_R}(t)$$

$\overline{V_L}(t) = 0$ in steady state

$$\bar{V}(t) = \overline{V_R}(t) = \frac{40}{100} \times 200 = 80\ V$$

$$\bar{\imath}(t) = \frac{80\ V}{10\ \Omega} = 8\ \mathrm{A}$$

Example 6



Q is switched at a frequency of 10kHz and a duty cycle of 30%

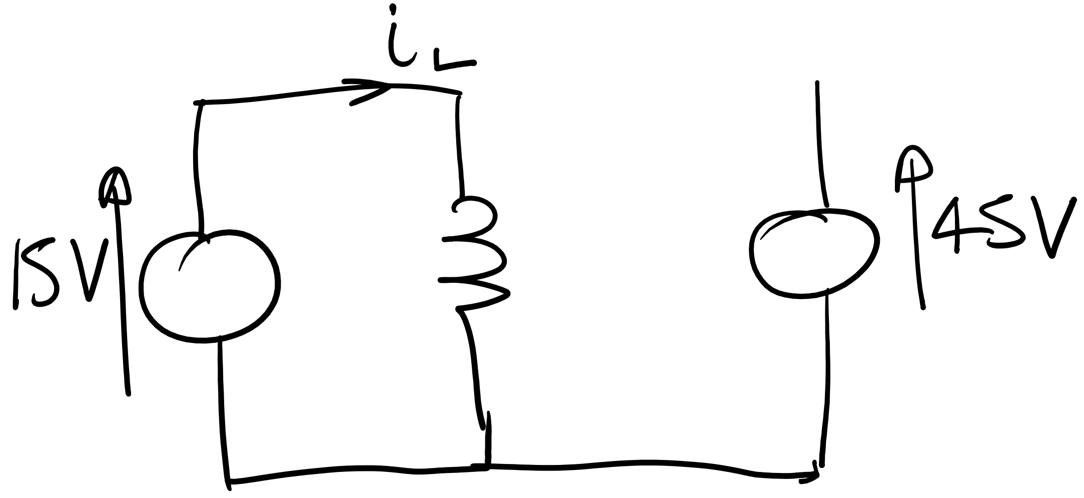
Note – there is no resistor in series with L this time

Sketch V_L, i_L, i_Q and i_D

Explain what the circuit achieves and calculate its efficiency

Example 6

When Q is ON, D is OFF – equivalent circuit is:



i_L increases LINEARLY

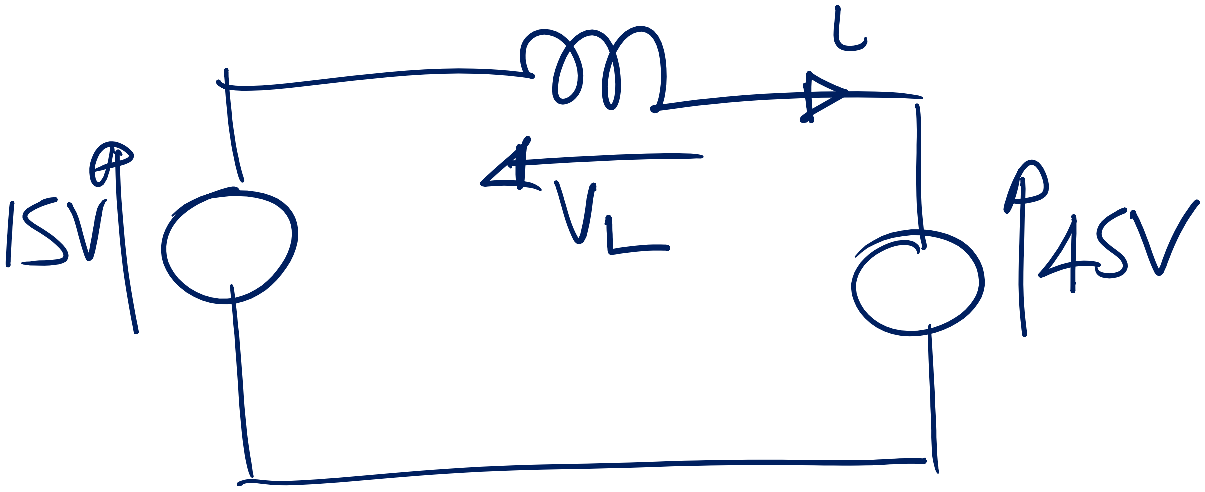
$$\Delta i = \frac{VT_A}{L} = \frac{15 \times \overset{d}{0.3} \times 100\mu S}{10 \times 10^{-6}}$$

ON-TIME FOR Q

$$\Rightarrow \Delta i_L = \underline{\underline{45A}}$$

Example 6

When Q is turned OFF, the current in L commutates to D – equivalent circuit is:



Note i_L flows from the 15V source to the 45V source because of the ENERGY stored in L

$V_L = -30V$

Example 6

$V_L = -30\,V$ ➔ i_L decreases <u>LINEARLY</u>

When it reaches 0 the diode turns off.

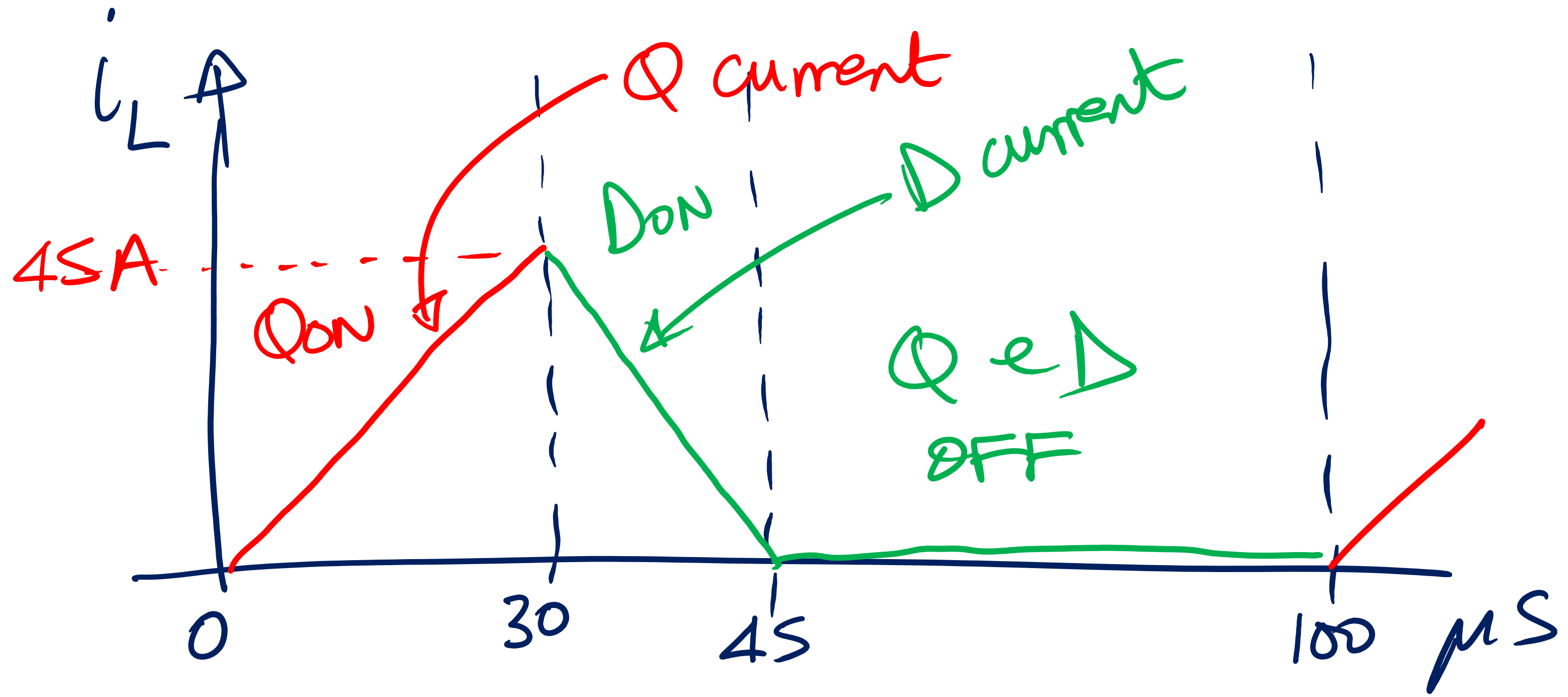
Time to get to 0?

$$\Delta i = \frac{VTA}{L} = -45 = \frac{-30 \times time}{10\,\mu H}$$

=> Time = 15 μs to get back to zero.

Example 6

Current waveform is:



What does the circuit achieve?

Transfers ENERGY from the 15V battery to the 45V battery.

Example 6

Efficiency?

Power input = 15V*average current in L

$$15\times \underbrace{\frac{45}{2}\times\frac{45\mu s}{100\mu s}}_{\bar{i_L}} = 151.9\,W$$

Power output = 45V*average current in D

$$45\times \underbrace{\frac{45}{2}\times\frac{15\mu s}{100\mu s}}_{\bar{i_D}} = 151.9\,W$$

=> Efficiency = 100 %   !!!

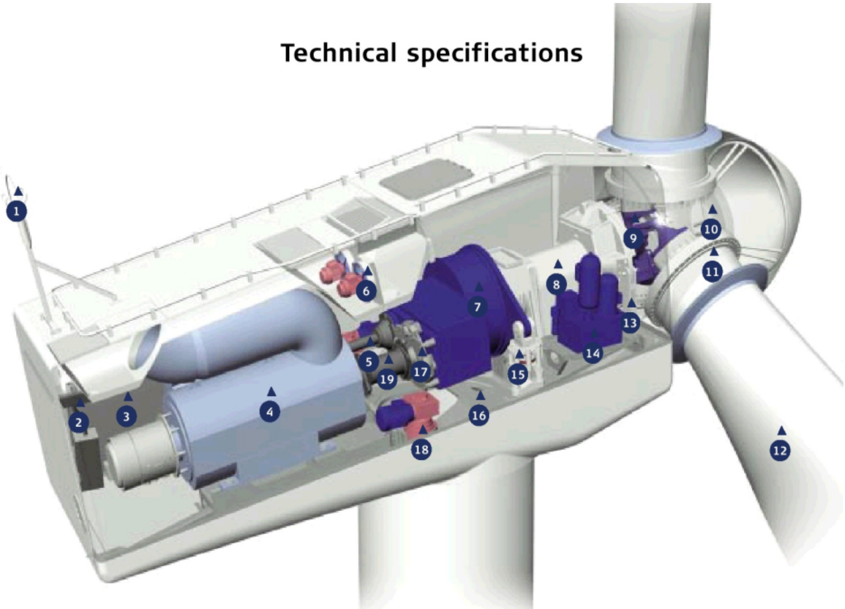
Example 6

In a real practical circuit, the efficiency will not be 100 % - because of:

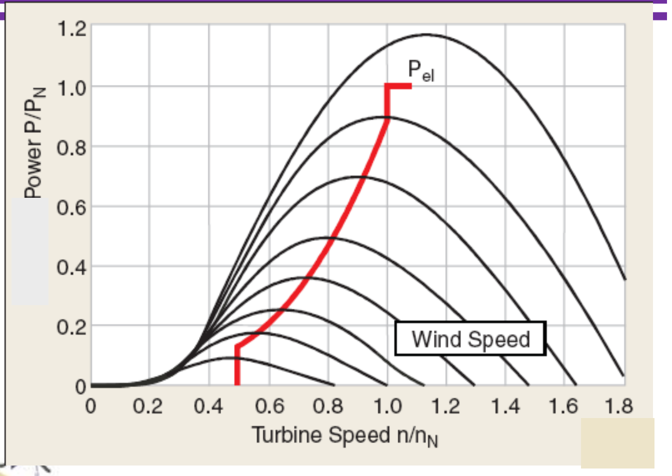
- Resistive loss in L
- Forward voltage drop of Q and D when conducting which leads to conduction loss
- IMPERFECT SWITCHING leading to switching loss
- LOSS in the CORE of L due to eddy currents and hysteresis.

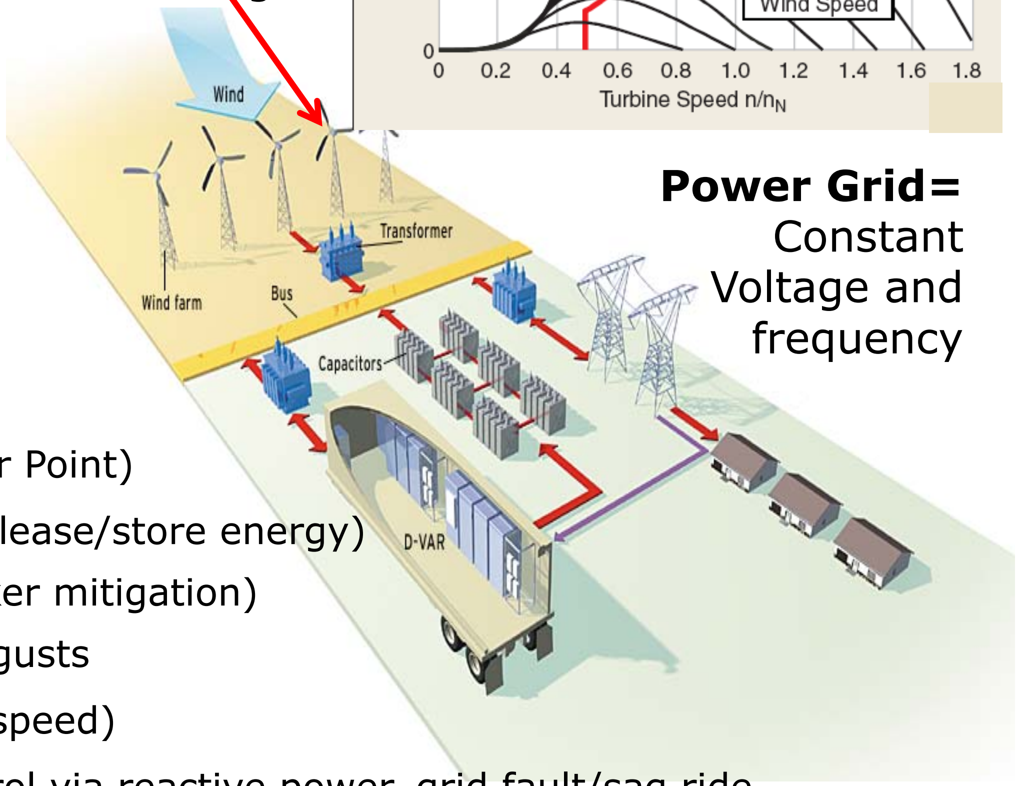
Some examples of where and why we use Power Electronics

Renewable Energy/reduce CO2 emissions



Generator = Variable speed, frequency and Voltage



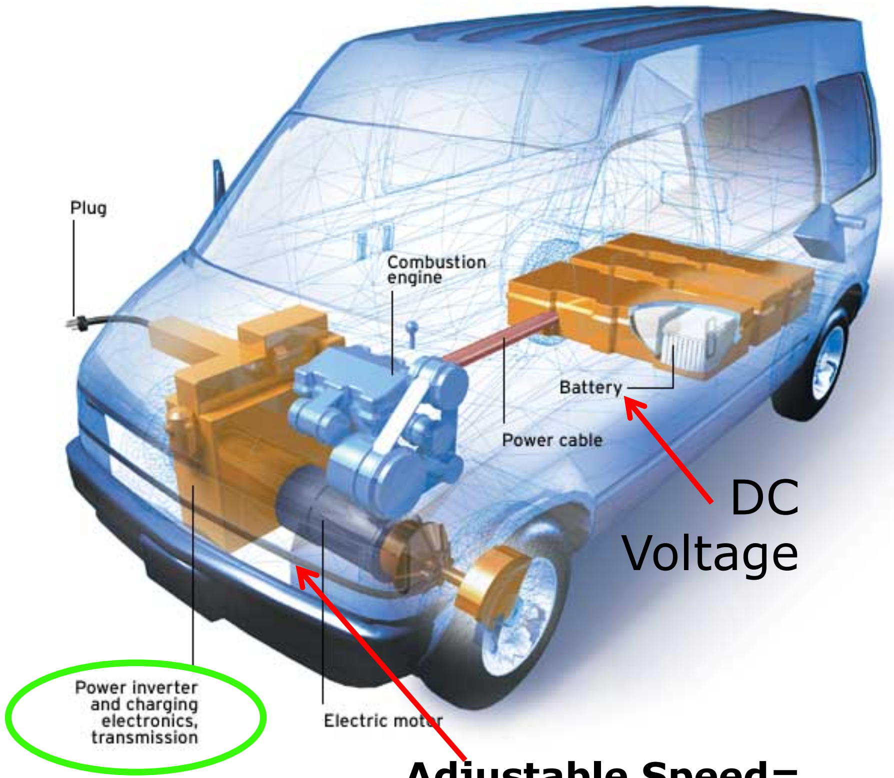


Power Grid= Constant Voltage and frequency

Benefits of Variable Speed

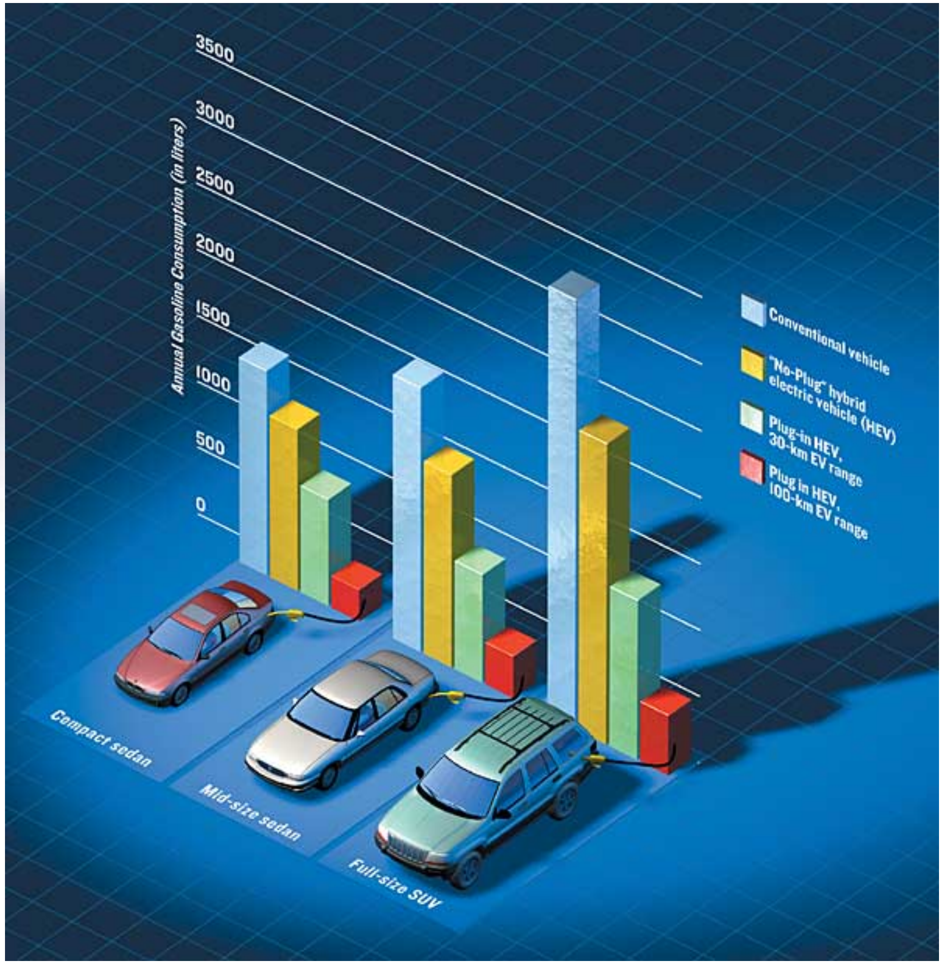
- Capture "ALL" wind energy (follow Max Power Point)
- Use inertia of the blades (de/accelerate to release/store energy)
  - Smooth power flow into the grid (=flicker mitigation)
  - Reduce mechanical stress during wind gusts
- Reduce noise (optimise rotor speed vs wind speed)
- Add **additional functionality** (voltage control via reactive power, grid fault/sag ride through etc).

Some examples of where and why we use Power Electronics



DC Voltage

Adjustable Speed=
Variable AC Voltage &Frequency

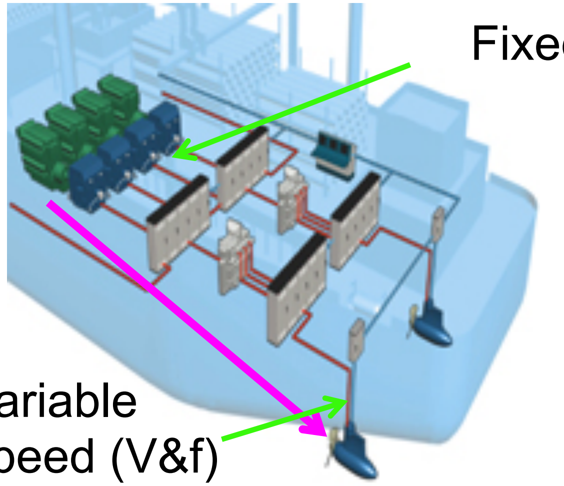


<u>Hybrid/Electric Car</u>

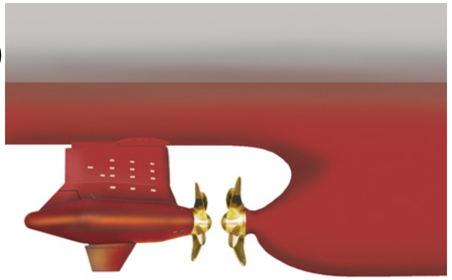
- **Smaller combustion engine** for mean power
- Electrical motor for acceleration & <u>**braking**</u>
- Reduce fuel consumption/better efficiency

Some examples of where and why we use Power Electronics

All/More Electric Ship



- Electrical ⇒ **No mechanical coupling**
- Variable speed propellers (no need for adjustable pitch to adjust thrust)
- Fixed pitch ⇒ simpler/cheaper/more robust propellers
- Multiple Diesel/Turbo generator sets/different power ⇒ redundancy
- Multiple pods= **added functionality**: steering, reduce turbulence, **improve efficiency**/ Reduce fuel consumption



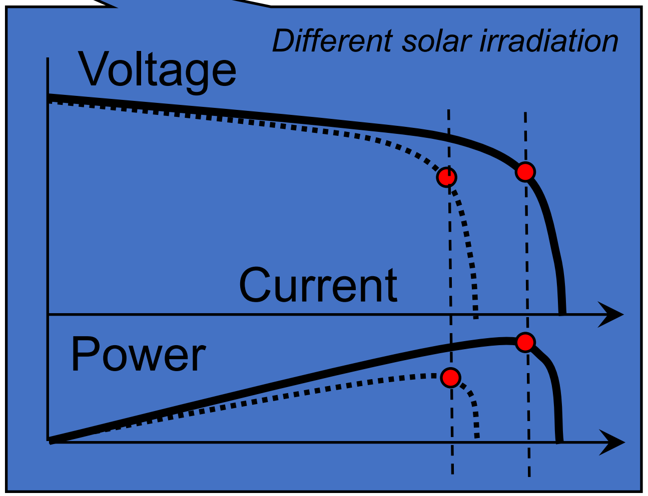
Some examples of where and why we use Power Electronics

Power supplies for TVs, PCs, Laptops, mobile phones

Washing machines, Vacuum cleaners, Air conditioning, Fridges

Interface with Renewables (photovoltaics)

Max Power Point Tracking



Compact Fluorescent Lamps

Connecting large power systems via DC

Levitated Trains/Electric Trains

All/More Electric Airplanes

Electric Railgun

Electric Catapult for Airplanes

Power electronics inside