Electeng 311

Electronics Systems Design

Diodes, capacitors and isolation

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Contents

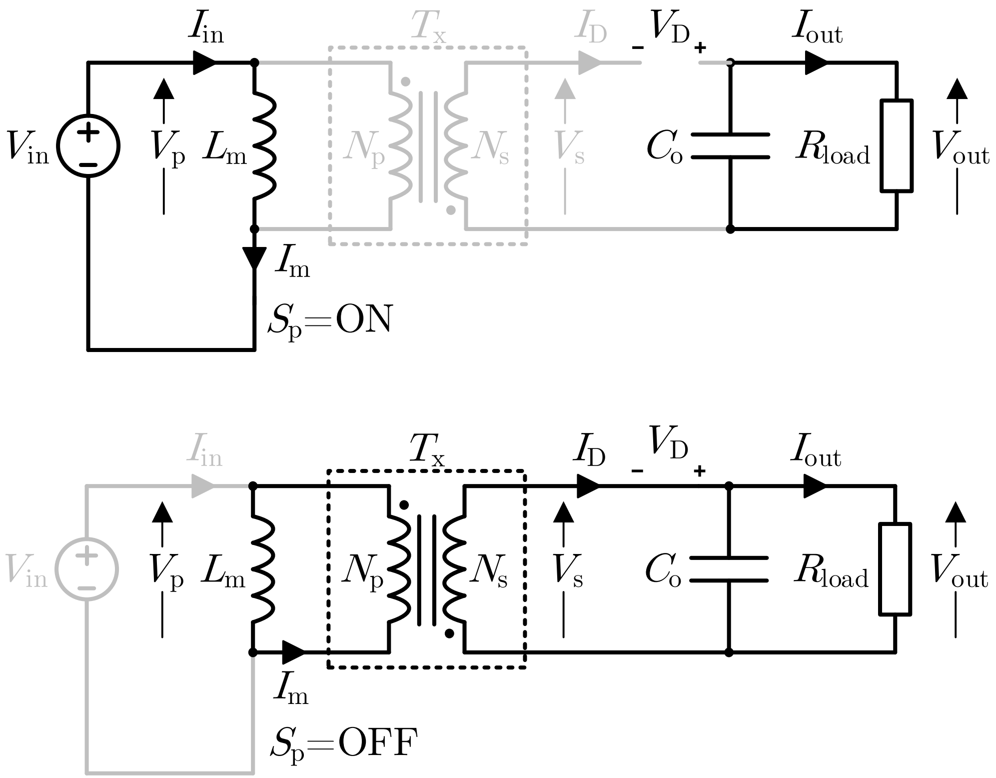
Learning outcomes

- Understand the role of the diode in a flyback converter.
- Be able to estimate the power losses in a diode.
- Understand why Schottky diodes are used for switch-mode power supplies.
- Be able to estimate the size of the output capacitor.
- Understand the use of decoupling capacitors.
- Be able to identify different types of capacitors and their applications.
- Understand isolation and devices used to implement isolation.

Diodes

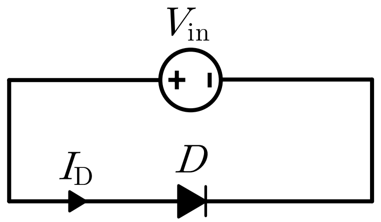
Diode – passive switch

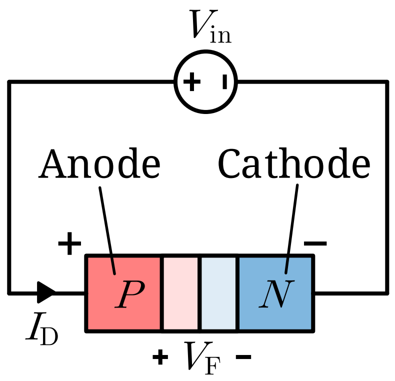
- Flyback converter uses the diode as a passive ‘switch’.
- When the MOSFET is turned on, the diode blocks current flow so the flyback transformer charges up.
- When the MOSFET is turned off, the diode conducts current from the flyback transformer to the load and the output capacitor.
- Diode needs to
  - withstand the voltage and current ratings.
  - have low forward voltage drop to minimise conduction loss.
  - transition quickly between on-state and off-state to minimise switching loss.



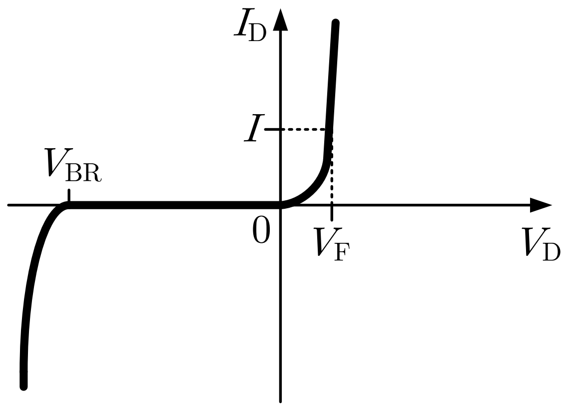
Diode – characteristic curve

- A typical diode is made up of a p-n junction and a depletion zone forms in the middle of the junction.
- Due to the depletion zone, a small voltage differential (V_F) is formed between the P and N regions.
- V_F is called **diode forward voltage**.
- The diode is considered to be 'turned on' when the input voltage (V_{in}) is forward biasing the diode to overcome V_F.
- When the diode is reverse biased, only a very small leakage current flows through the diode. Essentially blocking current flow in reverse.
- When the diode is reverse biased past the rated breakdown voltage (V_{BR}), the diode starts conducting current. This should be avoided as high voltage and current would result in diode failing.





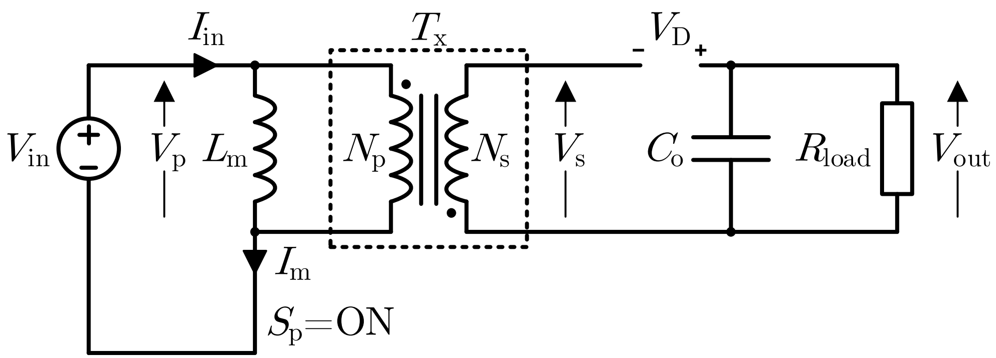
- Circuits with a diode



- I-V characteristic curve

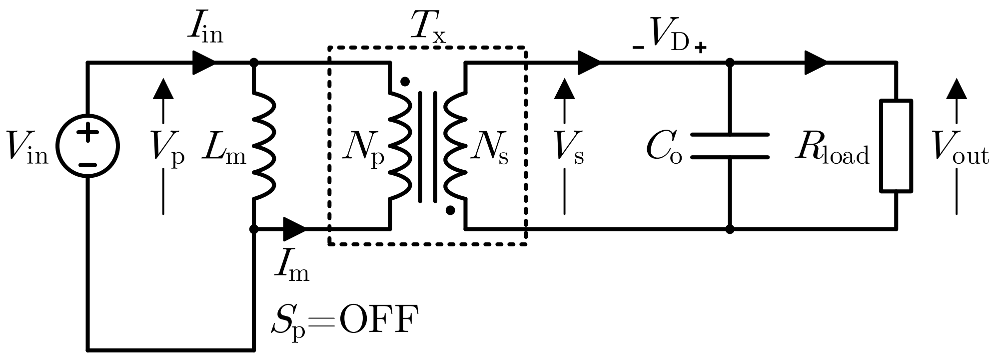
Diode – breakdown voltage

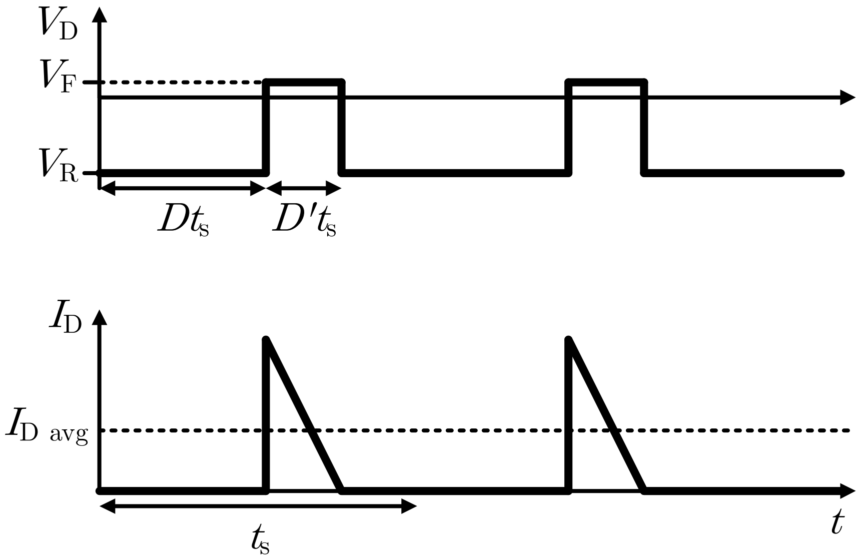
- In the flyback converter, the diode blocks the current when the switch is turned on.
- There are two sources of voltages that the diode sees in reverse bias.
- The voltage from the primary to secondary side is:
- $V_s = \frac{N_s}{N_p} V_p$
- The only voltage input to the transformer is from V_{in}
- $\therefore V_s = \frac{N_s}{N_p} V_{in}$
- At steady-state capacitor holds up the voltage in the output (V_{out}).
- So the diode is reverse biased by:
- $V_D = \frac{N_s}{N_p} V_{in} + V_{out}$
- The breakdown voltage (V_{BR}) of the diode has to be above the calculated voltage.



Diode – conduction loss

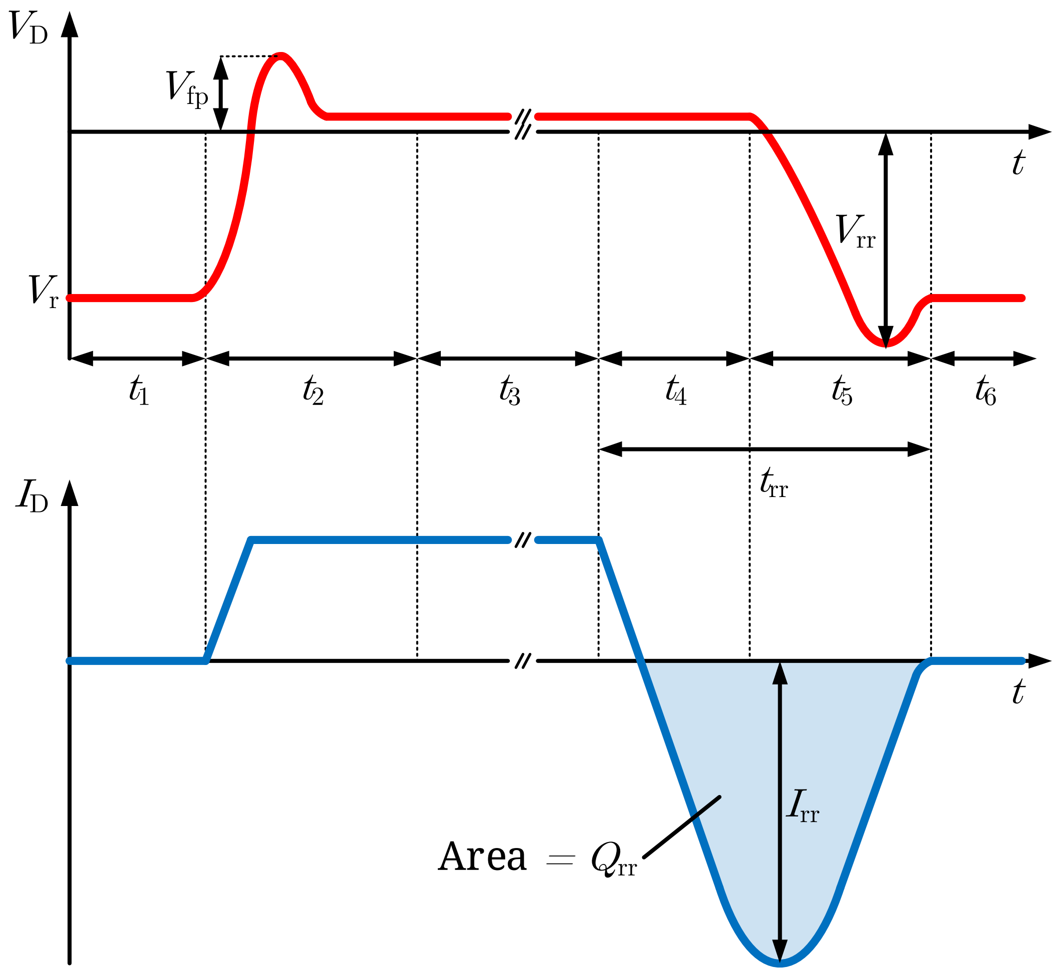
- When the diode is on, the conduction loss is:
- $P_{\mathrm{D}} = V_{\mathrm{F}} \times I_{\mathrm{D}}$
- In an ideal diode, $V_{\mathrm{F}} = 0\mathrm{V}$. There would be no drop in voltage across the diode so $P_{\mathrm{D}} = 0\mathrm{W}$.
- Typical V_{F} for diodes is 0.7~1V.
- V_{F} varies depending on the chemical composition and temperature of the diode.
- For the flyback converter, the diode loss is:
- $P_{\mathrm{D}} = \frac{1}{t_{\mathrm{s}}} \int_0^{t_{\mathrm{s}}} V_{\mathrm{F}} I_D \, dt$
- $P_{\mathrm{D}} = \frac{V_{\mathrm{F}}}{T_{\mathrm{s}}} \int_{Dt_{\mathrm{s}}}^{(D+D')t_{\mathrm{s}}} I_D \, dt$
- $P_{\mathrm{D}} = V_{\mathrm{F}} I_{\mathrm{D,avg}}$





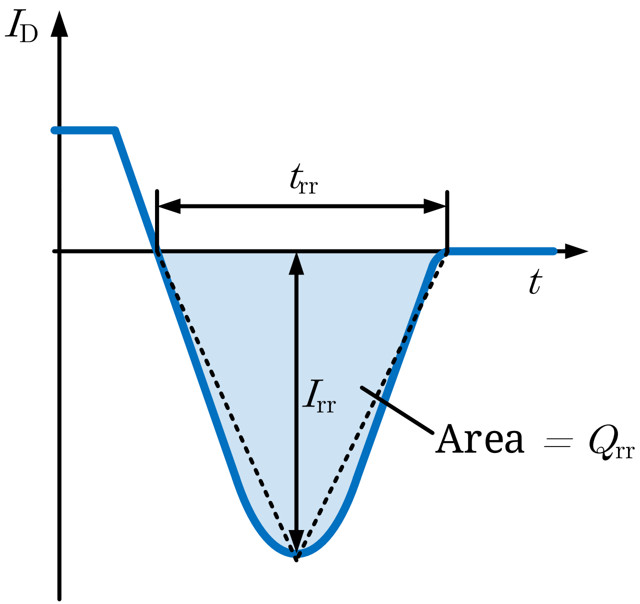
Diode – switching waveforms

- Diodes take time to transition between on-state and off-state.
- At t_1, the diode is in off-state so it is blocking a voltage (V_r) and a negligible leakage current passes in reverse direction.
- At t_2, the diode transitions to on-state and starts conducting current. The voltage across the diode overshoots to (V_{fp}), but eventually settles down to V_f.
- At t_3, the diode stays in the on-state for some time.
- At t_4 and t_4, the diode transitions back to the off-state. A significant amount of current drops down to reach I_{rr} then back to blocking current. The voltage also overshoots to reach V_{rr} before settling to V_r.
- At t_6, the diode returns to the off-state and blocks current.



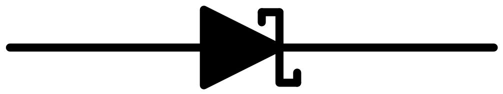
Diode – reverse recovery

- The **reverse recovery charge** (Q_{rr}) is the charge accumulated within the diode when the diode is conducting current.
- Q_{rr} needs to be discharged from the diode before the diode can transition into off-state and block current flow.
- I_{rr} is the reverse recovery current due to the Q_{rr} being discharged from the diode over reverse recovery time (t_{rr}).

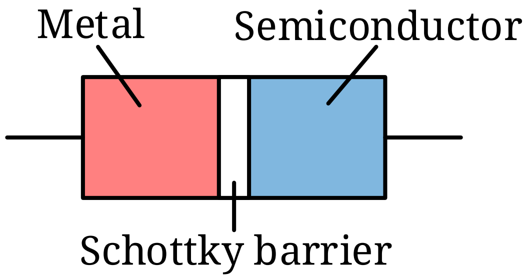


Diodes – Schottky

- In discontinuous mode flyback converter, a large current can flow in the diode every cycle so diode losses can be detrimental to converter efficiency.
- Reducing the value of V_F would reduce the conduction loss of the diode.
- One of the diode types that often used in this case is the Schottky diode.
- Unlike the p-n junction of a regular diode, the Schottky diode junction is made up of metal on one side and semiconductor on the other side
- Schottky diodes are:
  - Low V_F.
  - No reverse recovery.
  - Higher reverse leakage current.
  - Lower breakdown voltage (V_{BR}).
  - Lower junction temperature (125°C to 175°C)
  - Relatively more expensive



- Symbol for Schottky diode



- Internal chemical composition for a Schottky diode

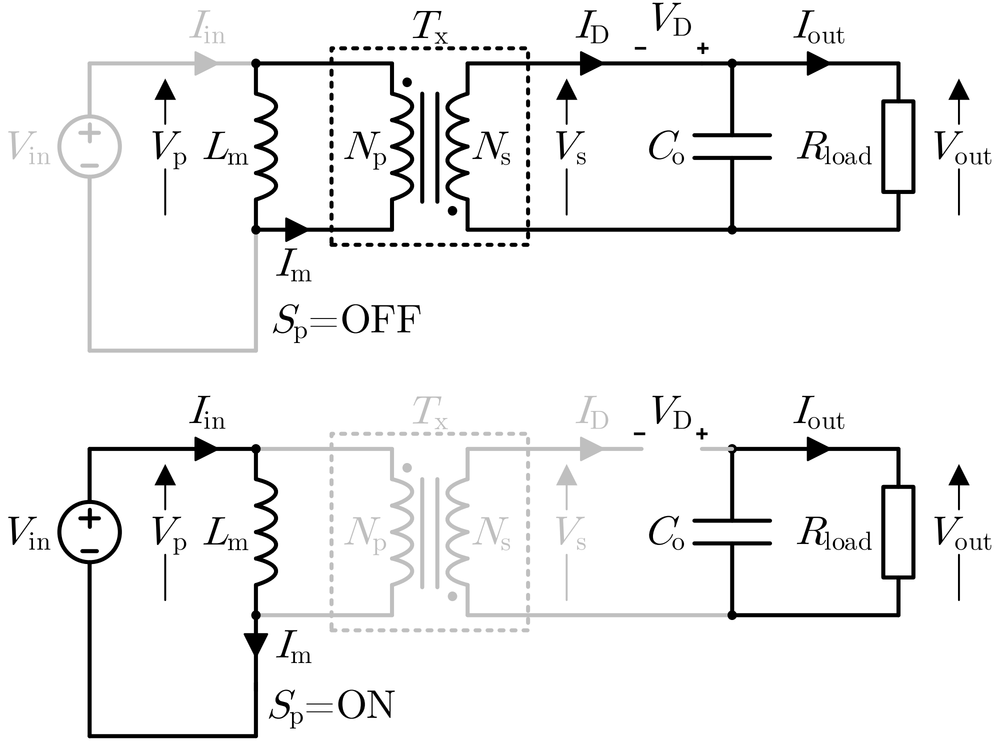
Diodes – summary

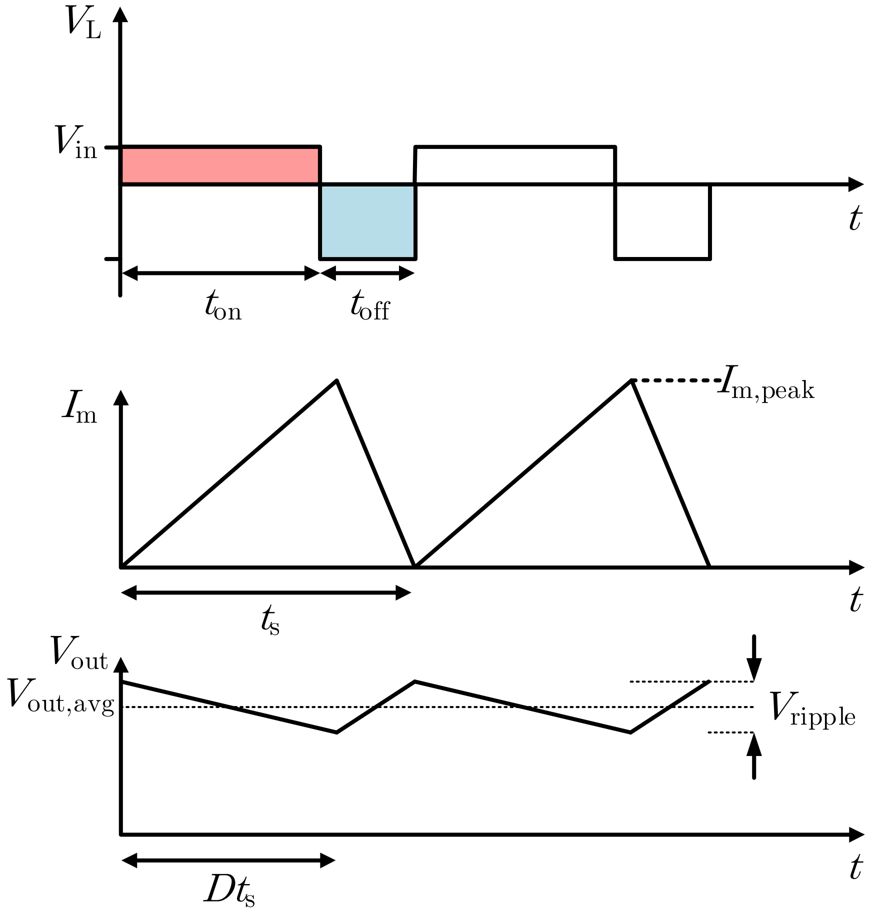
- Choosing the right diode for the flyback converter requires several parameters to be considered.
- Forward voltage (V_F)
    - Lower V_F is better to reduce conduction losses.
    - V_F varies with forward current and temperature.
    - Smaller V_F is a trade-off with larger leakage currents.
- Reverse recovery charge (Q_{rr}) and time (t_{rr})
    - Q_{rr} and t_{rr} should be minimised to reduce reverse recovery losses (P_{rr}).
    - Schottky diodes have negligible reverse recovery so effectively zero losses during transition.
    - Fast transition reduces the need for snubber circuits.
- Reverse breakdown voltage (V_{BR})
    - Calculate the maximum voltage blocked by the diode so V_{BR} is not exceeded.
    - Flyback converters often have transients that are higher than the calculated values due to leakage inductances in the flyback transformer and other parasitics.
- Reverse leakage current
    - A high reverse leakage current is undesirable for the flyback converter as energy would be transferred back to the flyback transformer.
- Temperature range

Capacitors

Capacitor – overview

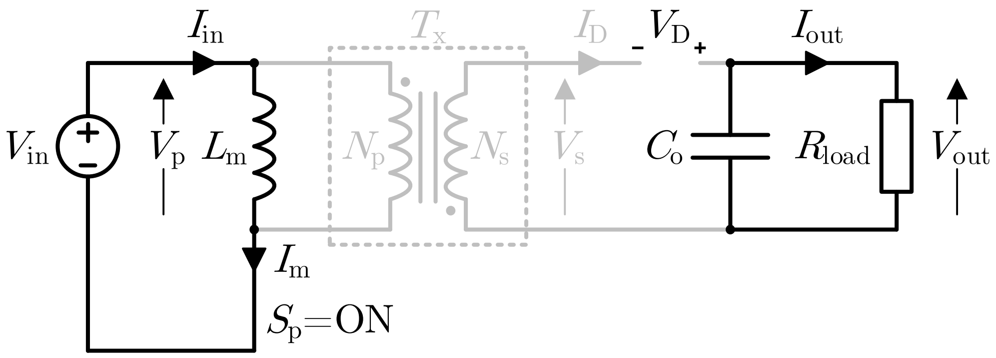
- There are two energy storages in a flyback converter - the flyback transformer and the output capacitor.
- Each energy storage is charged and discharged out of phase with each other.
- At steady-state, a ripple is present in the voltage of the output capacitor (C_o) as the energy goes in and out.

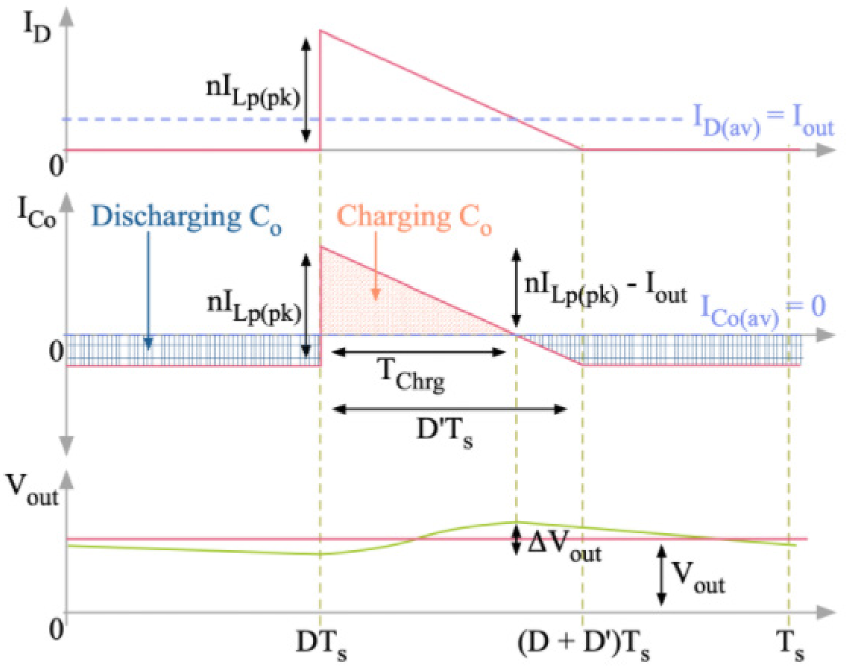




Capacitor – output ripple

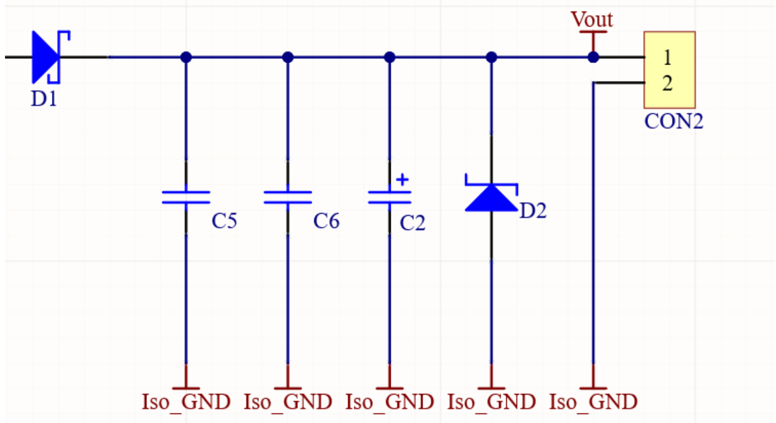
- When switch is on, I_{out} is provided entirely by C_{o}.
- If $D't_s$ is assumed to be a very small period of time, I_{out} can be assumed to be constant.
- The time the capacitor spends charging (t_{Chrg}) can be given as:
- $t_{\text{Chrg}} = \frac{(NI_{\text{Lp(pk)}} - I_{\text{out}})D't_s}{NI_{\text{Lp(pk)}}}$
- Rearranging $I_c = C\frac{dV}{dt}$, output voltage ripple (ΔV_{out}) is given as:
- $\Delta V_{\text{out}} = \frac{1}{C_{\text{o}}}\int_0^{t_{\text{Chrg}}} I_{\text{C}}\,dt = \frac{1}{2C_{\text{o}}}(NI_{\text{Lp(pk)}} - I_{\text{out}})t_{\text{Chrg}}$
- Output capacitor (C_{o}) is given as:
- $C_{\text{o}} \geq \frac{1}{2\Delta V_{\text{out}}}\frac{(NI_{\text{Lp(pk)}} - I_{\text{out}})^2}{NI_{\text{Lp(pk)}}}D't_s$



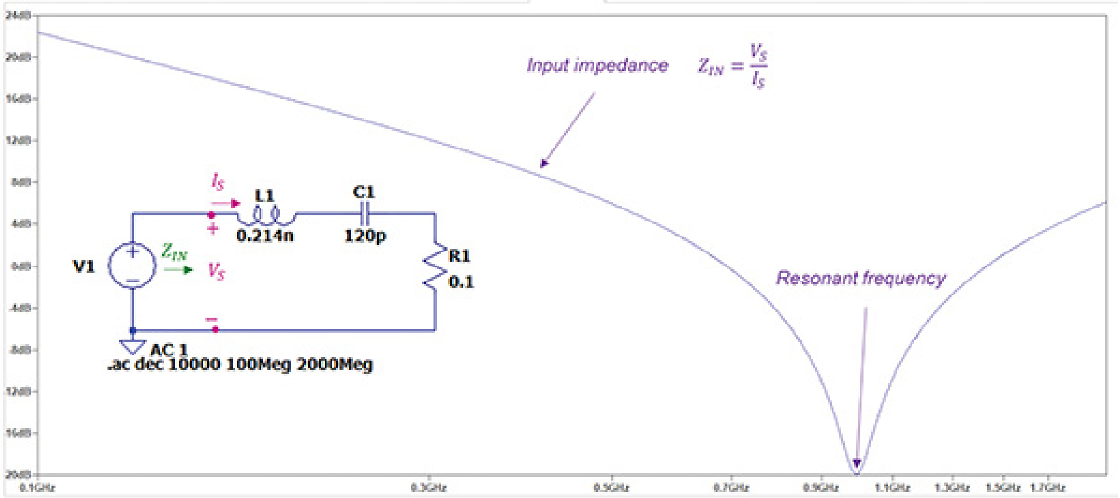


Capacitors – decoupling capacitors

- In the flyback PCB, several capacitors are placed in parallel with the output capacitor (C_o).
- These **decoupling capacitors** provides a low impedance path for the high frequency input to the ground so the output would see less fluctuations.
- If input voltage fluctuates higher, the decoupling capacitors provide a low impedance path for current.
- If input voltage is lower, the decoupling capacitors provide power to maintain the voltage level.
- Capacitors have equivalent series inductance (ESL).
- The resonant frequency (f_0) of a capacitor is given by its capacitance and ESL: $f_0 = \frac{1}{2\pi\sqrt{LC}}$
- Past f_0 the capacitor behaves increasingly like an inductor.



- Secondary side of the flyback converter



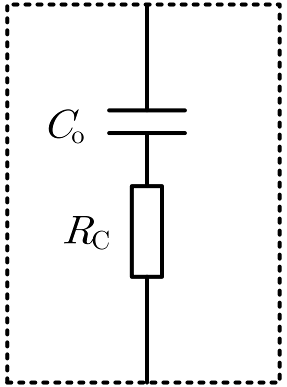
- Impedance of a capacitor against frequency [1]

[1] https://incompliancemag.com/article/emc-resonance-part-ii-decoupling-capacitors/

Capacitor – ESR

- All passive components have an equivalent series resistance (ESR).
- ESR is often a combination of multiple factors that induce real power loss in the component.
  - Losses in the dielectric material as the material is polarised
  - Losses in the metallic terminals and internal wiring
- The power loss in the capacitor generates thermal stress and must be minimised.
- Over the lifespan of capacitors, the ESR will gradually increase and the capacitors may physically deform or eventually vent open.

- An example electrolytic capacitor [4]



C_o *with ESR*

◆STANDARD RATINGS

WV (V_{dc})	Cap (μF)	Size code	ESR (Ω max./100kHz) 20℃	ESR (Ω max./100kHz) −40℃
100	110	KE0	0.17	2.5
	150	KG5	0.13	1.8
	160	LH0	0.098	1.3
	200	MH0	0.091	0.98
	240	LN0	0.063	0.80
	330	MN0	0.059	0.59

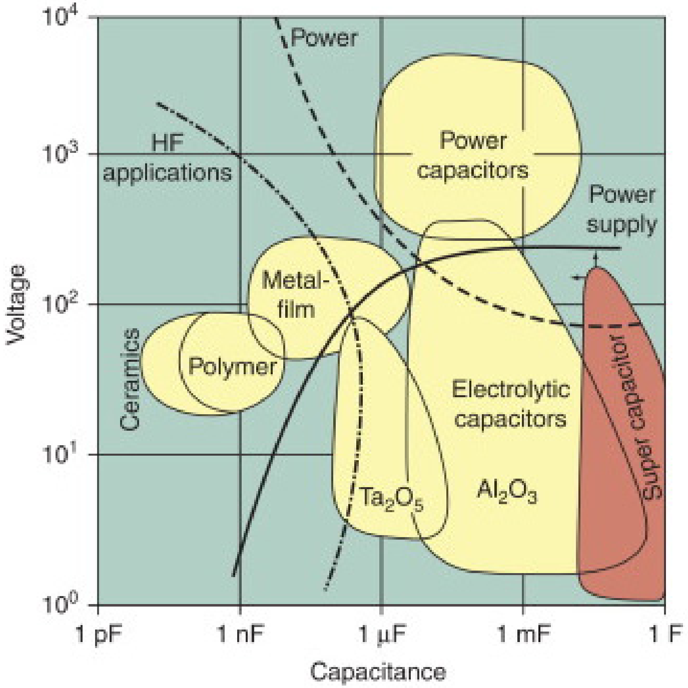
- Capacitor ratings and ESR [2]

[2] https://www.chemi-con.co.jp/products/relatedfiles/capacitor/catalog/MHSRA-e.PDF

Capacitors – types

- Different types of dielectrics are used in capacitors. Each dielectric has different characteristics:
- Electrolytic
  - Generally larger values of capacitance
  - High voltage ratings
  - High ESR at high operating frequencies
  - High tolerances and capacitance drift
  - Typically polarised
- Ceramic
  - Well-suited for high frequency filtering
  - High capacitance for small volume
  - Cheap
  - Non-linear temperature response*
- Film
  - Wide different range of film materials
  - Higher operating temperature & relatively long life
  - Generally cheap
  - Can stack a lot of film capacitors to make power capacitors
  - Relative large due to low permittivity
  - Relatively low capacitance

- Electrolytic capacitor [3], ceramic capacitor [4] and film capacitor [5]

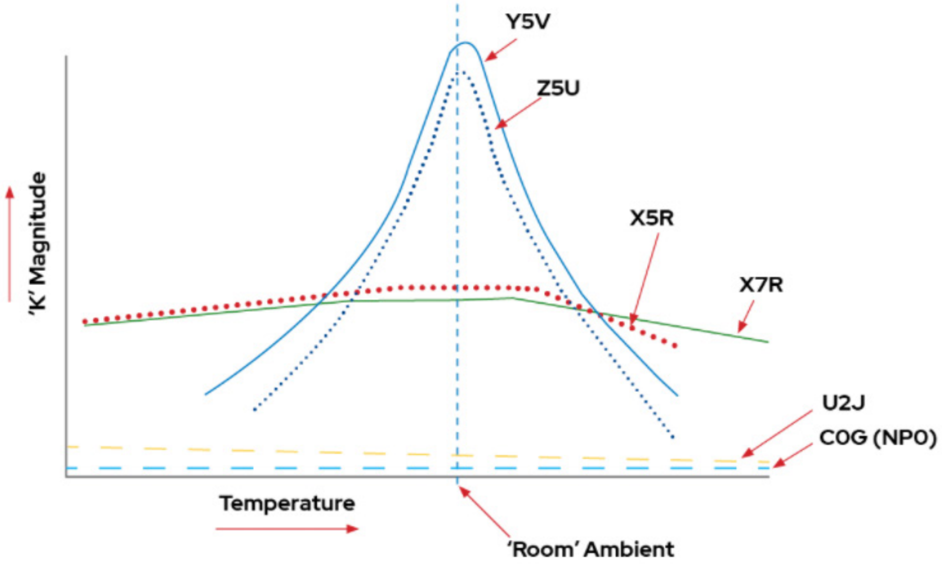


- Voltage rating against capacitance for different types of capacitors [6]

[3] https://www.digikey.com/en/products/detail/nichicon/UVR2A0R1MDD1TD/4328496
[4] https://www.digikey.com/en/products/detail/vishay-beyschlag-draloric-bc-components/S152K47Y5PR63K7R/2356797
[5] https://www.digikey.com/en/products/detail/illinois-capacitor/223MKP275KC/5411412
[6] CAPACITORS | Electrochemical Double-Layer Capacitors, P. Kurzweil, Encyclopedia of Electrochemical Power Sources, 2009

Capacitors

- A view of capacitors available online.
- Electrolytic
  - capacitances easily well above 100μF, but ESR around 600 mΩ at DC.
  - Note the lifetime of the electrolytic capacitors are limited.
  - Smallest capacitance available is 22μF so not suitable for high frequency filtering.
- Ceramic
  - 100μF is the highest capacitance available. Voltage rating is very limited at 6.3V. Voltage rating further derates when capacitor under DC bias.
  - The capacitance varies with temperature. At 84°C, capacitance has dropped by more than 10%.
  - Ceramic capacitors with large values are expensive.
  - At 1nF, ceramic capacitors have a lot of options. X7R has a high ESR and the capacitance varies a lot with temperature. NP0 tends to be completely stable with temperature, but generally larger and more expensive.



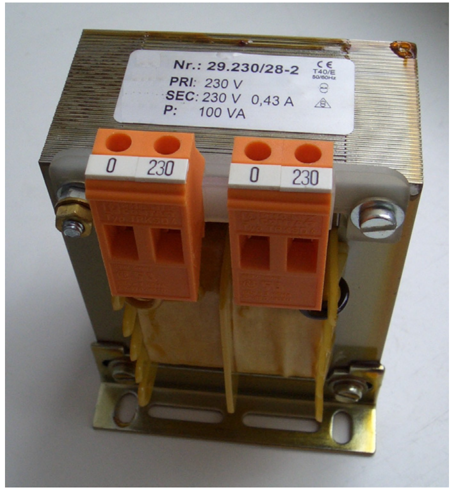
- Permittivity changes over temperature [7]

[7] https://ec.kemet.com/blog/mlcc-dielectric-differences/

Isolation

Isolation – overview

- Isolation is the electrical separation in two parts of a system.
- Protection for people and electronic circuits from high voltages.
  - Isolation transformers are often used to break ground loops in a circuit.
  - Gas-insulated substations use special pressurised gas to insulate the circuitry to mitigate arcs. The higher breakdown voltage allows equipment to be placed closer together.
- Reduce noise between different parts
- Handle potential differences between systems



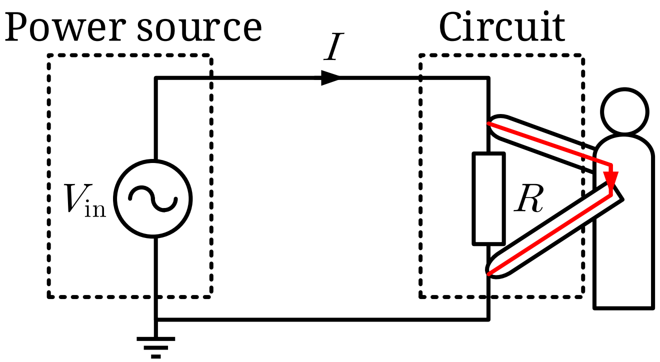
- Isolation transformer [8]

- Gas-insulated switchgear used in a substation [9]

[8] https://en.wikipedia.org/wiki/Isolation_transformer
[9] https://electrical-engineering-portal.com/gas-insulated-substations-gis

Isolation – galvanic isolation

- Electrical circuits operate by being connected to power sources, such as mains supply.
- If someone touched the circuit on both ends, the person would create another path for the current to flow.
- Even small currents, in the order of tens of mA can result in harm to people. More current could potentially lead to death.
- Electrical circuits are usually well protected using insulation and coverings to ensure safety of nearby people.



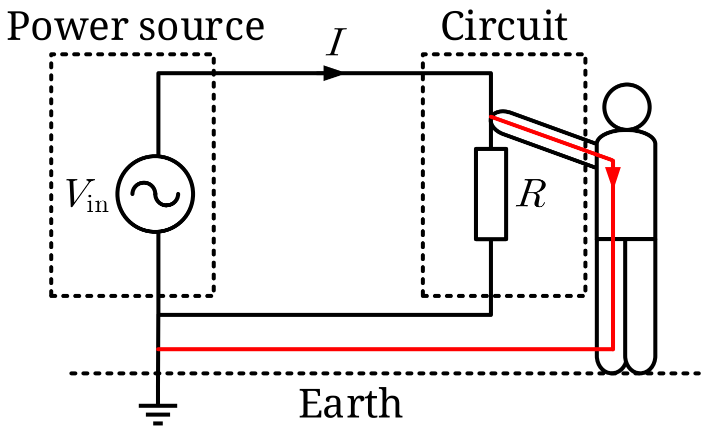
1 mA	Barely perceptible
16 mA	Maximum current an average man can grasp and "let go"
20 mA	Paralysis of respiratory muscles
100 mA	Ventricular fibrillation threshold
2 Amps	Cardiac standstill and internal organ damage
15/20 Amps	Common fuse or breaker opens circuit*

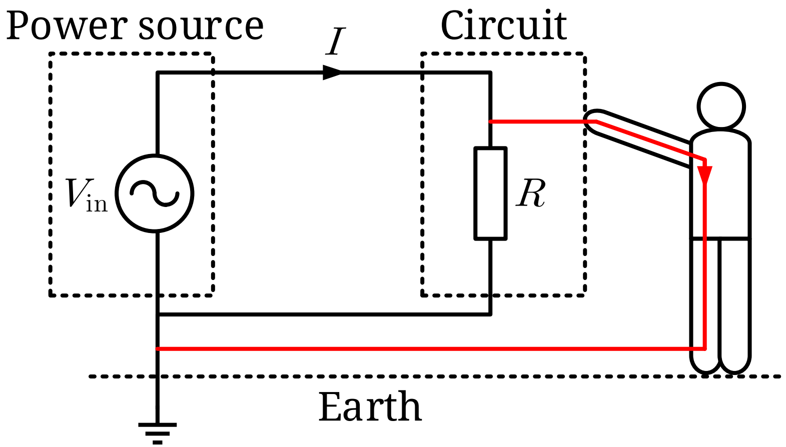
- Probably impact on people based on electrical current [10]

[10] https://www.cdc.gov/niosh/docs/98-131/pdfs/98-131.pdf?id=10.26616/NIOSHPUB98131

Isolation – galvanic isolation

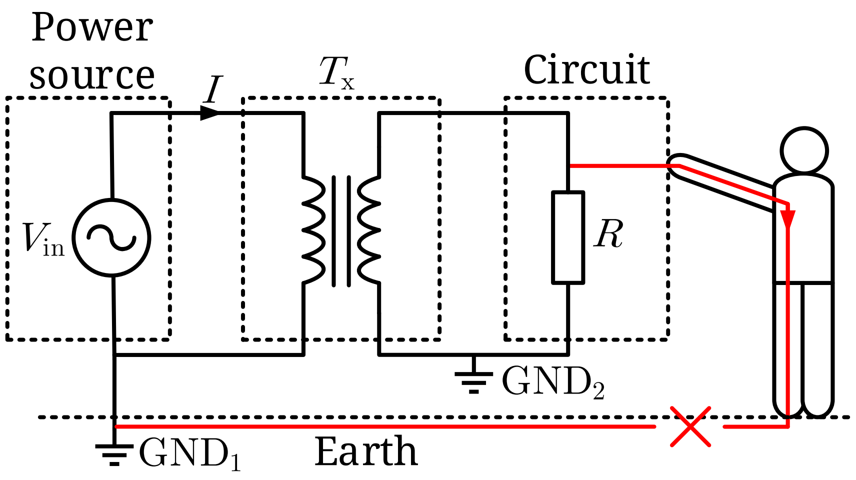
- In non-isolated circuits, touching just one side of the circuit could result in current flowing through the person.
- Power source is grounded to earth and with a high enough voltage, a connection is made from the circuit, through the person back to the power supply.
- In some cases, loose wires or connections could be touching the casing of the electrical circuit. A person simply touching the case could get an electric shock as the electric loop is completed.

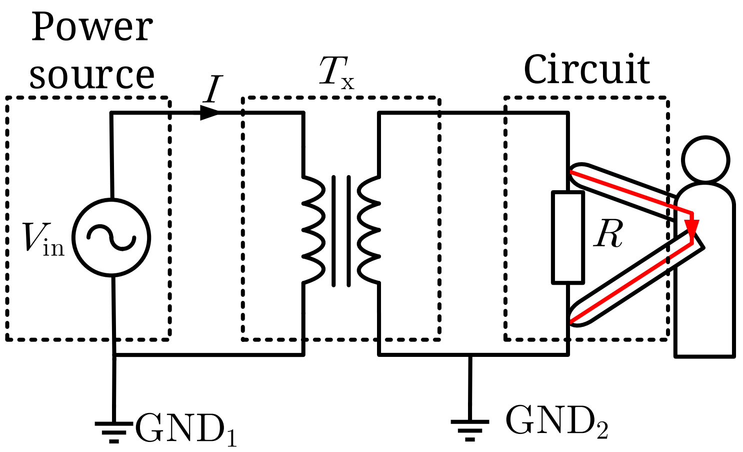




Isolation – galvanic isolation

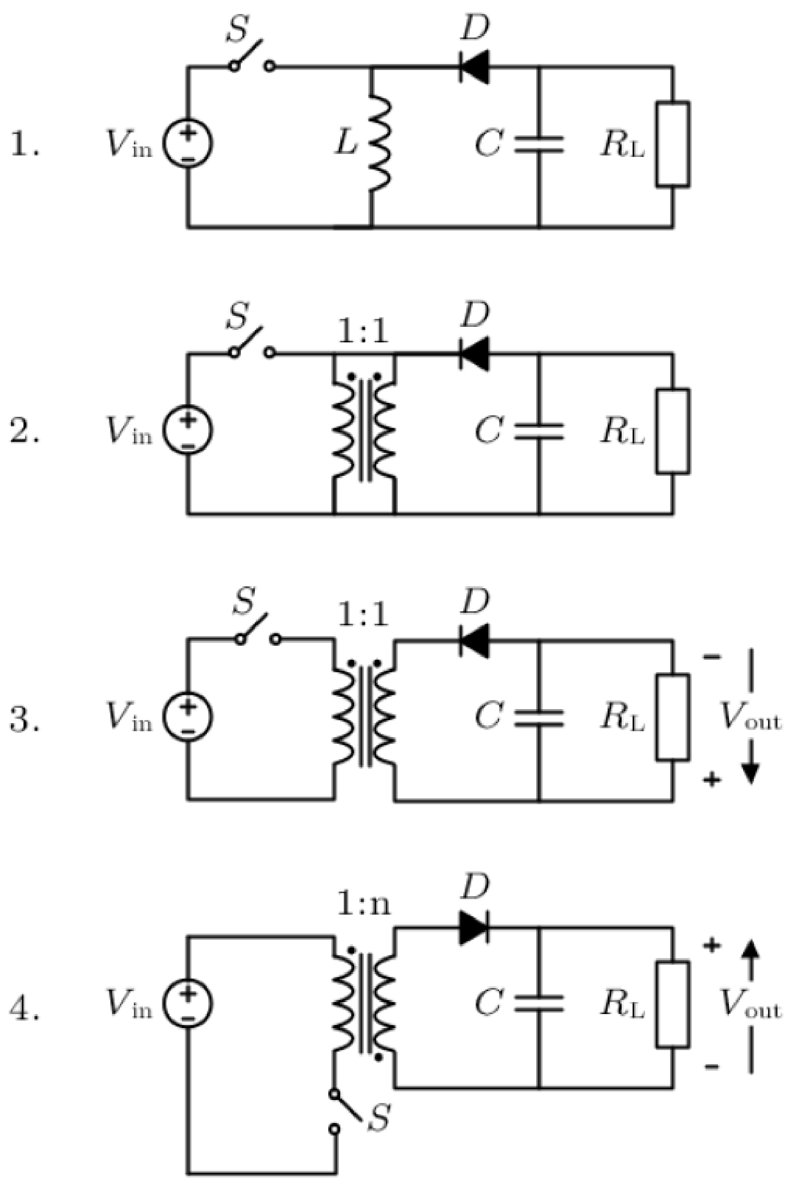
- Transformers are often used within circuits that deal with high voltages and current like a DC-DC converter to isolate the input and the output.
- The transformer breaks the physical connection between the primary and the secondary so there is no physical connection directly between the input and the output sides.
- Input and output sides have two different reference points.
- Given that electrical current always has to come back to the source, there is no path for the electric current from the power source to return so there is a less chance of an electric shock.
- Even with a transformer separating the input and the output, a person can still get electric shock on the output side if the voltage is high enough and the person creates a path for current to flow back to the secondary of the transformer.





Isolation – flyback converter

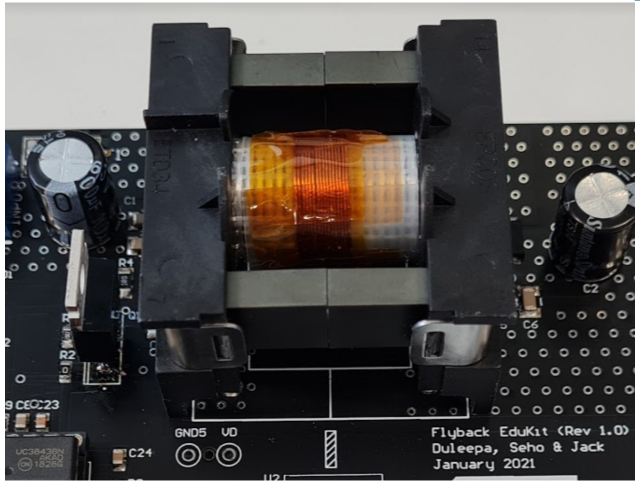
- A buck-boost converter is a non-isolated DC-DC converter that can step the output voltage up and down.
- The flyback converter is essentially the same as a buck-boost converter with the addition of a transformer in the middle.
- The inductor in the boost converter is separated into two tightly coupled inductors, which is essentially the flyback transformer.
- As the flyback converter has a flyback transformer, there is no direct electrical connection between the input and output of the flyback converter.
- The input and output are isolated so a flyback converter is considered as an isolated DC-DC converter.



- A buck-boost converter converted into a flyback converter

Isolation – flyback transformer

- The flyback transformer itself needs to be designed so the primary and secondary windings are insulated from each other.
- The wire used for the winding in the transformer for this course is an enamel wire. The enamel wire is coated with a very thin layer of insulating material that will break down easily at high voltages.
- Often, kapton tape and mylar sheets are used to insulate the primary and secondary windings of the transformer.
- At high frequencies, even a small transformer could result in high voltages across the winding and result in shorts.

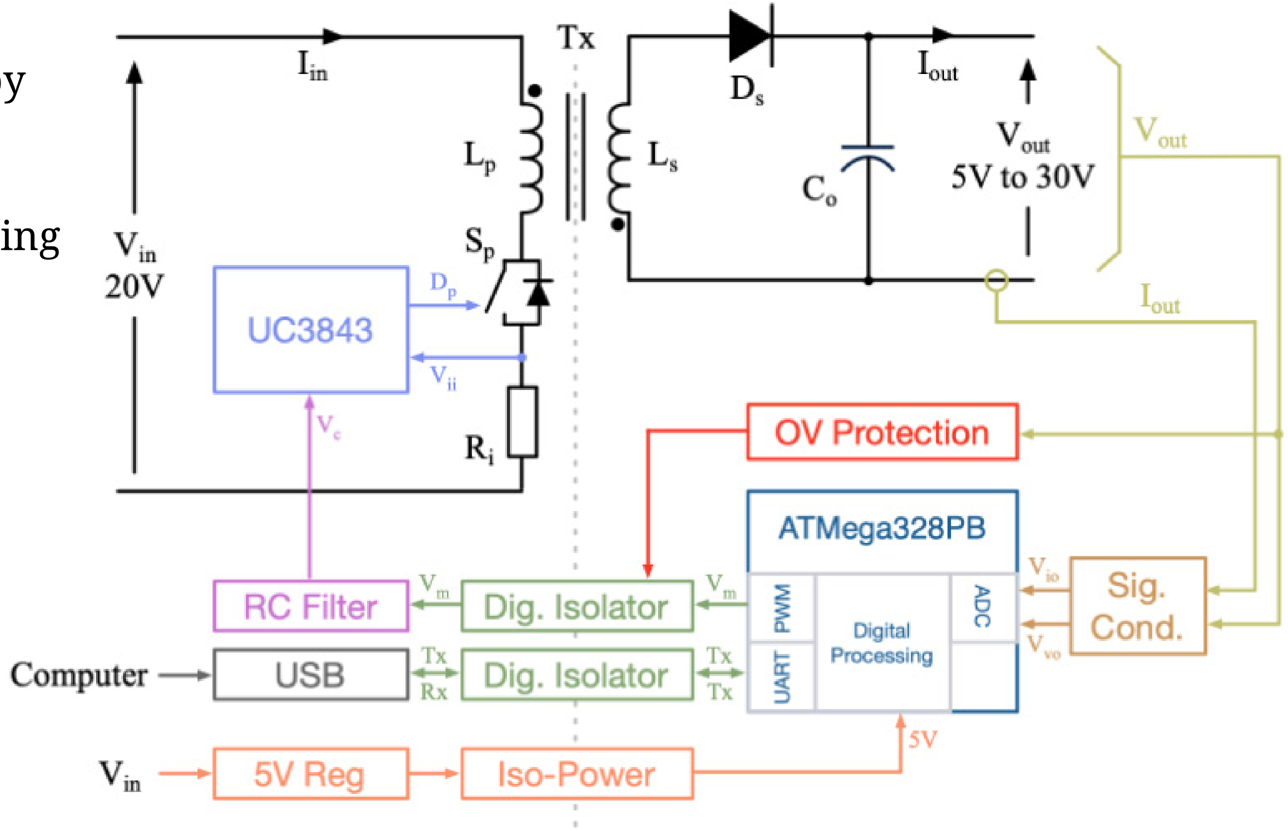


- An example transformer for the 311 project

- Insulations in Litz wire breaking down causing a short

Isolation – flyback converter

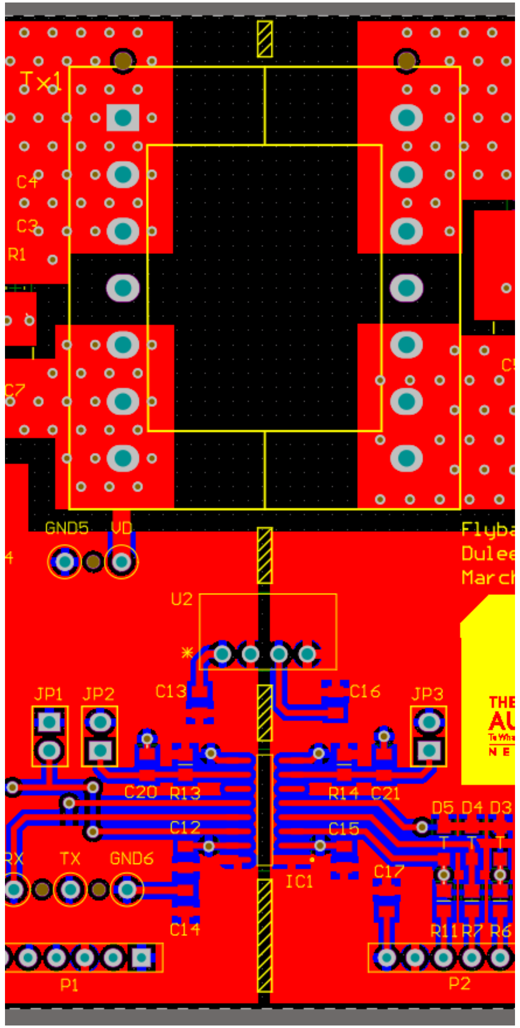
- The flyback converter designed in this course is isolated into different stages.
- The input and output of the power stage is isolated by the flyback transformer as shown previously.
- To ensure the ground connections are separated between the input and the output, the signal processing stage is isolated between the control and feedback.
- The feedback stage receives power from an isolated power regulator.
- The signals are passed between the control and feedback stages using digital isolators.



- Flyback converter implementation in this course

Isolation – PCB isolation gap

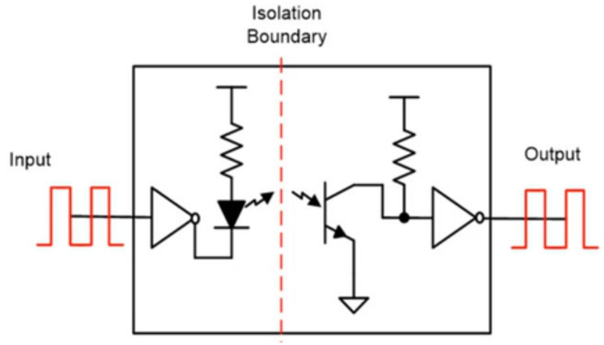
- The power stage is separated between the input and the output by the flyback transformer.
- The flyback converter has no direct electrical connection between the input and the output.
- In the signal stages, an isolation gap is implemented in the PCB.
- A physical gap ensures that there is no possible way for the electric current to flow from the input side to the output side.
- Signals are passed between different stages using signal isolators.



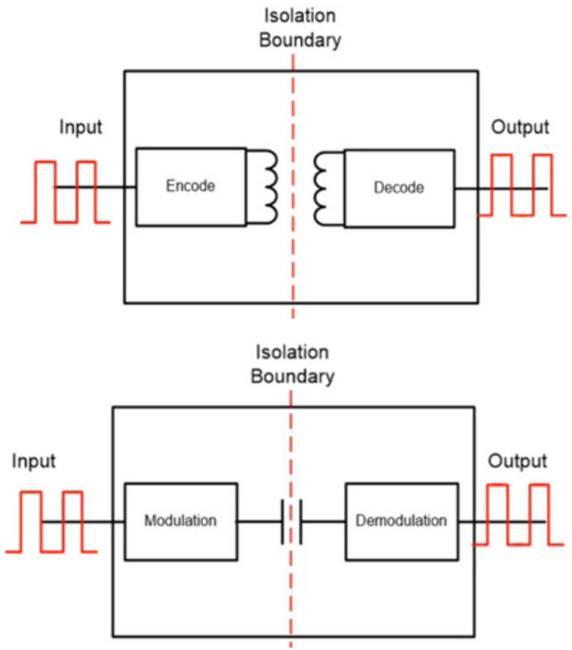
- Isolation gap in the flyback converter PCB

Isolation – devices

- Opto-couplers
  - Uses light to pass signal. Generally a light transmitter and a light-activated switch.
- Digital isolators
  - Signals passed through inductive or capacitive coupling between the input and the output sides.
- The digital isolator chosen for the project uses RF transmitter and receiver to transfer signals across the insulation barrier within the IC.
- Isolated power supplies
  - The power rails for the control stage and the feedback stage needs to be separated as well to ensure complete isolation between the input and output of the flyback transformer.



- Opto-coupler [11]

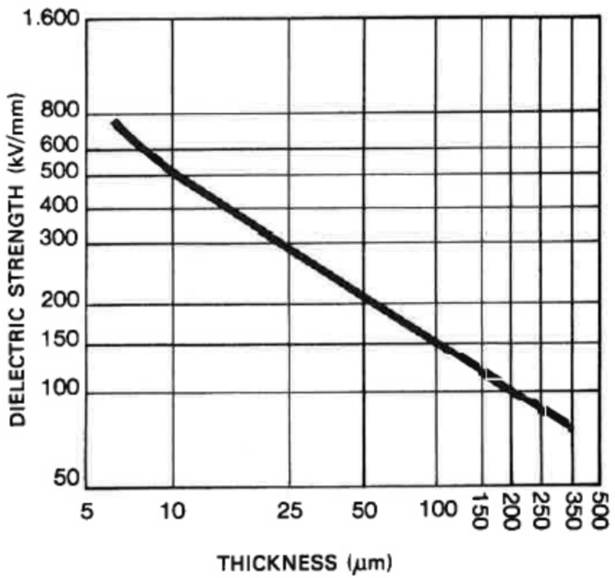


- Digital isolators [11]

[11] https://training.ti.com/ti-precision-labs-isolation-what-digital-isolator

Isolation – demo

- A demonstration of high voltages applied to two pieces of wire with and without insulation.
- The dielectric strength of air is approximately 3kV/mm.
- The insulation tester generates 5kV across the terminal.
- Without any insulation, the air between the two coils will breakdown and conduct electricity.
- Mylar sheet has a much higher dielectric strength than air so coils separated by mylar sheets should not create sparks between them.



- Mylar dielectric strength against thickness [12]

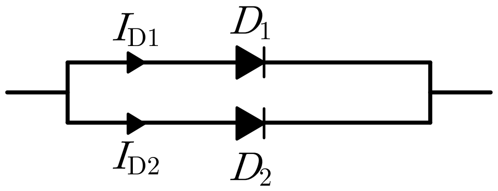
- Fluke 1550B insulation tester

[12] https://europe.dupontteijinfilms.com/media/2431/info-mylar-a-electrical-properties.pdf

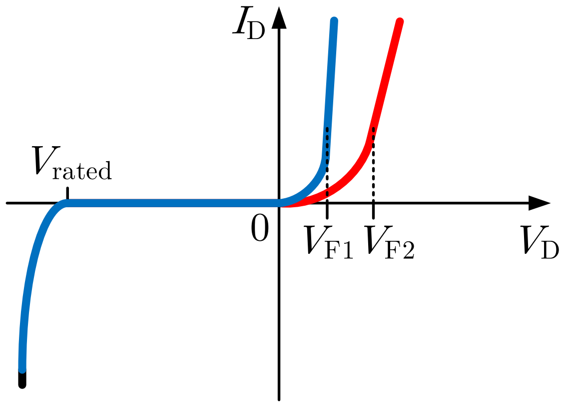
Appendix

Diode – temperature coefficients

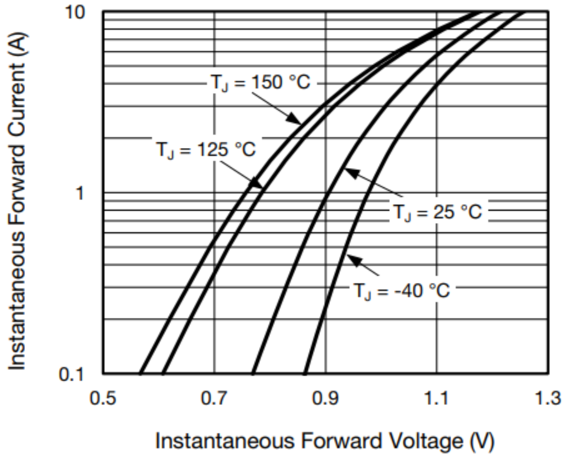
- Diodes in parallel generally do not share currents evenly as the diode with smaller V_F will carry more current.
- A diode carrying current will heat up and V_F is reduced further as typical diodes have negative temperature coefficient.
- As V_F is further reduced due to higher temperatures, one diode ends up carrying more and more current.
- Resistors can be added into the parallel circuit to ensure the currents are balanced.
- Schottky diodes can have positive temperature coefficients so V_F increases with temperature [14]. This naturally helps to share current between two diodes in parallel.
- Some Schottky diode packages have two diodes built in to improve current capacity, but the reverse leakage current tends to be much higher.



- Two diodes connected in parallel



- Characteristic curve of a diode at different temperatures

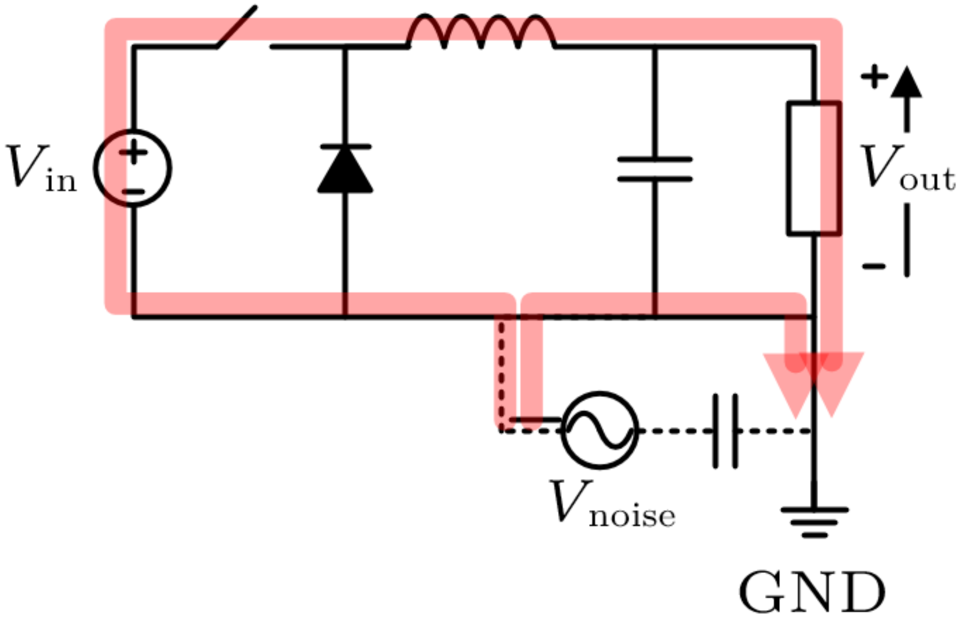


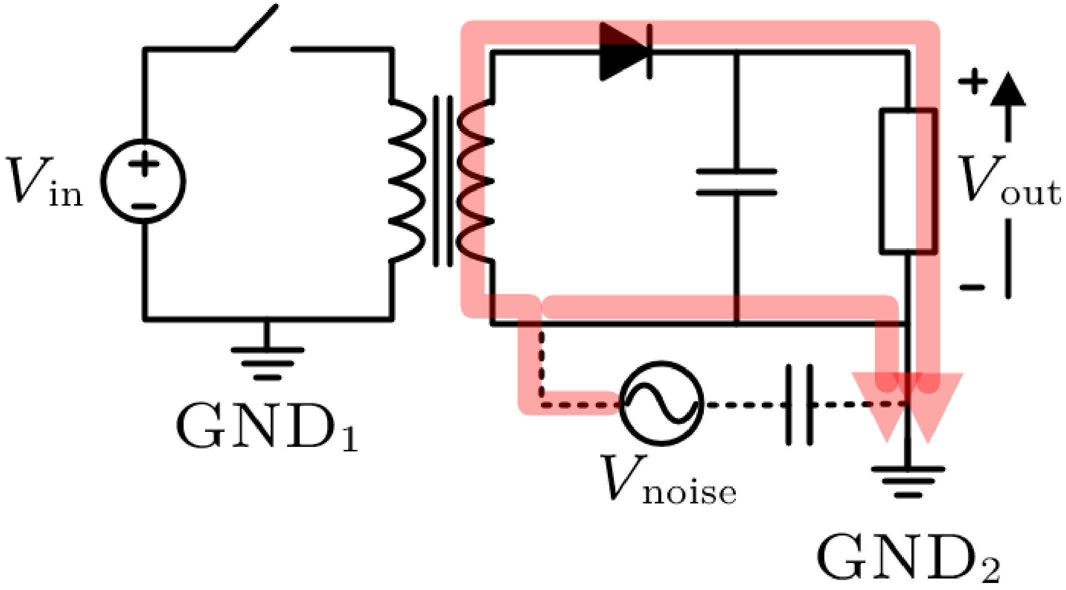
- SA2B diode forward characteristics [13]

[13] https://www.vishay.com/docs/88969/sa2b.pdf
[14] M. S. Chinthavali, B. Ozpineci and L. M. Tolbert, "Temperature-dependent characterization of SiC power electronic devices," Power Electronics in Transportation (IEEE Cat. No.04TH8756), 2004, pp. 43-47

Isolated DC-DC converters

- Reduced noise from breaking of ground loops
- Noisy parts can be isolated from rest of the system

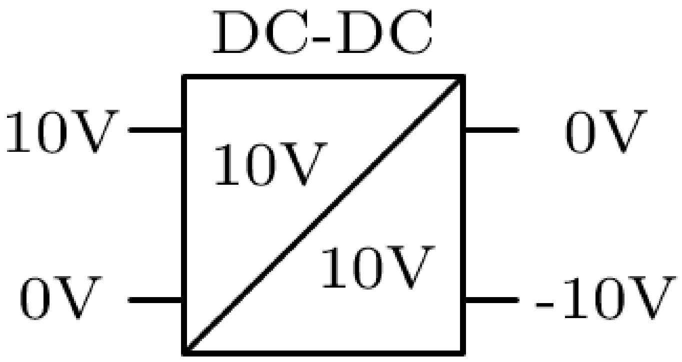




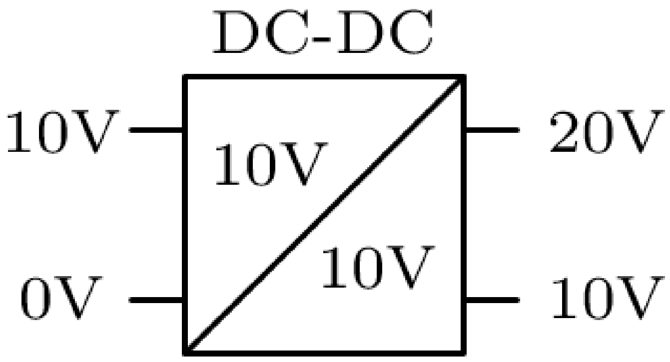
Isolated DC-DC converters

- Isolation allows different types of output connections to other systems as ground references are not tied together

Reverse polarity



Level-shifting



Dual-rail