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3.0 SMPS Topologies

Objectives

- Identify various types of switch mode converters.
- Determine the approximate current waveforms in SMPS circuits.

Here are some excellent documents:

<http://www.onsemi.com/pub/Collateral/SMPSRM-D.PDF>

<http://www.onsemi.com/pub/Collateral/AN920-D.PDF>

http://www.semiconductors.philips.com/acrobat_download/applicationnotes/APPCHP2.pdf

<http://www.ericsson.com/microe/tools/powermodules/powermodules.shtml>

<http://www.powerint.com/index.htm>

<http://www.cdnc1.com/>

http://henry.fbe.fh-darmstadt.de/smps_e/smps_e.asp

<http://www.coremaster.com/apnotes.htm>

<http://www.eetasia.com/HOME.HTM>

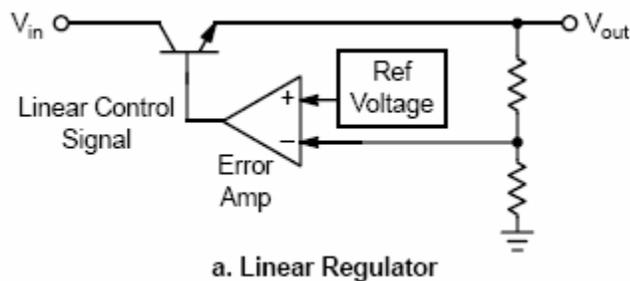
http://www.power-one.com/technical/articles/topo_e.pdf

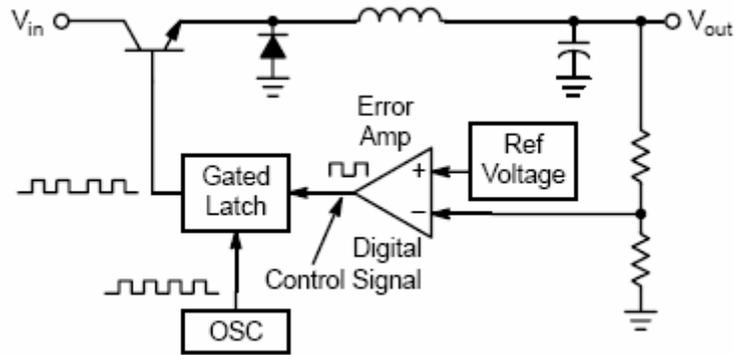
<http://www.st.com/stonline/products/promlit/pdf/sgsmmps-0102.pdf>

[Power Electronics](#) by Faz Rahman

Many of these illustrations are from *SWITCHMODE Power Supply Reference Manual*, rev 3, 2002, by ON Semiconductor.

A switching regulator topology is very similar to that of a linear regulator.





b. Switching Regulator

In addition to a regulator, a switching power supply consists of four external components:

- A switch – used to transfer a small portion of energy from the input
- An inductor – to store energy when the switch is closed and to discharge energy when the switch is open
- A capacitor – to store the energy from the inductor when the switch is closed and to provide energy to the load
- A diode – to govern the direction of the charging and discharging currents

These simple components can be used to create a bewildering array of power supplies, not attainable by linear methods.

Although each of the following circuits is quite complex, the basic operation can be understood by applying the Kirchoff's voltage and current laws to an RLC network. Each circuit type has only two states, one where the switch is ON and the other where the switch is OFF.

For the sake of simplicity, the circuitry need to control the switch will be considered later.

The voltage drop across the (transistor) switch is normally quite small (0.1 – 0.3 volts), but it will be included in the following analysis.

3.1 Basic Components

Switch

Bipolar and MOS transistors used to provide the switching function.

	Bipolar	MOS
Drive Circuit	Current	Voltage
Break down voltage	Higher	
Cost	Lower	
Switching speed		5 – 10 times faster

Capacitor

Because enormous amounts of charge must be transferred during the switching cycle, electrolytic capacitors are required. However, the ESR (equivalent series resistance) of these can be quite high and may pose some problems. If the ESR must be lowered, a tantalum capacitor of about $\frac{1}{4}$ the value can be placed in parallel.

Diode

<http://www.irf.com/technical-info/whitepaper/murdiodes.pdf>

The diode rectifier is often the highest source of loss in a switch mode power supply. The most important parameters are: forward voltage drop and reverse recovery time. For low voltage outputs, Schottky diodes are preferred.

Diode Type	Forward Drop	Reverse Recovery	Forward Recovery
Fast Recovery	1.0	150 nSec	1050 nSec
UltraFast Recovery	0.9	75 nSec	50 nSec
Schottky	0.5	<1 nSec	0

Inductors

[http://www.jwmiller.com/pdf2/How to Select Power Inductors for SMPS EP June%2020031.pdf](http://www.jwmiller.com/pdf2/How%20to%20Select%20Power%20Inductors%20for%20SMPS%20EP%20June%2020031.pdf)

<http://www.circuitprotection.com/coev/SpecifyinPowerInductorspaper.pdf>

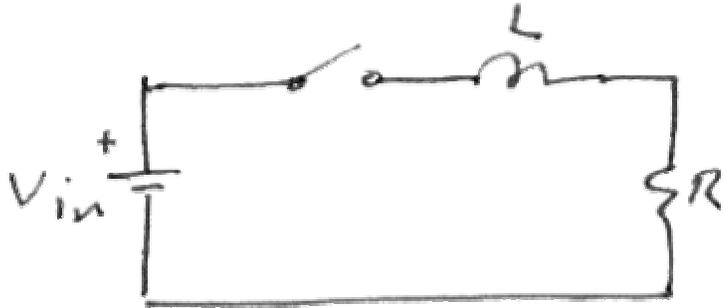
<http://www.torotelprod.com/handbook1-5.pdf>

If a constant current flows through an inductor, it will generate a voltage drop equal to that determined by Ohm's law $E=IR$, where R is equal to the winding resistance. However, if the current changes, the voltage generated across the inductor will change according to Faraday's law:

$$V = \frac{\Delta I}{\Delta t} L$$

This equation suggests that if the current is interrupted in a vary short time span (Δt), the resulting voltage can be quite high. In practice, several thousand volts can be generated when breaking a circuit.

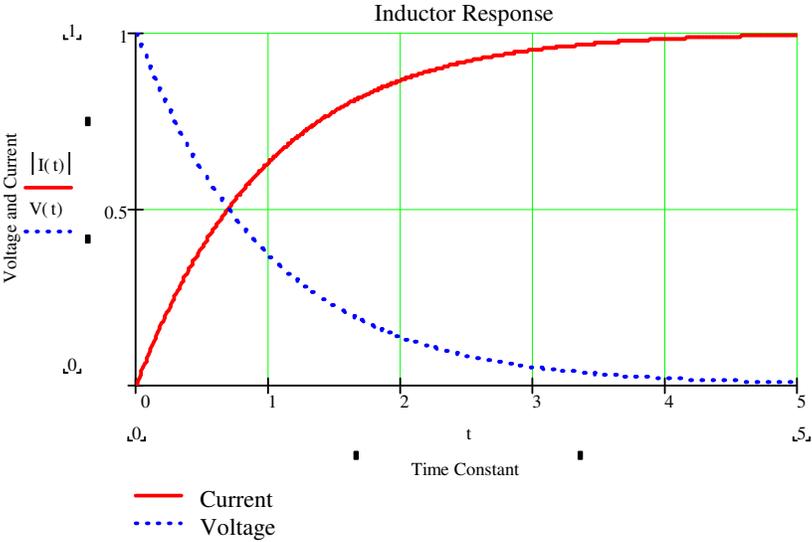
If a fixed voltage is applied to an ideal inductor, the current will rise linearly to infinity. A real inductor however will have the current rise linearly until the flux saturates the core, at which point the inductor essentially becomes a short circuit and the current increases to the limit of the power source. From this we note that an inductor must not be allowed to saturate. This can be accomplished by placing a current limiting resistor in series with the inductor.



Adding a resistor in series with an inductor creates a current waveform very much like the charging voltage waveform of a capacitor. This is because the voltage across the inductor is no longer constant and the current can now only

rise to a maximum of $I_{max} = \frac{V_{in}}{R}$

The voltage and current waveforms resemble:



The time constant is given by: $\tau = \frac{L}{R}$

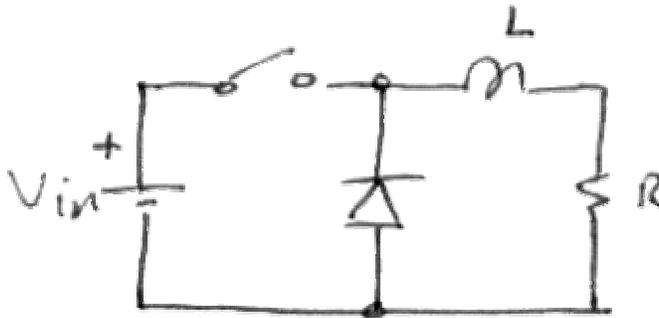
At any given time, the inductor voltage and current is given by:

$$I_L(t) = \frac{V_{in}}{R} \left(1 - e^{-\frac{t}{\tau}} \right)$$

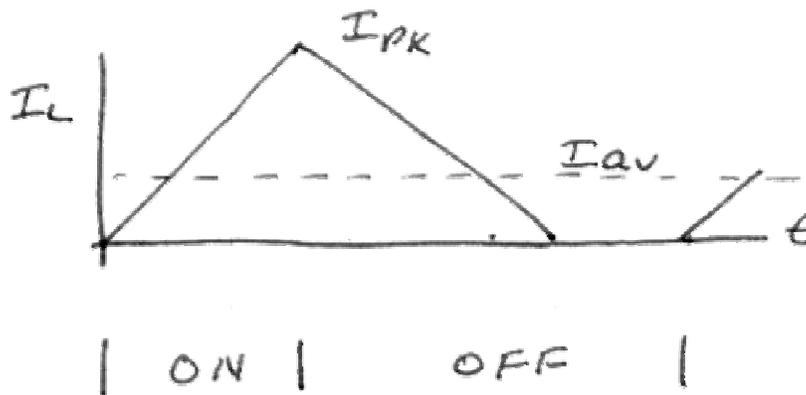
$$V_L(t) = V_{in} e^{-\frac{t}{\tau}}$$

It takes approximately 5 time constants (5τ) for the current (or voltage) to reach its final value. If the charging period is one time constant or less, the current essentially rises in a linear manner.

A diode can be added to provide a discharge path for the inductor when the switch is OFF.



Turning the switch ON and OFF results in a 'triangle' waveform, and if the switching time is fast enough, the current waveforms can be approximated by straight lines.

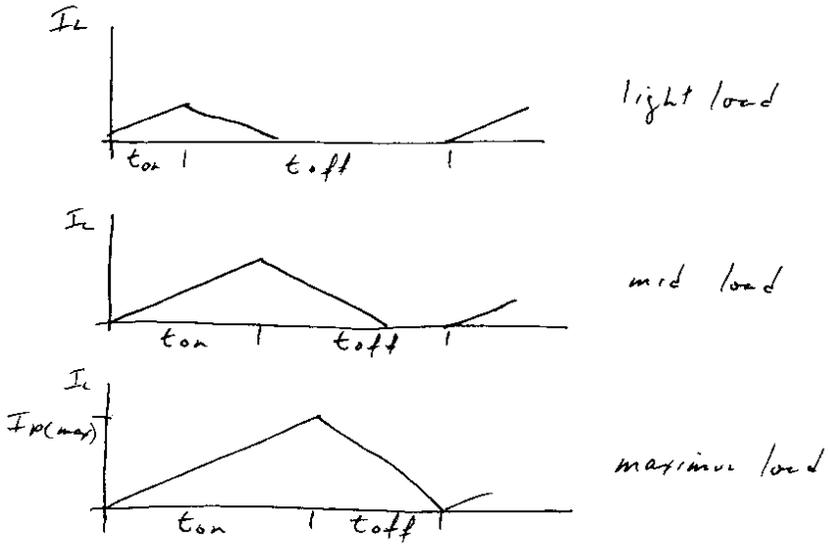


From this we observe that the average current value is somewhat lower than the peak current value. If the average current needs to be increased (or decreased) because of the load, the ON time can be increased (or decreased) accordingly.

During the ON period, energy is transferred from the input power source to the inductor. During the OFF period, energy is transferred from the inductor to the load side of the circuit.

A pulsing current is generally not directly usable by a load. Therefore a capacitor is required to accumulate the excess current and discharge it when required. This forms the basis of the simplest switching converter, namely the buck or step down converter.

Many of the design equations for a switch mode power supply can be derived by examining the inductor current waveforms.



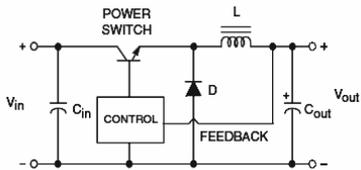
If the inductor current falls to zero, the circuit is operating in the discontinuous mode. If there is always a current in the inductor, it is operating in the continuous mode.

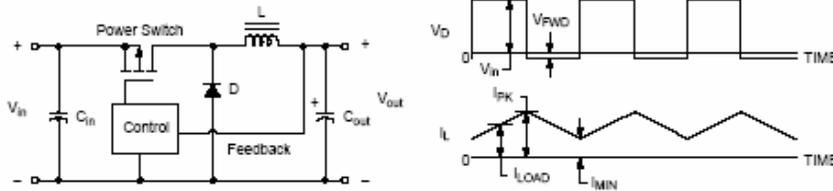
Most SMPS design equations can be derived when the inductor current is just at the continuous/discontinuous threshold.

The relationship between peak inductor current and inductor value can be determined if the slope of the current waveforms can be determined. The size of the inductor can then be determined by finding the relationship between the peak inductor current and the switch OFF time.

3.2 Buck (Step Down)

http://schmidt-walter.fbe.fh-darmstadt.de/snt/snt_eng/snte_pdf.html
http://alpha400.ee.unsw.edu.au/elec4240/Lecture_12.pdf

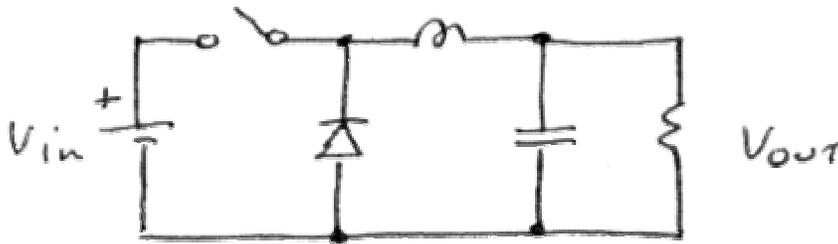




The output voltage is determined by the switch duty cycle:

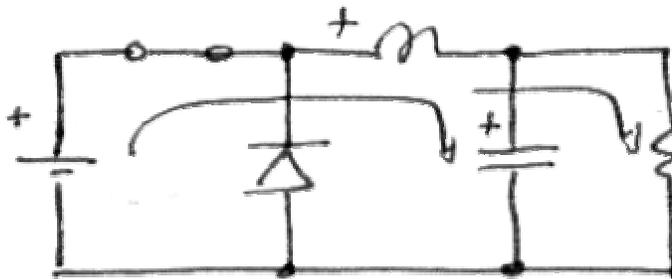
$$V_{out} = V_{in} \left(\frac{t_{on}}{t_{on} + t_{off}} \right)$$

Initial State (simplified circuit)



The output voltage is controlled by the switch ON time. The circuit operation can be observed by turning the switch ON and OFF.

Step 1 – Close the switch.



When the switch closes:

The inductor starts to store energy.

Current starts to flow in the capacitor and load.

The diode does not conduct.

The voltage drop across the switch is quite low and is equal to the saturation voltage of the particular transistor used. $V_{sw} = V_{sat} = low$

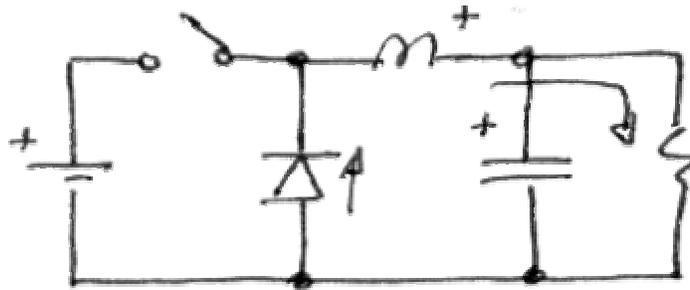
The current during the ON period is:

$$I_L(t) = \frac{V_{in} - V_{sat} - V_{out}}{L} t$$

and reaches a maximum of:

$$I_{pk} = \frac{V_{in} - V_{sat} - V_{out}}{L} t_{on}$$

Step 2 – Open the switch.



When the switch opens:

The voltage across the inductor reverses polarity.

The inductor releases its stored energy to the capacitor and load.

The diode starts to conduct.

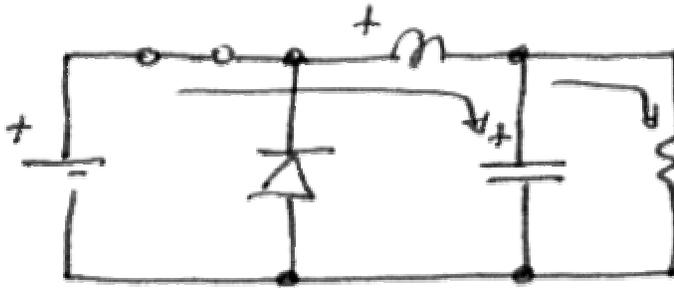
The current during the OFF period is:

$$I_L(t) = I_{pk} - \frac{V_{out} + V_D}{L} t$$

The slope of the falling inductor current is:

$$I_L = -\frac{V_{out} + V_D}{L}$$

Step 3 – Close the switch.

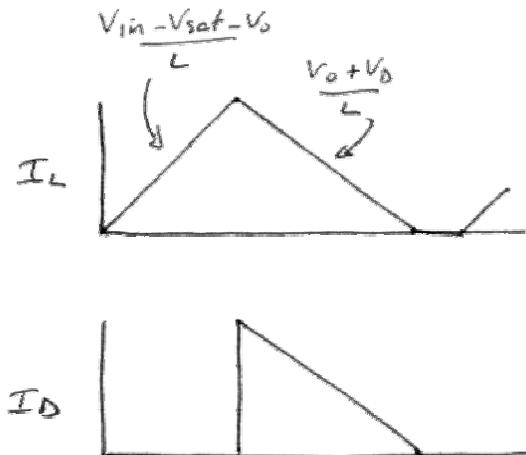


When the switch closes:

The voltage across the inductor reverses polarity.

The process repeats.

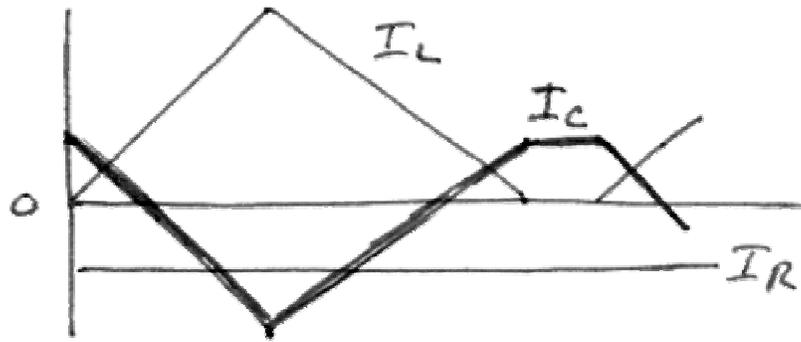
Current Waveforms



The direct currents in the inductor, diode, and load resistance are quite easy to approximate. The capacitor current however is more complex since it is AC.

The capacitor will alternately accept current from the inductor, thus storing charge when the switch is ON, and discharge through the load when the switch is OFF. The capacitor current can be approximated by using Kirchoff's current law: the sum of all currents in a node is zero.

$$I_C + I_L + I_R = 0$$



Positive values in the above diagram represent currents entering the node and negative values represent currents leaving the node.

From this we observe that the inductor and load currents are DC, however the capacitor current is AC. The positive capacitor currents represent it discharging current to the load and the negative values represent it being recharged by the inductor.

The principle losses will be the voltage drop across the switch (a transistor) and the resistive loss across the inductor (generally very small).

Deriving the Minimum Inductor Value

From the falling inductor current waveform, (assuming continuous operation) we can deduce:

$$I_{pk} = \frac{V_{out} + V_D}{L} t_{off}$$

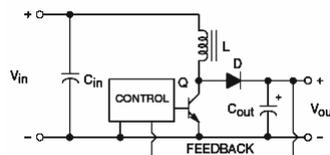
Rearranging we obtain the minimum inductor value:

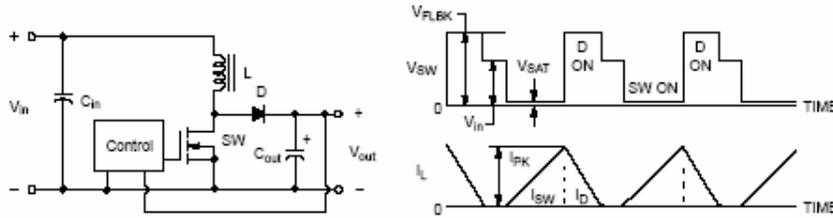
$$L = \frac{V_{out} + V_D}{I_{pk}} t_{off}$$

3.3 Boost (Step Up)

http://schmidt-walter.fbe.fh-darmstadt.de/snt/snt_eng/snte_pdf.html

http://alpha400.ee.unsw.edu.au/elec4240/Lecture_13.pdf

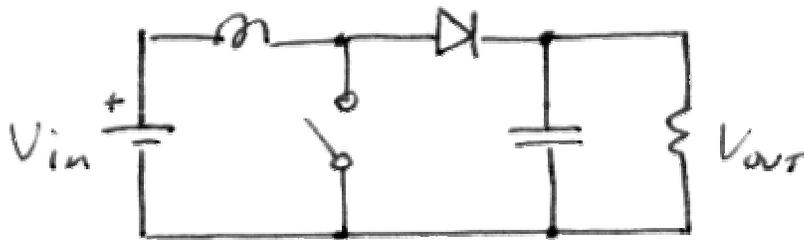




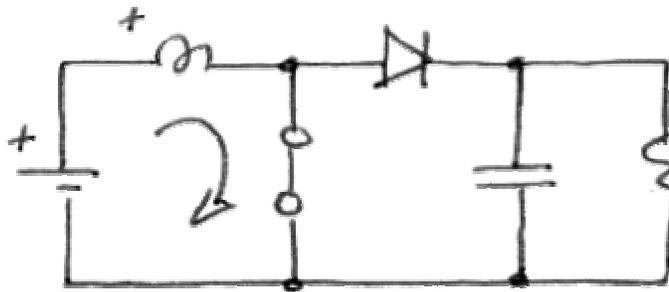
The boost circuit takes advantage of reverse polarity generated across the inductor during the OFF period, and places it in series with the input voltage. This allows the output voltage to exceed input voltage. The output is determined by the switch duty cycle.

$$V_{out} = V_{in} \frac{t_{on}}{t_{off}} + V_{in} = V_{in} \left(\frac{t_{on}}{t_{off}} + 1 \right)$$

Initial State (simplified circuit)



Step 1 – Close the switch.



When the switch closes:

The inductor starts to store energy.

The diode does not conduct.

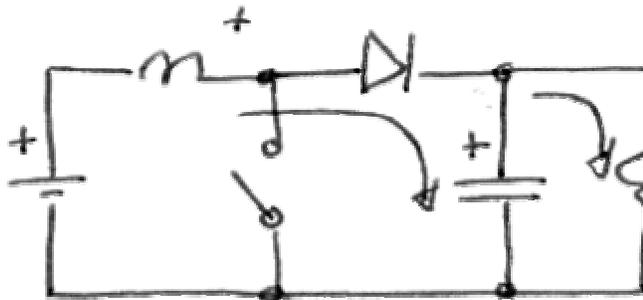
The inductor current during the ON period is:

$$I_L(t) = \frac{V_{in} - V_{sw}}{L} t$$

and reaches a maximum of:

$$I_{L(\max)} = \frac{V_{in} - V_{sw}}{L} t_{on}$$

Step 2 – Open the switch.



When the switch opens:

The voltage across the inductor reverses polarity.

The diode starts to conduct.

The inductor current during the OFF period is:

$$I_L(t) = I_{pk} - \frac{V_{out} + V_D - V_{in}}{L} t$$

The slope of the falling inductor current is:

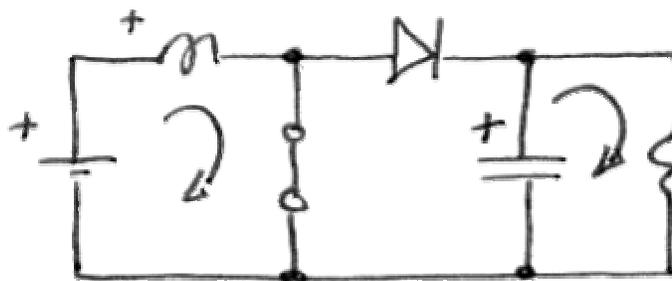
$$I_L(t) = -\frac{V_{out} + V_D - V_{in}}{L} t$$

The output voltage rises to:

$$V_{out} = V_L + V_{in} - V_D$$

The inductor discharges its energy to the capacitor and load.

Step 3 – Close the switch.



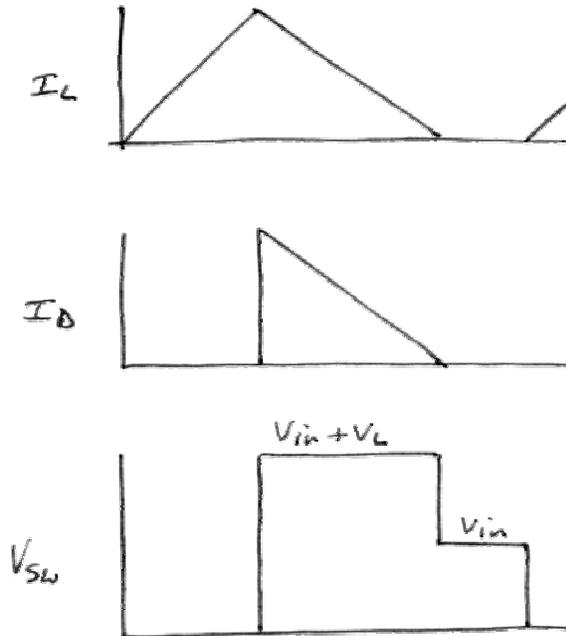
When the switch closes:

The voltage across the inductor reverses polarity.

The capacitor discharges into the load.

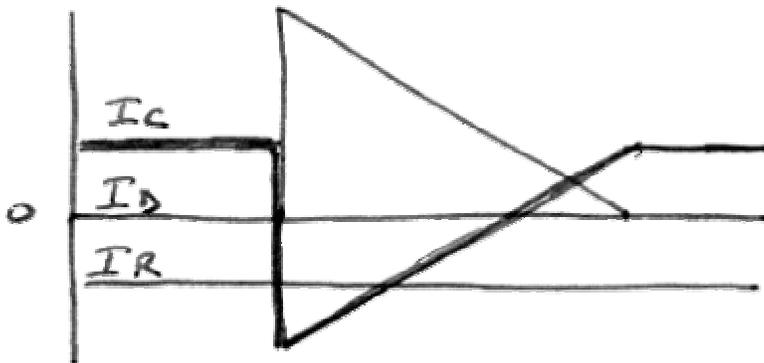
The process repeats.

Principle Waveforms



The capacitor current can be approximated by using Kirchoff's current law: the sum of all currents in a node is zero.

$$I_C + I_D + I_R = 0$$



By increasing the ON time, this circuit can create an output several times the input voltage.

Notice that the stored energy in the inductor is transferred to the load when the switch is OFF. This creates very high surge currents through the diode. It also creates very high voltages across the switch.

Deriving the Minimum Inductor Size

From the falling inductor current (assuming it falls to zero at the end of the cycle) we obtain:

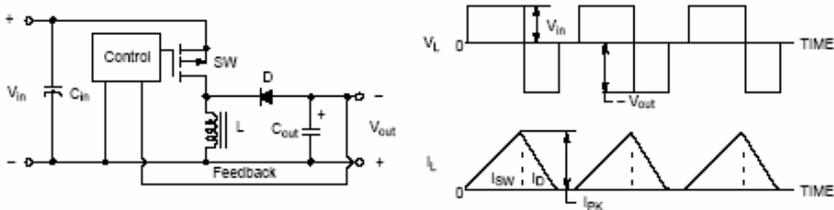
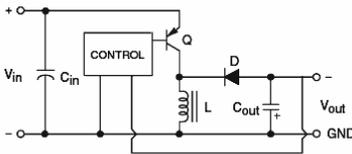
$$I_{pk} = \frac{V_{out} + V_D - V_{in}}{L} t_{off}$$

From this we can determine the inductor size:

$$L = \frac{V_{out} + V_D - V_{in}}{I_{pk}} t_{off}$$

3.4 Inverter (Buck/Boost)

http://schmidt-walter.fbe.fh-darmstadt.de/snt/snt_eng/snte_pdf.html

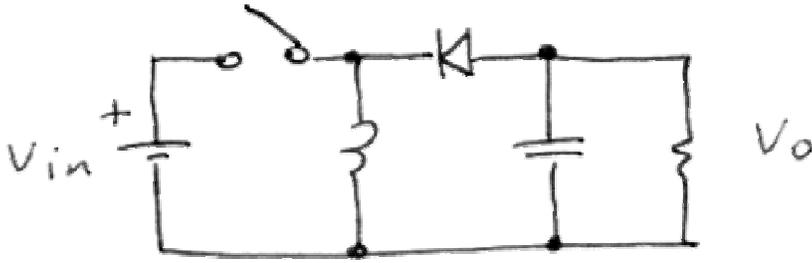


This circuit simply reverses the polarity of the input voltage.

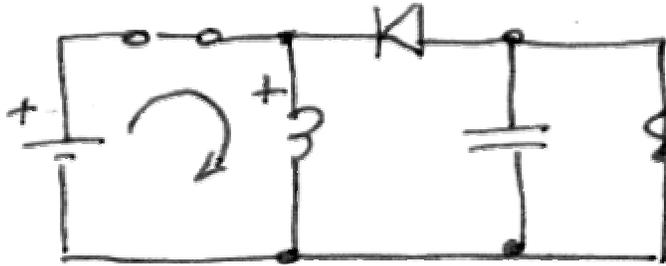
The output magnitude can be less than, equal to, or greater than that of the input.

$$V_{out} = -V_{in} \frac{t_{on}}{t_{off}}$$

Initial State (simplified circuit)



Step 1 – Close the switch.



When the switch closes:

The inductor starts to store energy.

The inductor current during the ON period is:

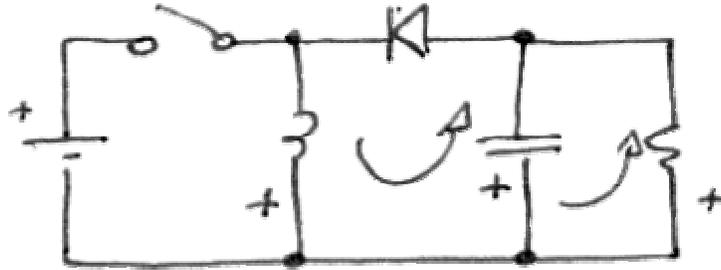
$$I_L(t) = \frac{V_{in} - V_{sw}}{L} t$$

and rises to a maximum of:

$$I_{pk} = \frac{V_{in} - V_{sw}}{L} t_{on}$$

The diode does not conduct.

Step 2– Open the switch



When the switch opens:

The voltage across the inductor reverses polarity.

The diode starts to conduct.

The inductor discharges its energy to the capacitor and load.

The inductor current during the OFF period is:

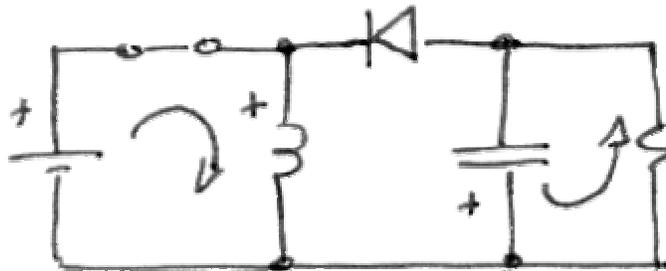
$$I_L(t) = I_{pk} - \frac{V_{out} + V_D}{L}t$$

The slope of the falling inductor current is;

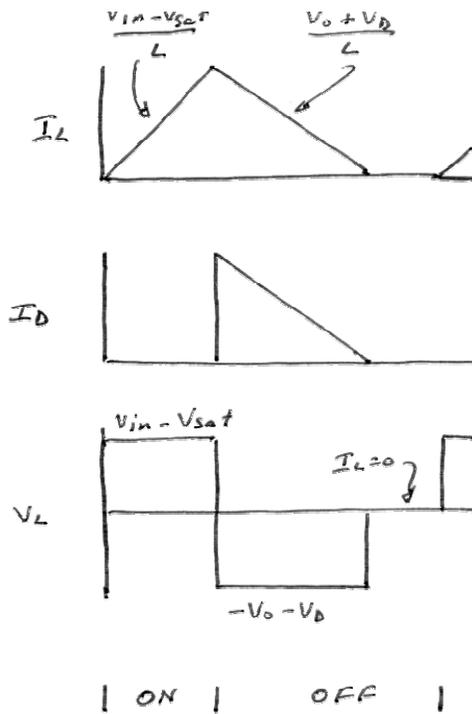
$$I_L = -\frac{V_{out} + V_D}{L}$$

The output voltage is negative.

Step 3– Close the switch.

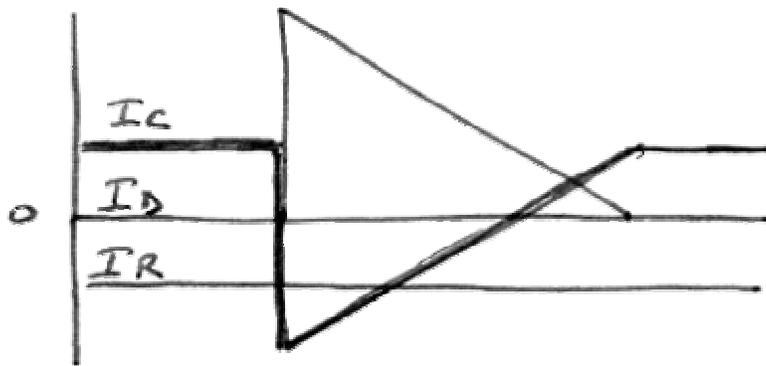


Principle Waveforms



The capacitor current can be approximated by using Kirchoff's current law: the sum of all currents in a node is zero.

$$I_C + I_D + I_R = 0$$



Deriving the Minimum Inductor Size

From the falling inductor current, we observe that:

$$I_{pk} = \frac{|V_{out}| + V_D}{L} t_{off}$$

Rearranging, we obtain:

$$L = \frac{|V_{out}| + V_D}{I_{pk}} t_{off}$$

3.5 Flyback Converter

http://schmidt-walter.fbe.fh-darmstadt.de/snt/snt_eng/snte_pdf.html

http://schmidt-walter.fbe.fh-darmstadt.de/snt/snt_eng/snteng3b.pdf

<http://www.national.com/appinfo/power/files/flyaback-cont2000-5000-new.pdf>

<http://www.national.com/appinfo/power/files/f17.pdf>

<http://www.fairchildsemi.com/an/AN/AN-4137.pdf>

<http://www.fairchildsemi.com/an/AN/AN-4140.pdf>

http://www.eetkorea.com/ARTICLES/2003MAY/A/2003MAY28_AMD_POW_AN.PDF

http://www.eetkorea.com/ARTICLES/2003SEP/A/2003SEP19_AMD_POW_AN02.PDF

<http://pdfserv.maxim-ic.com/en/an/AN1166.pdf>

http://www.powerdesigners.com/InfoWeb/design_center/Appnotes_Archive/5956.pdf

<http://focus.ti.com/lit/ml/slup076/slup076.pdf>

<http://focus.ti.com/lit/ml/slup058/slup058.pdf>

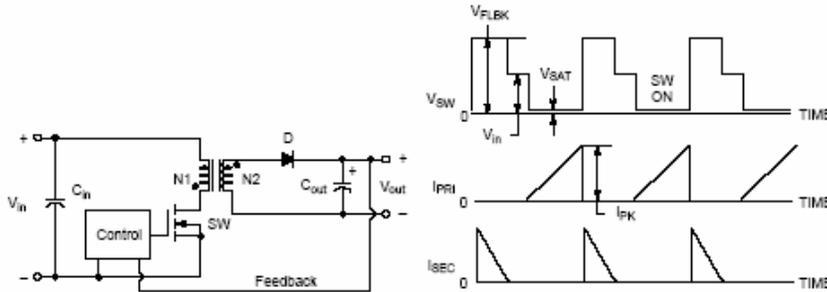
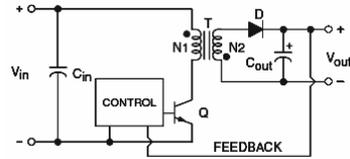
http://alpha400.ee.unsw.edu.au/elec4240/Lecture_15.pdf

The single-ended flyback converter is the simplest isolated converter. The transformer is actually a close-coupled inductor and is energized by means of a unipolar pulse.

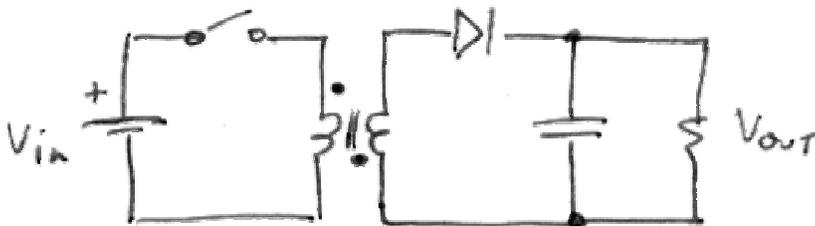
This circuit can be configured to operate as a boost, buck, or inverting converter. The output circuit is also isolated from the input.

This technique can be used to create multiple output power supplies since load changes on one winding have little effect on the others. A disadvantage of this approach is the need for large filter capacitors since the entire load current is ultimately supplied during the transistor OFF period. The capacitor should have a low ESR.

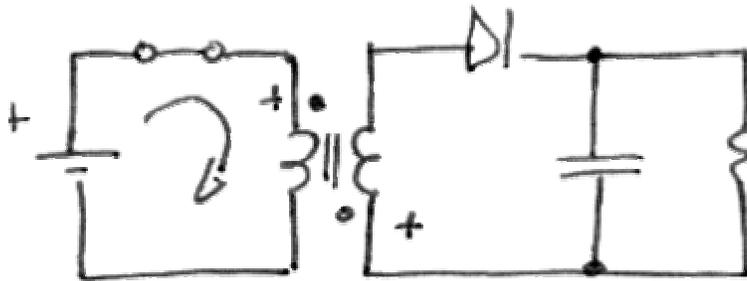
Flyback converters are relatively inexpensive and are widely used in high voltage monitor supplies.



Initial State (simplified circuit)



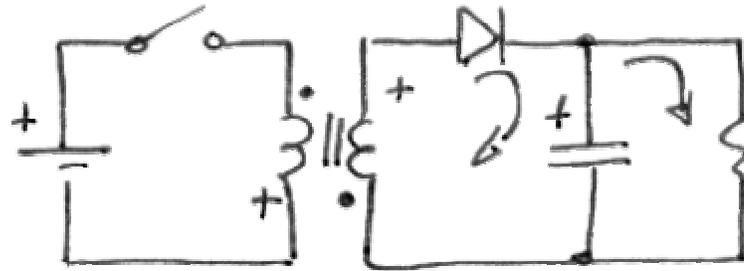
Step 1 – Close the switch.



When the switch closes:

Current begins flowing in the primary inductor, but not in the secondary.

Step 2 – Open the switch.



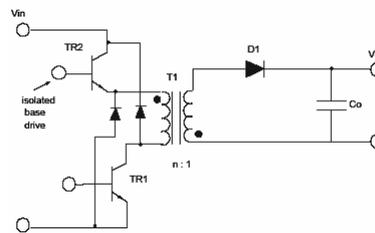
When the switch opens:

An initial high inductive kickback voltage is generated across the primary.
(The forward converter removes this high voltage spike by adding a diode and clamp winding across the primary)

Current begins flowing in the secondary inductor, but not in the primary.

The secondary winding voltage is reflected across the primary.

Two-Transistor Flyback Converter

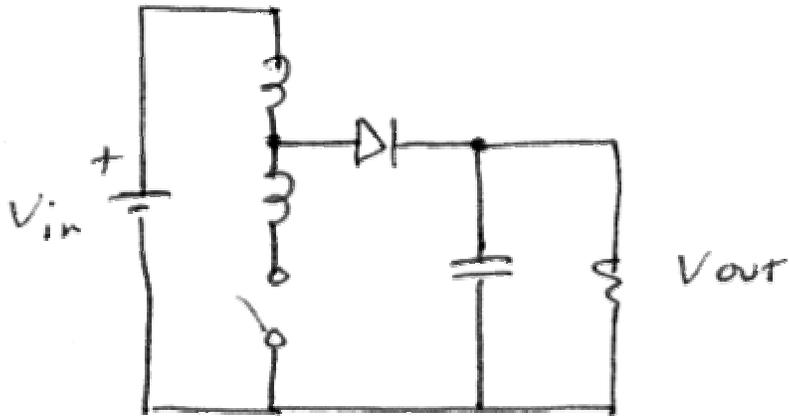


The very high inductive kickback which occurs when the switch turns OFF places a great deal of strain on the transistor. This can be reduced by using two transistors and a pair of steering diodes. This prevents the voltage across either switch from exceeding the input voltage level.

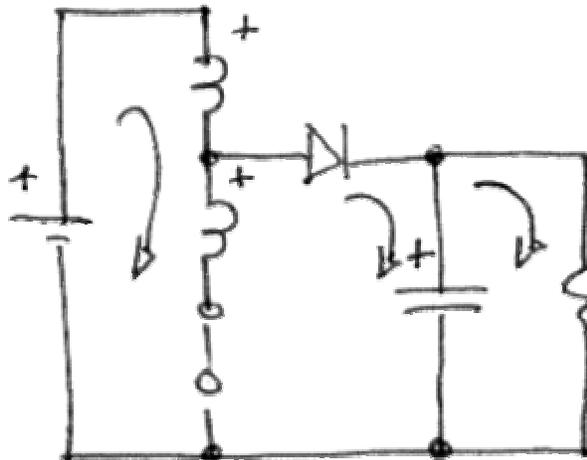
3.6 Current Boosted Boost

This arrangement allows current to flow from the input to the load at all times thus reducing the current demands on the transistor switch. However, the transistor switching voltage increases.

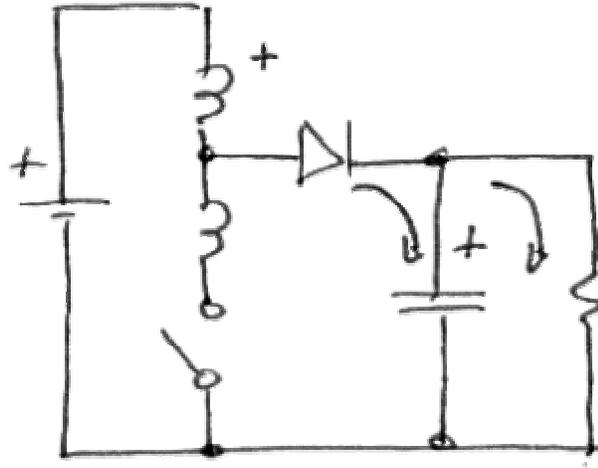
Initial State



Step 1 – Close the switch.



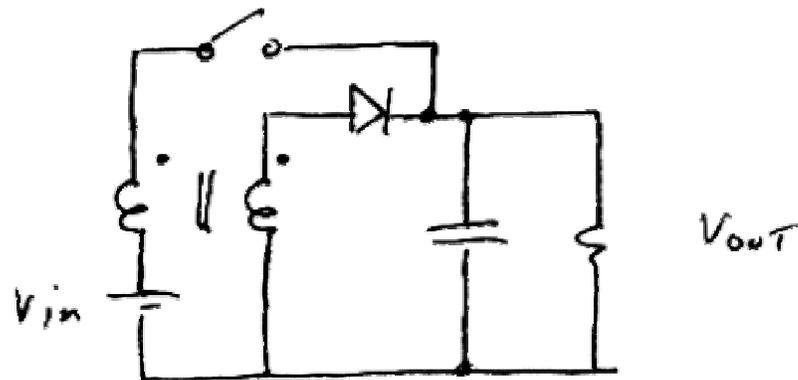
Step 2 – Open the switch.



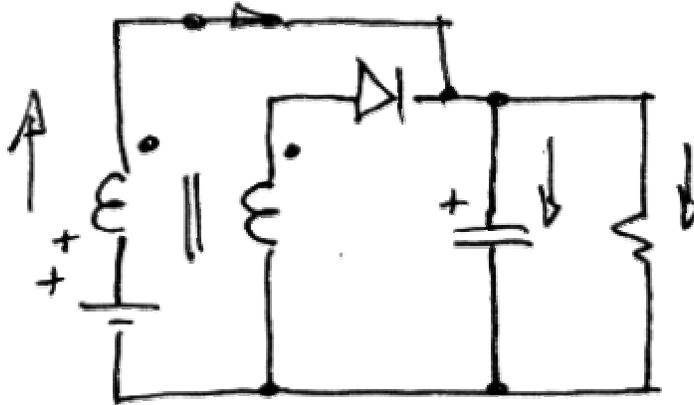
3.7 Current Boosted Buck

This circuit uses a transformer to increase the output current. This effectively decreases the current rating of the transistor but unfortunately increases its voltage rating.

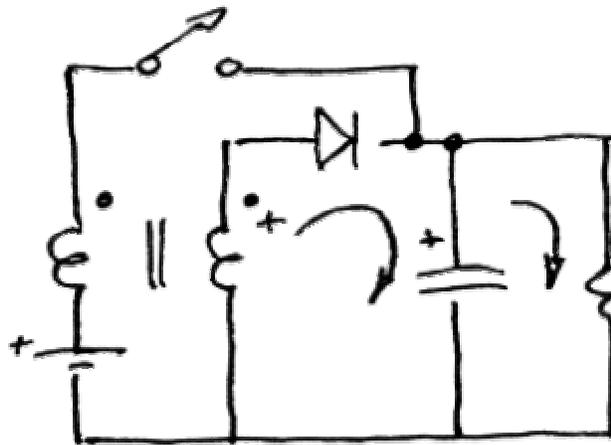
Initial State



Step 1 – Close the switch.



Step 2 – Open the switch.



3.8 Forward Converter

<http://www.onsemi.com/pub/Collateral/AND8039-D.PDF>

<http://www.fairchildsemi.com/an/AN/AN-4134.pdf>

<http://www.national.com/appinfo/power/files/f22.pdf>

<http://www.national.com/an/AN/AN-776.pdf>

<http://www.powerint.com/PDFFiles/an31.pdf>

http://www.eetasia.com/ARTICLES/2004DEC/A/2004DEC01_MPR_AN03.PDF

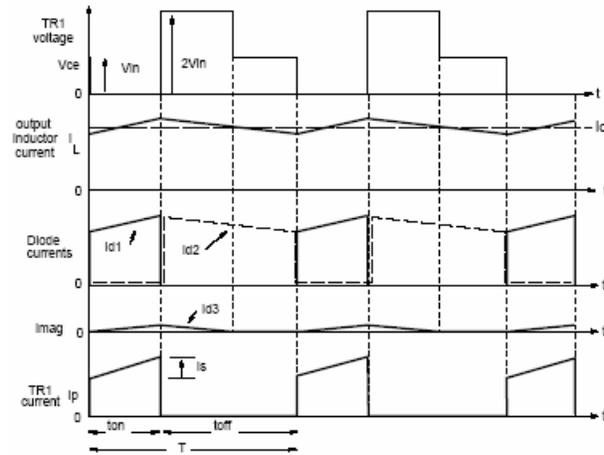
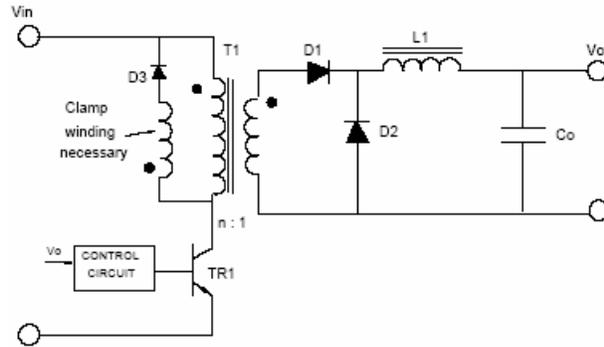
<http://www.coremaster.com/appnotes/an106.pdf>

<http://www.coremaster.com/appnotes/an107.pdf>

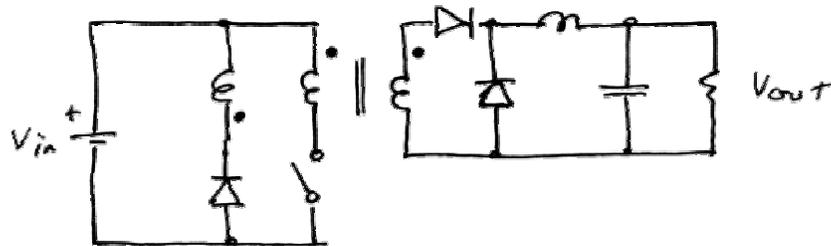
<http://www.coilws.com/AppNotes/FTT%20AN02.pdf>

<http://alpha400.ee.unsw.edu.au/elec4240/Lecture%2016.pdf>

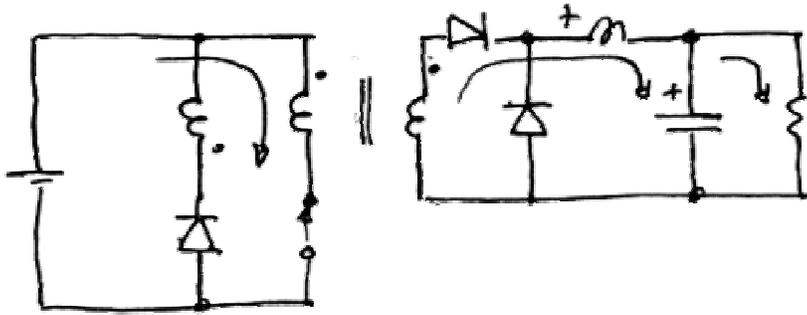
The reset winding (left) dumps the stored energy in the primary winding back to the input source. If this did not happen, the voltage across the primary would attempt to rise to infinity and blow the switching transistor. Magnetizing flux would also buildup and saturate the core.



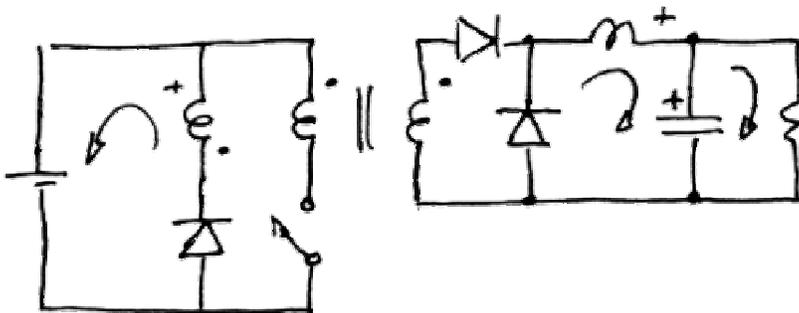
Initial State



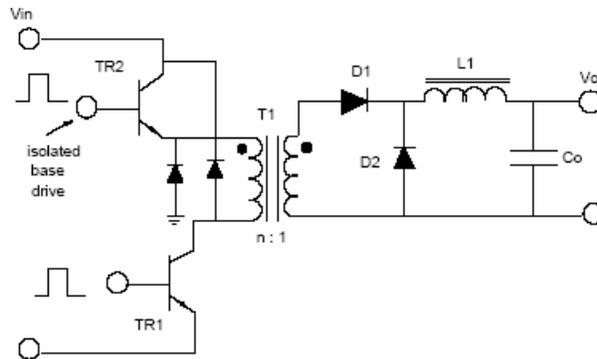
Step 1 – Close the switch.



Step 2 – Open the switch.



Two-Transistor Forward Converter



3.9 Cuk Converter

This very popular converter has low input and output ripple. By controlling the duty cycle, it can be operated as a boost or buck regulator.

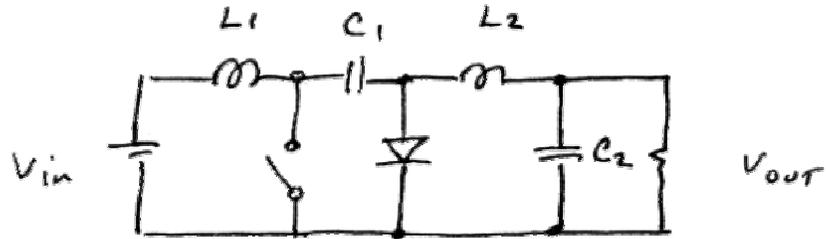
<http://focus.ti.com/lit/an/slva158/slva158.pdf>

<http://www.irf-japan.com/technical-info/appnotes/an-1077.pdf>

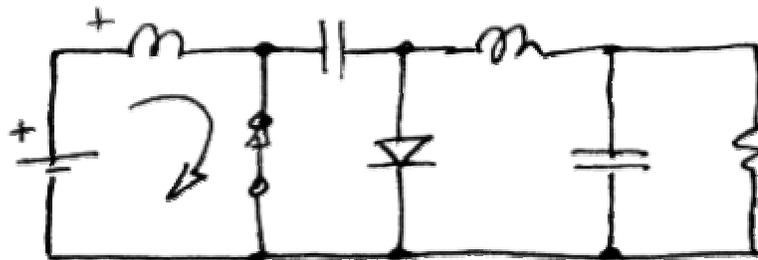
<http://www.national.com/ds/LM/LM2611.pdf#page=1>

http://alpha400.ee.unsw.edu.au/elec4240/Lecture_14.pdf

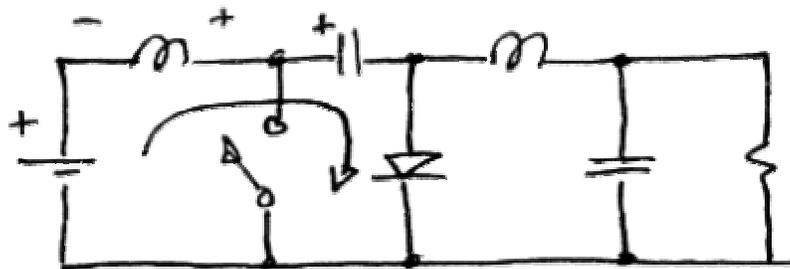
Initial State



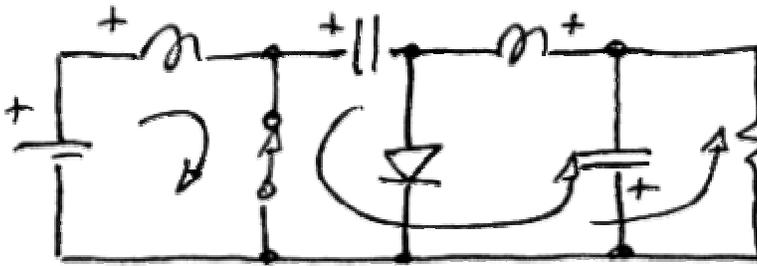
Step 1 – Close the switch.



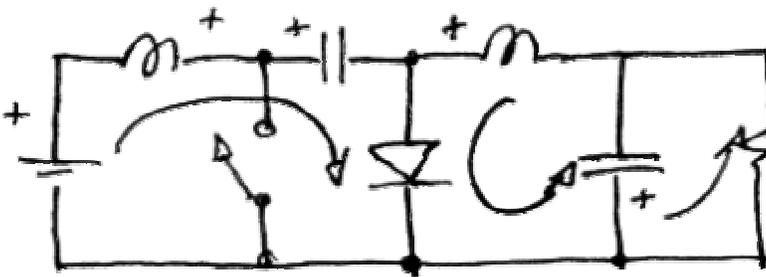
Step 2 – Open the switch.



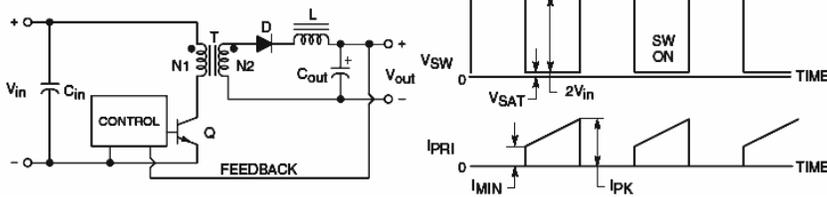
Step 3 – Close the switch.



Step 4 – Open the switch.

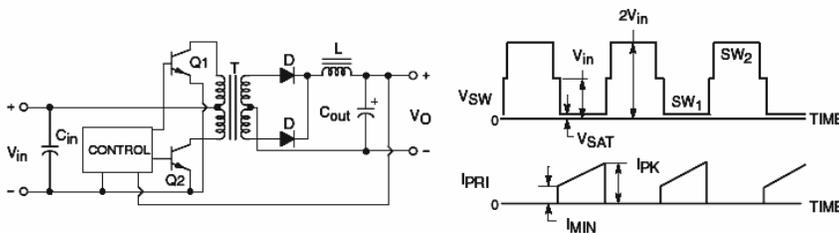


3.10 Half-Forward Regulator

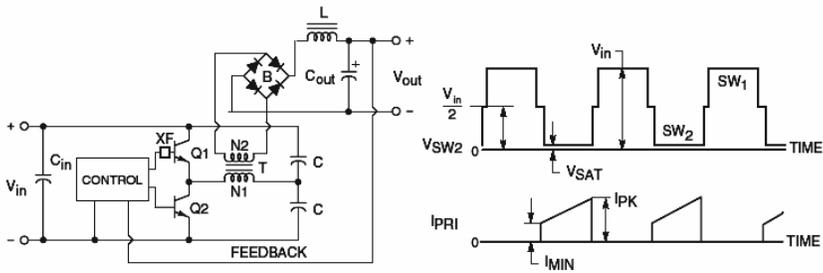


3.11 Push-Pull Regulator

<http://alpha400.ee.unsw.edu.au/elec4240/Lecture%2017.pdf>



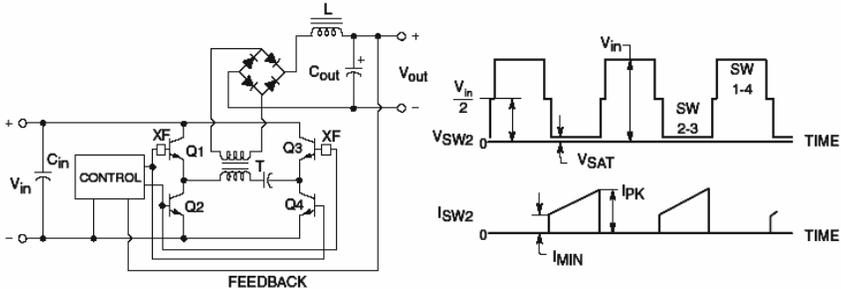
3.12 Half-Bridge Regulator



3.13 Full-Bridge Regulator

http://alpha400.ee.unsw.edu.au/elec4240/Lecture_14.pdf

<http://alpha400.ee.unsw.edu.au/elec4240/Lecture%2017.pdf>



Assignment Questions



On-Line Test

Quick Quiz

1. If a fixed voltage is applied to an ideal inductor, the current will attempt to increase [linearly, exponentially].
2. Adding a resistor in series with an inductor does not alter the current waveform. [True, False]
3. It takes approximately [2, 5, 7] time constants for the current in an inductor to reach its final value.
4. If the switch duty cycle is 50%, the peak current is approximately [on half, twice] the average current.
5. Most loads require a pulsing current source. [True, False]
6. A buck regulator is also known as a step up converter. [True, False]
7. The boost circuit does not take advantage of the polarity reversal across the inductor during the OFF period. [True, False]
8. In more expensive SMPS devices, the capacitor is integrated on the chip. [True, False]
9. Switching power converters achieve an efficiency of 70% or better. [True, False]
10. SMPS bipolar switching transistors should have a gain-bandwidth product of approximately _____ MHz.
- 11.

Composition Questions

To answer these questions, it will be necessary to do some research.

1. What are the four main components in a SMPS?
2. List the three modulation schemes used in SMPS.
3. The sampling circuit generally consists of a simple voltage divider. [True, False]
- 4.

Analytical Questions

1.



For Further Research

