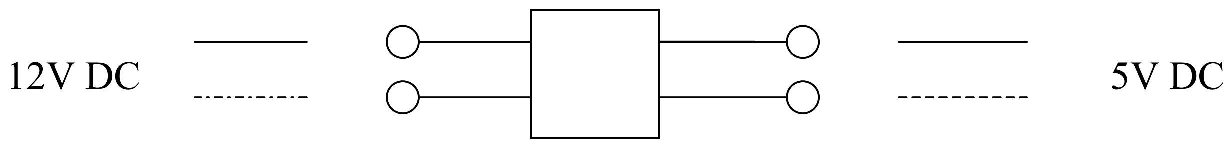
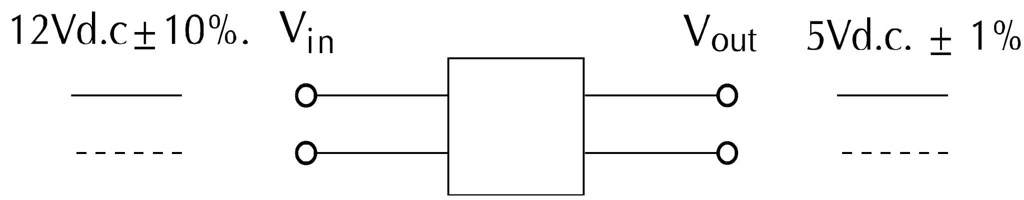
The Voltech Handbook of Power Supplies

1 Introduction

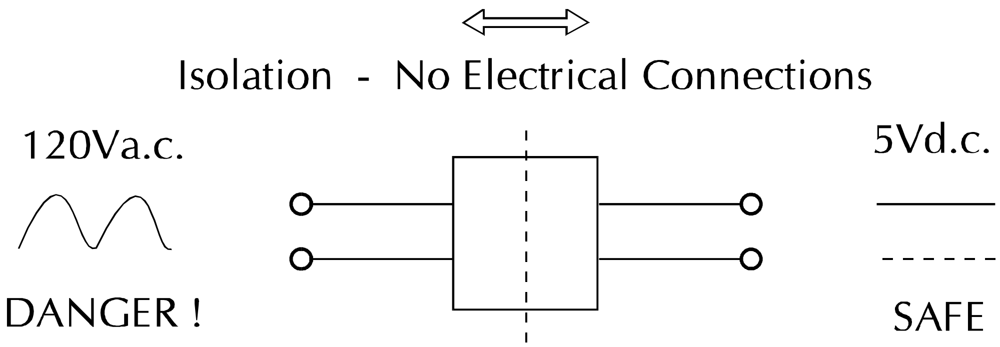
Power supplies are used to convert electrical power from one form to another. Inputs and outputs may be at different voltages and either DC or AC:



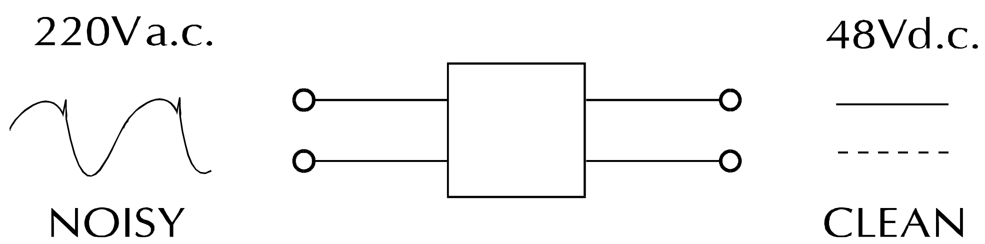
Power supplies may be used to improve the voltage tolerances that are available:



to provide isolation from dangerous voltages:



or to provide immunity from noisy inputs:



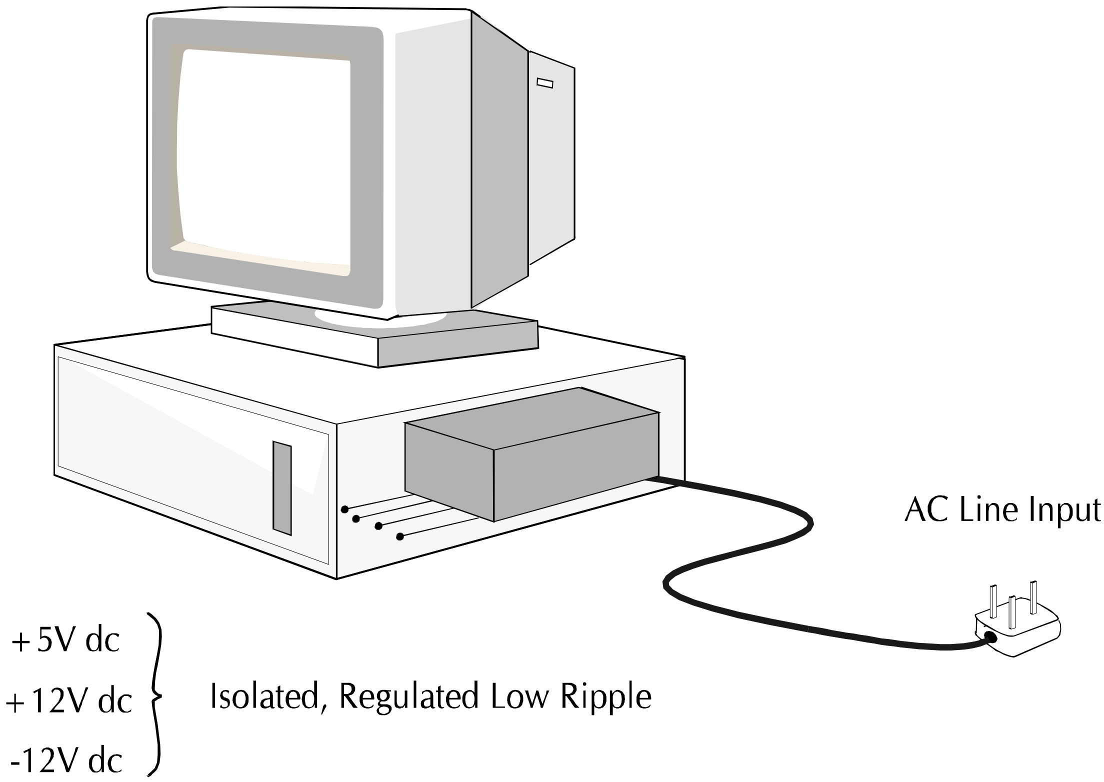
This handbook reviews some of the circuits and techniques that are found in modern power supplies. In section 2, two popular power circuit "topologies" are presented along with their waveforms.

Pulse Width Modulation (PWM) circuits are discussed in section 2.3. Power factor correction and Inrush Current protection are reviewed in section 2.4 and 2.5.

Modern power supplies are required to operate with high efficiency over a wide range of input conditions. The harmonic content of the input current may be limited by specification or international standards. It is essential to make accurate measurements of the input and output quantities to ensure the power supply is functioning correctly and/or verify its design. Power supply measurements are discussed in section 3.

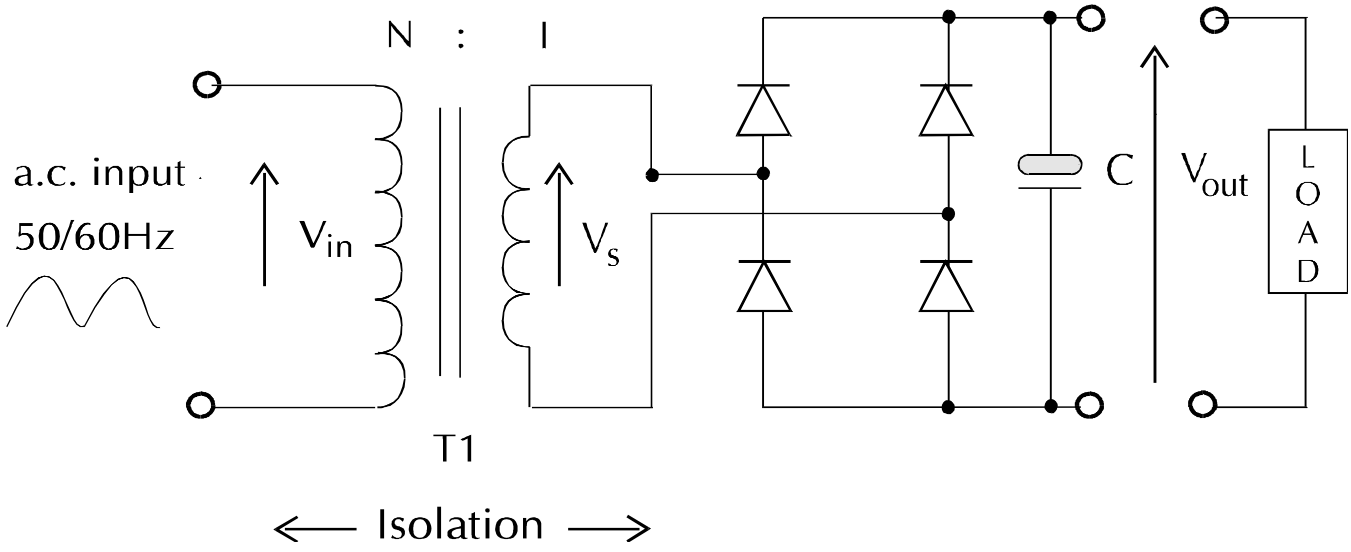
2 AC Line to DC Power Supplies.

The electronic circuits found inside computers, photocopiers, televisions and many other common goods need low voltage dc power. The ac line is a convenient source, and power supplies are used to convert power from the high a.c. line voltage to low voltage dc.



A typical power supply provides several low voltage d.c. outputs that are:

- ISOLATED from the a.c. supply
- REGULATED i.e. the outputs change little when
- either the load current or line voltage changes.
- and contain LOW RIPPLE and NOISE.



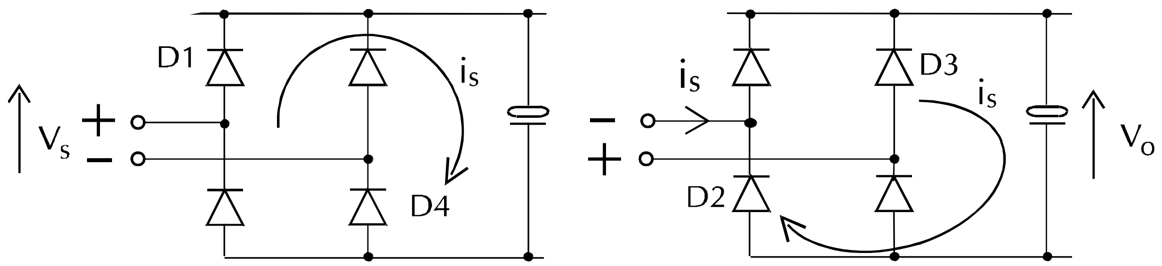
A simple ac line to dc power supply:

2.1 Circuit Description.

Transformer T1 steps down the input voltage and isolates the rest of the circuit from the line.

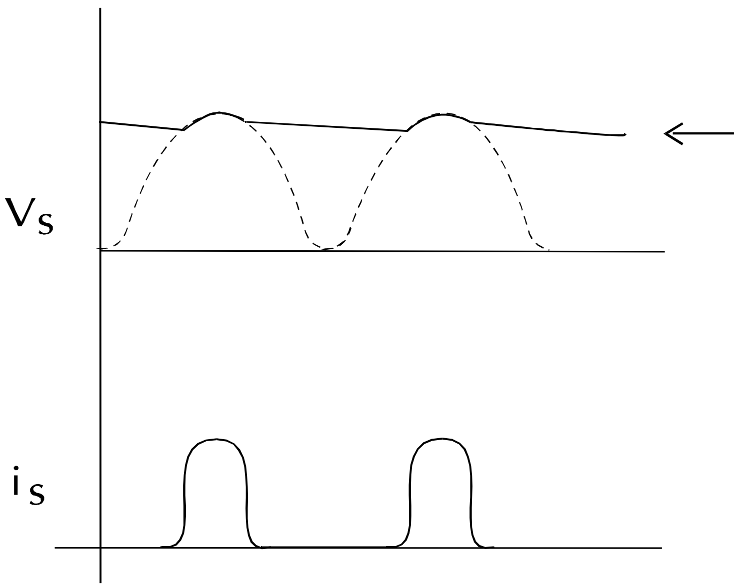
$$V_s = \frac{V_{in}}{N}$$

The diode bridge rectifies the ac output of the transformer into dc.



Current flows through diodes D1 and D4 when the dot end of the transformer is positive, and through D3 and D2 when the non-dot end is positive.

The output voltage stays at near the peak of the transformer secondary voltage:

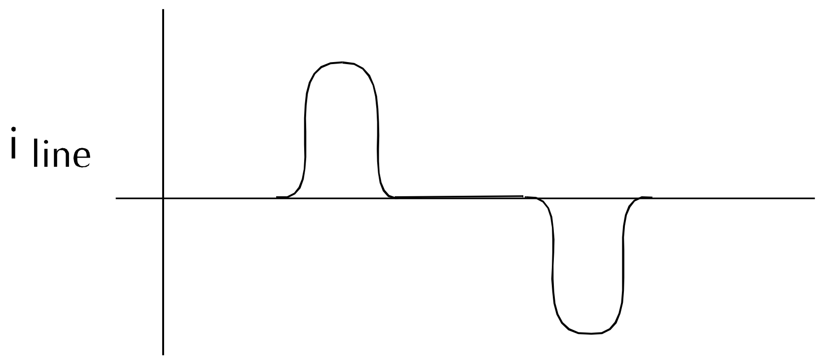


$$Vout = \frac{Vin \times \sqrt{2}}{N}$$

Where N = transformer turns ratio

Current will only flow into the capacitor when Vs > Vout. The current is no longer sinusoidal, but distorted because current only flows near the voltage peaks.

A similar current is drawn from the ac line.



Even in the simplest ac line to dc power supplies the current waveform can be heavily distorted.

Transformer, rectifier and capacitor circuit:

Advantages:

Simple, low cost.

Low EMI

Disadvantages:

Poor regulation.

Large output ripple at twice the line frequency.

Applications:

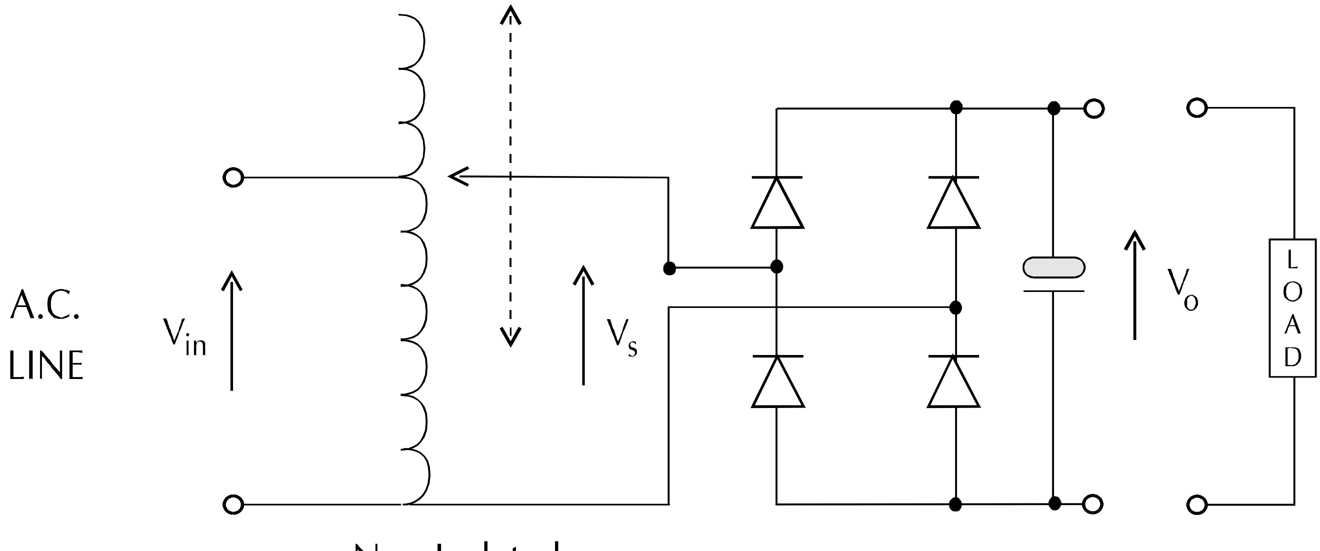
Where only crude d.c. power is required.

Battery chargers.

Electrochemical - e.g. Aluminium smelting

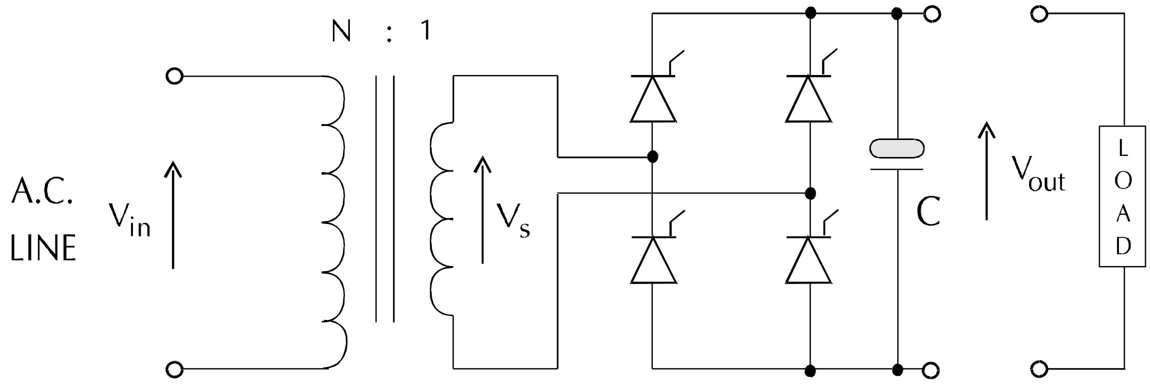
Regulation can be improved by controlling the voltage at some point in the circuit. Examples of these are:

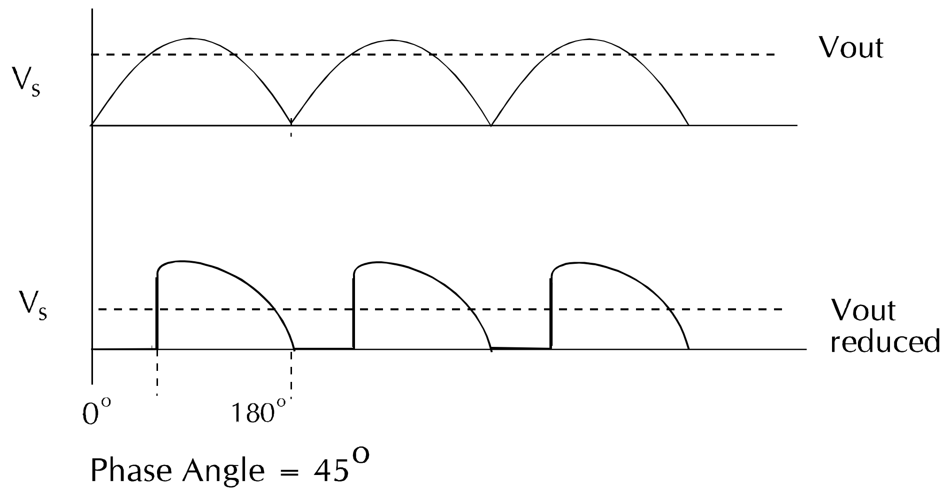
(i) At the input with an auto - transformer.



The output voltage is regulated by changing the effective input voltage, V_S

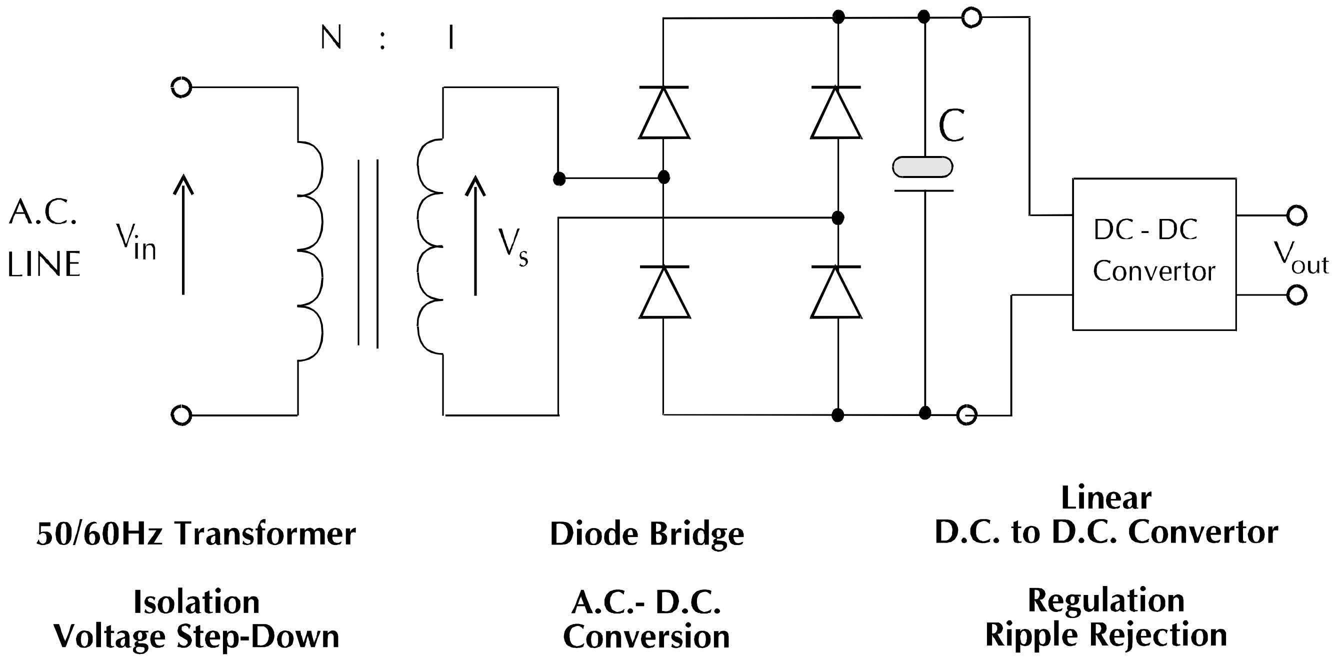
(ii) In bridge circuit by using SCR's (Silicon Controlled Rectifiers or thyristors)





SCR's have to be triggered into a conducting 'ON' state. If the point in the cycle where this occurs is varied, then the average value of voltage presented to the capacitor is also changed. This is called phase control.

(iii) By using a regulated dc to dc convertor. e.g. **A Linear Power Supply**



Linear Power Supply:

Advantages:

Simple, Low cost, Low EMI.

Disadvantages:

Transformer constructed using an iron core will be

Relatively large and heavy.

Large value of C required to reduce output ripple

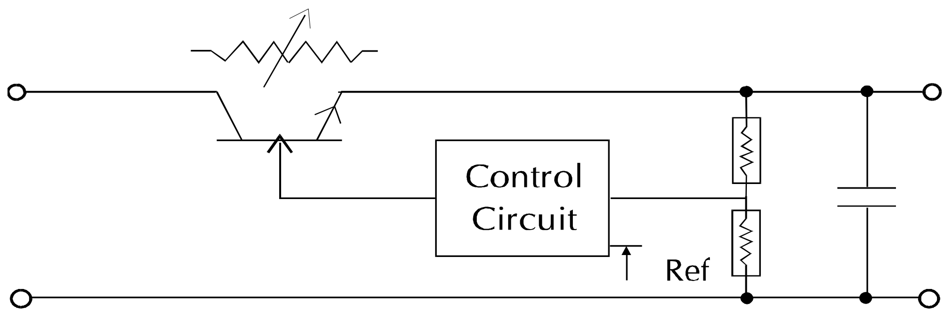
Linear d.c. to d.c. convertor inefficient.

Applications:

Common <100W where size and weight are not important.

3 Linear DC to DC converters.

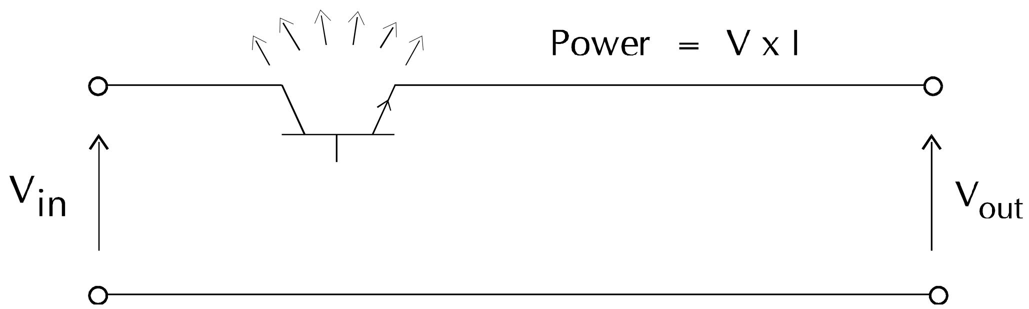
A common and simple form of DC to DC convertor is the series pass regulator. The effective resistance of the transistor is controlled so as to maintain a constant output voltage over a range of input and output conditions.



The control circuit operates by first amplifying the difference between a sample of the output and a reference voltage. This voltage is then used to control the effective resistance of the transistor by changing its base current.

Power is lost in the series pass transistor and dissipated as heat. For a 12V to 5V linear DC to DC convertor rated at 1A the power loss will be:

$$(12V - 5V) \times 1A = 7 \text{ Watts}$$



In the above case the efficiency will be:

$$\frac{\text{Output Power}}{\text{Input Power}} \times 100\% \qquad \frac{5V \times 1A}{12V \times 1A} \times 100\% = 42\,\%$$

The transistor is operating in its linear region. That is the transistor is neither fully on nor fully off. Power supplies that use this type of DC to DC convertor are called linear power supplies.

Advantages:

Low output noise,

Low cost.

No RFI or EMI.

Fast transient response.

Disadvantages:

Poor efficiency, which means unnecessary heat loss.

The output voltage has to be lower than the input voltage, i.e. it is a step down convertor.

There is no electrical isolation between input and output.

Applications:

Up to 50W. Local Regulation.

4 Switched Mode DC to DC Convertors.

The overall size of common electrical and electronic equipment is being constantly reduced. The large scale integration and improved packaging of electronic circuits has made this possible. The size of the power supply is reduced to match.

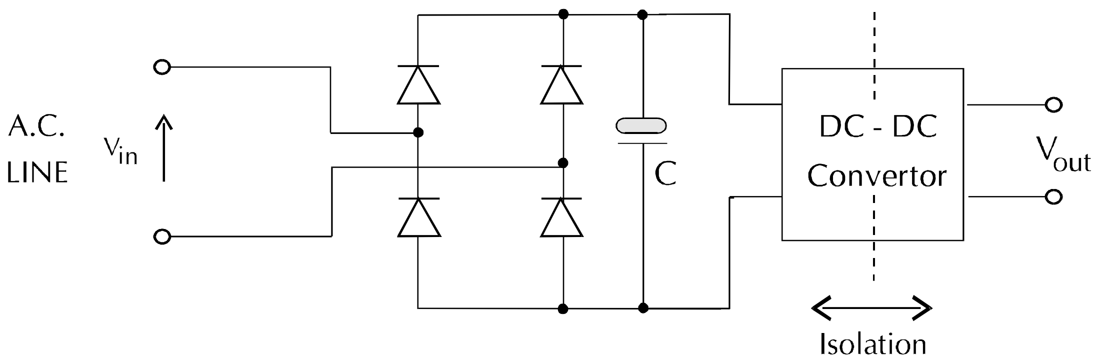
The waste heat generated by a power supply must now be dissipated over a smaller area. To avoid large temperature rise the power supply losses must be reduced.

$$\text{Power Loss} = \text{Input Power} - \text{Output Power.}$$

$$\text{Efficiency} = \frac{\text{Output Power} \times 100\%}{\text{Input Power}}$$

This led to the development of switched mode dc. to dc. convertors that operate at high frequency (>20kHz) with improved size, weight and efficiency.

Isolation can be built in to a switched mode dc to dc converter, a small ferrite cored transformer then replacing the large iron cored 50Hz transformer. Typically then, the line input is rectified directly to produce a high voltage dc which is the input to an isolated dc to dc convertor.



4.1 Forward Convertors.

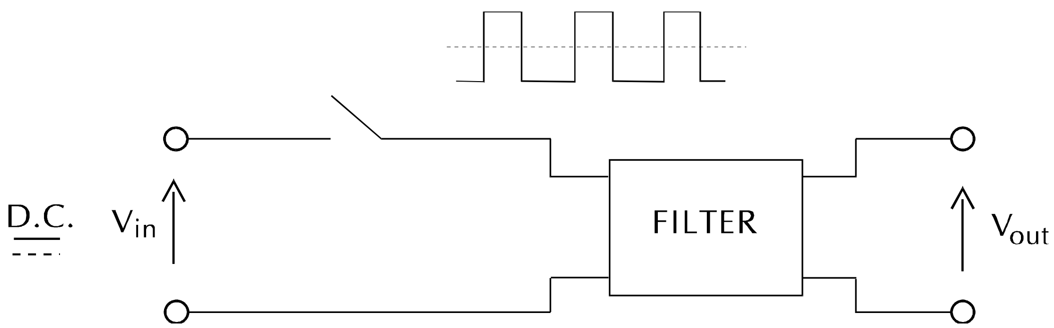
The principle of a Forward Convertor is that it chops the input D.C. voltage and transfers power to the output during the 'on' state while energy is simultaneously stored in an inductor. This stored energy is used to transfer power to the output during the 'off' state.

The buck regulator is a simple example of a non-isolated forward convertor, and its operation is described in detail below.

The toplogies that follow the buck regulator (4.1.2 - 4.1.6) have the additional benefit of transformer isolation. In addition, the transformer turns ratio allows for large differences between the input and output voltages whilst maintaining reasonable cycle on/off ratios.

4.1.1 Buck Regulator.

Switched mode DC to DC convertors can overcome all of the linear regulator disadvantages. They use a power switch to chop the DC input voltage into AC, which is then filtered to produce a DC output.



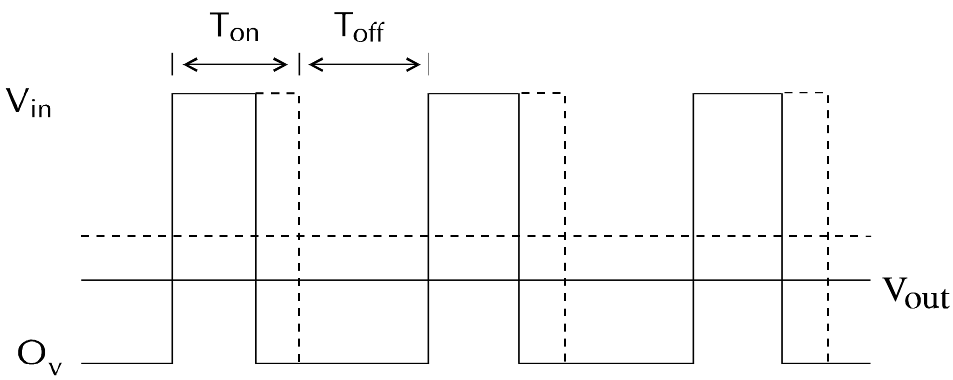
The output voltage will be the average value of the AC waveform.

The switch (normally a transistor) is either fully on or completely off. When the switch is on, a large current flows through it, dropping only a small voltage. Power loss (V x I) is also small.

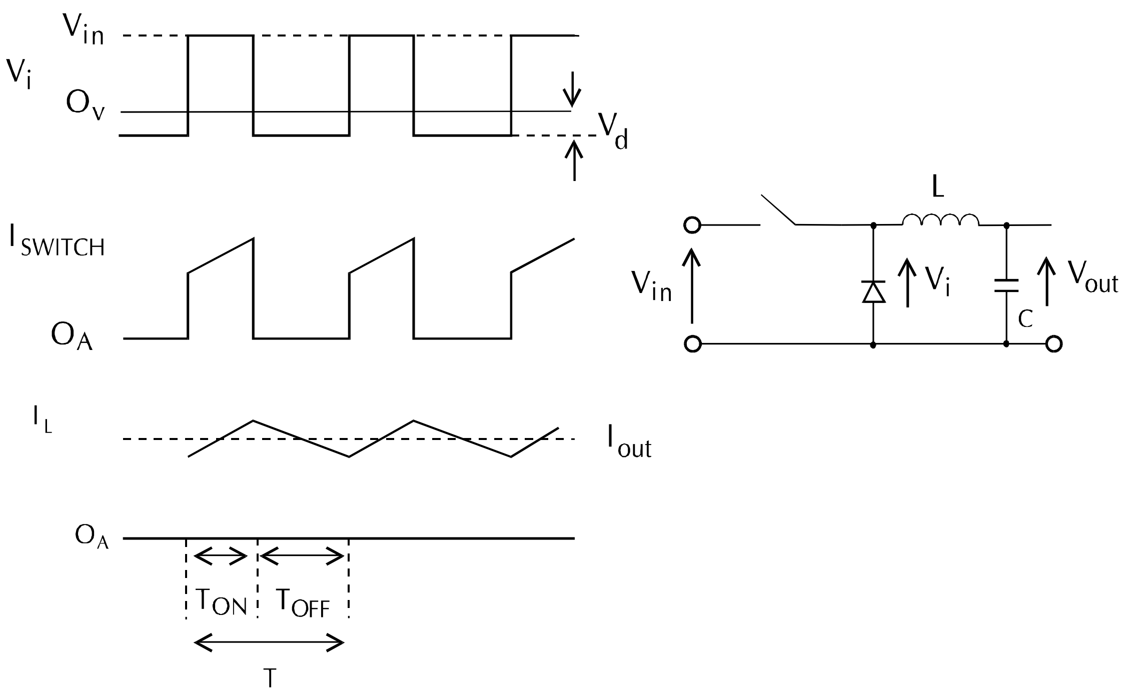
When the switch is off, there is a large voltage across it, but very little current flow. The power loss is again small.

The switch only operates in its dissipative linear region for very brief periods of time. The overall power loss is much less than for a linear dc to dc convertor.

The switch is closed for the time T_{on}, and open for the time T_{off}.



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



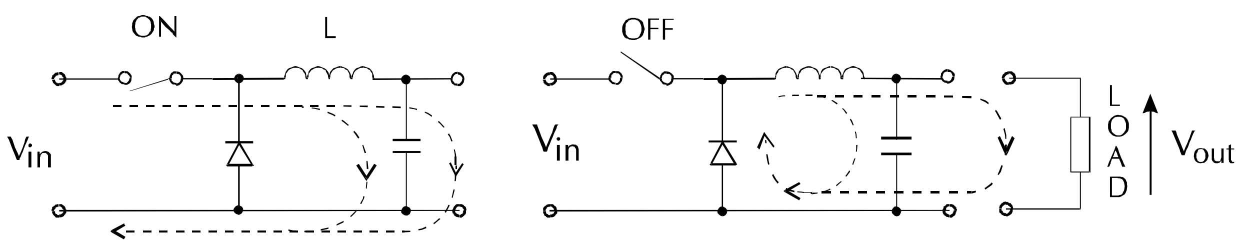
When the switch is closed, there is a constant voltage (V_{in} - V_{out}) across the inductor L, and the current in the inductor ramps up at a rate given by:

$$V = \frac{di}{dt} \qquad \frac{di}{dt} = \frac{(V_{in} - V_{out})}{L} \qquad \text{during } T_{on}$$

When the switch is opened, the voltage across L reverses as it tries to maintain the same current through itself. This voltage is clamped by the diode and the previous current is then restored. The voltage across L is now reversed, however, and equal to V_{out} + V_d. where V_d is the forward voltage drop of the diode. The current thus ramps down at a rate:

$$\frac{di}{dt} = \frac{(V_{out} + V_d)}{L} \qquad \text{during } T_{off}$$

The current in L is the sum of the switch current (during T_{on}) and the diode current (during T_{off}). The average value of these currents is the output current.

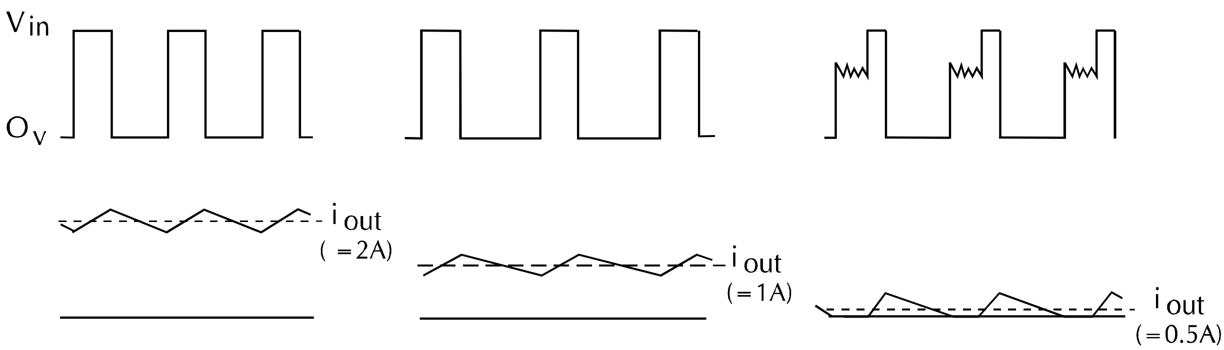


FORWARD CONVERTOR - Energy stored in L during ON time. $V_{out} < V_{in}$

The inductor operates with a high DC bias current. It is made with a gapped ferrite core, or a powdered alloy core which has an effective distributed air gap.

T_{on} and T_{off} remain constant for output current changes if the input and output voltages remain the same. The waveforms remain essentially the same, except that the DC current in the inductor changes. For very low output currents the inductor current will fall to zero for some period of time. The inductor current is said to be discontinuous, the DC to DC convertor operating in discontinuous mode.

For example:

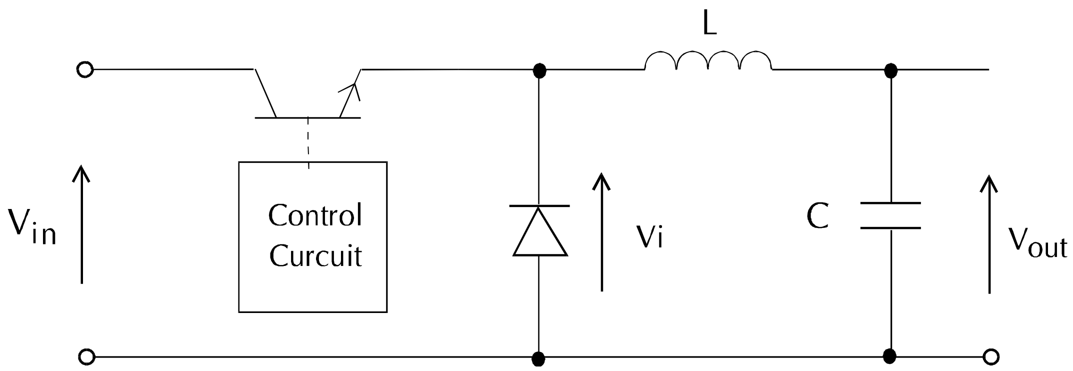


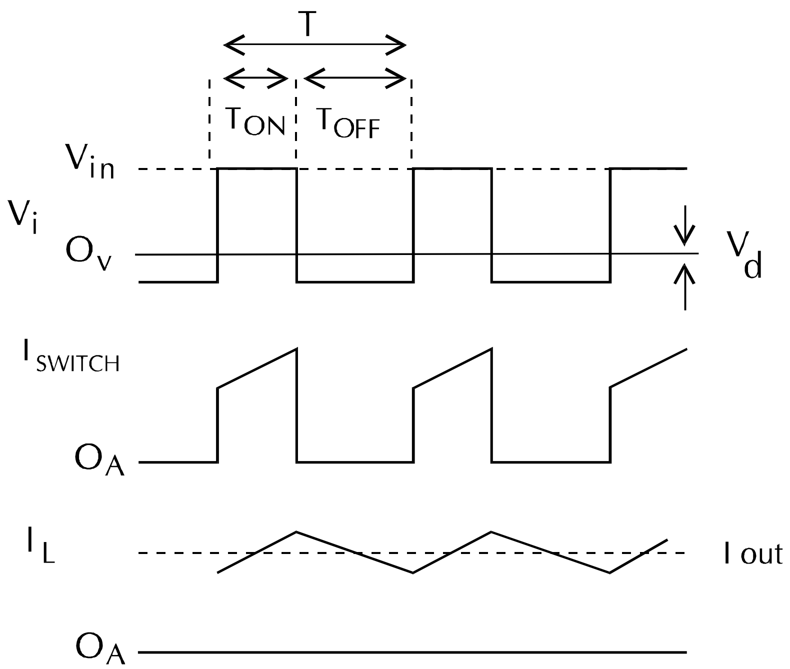
When the inductor current is zero, the voltage across it will also tend towards zero, often ringing first. The relationship:

$$\text{Vout} = \text{Vin} \times \frac{\text{Ton}}{\text{Ton} + \text{Toff}}$$

no longer holds. This can cause problems in the design of the control circuit, and regulation problems in buck type convertors with more than one output.

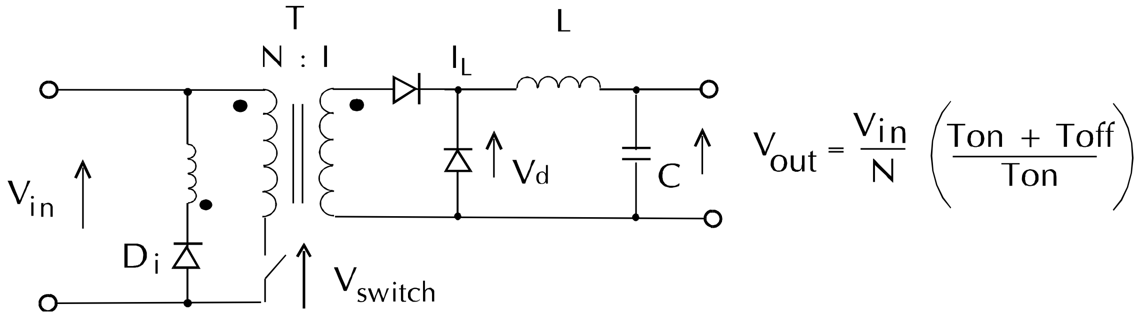
Buck Regulator (Summary):

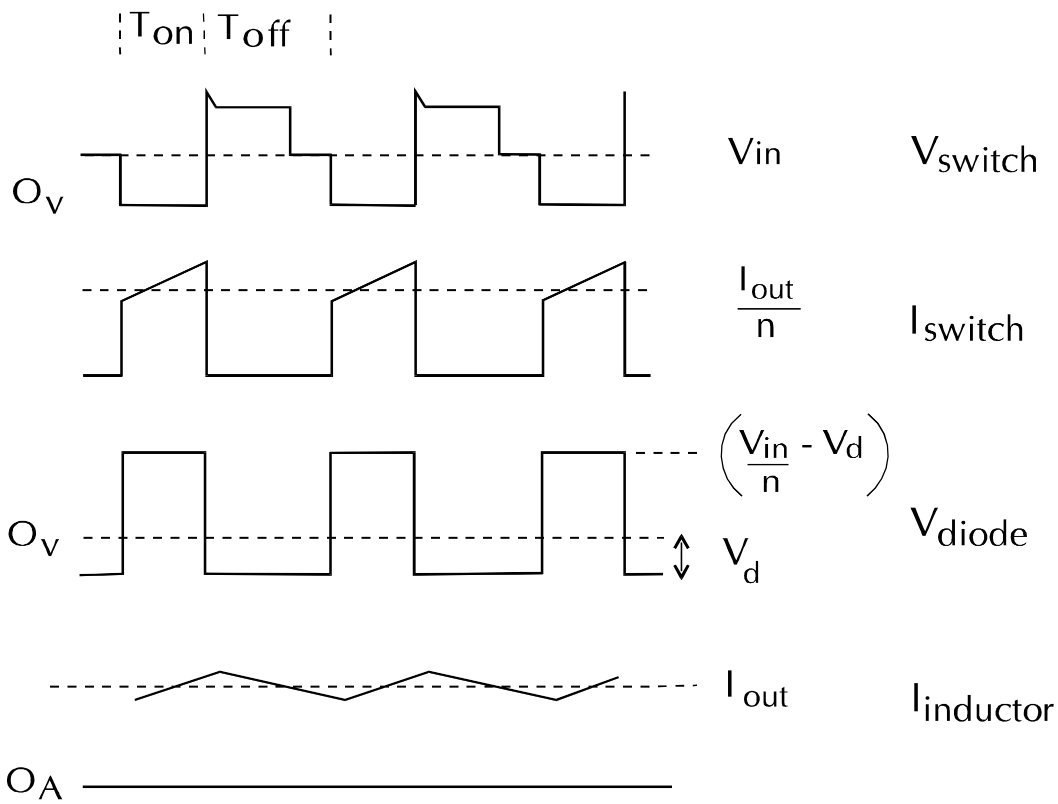




Advantages:	Efficient
	Simple, low cost.
Disadvantages:	No isolation
	Only one output
	Higher output ripple than linear.
	Step down only.
	High frequency switching generates RFI and EMI.
Applications:	5 to 50W. Local regulation

4.1.2 Single Ended Forward Convertor.





Advantages:

Isolated.

Relatively simple.

No flux symmetry problems.

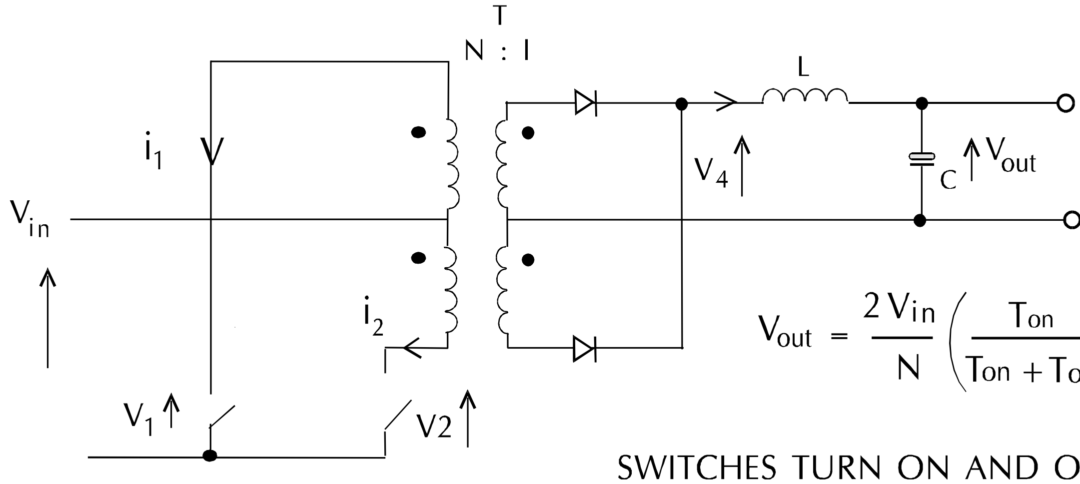
Disadvantages:

Switch must withstand twice the input voltage.

Applications:

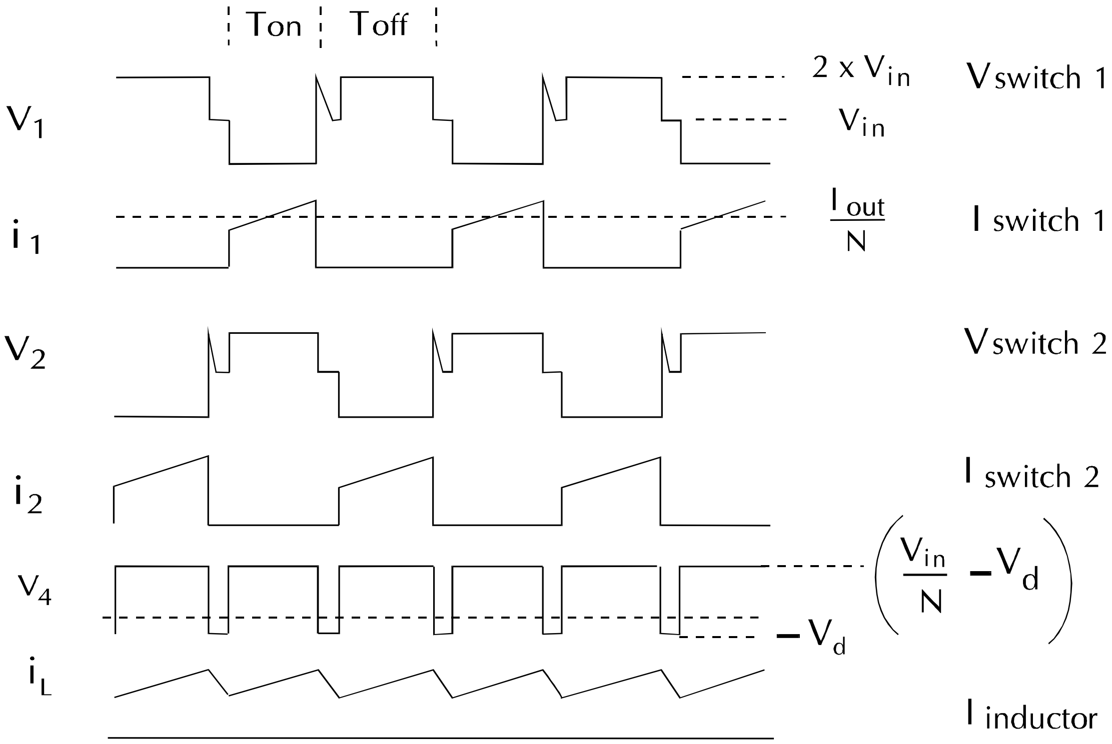
Up to 250W

4.1.3 Push-Pull Convertor.



$$V_{out} = \frac{2V_{in}}{N}\left(\frac{T_{on}}{T_{on}+T_{off}}\right)$$

SWITCHES TURN ON AND OFF ALTERNATELY



Advantages:

Good use of transformer magnetic material.

Both parts of B-H loop used.

Disadvantages:

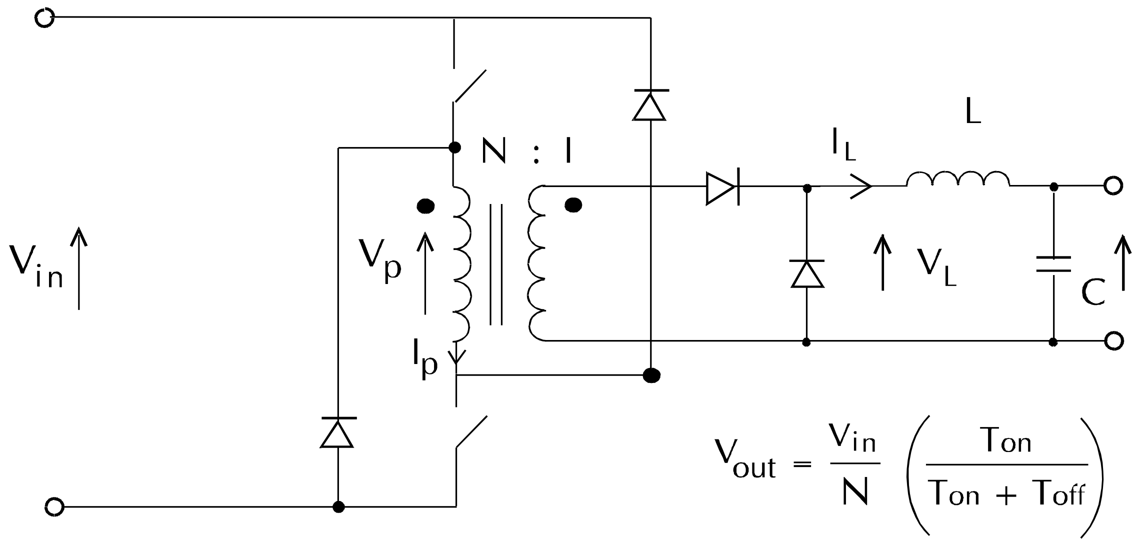
Problems of Volt-second imbalance

when switch times are different.

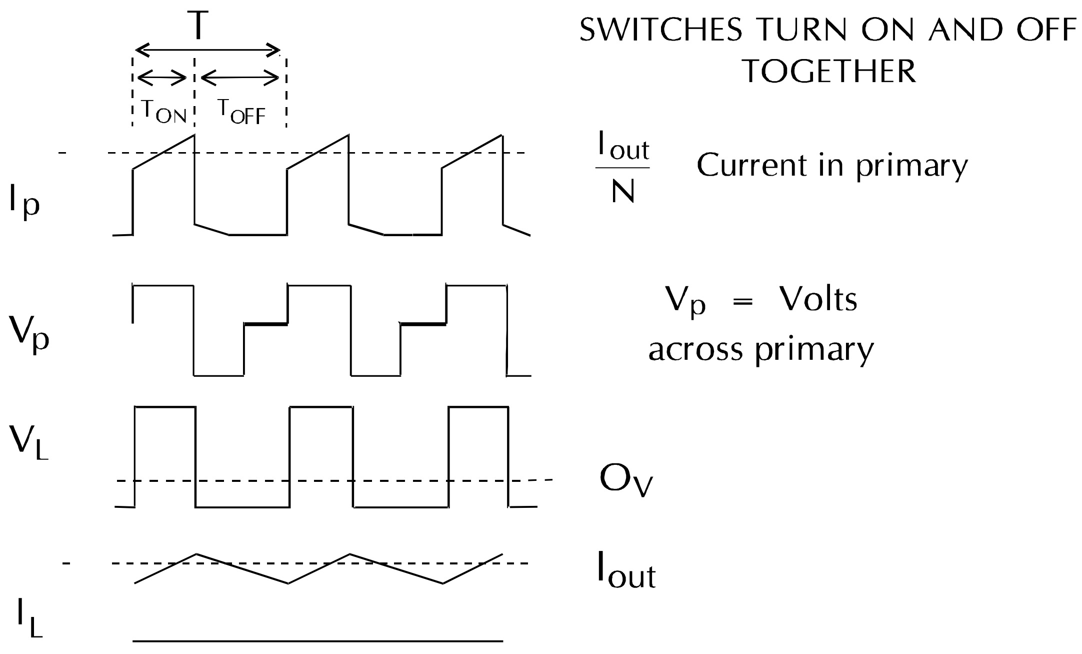
Applications:

Up to 3000W. Lower voltage inputs.

4.1.4 Two Transistor Forward Convertor.



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



Adavantages:

Switches operate at V_{in}

Magnetising current, leakage current, returned to supply.

Disadvantages:

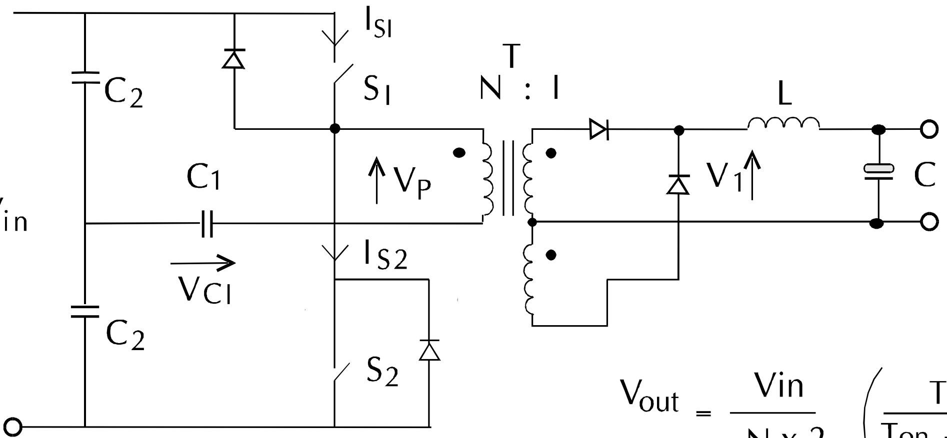
Poor use of transformer B-H loop.

Floating' switch drive required.

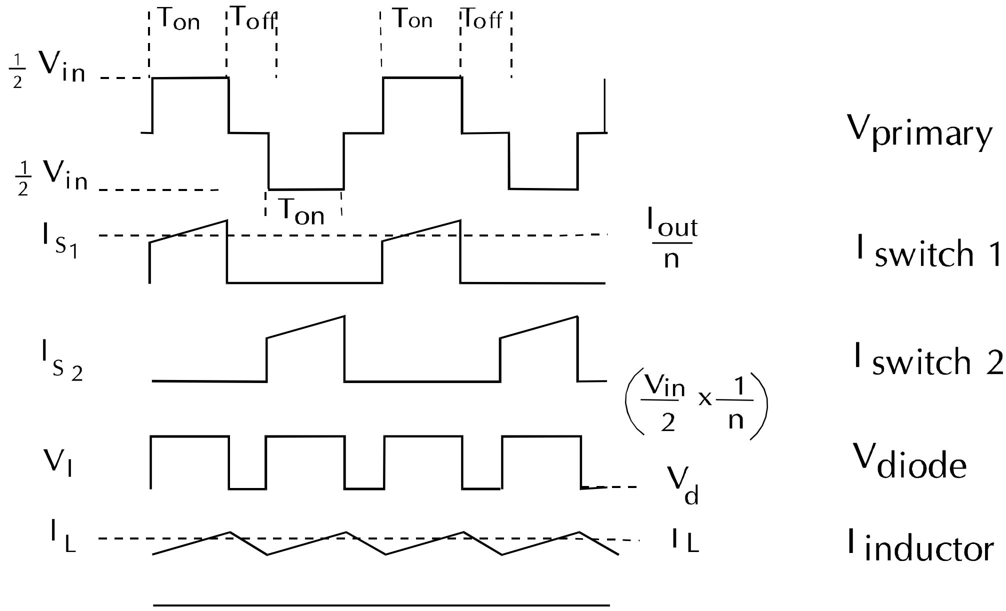
Applications:

Up to 500W. Higher input voltages.

4.1.5 Half Bridge Convertor.



$$V_{out} = \frac{Vin}{N \times 2}\left(\frac{Ton}{Ton + Toff}\right)$$



Advantages:

Volt-second balance ensured by C1.

Switches rated at V_{in}.

Both parts of B-H loop used.

Disadvantages:

Extra high frequency capacitor (C1) required.

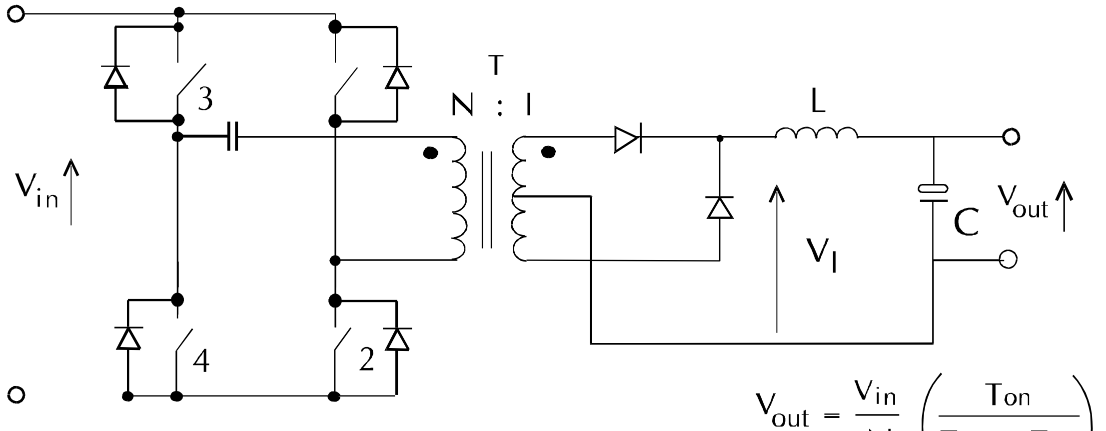
'Floating' switch drive required.

Only ½ Vin applied to transformer primary.

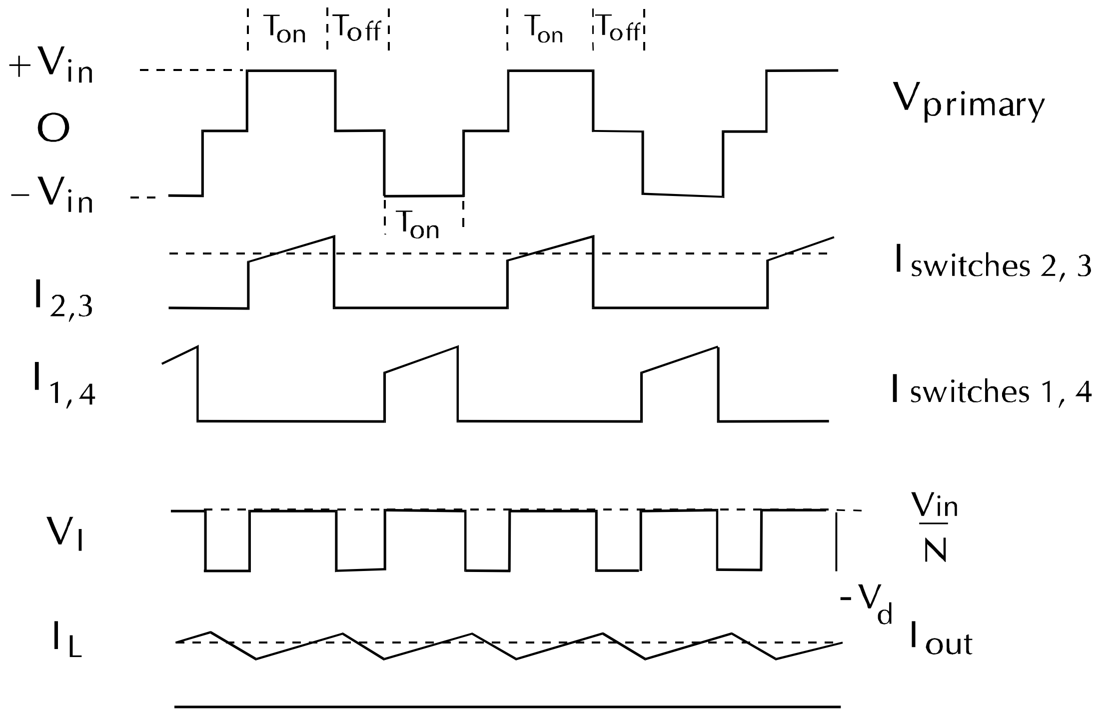
Applications:

Up to 500W.

4.1.6 Full Bridge Convertor.



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



Advantages:

No flux symmetry problems.

Transformer stored energy returned to supply.

Transistors rated at V_{in} nominally.

Good utilization of transformer magnetic material

Disadvantages:

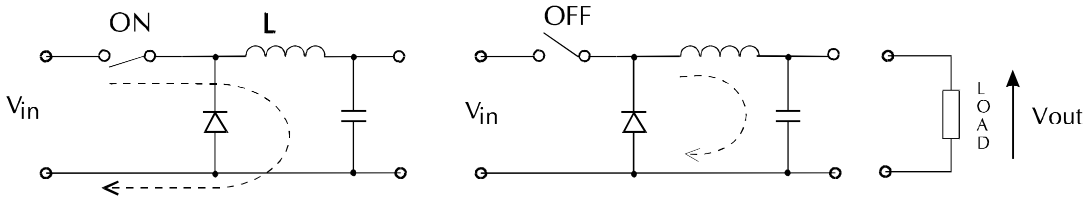
Transistors, and 4 transistor drive circuits required.

Applications:

200 to 2000 Watts

4.2 Flyback (Boost) Convertors.

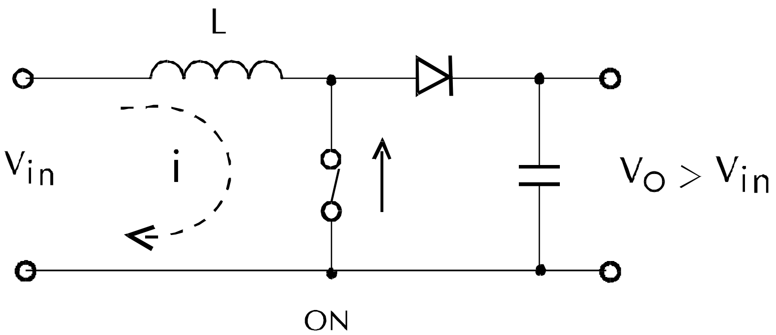
All the DC to DC convertors described so far have been examples of forward convertors. That is energy is transferred from the input to the output filter during the on time of the switch.



FORWARD CONVERTOR - Energy stored in L during ON time. $V_{out} < V_{in}$

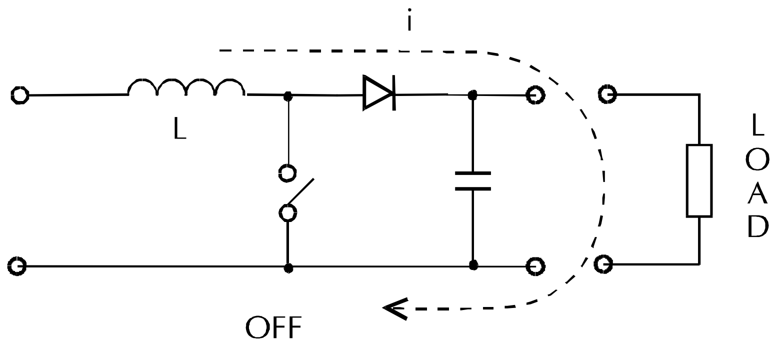
In the flyback - or boost convertor, energy is stored in the inductor during the on time, and released to the output during the off time only.

4.2.1 Boost Convertor



When the switch is closed, current ramps up in the inductor, L.

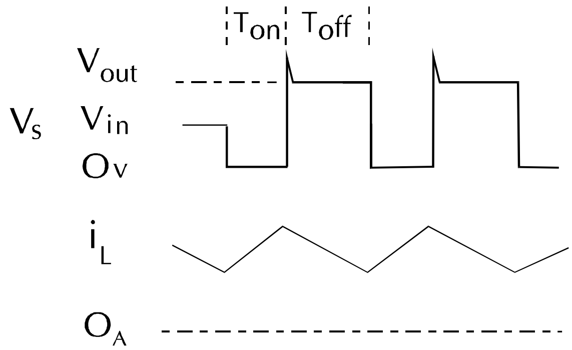
$$\frac{di}{dt} \approx \frac{Vin}{L} \text{ or } \Delta = \frac{Vin\ Ton}{L}$$



When the switch is opened the inductor tries to maintain the previous current flow. The inductor voltage reverses rapidly until it reaches the output voltage, when the diode conducts.

Current then flows into the output, ramping down at a rate:

$$\frac{di}{dt} = \frac{Vout - Vin}{L} \quad \text{or} \quad \Delta i = \frac{(Vout - Vin)}{L} \, Toff$$



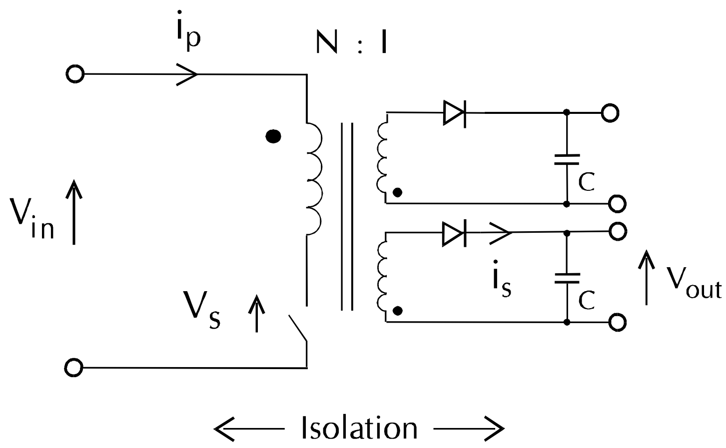
$$V_{in} T_{on} = V_{out} T_{off} - V_{in} T_{off}$$

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

Advantages:	Low cost. Few components.
Disadvantages:	Large di/dt generate noise and EMI Fast rectifier required.
Applications:	Step up convertors. PFC circuits.

4.2.2 Discontinuous Flyback.

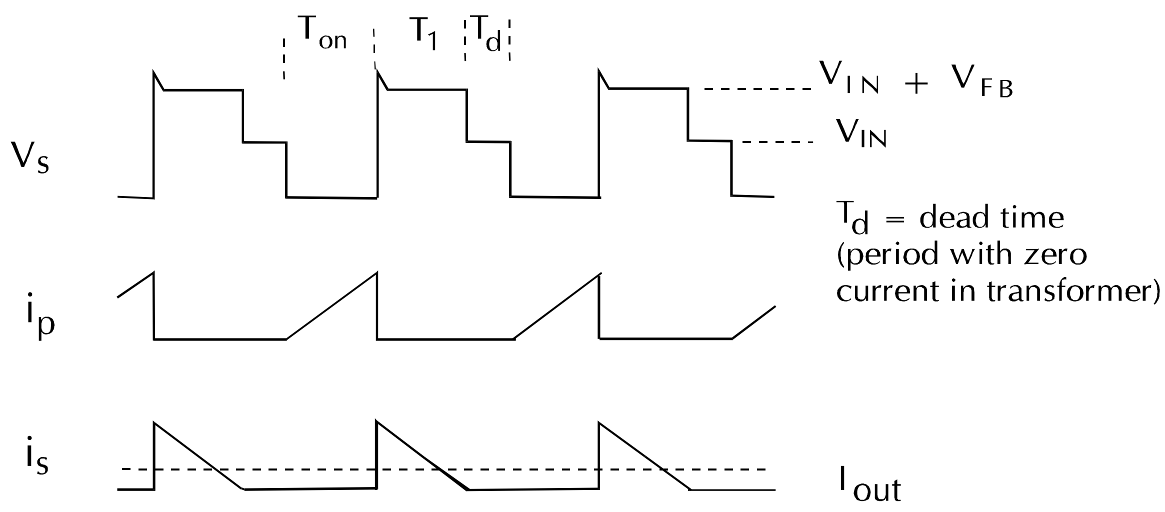
Extra windings are added to the inductor of the boost convertor to form the transformer/inductor of the flyback convertor.



When the switch is opened the voltage across the transformer/ inductor reverses until current flows in the outputs. The voltage across the transformer primary will then be:

$$V_{fb.} = (V_{out} + V_{diode}) \times N$$

V_{fb}. is called the Flyback voltage.



Note the orientation of the windings. The dot end is positive during T_{on} - current flows in the primary.

The non dot end is positive during T_{off} - current flows in the secondary.

Volt-second balance is maintained

$$V_{in} T_{on} = V_{fb} T_1$$

The transformer/choke current is zero during the time Td. The convertor is said to be operating in discontinuous mode.

Advantages:

Only one magnetic component - even for multiple outputs with isolation.

Only one diode per ouput.

Disadvantages:

Large peak currents in all components.

Large current and voltage changes generate noise and EMI.

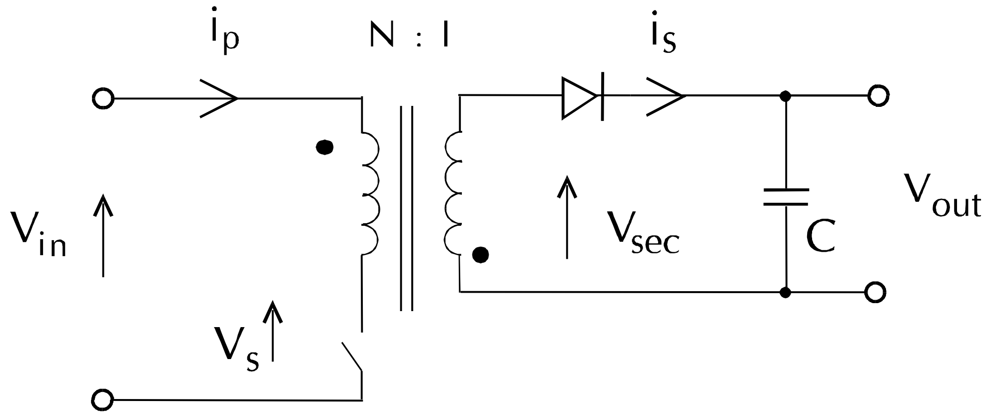
Switch rated at $V_{in} + V_{fb}$ + leakage spike.

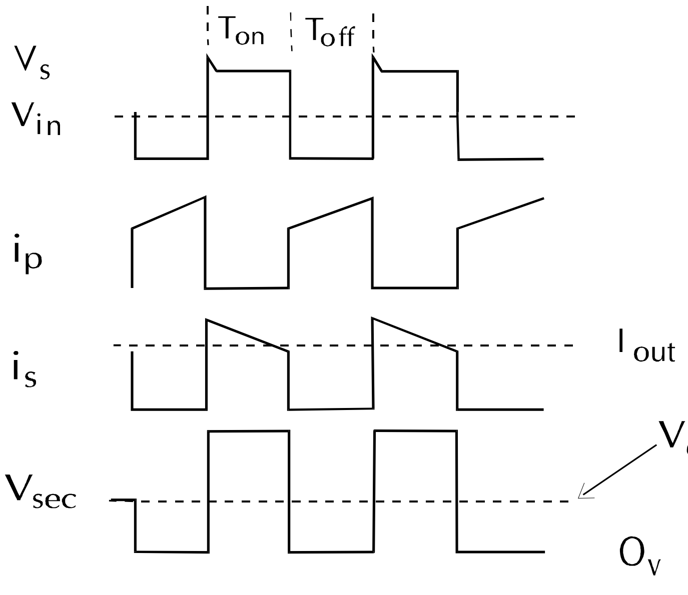
Applications:

Up to 200W. Low cost, multiple outputs.

4.2.3 Continuous Flyback.

Flyback convertors can also be operated in continuous mode:





$$V_{out} = \frac{V_{in}}{N} \times \left(\frac{1}{\frac{1}{\delta} - 1} \right)$$

Where $\delta = \left(\frac{T_{on}}{T_{on} + T_{off}} \right)$

Advantages:

Peak currents reduced from discontinuous flyback.

Only one magnetic component - even for multiple outputs.

Only one diode per output.

Disadvantages:

Magnetics larger (for DC bias)

Large peak currents in all components.

Large current and voltage changes generate noise and EMI.

Switch rated at $V_{in} + V_{fb}$ + leakage spike.

Applications:

Up to 200W. Low cost, multiple outputs.

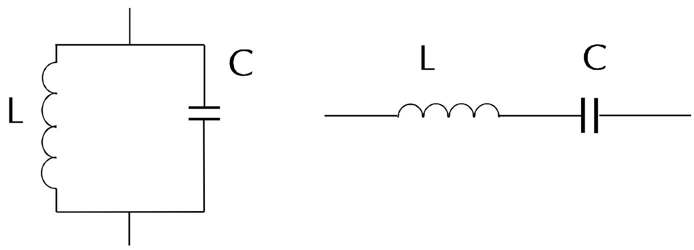
4.3 Resonant Convertors.

To further reduce the size and weight of the filter components in a dc to dc convertor (and hence reduce the size and weight of a power supply) higher operating frequencies are used.

It is also desirable to improve efficiency to minimise losses and reduce temperature rises.

Switching losses limit ‘square wave’ operation to about 200kHz.

Resonant convertors use LC circuits, which operate with sinusoidal currents at near the resonant frequency (F) of the L and C.



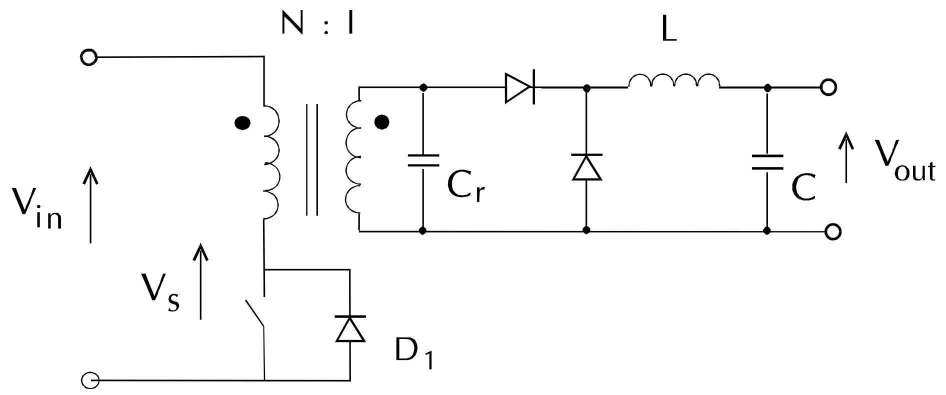
$$F = \left(\frac{1}{2\pi\sqrt{LC}} \right)$$

Parallel and Series L - C Circuits

The switching device can be arranged to operate when either the voltage or current is naturally zero, thus minimizing switching losses.

There are many different types of resonant convertor, operating in different ways. Some switch at zero current (ZCS) or zero voltage (ZVS) with parallel or series L-C circuits.

A simple form of resonant convertor can be made by adding a capacitor to the circuit of a forward convertor. The filter L and C operate in much the same way as in the conventional forward convertor. The transformer is deliberately wound with a large value of leakage inductance.

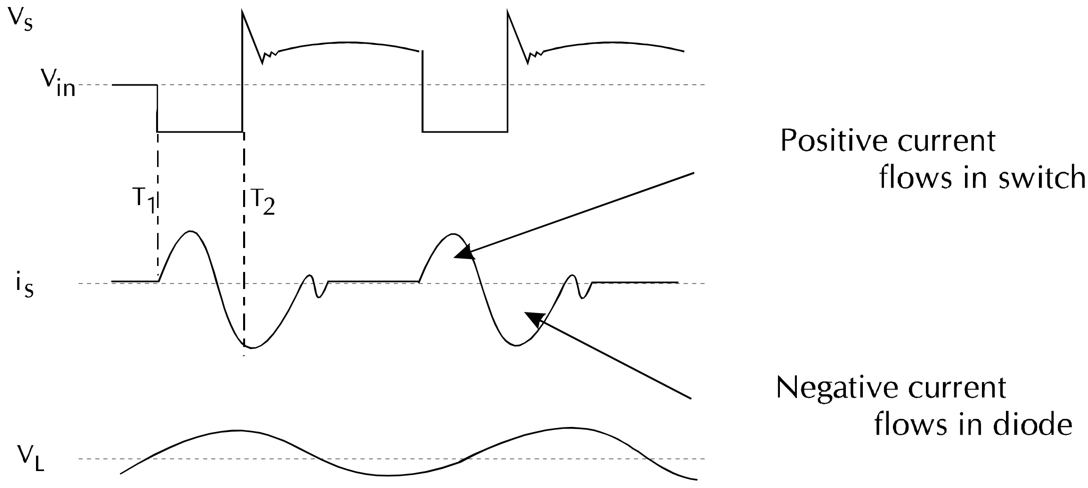


The leakage inductance of the transformer (L_L) and the reflected value of the resonant capacitor C_r form a series resonant circuit

$$F = 1/ 2p \sqrt{(L_L C_r(N_S/N_p)}$$

Referring to the following diagram when the switch is closed, a sinusoidal current begins to flow in the resonant circuit. Energy is transferred to the output during this time. The negative half cycle of current flows in the diode D1. The transistor may be switched off at any point during this time, since there is no current flowing in it.

$$T_1 < T_{on} < T_2$$



No current in switch when it is turned off - Reduced turn off loss

When D1 stops conducting, current can only flow in the parallel magnetising inductance/resonant capacitor circuit. The transformer core is reset during this time.

The pulse width is fixed by the values of L and C, however. The output voltage is controlled by varying the frequency of operation.

Advantages:

Lower weight and volume, high efficiency

EMI from switching transients reduced.

'Stray' circuit elements - capacitance, leakage inductance, etc. utilised.

Disadvantages:

High peak currents in all components.

Variable frequency operation

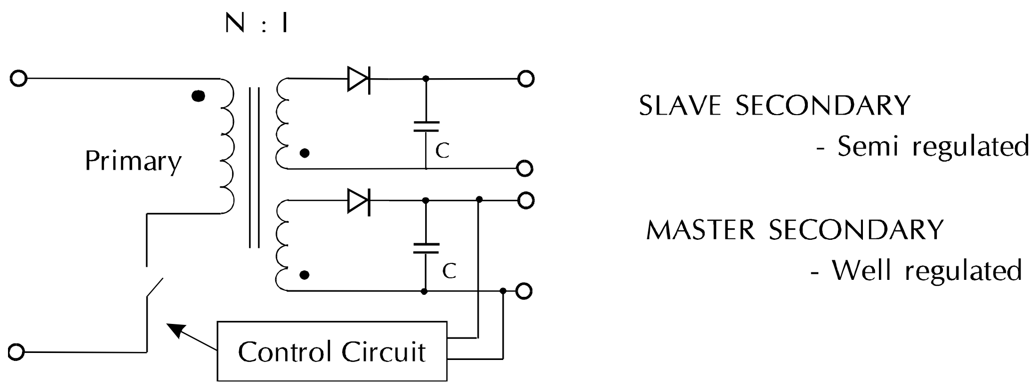
- cannot be synchronised to external frequency.
- more difficult to design against EMI.

Applications:

Where reduced size/weight and improved efficiency required.

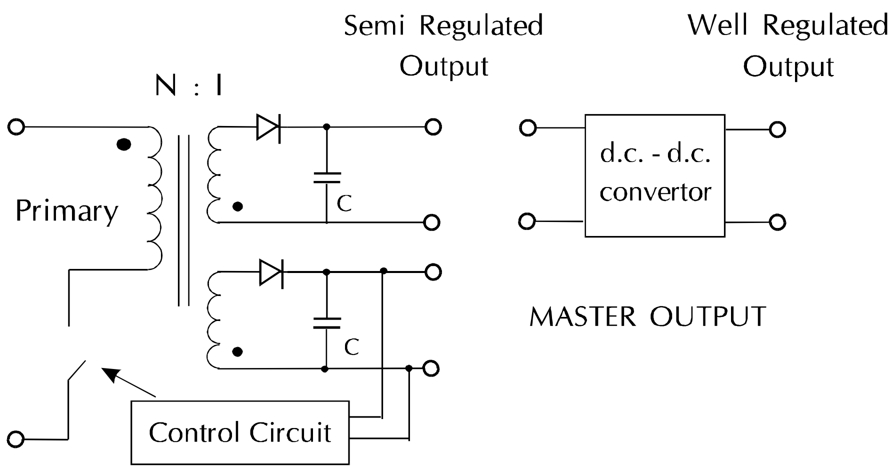
4.4 Magnetic Amplifiers.

Dc to dc convertors may have several outputs. One 'master' output is well regulated by a control circuit, other 'slave' outputs are at nominally the correct voltage, but will have poor load and line regulation.



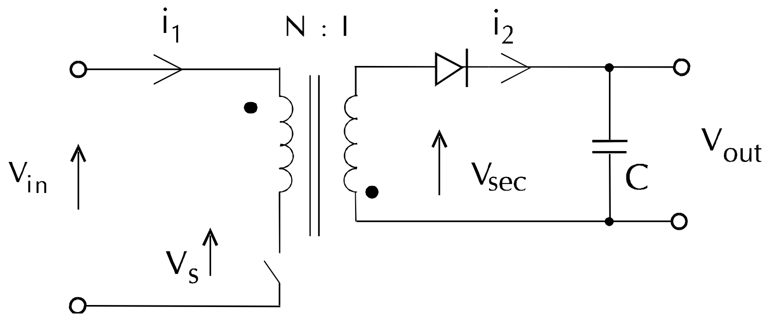
Cross regulation may also be observed. This is the voltage change on one output due to the load current change on another.
Slave output regulation can be improved by increasing the coupling between transformer windings or sharing regulation.

If the best regulation - or a separately adjustable output - is required then further dc to dc convertors (linear or switched mode) can be used.

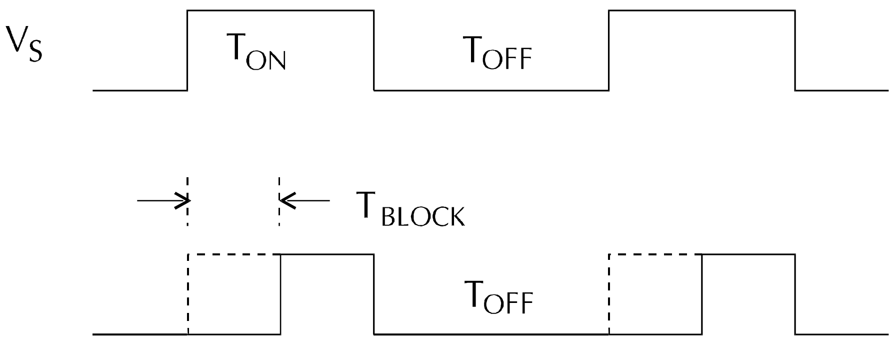


In forward convertors, magnetic amplifiers can be used to perform the post regulation.

The magnetic amplifier acts as a switch in series with a secondary winding in a forward convertor



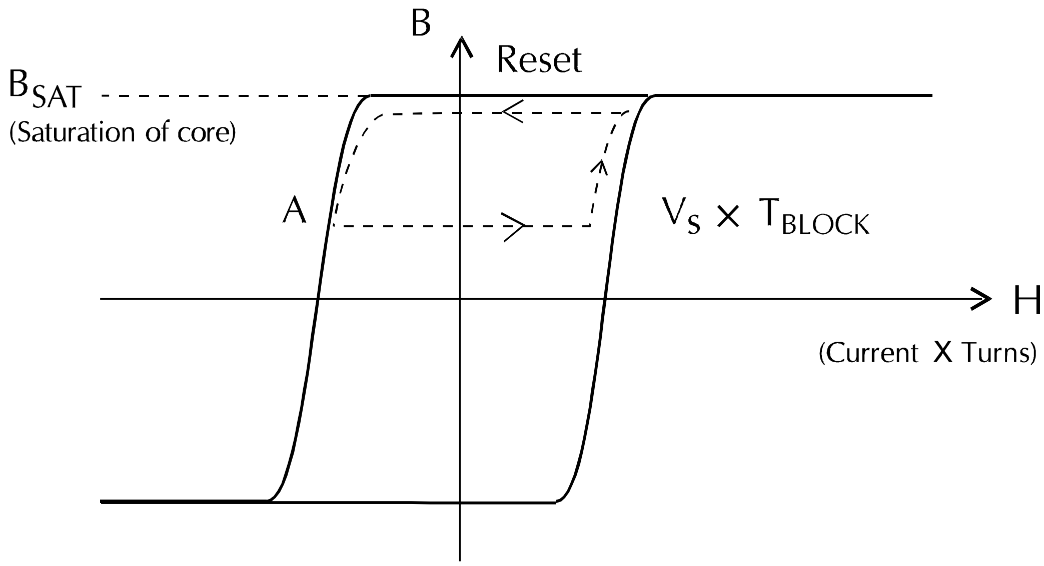
$$\text{Normally, } V_{OUT} = V_{SEC} \times \frac{T_{ON}}{T_{ON} + T_{OFF}}$$



The magnetic amplifier works by introducing a time T_{block} to reduce the effective pulse width and hence the output voltage.

$$V_{OUT} = V_{SEC} \times \frac{(T_{ON} - T_{BLOCK})}{T_{ON} + T_{OFF}}$$

A magnetic amplifier consists of a number of turns of wire wound on a core that has a very square B-H loop.



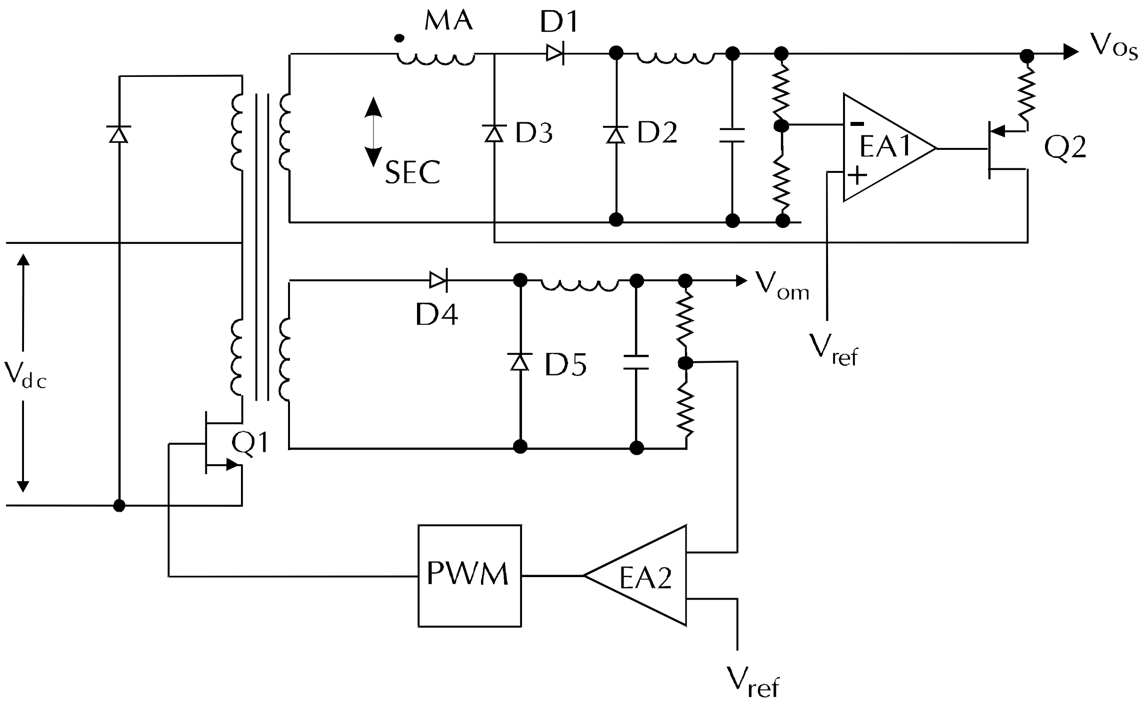
In the steep, vertical parts of the B-H loop μ_r and hence the inductance is very high. SWITCH = OPEN.

When B_{sat} is reached a large current flows. SWITCH = CLOSED.

At the start of a cycle, the core is at point A on the B-H loop. When V_s becomes positive, very little current flows until B_{sat} is reached. This takes a time T_{block}. (Volt-seconds = $V_s.T_{block}$)

Once B_{sat} is reached the voltage across the Magnetic amplifier (MA) collapses and a large current flows.

Once V_S collapses the magnetic amplifier core is reset by a control circuit. If the core is reset to a point other than A then the time taken to reach B_{sat} (T_{block}) on the next cycle will be different.



The current through D3 resets the core of the Magnetic amplifier (MA). The point on the B-H loop to which the MA is reset controls the blocking time (T_{BLOCK}) when V_{SEC} next goes positive. T_{BLOCK} is varied so as to regulate the ouput voltage.

4.5 PWM Control Circuits.

4.5.1 Voltage Mode.

The output voltage of switched mode dc to dc convertors is controlled by changing the ratio:

$$\frac{T_{ON}}{T_{ON} + T_{OFF}}$$

T_{on} or T_{off} may be varied, but common control circuits operate at a fixed frequency ($T_{on} + T_{off}$ = constant) and vary T_{on}.

E.g.

If V_{out} = 5V required, and $V_{out} = d \times V_{in}$

V_{in} = 20V, d = 0.25

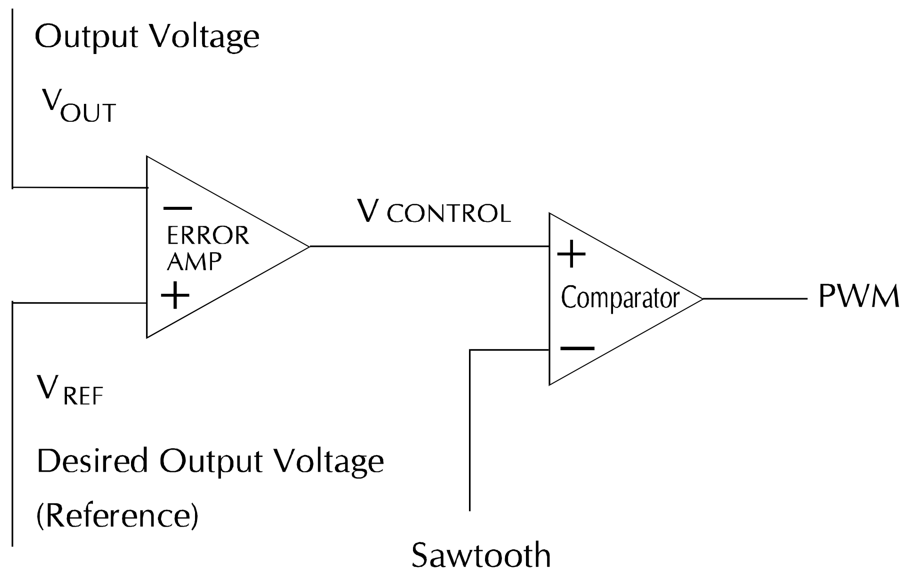
Vin = 25V, d = 0.20

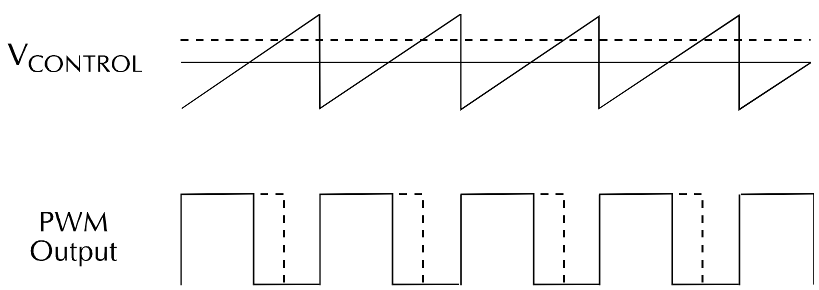
PWM circuits consist of:

An error amplifier which amplifies the difference between a reference voltage (desired output voltage) and the actual output voltage.

A comparator which compares the error amplifier output voltage (control voltage) with a sawtooth waveform. The output of the comparator is a pulse waveform at the frequency of the saw-tooth. The pulse width varies directly with the control voltage.

If V_{out} tries to rise, $V_{control}$ falls and T_{on} is reduced, maintaining V_{out}.



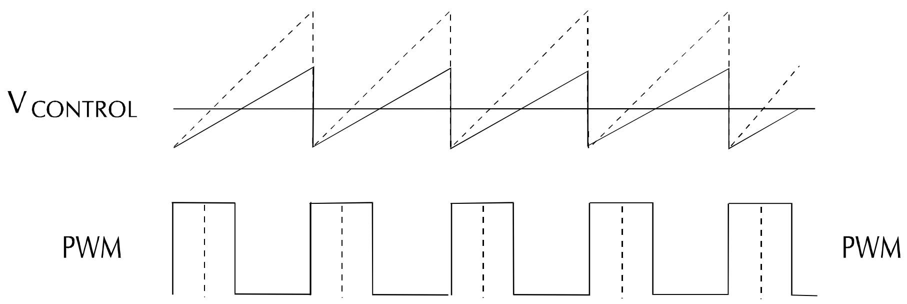


Low cost integrated PWM circuits are available that contain the required error amplifier, comparator and oscillator/sawtooth generator.

- Other useful features often included are:
- On chip oscillator/sawtooth generator.
- Drive transistors for easy connection to power switch transistors.
- Extra error amplifiers/comparators for overcurrent protection,
- remote shutdown etc.
- Logic to provide push - pull outputs.
- Under voltage lock out (UVLO) to inhibit operation if a reasonable reasonable if a reasonable input voltage is not present.

Voltage feed forward technique.

With this technique, the amplitude of the sawtooth waveform is changed with the input voltage. The duty cycle, d, is reduced automatically. The output voltage is maintained without the control voltage changing.



The benefits are:

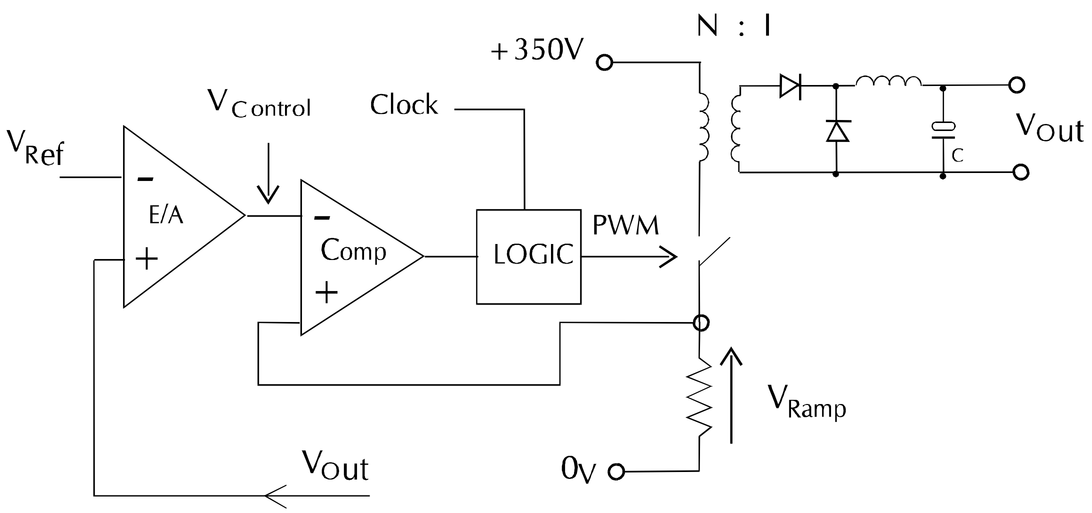
- Quick responses to input voltage changes.
- Inherently good line regulation - and hence,
- Less error amplifier gain required - easier to stabilize loop.

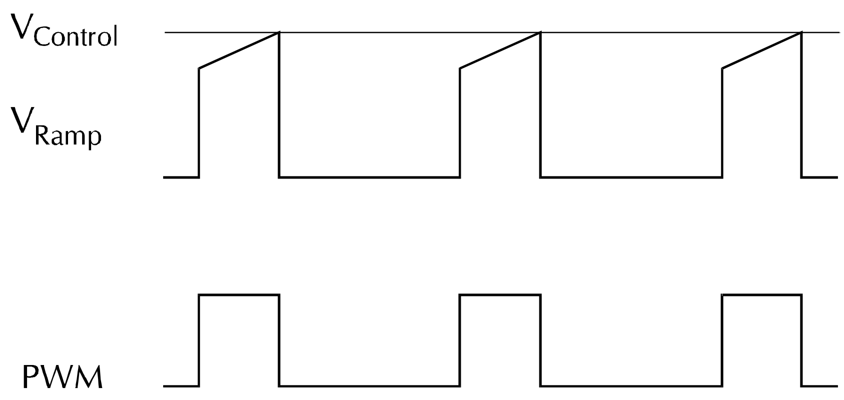
4.5.2 Current Mode.

In current mode control, the peak inductor current is controlled, rather than the duty cycle directly.

This is done by using the inductor current ramp waveform as the sawtooth input to the PWM comparator.

E.g. Continuous mode forward convertor.





At the start of a clock cycle, the PWM output goes high, turning the switch ON. Current ramps up in the output inductor and transformer primary. This current forms the ramp voltage which is compared to the control voltage. When the ramp voltage reaches $V_{CONTROL}$ the PWM output goes low and the switch is turned OFF, due to the combination of comparator action and logic control.

The voltage error amplifier now controls the peak inductor current, which is varied so as to maintain the desired output voltage.

Current Mode Control

Advantages:

Inherent pulse by pulse current lmiting.

Protects switching device(s) from overcurrent.

Volt - second balance maintained in push-pull circuit since alternate current pulses must have the same amplitude.

Inherent voltage feed forward.

The slope of the ramp varies with input voltage.

Easier feedback loop stabilisation.

The voltage feedback loop now controls the inductor current. In a continuous mode forward convertor the small signal model feeding the output capacitance and the load resistance. The gain/phase response of the inductor is eliminated.

Advantages (contd)

Easier paralleling of convertors.

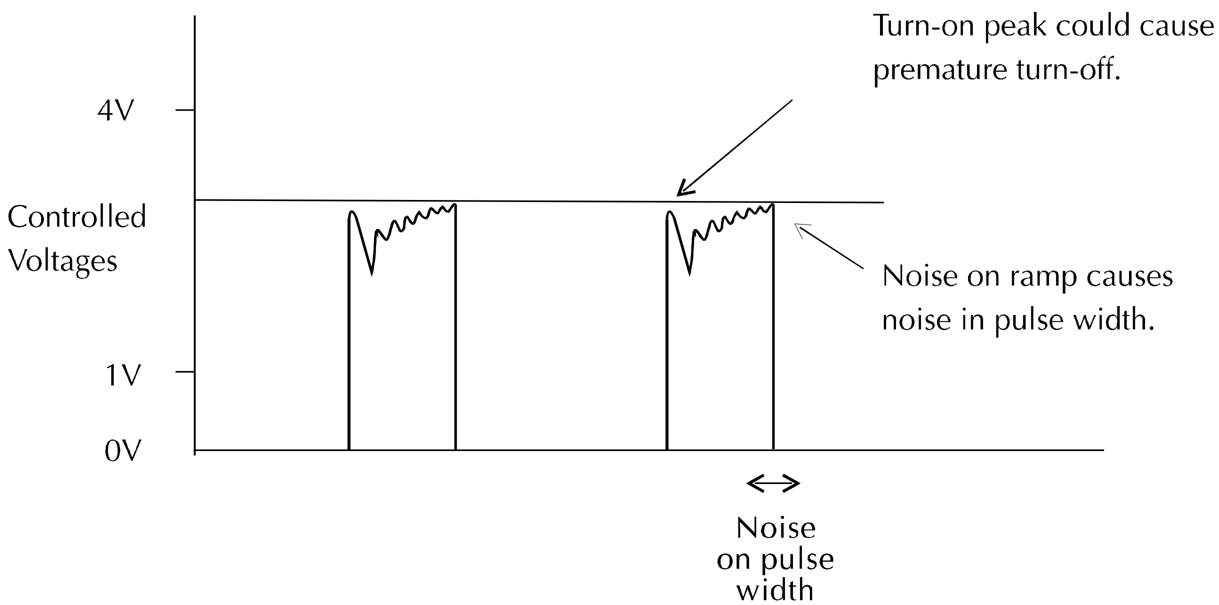
A common control voltage is fed to the comparator of each current mode controlled convertor. The same current must then flow in each convertor.

Disadvantages:

Poor noise immunity.

The ramp voltage is shallow compared to the voltage mode sawtooth.

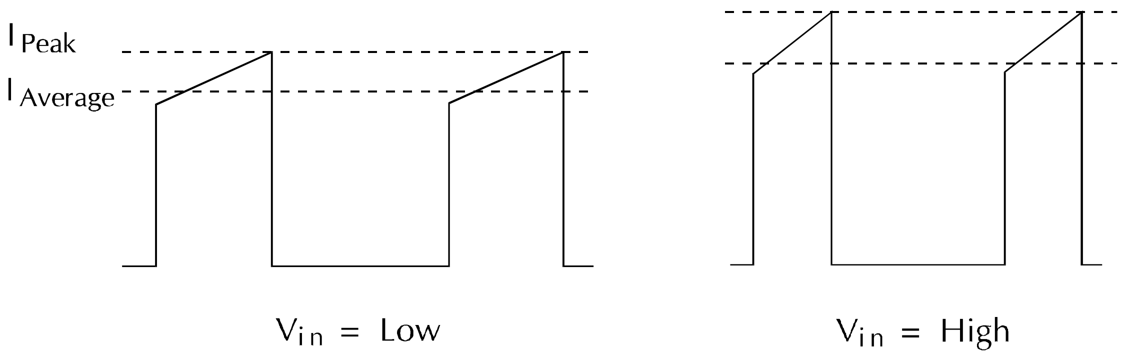
The ramp voltage is derived from a real circuit current - often the switch current - which will contain noise, and a large turn on peak.



Current Mode Control Slope Compensation

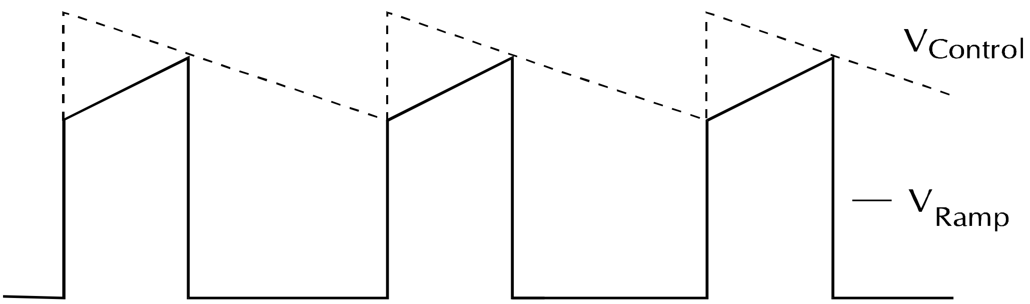
Ideally, the current mode controller should control the average inductor current rather than the peak to optimise the small signal performance of the dc to dc convertor.

The difference between peak and average current changes with input voltage, since the slope of the ramp changes.



Average inductor current control is achieved by introducing a compensating slope into the control voltage. (Most current mode IC's provide a convenient way of doing this)

Slope compensation also improves the noise immunity.

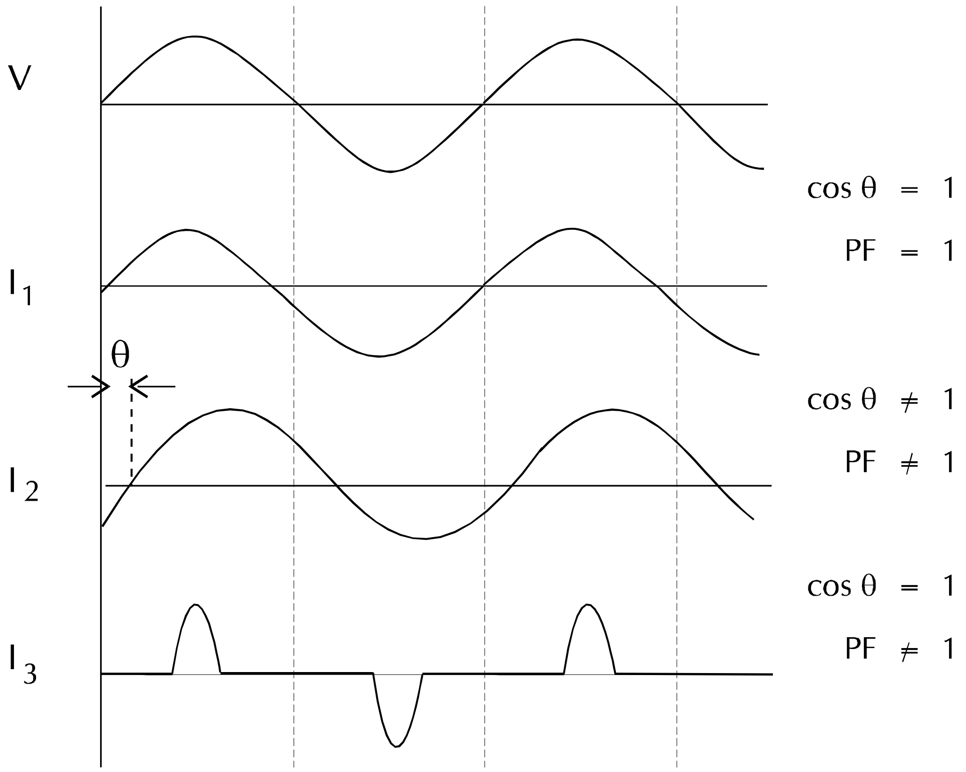


5 Power Factor Correction.

Power factor is defined as the ratio:

$$PF = \frac{\text{Watts}}{\text{VA}}$$

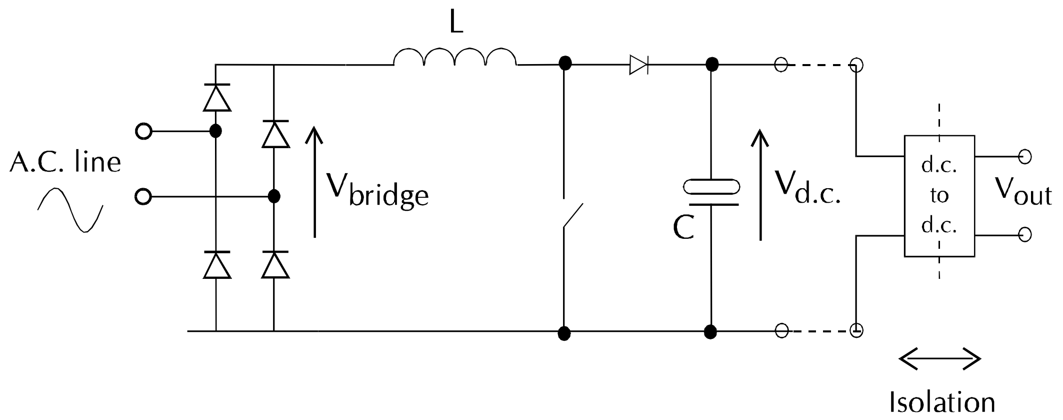
Power factor is only equal to 1 when both waveforms are of the same shape and in phase.



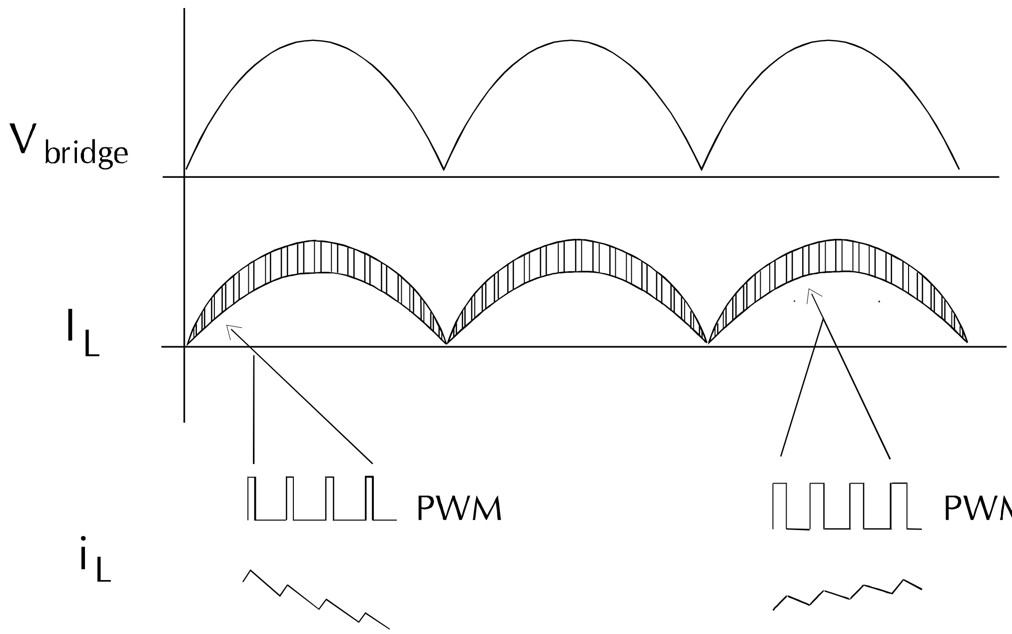
The current drawn by a line input power supply is heavily distorted as in I_3. **Cos Ø may be equal to 1, but PF is not equal to 1.**

A power factor correction (PFC) circuit can be introduced which forces the input current to follow the voltage input in shape and phase.

A typical PFC circuit consists of a continuous mode boost converter between the bridge rectifier and reservoir capacitor of a line input power supply.



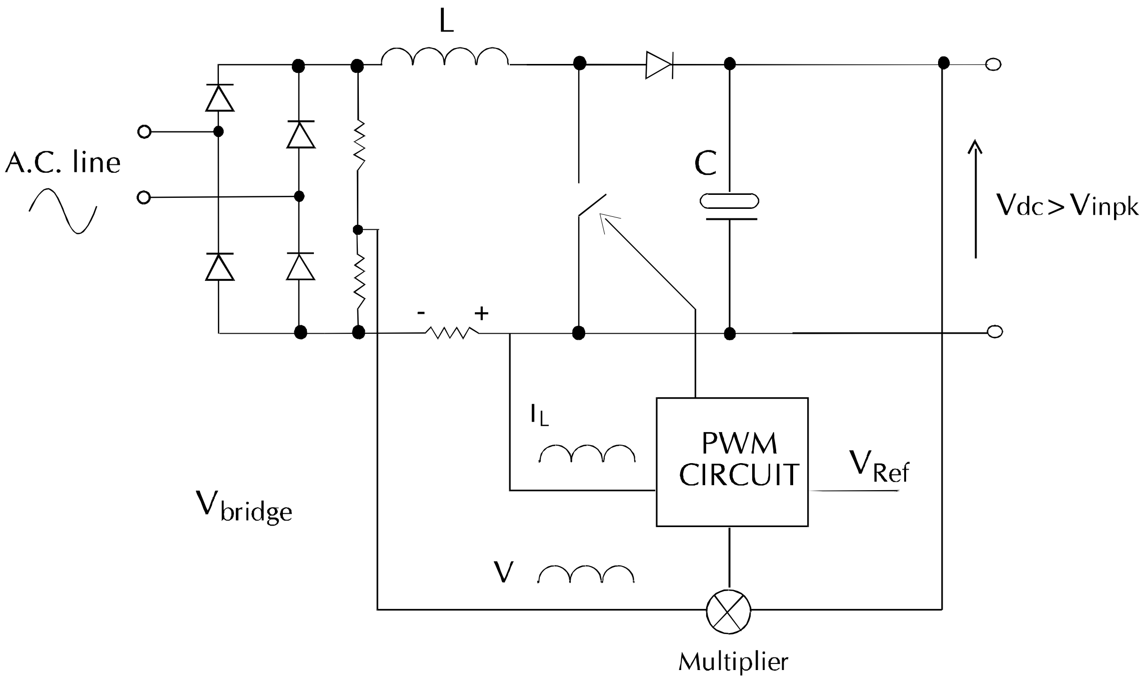
The switch operates under PWM control, such that the average inductor current follows the rectified input voltage V_{bridge}.



The rectified input voltage, V_{bridge}, forms the reference for the PWM error amplifier. The PWM circuit ensures that the average boost convertor current 'follows' this voltage.

A second control loop modifies the amplitude of the reference voltage derived from V_{bridge} to maintain a constant boost output voltage, V_{dc}.

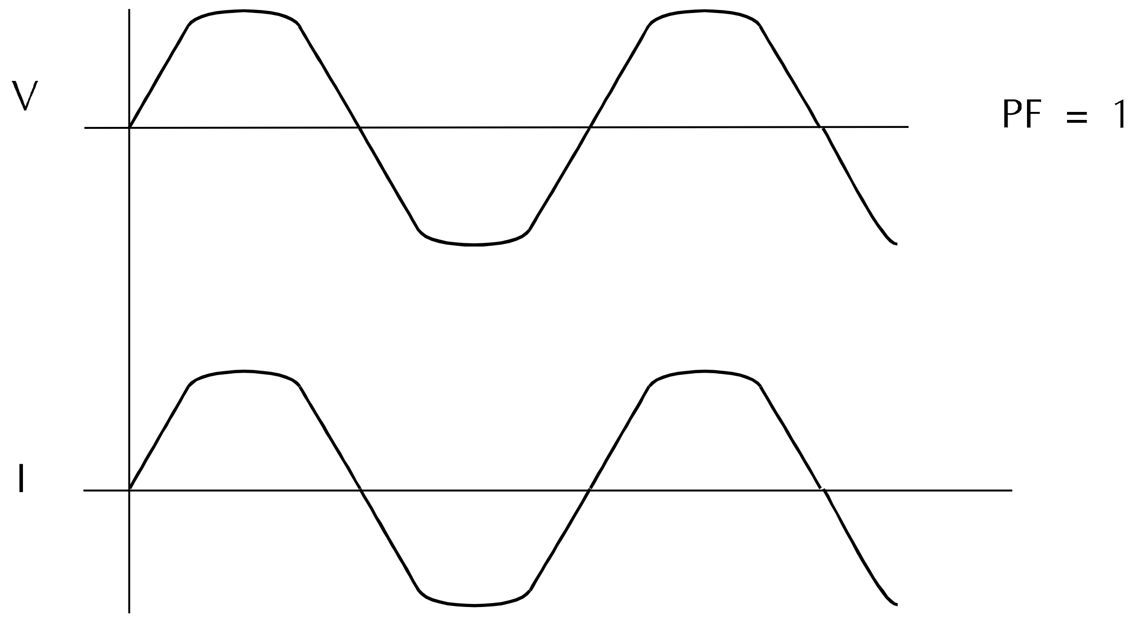
V_{dc} is maintained at a voltage above the peak input voltage to ensure correct operation.



The design of the isolated dc to dc converter can be simplified, and 'universal' input voltage readily achieved because the PFC circuit regulates V_{dc}.

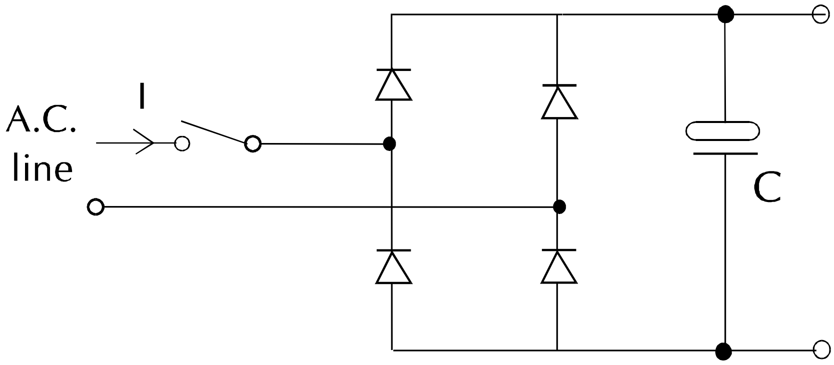
Current ripple due to the PFC boost converter can be removed by passive filtering at the input. The filter used for high frequency conducted noise (RFI) may be sufficient.

Note that if the voltage waveform is distorted, then the current waveform - since it follows the voltage - will also be.



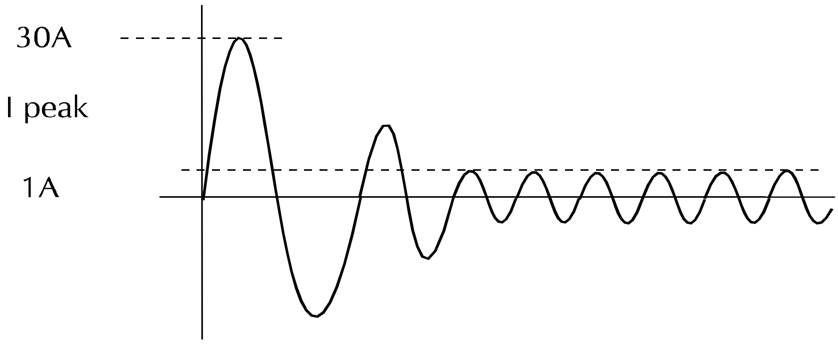
Since international standards like IEC6100-3-2 seek to limit the harmonic distortion in the current, and not power factor, this may be a problem in higher power applications.

6 Inrush Current protection.



When an ac line input power supply is first switched on a large current flows into the input reservoir capacitor, C.

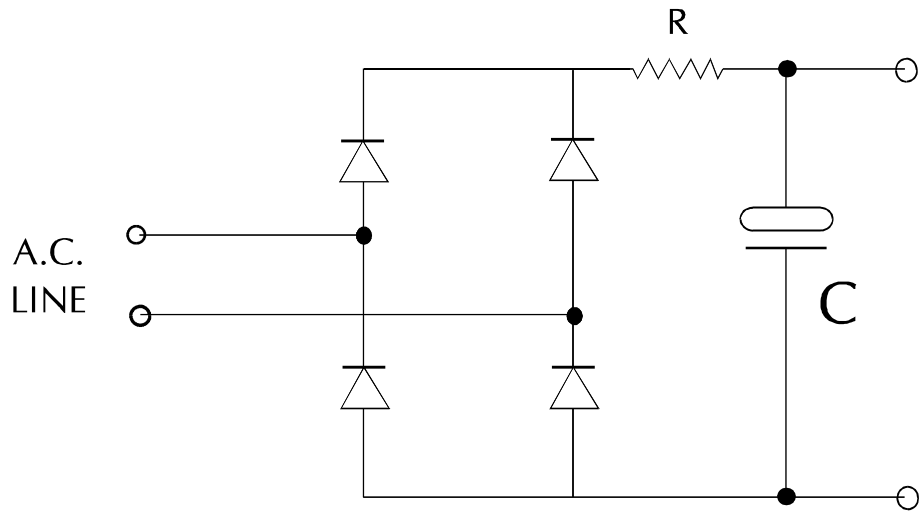
The capacitor is initially discharged and presents a very low impedance to the line. The peak current falls towards its normal operating value as the voltage across the capacitor builds up.



Large values of inrush current can:

- Disturb the a.c. line voltage.
- Exceed diode peak current ratings, shortening their life.
- Cause fuses or circuit breakers to open.

A resistor can be added to limit inrush current.



During normal operation the resistor dissipates power,

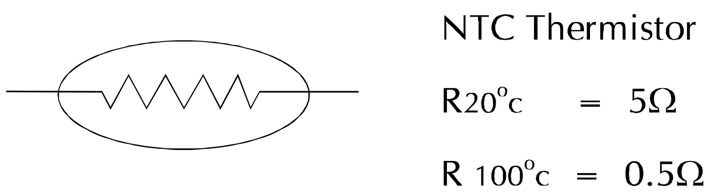
$$W = I_{rms}^2 R$$

This power may be several watts, degrading the power supply efficiency and causing local heating.

The resistor can be made of a material with a sharp negative temperature coefficient (NTC).

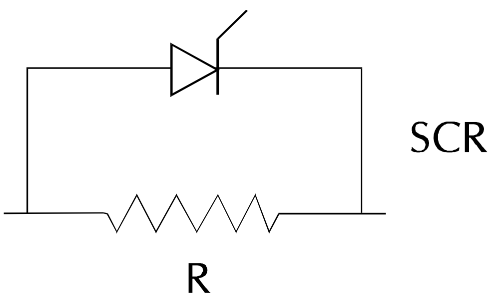
When cold the NTC 'thermistor' has a significant resistance which limits the inrush current.

As current continues to flow the thermistor heats up, and its resistance falls, reducing its continuous dissipation.

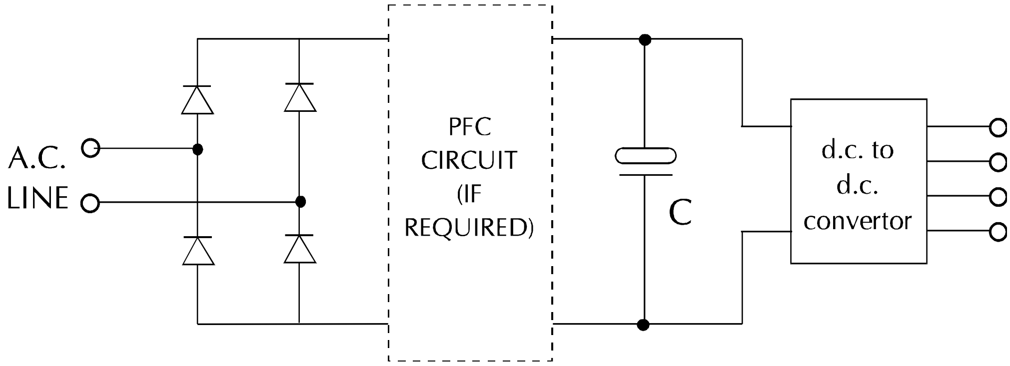


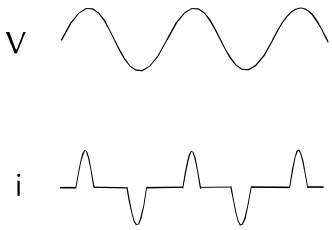
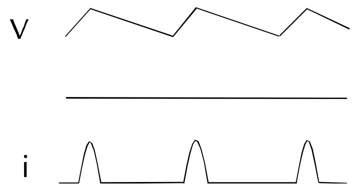
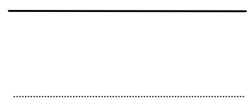
If the ac line is removed only briefly, the reservoir capacitor discharges, but the NTC thermistor will remain hot, allowing a large inrush current to flow when the ac line is restored.

Active inrush current limiting uses a semi-conductor device, an SCR, to short circuit the inrush limiting resistor once the normal operating current has been established.



7 Summary of Power measurements Required on Power Supplies.

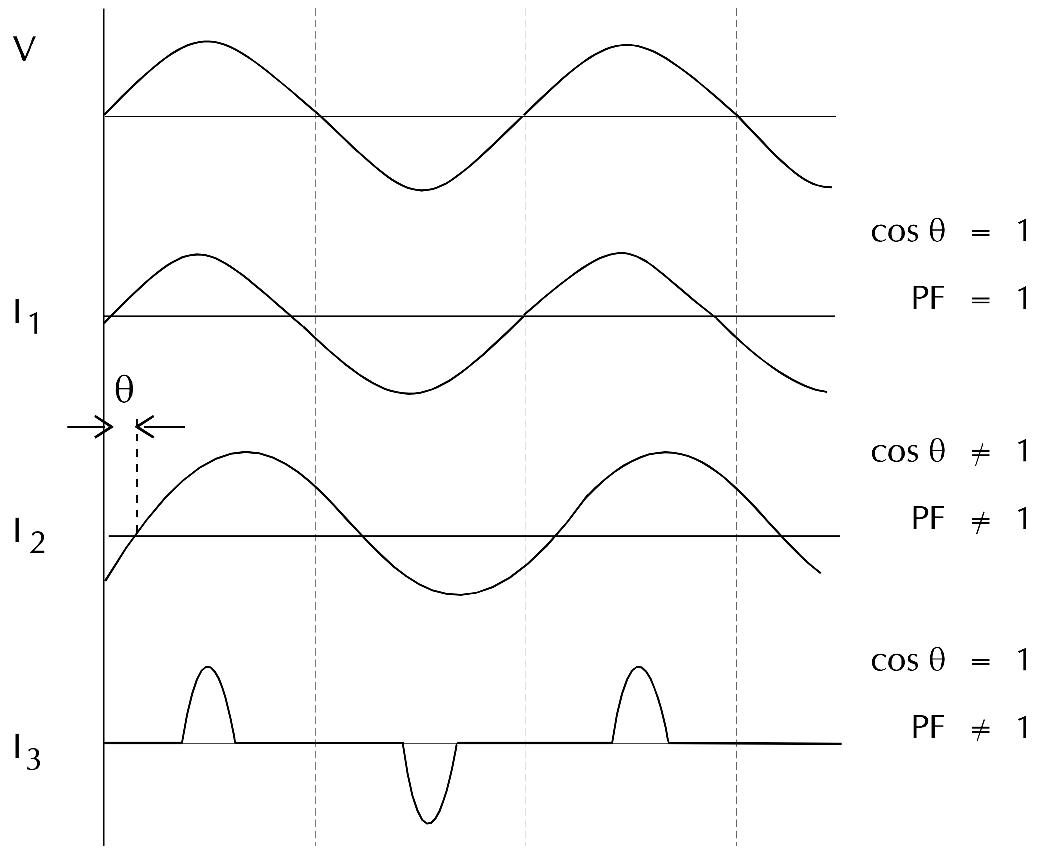


A.C. Line Input	**D.C. Bus**	**Regulated D.C. Outputs**
		
Volts - RMS Amps - RMS Amps - PEAK Amps - Harmonic Content Watts - Real Power VA - Apparent Power P.F. - True power factor Inrush Current	Volts - RMS a.c. Volts - BUS a.c. to d.c. Amps - RMS Amps - Peak Watts - Real Power Inrush Current	Volts d.c. Amps d.c. Watts d.c.
Efficiency of Input Circuit (including PFC) D.C. to D.C. Converter Efficiency. Overall Efficiency.		

8 Power Supply Measurements.

8.1 Volts, Amps and Watts.

Power supplies connected to the ac line generally draw distorted, non sinusoidal currents as in i_3 below.



Many ac voltage and current meters respond to the average value of a waveform and although calibrated in rms are only accurate for pure sine waves. (Crest factor A cf = $\sqrt{2}$)

Even bench top ‘True RMS’ electronic meters may specify maximum crest factors as low as 3. There may also be dc components present which will be ignored by ac coupled instruments.

Voltech power analyzers obtain RMS (Root Mean Squared) values by taking a large number of instantaneous voltage and current samples over a few cycles of a waveform with period, T.

$$V_{rms} = \sqrt{\frac{I}{N} \sum_{n=o}^{n=N} V_n^2} \quad \text{and} \quad I_{rms} \quad \sqrt{\frac{I}{N} \sum_{n=o}^{n=N} I_n^{\;2}}$$

according to the definition of RMS values.

Thus true RMS values are obtained, even for highly distorted waveforms. Voltech power analysers are also AC + DC coupled.

In a similar fashion, power (Watts) is computed by summing the product of the simultaneous and instantaneous v and i sample over a number of samples.

$$\text{Watts} = \frac{I}{N} \sum_{n=o}^{n=N} (V_n \times I_n)$$

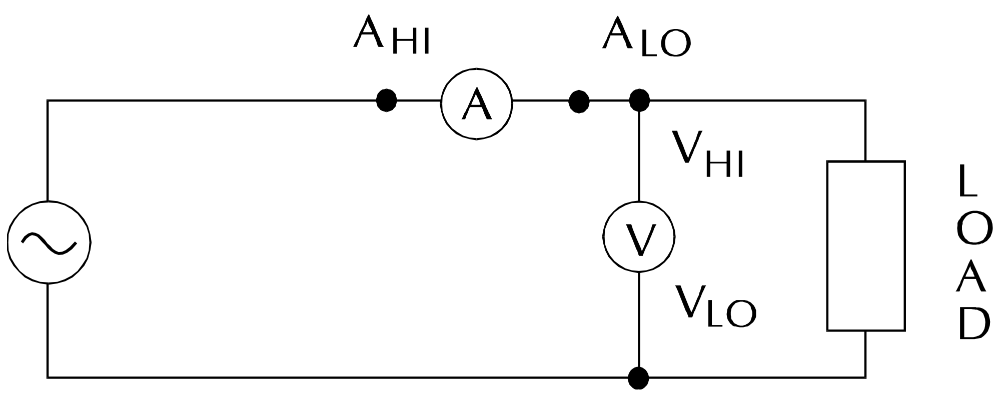
This is the best method of determining true power.

To measure volts, amps and watts:

Connect the analyzer as shown below.

Select normal measurement mode on PM1000+

RMS	Measure accurately true RMS value of input voltage.
A RMS	Measure accurately true RMS value of input current, even for highly distorted waveforms. Size conductors, fuses, filters, rectifiers, etc.
WATTS	Measure true input power.



connection diagram

8.2 VA and PF

Apparent power, VA, is computed as : $VA = V_{rms} \times A_{rms}$

The true power factor is then $PF = Watts \div VA$

For sinusoidal voltages and currents, power is often expressed as:

$$Power(W) = Vrms \times Arms \; \phi \times \cos \phi.$$

Were ϕ is the phase angle between the voltage and current waveforms.

The distorted current drawn by a power supply may be in phase (cos ø = 1) but will have a low power factor due to the harmonic distortion in the current waveform. See Appendix D.

To measure VA, PF:

Connect the analyser as shown in the connection diagram on page 68

Select VA and PF in measurement mode.

VA is often measured to ensure that the ac supply has sufficient capacity - Uninterruptable power supplies (UPS). For example:

PF includes effect of harmonic as well as phase distortion.

Confirms operation of a PFC circuit.

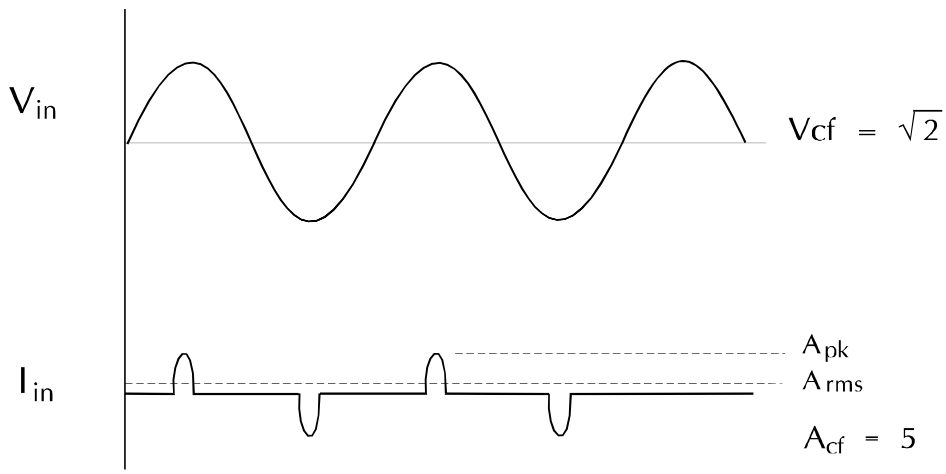
8.3 Peak Repetitive Current and Current Crest Factor.

A sinusoidal current has a crest factor of $\sqrt{2}$ (=1.41).

$$I_{pk}(\text{sinewave}) = \sqrt{2} \times I_{rms}$$

$$\text{Crest factor} = I_{pk}/I_{rms}$$

In power supplies which rectify the AC line input the repetitive peak current can be several times larger than its RMS value.



To measure current crest factor

Connect the analyser as shown in the connection diagram on page 68.

Select Acf in the measurement mode of PM1000+

Peak current may also be displayed on a PM3000A -

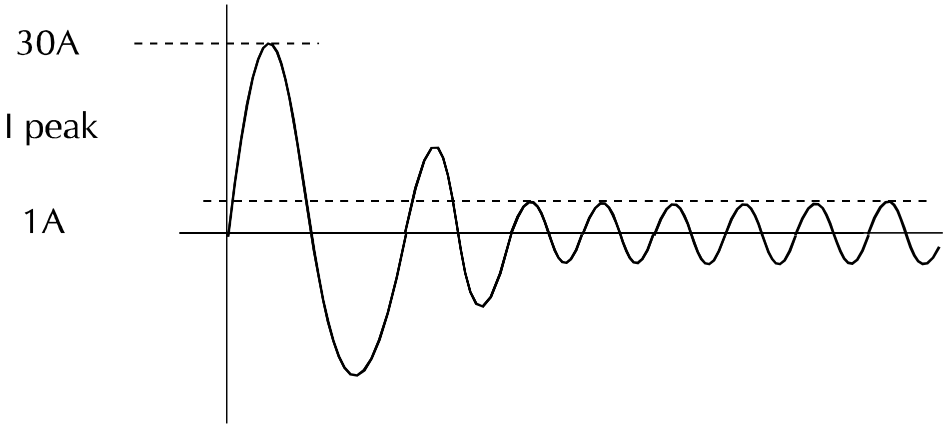
Measurements should be made with a low impedance ac supply. Isolating transformers and autotransformers have an impedance which may reduce the crest factor.

A_{pk} and A_{cf} are measured to ensure that the ac supply can deliver the peak current requirement. Very important if the supply is a UPS for example.

V_{pk} may also be measured on the dc bus. Peak voltage will determine the capacitor voltage rating.

8.4 Peak Inrush Current.

Every time a power supply is switched on it draws an inrush current which can be several times larger than the steady state peak current.



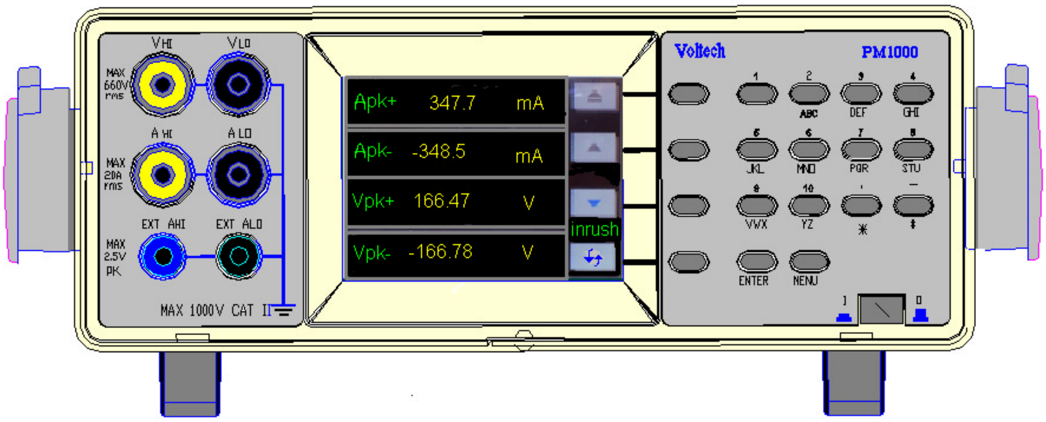
INRUSH A
Correctly specify I^2t rating of fuses and circuit breakers.
Determine peak current rating required for rectifier diodes etc.
Determine effect of the inrush current on the a.c. supply

To measure inrush current:

Connect the analyser as shown in the connection diagram on page 68

Select INRUSH mode

Select a suitable amps range.



Voltech PM1000+ Power Analyser

A worst case measurement will be made when:

There is a low impedance connection to the supply.

The power switch is closed at the peak of the voltage cycle.

The reservoir capacitor has fully discharged.

NTC thermistor (if used) is still warm.

Thus by repeating the measurement many times, a reliable worst case figure may be established.

Measurements can be simplified by using a solid state switch in line with the AC supply, such as the Voltech PS1000. This allows the AC supply to be accurately turned on at either the zero-crossing or the peak value of the voltage waveform. The PS1000 is self powered, rated to 200A peak, and has a fully isolated oscilloscope trigger output to allow viewing of the waveform. In this case, it will only be necessary to make a single measurement to obtain peak reading..

Voltech PS1000 Inrush Switch

8.5 Losses and Efficiency.

The efficiency of a power supply is usually expressed as a percentage,

$$\text{Efficiency} = \frac{\text{Output Power x 100\%}}{\text{Input power}}$$

e.g. for a 3 (d.c.) output power supply:

$$\text{Efficiency} = \left[\frac{(V1 \times A1) + (V2 \times A2) + (V3 \times A3)}{\text{Input Power}}\right] \times 100\%$$

Ordinary multimeters of sufficient accuracy can be used to measure the output power, since they are true dc.

An electronic power analyzer such as the Voltech series is essential for measuring the true input power.

Power Losses = Input power - output power

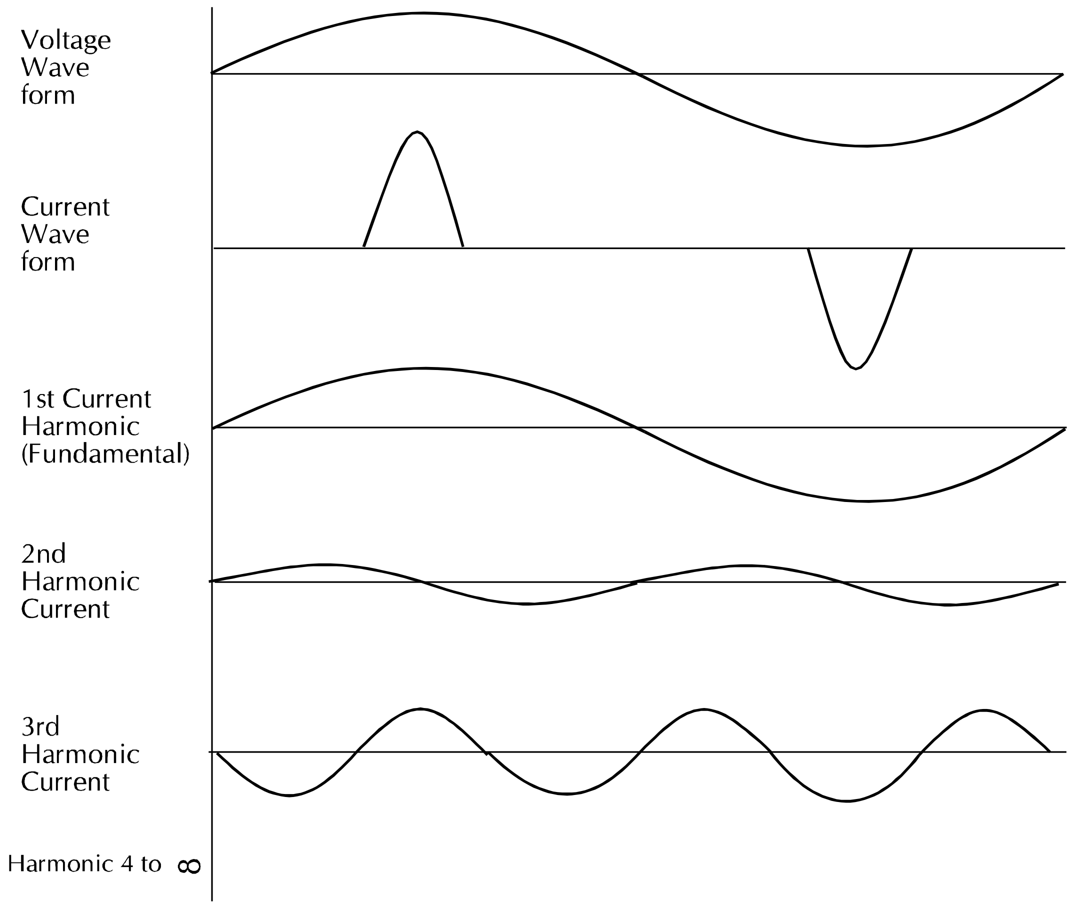
The power lost in a power supply is generally dissipated in the form of heat. Inadequate heat-sinking and ventilation will lead to excessive component temperatures. When verifying a design it is important to account for all losses and ensure that the individual component losses are within their design limits.

Voltech analyzers can also make accurate power measurements on the dc bus of a power supply. This is especially useful when determining the efficiency of a power factor correction circuit.
The PM6000 will measure and display efficiency directly.
For example, measuring the efficiency of a PFC circuit a PM6000 will group up to 2 sets of 3phase measurement channels, for example power input as Group A and power output as Group B.
With the on board math function efficiency can displayed directly on the screen of the PM6000.

Voltech PM6000 Power Analyzer

8.6 Amps Harmonics

Using Fourier analysis, a distorted current waveform, such as that drawn by a power supply, can be shown to consist of a fundamental component (at the supply frequency) plus a series of harmonic components (at multiples of the supply frequency):-

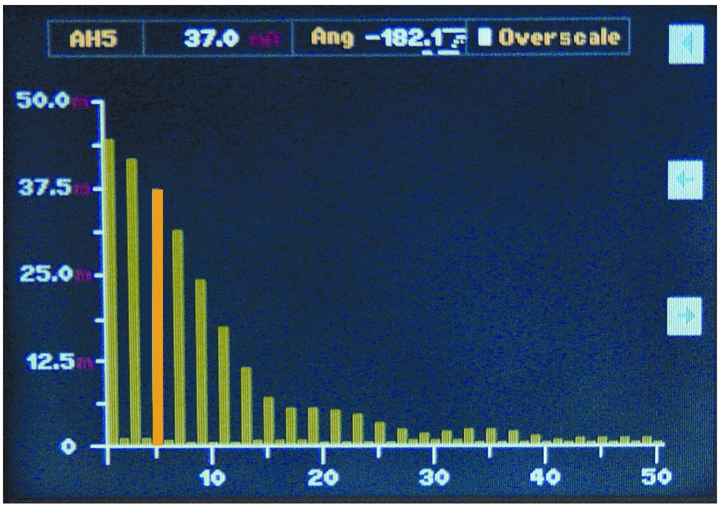


International standards such as EN61000-3-2 specify limits for the amplitude of each harmonic up to the 40th.

Measuring to EN61000-3-2.

The standard specifies different limits for different types of equipment in four Classes A, B,C, and D. Also, the measurement method is complicated with specific measurement window and digital sampling and filtering techniques specified. For measurement in full-compliance to the standard, please see the detailed information available for the Voltech PM6000 power analyzer on our website at www.voltech.com. The PM6000 full-compliance methods are used by leading EMC Test Laboratories across the world.

The PM1000+ power analyzer is suitable for making pre-compliance EN61000-3-2, by comparing the measured harmonic amplitudes with the specified limits. Please contact your Voltech supplier for more information.



PM1000+ Real time Harmonic Display

8.7 Total Harmonic Distortion (THD)

THD is a measure of the distortion of a waveform.

Voltage THD is used to check the purity of the voltage supply to a power supply. A very pure voltage supply should be used when checking current harmonics in accordance with standards like IEC61000-3-2.

Current THD may be used to check the power supply against specification and to help confirm the correct operation of power-factor correction circuits.

THD is calculated from harmonic measurements according to the formula:

$$thd = \frac{\sqrt{H2^2 + H3^2 + H4^2 + H5^2 + \ldots}}{REF}$$

8.8 Line Regulation

This is a measure of the ability of the power supply to maintain (or regulate) its output voltage when the input ac line changes.

To measure line regulation, the main output voltage, Vo, is measured at three points with the output load current kept constant.

$$\text{Line regulation} = \frac{\text{Vo (Highline)} - \text{Vo (Lowline)}}{\text{Vo (Nominalline)}} \times 100\ \%$$

Where Vo (Highline) = Vo at maximum ac input voltage
Vo (Lowline) = Vo at minimum ac input voltage
Vo (Nominalline) = Vo at nominal line voltage.

8.9 Load Regulation

This is a measure of the ability of the power supply to maintain (or regulate) its output voltage when the output load changes.

To measure load regulation, the main output voltage, Vo, is measured at three points with the ac input voltage kept constant.

$$\text{Load regulation} = \frac{\text{Vo (Highload)} - \text{Vo (Lowload)}}{\text{Vo (Nominalload)}} \times 100\ \%$$

Where Vo (Highload) = Vo at maximum dc load

Vo (Lowline) = Vo at minimum dc load current

Vo (Nominalload) = Vo at nominal load.

Cross regulation may also be measured and is calculated as the percentage change on one dc output when another dc output load is changed from minimum to maximum as above.

9 Example Power Supply Measurements.

PM1000 Output

RESULTS OF MEASUREMENTS			
Watts	+86.61100 W		
VA	134.58000 W		
PF	- 0.64355		
Vrms	246.80000 V		
Arms	0.54528 A		
Vcf	1.38		
Acf	2.55		
Freq	50.10700 Hz		
AH0	- 0.00422 A	- 1.16 %	0.0 deg
AH1	0.36558 A	100.00 %	- 349.1 deg
AH2	0.00266 A	0.72 %	- 244.7 deg
AH3	0.30718 A	84.01 %	- 179.9 deg
AH4	0.00233 A	0.62 %	- 44.4 deg
AH5	0.21917 A	59.94 %	- 3.1 deg
AH6	0.00157 A	0.42 %	- 194.4 deg
AH7	0.12045 A	32.94 %	- 182.6 deg
AH8	0.00105 A	0.27 %	- 345.1 deg
AH9	0.03613 A	9.88 %	- 2.9 deg
AH10	0.00076 A	0.19 %	- 106.1 deg
AH11	0.01948 A	5.32 %	- 0.8 deg
AH12	0.00092 A	0.24 %	- 218.8 deg

AH13	0.04179 A	11.42 %	- 180.2 deg
AH14	0.00106 A	0.28 %	- 19.2 deg
AH15	0.03770 A	10.30 %	- 357.9 deg
AH16	0.00077 A	0.20 %	- 164.0 deg
AH17	0.01750 A	4.78 %	- 166.6 deg
AH18	0.00077 A	0.20 %	- 300.5 deg
AH19	0.00735 A	2.01 %	- 232.0 deg
AH20	0.00076 A	0.19 %	- 70.3deg
AH21	0.01931 A	5.28 %	- 18.6 deg
AH22	0.00074 A	0.19 %	- 214.9 deg
AH23	0.01980 A	5.40 %	- 192.1 deg
AH24	0.00071 A	0.18 %	- 11.1 deg
AH25	0.01127 A	3.08 %	- 6.6 deg
AH26	0.00077 A	0.20 %	- 117.9 deg
AH27	0.00195 A	0.52 %	- 96.7 deg
AH28	0.00057 A	0.14 %	- 260.9 deg
AH29	0.00882 A	2.41 %	- 207.6 deg
AH30	0.00073 A	0.19 %	- 46.8 deg
AH31	0.01071 A	2.92 %	- 25.7 deg
AH32	0.00047 A	0.12 %	- 227.6 deg
AH33	0.00621 A	1.69 %	- 204.1 deg
AH34	0.00017 A	0.03 %	- 333.4 deg
AH35	0.00008 A	0.01 %	- 201.7 deg
AH36	0.00079 A	0.20 %	- 182.0 deg
AH37	0.00524 A	1.43 %	- 23.1 deg
AH38	0.00028 A	0.06 %	- 220.5 deg
AH39	0.00636 A	1.74 %	- 201.1 deg
AH40	0.00034 A	0.08 %	- 66.9 deg

10 Measurement Instrumentation.

To make credible measurements of on power supplies it is essential to use appropriate equipment. The power analyzer must be accurate on all waveforms and safe and easy to use. A power analyzer such as the Voltech PM1000+ provides the following:

- Fully isolated inputs, using 4mm safety connectors.
  Safe to use and connect.
- Wide range of input voltage, current and frequency.
  Up to 600V, 20A, 1Mhz
  Range from uA to MA with external transducers
- Accuracy on all ranges
  0.1% basic

- Harmonics as standard
  harmonic 0 to 50
- Versatile display
  4 or 14 measurements on the front panel
- Waveform display
  Volts, amps and watts
- Harmonic barchart display
  For an easy overview of harmonics.
- Easy to use
  On-board menu and help system
- Interface for production automatic test
  RS232, GPIB, USB and Ethernet
- PC Software
  for control and recording of measurements.

For the latest information, please see our website at:

www.voltech.com