THE ESSENTIAL GUIDE TO

Power Supplies

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The Essential Guide to Power Supplies is designed for power supply users, considering the many aspects of power supplies & DC/DC converters and their integration into today's electronic equipment.

The new guide includes details on the latest safety legislation such as the new IEC standard to replace IEC60950, new requirements for CE marking and the latest energy efficiency levels required by energy star and the EU code of conduct.

Also included are sections on subjects as varied as green mode topologies, power supply de-rating and electrolytic capacitor & power supply lifetime.

Whether you're new to designing-in a power supply or DC-DC converter or an 'old hand', this book offers an invaluable resource and all the information you'll need in one easy reference guide.

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THE ESSENTIAL GUIDE TO Power Supplies

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Introduction to Power Conversion

• Introduction

Electronic equipment requires low voltage DC power supplies. These DC supplies must be accurately regulated with low noise and present a low output impedance to support load changes. They must also provide protection for both the power supply itself and the end equipment.

AC power supplies and DC/DC converters are designed to provide these desirable characteristics and also provide isolation from input to output for safety, noise reduction and transient protection where required.

End applications may require a combination of AC/DC and DC/DC or Non Isolated Point Of Load (NIPOL or POL) converters to support the various power supply, power system and isolation needs of sub systems such as control electronics, battery charging, communications ports and electromechanical or applied parts.

Standard AC power supplies are typically designed to support global markets offering wide input range capability and standard DC/DC converters commonly offer 2:1 or 4:1 input ranges to cater for multiple nominal battery voltages. These wide or universal input ranges broaden potential markets for individual standard products increasing volumes and reducing cost. Standard product designs also incorporate features to cover multiple applications and carry multiple agency approvals to support world-wide requirements.

For high volume equipment it may be advantageous to consider an application specific or custom power solution where the initial design & approval costs and risks may be outweighed by reduced unit cost by ensuring that the power supply has only the exact electrical and mechanical properties required for the end application. However, the ever growing and extensive range of standard format power supply products available often negates this approach.

AC power supplies and DC/DC converters come in many different mechanical formats or packages to suit a wide variety of end applications and power ranges. They may be integrated into the end equipment in open frame, PCB mount, chassis mount, base plate cooled or enclosed formats, be kept external to the equipment in plug top, desk top or rack mounted formats or may be designed to suit specific applications such as DIN Rail equipment.

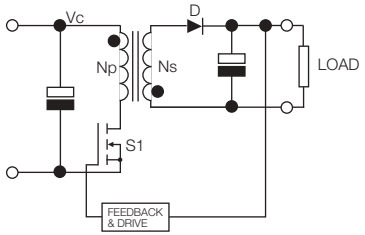
Switching power supply and DC/DC converter performance continues to advance. Developments in areas such as ZVS (Zero Voltage Switching) & ZCS (Zero Current Switching) resonant topologies & synchronous rectification techniques provide higher conversion efficiency and reduced heat dissipation. These advances allow higher switching frequencies and along with advanced packaging techniques mean continued improvement in power density reducing overall volume and waste heat. Efficiencies above 90% are commonplace in AC power supplies with products peaking as high as 95%.

The Essential Guide to Power Supplies addresses input & output specifications, EMC considerations, safety legislation, cooling & thermal management, reliability, lifetime and much more.

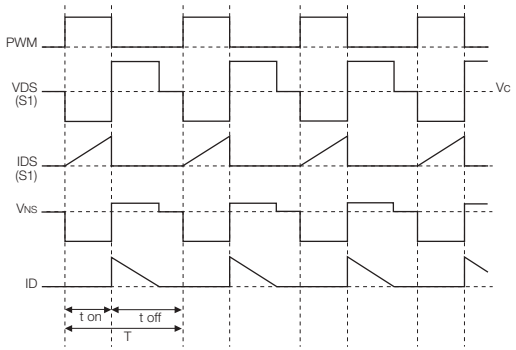
• Common Topologies

Isolated Fly-back Converter

Isolated fly-back converters are typically used in power converters up to 150 W. The topology uses only one major magnetic component, which is a coupled inductor providing both energy storage and isolation. Energy transfer to the secondary and the load occurs during the switching element off-time.



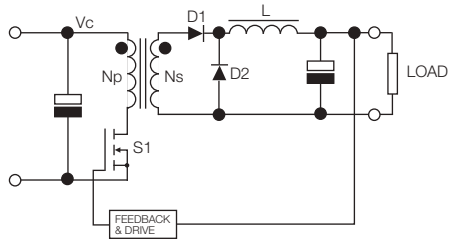
Isolated Fly-back Converter



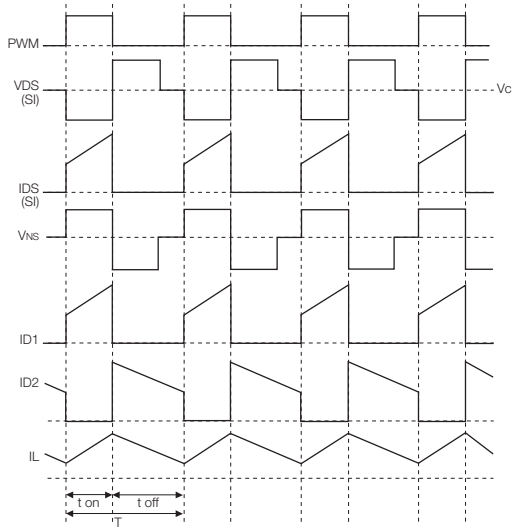
This topology provides a low cost means of converting AC to DC power due to its simplicity and low component count. The power level is restricted by the high levels of ripple current in the output capacitor and the need to store high levels of energy in the coupled inductor in a restricted volume. Flyback converters commonly utilize valley or transition mode controllers to reduce switching losses and green mode controllers to minimize no load power consumption.
The fly-back converter is used in DC/DC converters but only at low power (<50 W) due to the low input voltage and high ripple currents. Waveforms above are for discontinuous mode.

Forward Converter

Forward converters are typically used in power supplies which operate in the range 100-300 W. This topology uses two major magnetic components; a transformer and an output inductor. Energy transfer to the secondary and the load occurs during the switching element on-time. Forward converters are used in both AC power supplies and DC/DC converters.



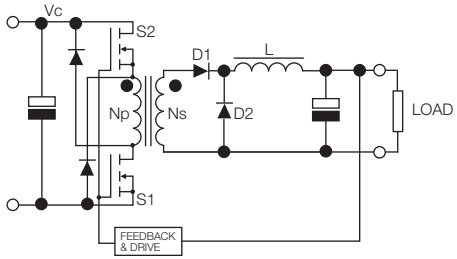
Forward Converter



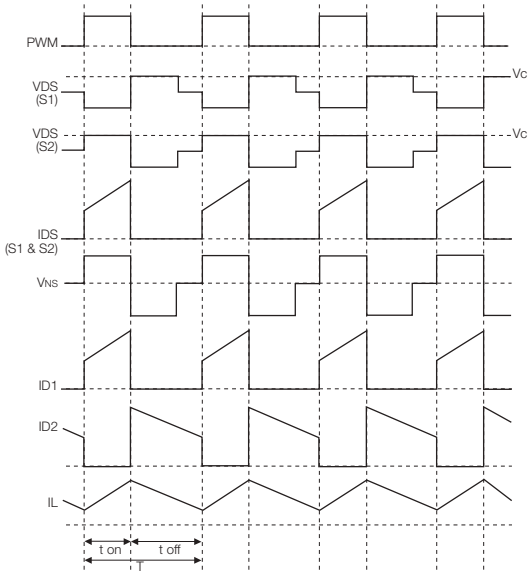
There is no energy stored in the transformer; energy is stored in the output stage of the converter in the inductor and capacitor. The output inductor reduces the ripple currents in the output capacitor and the volume of the transformer is dependent on switching frequency and power dissipation.

Two Transistor Forward Converter

At the higher end of the power spectrum, two transistor forward converters can be employed (see below). The two switching elements operate simultaneously, halving the voltage on each switching element and allowing the use of a device with a higher current rating.



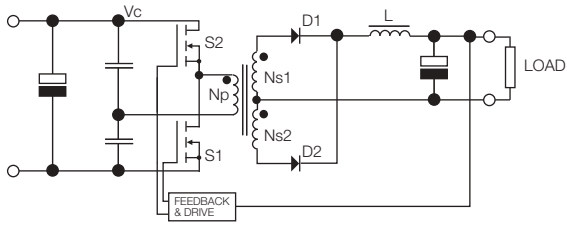
Two Transistor Forward Converter



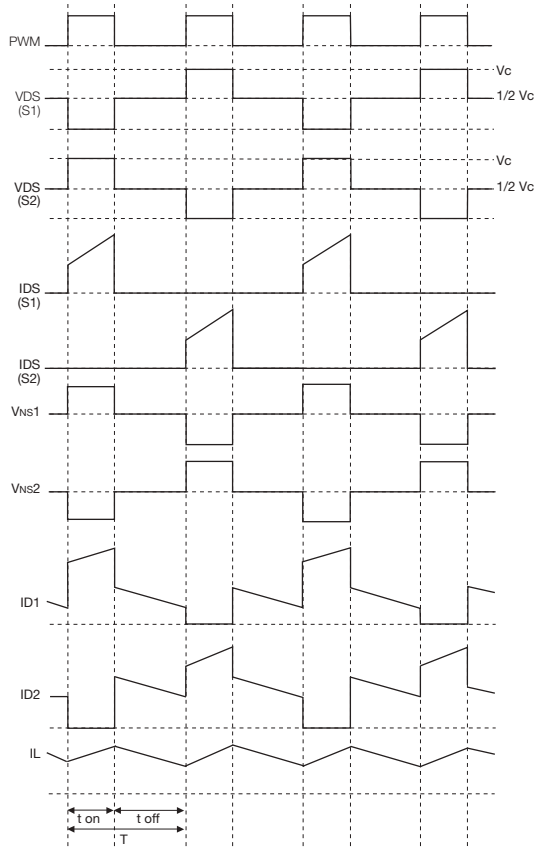
As the power rating increases, it is desirable to utilize the transformer core more efficiently by driving it through two quadrants of its available area of operation, rather than the one utilized in forward converters. This is achieved in half bridge or full bridge converters.

Half Bridge & Full Bridge Converters

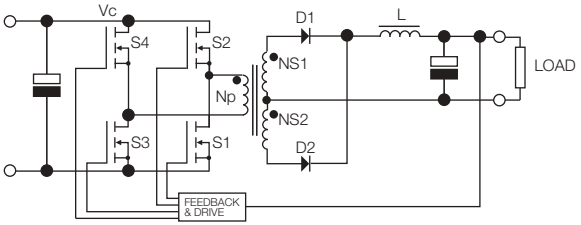
Half bridge converters are utilized in power supplies in the power range of 150-1000 W. This topology also uses two major magnetic components, a transformer and an output inductor, but in this case the transformer core is better utilized than in a forward converter. The switching elements operate independently, with a dead time in between, switching the transformer primary both positive and negative with respect to the center point.



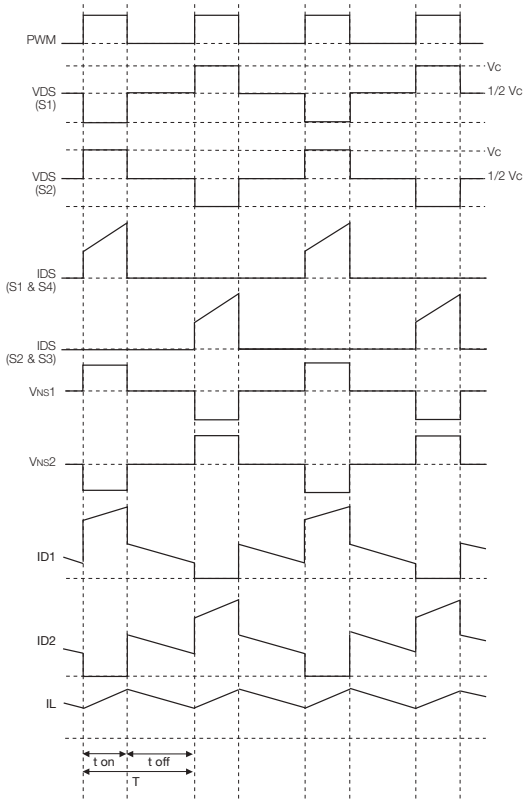
Half Bridge Converter



Energy is transferred to the secondary and the load during each switching element on-time by utilizing a split secondary winding. This has the added benefit of doubling the switching frequency seen by the secondary, helping to reduce the volume of the output inductor and capacitor required and halving the voltage seen by each switching element. In higher power solutions a full bridge converter can be employed (see below).

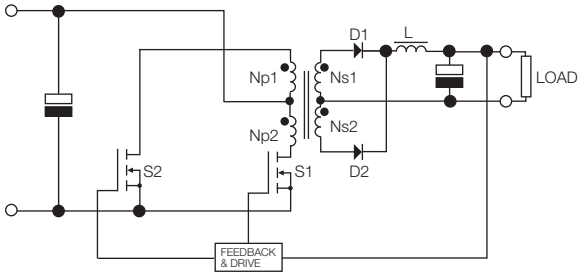


Full Bridge Converter

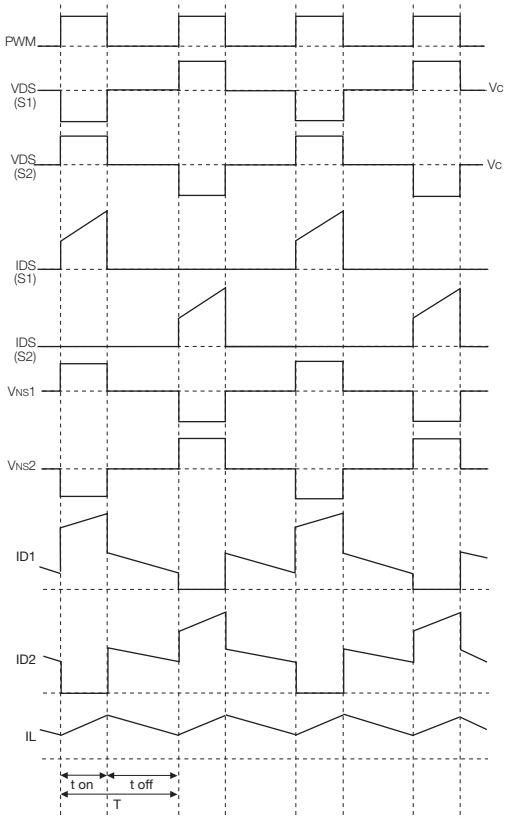


This topology will provide double the output power for the same primary switching current, but increases the complexity of switching element drive circuits, compared to the half bridge. Half bridge and full bridge converters are used in AC input power supplies. There is also a trend to utilize this topology in low voltage bus converters.

In DC/DC converters a similar topology to the half bridge is employed, called a push-pull converter. As the voltage applied to the switching element is typically low, this arrangement is designed to halve the primary switching current in each switching element, otherwise operation is similar to a half bridge.

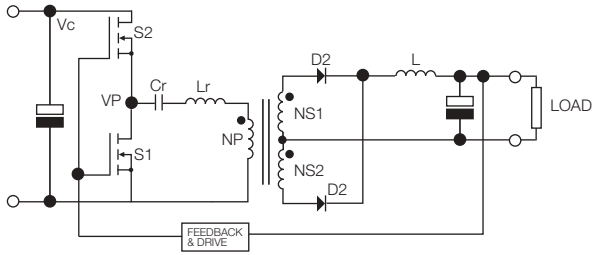


Push-Pull Converter

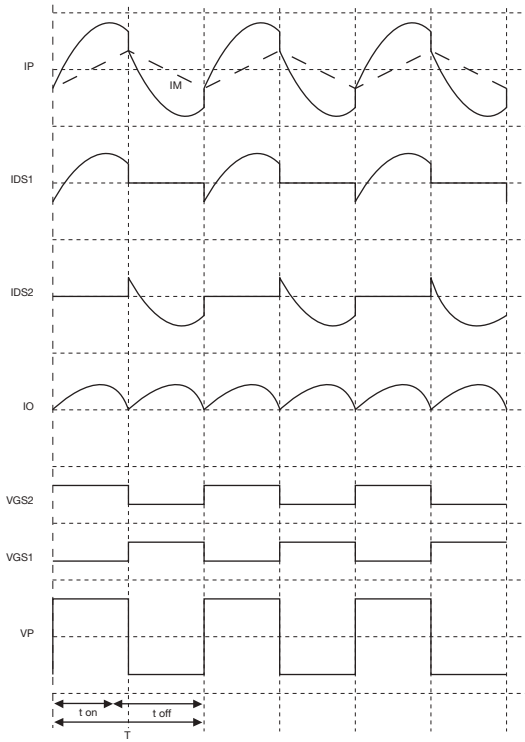


LLC Half Bridge Converter

LLC half bridge converters are popular in power ranges from 100 W to 500 W. This resonant topology utilizes Zero Voltage Switching (ZVS) to minimum switching losses and maximize efficiency. Frequency modulation is employed to regulate the output over the load range. Power transferred to the secondary, and the load, increases as the switching frequency nears the frequency of the resonant network and reduces as the frequency moves further away. The resonant inductor (Lr) is often combined with the power transformer by controlling the leakage inductance. The LLC converter is exclusively used with a pre-regulator usually in the form of a PFC boost converter as it has limited ability to compensate for changes in input voltage.

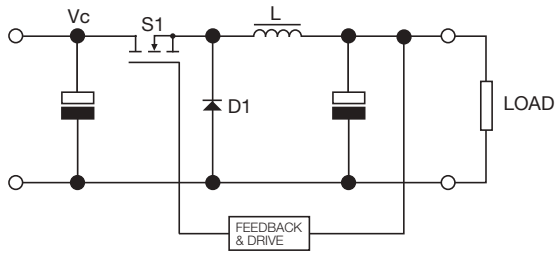


LLC Half Bridge Converter

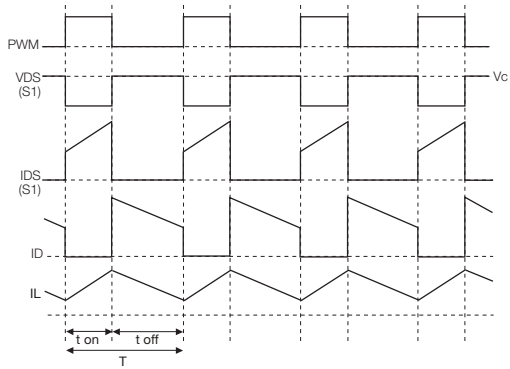


Buck Converter

Buck converters are used to step down the input voltage to produce a lower output voltage. This basic topology is widely employed in Non Isolated Point of Load (NIPOL or POL) converters used to produce locally regulated supplies in distributed power architectures.



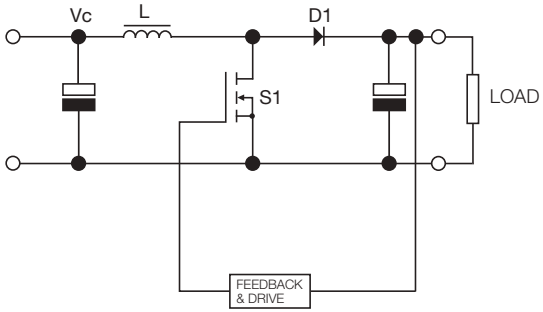
Buck Converter



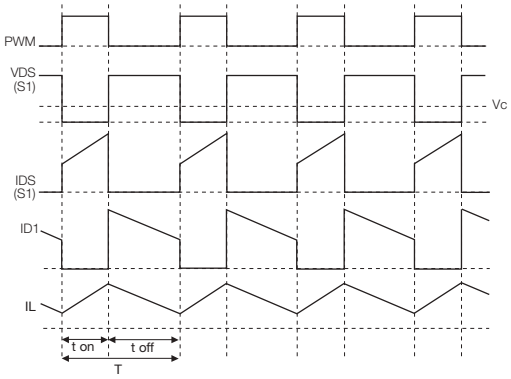
During the switching element on-time the current through the inductor rises as the input voltage is higher than the output voltage and the inductor acquires stored energy. When the switch opens the current freewheels through the diode and supplies energy to the output.

Boost Converter

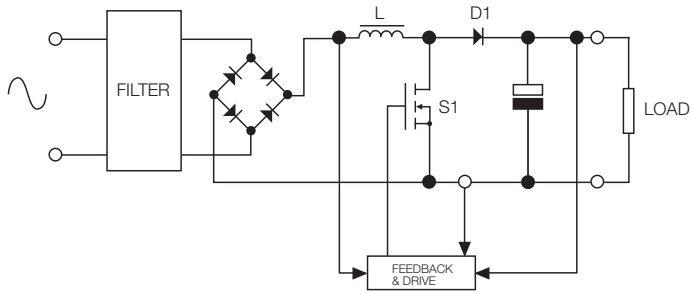
Boost converters are used to step up the input voltage to produce a higher output voltage. They can be used to boost DC supplies but are most commonly used in AC input power supplies above 100 W configured to provide active Power Factor Correction (PFC). The following are diagrams of a standard boost converter and a boost converter in a PFC application.



Boost Converter



Energy is stored in the inductor during the switching element on-time, the voltage across the inductor is added to the input voltage and transferred to the output capacitor during the switching element off-time. Practically, output voltages of up to five times the input voltage can be achieved.

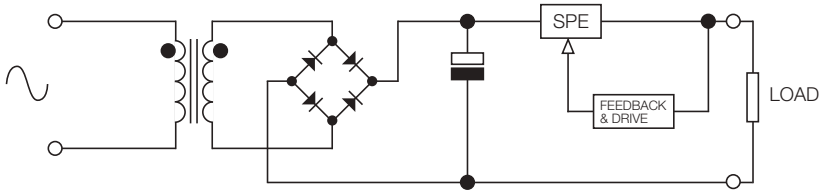


PFC Boost Converter

In active PFC configurations, the pulse width of the switching current is controlled so that the average input current to the boost converter is proportional to the magnitude of the incoming AC voltage. This forces the input current to be sinusoidal. The input filter removes the switching frequency ripple. See page 36 for more information.

• Linear Power Supplies

Linear power supplies are typically only used in specific applications requiring extremely low noise, or in very low power applications where a simple transformer rectifier solution is adequate and provides the lowest cost. Examples are audio applications (low noise) and low power consumer applications such as alarm panels (low cost).



Linear Power Supply

The 50/60 Hz mains transformer reduces the voltage to a usable low level, the secondary AC voltage is peak-rectified and a Series Pass Element (SPE) is employed to provide the necessary regulation. The benefits of this solution are low noise, reliability and low cost. On the downside, these units are large, heavy and inefficient with a limited input voltage range.

• Green Mode Power Supply Topologies

Many power supply products are marketed under the “Green Power” label meaning that they are designed to maximize efficiency across the load range (known as average active mode efficiency) and minimize power consumed at no load. Active mode efficiency is the average of four measurements made at 25, 50, 75 & 100% of full load.

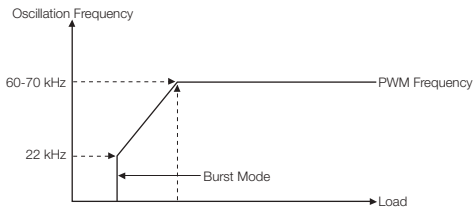
There are multiple pieces of legislation applicable to external power supplies (EPS) including the ErP directive (Energy related Products), CEC (California Energy Commission), EISA (Energy Independence & Security Act), NRCan (Natural Resources Canada). Many power supply makers are also marketing component power supplies with similar specifications such as XP’s “Green Power” products, designed to enable users to meet green criteria for end applications.

Green mode off line fly back converters

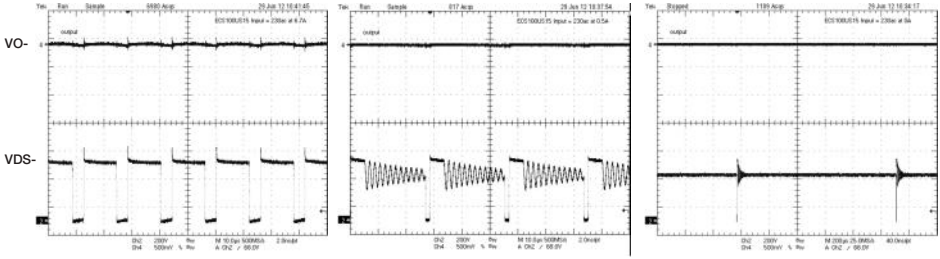
The simplest approach is the green mode off line fly back converter which is suitable for supplies up to around 100 W.

At higher loads the switching frequency is typically 60 – 70 kHz. As the load reduces the switching frequency also reduces to minimize the number of switching cycles per second, reducing switching losses and maximizing efficiency across the load range. The switching frequency reduction stops at around 22 kHz to remain in the ultrasonic range of the human ear. At very light or zero load the power supply enters burst mode to minimize the power consumption.

The graph below shows the general concept.



The oscilloscope traces overleaf show the switching waveform and output voltage of XP’s ECS100 green mode component power supply at full load (switching at 62 kHz) at 10% load (switching at 35 kHz) and at zero load when the supply has entered burst mode to reduce the power consumed to <0.5 W. Individual bursts occur at a repetition rate of 900 Hz.



100% Load 10% Load Zero Load

A side effect of burst mode operation can be audible noise at no load or very light load as components with parts which can move under electrical stress can act as transducers and emit audible noise. These may be wound components, filter capacitors, line capacitors & snubber capacitors. This low level audible noise is normal and does not indicate malfunction.

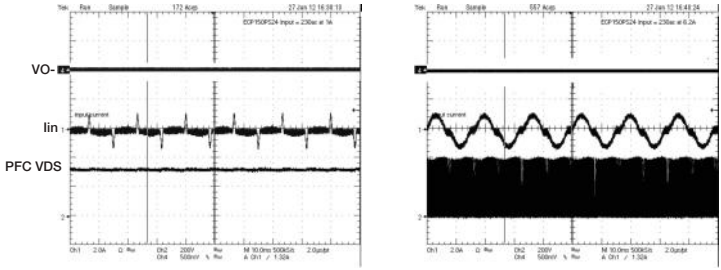
Active power factor correction & fly back converter combination

This topology combines an active power factor correction boost converter stage with a fly back main converter, typically used up to around 150 W and driven by green legislation which demands high power factor for power levels above 100 W.

The use of two conversion stages means that both must be considered when optimizing active mode efficiency across the load range. An effect of this optimization is that the PFC boost converter will switch off at lower loads, typically less than 50 - 60 W as harmonic correction is not required and the losses from the boost converter are removed. The fly back converter is able to operate over a wide range of input voltages so there is no impact on the output voltage from the loss of the regulated supply generated by the boost converter.

When the PFC boost converter is disabled at lower loads the power factor reduces significantly, from >0.9 to around 0.5, as the power factor correction is no longer active and the input current reverts to the non sinusoidal shape with higher levels of harmonic current associated with non PFC converters.

The traces below show the typical operation of the PFC boost converter on XP's ECP150 series green mode power supply incorporating active PFC at higher load.



PFC Off PFC Active

During the on/off transition of the PFC boost converter it may be possible to detect some audible noise.

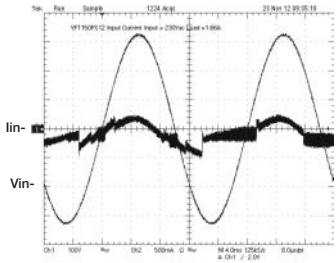
As the load continues to decrease the fly back converter element of the design performs in the same manner as the off line fly back converter above reducing the switching frequency with load and entering burst mode at very light or zero load with the same potential side effects.

Active power factor correction & LLC resonant converter combination

LLC resonant converters are common place providing a cost effective high efficiency solution for power supplies in the 100 – 500 W range when combined with an active PFC boost converter.

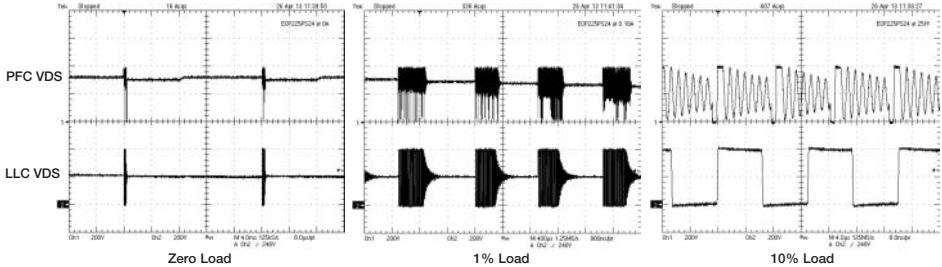
LLC converters are not able to operate over wide input ranges, requiring a stable input supply which is provided by the boost converter stage. This characteristic of the LLC converter means that the PFC boost converter cannot be disabled at lower loads and enters a burst mode to maximize active mode efficiency while maintaining the stable supply to the main converter. This burst mode switching results in a lower power factor and non-sinusoidal input current.

The input current wave shape is also asymmetrical during boost converter burst mode operation. The trace below shows typical input current wave shape under boost converter burst mode operation.



In addition to the non-sinusoidal input current it may be possible to detect audible noise as the boost converter transitions on/off.

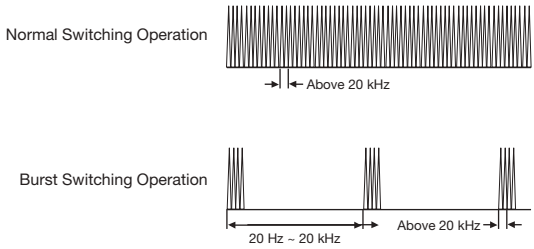
The LLC main converter changes frequency by a small amount across the load range by nature of its operation but at light and zero loads it must also burst fire to achieve the low and no load power dissipation. At light loads both the PFC boost converter and the main LLC resonant converter are burst firing. The traces overleaf show the PFC converter (top trace) and the LLC converter (bottom trace) at zero load, 1% load and 10% load of a typical product.



Noticeable effects when using this topology are reduced power factor, non-sinusoidal input current and audible noise from both the PFC boost converter and the LLC resonant converter.

Audible noise in green mode power supplies

A consequence of green mode operation is the potential for audible noise created by the repetition rate or frequency of the burst which is in the audible range between 20 Hz & 20 kHz. While this does not indicate malfunction and is not harmful to the power supply it is undesirable if it is noticeable in the end application. The diagram below explains burst mode operation pictorially.



Steps are taken to mitigate audible noise such as varnish impregnation of transformers and other wound components, changing ceramic capacitors to film types in key areas to avoid piezo electric effects and controlling burst mode frequency to avoid the areas most sensitive to the human ear (2 kHz – 4 kHz). These steps may not eradicate audible noise under all conditions but go a long way to minimize the effects.

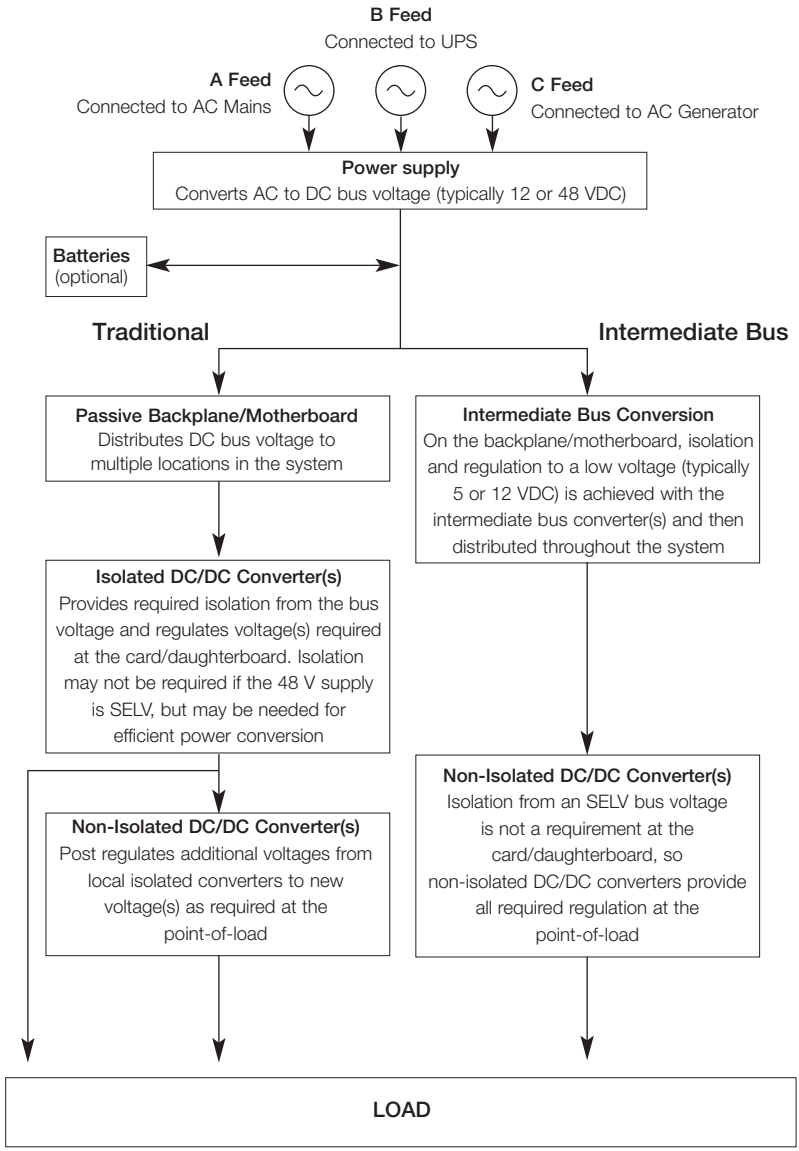
• Distributed Power Architecture

Distributed Power Architectures (DPA) deliver power utilizing multiple power converters throughout the system. Typical components found in traditional DPA and intermediate bus DPA systems are outlined in the diagram (next page).

The power supply provides the primary point of isolation between AC mains high voltage and the end user. The type of power supply used in distributed power applications is typically referred to as front end or rectifier. Front end power supplies and rectifiers have similar functions, such as hotplug/hot-swap capability, redundant operation, blind-mate connection and various status and control options.

Front ends are most often used in enterprise, network and data storage equipment. Front ends provide a regulated bus voltage throughout all regions of the system. Redundancy is usually gained by supplying multiple input sources, such as AC mains, UPS systems and/or generated power and multiple power supplies. This approach ensures that the loss of one input source or power supply does not result in a catastrophic system shut-down. The DC bus voltage in this type of system is regulated and should never swing by more than ±10% from the power supply's 48 VDC output setting. For this reason, intermediate bus converters which have a narrow input range of only 42-53 VDC may be used in this type of system.

Rectifiers are most often used in telecommunications equipment where redundancy is gained by backing up the DC bus voltage with batteries. A rectifier must be capable of driving both the system load and battery recharging load requirements. The bus voltage in a rectifier power system can vary more widely due to changes in the status of the batteries during charge and discharge modes. For this reason, traditional intermediate bus converters that have a narrow input range of only 42-53 VDC may not be used in this type of system.



Distributed Power Architecture

Input Considerations

• Power Sources

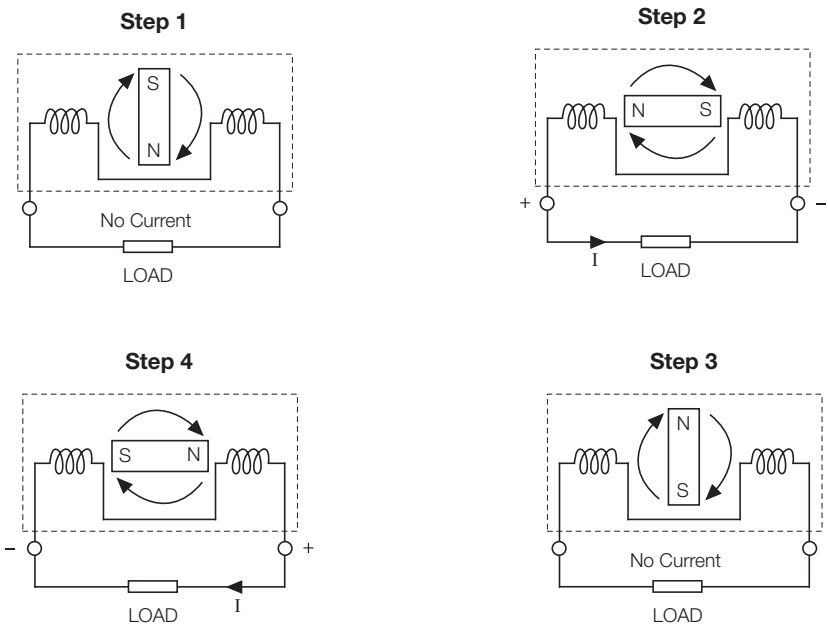
Sources of electricity (most notably rotary electro-mechanical generators) naturally produce voltages alternating in polarity, reversing positive and negative over time, known as alternating current (AC). AC power is typically derived from the local power company grids, either as a single or three-phase source. This is then converted to DC within the majority of electronic equipment.

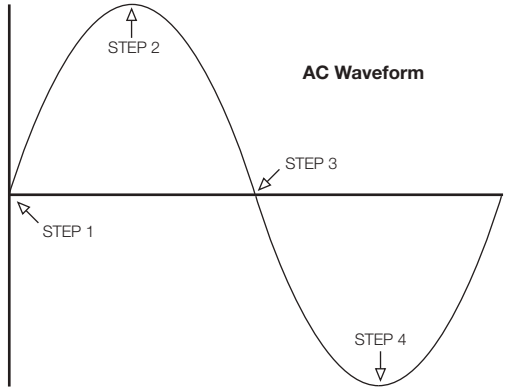
AC Power Sources

In applications where electricity is used to dissipate energy in the form of heat (heaters, light bulbs), the polarity or direction of current is irrelevant so long as there is enough voltage and current to the load to produce the desired heat (power dissipation). However, with AC it is possible to build electric generators, motors and power distribution systems that are far more efficient than a DC equivalent. For this reason, AC is used predominantly in high power applications.

AC Generator

In an AC generator, a magnetic field is rotated around a set of stationary wire coils, the resultant AC voltage/potential produced as the field rotates being in accordance with Faraday's Law of electromagnetic induction. The basic operation of the AC generator, also known as an alternator, can be seen below:





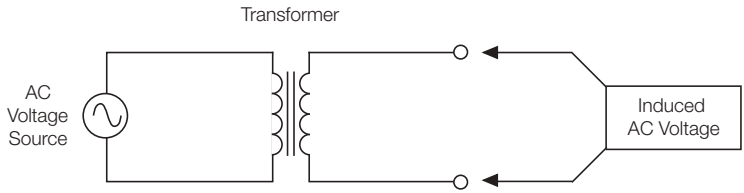
The polarity of the voltage across the wire coils reverses as the opposite poles of the rotating magnet pass by. Connected to a load, this reversing voltage polarity creates a reversing current direction in the circuit.

The frequency of the resultant wave form is dependent on the speed of the rotating magnetic field.

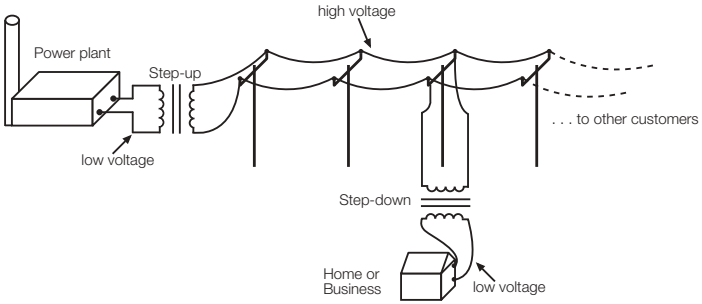
Frequency	**=**	**No. of cycles/second**
	=	**No. of revolutions/second**

AC generators and AC motors are generally simpler in construction than DC generators and DC motors. AC generators & motors also benefit from the effect of electromagnetism, also known as mutual induction, whereby two or more coils of wire are positioned so that the changing magnetic field created by one induces a voltage in the other.

The diagram below shows two mutually inductive coils. Energizing one coil with AC voltage creates an AC voltage in the other coil. This is a transformer:



The transformer's ability to step AC voltage up or down gives AC an advantage unmatched by DC in power distribution. When transmitting electrical power over long distances, it is more efficient to do so with higher voltage and lower current allowing smaller diameter wire with lower resistive power losses, then to step the voltage back down and the current back up for industry, business or consumer use.



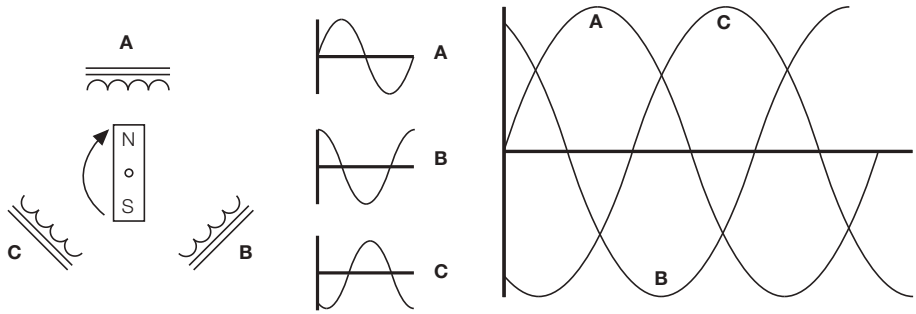
Power distribution

Transformer technology has made long-range electric power distribution practical. Without the ability to efficiently step voltage up and down, it would be prohibitively costly to construct power systems for anything but close-range use.

Three-phase AC

The power delivered by a single-phase system pulsates and falls to zero during each cycle, whereas the power delivered by a three-phase circuit also pulsates, but never to zero. In a balanced three-phase system, the conductors need be only about 75% the size of the conductors for a single-phase two-wire system of the same kVA rating.

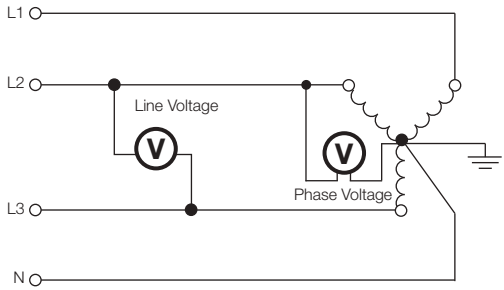
If three separate coils are spaced 120° apart, the three voltages are produced 120° out of phase with each other, when the magnetic field cuts through the coil.



There are two basic three-phase connections used:

Star or Wye Connection

Connecting one end of each of the coils together, as shown on the right, makes a star or wye connection. The phase voltage (or phase to neutral voltage) is the voltage measured across a single coil. The line voltage (phase to phase voltage) is measured across two coils.



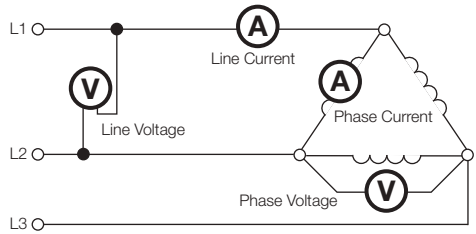
In a star or wye-connected system, the line voltage is higher than the phase voltage by a factor of the square root of 3 (1.732).

$$V_{LINE} = V_{PHASE} \times \sqrt{3}$$
$$V_{PHASE} = V_{LINE} / \sqrt{3}$$

This is a 4-wire plus earth system.

Delta Connection

The three separate coils are connected to form a triangle in a delta-connected system, which derives its name from the fact that a schematic diagram of this connection resembles the Greek letter delta (Δ).



In this configuration the line voltage and phase voltages are the same.

$$V_{LINE} = V_{PHASE}$$

However, the line current is higher than the phase current by a factor of the square root of 3 (1.732). The reason for this difference in current is that current flows through different windings at different times in a three-phase circuit.

At times, current will flow between two lines only, at other times current will flow from two lines to the third.

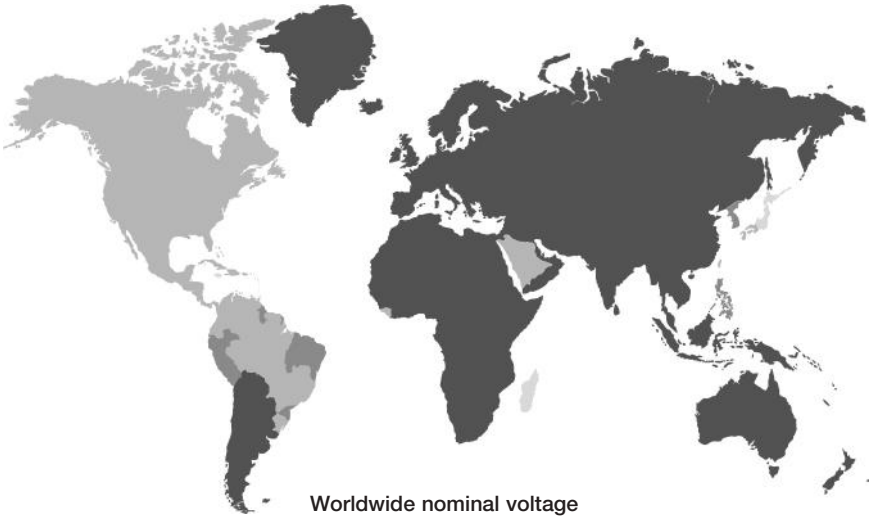
Single-Phase Voltage and Frequency

Europe and most other countries in the world use a mains supply voltage which is nominally between 220 and 240 volts. In Japan and in most of the Americas the voltage is nominally between 100 and 127 volts. New buildings in the USA are supplied with two phases and neutral to provide a higher phase to phase voltage where required for higher power appliances. Switch mode power supplies are typically designed for global use and cover an input range of 90-264 VAC to cater for the various nominal supplies and their tolerance.

Three-Phase Voltage and Frequency

Although single-phase power is more prevalent, three phase supplies are the power of choice for many applications. As previously discussed, power stations supply three-phase electricity and it is often used in industrial applications to drive motors and other devices. Three-phase electricity is a smoother form of power than single or two-phase systems allowing machines to run more efficiently and extending their lifetime.

220 – 240 VAC single phase supplies are derived from 400 VAC three phase systems and 100-127 VAC single phase supplies from 200 VAC three phase systems. In the USA there is also a 480 VAC three phase system used for some high power applications which results in a nominal 277 VAC single phase supply often used for applications such as street furniture & street lighting.



Worldwide nominal voltage

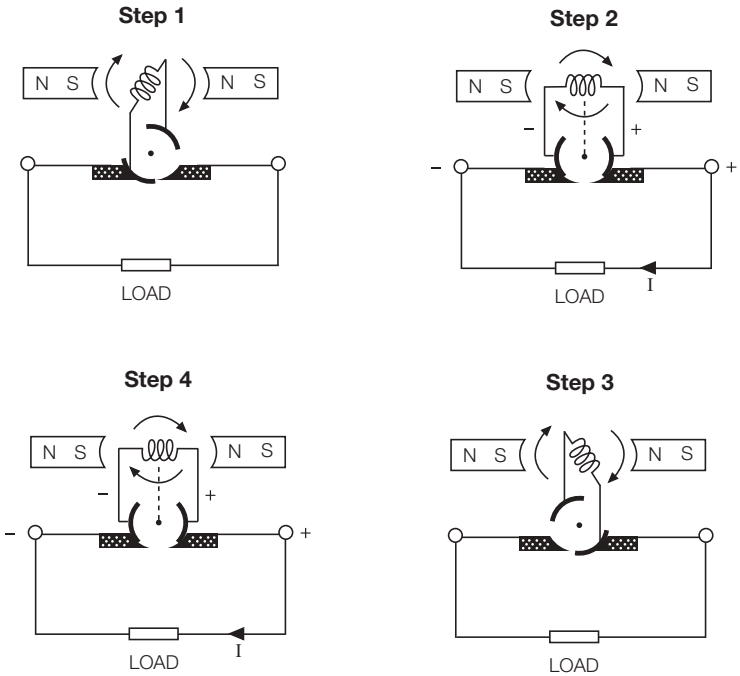
Single Phase	3 Phase
220-240 V - 50 Hz	380-415 V - 50 Hz
220-240 V - 60 Hz	380-415 V - 60 Hz
100-127 V - 60 Hz	170-220 V - 60 Hz
100-127 V - 50 Hz	170-220 V - 50 Hz

DC Power Sources

DC power sources are produced by rectifying an AC source, an electrochemical reaction in the form of a battery or by a DC generator.

There is a move in data centers to DC power systems, where the incoming utility supply is rectified to a nominal 400 VDC bus which is then distributed around the facility. This eliminates the first stage of power conversion within the individual computers and servers resulting in significant component count reduction, increased efficiency and reliability, improved ride-through characteristics and lower running costs.

DC generators work on the principle of electromagnetic induction, their construction is more complicated than the AC equivalent. In a DC generator, the coil of wire is mounted in the shaft where a magnet would be found in an AC generator, and electrical connections are made to this spinning coil via stationary carbon brushes contacting copper strips on the rotating shaft. This is necessary to switch the coils, changing output polarity, so that the external circuit sees a constant polarity.



The simplified example above produces two pulses of voltage per revolution of the shaft, both pulses in the same polarity. For a DC generator to produce constant voltage there are multiple sets of coils making intermittent contact with the brushes.

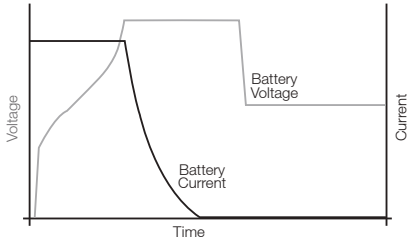
Batteries

There are four battery chemistries in common use: Valve Regulated Lead Acid (VRLA), Nickel Cadmium (NiCad), Nickel Metal Hydride (NiMH) & Lithium (Lithium Ion & Lithium Polymer).

Valve Regulated Lead Acid

Valve Regulated Lead Acid (VRLA) batteries are widely used in industrial control applications, Uninterruptible Power Supplies (UPS), alarm & security systems and telecommunications to provide standby power in the event of mains failure. These batteries are simple to charge and maintain, requiring a charger with a constant current characteristic of typically 0.1 times capacity (0.1C) for the initial charge period followed by a constant voltage of 2.25 V/cell to complete the charge and trickle charge thereafter, the constant voltage trickle charge is connected indefinitely to compensate for self discharge. This is known as a float charge system and for best performance the voltage applied should be temperature compensated at 3 mV/ºC per cell decreasing above 20 ºC and increasing below 20 ºC.

VRLA batteries are often boost or equalize charged at the higher voltage of 2.4 V/cell for an initial period to speed the charging process and equalize the cell voltages to restore full capacity, this is a three step charging regime as shown in the diagram below.



Three step charge curve

Manufacturer's capacity, discharge and service life data is generally given for temperatures in the range of 20 – 25 ºC. At lower temperatures the capacity is significantly reduced to around 80% at 0 ºC. At higher temperatures the service life is significantly reduced to around 40% at 40 ºC and as low as 10% at 50 ºC. In extreme cases high temperatures can result in thermal runaway resulting in excess gas production and battery swelling which is irrecoverable.

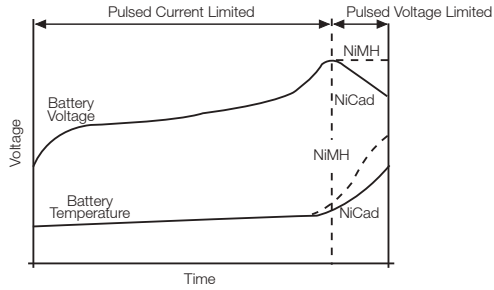
Nickel Cadmium and Nickel Metal Hydride

Nickel Cadmium (NiCad) is an older technology typically used in portable applications and has the advantages of high power density and high current discharge rates 20 to 30 times capacity (20-30C) typical but has the disadvantage of memory effect when the battery is not fully cycled losing capacity. This can be overcome but requires a complex charging regime to achieve a recovery.

Nickel Metal Hydride (NiMH) is a more recent evolution of NiCad and does not suffer with the same memory effect when used in a non cycled system.

Both of these chemistries are best charged using a delta peak charging regime. The battery is charged with a constant current up to 5 times capacity (5C) and the voltage monitored. The voltage on the cell will rise for the majority of the charge period. During the charge period the charge power is applied to the battery for a period then removed to monitor the cell voltage then reapplied. This is repeated until the battery unit achieves 95% of charge when the cell voltage will drop slightly, this is the knee point. The charger will recognize this and revert to constant voltage trickle charging to achieve the final 5% of charge; the advantage is that the battery is fast charged to 95%.

NiCad and NiMH batteries can also be charged at 0.1C permanently as the battery is able to dissipate the excess charge as heat without damage to the cell structure.



NiCad/NiMH Battery Charging Characteristics

Lithium

Lithium batteries are also typically used in portable applications and have a higher power density than VRLA or Nickel batteries, they are also lighter than VRLA batteries. There are many chemistry derivatives including lithium iron phosphate, lithium manganese, lithium manganese cobalt and lithium titanate, all have similar properties.

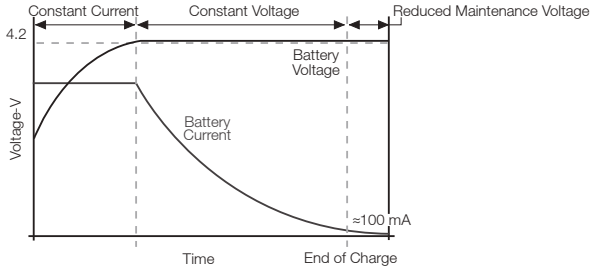
	Li-Ion	NiCad	NiMH
Energy Density Whr/kg	90	90	90
Energy Density Whr/l	210	100	140
Operating Voltage	3.6	1.2	1.2
Lifetime (approx. cycles)	1000	1000	800
Self Discharge	6%/month	15%/month	20%/month

A stringent charging regime is required for lithium technologies as incorrect charging may result in irreversible damage to the battery or, in the worst case, a fire which is virtually inextinguishable as the battery has both the fuel and an oxidant to supply oxygen.

Initially these battery chemistries could only be charged at a maximum rate of 1C and discharged at no more than 5C. At the time of writing this has improved to charge rates up to 3C and discharge rates up to 35C.

The general charging requirements for a Lithium Ion (Li-Ion) or Lithium Polymer (Li-Po) batteries are given below.

The battery must never be discharged below 3.0 volts per cell as this will cause irreversible damage. The battery is charged at a constant current of 1C until the cell voltage rises to 4.25 volts then at a constant voltage until the current drawn falls to 0.05C. At this point it is deemed to be 98% charged. From this point on a trickle charge is applied at 0.05C indefinitely. The trickle charge applied is a constant voltage 0.05 V above the battery terminal voltage, current limited to around 100 mA.

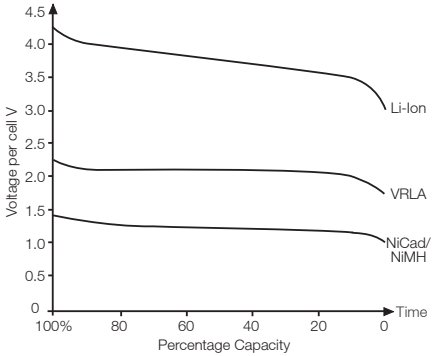


Li-Ion Battery Charging Characteristics

During charging certain parameters are monitored to avoid damage or fire risk. These include over voltage, over temperature & charging balance of series strings. If these parameters are found to be outside specification then the charger is shut down. Smart battery packs are available with built in protection. Many also include a serial interface which reports a fuel gauge indicating charge status, charge cycles, cell temperature, serial number and capacity.

Due to inconsistencies in manufacturing, a string of cells may each have slightly different capacity. When they are charged as a complete string the charge state of each will also differ. This imbalance can be corrected by cycling the battery through 2 or 3 balance charges to equalize the cell voltages. Balance charging is effected by the addition of a voltage monitor on each of the battery cells via a balance connector on the battery pack. The monitoring circuit measures the cell voltage and dissipates excess charge as an individual cell becomes charged allowing other cells in the string to catch up. If this is not done imbalance becomes more noticeable and the capacity of the battery is reduced.

Typical Battery Discharge Curves



• Input Protection

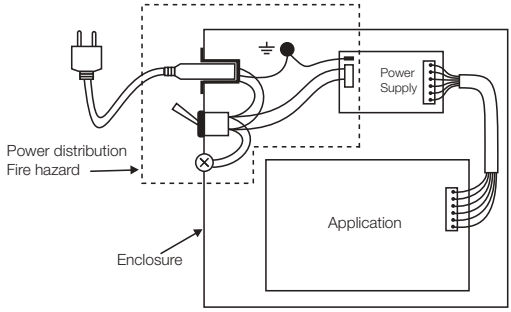
Input Current Protection

Input protection is implemented in power supplies and DC/DC converters to ensure safe operation. The input fuse fitted within a power supply is not intended to be field-replaceable, it is rated such that only a catastrophic failure of the power supply will cause it to fail. It will not be cleared by an overload as the power supply will have some other form of overload protection, usually electronic. The fuse will often be soldered into the PCB rather than being a replaceable cartridge type fuse.

The power supply fuse is listed as a critical part of the safety approval process and is used to ensure that the power supply does not catch fire under a fault condition. If the fuse clears the most likely cause is that the converter has failed short circuit presenting a short circuit to the mains supply. In this event the fuse will clear very quickly.

As previously discussed, the fuse in the power supply is not intended to be field-replaceable, and should only be replaced by competent service personnel following repair. When using a component power supply, there will be additional mains wiring within the enclosure before the power supply and its fuse. This is where an additional fuse or circuit breaker as a protection device is fitted to ensure that the wiring and associated components do not present a hazard.

When the end equipment is tested for safety it will also go through fault analysis to ensure that it will not present a fire hazard under a fault condition. If a fault were to occur many hundreds of Amps can flow causing wires to heat up very quickly, causing noxious fumes from the melting plastic insulation and creating a potential fire hazard.



Typical Application

Input Voltage Protection

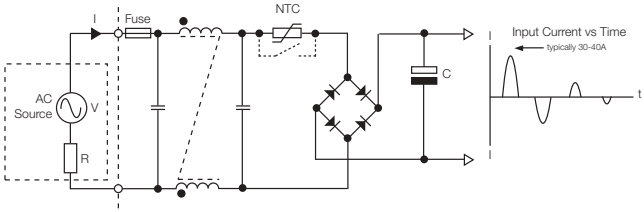
The input of the equipment may be subjected to a number of transient voltage conditions. These differ between AC & DC systems.

AC Systems	Switching transients Lightning strikes Spikes
DC Systems	Engine cranking transients DC line transients Reverse polarity

The AC system transients are explained in the EN61000-4-x series of standards. The DC transients relate to DC systems in vehicle, traction and telecommunications applications and have other applications specific standards.

Inrush Current

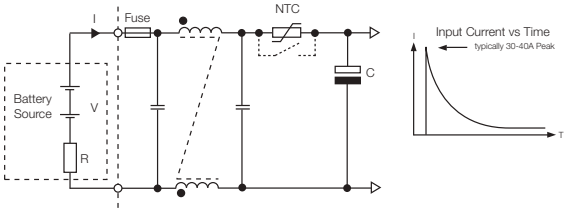
An AC mains system is a low impedance power source meaning that it can supply a large amount of current. In a power supply, at the instant of switch-on, the reservoir capacitor is discharged giving the appearance of a short circuit. Without any additional precautions the input current will be very large for a short period of time until the capacitor is charged.



Typical power supply input circuit

Precautions are taken to limit the inrush current as this will cause disturbances on the supply line and could damage any switches or relays and nuisance-blow fuses or circuit breakers. Fuses and circuit breakers need to be of a size and characteristic to cope with this inrush current without nuisance tripping. The most commonly used technique, due to its simplicity and low cost, is the fitting of a Negative Temperature Coefficient (NTC) thermistor. These devices have a high resistance when cold and a low resistance when hot. Inrush current is often specified from a cold start and at 25 °C due to thermal inertia and the time it takes for the thermistor to cool down following switch off of the power supply. In some applications, in order to solve this problem and improve efficiency, the thermistor is shorted by a relay following the initial inrush. There are other techniques using resistors and triacs but these are more complex and less common. A typical value of inrush current in an AC power supply is 30-40 A lasting 1-2 ms but can it be as high as 90-100 A in some products. There is a trade off to be made between lower inrush current and higher efficiency due to the power dissipated in the thermistor.

The same principles apply to DC circuits; the source impedance is very low, only this time it is a battery and not the mains supply. As with the AC circuit the peak will be over within a millisecond or so.



Typical DC/DC converter input circuit

Batteries have short circuit ratings measured in thousands of Amps and when the reservoir capacitor is discharged there appears to be a short circuit. Once again, the protection devices need to be sized to be able to cope with this. Inrush current levels tend to be higher, as is the nominal current, due to the efficiency trade-off. Often the inrush current will be specified as a multiple of the nominal current.

Sizing of Fuses & Circuit Breakers

So that the rating of the fuse or breaker can be determined, the nominal input current of the power supply needs to be established. If the application has more than one power supply or other mains powered equipment these will need to be taken into account.

To determine the input current, we need first to determine the input power and, in AC systems, remember to take into account the power factor and use the lowest operating input voltage.

Input Power = Output Power / Efficiency

Input Current = (Input Power / Input Voltage) / Power Factor

Choose fuse or CB rating at least 1.5 x Input Current - Time Lag

It is advisable to use a time lag fuse or breaker to avoid nuisance tripping on start up. The 1.5 x input current rating is to overcome the ageing effects of fuses.

Fuses are rated FF, F, T, TT (ranging from super fast to long time lag). For power supplies it is recommended that T or TT types are used.

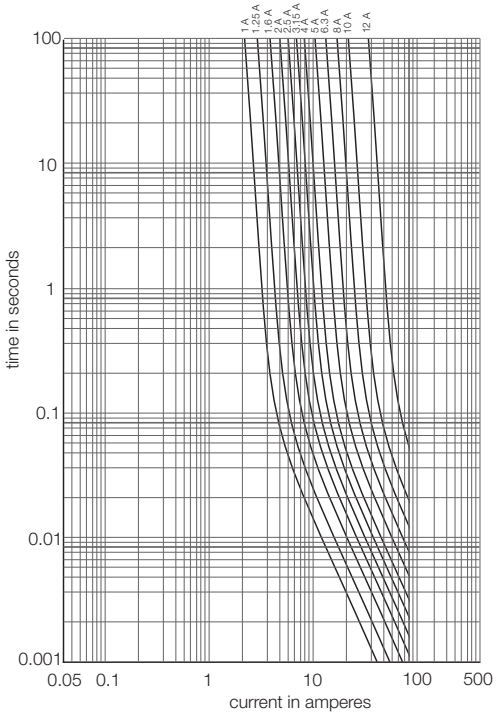
Circuit breakers are A-K (very fast to long time delay). For power supplies, C or above would be recommended.

Fuse Characteristics

Fuses are thermal devices and do not react instantly, even fast-blowing types. It is important to look at the actual rupture current of a given fuse. See the graph to the right.

Looking at the curve for a 1 A fuse, it can be seen that it will not clear at 1 A or 2 A. It would take 0.5 seconds before the fuse clears at 3 A. It would need 20 A to clear this fuse in 3 ms. This should be taken into account when ensuring nuisance tripping does not occur.

Looking at the 5 A fuse, it would take 80 ms to clear the fuse at a current of 30 A.

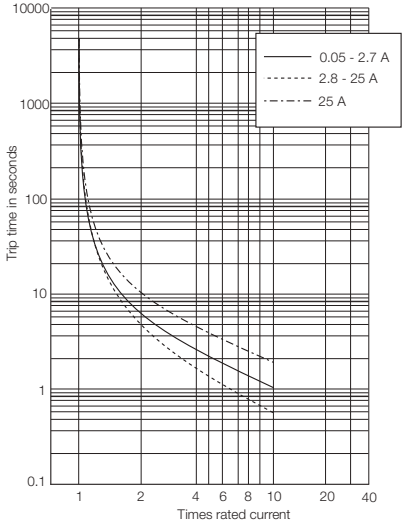


Circuit Breakers - Thermal

Circuit breakers are available in two basic technologies, thermal and magnetic. The thermal types have similar characteristics to a fuse and it is necessary to ensure there is adequate time lag to prevent nuisance tripping.

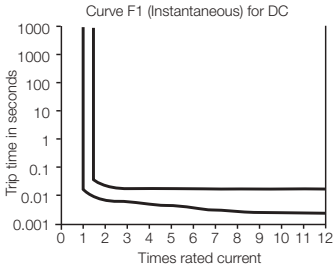
In the case opposite, for the 0.05-2.7 A breaker at 10 times the rated current, it would take 1 second for the break to occur. The temperature derating of the device should also be considered to ensure that it complies with the environmental parts of the specification.

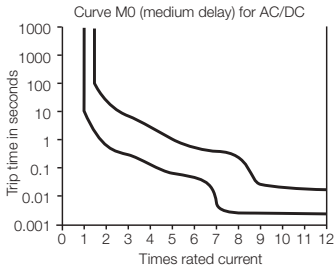
If a battery source is being used, it is also important to check the short circuit rating of the battery and the interrupt capacity of the circuit breaker. Because it has contacts, excessive current may cause it to weld shut rather than break.

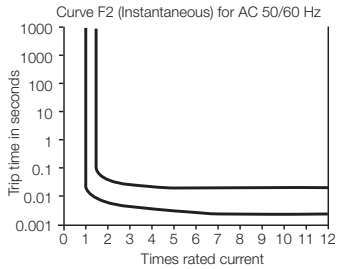


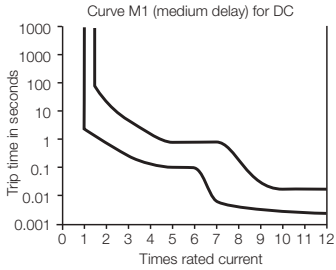
Circuit Breakers – Magnetic

The other type of circuit breaker is a magnetic type, which is far more accurate and is manufactured to allow for different delay times, allowing accurate selection of a device suitable for the application.









The important issues are the same; ensuring that there is adequate time delay to prevent tripping during the initial inrush and the breaking current if it is being used in a battery application.

Input Voltage Transient Protection

Input overvoltages include spikes, surges and fast transients. These are created by the switching of other loads (spikes), motors and fluorescent lamps (fast transients) and surges, which are created by lightning strikes. These transients are regulated to the following standards:

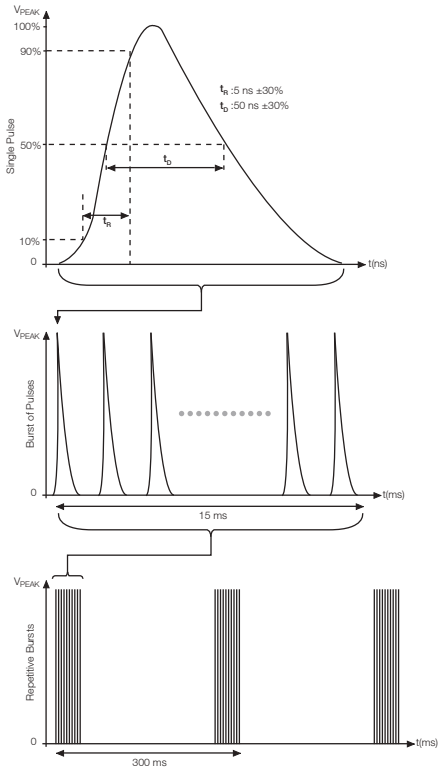
EN61000-4-4	Electrical fast transient (EFT)/burst immunity test	Switching transients
EN61000-4-5	Surge immunity test	Near lightning strikes

There are four levels within these standards, plus one user-defined level. The four levels are detailed in the table below. Standard power supplies are typically specified to level 3 and installation class 3.

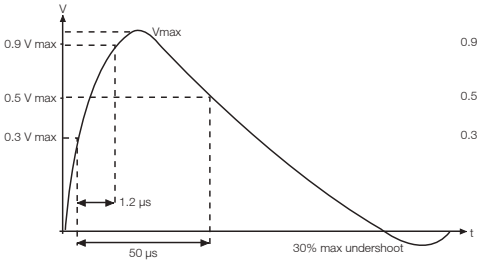
Fast Transient Burst EN61000-4-4		Surge EN61000-4-5			
		Common Mode L/N - ⏚		Differential Mode (L-N)	
Level 1	0.5 kV	**Installation Class 1**	0.5 kV	**Installation Class 1**	N/A
Level 2	1 kV	**Installation Class 2**	1 kV	**Installation Class 2**	0.5 kV
Level 3	2 kV	**Installation Class 3**	2 kV	**Installation Class 3**	1 kV
Level 4	4 kV	**Installation Class 4**	4 kV	**Installation Class 4**	2 kV

The standards differ in that EN61000-4-4 specifies a short pulse with little energy while EN61000-4-5 specifies a longer pulse, which contains substantially more energy.

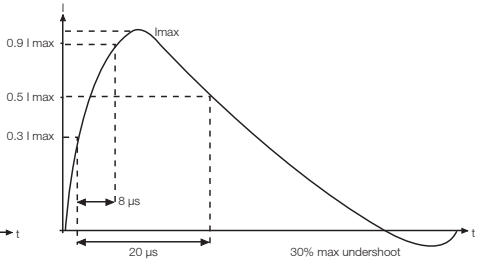
EFT Waveforms



Surge Waveforms



Open Circuit Voltage

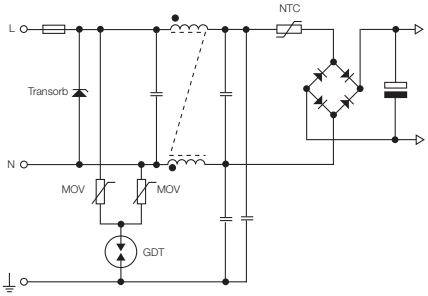


Short Circuit Current

The devices listed below are the major components used to protect electronic equipment from damage caused by these transients. These components have varying response times and energy absorption capabilities and are usually used in combination to provide effective protection.

Device	Description
Transorb	**- Semiconductor device** Sharp characteristics Fast response low energy
MOV (Metal Oxide Varistor)	**- Voltage dependent resistor** Soft characteristics Medium response high energy
GDT (Gas Discharge Tube)	**- Gas-filled spark gap** Slow response very high energy Used in conjunction with MOV
Active electronic protection	**- Used for vehicle traction applications** Linear regulator or open circuit

The diagram on the right shows a typical application of a GDT and MOVs providing a high level of protection. The MOV prevents the fuse blowing when the GDT fires and the two MOVs are in series across line and neutral providing protection against differential disturbances. These components may be added prior to a standard power supply to enhance the protection in harsh environments.

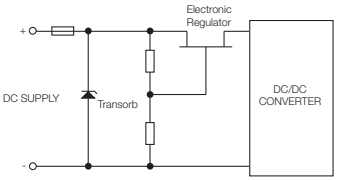


Typical application of GDTs and MOVs

In DC applications, such as vehicle, train and traction applications, none of the devices listed previously are adequate, due to the magnitude and duration of the transients which contain higher levels of energy. Practical solutions include the addition of a regulator prior to the DC/DC converter or a circuit to disconnect the DC/DC converter during the transient using capacitors to provide hold-up during the disconnect period.

In the diagram to the right, the regulator is controlled so that its output voltage does not exceed the input voltage of the DC/DC converter.

The disconnect method works in a similar way but with the regulator being replaced with an electronic switch, such as a MOSFET. In this method, the switch is opened when the input voltage is too high. The output is held up using additional capacitance either at the input of the DC/DC converter or at the load.

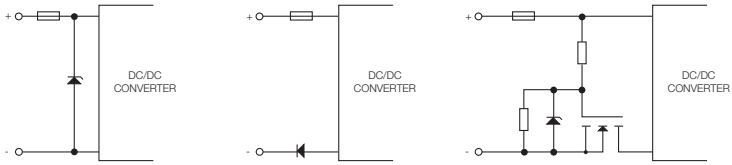


Typical application of DC input surge protection

Reverse Polarity Protection

For reverse polarity protection there are two commonly-used techniques; shunt diode/transorb and series diode or MOSFET. In the shunt technique the fuse blows if the input is reverse-connected, as the diode is forward biased. This will prevent damage to the DC/DC converter but means that the fuse will need to be replaced. In this configuration the diode must be sized so that it will not fail before the fuse ruptures.

The second option is to implement a series diode or MOSFET which, in the event of reverse connection, will block the current path. The fuse will not blow and no damage will occur. The disadvantage of the method is that the diode or MOSFET is permanently in circuit causing inefficiency and raising the minimum input operating voltage of the DC/DC converter solution.



Shunt diode/transorb **Series diode** **Series MOSFET**

• AC Input Current & Harmonics

Power Supply Harmonic Distortion

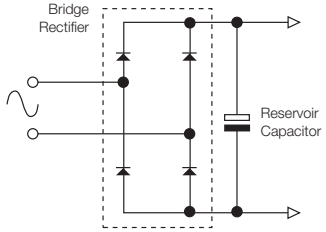
As a result of the peak rectification techniques used in power supplies, harmonic currents are generated. To limit these harmonics, legislation has been introduced. The relevant standard is EN61000-3-2 for equipment with an input current ≤16 A per phase.

EN61000-3-2 establishes four classes of equipment, each with their own limits for harmonic emissions.

Class D - T.V.'s, personal computers & monitors consuming ≤600 W
Class C - Lighting equipment
Class B - Portable tools
Class A - Everything else

Equipment Classes A & B have absolute limits for harmonics whatever the input power, Class C equipment has limits expressed as a percentage of the 50 Hz current consumed and for Class D equipment the harmonic current limits are proportional to the mains power consumed. Equipment categorized in Classes C & D will normally require a power supply incorporating active power factor correction.

In the diagram below right, the incoming AC voltage wave form is identified as V_{LINE}, the dotted line represents the rectified AC voltage following the bridge rectifier.



The bulk capacitor is charged during the conduction angle and is discharged slowly by the power stage of the power supply (V_{CAP}). As soon as the input sine wave voltage falls below the bulk capacitor voltage then the diode in the bridge rectifier is reverse biased and no current flows until the incoming rectified sine wave is once again higher than the bulk capacitor voltage. The conduction angle is typically 2-3 ms.

The complex input current waveform generates the harmonics which are of concern to the power generator. The harmonics contribute to the apparent power. Real power and apparent power are discussed later in more detail. The current wave form shown will result in a power factor of around 0.5 - 0.6.
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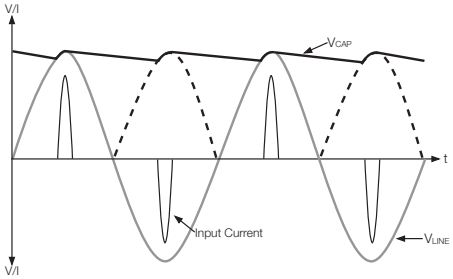


Why is Harmonic Distortion a Problem?

The utility provider must supply the voltage and all of the current, even though some of the current is not turned into useful output power – *See the section entitled Real Power, Apparent Power and Efficiency on page 37*. The provider has no means of charging for the extra current because the power is charged in kWh.

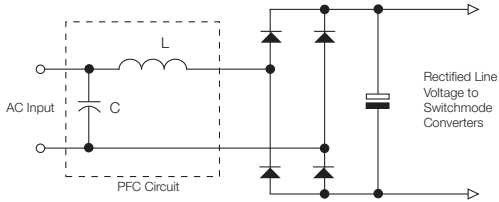
The combined effect of millions of power supplies is to clip the AC voltage because all of the current is drawn at the peak of the sine wave. Power conductors must be sized to carry the extra current caused by the low power factor. Neutral conductors can overheat because they are typically not sized to carry all of the harmonic currents which do not exist for high power factor loads.

Solutions for Power Supplies

In order to meet the legislation for harmonic distortion there are two main solutions available for power supplies:

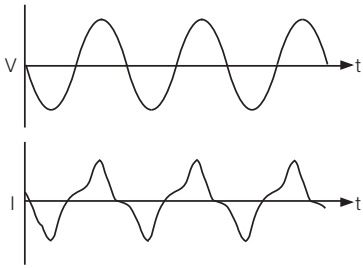
Passive Power Factor Correction

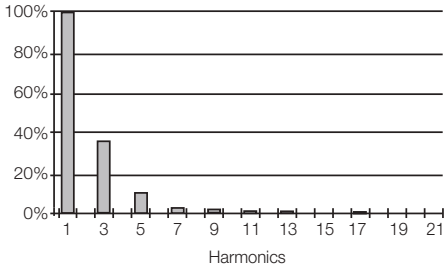
Passive power factor correction typically involves the addition of a line frequency inductor or resistor into the AC line. The effect of the inductor is to squash the current wave shape as the inductor is a reactive component which resists change in current. The effect of the resistor is to reduce the peak current.



The smoother the current wave-shape the less harmonic distortion will be present.

This is a very simple solution which has some advantages and some disadvantages. It is not really practical in power supplies above 300 W due to the size of the components required to provide adequate inductance at 50/60 Hz and to keep the resistive losses low enough. This solution is not adequate in lighting, personal computing or color television applications, but is a viable solution for Class A equipment. The diagram below shows real time measurement of passive power factor correction and the harmonic current levels.

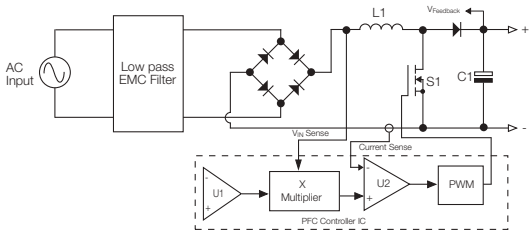




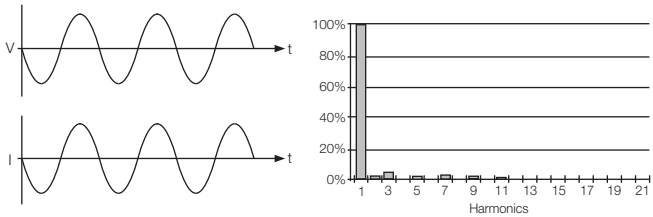
Active Power Factor Correction

Active power factor correction uses a boost converter running at high frequency to electronically control the wave-shape of the input current. The incoming AC voltage is monitored and used as a reference to determine the pulse width of each current pulse of the high frequency switched current.

The current is drawn in a series of pulses at around 100 kHz which equates to 2000 pulses per cycle of the mains voltage.



The low pass EMC filter takes the high frequency element and filters it out so that the current seen by the mains supply is sinusoidal. The system regulates the DC output at approximately 400 VDC. The diagram below shows real time measurement of active power factor correction.



Comparison between Passive and Active Power Factor Correction

Passive Power Factor Correction

Advantages
Simple
Cost effective
Rugged and reliable
Noise (EMI)
Assists filtering

Disadvantages
Heavy and bulky components
AC range switching required
Low power factor
Cannot use multiple PSUs in a system

Active Power Factor Correction

Advantages
High power factor >0.9
Low input current
Universal input
Regulated high voltage bus
Hold up time
Multiple PSUs can be used

Disadvantages
Higher cost
Higher complexity
Higher component count
Lower calculated MTBF

• Real Power, Apparent Power and Efficiency

Power

Power is the rate at which work is done. The more power available in a system, the more work can be completed in the same period of time. In terms of electricity, increasing power means the ability to do more electrical work (energy) in the same number of seconds, for example, running more appliances, spinning a motor faster, or running a faster CPU. Power is measured in Watts (W). One Watt equals one Joule of energy expended in one second.

$$\text{Power (W)} = \frac{\text{Work or Energy (J)}}{\text{Time (s)}}$$

Conversely, the amount of energy used by a device can be computed as the amount of power it uses multiplied by the length of time over which that power is applied.

$$\text{Work or Energy (J)} = \text{Power (W)} \times \text{Time(s)}$$

Computing electrical power can be very simple or very complicated. With direct current, power (in Watts) is just the product of the voltage (in Volts) and the current (in Amps) of the circuit.

$$\text{Power (W)} = \text{Voltage (V)} \times \text{Current (I)}$$

More work is done when electrons push with more force (higher voltage) and when there are more of them per period of time (higher current). Since P = V x I, and I = V/R, another way to express power is

$$P = V^2 / R$$

In a DC system power is measured and calculated as shown above. In an AC system it is more complicated because phase shift and wave form shape must be taken into consideration.

Real Power

Real, true or active power is the measurement of power dissipated in the load. It can be shown as

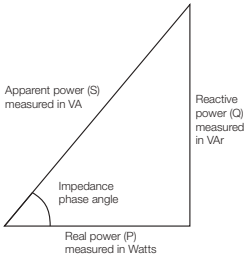
$$P\ (W) = V\ (V) \times I\ (A)$$

Reactive Power

Reactive power is power which is supplied to the load and returned to the source, rather than being dissipated in the load. This is caused by the reactive elements in an AC circuit, specifically inductors and capacitors which charge and discharge during normal operation. Reactive power is measured as Volt-Amps-reactive (VAr).

Apparent Power

This is the total power in a circuit at any one time. It includes both dissipated (real) and returned (reactive) power.
Apparent power is measured in Volt-Amps (VA). The relationship between these three types of power can be described using the power triangle as shown to the right.



Real, reactive and apparent power are trigonometrically related to each other. Each power type can be described as follows:

P (real power) is the adjacent length
Q (reactive power) is the opposite length
S (apparent power) is the hypotenuse

In this form we can see that the opposite angle gives us the impedance of the circuit. Using the cosine of this angle provides the ‘power factor’ of the circuit.

What is Power Factor?

Power Factor is a characteristic of AC circuits. It is always a number between zero and one, the closer to one, the better the system’s Power Factor.

Power Factor = Real Power/Apparent Power

Using the previously discussed data, it is now possible to add in this third element to the formula:

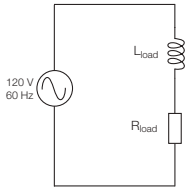
Power (W) = Apparent Power (VA) x Power Factor (PF) or
Apparent Power (VA) = Power (W)/Power Factor (PF)

Power factor is a measure of the efficiency of energy transfer from source to load. The greater the efficiency the closer to unity power factor. If power is not being dissipated in the load but simply circulates round the reactive elements of the circuit (inductors and capacitors), then energy transfer is not as efficient and the power factor will be less than unity. Two key elements affect the power factor of any system. These are known as phase shift and harmonics.

Effects of Phase Shift on Power Factor

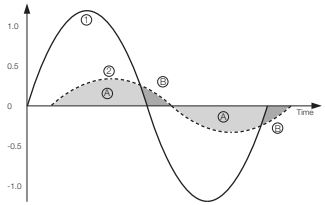
To understand how phase shift affects the power factor of a system, following are two examples:

AC Motor Load



The diagram to the right shows a simple circuit description of a motor load. The load is primarily inductive (motor windings) with a small resistive component (the resistance of the windings).

If the voltage is plotted against current in this system, two waveforms appear out of phase with each other, as shown right.

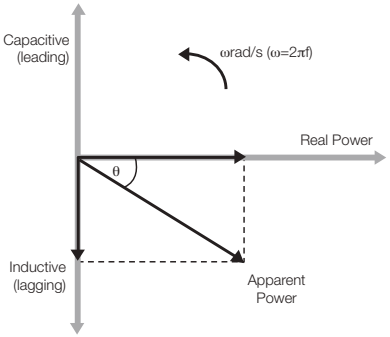


Key:
① Voltage
② Current
Ⓐ Real power
Ⓑ Reactive power

The current waveform is lagging behind the voltage wave form. This lagging phase shift is measured as an angle. One cycle of the mains is a full 360 degrees, any difference along the horizontal axis can be shown as a phase angle measured in degrees. This phase angle can be used to calculate the PF of the system. While the voltage and current are in phase i.e. both positive or both negative real power is delivered Ⓐ. When voltage and current are out of phase then reactive power is delivered to and returned by the load Ⓑ.

The phasor diagram, below, can be used to illustrate the phase relationship. This is shown static but is continuously rotating through 360 degrees.

Here, active or real power is shown on the horizontal portion of the phasor diagram, the apparent power as a lagging phasor, reactive power being shown on the vertical. This is the origin of the power triangle discussed earlier.



Phasor diagram of motor load

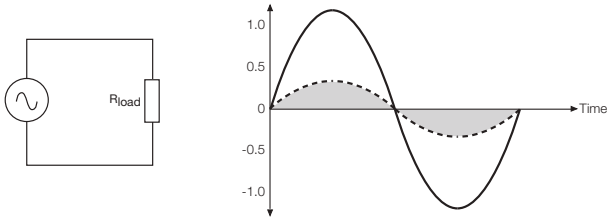
If the triangle has its vertical (reactive portion) positive, then the reactive portion is capacitive. If the vertical is negative then the reactive portion is inductive. If the angle of the opposite is 30 degrees, then the cosine of this angle will give us the power factor of this system:

$$\text{Cos } 30 = 0.87 \text{ lagging}$$

87% of the energy supplied by the source is being dissipated in the load. The other 13% is circulating currents not being dissipated in the load (reactive power).

AC Resistive Load

Below are the circuit diagram of a resistive load and the voltage and current waveforms. There are no reactive elements, and because of this there is no phase shift between voltage and current.



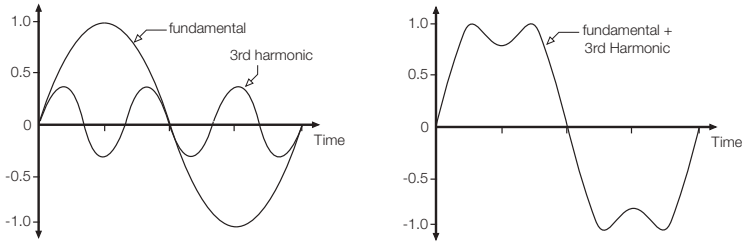
The phase angle between voltage and current is zero, the two elements are in phase.

Cos θ = 1

Therefore the power factor of the system is unity. All of the energy supplied by the source is dissipated by the load. The energy transfer is 100% efficient.

Effects of Harmonics on Power Factor

The following diagrams show how a waveform is distorted by adding the 3rd harmonic to the fundamental. The resultant waveform is shown below right.



Any waveform that is not sinusoidal contains harmonics. Any distortion or harmonic content will cause the power factor of the system to fall. As with phase shift, any power not being dissipated as useful power to the load is known as reactive power. The effects of harmonic currents within a system cause a reduction in power factor and therefore reduce the efficiency of energy transfer from source to load.

Effects of a Low System Power Factor

Both phase shift and harmonics can cause a reduction in the power factor of the system. This reduction in power factor means that more current has to be generated at source to deliver the power to the load. This in turn means that, unless power factor correction is applied, a number of problems are caused. Power factor correction can be either passive or active. Whichever form it takes, it will be used to ensure that the amount of harmonics specifically within a system is reduced; this will increase the power factor of the system and increase the source-load energy transfer efficiency.

In phase shift applications (e.g. motor load), passive power factor correction can be applied (adding inductance or capacitance to circuit) to correct any phase shift between voltage and current. This again will increase source-load energy transfer efficiency.

Common examples of problems with low power factors within a system can be seen in the list below:

Mains voltage distortion	Caused by harmonics which can cause problems such as light flicker.
Oversizing of conductors	Necessary as circulating currents must also be allowed for when cable sizing.
Overheating of neutral conductors	Caused because protection is generally in the live wire only.
Electromagnetic load failures	Generally occur when harmonics present cause the magnetic device to heat up.
Circuit breakers tripping	Circulating currents, due to reactive power, not considered.

Calculating Power Supply Efficiency

When calculating the efficiency of AC/DC power supplies it is imperative that power factor is taken into consideration. Power supplies that do not incorporate active power factor correction may exhibit a power factor between 0.5 and 0.6 causing a large error in any efficiency calculation were it based on apparent power (VA) rather than real power (W). In power supplies which incorporate active power factor correction the error would be smaller but still significant as efficiencies increase above 90%.

Efficiency is given:

Efficiency = Output power/Input power x 100 and is expressed as a percentage.

Where:

Input power = Input Voltage x Input Current x Power Factor

Output power = Output Voltage x Output Current

• Earthing / Grounding

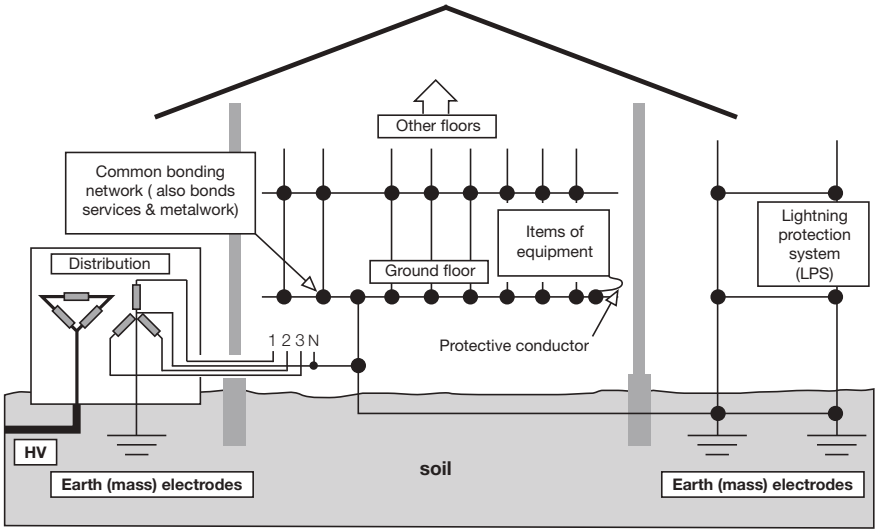
Earth or Ground is a place of zero potential, a place where fault currents can be directed of sufficient capacity to enable fuses to rupture. It is usually the substance beneath our feet and we connect to this in a number of different ways.

Buildings are connected to the ground and therefore the floors on which we stand are at the same potential.

The electrical connections that come into our homes and offices need to be safe. This is why the earth connection in a domestic location is usually made to a metal pipe (generally the mains water supply) somewhere close to where it enters the ground.

The distribution transformer has an earth connection, usually in the form of a copper rod anchored in the ground.

Lightning conductors that are found on tall buildings will also be rooted in the ground, so that in the event of a lightning strike the current passes harmlessly to ground and not into the structure of the building, saving the building from damage.



Earthing overview

Ground Resistivity

The wetter the ground, the less resistance it will have. This is the reason buildings have their own earth connection and do not rely on the earth point at the distribution transformer.

Type of ground	Ground resistivity *p* (Ωm)	
	Range of values	Typical value
Boggy ground	2 - 50	30
Adobe clay	2 - 200	40
Silt & sand-clay ground, humus	20 - 260	100
Sand and sandy ground	50 - 3,000	200 (moist)
Peat	200+	200
Gravel (moist)	50 - 3,000	1,000 (moist)
Stony and rocky ground	100 - 8,000	2,000
Concrete: 1 part cement + 3 parts sand	50 - 300	150
Concrete: 1 part cement + 5 parts gravel	100 - 8,000	400

Earthing for Safety

For an electrical system to be safe, a sufficient level of protection must be provided. This can be achieved by the use of insulation and earthing. The table below details the level of protection (LOP) provided by different types of insulation and earth.

Abbreviation	Earth Type	Level of Protection (LOP)
FE	Functional Earth	0
PE	Protective Earth	1

Abbreviation	Insulation Type	Level of Protection (LOP)
OP	Operational (Functional)	0
B	Basic	1
S	Supplementary	1
D	Double	2
R	Reinforced	2

For a system to be safe a total LOP of 2 must be provided.

The next table specifies the distance required between two conductors for the different types of insulation for IT and industrial applications. Basic insulation does not require such a large gap as double or reinforced and therefore provides a lower level of protection.

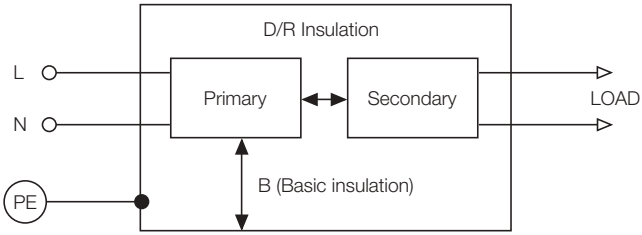
Insulation Type	Clearance	Creepage
Functional	1.5 mm	3.2 mm
Basic/Supplementary	2.0 mm	3.2 mm
Double/Reinforced	4.0 mm	6.4 mm

The distances above are based on a 300 VAC working voltage. The working voltage is the voltage between the two circuits to be isolated. The lower the working voltage, the lower the creepage and clearance distances required. If the peak working voltage exceeds the peak value of the AC mains supply additional distance is required.

To ensure that the insulation is correct and not damaged or manufactured incorrectly a test voltage must be applied. The table below shows the test voltages for a 300 VAC working voltage.

Insulation Type	Test Voltage
Basic/Supplementary	1500 VAC or DC equivalent
Double/Reinforced	3000 VAC or DC equivalent

Two types of earth can be present in a system.
FE – Functional Earth – This does not provide a safety function.
PE – Protective Earth – This provides protection against electric shock in a class 1 system.



The diagram above represents a complete class 1 power supply. Primary to earth protection is provided by basic insulation and protective earth (LOP 2). Primary to secondary protection (240 VAC to 12 VDC) is provided by double/reinforced insulation (Total LOP 2).

DC Output Considerations

• Output Regulation

Line Regulation

Line regulation is a static performance measure of changes in output voltage due to changes of the input voltage. It defines the change in output voltage or current resulting from a change in the input voltage over a specified range and is normally expressed as a percentage.

$$\% \text{ Line Regulation} = \left(\frac{V_{OUT(Max)} - V_{OUT(Min)}}{V_{OUT(Nominal)}}\right) \times 100$$

where $V_{OUT(Nominal)}$ is the output voltage at nominal line input voltage
$V_{OUT(Max)}$ is the maximum output voltage measured over the specified input range
$V_{OUT(Min)}$ is the minimum output voltage measured over the specified input range

Example: A power supply's output voltage is nominally 5.02 V but when the AC input is varied from its minimum to maximum value the output varies from 5.015 V to 5.03 V.

$$\% \text{ Line Regulation} = \left(\frac{5.03 - 5.015}{5.02}\right) \times 100 = 0.29\%$$

Load Regulation and Cross Regulation

Load regulation is the static performance measure, which defines the ability of a power supply to remain within specified output limits for a predetermined load change. Expressed as a percentage, the range is dependent upon the product design and is specified in the product data sheet.

$$\% \text{ Load Regulation} = \left(\frac{V_{OUT(Load\ Max)} - V_{OUT(Load\ Min)}}{V_{OUT(Nominal)}}\right) \times 100$$

where $V_{OUT(Nominal)}$ is the nominal output voltage
$V_{OUT(Load\ Max)}$ is the output voltage at maximum output current
$V_{OUT(Load\ Min)}$ is the output voltage at minimum output current

Example: A power supply manufacturer specifies that for a load change of 5% to 100% its power supply output changes from 5.05 V to 5.02 V around a nominal voltage of 5.02 V.

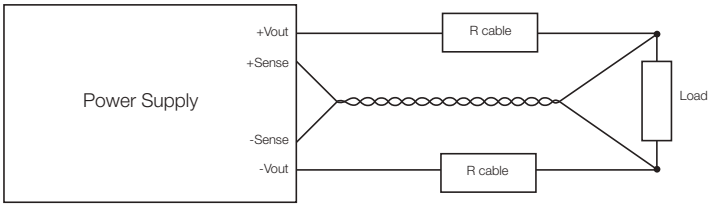
$$\% \text{ Load Regulation} = \left(\frac{5.05 - 5.02}{5.02}\right) \times 100 = 0.6\%$$

For multiple output power supplies, another factor affecting the output voltage is cross regulation. This is an extension of the load regulation test and determines the ability of all of the power supply outputs to remain within their specified voltage rating for a load current change on another output. It is calculated in the same manner as load regulation and is often specified as a percentage change in output voltage for a percentage change in another output load, e.g. V1 cross regulation = 1% per 10% change in V2.

Remote Sense

Remote sense enables the output voltage regulation to be maintained at the load rather than at the output pins of the power supply. This is achieved by using two sense lines connected from the remote sense pins of the power supply to the load which may be located some distance from the power supply.

Remote sense can compensate for voltage drops in the order of hundreds of mV, typically a maximum of 500 mV. The sense lines (one to the load, and one return from the load) monitor the voltage at the load and regulate the power supply output, thus compensating for drops in voltage across the load cables. Remote sense is normally used when the load current varies resulting in irregular lead voltage drop. If the load is constant and the voltage drop is fixed the trim or adjustment feature can be used to compensate for the voltage drop over the load line.



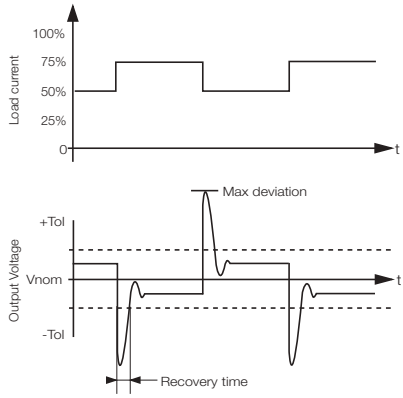
The voltage drop between the power supply output terminals and load is mainly caused by the cable resistance. However, when there is substantial inductance between the load cables or circuit traces from the supply to the load, a dynamic Ldi/dt drop may be significant. This dynamic Ldi/dt drop and noise formation can be minimized by connecting a 0.1 µF ceramic capacitor in parallel with a 10 µF electrolytic capacitor at the load. Remote sense leads should be twisted to minimize noise.

If ORing diodes or MOSFETs are used in a redundant application, remote sensing can also be used in conjunction with active current or power sharing to compensate for the forward voltage drop across the ORing diodes or IxR drop across the MOSFET. The volt drop depends on magnitude of current and the diode's junction temperature or MOSFET RDSon. Trimming or adjustment can also be used to compensate for this drop, if it is a known value.

The maximum remote sense voltage compensation is specified in the power supply's data sheet. Raising of output voltage at the output connector as the result of remote sensing and output trimming must not exceed the maximum output voltage or power rating of the power supply.

Transient Load Response

Transient response measures how quickly and effectively the power supply can adjust to sudden changes in current demand. The figure below shows the behavior of a typical converter during a load-current transient and the resultant output voltage wave form.



The transient load response is normally specified as a maximum percentage change and recovery time of the output, to within specification, following a step load change, e.g. 4% maximum deviation, 500 µs recovery for a 25% step load change.

• High Peak Loads

Some power supplies specify a peak load capability to support loads that are higher than the nominal continuous power for short periods. In these applications the average power required is typically significantly lower than the peak demand.

Applications that require high peak currents include print heads, pumps, motors, and disk drives. These products are found in factory automation, medical pumping systems, fluid and material handling, robotics, power tools, machining, packaging, test, dispensing systems & printers.

Using a power supply that is capable of supporting high peak loads will result in a physically smaller power supply reducing system size, weight and cost. In a system that requires 800 W for a short duration, using a 400 W power supply with an 800 W peak rating will result in significant savings in volume and cost over a supply rated at 800 W continuous power.

There are five typical characterizations of peak load capability.

1. The power supply is rated for up to 30 seconds with a duty cycle of 10 to 15% at a peak load that is just below the Over Current Protection (OCP) limit. The OCP is usually set around 20 to 50% above the continuous current rating. The product is designed to give short duration headroom over and above the nominal continuous rating. The average power must not exceed the continuous rating. There are many applications that require an additional 20-30% of power for short durations. Electromechanical applications normally demand higher peak current for short durations.

2. A very high peak of up to 200% of nominal for a very short duration where the OCP does not react to the overload condition. Typically this allows peak current handling for 200 - 500 us. This peak capability covers a limited range of applications.

3. A higher power rating at high-line, normally meaning 180 VAC and above. For example, a 1200 W power supply may be able to provide 1500 W of continuous power when operated at an AC input voltage greater than 180 VAC. This is a genuine size and cost benefit if the AC input is in the higher range and is often specified for higher power products which are connected from phase to phase when the nominal single phase supply is low.

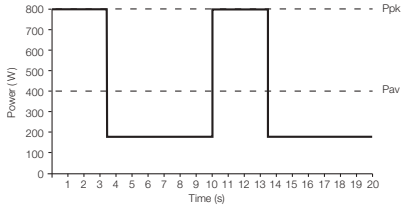
4. A power supply with convection cooled rating and a higher power forced cooled rating. This will support a peak current in a convection cooled application where the peak current does not exceed the forced cooled rating and the average power is lower than the convection rating. This needs to be carefully considered in terms of the duration of the peak to ensure that components to not overheat during the peak load period. In general the larger the difference between the convection and forced cooled ratings the shorter term the peak capability. Measurement of critical components during development will confirm safe and reliable operation.

5. A power supply with the architecture, overload protection, energy storage, efficiency and thermal design to support high peak electromechanical loads. Such units will typically deliver up to twice their nominal power for up to 10 seconds with duty cycles up to 35%. XP's fleXPower modular power system is one example which allows several standard outputs alongside one that provides a high peak current.

When selecting a power supply for a high peak power application the key parameters are the peak power that can be provided, the maximum duration of the peak, the duty cycle and power consumed by the load during the non-peak duration to ensure that the average or continuous rating of the power supply is not exceeded.

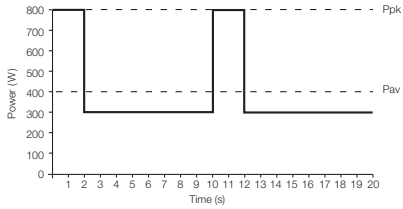
For example, the specification of a 400W power supply that can provide 800 W peak for up to 10 seconds at a 35% duty cycle defines the operating envelope within which the requirement must fall where the average power does not exceed the continuous rating of 400 W.

If the maximum rated peak power (Ppk) is required for the full 35% duty cycle then the available power during the non-peak duration (Po) will be approximately 180 W in order that the average power rating (Pav) is not exceeded.



$$Pav = \frac{(Ppk \times T1) + (Po \times T2)}{T1 + T2}$$

Using the same criteria, if the duty cycle is reduced to 20%, then the non-peak power can be increased to 300 W. without exceeding the average continuous power rating of 400 W.



• Powering Light Emitting Diodes (LEDs)

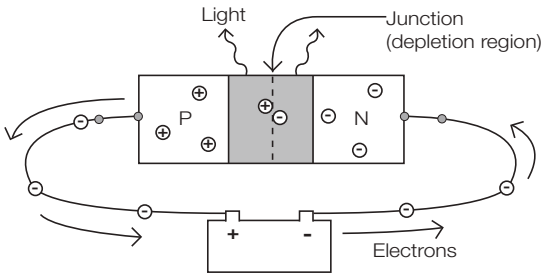
LEDs have become the prevalent light source in many applications. Applications vary from street and tunnel lighting, domestic lighting, decorative and architectural lighting through to moving signs and traffic signals and non-visible applications such as data transmission & pulse oximeters. The LED provides more light output per watt than other light sources combined with significantly longer life than conventional incandescent & fluorescent solutions. This combination of attributes offers significant reductions in both running and maintenance costs. As LEDs are solid state they are also shock resistant.

LEDs have high Spectral Power Density (SPD), defined as power per unit frequency or Watts/Hertz making them very efficient as light is radiated at very specific frequencies. This is an advantage over incandescent, fluorescent and High Intensity Discharge (HID) lamps which radiate light at all frequencies both visible and invisible. The table below shows the comparative power consumption for a given light output for incandescent bulbs, compact fluorescent tubes and LEDs. The figures in parenthesis express this in Lumens per Watt.

Lumens	Incandescent Bulb	Compact Fluorescent	LED
450	40 W (11.25)	12 W (37.5)	4 W (112.5)
800	60 W (13.30)	14 W (57.1)	7 W (114.3)
1100	75 W (14.67)	20 W (55.0)	10 W (110.0)
1600	100 W (16.00)	25 W (64.0)	18 W (88.9)
2600	150 W (17.33)	40 W (65.0)	25 W (104.0)

Lumens per Watt of various light sources

An LED functions in the same way as a normal diode. Current flows from positive to negative when the diode is forward biased, with electrons flowing from negative to positive. Inside the junction the electrons combine with holes and release light. The color of the light is determined by the material.



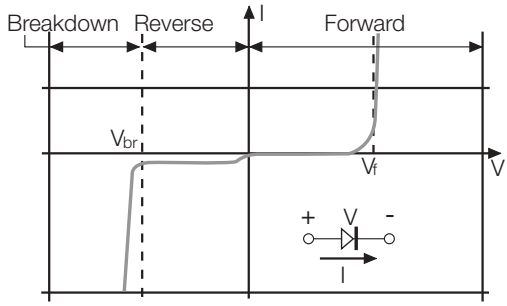
LED Junction

The forward volt drop of the LED is significantly higher than a typical signal or rectifier diode. The table below shows the typical forward volt drop range and materials used dependent on the color of the LED.

Color	Potential Difference	Materials
Infrared	1.6 V	Aluminum gallium arsenide (AlGaAs)
Red	1.8 V - 2.1 V	Aluminum gallium arsenide (AlGaAs), Gallium arsenide phosphide (GaAsP), Gallium phosphide (GaP)
Orange	2.2 V	Aluminum gallium indium phosphide (AlGaInP), Gallium arsenide phosphide (GaAsP)
Yellow	2.4 V	Aluminum gallium indium phosphide (AlGaInP), Gallium arsenide phosphide (GaAsP), Gallium phosphide (GaP)
Green	2.6 V	Aluminum gallium phosphide (AlGaP), Aluminum gallium indium phosphide (AlGaInP), Gallium nitride (GaN)
Blue	3.0 V - 3.5 V	Gallium nitride (GaN), Indium gallium nitride (InGaN), Silicon carbide (SiC), Sapphire (Al2O3), Zinc selenide (ZnSe)
White	3.0 V - 3.5 V	Gallium nitride (GaN [if AlGaN Quantum Barrier present]), Gallium nitride (GaN) based - Indium gallium nitride (InGaN) active layer
Ultraviolet	3.5 V	Indium gallium nitride (InGaN), Aluminum nitride (AlN), Aluminum gallium nitride (AlGaN)

Typical LED forward voltage

The graph below shows a typical diode electrical characteristic. As the forward voltage rises the current rises sharply once the junction voltage is reached meaning that the LED must be driven by a current limited source. This is most efficiently achieved using a constant or regulated current supply which is generally referred to as an LED driver.



Typical Characteristics

Dimming

A benefit of using LEDs in lighting and display applications is the ease of varying the brightness. This can be achieved by varying the current through the LED which proportionally varies the amount of light emitted however, running the LED with less than its maximum current reduces the efficiency and may result in slight color changes. The preferred method is to pulse the current between zero and maximum to vary the average light emitted. As long as this is done at a high enough frequency to avoid the pulsing being seen as flicker by the human eye this is the optimum way to achieve dimming. Pulsing of the current is normally at a fixed frequency with the mark space ratio being changed. This is the pulse width modulation (PWM) method which results in maximum efficiency, lifetime and color consistency.

LED Drivers

While LEDs are very efficient and produce a bright light source most applications require a number of devices to achieve the desired light output. There are a number of possible configurations for powering multiple LEDs. The individual LED specified will define the drive current required and the number of devices. The configuration of the LEDs will define the string voltage, the current rating and the power required from the LED driver.

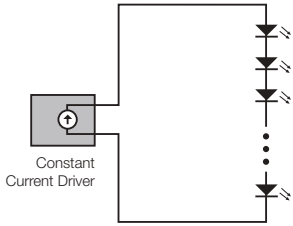
There are wide ranges of AC input and DC input standard drivers available from 1 W to 300 W and above in both constant current & constant voltage versions to satisfy the various potential LED configurations and the wide range of indoor & outdoor applications. Constant voltage LED drivers are used where there is another regulation or control function between the driver and the LED load.

Control or dimming requirements will determine any features needed including simple current programming by external resistance or voltage and PWM control. Where more complex control functions are required they are often designed independently and implemented locally for the specific application. In such cases a simple constant voltage power supply or driver is adequate.

Examples of potential configurations are given below with varying advantages and disadvantages.

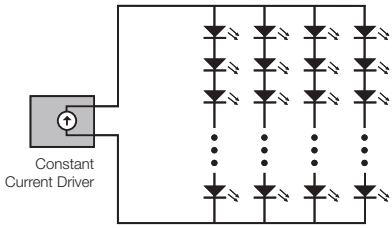
Series configuration

In series configuration the string voltage is the sum of the forward voltage of all LEDs and can be high. There are no current balance issues as there is only one current path. There is no need for ballast resistors and short circuit failure of one LED has no impact on the remainder of the string. Open circuit failure of one LED will result in total system failure.



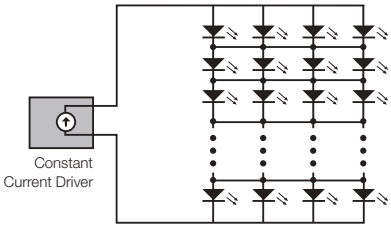
Parallel configuration

In parallel configuration the total string voltage is reduced by a factor of the number of strings. Current imbalance can result from small variations in the forward voltage in each leg. A ballast resistor can be used in each leg to balance the current but this reduces overall system efficiency. Any failure of a single LED either short circuit or open circuit will result in increased current flow and stress; short circuit failure will cause increased current in the affected leg and dimming of the other legs while open circuit will result in failure of the affected leg and increased current in the others.



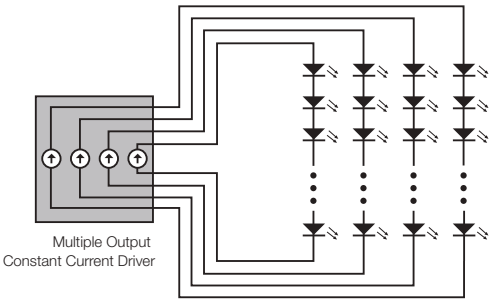
Matrix configuration

In matrix configuration the string voltage is the same as parallel configuration. Current imbalance can still result from variations in forward voltage but due to the multiple paths it cannot be corrected with ballast resistors. The selection of pre-scanned higher quality LEDs reduces the forward volt drop variations at a higher cost. Short circuit failure of an LED will result in a complete row ceasing to operate but current flow in the other LEDs remains unchanged. Open circuit failure results in increased current flow in other LEDs in the same row.



Multiple channel configuration

In multi channel configuration the string voltage is the same as parallel & matrix configurations. Each string has a dedicated constant current supply and is not affected by the other strings in the system. Any effects of LED failure are limited to the particular string. This system has the disadvantage of complexity and cost due to the need for multiple lower power LED drivers.



LED drivers are typically high efficiency products as the application itself is driven by efficiency gains and low cost of ownership. With the exception of some lower power devices, AC input drivers typically employ active power factor correction and are designed to meet the power factor and harmonic distortion requirements of the utilities from which the power is drawn.

In Europe there is specific legislation and limits (EN61000-3-2 class C) for harmonic distortion in lighting applications utilizing supplies up to 16 A per phase. Lighting applications also have specific safety agency approvals including UL8750 in North America and EN61347 in Europe.

Harmonic Currents in Lighting Applications

Lighting applications generally require harmonic current emissions to meet the requirements of EN61000-3-2. Lighting equipment is subject to the limits in class C. Within class C there is one set of limits above 25 W active input power and another set for 25 W and below. However, the standard specifically only mentions discharge lighting for 25 W and below.

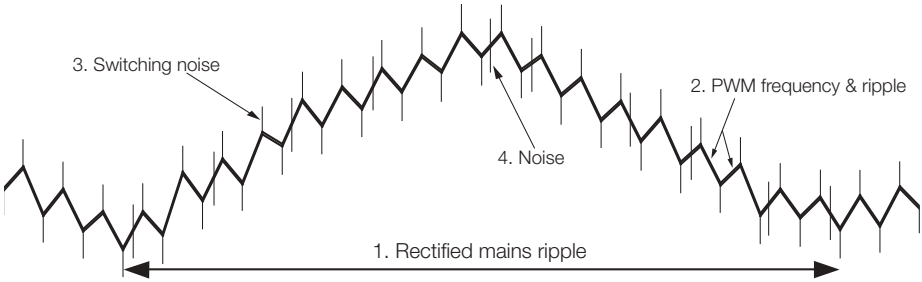
Meeting the limits above 25 W will generally require power factor correction and, as the limits are calculated as a percentage of the fundamental rather than as an absolute value of Amps, it may be better to use a power source designed specifically for lighting applications rather than an ITE type power supply. However, an ITE power supply, incorporating active power factor correction, will probably meet the limits as long as the lighting load is above 40-50% of the power supply's full load rating.

Safety Standards for Lighting Applications

There are safety standards that apply to lighting systems. Internationally there is IEC61347, Part 1 of which, covers the general safety requirements of lamp control gear and Part 2 Section 13 which is applicable to power sources for LED modules. The US has UL8750 and Europe has EN61347 following the IEC format for section naming.

• Ripple and Noise

Switching power supplies and DC/DC converters have the fundamental advantage of smaller size and higher efficiencies when compared to linear voltage regulators. However, the switching technique has the associated disadvantage of relatively high AC content on the output.



Typical output ripple and noise trace

Four AC components can be identified:

1. Low frequency ripple at two times the AC mains input frequency.

2. Switching frequency ripple.

3. Switching noise, which is high frequency pulse noise.

4. Aperiodic noise that is not related to the AC source frequency or the switching frequency of the converter.

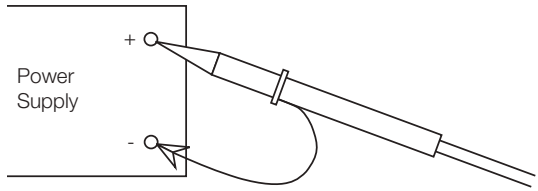
These AC components are normally specified as a peak to peak noise amplitude so that the best method for testing is by an oscilloscope with the bandwidth set as specified in the data sheet, often 20 MHz. Some data sheets also specify a requirement to fit external components to the measurement point, such as electrolytic and ceramic capacitors, to mimic typical applications.

Accurate measurement of the output noise and ripple requires special attention to the equipment used, measuring probes and an understanding of noise being measured. The switch mode converter switches large amounts of power quickly when compared to the amplitude of the noise being measured. This means that even a few inches of ground wire loop in the oscilloscope probe will pick up fractions of Volts of noise. These probes must be properly connected to the measurement point.

Measurement of the noise is performed as close as physically possible to the converter's output terminals to reduce radiated noise pick-up. The greatest source of error is usually the unshielded portion of the oscilloscope probe. Voltage errors induced in the loop by magnetic radiation from the supply can easily swamp the real measured values.

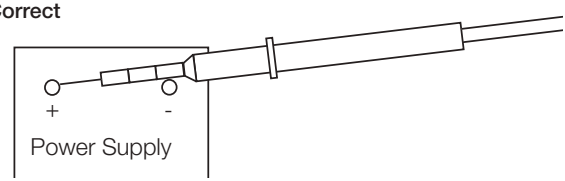
To reduce these measurement errors unshielded leads must be kept as short as possible. The figure below shows the wrong method, because the ground wire of the probe can collect radiated noise and the oscilloscope display is strongly dependent on the probe position and ground lead length.

Incorrect



To prepare the probe for high frequency measurement, first remove the clip-on ground wire and the probe body fishhook adapter and then attach a special tip and ground lead assembly as shown in the figure below.

Correct



The ground ring of the probe is pressed directly against the output ground of the power supply and the tip is in contact with the output voltage pin.

• Output Protection

Output protection is implemented on power supplies and DC/DC converters to prevent damage to both the power supply and the end equipment. Power supplies are protected against overload and the end equipment against over-voltage and excessive fault current.

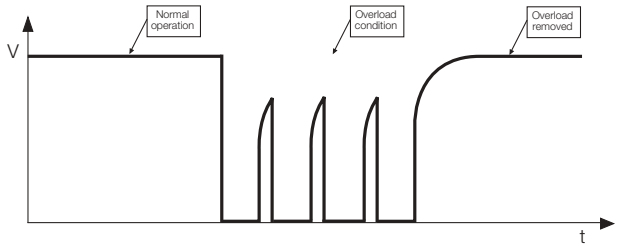
Overload Protection

In the case of an overload or short circuit being applied at the output, circuits are employed to limit the current or power that the unit will supply, protecting both the power supply and the load from excessive current. Overload protection is typically implemented using one of the techniques listed below:

Trip & restart or 'Hiccup' mode
Constant power limit
Constant current limit
Fold-back current limit
Fuses or circuit breakers

Trip & Restart or 'Hiccup' Mode

In this mode, the power supply detects an overload condition and the controller shuts the power supply off for a given time. After this time the power supply will try to start again. If the overload condition has been removed the power supply will start and operate normally. If the overload condition remains then the supply will switch off again, repeating the previous cycle. This condition will repeat until such time as the overload is removed. The off-time period may vary and the voltage reached will vary with the impedance of the overload. A typical wave form is shown below.

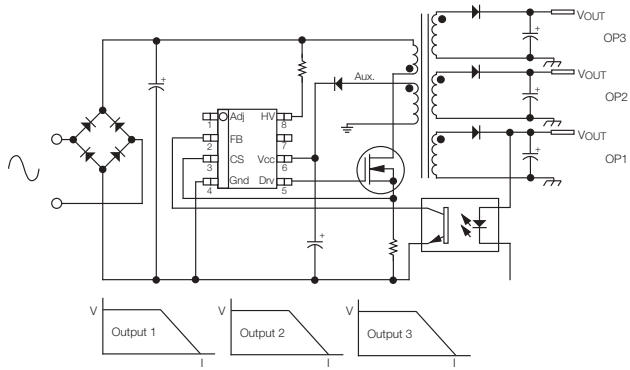


Trip & restart, or ' hiccup' mode

This type of overload limit is generally unsuitable for high inrush loads, such as capacitive loads and lamps or for battery-charging applications which benefit from constant power or constant current characteristics.

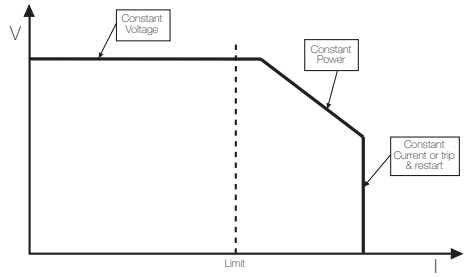
Constant Power Limit

Constant power overload limits are often used in multiple output power supplies where the primary power is monitored and limited. This has the benefit of allowing power trading across the outputs while ensuring that the overall load is not exceeded.



Multiple output power limit

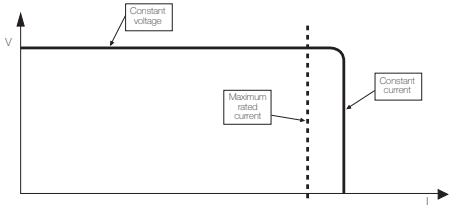
This technique is also used on single output supplies in battery-charging applications as the current is maintained during an overload with the output voltage falling. Normally the constant power output will be maintained until the current reaches a point where damage may be caused, at which point the power supply will either go into a constant current mode or a trip & restart mode. When the overload condition is removed the power supply will recover automatically.



Single output power limit

Constant Current Limit

In this case the current is held constant at a pre-determined level at a point where the load current exceeds the maximum allowed limit.

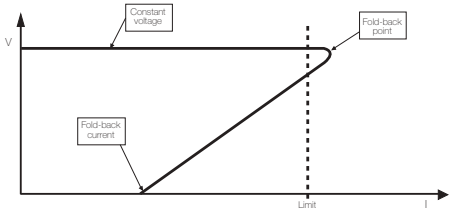


Constant current limit

This technique allows high inrush capacitive loads, lamps, motors etc to start and is often utilized in battery-charging and standby battery applications. In some instances a reduction in current will occur below a certain voltage limit. The power supply will recover, following the curve, when the overload condition is removed.

Fold-back Current Limit

Fold-back current limit decreases both the voltage and the current when an overload condition is detected. The voltage and current decrease simultaneously as the load impedance decreases. This technique is employed extensively on linear power supplies to prevent excessive dissipation in the series pass element and where crowbar over-voltage protection is employed, limiting the fault current.



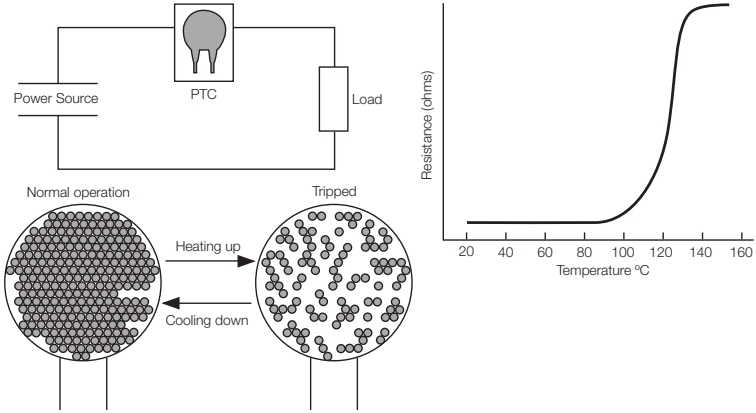
Fold-back current limit

The output voltage will recover once the overload condition is removed, following the overload curve as the load impedance increases. This technique is not suitable for high inrush or battery applications.

Fuse or Circuit Breaker Protection

Fuses and circuit breakers are generally only used in large output distribution and battery systems. If there are many branches in an output distribution system then each individual branch needs to be protected against excessive current flow. Circuit breakers are also employed where batteries are used as there is the potential for extremely high fault currents due to the low impedance of the source. Both of these require manual intervention to reset following the removal of the fault.

In some multiple output power supplies a resetting fuse is used, in the form of a Positive Temperature Coefficient (PTC) thermistor. An overload condition will cause the thermistor to heat up to a point where a very sharp transition of resistance occurs creating a high impedance and restricting the current. The unit will require an off/on cycle or the complete removal of the load to reset.



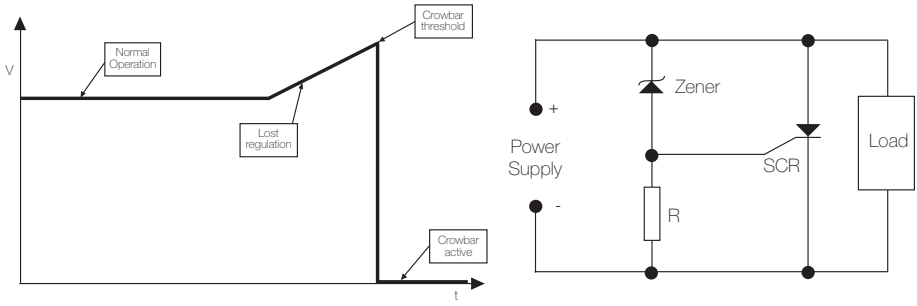
Resetting PTC thermistor fuse characteristics

Over Voltage Protection

Over voltage protection is implemented using one of two basic techniques; crowbar protection, where the output is clamped by a thyristor or Silicon Controlled Rectifier (SCR), and electronic protection, where the unit is shut down by an independent control loop.

Crow-bar Over Voltage Protection

Should the output voltage exceed the limit set by the zener diode then the SCR is fired, clamping the output to around 1 VDC and forcing the power supply into an overload condition. The clamp remains in place until the power supply is turned off and reset. This technique must be used in conjunction with a fold-back current limit.



Crow-bar over-voltage protection

Electronic Control Loop Over Voltage Protection

If an excursion of the output voltage is detected beyond the set limit, the power supply output is turned off usually via a second feedback loop. The second loop is utilized as it may be that the fault has arisen due to a failure in the main feedback loop. This is usually a latching condition that requires an off/on cycle to be performed to enable reset.

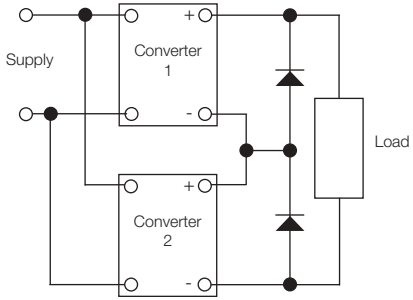
The characteristics of the output will be identical to the crowbar example, though the time for the output to fall to zero will depend upon the load applied. This system is utilized in most switching power supplies.

• Series & Parallel Operation

When implementing multiple power supplies in an application, consideration must be given to the overall system earth leakage current to ensure compliance with safety standards.

Series Operation

In general, power supplies can be operated with outputs connected in series. Some care is needed to ensure that one power supply doesn't affect the operation of the other. The total output voltage must not exceed the working output to earth breakdown voltage of either one of the power supplies.



Common practice when putting two power supplies in series is to connect reverse-biased diodes across the output of each series connected supply. This protects the output from the reverse voltage of the other in the event of a failure.

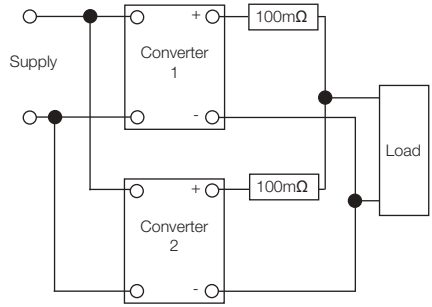
Power supplies with constant current or constant power limit are recommended for series operation. If a power supply with foldback current limit is used, lock-out can occur at switch-on because of the differing ramp-up times of the units. Power supplies with trip and restart or hiccup mode current limits can also be used in the majority of cases.

A frequent application of power supplies in series is when using a dual output converter in order to obtain one single output of a higher voltage. In this configuration 24 V, 30 V, or 48 V outputs can be achieved from +/-12, +/-15 or +/-24 Volt dual output power supplies.

Parallel Operation

If greater power is needed, a common solution is to connect two power supplies in parallel. The connections will normally be made with the load in a star formation, with the load being the star center. This will ensure that the lead lengths are very nearly equal. One power supply should not be looped to the next as connectors could be overloaded and sharing will be poor.

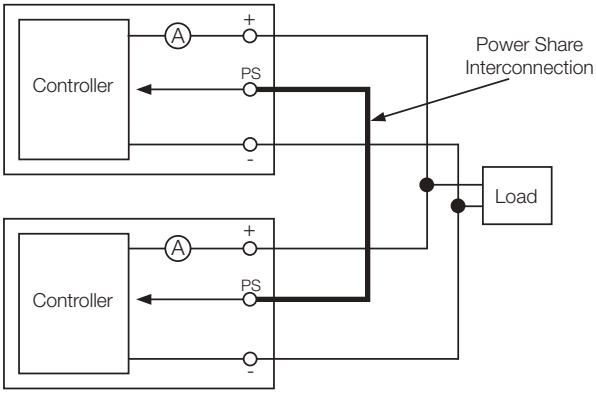
Sharing can be created by adjusting output voltages so that they are as close as possible and matching the impedances of the load cables, i.e. equivalent wire lengths and ring-crimped terminals.



The supply with the highest voltage will supply all of the load and this unit may run in current limit. If this happens the output voltage will drop to the voltage of the other power supply. This condition can be alleviated by the use of series resistors to balance the output load currents, but this method is not 100% accurate. Assuming that the two resistors are equal, small output voltage differences will still cause large current imbalances. This method does have a number of other downsides. Firstly, the use of the series resistors will degrade the output regulation. Secondly, allowing for the possible imbalances of up to 50%, each power supply must be capable of supplying not just 50% of the load current but up to 75%.

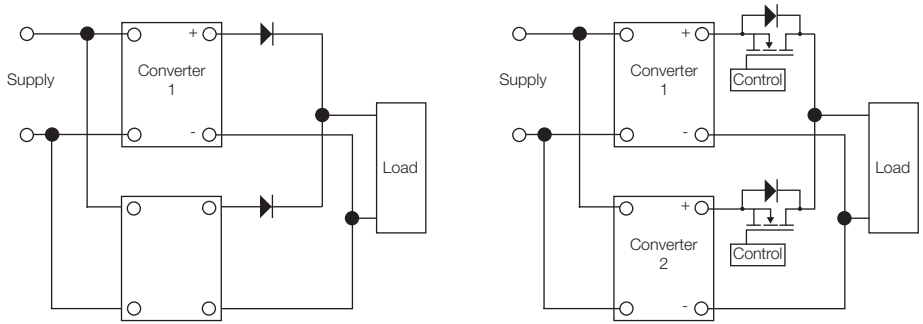
Active Power Sharing

In active power sharing each unit has an additional control terminal through which the power supplies are interconnected. This connection has many different names, the two most common being Power Share and Current Share. This connection enables the control circuits of the two power supplies to communicate and adjust the output voltage so that they share the load equally.
In practice the units will typically share within +/-10%.



• Redundant Operation

Redundancy is implemented when continuous operation of the system is required in mission critical applications. Some of the most common areas are in communications, oil and gas, and other applications where revenue is generated by the system.

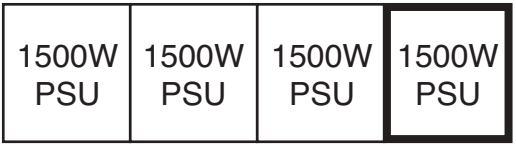


Diodes or MOSFETs can be used in redundant systems so that if one power supply fails the other will continue to operate without the failed power supply pulling down the output rail. Diodes and MOSFETs should always be rated higher than the power supply output current limit.

Adding diodes in the output lines of a power supply causes degradation of the output regulation due to the voltage drop across the diode at different current levels and reduced system efficiency, the use of MOSFETs in place of diodes reduces the power loss but is more complex and less reliable. This needs to be considered when using a redundant system as a solution as the load must be able to accept the poorer regulation. To overcome this problem it is possible to use the remote sense function and connect it after the diode. When doing this, the current share connection will also need to be made. This will allow the power supply to compensate for the diode voltage drop.

N+M Redundancy

It is common to have a redundant system, whereby a single unit or a number of units are required to support the load and another unit or number of units complete the system in order to provide 100% redundancy. In some applications it is not cost-effective to have 100% redundancy, although this approach will offer a sixty times improvement in reliability over a standalone PSU. A much more common approach is to use N+M redundancy, where N is the number of units required to support the load and M is the number of redundant units. In the example below a 3+1 system is shown, using 3 x 1500 W to support the 4500 W load and 1 x 1500 W unit in redundancy. This solution offers a twenty-fold increase in system reliability.



• Power supply de-rating

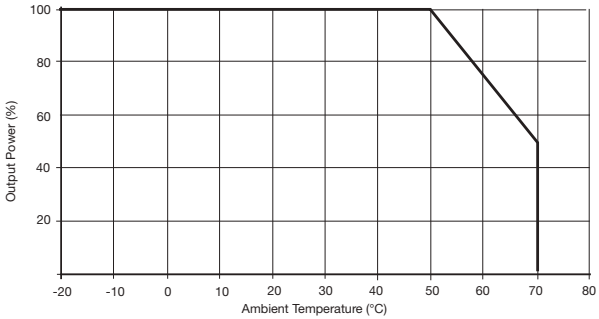
With mounting market pressure on power supply size, power density and cost there are an increasing number of AC-DC power supplies released which rely on de-rating specifications to improve their headline power ratings.

This de-rating information may not be immediately apparent and is typically located at the end of the product data sheet, well away from the headline data. In some cases the short form or catalog version of the data does not include this level of detail, so care must be taken when selecting the product to ensure that it is truly suitable for a given application.

De-rating specifications are based on reducing the specified output power rating of the power supply during high temperature operation or low line input voltage operation to mitigate excessive component temperature rises and ensure that safety critical isolation components do not exceed their thermal limits.

Temperature de-rating

Virtually all power supplies have a de-rating curve based on ambient temperature – see example below. For products designed for integration into end equipment, this de-rating typically starts at ambient temperatures in excess of 50 °C. This allows for temperature rises within the end equipment, while maintaining the full specified power rating of the power supply. The output power rating will usually fall to 50% at a maximum ambient temperature of 70°C. There are also a small number of manufacturers who de-rate products below 0 °C based on their ability to start at low temperature.



Output power derating curve based on ambient temperature

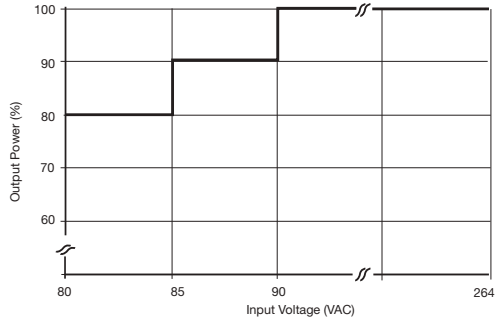
For external power supplies the de-rating normally starts at 40°C as these products are not exposed to the temperature rises within the end equipment.

In recent times, open frame power supplies are being introduced by some manufacturers which limit the maximum ambient temperature for full power operation to 40 °C with the output power reducing to 50% at a maximum ambient of 60 °C. This is due to component temperature rises which are too high to allow full headline power operation at 50 °C limited by component specifications, lifetime and product safety requirements.

While such “specmanship” provides a higher headline power rating and, at first sight, appears to offer smaller size or lower cost, when integrated into end equipment which needs to operate in an ambient of 40 °C the available output power is reduced immediately by 25% or more. Put another way this means that such a product with a head line power rating of 100W is actually a 75 W product.

Input voltage de-rating

Products designed for world-wide operation have a universal input range typically covering 90 – 264VAC. Conventionally a product with universal input is expected to offer its full power rating across this input range with some products offering a de-rated output for lower input voltages down to 85 or 80VAC to cover operation in areas where the AC supply is prone to brownout.



Output power derating curve based on input voltage

It has become commonplace for some manufacturers to increase the power rating of the product and specify de-rating for input voltages less than 100VAC or even 115VAC in some instances. In the worst case, this input de-rating can be as much as 20% when operating at 90 VAC.

Using specification de-rating in this way makes the product appear to offer increased power density & lower cost. However if the application is required to operate globally a higher power version of the product would be required. Put another way a power supply with a headline rating of 100 W can only practically be rated at 80 W.

Input voltage de-rating is employed to mitigate overheating in the input filter, bridge rectifier & PFC boost converter as the input current increases. Some losses increase proportionally to the current but resistive losses, such as those found in EMC chokes, increase by the square of the current.

If the end equipment is intended for sale on a world-wide basis care must be taken to ensure that the power supply rating is adequate at low line voltages as exceeding the de-rating curves may result in reliability and lifetime problems.

In some instances both thermal and low line de-rating are specified in combination giving a 40 °C rated 100 W power supply a rating as low as 60W if used in an ambient of 50 °C with a line voltage of 90 VAC. Clearly this product cannot be compared to those offering a 100 W power rating over the entire input and temperature range required and should be compared to a 60 W rated product negating any apparent size, power density & cost benefits.

While the product specification requires de-rating under certain line voltage and ambient temperature conditions the power supply will not limit the available power at the output and will continue to operate. If the product is operated outside of the de-rating curves there are serious consequences in terms of reliability, product lifetime and potentially safety if the thermal limits of the isolation barriers are exceeded.

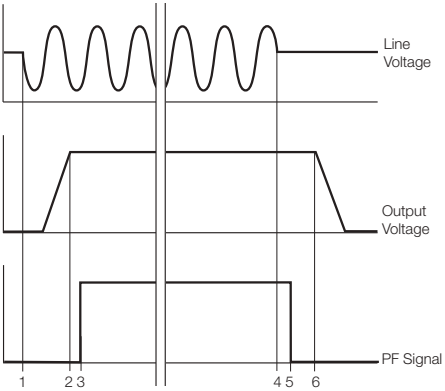
• Status Signals and Controls

Status signals and controls provide the user with the ability to remotely monitor the condition of certain parameters within a power converter and to remotely control the power converter using signal level instructions. Signals provide information and have no influence on the function of the power supply. Controls allow for changes in parameters or function.

Common status signal outputs include power fail or AC OK, DC OK or power good, fan fail, fan speed and over-temperature. Interfaces include remote enable, remote inhibit, current share, voltage programming and voltage margining.

Power Fail (PF) or AC OK

This signal indicates the condition of the input voltage to the power supply. The signal changes condition following the application of an in-specification input voltage. This signal is most useful at mains failure as it is normally set to change condition several milliseconds prior to the output falling from specification. This allows data save routines to be carried out. These signals often require the converter to be running as they can be generated on the secondary side of the main power transformer.



Timing diagram for a typical power fail/AC OK signal

1 = Line voltage is switched on
2 = Output voltage established
3 = PF signal changes state indicating input within tolerance
4 = Line voltage fails or is switched off
5 = PF signal detects line failure
6 = Output voltage falls outside tolerance
5 – 6 = PF warning period

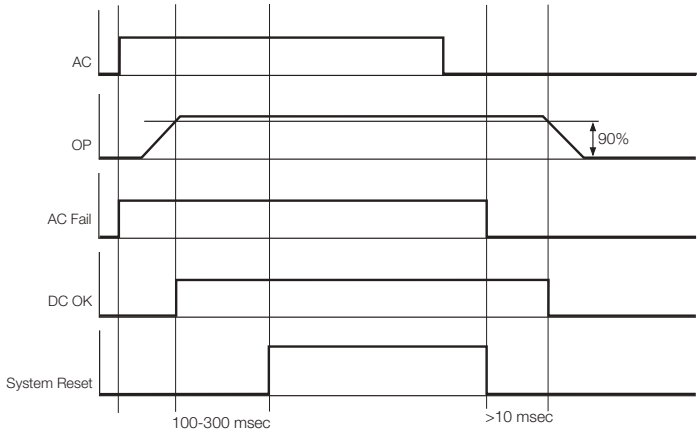
DC OK or Power Good

This signal indicates that the output voltage is within a set tolerance, usually above a minimum. This is normally only of interest at start-up as there is little or no warning of impending failure. Typical use of this signal is to ensure that a voltage rail is within tolerance and stable before enabling a load or to detect unit/output failure in redundant applications.

This signal can be used in combination with a PF or AC OK signal to enable a warning period prior to the output falling from tolerance in a line failure condition. This is often used in critical applications such as VME and is known as system reset (SRS).

System Reset (SRS/VME) Signals

The system reset signal indicates that the system voltage is OK. It is a combination of AC Fail (ACF) and DC OK. When ACF and DC OK are high and after a delay of 100-300 ms the SRS signal changes to high. If either ACF or DC OK changes to low then SRS changes to low.



The System reset signal is the only signal that is described in a standard (the VME standard) and is typically used in industrial computing applications. The user may not see the ACF & DC OK signals as these are used internally to create the SRS signal.

Remote On/Off, Inhibit and Enable

This interface is used to switch a power converter on and off via a signal level control, without the need to switch the input supply. This removes the need for large and expensive switch gear, has the added advantage that there is no inrush current once the unit has been powered for the first time and ensures faster response at the output at switch-on. On many configurable multiple output power supplies the outputs can be switched on and off independently, enabling control of output sequencing.

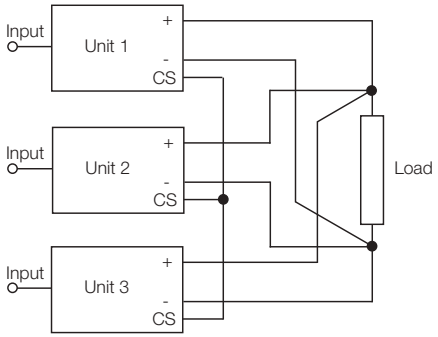
An Inhibit interface requires that the user intervenes to inhibit or switch off the unit. An Enable interface requires that the user intervenes to enable or switch the unit on. Where a converter is fitted with an enable signal, the output will not be present when the input power is applied until the user intervenes.

Signals can be active high or low and often open or short circuit to allow for simple relay control.

Current Share, Power Share or Single Wire Parallel

This interface is used to allow converters to communicate with each other when connected in parallel to ensure that the load is distributed evenly amongst the available resources. Typical load share accuracy is +/-10%. This ensures that no individual supply is overloaded.

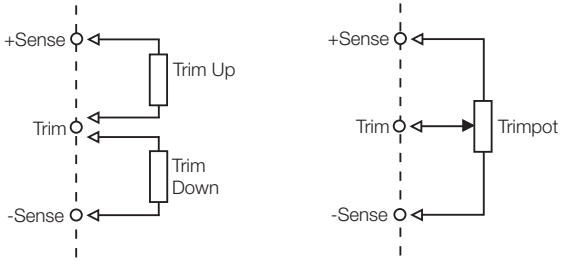
In low voltage redundant applications, where remote sensing of the output voltage is necessary, this interface will be needed to ensure load sharing and has the added benefit of reducing the stress on individual units and further improving reliability.



The connection between the units interfaces directly with the internal regulation circuit. The output current is monitored and the output voltage adjusted until the load current is shared equally.

Voltage Adjustment and Programming

The most common means of adjusting the output voltage of a power converter is via the internal adjustment potentiometer. Normally the output can be adjusted by up to +/-10%. Many converters can also be adjusted via an external potentiometer or resistor connected via the trim interface, an example of which is shown below.



Another option on some converters is the ability to program the output voltage using an external voltage or current. Common programming voltages are 0-5 VDC or 0-10 VDC for a 0-100% change in output voltage. Current programming can also be implemented where a 4-20 mA standard module can be utilized.

Because the programming signals interface directly with the converter's regulation circuit, precautions against noise interference should be implemented.

Output Margining

Margin interfaces are used to increase or decrease the output by 5 to 10% by connecting the margin pin to plus or minus sense. This function is most commonly used in parallel systems or standby battery applications to test system elements without exposing the load.

In parallel systems, the approach is to shift the load to the higher output voltage unit to ensure that it can supply the full load. The remaining units are still operating so that there is no risk to the load should the output of the unit under test collapse.

In standby applications the charger output is reduced, shifting the load to the battery. Should the battery not support the load then the charger or rectifier is still present to ensure that the load is not dropped.

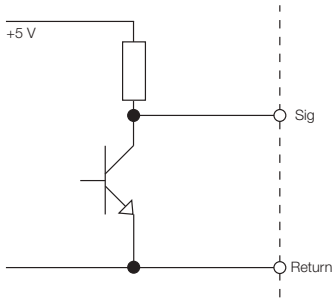
Common Topologies for Signals

Signal outputs can be presented in a number of topologies varying from converter to converter and manufacturer to manufacturer. The most common topologies are TTL compatible, open collector and volt free opto-couplers & relay contacts.

TTL Compatible Signals

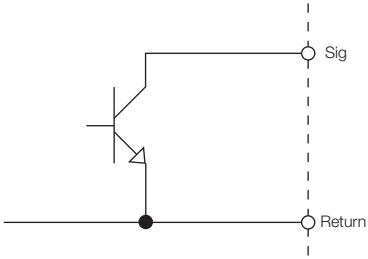
Signal outputs are designed to interface directly with TTL logic circuits. They provide a signal output of 0 VDC or 5 VDC and can be active high or active low.

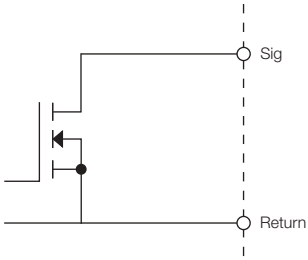
Signal outputs follow the standard rules for TTL circuits where a low signal is <0.8 V and a high signal is >2.8 V. A standard TTL signal will sink and source a minimum of 16 mA. The TTL signal output from a power converter is typically formed from a signal transistor with a pull up resistor to an internal auxiliary 5 V rail.



Open Collector or Open Drain Signals

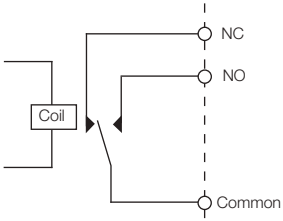
Open collector or drain signals provide a signal transistor with its emitter or source connected to the zero volt output of the converter and the collector or drain left floating. This allows the user to connect the signal as the application demands using external components, the limit being the voltage and current ratings of the device used.



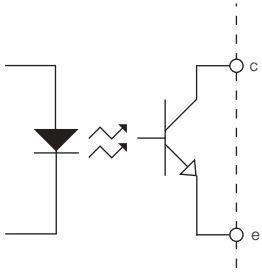


Isolated Signal Outputs

Isolated signal outputs are provided as opto-coupler transistors or relay contacts. These signals allow the user to configure the signals as either high or low as the application demands. Relay contacts also provide easy interface with industrial Programmable Logic Controllers (PLCs) and the inhibit interfaces of downstream DC/DC converters. Relay interfaces are typically small signal relays able to switch up to 1 A at 24 VDC and 0.5 A at 120 VDC.



Relay Signal Output



Opto-coupler Signal Output

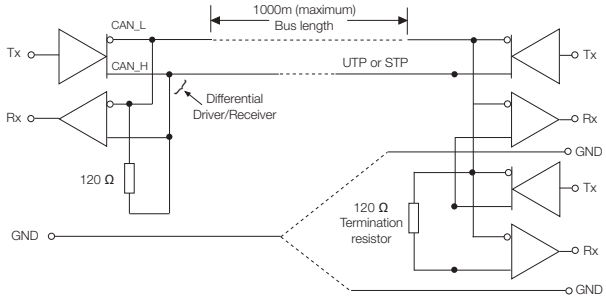
Another benefit of isolated signals is that multiple converters can be used in series or parallel combinations allowing the user to create combined series or parallel signal outputs, regardless of positive or negative output configurations.

Digital Communication Interfaces

Direct communication with power supplies is increasingly common as power supplies become integrated into control systems or building management systems. Alarm status can be requested from, or flagged by, the power supply and operating parameters such as alarm trip levels, output voltage and current limit levels can be maintained or programmed during operation. In some cases, power supplies will have their serial number or build dates available for system interrogation. Three common digital buses are described overleaf.

Controller Area Network (CAN) Bus

The CAN bus is a differential 2 wire system used for data communication at high speeds (1 Mbps, 40 m line length) or slow speeds (10 kbps, 1 km line length). The CAN bus was designed by Bosch for automotive use and is therefore ideally suited to use in harsh, electrically noisy environments. Because of this, the CAN bus is widely used in industrial environments and many controller devices are available to implement a network. Data is transmitted serially using a Non-Return to Zero (NRZ) format for both efficiency of message length and integrity of data. The CAN bus standard defines the data packet makeup for transmission and this may be built in to the bus controlling devices but there are higher level protocols, such as CANopen and DeviceNet which can be used to simplify their use. These allow easy programming of a communication system using a variety of different manufacturers' controllers.



Inter Integrated Circuit (I^2C) Bus

The I^2C bus was developed by Philips Semiconductors in the 1980's as a method of bi-directional data transmission between ICs. The bus has been adopted for communication between general parts of circuits and application specific circuits. The bus is serial and consists of two wires, one called SDA (Serial DAta) for data and the other called SCL (Serial CLock) for clocking. A ground return is also required. The bus utilizes a master/slave architecture in which there can be multiple masters, though when one has control, the others act as slaves. The bus will operate at speeds of 100 kbps as standard though there is a fast mode of 400 kbps or a high speed mode with speeds of up to 3.4 Mbps. The faster modes have tighter limits on the amount of noise that can be present. The maximum line length is typically 3-4 m, though if the clock speed is reduced to 500 Hz, the line length could be as long as 100 m. Normally, the limiting factors are the amount of noise pick up, which can obliterate the data, and data loss due to volt drops. Active current sources can be used to help to compensate for this.

Power Management (PM) Bus

The PM bus is an open power system standard, with a defined language, which is used to provide communications between power supplies/converters and other devices utilized in a power system. The PM bus protocol is implemented using the System Management (SM) bus which has become an industry standard serial interface for low speed system management communications. The PM bus is designed to allow programming, control and monitoring of suitably designed power conversion products. A typical implementation of PMbus in XP's EMH350 series has the following features.

Controls

The digital interface allows the output voltage to be adjusted via the PMBus and the microcontroller also activates the overload protection which can also be programmed via the Bus. The microcontroller can be factory programmed to cater for application specific requirements such as high peak loads & timed power boost. As standard the interface allows voltage adjustment of +/-10% and overload protection adjustment from 0 – 110%.

Signals

The following parameters are measured by the microcontroller and communicated via the PMBus:
- Output Voltage
- Output Current
- Fan Supply Voltage
- Internal Ambient Temperature
- Fan Status (Fan warning alert after 30 seconds. Fan fail alert after 1 minute 30 seconds)

Supported PMBus Commands

Command Code	Command Name	SMBus Transaction Type	Number of Data Bytes
81h	STATUS_FANS_1_2	Read Byte	1
8Ah	READ_VCAP	Read Word	2
8Bh	READ_VOUT	Read Word	2
8Ch	READ_IOUT	Read Word	2
8Dh	READ_TEMPERATURE_1	Read Word	2
98h	PMBUS_REVISION	Read Byte	1
99h	MFR_ID	Block Read	Variable
9Ah	MFR_MODEL	Block Read	Variable
9Bh	MFR_REVISION	Block Read	Variable
9Eh	MFR_SERIAL	Block Read	Variable
D0h	READ_VFAN*	Read Word	2
E4h	VOLTAGE_TRIM*	Write Byte	1
E5h	CURRENT_LIMIT_TRIM*	Write Byte	1

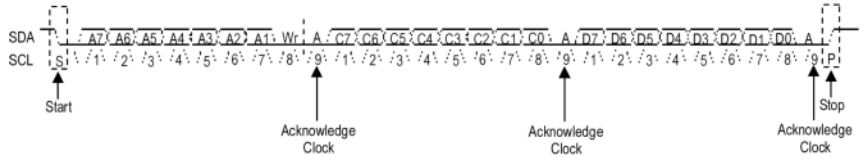
Data transfer

All data transactions are initiated by a START (S) bit where the data line (SDA) is pulled from low to high while the clock (SCL) is held high. Subsequent to this the 7-bit device address is sent followed by a WR bit (R/W=0) and then an acknowledge (A) bit. Acknowledge bits are sent from the slave to the master and vice versa depending on the transaction type. Following this the 8-bit PMBus command is sent followed by an A bit. This start procedure is standard for all commands and any differences will be found by the second A bit.

All transactions end with a stop (P) bit. The three standard transaction types are shown below together with a typical timing diagram for the write byte transaction. Gray boxes indicate that the data is being transferred from the slave to the master. For further information refer to the PMBus 1.1 specification.

Write Byte transaction

1	7	1	1	8	1	8	1	1
S	Slave Address	WR	A	Command Code	A	Data Byte	A	P



Read Byte transaction

1	7	1	1	8	1	1	7	1	1	8	1	1
S	Slave Address	WR	A	Command Code	A	S	Slave Address	Rd	A	Data Byte	A	P

Read Word transaction

1	7	1	1	8	1	1	7	1	1	8	1	8	1	1
S	Slave Address	WR	A	Command Code	A	S	Slave Address	Rd	A	Data Byte	A	Data Byte High	A	P

Block Read transaction

1	7	1	1	8	1	1	7	1	1	8	1
S	Slave Address	WR	A	Command Code	A	Sr	Slave Address	Rd	A	Data Count = N	A

8	1	8	1
Data Byte 1	A	Data Byte 2	A

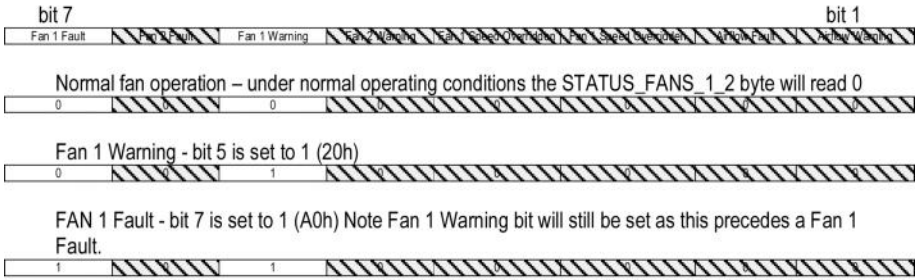
8	1	1
Data Byte N	A	P

Custom commands

STATUS_FANS_1_2

These bits change depending on the fault condition generated. After 30 seconds of the fan tacho output measuring a fault condition the Fan 1 warning is flagged, after an additional 30 seconds of the tacho output measuring a fault condition Fan 1 failure is flagged.

STATUS_FANS_1_2 Byte (grayed out sections are not currently used)



VOLTAGE_TRIM and CURRENT_TRIM

Both of these commands are used to set internal references to trim the output voltage & set the current limit. Should the device power down the last known values for both outputs are restored on power up.

The VOLTAGE_TRIM command accepts a HEX value between zero and 65; any value greater than 65 is ignored and assumed to be 65. Zero and 65 will set the minimum and maximum trim values as per the power supply specification with the default set at nominal output voltage during manufacture.

The CURRENT_TRIM command also accepts a HEX value between zero and 65; again any value above 65 is assumed to be 65. Zero and 65 will set the current limit between its minimum and maximum values as per the power supply specification.

READ_VFAN

This command operates in the same way as standard PMBus read voltage commands.

In summary, the modular structure adopted for the device code allows for it to be readily adapted facilitating changes to meet customer and application specific requirements. Additional functions include the ability to interrogate serial number, model number and manufacturing date codes.

Thermal Management

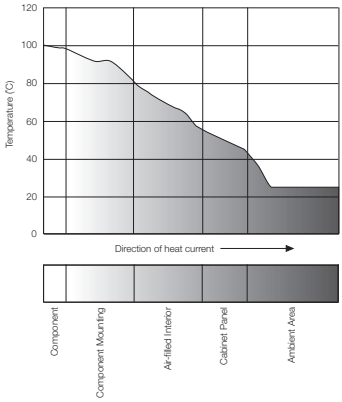
• System Cooling Fan Selection

Power Losses

Power losses occur in all electronic components. The effect of these losses becomes greater as more and more components are squeezed into smaller spaces. The result of this miniaturization is higher levels of heat per cubic volume of space. This waste heat can be considered to be system losses and expressed as follows:

Input power = output power + losses
Efficiency = output power/input power (always less than 1)

Losses can be in the form of heat, noise, light or work, and are expressed in Watts. The heat generated by a component does not only pass into the air around that component, it is also absorbed by adjacent components, the PCB and the equipment case. This waste heat affects the performance of the adjacent components causing them to operate in higher ambient temperatures. Although design aids such as fluid dynamic analysis can assist in the thermal design of equipment, the costs associated with the system often restrict its use. The majority of equipment designers rely upon experience and knowledge to select a cooling system.



Representation of the temperature gradient of a device

The dilemma is whether equipment can be designed to ensure that all waste heat can be removed by convection alone, or whether best practice calls for the incorporation of forced cooling. The thermal control of electronic equipment should be considered as part of the overall design specification resulting in a coherent design exhibiting greater reliability and life expectancy.

Establishing Allowable Temperature Rise

First establish the maximum operating temperature in which either the power supply or the electronics can safely operate. This could be 50 °C, the typical maximum operating temperature of a power supply when operated at full load. If the enclosure in which it is contained is to be used in a non air-conditioned environment, where the maximum temperature could reach as high as 40 °C, the maximum temperature rise allowed is 10 °C.

Establish Power to be Dissipated

If the application has all the load within the equipment then the total power dissipated within the enclosure is the power dissipated by the load and the power dissipated by the power supply due to its inefficiency. Below is an example for a 260 W load supplied by an 85% efficient power supply.

The load power is 260 W
+
The power lost due to the inefficiency of the power supply,
which is 85% efficient, so the power lost is 46 W

Total power to be dissipated is 306 W

The airflow needed through a system can be calculated as follows:

$$\text{Air flow } (m^3/hr) = \frac{2.6 \times \text{Power (W)}}{T_c}$$

Where Tc is the allowable temperature rise of the air in the equipment in °C, calculated as the maximum air temperature required minus the maximum temperature of air coming into the equipment (the ambient temperature). Airflow is measured in m^3/hr, and the power in Watts is the amount of heat dissipated into the box.

The power supply often has its flow rate given as a linear figure, while fan manufacturers typically specify a volumetric flow rate. To convert from one to the other, convert the volumetric flow rate in m^3/hr to m^3/s (divide by 3600), then divide the resultant figure by the active area of the fan. The active area of the fan is the area traced by the tips of the blades minus the area of the central hub (which is not directly contributing to air movement).

$$\text{Linear flow rate (m/s)} = \frac{\text{Volumetric flow rate } (m^3/s)}{\text{Active fan area } (m^2)}$$

Therefore in our example:

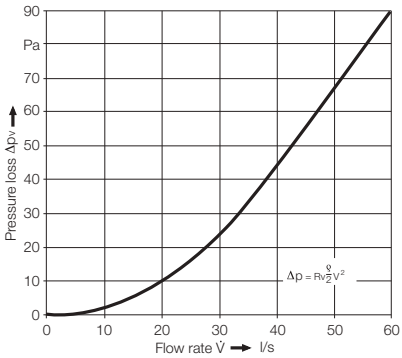
$$\text{Air flow } (m^3/hr) = \frac{2.6 \times \text{total power dissipated (W)}}{\text{Allowable temp rise } (^\circ C)}$$

$$= \frac{2.6 \times 306 \text{ W}}{10^\circ C}$$

$$= 79.56 \ m^3/hr \ (46.86 \text{ CFM})$$

To convert m^3/hr to cubic feet per minute (CFM) multiply by 0.589.

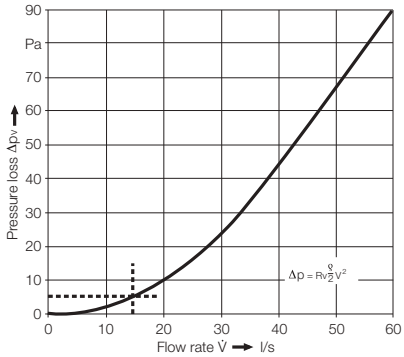
Characteristic Curves for Equipment Pressure Drop



Airflow figures published for fans are given in free air. In practice, an enclosure provides resistance to air movement. This resistance will change with each equipment design due to PCB sizes and positions and the effect of other components which will provide resistance to airflow. There is an approximation to back pressure which can be applied. This graph is an approximation or an average, based on accumulated historical data from fan manufacturers and is applicable to most electronic equipment. The graph shows the flow rate along the horizontal axis in liters per second and the back pressure on the vertical axis in Pascals.

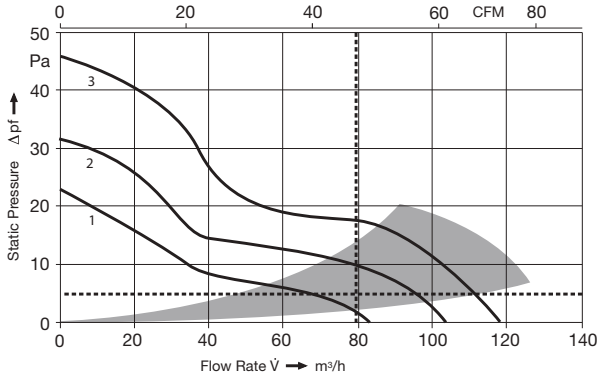
Estimating Back Pressure

The graph above is then used to estimate the back pressure, so for a system which requires 14.2 l/s, the back pressure is 5 Pascals.



Using Fan Characteristic Curves

We know that the back pressure is 5 Pa and we require 79.56 m³/hr. Therefore, from the graph below it can be seen that fan 2 is the suitable selection. The shaded area in the graph indicates the optimum performance area of the fan.



Curve	Type
1	FAN 1
2	FAN 2
3	FAN 3

• Cooling Power Supplies

Power supplies generate waste heat which has to be dissipated. They typically have either convection cooled or forced cooled ratings or, in some cases, both. Forced cooled power supplies may incorporate a cooling fan, or may specify the user cooling required to operate the unit at maximum load and ambient temperature.

Where user cooling is required it is most important that the power supply cooling is adequate for both safe operation and adequate service life. It is very application specific and dependent on the ambient temperature, applied load and physical location with respect to the cooling fan and other system assemblies.

The main difference between convection and force cooled products is in the power density offered. For a given efficiency, convection cooled products offer a lower power density, meaning that they occupy a larger volume. A power supply on a 3” x 5” industry standard footprint may have a convection rating of 150 W while the force cooled version may have a rating as high as 350 W.

Convection Cooling

Where the power supply has a convection cooled rating, it is intended to be used in an environment where there is free air. The system designer must ensure that there is adequate space around and above the unit for free air convection currents to cool the unit and must also ensure that the ambient temperature local to the power supply is controlled to a level within its maximum ratings.

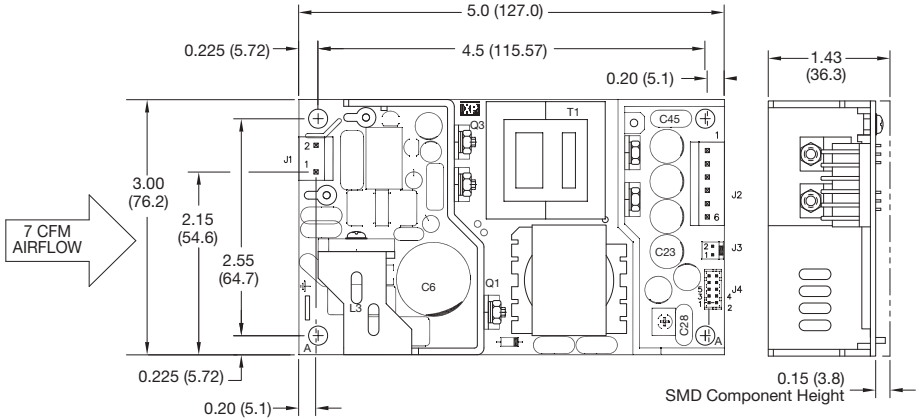
Forced Cooling

Force cooled products with integral cooling fans are easy to apply as it is a simple matter of ensuring that the maximum specified ambient temperature is not exceeded for a given load rating and that the intake and exhaust areas are not obstructed.

Typically, power supplies that require the user to provide forced air cooling will specify a minimum required airflow. This is usually for operation at 100% of the power rating at the maximum ambient temperature allowed.

The required airflow is often specified in Cubic Feet per Minute (CFM) which is also the common rating for cooling fans. The effectiveness of cooling fans installed in enclosures must be given consideration, as discussed earlier in this section, and the CFM rating deals in volume of air rather than air speed, which is the important factor. The object is to maintain the components used within the power supply at a safe operating temperature and to ensure adequate service life.

When the required airflow is specified in CFM it assumes that the power supply is installed in an area which is relatively similar to it’s own cross sectional area. This is rarely the case as the power supply is typically used as a sub-assembly within a complete equipment enclosure. It will also assume that the air is directed at the power supply, which may also not be the case, so converting to Linear Feet per Minute (LFM) or meters per second (m/s) provides a more valid criterion as linear air speed measurements specify where the air is flowing and directly relate to heat transfer.



In the case above, the power supply requires forced air of 7 CFM in the direction indicated by the arrow. The cross sectional area is:-

3” x 1.43” = 4.29 inches^2 or 0.0297 feet^2

Therefore the air velocity required is:-

7/0.0297 = 236 LFM or 1.2 m/s

This air speed can be measured locally to the power supply to ensure that sufficient forced air cooling is being applied.

Evaluation of the Application

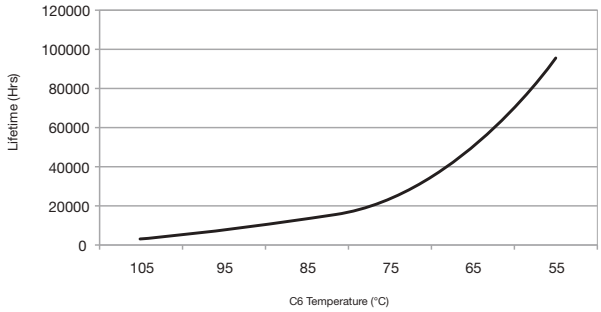
The object is to maintain the components used within the power supply at a safe operating temperature and to ensure adequate service life. Given the huge potential for variation between one application and another, the only real test is measurement of the temperature of the critical components within the power supply assembly when installed within the end application under the worst case external ambient conditions. The other option is to model the application exactly using a suitable software simulation.

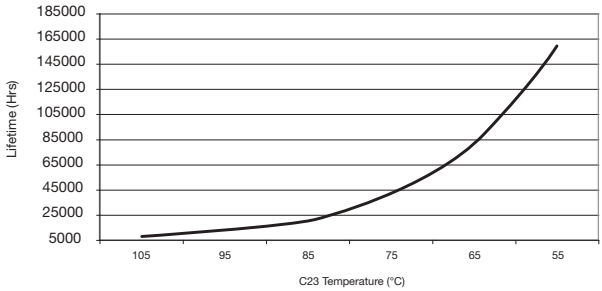
The criteria for safe operation will be specified for the power supply in question or can be obtained from the manufacturer. For the example above, the specific component temperatures for safe operation are given on the next page; these are typical for a power supply of this type.

Temperature Measurements (At Ambient 50 ℃)	
Component	**Max Temperature ℃**
T1 Coil	120 °C
L3 Coil	120 °C
Q1 Body	120 °C
Q3 Body	120 °C
C6	105 °C
C23	105 °C

While these figures will ensure safe operation they do not give any indication of the service life that can be expected. The lifetime of a power supply is largely determined by the temperature of the electrolytic capacitors, which have a wear out mechanism. As a general rule, capacitor lifetime can be doubled for every 10 °C drop in operating temperature.

The graph below indicates the expected service life of the power supply based on measurement of two key electrolytic capacitors.





• Cooling Power Modules

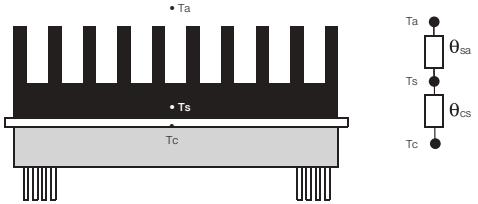
Power supplies and DC/DC converters have pre-defined thermal ratings for both convection and forced cooling. However, when power modules are used, additional thermal management is required.

Since operating temperature directly affects the lifetime and reliability good thermal management of the power system is key to overall system performance. Thermal resistance is defined as:

$$\theta = \frac{\Delta T}{Q}$$

where θ is thermal resistance in °C/W
ΔT is the temperature difference between two reference points in °C
Q is the heat flux or power passing through the two points in Watts.

This definition allows the calculation of junction temperatures using a thermal circuit similar to an electrical circuit:



θ_{SA} is thermal resistance heatsink–to–ambient ˚C/W

θ_{CS} is thermal resistance case–to–heatsink ˚C/W

Thermal resistance to the flow of heat from the power module to the ambient temperature air surrounding the package is made up of the thermal resistances of the case to heatsink and heatsink to ambient interfaces and can be added together to give an overall thermal resistance from power module to ambient θ_{CA}.

$$T_C = T_A + P_D (\theta_{CA})$$

where T_C = maximum power supply temperature
T_A = ambient temperature
P_D = power dissipation
θ_{CA} = case to ambient thermal resistance

From this equation, power module temperature may be calculated, as in the following examples.

Example: A power module package must operate in ambient temperature of +30 ˚C. What is its baseplate temperature? Let P_D = 5 W and θ_{CA} = 11.0 ˚C/W.

$$T_C = T_A + P_D\ \theta_{CA} = 30 + (5 \times 11.0) = +85.0\ ^\circ C$$

Where operation in a higher ambient temperature is necessary, the maximum power module temperature can easily be exceeded unless suitable measures are taken.

Example: The same device to be used at an ambient temperature of +50 ˚C, what is its case temperature?

$$T_C = T_A + P_D\ \theta_{CA} = 50 + (5 \times 11.0) = +105.0\ ^\circ C$$

This exceeds most power module maximum operating temperatures and therefore some means of decreasing the case–to–ambient thermal resistance is required.

As stated earlier, θ_{CA} is the sum of the individual thermal resistances; of these, θ_{CS} is fixed by the design of device and package and so only the case–to–ambient thermal resistance, θ_{CA}, can be reduced.

If θ_{CA}, and therefore θ_{SA}, is reduced by the use of a suitable heatsink, then the maximum T_{amb} can be increased:

Example: Assume that a heatsink is used giving a θ_{CA} of 3.0 ˚C/W. Using this heatsink the above example would result in a baseplate temperature given by:

$$T_C = T_A + P_D\ \theta_{CA} = 50 + (5 \times 3.0) = +65.0\ ^\circ C$$

These calculations are not an exact science because factors such as θ_{CA} may vary from device type to device type and the efficacy of the heatsink may vary according to the air movement in the equipment.

Where it is impossible to improve the dissipation capability of the heatsink, forced air cooling becomes necessary and, though the simple approach outlined above is useful, more factors must be taken into account when forced air cooling is implemented.

• Baseplate Cooling

The use of power supplies in harsh or remote environments brings many fundamental design issues that must be fully understood if long-term reliability is to be attained.

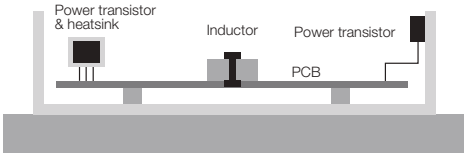
Under these conditions, it is generally accepted that electronic systems must be sealed against the elements making the removal of unwanted heat particularly difficult. The use of forced-air cooling is undesirable as it increases system size, adds the maintenance issues of cleaning or replacing filters and introduces a wear out mechanism in the fan.

A commonly adopted solution is to use a standard power supply and modify the mechanical design to enable removal of heat from the sealed system. This simple compromise does not really address the fundamental issues of power supply design for the applications described and a more practical approach is to select a power supply which has been designed specifically for sealed enclosure applications.

The extremes of ambient temperature encountered in remote sites can range from -40 ºC to over +40 °C. It is common for the temperature within the enclosure to rise some 15 to 25 °C above the external temperature. The positioning of the power supply within the enclosure can help minimize the ambient temperature in which it operates and this can have a dramatic effect on system reliability. As a rule of thumb, lifetime halves with every 10 °C rise in temperature. The power supply therefore needs to be able to operate from –40 °C to +65 °C as a minimum specification.

System enclosures are typically sealed to IP65, IP66 or NEMA 4 standards to prevent ingress of dust or water. Removal of heat from other electronic equipment and power supplies in a situation with negligible airflow is the challenge. From the power system perspective, the most effective solution is to remove the heat using a heatsink that is external to the enclosure. However, most standard power supplies cannot provide an adequate thermal path between the heat-dissipating components within the unit and the external environment.

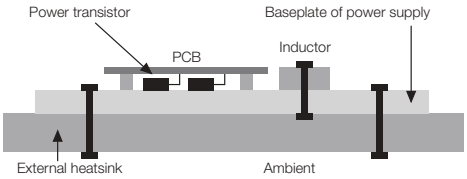
Conventional power supplies dissipate heat into small on-board heatsinks or onto a chassis. The basic construction is shown in below. Most of the heat is dissipated within the enclosure in which the power supply is used. Such units typically have to be derated from 50 °C, delivering 50% of their full rated power at 70 °C. The derating specification is a general guide based on individual components within the power supply not exceeding their maximum operating temperatures.



Construction of typical industrial AC-DC power supply

Fundamentally, the successful design of a power supply for use within sealed enclosures relies on creating a path with low thermal resistance through which conducted heat can be passed from heat-generating components to the outside world.

The components that generate the most heat in a power supply are distributed throughout the design, from input to output. They include the power FET used in an active PFC circuit, the PFC inductor, power transformers, rectifiers, and power switches. Heat can be removed from these components by mounting them directly onto a substantial base-plate that in turn can be affixed to a heatsink, rather than on to the PCB. As mentioned earlier, the heatsink is then located outside of the enclosure.



Basic construction of baseplate cooled PSU with all of the major heat-generating components fixed directly to the baseplate

This construction does demand accurate pre-forming of the leads of the components mounted on the baseplate, and accurate positioning of the PCB with respect to the baseplate but there is no significant increase in manufacturing complexity or costs.

With the appropriate heatsink, removal of heat can be so effective that there is no need to derate the unit until the ambient temperature reaches +70 °C. This eliminates the need to over-engineer the power supply for the application.

Dissipating the Heat: Heatsink Calculations

Three basic mechanisms contribute to heat dissipation: conduction, radiation and convection. All mechanisms are active to some degree but once heat is transferred from the baseplate to the heatsink by conduction, free convection is the dominant one.

Effective conduction between the baseplate and heatsink demands flat surfaces in order to achieve low thermal resistance. Heat transfer can be maximized by the use of a thermal compound that fills any irregularities on the surfaces. System designers should aim to keep thermal resistance between baseplate and heatsink to below 0.1 °C/W. This is the performance offered by most commonly used thermal compounds when applied in accordance with manufacturers' instructions.

Radiation accounts for less than 10% of heat dissipation and precise calculations are complex. In any case, it is good practice to consider this 10% to be a safety margin.

The degree of convection cooling depends on the heatsink size and type. Heatsink selection involves the following steps:

1. Calculate the power dissipated as waste heat from the power supply. The efficiency and worst case load figures are used to determine this using the formula:

$$\text{Waste heat} = \left(\frac{1 - \text{Efficiency}}{\text{Efficiency}}\right) \times P_{out} \quad \text{or} \quad \left(\frac{1}{\text{Efficiency}} - 1\right) \times P_{out}$$

Example: Assuming an efficiency of 85% and load of 100 W

$$\text{Waste heat} = \left(\frac{1 - 0.85}{0.85}\right) \times 100 = 17.65\ \text{W}$$

2. Estimate the resistance of the thermal interface between the power supply baseplate and the heatsink. This is typically 0.1 °C/W when using a thermal compound.

3. Calculate the maximum allowable temperature rise on the baseplate. The allowable temperature rise is simply:

   $T_B - T_A$ where T_A is the maximum ambient temperature outside of the cabinet and T_B is the maximum allowable baseplate temperature.

4. The required heatsink is defined by its thermal impedance using the formula:

$$\theta H = \frac{T_B - T_A}{\text{Waste Power}} - 0.1$$

5. The final choice is then based on the best physical design of heatsink for the application that can deliver the required thermal impedance. The system's construction will determine the maximum available area for contact with the baseplate of the power supply and the available space outside of the enclosure will then determine the size, number and arrangement of cooling fins on the heatsink to meet the dissipation requirement.

Conclusion

The reliability of remotely-sited electronic equipment is fundamentally dependent upon power supply reliability. The most cost-effective approach to power system design is to use power supplies designed for the application, which conduct heat via large, flat baseplates to heatsinks that can be mounted outside of the enclosure.

• Electrolytic Capacitor Lifetime

Electrolytic capacitor lifetime is a key parameter in power supplies which defines the lifetime of the product as the only component wear out mechanism. This may well define the service life of the end product or the service interval required for maintained equipment. The other major wear out mechanism is the power supply or system cooling fan, where fitted.

As power density requirements become more demanding capacitor lifetime needs careful consideration and it is important to understand the shortest lifetime part which, depending on factors such as topology, local heating effects due to layout and the design life of the specific part, may vary from product to product. It is not unusual for the external heating effects to outweigh the self heating effects. The key factors affecting capacitor lifetime are discussed below.

Design lifetime at rated temperature

Manufacturers of electrolytic capacitors specify the design lifetime at the maximum ambient temperature, usually 105 °C. This can vary from as little as one or two thousand hours to ten thousand hours or more. The higher the design lifetime the longer the component will last in a given application and ambient temperature.

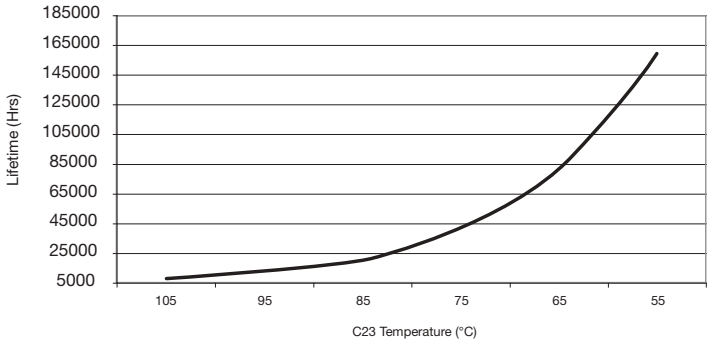
Ambient temperature and local heating effects

There are a number of lifetime calculations published by different manufacturers. All of these are based on the Arrhenius Equation for temperature dependence of reaction rates and determines that the reaction rate doubles for every 10°C rise in temperature. Put another way the reaction rate halves for every 10°C reduction in temperature. This means that a capacitor rated at five thousand hours at 105 °C would have a lifetime of ten thousand hours at 95 °C and twenty thousand hours at 85 °C.

The basic equation is given below and the curve shows this translated to a pictorial view of capacitor lifetime.

$$L = L_0 \times 2^{\left(\frac{T_{max} - T_a}{10}\right)}$$

L : Estimated life (Hr)
L_0 : Life at rated temperature (Hr)
T_{max} : Rated Temperature (°C)
T_a : Ambient Temperature (°C)



Magnitude and frequency of ripple current applied

In addition to the ambient temperature and local heating effects, the application of ripple current will further heat the capacitor. Ripple currents are generated by the rectification process on both the input and output stages of the power supply. The power dissipated in the capacitor is determined by the RMS ripple current and it's Equivalent Series Resistance (ESR), where $P=I^2R$. The temperature rise of the specific component is determined by the power dissipated, the radiation factor of the capacitor and the temperature difference factor or temperature slope from the core to the case. The radiation factor and temperature difference factors are specified by the capacitor manufacturer.

Manufacturers specify the maximum ripple current at maximum rated ambient temperature. Multiplication factors can be applied depending on the ambient temperature and the frequency of the applied ripple current as the ESR reduces as the frequency increases. Typically the ripple current rating can increase by a factor of 1.7 times when the temperature is reduced from 105°C to 85°C and by a factor of 1.4 - 1.5 when the ripple current is applied at 100kHz opposed to 100/120Hz.

Power supply lifetime

All of the above factors are taken in consideration during the design of a power supply and manufacturers will apply de-rating rules to ensure that the product lifetime is adequate. However, once the product is manufactured and installed in the end equipment the applied load, local environment, mounting orientation, positioning, surrounding space and any system cooling must also be taken into consideration.

Measurement of ripple current is typically not practical in this situation but a very good indication of the lifetime of each electrolytic capacitor can be determined by measuring the case temperature and applying the Arrhenius equation to the base specified component lifetime.

The table below shows the indicated lifetime of a capacitor rated at two thousand hours compared to a capacitor rated at five thousand hours at various temperatures. If the lifetime is calculated or indicated to be in excess of fifteen years then it should be assumed as fifteen years.

Temperature	2000 Hour Rated	5000 Hour Rated
105 ℃	2000 hrs (0.23 years)	5000 hrs (0.57 years)
95 ℃	4000 hrs (0.46 years)	10000 hrs (1.14 years)
85 ℃	8000 hrs (0.91 years)	20000 hrs (2.28 years)
75 ℃	16000 hrs (1.82 years)	40000 hrs (4.56 years)
65 ℃	32000 hrs (3.65 years)	80000 hrs (9.31 years)
55 ℃	64000 hrs (7.30 years)	160000 hrs (18.2 years)*

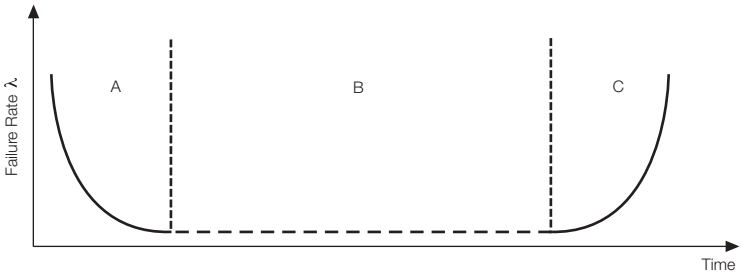
*Lifetime calculations above 15 years should be considered as 15 years maximum

Reliability

• Terminology

Failure Rate λ

Failure rate is defined as the percentage of units failing per unit time. This varies throughout the life of the equipment and if λ is plotted against time, a characteristic bathtub curve (below) is obtained for most electronic equipment.



The curve has three regions, A - Infant mortality, B - Useful life, C - Wear out.

In region A, poor workmanship and substandard components cause failures. This period is usually over within the first few tens of hours and burn-in is normally employed to prevent these failures occurring in the field. Burn-in does not entirely stop the failures occurring but is designed to ensure that they happen within the manufacturing location rather than at the customer's premises or in the field.

In region B the failure rate is approximately constant and it is only for this region that the following analysis applies.

In region C, components begin to fail through reaching end of life rather than by random failures. Electrolytic capacitors dry out, fan bearings seize up, switch mechanisms wear out and so on. Well implemented preventative maintenance can delay the onset of this region.

Reliability

Reliability is defined as the probability that a piece of equipment operating under specified conditions will perform satisfactorily for a given period of time. Probability is involved since it is impossible to predict the behavior with absolute certainty. The criterion for satisfactory performance must be defined as well as the operating conditions such as input, output, temperature, load etc.

MTBF – Mean Time Between Failures
MTTF – Mean Time To Failure

MTBF applies to equipment that is going to be repaired and returned to service, MTTF to parts that will be thrown away on failing. MTBF is the inverse of the failure rate and is often misunderstood. It is often assumed that the MTBF figure indicates a minimum guaranteed time between failures. This assumption is incorrect, and for this reason the use of failure rate rather than MTBF is recommended.

The mathematics are expressed as follows:

$$m = \frac{1}{\lambda}$$

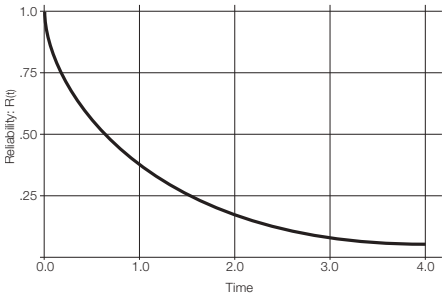
$$R_{(t)} = e^{-\lambda t} = e^{-(t/m)}$$

$$m = \frac{t}{\log_{(n)}\left(\frac{1}{R_{(t)}}\right)}$$

Where $R_{(t)}$ = reliability
e = exponential (2.178)
λ = failure rate
m = mtbf
t = time

This shows that for a constant failure rate, plotting reliability '$R_{(t)}$' against time 't' gives a negative exponential curve. When t/m = 1, i.e. after a time 't', numerically equal to the MTBF figure 'm', then

$$R_{(t)} = e^{-1} = 0.37$$



This equation can be interpreted in a number of ways:

a) If a large number of units are considered, only 37% of them will survive for as long as the MTBF figure.

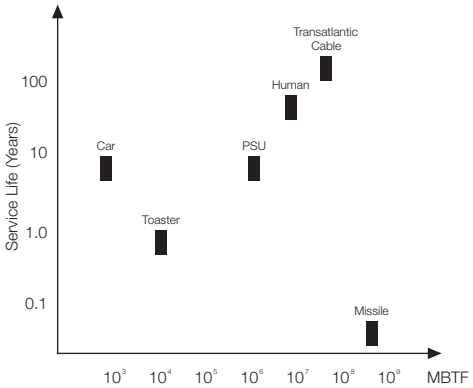
b) For a single unit, the probability that it will work for as long as its MTBF figure is only 37%.

c) The unit will work for as long as its MTBF figure with a 37% Confidence Level.

To put these numbers into context, consider a power supply with an MTBF of 500,000 hrs (or a failure rate of 0.002 failures per 1000 hrs), or as the advertisers would put it, an MTBF figure of 57 years. Using the above equation, R(t) for 26,280 hours (three years) is approximately 0.95 and if such a unit is used 24 hours a day for three years the probability of it surviving is 95%. The same calculation for a ten year period will give an R(t) of 84%. If 700 units are used, on average 0.2%/1000hrs will fail, or approximately one per month.

Service Life

There is no direct connection or correlation between service life and failure rate. It is perfectly possible to design a very reliable product with a short life. A typical example is a missile, which has to be very very reliable (MTBF of several million hours), but its service life is only around 4 minutes (0.06hrs). 25-year-old humans have an MTBF of about 800 years, (failure rate of 0.1% per year), but not many have a comparable service life. If something has a long MTBF, it does not necessarily have a long service life.



• Factors Affecting Reliability

The most important factor is good, careful design based on sound experience, resulting in known safety margins. Unfortunately, this does not show up in any predictions, since they assume a perfect design.

Many field failures of electronic equipment are not due to the classical random failure pattern discussed here, but to shortcomings in the design and in the application of the components, as well as external factors such as occasional voltage surges. These may be outside of the specification but no one will ever know as all that will be seen is a failed unit. Making the units rugged through careful design and controlled overstress testing is a very important part of making the product reliable.

The failure rate of the equipment depends on these three factors.

Complexity — Keep things simple, because what isn’t there can’t fail but, conversely, what isn’t there can cause a failure. A complicated or difficult specification will invariably result in reduced reliability. This is not due to the shortcomings of the design staff, but to the resultant component count. Every component used will contribute to the equipment's unreliability.

Stress — For electronic equipment, the most prominent stresses are temperature, voltage, vibration and temperature rise due to current. The effect of each of these stresses on each of the components must be considered. In order to achieve good reliability, various derating factors have to be applied to these stress levels. The derating has to be traded off against cost and size implications. Great care and attention to detail is necessary to reduce thermal stresses as far as possible. The layout has to be such that heat-generating components are kept away from other components and are adequately cooled. Thermal barriers are used where necessary and adequate ventilation needs to be provided.

The importance of these provisions cannot be overstressed since the failure rate of the components will double for a 10 ºC increase in temperature. Decreasing the size of a unit without increasing its efficiency will make it hotter, and therefore less reliable.

Generic — Generic reliability (also known as inherent reliability) refers to the fact that, for example, film capacitors are more reliable than electrolytic capacitors, wirewrap connections more reliable than soldered ones, fixed resistors more reliable than potentiometers. Components have to be carefully selected to avoid the types with high generic failure rates. Quite often there is a cost trade-off, as more reliable components can be more expensive.

Assessment — This is the most useful and accurate way of predicting the failure rate.
A number of units are put on life test, at an elevated temperature, and so the stresses and the environment are controlled.

Estimating the Failure Rate

The failure rate should be estimated and measured throughout the life of the equipment. During the design, it is predicted. During the manufacture, it is assessed. During the service life, it is observed.

The failure rate is predicted by evaluating each of the factors affecting reliability for each component and then summing these to obtain the failure rate of the whole equipment. It is essential that the database used is defined and used consistently. There are three databases in common use: MIL-HDBK-217, HRD5 and Bellcore. These reflect the experiences of the US Navy, British Telecom and Bell Telephone respectively.

In general, predictions assume that the design is perfect, the stresses known, everything is within ratings at all times, so that only random failures occur; every failure of every part will cause the equipment to fail and that the database is valid. These assumptions are incorrect. The design is less than perfect, not every failure of every part will cause the equipment to fail, and the database is likely to be 15 years out of date. However, none of this matters as long as the predictions are used to compare different topologies or approaches rather than to establish an absolute figure for reliability. This is what predictions should be used for.

Prediction

Parts stress method

In this method, each factor affecting reliability for each component is evaluated. Since the average power supply has over 100 components and each component about seven factors (stress ratio, generic, temperature, quality, environment, construction and complexity), this method requires considerable effort and time. Predictions are usually made in order to compare different approaches of topologies, i.e. when detailed design information is not available and the design itself is still in a fluid state. Under such circumstances it is hardly worthwhile to expend this effort and the much simpler and quicker Parts count method is used.

Parts count method

In this method, all like components are grouped together, and average factors allocated for the group. So, for example, instead of working out all the factors for each of the 15 electrolytic capacitors used there is only one entry of capacitor with a quantity of 15. Usually only two factors are allocated, generic and quality. The other factors, including stress levels, are assumed to be at some realistic level and allowed for in the calculation. For this reason, the factors are not interchangeable between the two methods. In general, for power supplies, HRD5 gives the most favorable result closely followed by Bellcore, with MIL-217 the least favorable. This depends on the mix of components in the particular equipment, since one database is ‘unfair’ on ICs, and another on FETs. Hence the importance of comparing results from like databases only.

During life tests and reliability demonstration tests it is usual to apply greater stresses than normal, so that the desired result is obtained more quickly. Great care has to be applied to ensure that the effects of the extra stress are known and proven to be calculable and that no hidden additional failure mechanisms are activated by the extra stress. The usual extra stress is an increase of temperature and its effect can be calculated as long as the maximum ratings of the device are not exceeded.

Prototype Testing

With all the sophisticated computer analysis available, there is still no substitute for thoroughly testing products or components. One way of doing this would be to perform HALT testing. HALT (Highly Accelerated Life Test) is used to test as many different conditions as possible and cycling the temperature, input and load independently.

Manufacturing Methods

Suppliers must be strictly controlled and deliver consistently good product with prior warning of any changes to processes. Because of the supply chain JIT and QA practices this can be achieved by dealing with a small number of trusted suppliers.

Manual assembly is prone to errors and to some random, unintentional abuse of the components by operators, such as ESD. This causes defects, which will show themselves later.

Changing settings produces inconsistency and side effects. A good motto is ‘if it works leave it alone, if it does not, find the root cause.’ There must be a reason for the deviation and this must be found and eliminated, rather than masked by an adjustment.

The results from the HALT test can be used to set test limits for production screening. Highly Accelerated Stress Screening (HASS) uses the same equipment as for HALT tests but knowing the operating and destruct (where possible) limits can be used to screen HALT tested products in production. This process differs from conventional stress screening in that the climatic and mechanical stimuli are much higher and consequently the test times are much shorter. HASS can be summed up as a process used in manufacturing to allow discovery of process changes and prevent products with latent defects from getting into the field.

• System Reliability

There are two further methods of increasing system reliability.

More reliable components	MIL standard or other components of assessed quality could be used but in industrial and commercial equipment this expense is not normally justified.
Redundancy	In a system where one unit can support the load and two units are used in parallel, the system is much more reliable since the system will still work if one unit fails. Clearly, the probability of both units failing simultaneously is much lower than that of one unit failing.

Redundancy has a size and cost penalty so normally an n+1 system is used, where n units can support the load, but n+1 units are used in parallel, 2+1 or 3+1 being the usual combinations. Supposing the reliability of each unit under the particular conditions is 0.9826, the system reliability for an n+1 system where n=2 would be 0.9991, an improvement of 20 times. (Nearly 60 times in a 1+1 system).

There are downsides to this approach. More units, higher cost and the need for faulty units to be brought to the operator's attention so that they can be replaced, changing units must not make the system fail (hot swap). The extra circuitry required to monitor all aspects and ensure reliability in itself increases the failure rate and cost of the system (see page 63 for more details on redundant operation).

Comparing Reliability

When comparing reliability figures, the following points must be satisfied.

- The database must be stated and must be identical. Comparing a MIL-HDBK-217F prediction with a MIL-HDBK-217E prediction or a Bellcore/Telcordia prediction is meaningless as there is no correlation.

- The database must be used consistently and exclusively. The result is meaningless if a different database is used for some components.

- The external stresses and environment must be stated and be identical. (input, load, temperature etc). The result is meaningless if all the environmental details are not stated or are different.

- The units must be form-fit function interchangeable. If, for example, the ratings are identical, but one needs an external filter and the other does not then there is no comparison (although you could work out the failure rate of the filter and add it to the failure rate of the unit).

There is no magic; if one manufacturer predicts 200,000 hours and another states 3,000,000 hours for a comparable product, then they must have used a different database, a different stress level or a different environment.

Legislation

• Power Supply Safety

Electrical equipment must be designed to reduce the risk of injury or damage due to electric shock, fire, radiation, energy related hazards, heat related hazards and chemical hazards.

A safe power supply is an essential part of any electronic or electrical product and must comply with the relevant safety standards. There are a number of standards which are applicable to power supplies depending on the intended application of the end equipment.

There is an international product specific IEC standard for power supplies used to demonstrate compliance with safety requirements. This comes from the IEC61204 range of standards which covers both stand alone, or external power supplies, and component power supplies for building in to end equipment. IEC61204 references the product family standards such as IEC60950, IEC60601 etc.

Currently, most power supplies will use one or more of the following standards to demonstrate compliance for safety:

IEC60950 - Information Technology
IEC60065 - Audio & Video Equipment
IEC60355 - Household Appliances
IEC60601 - Medical Equipment
IEC61010 - Measurement, Control & Laboratory Equipment
UL508 - Industrial control equipment, often used for DIN Rail power supplies

IEC62368-1 was ratified in 2014 and is the new standard to replace IEC60950-1 and IEC60065-1 covering Audio/Video, Information Technology and Communication Technology Equipment which now use similar technology, similar environments and similar marketing and distribution channels. This standard has been widely adopted with national standards already published and will start to be introduced on new products from 2014 onwards.

Approvals are separately granted by a number of national test laboratories depending on the target markets. UL (Underwriters Laboratories) is commonly used for approvals in North America, CSA (Canadian Standards Association) for Canada and there are a number of European test laboratories which grant approvals for Europe wide use to the European Norm. UL & CSA also operate a scheme to grant approvals for both North American markets.

National approvals are generally granted under the CB scheme, the international system for mutual acceptance of test reports and certificates relating to the safety of electronic and electrical equipment. The CB scheme is based upon the use of IEC international standards with national deviations where appropriate.

In the major Asian markets other approvals are commonly required. The requirements are essentially as laid out in the IEC standards with some additional testing or labelling required.

CCC (China Compulsory Certification) China

CCC safety approval requires a CB report with the appropriate national deviations but also requires additional EMC testing from a CQC (China Quality Certification Center) accredited test house. CCC is compulsory for external power supplies sold into China and can also be applied to component power supplies to be used in end equipment destined for the Chinese market. Unlike other approval bodies, CCC does not recognize approvals for altitudes between 2000m and 5000m. Products approved for more than 2000m but less than 5000m can only be approved for 2000m and must be labelled to indicate that they are not approved for higher altitude.

PSE (Product Safety Electric Appliance & Materials) Japan

PSE safety approval requires a CB report with the appropriate national deviations along with compliance to J55022 conducted and radiated emissions. Japan's Electrical Appliance and Material Law (DENAN) requires a conformity assessment body to issue a DENAN certificate for type classification. PSE also requires that the name of the importer into Japan is included on the product label. The importer takes responsibility for ensuring that the product is compliant and must be resident in Japan.

KETI (Korean Electrical Testing Institute) Korea

KETI safety approval requires a CB report with the appropriate national deviations, compliance to KN22 conducted and radiated emissions, KN54 immunity standards and minimum energy performance standards (MEPS) for external power supplies. KETI also requires that the name of the manufacturer and country of manufacture is included on the product label along with the telephone number of the importer who must be resident in Korea.

BSMI (Bureau of Standards, Metrology & Materials) Taiwan

BSMI safety approval requires a CB report with appropriate national deviations and additional EMC testing. Labelling must include importer information who must be resident in Taiwan and the license is issued to the importer.

These are just a few examples. There are many other national approval bodies globally with slightly varying requirements which may need to be considered depending on the target markets of the end equipment.

Electrical Safety

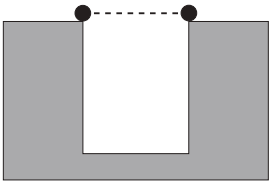
An electrically safe system relies on the use of safety earthing, the insulation of hazardous voltages and the control of leakage currents.

Insulation

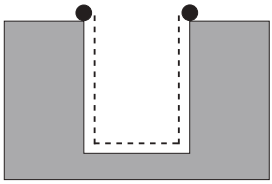
The five different types of insulation grades are listed below.

Operational/functional insulation	Insulation that is necessary only for the correct functioning of the equipment and does not provide any protection against electric shock.
Basic insulation	Insulation applied to live parts to provide basic protection against electric shock.
Supplementary insulation	Independent insulation applied in addition to basic insulation in order to provide protection against electric shock in the event of a failure of *basic insulation*.
Double insulation	Insulation comprising both *basic insulation* and *supplementary insulation*.
Reinforced insulation	Single insulation system applied to live parts which provides a degree of protection against electric shock equivalent to *double insulation.*

Creepage and clearance spacing specified in the safety standard must also be met. The requirement depends on the insulation type, working voltage and pollution degree. The insulation barriers must then undergo a high voltage test.



Clearance is the distance between two points through air



Creepage is the distance between two points over the surface

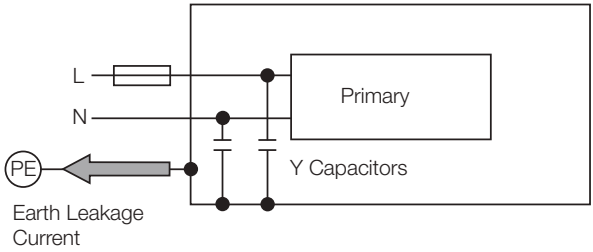
Earthing/Grounding

The two types of earth are listed below:

Functional earth	This does not provide any safety function, for example the screen on an external power supply output lead.
Protective earth	This provides protection against electric shock in a class I system and must meet certain performance criteria, such as resistance.

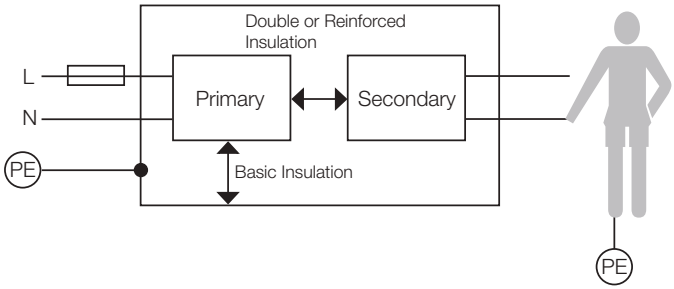
Earth Leakage Current

Current that flows down the earth conductor is defined as earth leakage current. To prevent the risk of electric shock in the event of the earth becoming disconnected, the maximum value is defined in the safety standard under touch current and is normally 3.5 mA for pluggable equipment. Higher values are permissible if the equipment is permanently connected. Within the power supply the main contributors to the leakage current are the EMC filter Y capacitors.



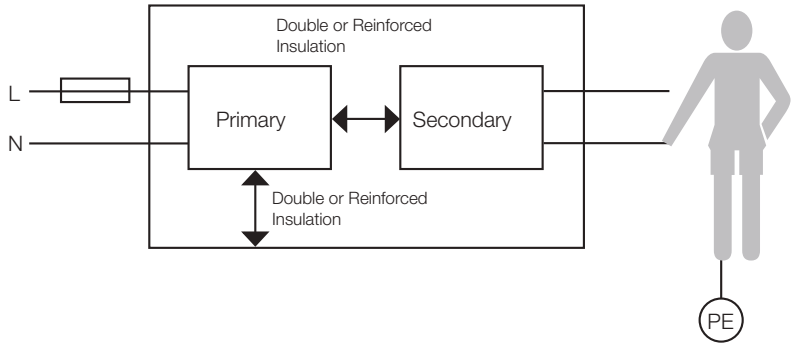
Class I Systems

Class I systems rely on earthing and insulation to provide a means of protection. In the event of the basic insulation between live and earth failing the protective earth provides a path for the fault current to flow, causing a fuse or circuit breaker to trip. The diagram below shows the insulation diagram of a class I power supply.



Class II Systems

Class II systems rely on insulation only to protect against electric shock. The diagram below shows the insulation diagram of a class II power supply.



• Medical Safety

Designing in safety is essential for medical products to succeed in both regulatory and marketing requirements. IEC60601-1 is the cornerstone document addressing many of the risks associated with electrical medical equipment.

The 60601-1 standard covers equipment, provided with not more than one connection to a particular mains supply and intended to diagnose, treat, or monitor patients under medical supervision and which makes physical or electrical contact with the patient and/or transfers energy to or from the patient and/or detects such energy transfer to or from the patient

The standard consists of four distinct parts, the base standard (60601-1), collateral standards (60601-1-x), particular standards (60601-2-x) and performance standards (60601-3-x). The base standard has been adopted in most major countries as the national standard either unchanged, such as EN60601-1 (Europe) or with national deviations such as UL60601-1 (USA) and CAN/CSA C22.2 No. 601.1 (Canada).

Currently the standard is available in both 2nd edition and 3rd edition. The 2nd edition is IEC60601-1:2003 and 3rd edition is IEC60601-1:2005. The 3rd edition was published in 2005 after 10 years of development. Its purpose is to harmonize the terminology contained in the 2nd edition with other standards such as IEC60950. In the USA the 3rd edition standard is ANSI/AAMI ES60601-1

The 3rd edition differs from the 2nd edition putting emphasis on the OEM implementing a risk management system compliant with ISO14971. It also introduces new concepts such as essential performance of equipment and distinguishes between the operator and the patient with MOOP (Means Of Operator Protection) and MOPP (Means of Patient Protection).

The concept of MOPP and MOOP allows the manufacturer relaxation in terms of creepage & clearance distances for MOOP if it is proven through risk management that the equipment will not come into contact with the patient in normal operation or under a single fault condition. The requirements for MOOP follow IEC60950 and for MOPP follow those required in IEC60601-1 2nd edition.

The structure of the base standard is hazard specific and provides requirements for evaluating the common hazards associated with electro-medical products. Its scope is to protect both patients and operators by reducing the likelihood of electric shock, mechanical, radiation, ignition of flammable anaesthetics, fire and excessive output energy hazards.

The basic concept of the standard requires that two means of protection (MOP) or two levels of protection (LOP) under IEC60601-1 2nd edition are employed in various areas of the product so that if one fails the product will retain another means of protection to contain any electrical shock hazard from either the patient or the operator.

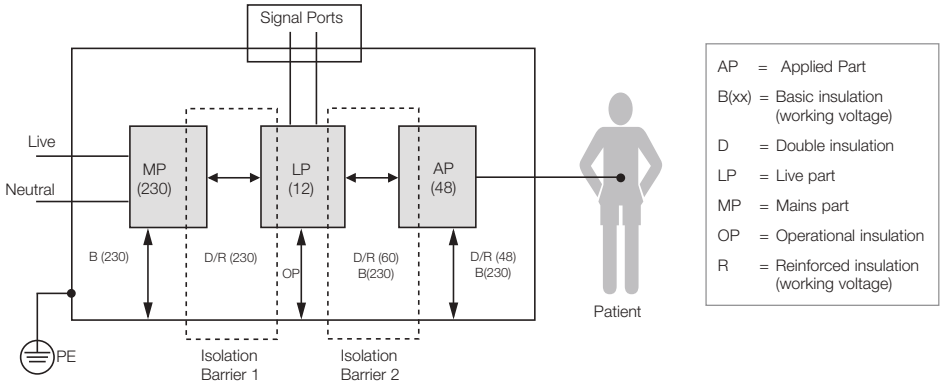
To achieve these two means of protection, 60601-1 permits the use of three building blocks used in different combinations. These building blocks are insulation, protective earth and protection impedance. For example protective earth (1 x MOP) used in conjunction with basic insulation (1 x MOP) provides the two means of protection required. The table below lists the permitted building blocks and the means of protection they provide.

Before the design can start the insulation class of the equipment must be determined; whether the equipment will be class I (reliant on protective earth) or class II (not reliant on protective earth) as must the classification of the applied part if applicable.

Building Block	Means of Protection Provided
Protective Earth	1
Basic Insulation	1
Supplementary Insulation	1
Double Insulation	2
Reinforced Insulation	2

Applied parts are circuits that deliberately come into contact with the patient and are classified as type B, type BF or type CF each providing a degree of protection against electric shock.

Once this has been defined an insulation diagram can be constructed identifying the main circuit blocks such as primary circuits, secondary circuits and applied parts. It allows differing concepts to be analyzed to achieve the required means of protection. Overleaf is a typical isolation diagram for a power supply meeting the requirements of a BF and CF applied part. Isolation barrier 1 is contained within a standard 230 VAC - 12 VDC power supply. Isolation barrier 2 is contained within a 12V - 48V DC/DC converter.



Typical medical device with patient connection

Once it has been determined whether Means of Operator Protection (MOOP) or Means of Patient Protection (MOPP) is required the insulation schemes, corresponding separation distances and test voltages required can be specified. The tables below are taken from IEC60601-1:2005 for MOPP.

Minimum creepage distances and air clearances providing means of patient protection

Working Voltage VDC up to and including	Working Voltage V r.m.s up to and including	Spacing providing one Means of patient protection		Spacing providing two Means of patient protection	
		Creepage Distance mm	Air Clearance mm	Creepage Distance mm	Air Clearance mm
17	12	1.7	0.8	3.4	1.6
43	30	2	1	4	2
85	60	2.3	1.2	4.6	2.4
177	125	3	1.6	6	3.2
354	250	4	2.5	8	5
566	400	6	3.5	12	7
707	500	8	4.5	16	9
934	660	10.5	6	21	12
1061	750	12	6.5	24	13
1414	1000	16	9	32	18
1768	1250	20	11.4	40	22.8
2263	1600	25	14.3	50	28.6
2828	2000	32	18.3	64	36.6
3535	2500	40	22.9	80	45.8
4525	3200	50	28.6	100	57.2
5656	4000	63	36.0	126	72.0
7070	5000	80	45.7	160	91.4
8909	6300	100	57.1	200	114.2
11312	8000	125	71.4	250	142.8
14140	10000	160	91.4	320	182.8

Test voltages for solid insulation forming a means of protection

Peak Working Voltage (U) V peak	Peak Working Voltage (U) V d.c.	AC Test voltages in V r.m.s							
		Means of Operator Protection				Means of Patient Protection			
		Protection from Mains Part		Protection from Secondary Circuits		Protection from Mains Part		Protection from Secondary Circuits	
		1 Moop	2 Moop	1 Moop	2 Moop	1 Mopp	2 Mopp	1 Mopp	2 Mopp
U <42.4	U <60	1000	2000	No test	No test	1500	3000	500	1000
42.4 <U ≤71	60 <U ≤71	1000	2000	551-708	882-1133	1500	3000	750	1500
71 <U ≤184	71 <U ≤184	1000	2000	708-1000	1133-1751	1500	3000	1000	2000
184 <U ≤212	184 <U ≤212	1500	3000	1000-1189	1751-1902	1500	3000	1000	2000
212 <U ≤354	212 <U ≤354	1500	3000	1189-1494	1902-2390	1500	4000	1500	3000
354 <U ≤848	354 <U ≤848	1474-2225	3000	1494-2225	2390-3000	√2U + 1000	2 x (√2U +1500)	2√U + 1000	2 x (√2U + 1500)
848 <U ≤1414	848 <U ≤1414	2225-2868	3000	2225-2868	3000	√2U + 1000	2 x (√2U +1500)	2√U + 1000	2 x (√2U + 1500)
1414 <U ≤10000	1414 <U ≤10000	2868-10607	3000-10607	2868-10607	3000-10607	U/√2+ 2000	√2U+ 5000	U/√2+ 2000	√2U + 5000
10000 <U ≤14140	10000 <U ≤14140	1.06 x U/√2	1.06 x U/√2	1.06 x U/√2	1.06 x U/√2	U/√2+ 2000	√2U+ 5000	U/√2+ 2000	√2U + 5000
U >14140	U >14140	If necessary, to be prescribed by particular standards							

Leakage Current

Whether the product is considered MOOP or MOPP the leakage current requirements must be met. A further change between the 2nd and 3rd edition is related to the earth leakage current requirements. The table below is taken from 2nd edition and defines the required maximum leakage current values. It should be noted that UL60601-1 has an earth leakage current requirement of 300 µA under the 2nd edition.

Allowable values of continuous leakage and patient auxiliary currents, in milliamperes

Current		Type B		Type BF		Type CF	
		N.C.	S.F.C	N.C.	S.F.C	N.C.	S.F.C
Earth Leakage Current General		0.5	1 (1)	0.5	1 (1)	0.5	1 (1)
Earth Leakage Current for Equipment according to notes (2) & (4)		2.5	5 (1)	2.5	5 (1)	2.5	5 (1)
Earth Leakage Current for Equipment according to note (3)		5	10 (1)	5	10 (1)	5	10 (1)
Enclosure Leakage Current		0.1	0.5	0.1	0.5	0.1	0.5
Patient Leakage Current according to note (5)	DC AC	0.01 0.1	0.05 0.5	0.01 0.1	0.05 0.5	0.01 0.01	0.05 0.05
Patient Leakage Current (Mains voltage on the signal input part or signal output part)		-	5	-	-	-	-
Patient Leakage Current (Mains voltage on the applied part)		-	-	-	5	-	0.05
Patient Auxiliary Current according to note (5)	DC AC	0.01 0.1	0.05 0.5	0.01 0.1	0.05 0.5	0.01 0.01	0.05 0.05

N.C - Normal Condition
S.F.C - Single Fault Condition

(1) The only S.F.C for earth leakage current is the interruption of one supply conductor at a time.

(2) Equipment which has no protectively earthed accessible parts and no means for the protective earthing of other equipment and which complies with the requirements for the enclosure leakage current and for the patient leakage current, if applicable.

(3) Equipment specified to be permanently installed with a protective earth conductor which is electrically so connected that it can only be loosened with the aid of a tool and which is so fastened or otherwise so secured mechanically at a specific location that it can only be moved after the use of a tool.

(4) Mobile X-ray equipment and mobile equipment with mineral insulation.

(5) The maximum values for the AC component of the patient leakage current and of the patient auxiliary current specified in the table refer to the AC-only component of the currents.

In the 3rd edition the earth leakage current requirement specified in notes (2) & (4) has been relaxed to 5 mA in normal operation and 10 mA under a single fault condition. The requirements for touch current (formally enclosure leakage current) remain at 100 µA in normal operation and 500 µA under a single fault condition.

For a power supply in a class I system the key parameter is the single fault earth leakage current. An allowable single fault condition is to open the protective earth. In this instance earth leakage current becomes touch current.

• High Voltage Safety Testing

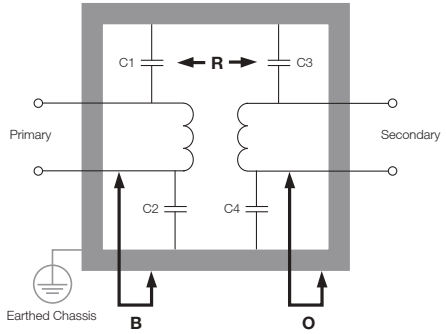
AC input power supplies are subjected to high voltage or hi-pot testing to verify the integrity of the insulation system employed. There are a number of types or classes of insulation required depending on the working voltage and the insulation class of the product which are well defined in the various safety standards. To test finished products requires care particularly with class I insulation systems where a protective earth is employed. Where class II insulation systems are employed the user may test to the specified primary to secondary isolation voltage.

Insulation Types

The diagram below shows a typical class I AC mains input power supply insulation system.

Between primary (AC input) and secondary (DC output) reinforced insulation is required
Between primary and earth basic insulation is required
Between secondary and earth operational insulation is required

Class I AC Power Supply Insulation System



R - Reinforced insulation

B - Basic insulation

O - Operational insulation

Test requirements for the power supply are categorized into two groups; type testing or design verification and production test.

Type tests are performed by the safety agency and are intended to prove that the construction of the power supply meets the requirements dictated by the relevant safety standard. For IT/Industrial products and medical products the type test requirements are as follows:

IT/Industrial	Primary to secondary	-	3000 VAC, or the equivalent DC voltage
	Primary to earth	-	1500 VAC, or the equivalent DC voltage
	Secondary to earth	-	No requirement provided the secondary voltage is less than 42.4 VAC or 60 VDC
Medical	Primary to secondary	-	4000VAC, or the equivalent DC voltage
	Primary to earth	-	1500VAC, or the equivalent DC voltage
	Secondary to earth	-	No requirement provided the secondary voltage is less than 42.4 VAC or 60 VDC

Production tests are performed during the manufacturing process and are intended to ensure integrity of safety critical insulation. Production line testing is conducted on both reinforced and basic insulation.

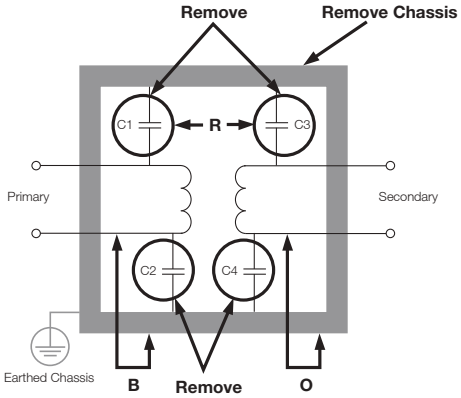
Reinforced insulation cannot be tested without over-stressing basic insulation on the end product. Safety agencies therefore allow manufacturers to test reinforced insulation separately during the manufacturing process meaning that transformers and other primary to secondary isolation barriers are tested prior to their incorporation into the product. Only primary to earth or basic insulation is tested on the final assembly prior to shipping each product.

Should a user or safety agency engineer require verification of the type tests on a complete power supply precautions must be taken to ensure that a correct result is achieved and the insulation is not damaged. Where basic insulation is to be verified no special considerations need to be taken and 1500 VAC can be applied from primary to earth. If the primary to secondary insulation is to be verified consideration must be made to how the test is performed.

Because only basic insulation exists between primary and earth and only operational insulation exists between secondary and earth applying 3000 VAC directly from primary to secondary on the finished product will over stress the primary to earth and secondary to earth insulation which may result in an apparent failure.

To test the reinforced insulation barrier the power supply needs to be removed from any earthed chassis and all paths to earth should be removed to ensure that basic and operational insulation barriers are not over stressed during the test. This entails removal of Y-capacitors and gas discharge tubes where used.

On many products not all potential paths can be removed. PCB's may utilize earth traces between primary and secondary while complying with creepage and clearance requirements. In some instances a breakdown or arcing may be observed between secondary and earth which can lead to component failure and render the power supply inoperable. This is a breakdown of operational insulation and does not indicate a failure of the reinforced insulation between primary and secondary that is the focus of the test.



Power Supply disassembly may be required for type testing

Type testing on a finished power supply may result in failure. It is difficult to isolate the test to the individual components and isolation barriers in question and this extends to testing performed once the product is installed in the end application. Over stressing components during these tests cannot always be avoided and if tests are performed incorrectly reliability may be affected.

• Electromagnetic Compatibility (EMC)

EMC describes how pieces of electrical and electronic equipment interact with each other when they act as either sources or receivers of noise. These two types of interaction are described as emissions and immunity.

Emissions

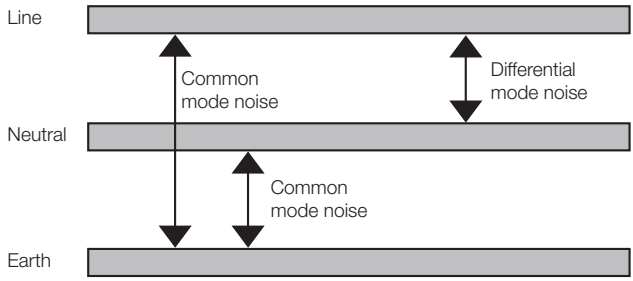
Emissions are electrical noise generated by the power supply or its electronic load and transmitted along the input and output cables as conducted noise or from the outer casing & cables as radiated noise. If left unchecked electrical noise could interfere with the correct and safe operation of nearby electrical equipment and it is therefore a requirement to restrict the amount of noise generated. The EMC directive was introduced in Europe in 1992 (89/336/EEC) and updated in 2004 (2004/108/EC) with the aim of imposing limits on the amount of noise that equipment can emit. In the USA, the limits are set by the FCC (Federal Communications Commission). VCCI (Voluntary Control Council for Interference by Information Technology Equipment) limits are the Japanese equivalent. In Asia the CISPR and FCC standards are widely accepted by the various approval bodies.

Conducted Noise

Conducted noise is that which travels along physical routes between pieces of equipment. We usually think of these paths as being the mains cables which can transmit noise generated by one piece of equipment along the mains supply (within an installation, a single building or even separate buildings) and which can then affect other pieces of equipment connected to the same mains system, or as the cables which directly connect one piece of equipment to another, such as DC cables or signal and control wires.

The noise takes one of two forms according to whether it is common to the ground system or exists between differing parts of the electrical circuit.

Common mode noise exists within different parts of the circuit and is common to the ground plane. On the mains input to a piece of electrical equipment it can be measured between the line conductor and the earth conductor, or between the neutral conductor and the earth conductor. Differential mode noise exists between parts of the circuit with different potentials. On the mains input to electrical equipment it can be measured between the line conductor and the neutral conductor.

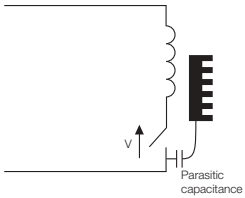


Differential Mode Noise

Differential mode noise is primarily generated by rapid changes in current. Within a switch mode power supply, the primary circuit is opened and closed by means of a switching device such as a BJT or MOSFET. The current flowing through the circuit goes through a continuous cycle of changing from a maximum value to zero and vice versa as the switch opens and closes. The rate of current change is very fast, perhaps in the order of 50 ns, and if the primary current was in the order of 1A, the change would be 1 A in 50 ns or put another way, 20 million A/s. The impedance of the printed circuit traces will be significant at current changes of this magnitude and unwanted voltages will be generated along the traces in the form of noise.

Common Mode Noise

Common mode noise is primarily generated by changes in voltage. The same switching device which is breaking the current in the primary circuit is also breaking a voltage. The voltage could be as high as 600 V and this may be being interrupted in the order of 50 ns meaning that there could be a voltage change rate of 12 V/ns or 12,000 million volts per second. The unwanted capacitance found around the switching element, for example between its case and the heatsink to which it is attached will be significant at these levels of voltage change and significant voltages in the form of noise will be generated.



Radiated Noise

Electrical noise can radiate from the enclosure or casing of the equipment and from its connecting cables. It will escape through the seams, ventilation slots, display areas and so on and travel in any direction through the air. In order to successfully propagate through air, the wavelength will be shorter than for conducted emissions meaning that frequencies will be higher. While conducted emissions are measured up to a frequency of 30 MHz, radiated emissions are typically measured up to 1 GHz.

Standards

In the US, EMC standards are written and enforced by the FCC. FCC 20870 covers both radiated and conducted noise. The FCC standard is harmonized with CISPR standards, and these are sometimes used instead to show compliance.

In Europe, the EMC directive does not define what the required levels are which need to be met so we must rely on international standards. There are three different types published. Product-specific standards define the allowable EMC performance of particular types of product. If a product-specific standard exists, then it MUST be used. Where a type of equipment doesn't have an associated product standard, generic standards can be used. As the term generic suggests, they contain requirements which cover many types of equipment and therefore some of the tests listed cannot be relevant or even adhered to. The product specific and generic standards refer to basic standards. These are the ones which define the exact test set up as well as the limits allowed. In Asia the CISPR and FCC standards are widely accepted.

CISPR Conducted Emission Limits

Class A limits (dBuV)

Frequency (MHz)	CISPR Limit	
	Quasi-peak	Average
0.15-0.5	79	66
0.5-30	73	60

Class B limits (dBuV)

Frequency (MHz)	CISPR Limit	
	Quasi-peak	Average
0.15-0.5	66-56[1]	56-46[1]
0.5-5	56	46
5-30	60	50

[1]Limit reduces with log frequency

CISPR Radiated Emission Limits

Class A limits (dBuV/m)

Frequency (MHz)	CISPR Limit
	10 m (Quasi-peak)[2]
30-230	40
230-1000	47
>1000 (average detector)	See note[1]

Class B limits (dBuV/m)

Frequency (MHz)	CISPR Limit
	10 m (Quasi-peak)[2]
30-230	30
230-1000	37
>1000 (average detector)	See note[1]

[1]For frequencies above 1000 MHz a 3 m, limit applies to equipment switching at a frequency >108 MHz. This does not usually apply to power supplies.

[2]3 m limits can also be applied using an inverse propotionality factor of 20 dB per decade.

For power supplies, the product-specific standard, IEC61204-3, takes precedence over the generic standards. For emissions, it defines the following basic standards:

CISPR22 for conducted emissions (maximum of level B)
CISPR22 for radiated emissions (maximum of level A)
IEC61000-3-2 for harmonic currents
IEC61000-3-3 for voltage flicker

Sometimes there are other basic standards which need to be applied. For example, EN55014 is applicable to motor operated household equipment, CISPR11 is applicable to industrial, scientific and medical equipment. These basic standards will be called into use by product family standards which may be applicable to end user equipment.

Methods of Measurement

Noise measurement techniques are defined by the relevant basic standard. The techniques will be generally similar whether it is an IT standard such as CISPR22 which is applicable or a military standard such as MIL 461 or DEF STAN 59-41.

Conducted Noise

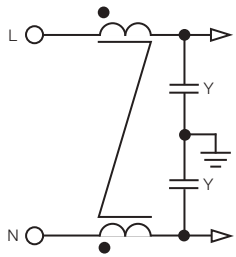
Conducted noise values will largely be dependent upon the local impedance of the mains system at the location at which the measurement is being done. Mains impedances will vary throughout a network and they could be vastly different throughout the world. A Line Impedance Stabilization Network (LISN), also known as an Artificial Mains Network (AMN) is used to give a defined mains impedance to the measurement system of 50 Ohms. In the case of the IT standard CISPR22, the noise will be measured from 150 kHz to 30 MHz and two readings must be taken. These are a quasi peak measurement and an average measurement. Both must be under their respective limit lines in order for the equipment to pass.

Radiated Noise

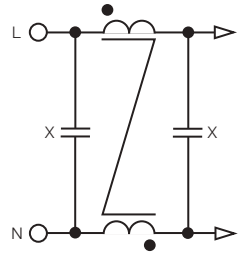
The services of a dedicated test house will normally be required to measure radiated noise. This is because the test should be performed on a large area known as an Open Area Test Site (OATS) which will not only be free of reflecting surfaces but will also be calibrated so that the influence of any reflections from far away is known as the reflections will either add to the original signal, or detract from it depending upon the phase shift of the reflection. The measuring equipment will consist of an antenna which will feed into a receiver. The emissions from all sides of the equipment must be taken and for each face the antenna will be moved between heights of one and four meters to obtain the worst case reading. In addition to this, the antenna will be positioned with its elements alternately horizontal and vertical, again to obtain the worst case reading. As this setup is impractical for most companies, alternative techniques are normally used to give an indication of the radiated emissions. This may consist of using near field probes to ‘sniff’ around the enclosure of the equipment or using conducted emission techniques to measure at frequencies into the hundreds of MHz band. This is a relevant test as it will often be the cables themselves that are the source of the radiation.

EMC Filtering

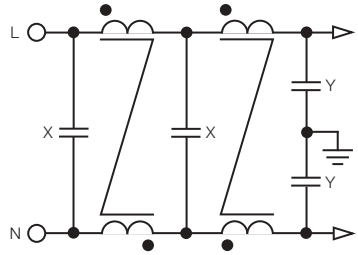
A power supply or DC/DC converter will have an in-built input filter to reduce the conducted emissions. It will have two parts; one to reduce the common mode noise, the other to reduce the differential mode noise. Common mode noise can be reduced by use of Y capacitors between line and ground and another one between neutral and ground in conjunction with a common mode inductor.



Differential mode noise can be reduced by use of an X capacitor between the line and the neutral in conjunction with a differential mode inductor. In some instances the differential mode inductor is formed from the leakage inductance of the common mode inductor so that there is only one visible wound component.



When combined the resulting filter may look like this:



Sometimes the built-in filter will give an inadequate performance for a given application. This may be where the power supply is designed to meet the lesser requirements of an industrial environment but is being used in the more stringent light industrial or residential environment. Perhaps several power supplies are being used in a single piece of equipment and the resulting emissions must be reduced, or perhaps noise from the load itself is being coupled into the input of the power supply. In all these instances some form of external filtering will be required.

Filter Selection

There are some basic steps to follow when choosing a filter, some of which are straightforward and others less so.

Mechanical format — Is the filter going to be mounted within the equipment where it can be fixed to a panel or should it also provide the extra functions of being the mains input connector and perhaps contain an on/off switch? If it is the former, a chassis mount filter can be used. These will generally have faston terminals for easy connection but may also come with flying leads. IEC inlet filters can have built-in on/off switches and even fuse holders. They can be mounted by either screwing them down to the equipment or by use of self locking lugs. Generally, for metal chassis equipment, the bolt-down variety will provide a lower impedance earth path for the circulating noise down to ground.

Input current	The filter should be able to pass the maximum working current of the equipment so as not to overheat but generally the lower the current capacity within a filter series, the higher its filtering performance.
Attenuation required	A filter will be required to reduce the noise at certain frequencies. By how much and at which frequencies is information which will not readily be known without having first performed a conducted noise measurement. Filters have differing amounts of attenuation and, for a given current rating, the higher the attenuation the larger the filter. As there will be a practical limit on the size of filter components, large amounts of attenuation will require the use of multi-stage filters.

Immunity

Immunity is concerned with how a piece of equipment will behave when subject to external electrical or magnetic influences in the form of noise. The noise will exist as either conducted or radiated noise and will be from natural sources such as lightning, electrostatic build up or solar radiation or may be from man made sources such as radio or mobile phone transmissions, commutation noise from electrical motors or emissions from power supplies and other switching devices.

Conducted Immunity Phenomena

A power supply or piece of electrical equipment will be subject to conducted noise either via the mains connection, a DC output or via the signal and control lines. The noise could take various forms from brown-outs of the mains, to single short duration but high voltage spikes, to RF frequency noise coupled into the cables and conducted into the equipment.

Radiated Immunity Phenomena

Noise can also directly enter a system via the air in the form of electrical or magnetic fields. The field is picked up by the cables attached to a piece of equipment or by the internal PCBs themselves and can be in the form of electromagnetic fields generated by a mobile phone or the magnetic field generated from a nearby transformer.

Standards

The product standard for power supplies, EN61204-3, lists all of the basic immunity standards that are applicable to a power supply. These are listed below. For each type of test there are two important factors: the test severity level and the performance criteria which defines how the equipment operates while the test is being carried out.

Performance criteria A	There is no change in operating status of the equipment. For a power supply this means that it will continue to operate and no signals will change state.
Performance criteria B	There is a loss of function while the test is being applied, but when the test stops, the operating parameters automatically return to normal. For a power supply, this means that the output may go out of regulation and signals may change state but only during the test.
Performance criteria C	There is a loss of function while the test is being applied and a manual reset or intervention is required to restore the original operating parameters.

Electrostatic discharge: IEC61000-4-2

There are three types of test specified in the standard; contact discharge, air discharge and discharge onto a coupling plane. The test is to simulate the effect of a person charging themselves up (to many kV) and then touching either the equipment directly or adjacent equipment which could in turn affect the equipment's behavior. For open frame power supplies, this test is not normally applicable but for other power supplies, the pass conditions are ±4 kV for contact discharge and ±8 kV for air discharge and coupling plane discharge, all with minimum performance criteria B.

RF electromagnetic field: IEC61000-4-3

This test simulates the fields given off by mobile phones and DECT phones. The field is generated by a sweeping signal generator with a 1 kHz modulation function. The signal is amplified and radiated using an antenna. The field strengths are high enough and in the frequency band (80 MHz to 1 GHz) to prevent local radio and TV stations and more importantly emergency services communications from working so the test must be performed in a screened chamber. For power supplies intended to operate in a light industrial or residential environments, the field strength is 3 V/m but for industrial power supplies the required field strength is 10 V/m. Minimum performance criteria is B in both cases.

Electrical fast transients: IEC61000-4-4

This test is to simulate switching transients generated by motor or solenoid activation or perhaps from fluorescent lighting. The pulse is very short, only 50ns with a 5ns rise time and is applied between the two lines and the earth. Generally, the test is only applied to the AC input as the DC lines and the signal and control lines on a power supply are normally too short. For power supplies intended to operate in light industrial or residential environments the pulse is ±1 kV but for industrial power supplies the required pulse is ±2 kV. Minimum performance criteria is B in both cases.

Voltage surge: IEC61000-4-5

This test is to simulate the effects of a near lightning strike. The duration and energy content of the pulse are much greater than for the electrical fast transients test with the duration being 50 µs with a 1.2 µs rise time. The pulse is applied between each line and earth and also between lines themselves. For power supplies the pulse is ±2 kV common mode, ±1 kV differential, with a minimum of performance criteria B in both cases.

RF conducted: IEC61000-4-6

This test is similar to the RF radiated electromagnetic field test and must be applied under similar conditions within a screened chamber though the frequency range is 150 kHz to 80 MHz. For power supplies intended to operate in a light industrial or residential environments, the coupled noise is 3 Vrms but for industrial power supplies the coupled noise is 10 Vrms. Performance criteria B is the minimum applicable in both cases.

Voltage dips and interruptions: IEC61000-4-11

A voltage dip represents the brown-out conditions experienced from time to time on the power grid, while a voltage interruption represents a complete black out condition. There are 3 parts to the test; a 30% dip for 10 ms with minimum performance criteria B, a 60% dip for 100 ms with minimum performance criteria C and a >95% interruption for 5 seconds with minimum performance criteria C.

• CE Marking

CE marking within Europe was established as a means of identifying a product as meeting all the relevant European directives. These directives have been introduced as a way of allowing free trade within the EU member states as individual members are no longer allowed to prevent trade on technical grounds. By displaying the CE mark, the product is identified to customs and border controls as complying with the necessary directives. There are many directives which are applicable for CE marking and these include:

- Low voltage equipment
- Restriction of hazardous substances (RoHS)
- Toys
- Electromagnetic compatibility
- Personal protection equipment
- Active implantable medical devices
- Hot water boilers
- Medical devices
- Recreational craft
- Refrigeration appliances
- Telecommunications terminal equipment
- Radio & telecommunications terminal equipment
- Simple pressure vessels
- Construction products
- Machinery
- Non automatic weighing machines
- Gas appliances
- Civil explosives
- Potentially explosive atmospheres
- Lifts
- Pressure equipment
- In vitro diagnostic medical devices

For component power supplies only the Low Voltage Directive (LVD) and restriction of hazardous substances (RoHS) are applicable. For external power supplies the EMC directive and the Energy Related Products (ErP) directive also apply.

Low Voltage Directive (LVD) 2006/95/EC

The LVD is applicable to equipment designed for use with a voltage rating of between 50 and 1000 VAC and between 75 and 1500 VDC. The directive itself does not define how to comply with it but by conforming to one of the relevant standards, such as the IT safety standard EN60950, compliance is demonstrated. The route to compliance is by generating a Technical Construction File (TCF) which includes the following:

- General description of the electrical equipment
- Conceptual design and manufacturing drawings
- Description and explanation of these designs and drawings
- Listing of the product standards used as safety reference
- Results of design calculations and examinations
- Test reports

Electromagnetic Compatibility (EMC) Directive 2004/108/EC

This directive is applicable to apparatus liable to cause electromagnetic disturbance or the performance of which is liable to be affected by such disturbance. Again, the directive does not state how compliance should be achieved, but there are two routes to compliance. The first is the standards route whereby the product is tested against either product specific or generic standards. The second is the technical construction file route. This would be chosen where a piece of equipment may be too large to undergo testing, or it may be that some of the tests are just not relevant. The arguments for this would be laid down in the TCF which would be assessed and signed off by a competent body.

Energy Related Products Directive (ErP) 2009/125/EC

The ErP (formerly known as EuP) Directive provides a framework for setting eco-design requirements for energy related products. Commission regulation No 278/2009 implements the directive for external power supplies with regard to no load power consumption and active efficiency based on the quantity sold within the EU and the end application.

Restriction of Hazardous Substances (RoHS) 2011/65/EU

The Restriction of Hazardous Substances Directive 2011/65/EU, also known as RoHS II, entered into force in July 2011 and became a CE marking directive at the same time. This directive restricts the use of hazardous materials in electronic and electrical equipment. It is closely linked with the Waste Electrical and Electronic Equipment Directive (WEEE) 2002/96/EC which sets collection, recycling and recovery targets for electrical goods.

Declaration of Conformity (DofC)

The CE mark must be accompanied by a declaration of conformity. This will list:

- Name & address of the manufacturer
- Description of the equipment
- Reference to harmonized product standards used
- Name of the signatory and their position
- Last two digits of the year in which the CE marking was affixed

This is a self declaration that the manufacturer (or person who places the product on the market in the EU) has taken all necessary steps to ensure compliance with all the relevant directives.

The Low Voltage and RoHS directives relate to open frame, component and external power supplies. The EMC Directive also relates to external power supplies. The ErP Directive relates to external power supplies sold in high volumes within the EU for office equipment and consumer electronics applications. The CE mark on an open frame or component power supply shows that it complies to the LVD and RoHS, the CE mark on an external power supply shows that it complies with the LVD, RoHS and EMC Directives and where applicable the ErP Directive.

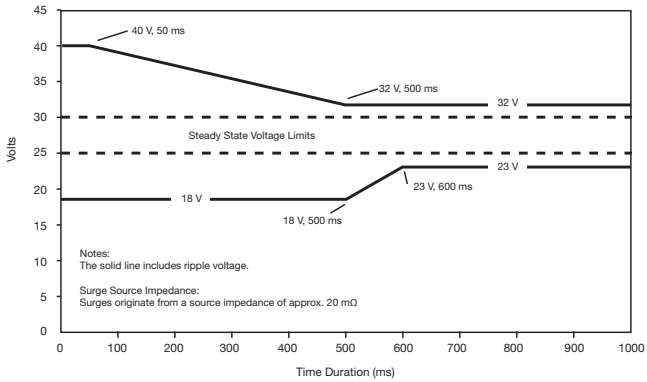
• Defense and Avionics EMC Standards

For power supplies operated in these environments there are standards maintained by government or international organizations such as the US Department of Defense (MIL-STD), the UK Ministry of Defense (DEF STAN), the French military (GAM-EG) & NATO (STANAG). Many countries use the MIL-STD series of standards maintained by the US Department of Defense, but have national deviations covering specific conditions or equipment used by their armed forces. EMC standards are typically organized by service (air force, army, navy etc.), environment (above and below deck for example), test details, equipment and specification limits. There are standards covering immunity, conducted emissions and radiated emissions. The key elements for power supplies are the conducted immunity and conducted emissions standards which are discussed below. MIL-STD 1275, MIL-STD 704 & DEF STAN 61-5 are commonly used immunity standards. MIL-STD 1275 covers requirements for military vehicle applications, MIL-STD 704 covers military aircraft applications and DEF STAN 61-5 covers military vehicles, naval vessels and aircraft.

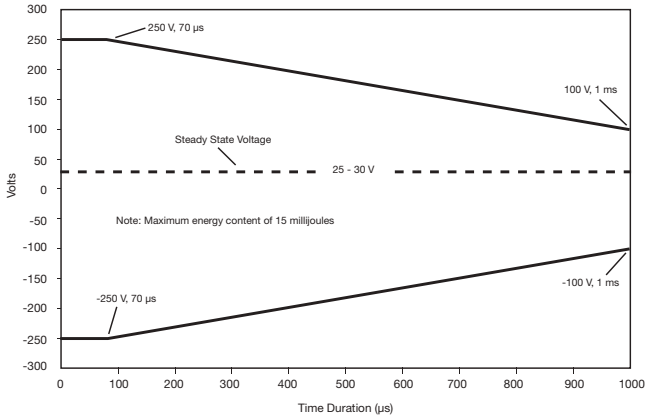
Within the susceptibility standards there is no pass or fail criteria for the power system as this is up to the user to define. If a power supply is damaged by a surge then it would be considered a failure but a power supply showing higher level of output ripple during a conducted susceptibility test may be acceptable to the end equipment and deemed to pass. Typical susceptibility tests cover abnormal operating voltages which may be created by generator only supplies or emergency power, voltage surges, voltage spikes & voltage drop outs. The tables and graphs following outline some of the key criteria for 24/28 V nominal supplies.

MIL-STD 1275-D Normal Operating Mode

Test	Voltage	Duration	Polarity	Notes
Steady State	25-30 VDC	Infinite	Positive	20 mΩ source impedance
Normal Operation Surge	40 VDC	50 ms	Positive	20 mΩ source impedance
Normal Operation Surge	32 VDC	500 ms	Positive	20 mΩ source impedance
Normal Operation Brown Out	23 VDC	600 ms	Positive	20 mΩ source impedance
Normal Operation Brown Out	18 VDC	500 ms	Positive	20 mΩ source impedance
Normal Operation Spike	250 VDC	70 µs	Positive & Negative	50 Ω in parallel with 5 µH
Normal Operation Spike	40 VDC	1 ms	Positive & Negative	50 Ω in parallel with 5 µH



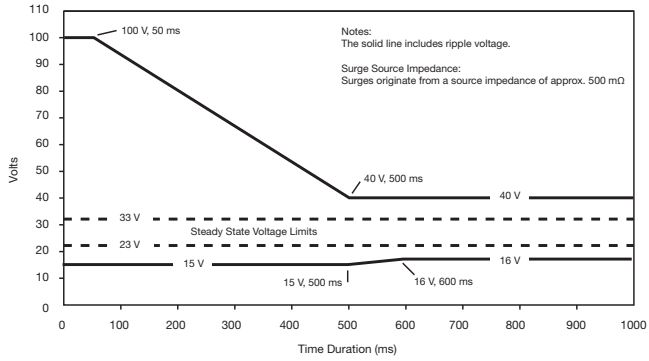
Envelope of surges in normal operating mode for 28 VDC systems



Envelope of spikes in normal operating mode for 28 VDC systems

MIL-STD 1275-D generator only operating mode

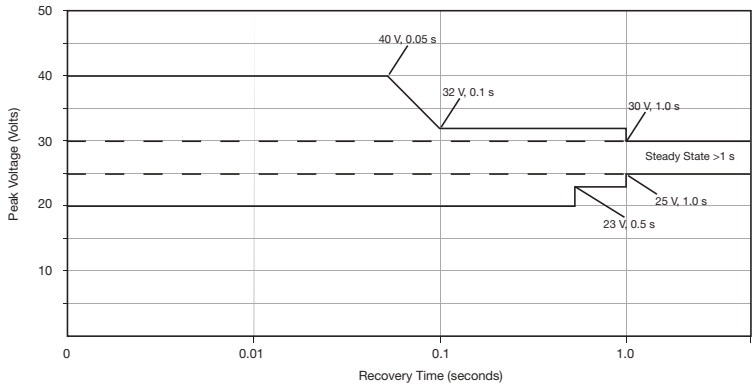
Test	Voltage	Duration	Polarity	Notes
Steady State	23-33 VDC	Infinite	Positive	Generator only operation
Generator Only Surge	100 VDC	50 ms	Positive	500 mΩ source impedance
Generator Only Surge	40 VDC	500 ms	Positive	500 mΩ source impedance
Generator Only Brown Out	15 VDC	500 ms	Positive	500 mΩ source impedance
Generator Only Brown Out	16 VDC	600 ms	Positive	500 mΩ source impedance
Generator Only Spike	100 VDC	1 ms	Positive & Negative	50 Ω in parallel with 5 µH



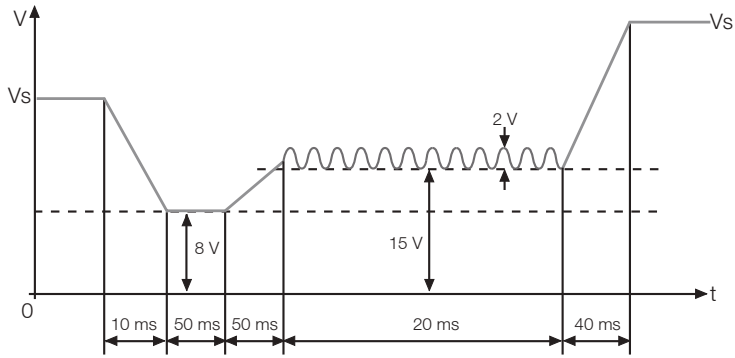
Envelope of surges in generator only mode for 28 VDC systems

DEF STAN 61-5 pt 6

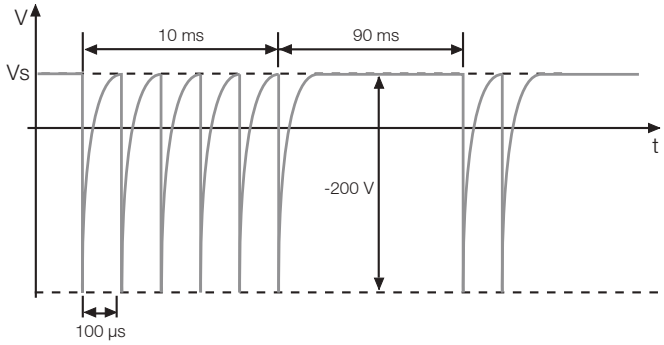
This standard specifies the voltages present in a 12 V or 24 V vehicle system or platform. It also specifies the voltages expected to be presented to any equipment (Terminal). The following graphs outline the requirements for a 24 V terminal system.



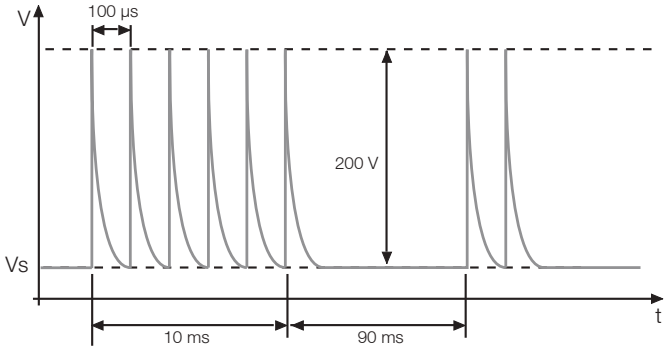
Envelope of spikes in normal operating mode for 28 VDC systems



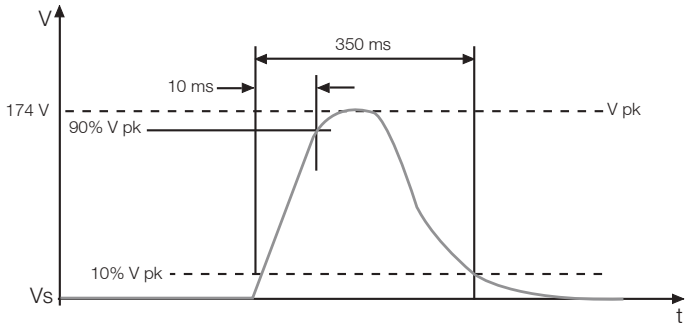
Typical Test Configuration



Negative Test Pulse - Pulse Train A



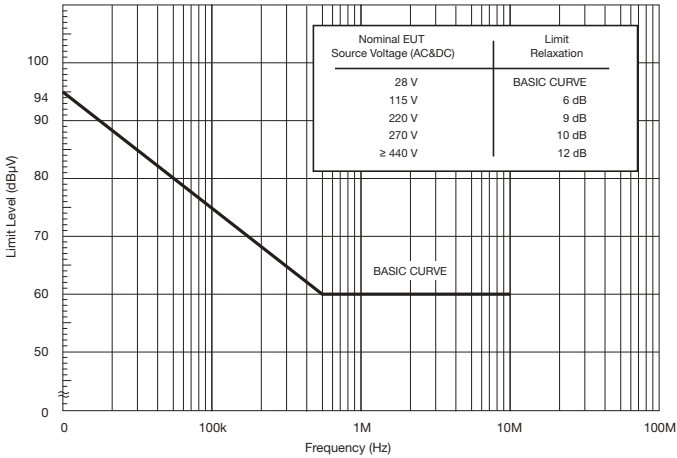
Positive Test Pulse - Pulse Train B



Surge (Load Dump)

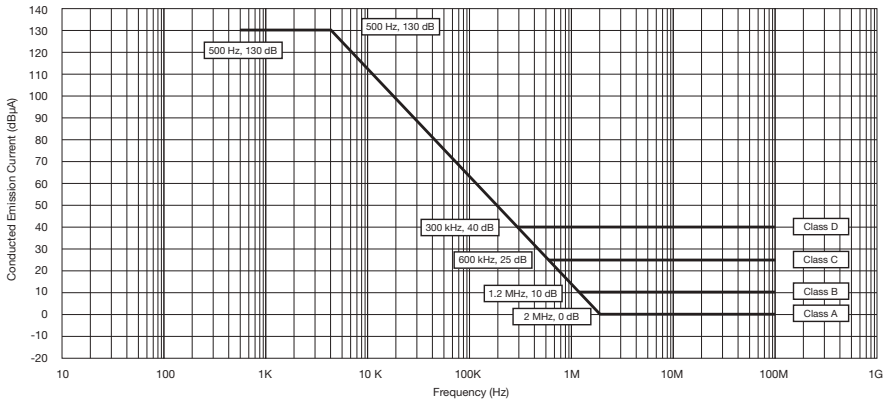
Conducted Emissions

MIL-STD 461F is commonly specified for conducted emissions and, in the UK, DEF STAN 59-41 and more recently DEF STAN 59-411 is required. The test requirements for these standards are quite different using different Line Impedance Stabilization Networks and different measurement or detection techniques.



MIL-STD 461F conducted emissions limits

For a 28 V system the basic curve is used and as the supply voltage increases relaxation factors are employed.



DEF STAN 59-41 & 59-411 limits for land service use

The limit (class A, B, C or D) is defined by the specific application.

• Power systems for railway applications

Rail applications demand that equipment is able to withstand the harsh climatic, mechanical and electrical environments encountered on traction vehicles and rolling stock. Electronic equipment, from lighting through passenger information and entertainment, to control, safety & engine management systems require DC/DC power conversion and must perform safely and reliably.

Within Europe, many countries historically developed their own national rail standards such as the BRB/RIA standards commonly used in the UK and the NF F 01-510 for applications in France. With the privatization of national rail companies, and the general move to harmonization of national standards within the European Union, two standards for electronic equipment (EN50155 & EN50121) have largely replaced the older national standards, though the older national standards are still occasionally required and cannot be entirely dismissed.

EN50155: 2007

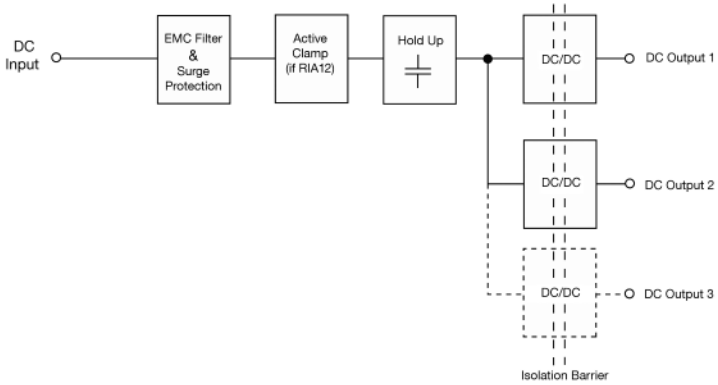
The most frequently cited design specification is the European Norm EN50155 “Electronic Equipment used on Rolling Stock”. The key elements when considering the selection of DC/DC converters and power sub-assemblies are:

- **Power Supply**

  - Variation
  - Interruptions
  - Surges, electrostatic discharge (ESD) and transient burst
  - Electromagnetic compatibility (EMC)

- **Environmental Service Conditions**

  - Ambient temperature
  - Relative humidity
  - Shock and Vibration



DC/DC converter block schematic for railway applications

Power Supply

Electronic systems & apparatus used within the railway environment experience a wide variation in input supply with brownout operation, transients and spikes. They also typically require continuous operation through supply interruptions up to 10 ms that must be catered for in the equipment design. The UK national standard BRB/RIA12 “General Specification for Protection of Traction and Rolling Stock from Transients and Surges in DC Control Systems” requires a specific surge withstand of 3.5x nominal voltage for 20 ms that typically results in an additional active clamp filter to be fitted to protect downstream DC/DC converters.

The table below details, for each of the nominal input voltages used within the industry, the input ranges, brownouts and transients that must be met to comply with EN50155 and compares this with the national BRB/RIA12 & NF F 05-510 standards.

Continuous Input Range, Brownout and Transient Requirements						
Standard	Nominal Input (Vnom)					Specification
	110	96	72	48	24	
EN50155	77.0-137.5 V	67.2-120.0 V	50.5-90.0 V	33.6-60.0 V	16.6-30.0 V	Continous range 0.7-1.25 x Vnom
	66.0 V	57.6 V	43.2 V	28.8 V	14.4 V	Brownout 100 ms 0.6 x Vnom
	154.0 V	134.4 V	100.8 V	67.2 V	33.6 V	Transient 1s 1.4 x Vnom
NF F 05-5110	77.0-137.5 V		50.0-90.0 V		18.0-34.0 V	Continuous range
	55.0 V		36.0 V		12.0 V	Brownout 100 ms 0.5 x Vnom
	176.0 V		115.0 V		40.0 V	Transient 100 ms
BRB/RIA12	77.0-137.5 V	67.2-120.0 V	50.4-90.0 V	33.6-60.0 V	16.6-30.0 V	Continuous range 0.7-1.25 x Vnom
	66.0 V	57.6 V	43.2 V	28.8 V	14.4 V	Brownout 100 ms 0.6 x Vnom
	165.0 V	144.0 V	112.5 V	72.0 V	36.0 V	Transient 1s 1.5 Vnom
	385.0 V	336.0 V	252.0 V	168.0 V	84.0 V	Transient 20 ms 3.5 x Vnom

Surges, ESD, transient burst & EMC are referenced to the EN50121-3-2:2006 “Electromagnetic compatibility – Rolling stock – Apparatus” standard.

EN50121

EN50121 is a set of standards that specify the limits for electromagnetic emissions of the railways to the outside world, and the electromagnetic emission and immunity for equipment working within the railways. EN50121-3-2:2006 defines the electromagnetic compatibility requirements for rolling stock apparatus. The older national standards have differing requirements from those defined in EN50121 above, which need to be considered separately where these standards are required.

A summary of the conducted emissions & conducted immunity levels are given in the tables below:

Conducted Emissions	
Frequency Range	**Specification**
9 kHz-150 kHz	No limit
150 kHz - 500 kHz	99 dBuV quasi peak
500 kHz - 30 MHz	93 dBuV quasi peak

Conducted Immunity				
Environmental Phenomenon	**Specification**		**Reference Standard Performance Criteria**	
Surges	1.5/50 µs ±1 kV 42 Ω 0.5 µF ±2 kV 42 Ω 0.5 µF	Line to Line Line to Ground	EN61000-4-5	B
Fast Transient Burst	5/50 ns 5 kHz ±2 kV	Tr/Th Repetition freq Peak	EN61000-4-4	A
Radio Frequency Common Mode	0.15 MHz-80 MHz 80% AM, 1 kHz 10 Vrms	Unmodulated Carrier	EN61000-4-6	A
Electrostatic Discharge	±6 kV ±8 kV	Contact Air	EN61000-4-2	A

Performance Criteria Definitions

Criteria A: The apparatus shall continue to operate normally during and after the test, no degradation of performance.

Criteria B: Indicates that normal operation will resume after the test and that their may be a loss of performance during the test.

DC/DC converters and sub assemblies are normally considered as a component while the standards apply to the finished product intended for installation on the rolling stock. Products designed for rail applications are independently evaluated against these requirements though emissions, susceptibility and ESD must be re-evaluated on the final equipment

Environmental

Four grades of operating temperature are specified within EN50155, which are further divided in to internal cubicle temperature, cubicle over temperature & ambient PCB temperature as shown in the table overleaf.

Class	Ambient Temperature outside vehicle	Internal cubicle temperature	Additional cubicle temperature during 10 minutes overtemperature	Air temperature surrounding the PCB assembly
T1	-25 °C to +40 °C	-25 °C to +55 °C	+15 °C	-25 °C to +70 °C
T2	-40 °C to +35 °C	-40 °C to +55 °C	+15 °C	-40 °C to +70 °C
T3	-25 °C to +45 °C	-25 °C to +70 °C	+15 °C	-25 °C to +85 °C
TX	-40 °C to +50 °C	-40 °C to +70 °C	+15 °C	-40 °C to +85 °C

Relative Humidity

Electrical equipment shall be designed for the relative humidity stress limits over the external enclosure temperature ranges defined above as follows:

- Yearly average with ≤ 75% relative humidity
- 30 days per year consecutively with a 95% relative humidity

Mechanical

Equipment used on or close to rolling stock will be subject to a constant vibration of varying frequency and magnitude. DC/DC converters and subassemblies are typically robust in their construction but their mounting in the end apparatus needs careful consideration, as they are likely to be among the heavier components.

EN50155, and the older national standards, specify the levels electrical equipment must comply with depending on its location within the vehicle. EN50155 references EN61371:2010 to define the severity of the tests. There are 3 categories within EN61371 as follows.

- Category 1: Body Mounted
  - -Class A: Cubicles, sub assemblies, equipment and components mouted directly on or under the car body.
  - -Class B: Anything mounted inside an equipment case which is in turn mounted directly on or under the car body.
- Category 2: Bogie Mounted
- Category 3: Axle Mounted

Test levels become more severe from category 1 to category 3 for both shock and vibration.

• No Load Power Consumption and Efficiency Legislation for External Power Supplies

Two important reasons for controlling the power consumed by external power supplies are continuity of the energy supply and reduction of environmental impacts. Targets are given for external supplies because high quantities are sold, they normally do not have an off button and they are commonly left plugged into the mains supply when not in use. Many areas of the world have introduced limits for no load power consumption and active efficiency of external power supplies. In the US there are three main parties, these being: California Energy Commission (CEC), US Congress with its Energy Independence and Security Act (EISA), both of which are mandatory and finally Energy Star which is voluntary. In Europe there is the Energy related Products (ErP) Directive formerly known as the Energy using Products (EuP) Directive, which is mandatory.

There is also the EU Code of Conduct for external power supplies which is voluntary. Other parts of the world that are enacting legislation are mainly basing their limits on previous Energy Star requirements.

The tables within Summary of Limits show the limits imposed by the five bodies. The average efficiency is taken as the mean of individual efficiencies at 25%, 50%, 75% and 100% loads. The EU Code of Conduct introduces a 10% load efficiency requirement to address applications which spend significant periods in low power or idle modes.

Energy Independence & Security Act 2007 (EISA)

In 2007 the US Congress passed a law effective 1st July, 2008, called the Energy Independence and Security Act of 2007 (EISA). This states that single output external power supplies of less than 250 W manufactured on or after 1st July 2008 should meet maximum no load power consumption, and minimum active load efficiency limits with an input of 115 VAC, 60 Hz. These requirements are identical to the 1st July, 2008 CEC limits meaning that any power supply meeting efficiency level IV will comply with the EISA requirements. There are four exceptions included in the EISA legislation:- The power supply is to be used in an application requiring Federal Food and Drug Administration listing and approval as a medical device. The power supply is charging either a detachable battery pack or the internal battery pack of a product which is primarily motor operated. The power supply is to be used for spares for a product that was manufactured before 1st July, 2008. The power supply is to be subsequently exported outside of the US.

ErP Directive 2009/125/EC

This is a framework Directive for the setting of eco-design requirements for energy related products. Parts of this are being enacted separately and there is a Commission Regulation No 278/2009 of 6th April 2009 which implements the Directive with regard to no load power and active efficiency of external power supplies. Article 15, paragraph 2(a) of the Directive states that the volume of sales should be indicatively more than 200,000 units per year within the EU. Paragraph 2 of the Commission Regulation defines that it is external power supplies used in office equipment and consumer electronics which are covered by the Directive.

California Energy Commission (CEC) Appliance Efficiency Regulations

Before the US Congress passed the EISA in 2007 the requirement for meeting energy efficiency targets for external power supplies in the USA was largely voluntary except for in California where state law had made it mandatory. The EISA requirements are based on the CEC limits so both are the same.

Energy Star

Energy Star is a body which promotes energy efficiency through use of the Energy Star logo. Product which meets the minimum requirements can have the blue star logo applied. For external power supplies this is not allowed. Meeting the Energy Star requirements is voluntary but there is increasing legislation around the world basing mandatory requirements on the Energy Star limits.

Summary of Limits

Energy Star (10th Feb 2016)

No load power limits	
Rated power	No load consumption
0 W to ≤1 W	≤0.1 W
>1 W to ≤49 W	≤0.1 W
>49 W to ≤250 W	≤0.21 W
>250 W	≤0.5 W

Active mode efficiency, O/P < 6 V	
Rated power	Average efficiency
0 W to ≤1 W	≥0.517 x Pout + 0.087
>1 W to ≤49 W	≥0.0834 x Ln (Pout) - 0.0014 x Pout + 0.609
>49 W to ≤250 W	≥0.87
>250 W	≥0.875

Active mode efficiency, O/P ≥ 6 V	
Rated power	Average efficiency
0 W to ≤1 W	≥0.5 x Pout + 0.16
>1 W to ≤49 W	≥[0.071 x Ln (Pout) - 0.0014 x Pout] + 0.67
>49 W to ≤250 W	≥0.88
>250 W	≥0.875

EU Code of Conduct (Jan 1st 2014 and Jan 1st 2016)

No load power limits		
Rated power	No load consumption	
	Tier 1 (1st Jan 2014)	Tier 2 (1st Jan 2016)
0 W to ≤1 W	≤0.15 W	≤0.075 W
>1 W to ≤49 W	≤0.15 W	≤0.075 W
>49 W to ≤250 W	≤0.25 W	≤0.15 W

Active mode efficiency, O/P < 6 V		
Rated power	Average efficiency	
	Tier 1 (1st Jan 2014)	Tier 2 (1st Jan 2016)
0 W to ≤1 W	≥0.51 x Pout + 0.085	≥0.517 x Pout + 0.087
>1 W to ≤49 W	≥[0.0755 x Ln (Pout)] + 0.585	≥0.0834 x Ln (Pout) - 0.0014 x Pout + 0.609
49 W to ≤250 W	≥0.88	≥0.88

Active mode efficiency, O/P ≥ 6 V		
Rated power	Average efficiency	
	Tier 1 (1st Jan 2014)	Tier 2 (1st Jan 2016)
0 W to ≤1 W	≥0.5 x Pout + 0.145	≥0.5 x Pout + 0.16
>1 W to ≤49 W	≥[0.0626 x Ln (Pout)] + 0.645	≥[0.07 x Ln (Pout) 0.0014 x Pout] + 0.67
49 W to ≤250 W	≥0.89	≥0.89

EU Code of Conduct (Jan 1st 2014 and Jan 1st 2016)

10% Efficiency Requirement, O/P <6 V		
Rated power	10% Efficiency Requirement	
	Tier 1 (1st Jan 2014)	Tier 2 (1st Jan 2016)
0 W to ≤1 W	≥0.5 x Pout	≥0.517 X Pout
>1 W to ≤49 W	≥[0.0755 x Ln (Pout)] + 0.485	≥0.0834 X Ln (Pout) - 0.0014 x Pout + 0.509
49 W to ≤250 W	≥0.78	≥0.78

10% Efficiency Requirement, O/P ≥ 6 V		
Rated power	10% Efficiency Requirement	
	Tier 1 (1st Jan 2014)	Tier 2 (1st Jan 2016)
0 W to ≤1 W	≥0.5 x Pout + 0.045	≥0.5 x Pout + 0.06
>1 W to ≤49 W	≥[0.0626 x Ln (Pout)] + 0.0545	≥[0.071 x Ln (Pout)] - 0.0014 x Pout] + 0.57
49 W to ≤250 W	≥0.79	≥0.79

Energy Star (Nov 1st, 2008) & ErP (April 2011)

No load power limits	
Rated power	No load consumption
0 W to <50 W (≤ 51 W)	0.3 W
≥50 W to 250 W (> 51 W)	0.5 W

Active mode efficiency, O/P < 6 V	
Rated power	Average efficiency
0 W to 1 W	≥ 0.497 x rated power + 0.067
>1 W to ≤49 W (≤ 51 W)	≥[0.0750 x Ln(Rated power)] + 0.561
>49 W (>51 W)	≥ 0.86

Active mode efficiency, O/P ≥ 6 V	
Rated power	Average efficiency
0 W to 1 W	≥ 0.48 x rated power + 0.14
>1 W to ≤49 W (≤51 W)	≥[0.0626 x Ln(Rated power)] + 0.622
>49 W (>51 W)	≥ 0.87

Figures in ( ) are for ErP limits

In addition, Energy Star power supplies with an input power of 100 W and above must have minimum power factor of 0.9 at 115 VAC 60 Hz.

California Energy Commission (July 1st, 2008 limits), EISA (2007 limits) & ErP (April 2010 limit)

No load power limits	
Rated power	No load consumption
All	≤0.5W

Active mode efficiency	
Rated power	Average efficiency
0 W to 1 W (<1 W)	≥0.5 x Rated power
>1 W to 49 W (≤51 W)	≥[0.09 x Ln(Rated power)] + 0.5
>49 W (>51 W)	≥0.85

Figures in ( ) are for ErP limits

Measurement Technique

The US Environmental Protection Agency (EPA) has devised a procedure for measuring the no load power consumption and active mode efficiency of external supplies. This procedure has been adopted as an acceptable test method to demonstrate compliance with Energy Star, California Energy Commission, EISA and the ErP. The document can be found on the www.energystar.gov website and is titled "Test Method for Calculating the Energy Efficiency of Single-Voltage AC-DC and AC-AC Power Supplies" and is dated 11th August, 2004. This document sets out a standardized test method including test room conditions, accuracy of measuring instruments, quality of applied mains voltage and accuracy of load conditions. The document also details the information that is required for the test report.

Marking Requirements

To demonstrate compliance with the Energy Star and CEC requirements a mark must be placed on the product. The mark is made up of a Roman numeral which, at the time of writing, should be a minimum of IV to show compliance with current requirements of CEC, EISA, a V to show ErP compliance and a VI to show compliance with the latest Energy Star criteria.

While it is apparent that not all applications and equipment that utilize external power supplies need to comply with these environmental standards, external power supply designs are being constantly upgraded to meet the latest no load power consumption and active efficiency standards. Very low standby power component power supplies with ever increasing efficiency are also being introduced by the leading manufacturers to support energy efficiency in all types of equipment.

• Energy Efficiency of Component Power Supplies

There is no current legislation for energy efficiency in component power supplies though end equipment using these supplies may well need to comply with product specific energy efficiency standards. The latest power supply designs minimize no load power consumption and maximize active efficiency by employing the green mode techniques outlined on pages 12 -15 of this guide.

The size or power density of a power supply are key criteria when selecting the optimum product for the end application. In convection cooled applications, where fans are not desirable due to audible noise, reliability or service concerns, efficiency becomes a primary concern.

AC/DC power supply technology has evolved to a point where efficiencies in the 90 - 95% range are available and, by considering efficiency as a key criteria, designers can affect the overall system design in a positive way by:

- Eliminating or reducing the need for system fan cooling
- Reducing audible noise
- Reducing the weight and size of the system
- Reducing system internal temperatures and improving reliability
- Reducing overall energy usage and end user operating costs

As there is no legislation governing the no load power or energy efficiency of component power supplies, leading manufacturers highlight the latest "green" products in their portfolio such as the "green power" logo below, used by XP to signify compliance to defined no load power and active mode efficiency limits and enabling system designers to easily identify the power supplies that can bring real benefits to the end equipment.

GREEN XP POWER

The latest component power supply designs minimize no load power consumption and maximize active efficiency by utilizing green mode control ICs and so provide OEM's with the best possible starting point enabling the design and manufacture of Energy Star compliant product.

• Understanding Efficiency

Efficiency is a key consideration when selecting the best switch mode power supply for an end application. Pressure to provide greater functionality in ever decreasing form factors has a direct impact on the power supply resulting in a need for more power from a smaller footprint. This increase in power density, coupled with more demanding environmental legislation and the desire to minimize or eliminate fan cooling in many applications, drives equipment designers to look for more efficient power supplies.

Higher efficiency results in less power dissipation, less waste heat and lower temperatures in a given form factor. Efficiency therefore has an effect on the lifetime and reliability of both the power supply and the end equipment as less heat is generated reducing the temperature inside the equipment enclosure. Higher efficiency may also mean that the equipment can be designed with significantly reduced fan cooling or remove cooling fans altogether reducing or eliminating audible noise which is very desirable in many applications.

Having determined that higher efficiency is a desirable feature for the equipment power supply, the equipment designer turns to the power supply manufacturer's web-site and data sheets to compare the key parameters between products.

The headline efficiency presented in marketing material or power supply data sheets is likely to be the efficiency of the product under the most favorable input voltage and load conditions. The efficiency under the conditions required for the end equipment may be very different. If, as is commonly the case, the equipment is to be sold to the world-wide market the low line efficiency will be crucial. The system design must be based around the worst case efficiency not the headline efficiency. The headline efficiency at high line (230VAC) is likely to be very different from the efficiency at low line (100VAC), "universal input" does not mean that the efficiency is maintained across the input range.

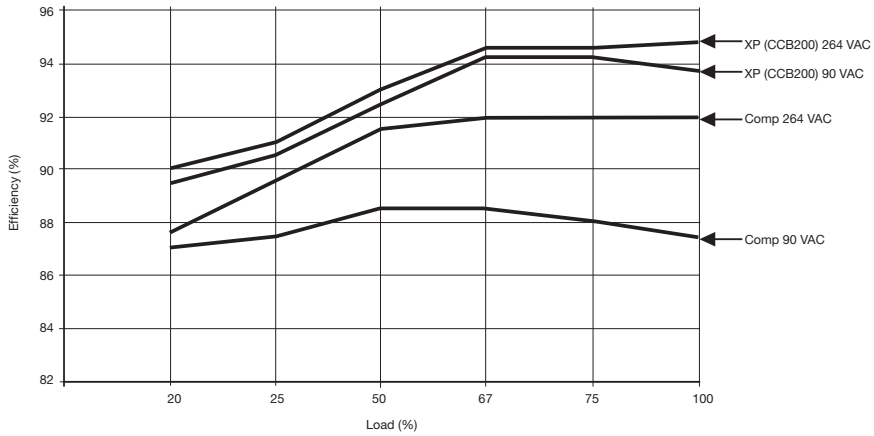
Finding the worst case efficiency will require some investigation into the real data for the selected power supply product. While some manufacturers will make this clear in their product data sheets this is not always the case. Selecting a product with good headline efficiency, perhaps with an attractive price, may result in problems later in the development when it becomes clear that the solution is not viable under the required operating conditions. Incorrect selection at the start of the program may be costly later on.

Efficiency in an AC/DC power supply is calculated as the output power (Vout x Iout) divided by the input power (Vin x In x PF) and is usually expressed as a percentage The difference between the input power and the output power is dissipated as waste heat.

Input Voltage

As the input voltage decreases the input current increases for the same output power. This results in increased losses in the primary of the power converter. The losses in diodes increase in proportion with the input current but the losses in inductors, transformers and MOSFETs increase in proportion to the square of the input current which results in more than 4 times the losses for a 50% reduction in input voltage.

This is the same for increases in output current so that, for the same output power, it is likely that higher voltage output products exhibit higher efficiency. Comparing the efficiency of what may appear to be similar products gives an insight into the efficiency that can be expected over the operating range specified in the data sheet. Figure 1 below, shows a comparison between the efficiency of XPs CCB200 and an AC/DC power supply from another manufacturer with similar headline ratings over the full input voltage and load range. Both supplies are rated at 200 W maximum power.



Power supply efficiency over variable load conditions, with different supply voltages. Curves for the XP CCB200 and a comparable supply from another manufacturer are shown.

The curves show the efficiency at the lowest continuous input voltage (100VAC nominal minus 10%) and the highest continuous input voltage (240VAC nominal plus 10%).

The difference in headline efficiency at just 3% actually results in the CCB200 dissipating just 10.5W while the alternative product would dissipate 17.5W or 40% more.

At 100% load, the efficiency of the CCB200 reduces by 1-2% from the highest input voltage to the lowest input voltage from around 95% to 93.5%. The alternative other supply's efficiency falls by 5 percentage points from 92% to 87%.

This reduction in efficiency results in increased power dissipation of 4W for the CCB200 (bringing the total power dissipation up to 14.5W). For the alternative supply this results in an increase in dissipation or around 10W (bringing the total waste power up to 27.5W). Under low line conditions the difference in power dissipated as heat within the enclose would be almost double for the alternative supply. This additional power dissipation means that both the power supply and the end equipment will be subjected to additional thermal stresses reducing reliability and lifetime in low AC line areas.

Load

The actual load drawn by the application is also a consideration. Power supply efficiency typically peaks close to full load as can be seen from the curves above. The power supply has an element of fixed power losses which do not change as the load increases or decreases.

Green mode topologies compensate for reduced efficiency by reducing the switching frequency as the load falls to reduce switching losses and comply with environmental legislation requirements for active mode efficiency.

While this drop in efficiency is not problematic at lower loads, as the power dissipation overall is lower, it may mean that the efficiency in the equipment is not as high as expected.

Topology

Different power supply topologies have differing efficiency expectations and differing cost expectations. Products with peak conversion efficiencies to 95% are now available using the latest resonant designs combined with synchronous rectification but the implementation of elements such as input rectification, power factor correction and EMC filtering may mean a sharp reduction in efficiency under low input voltage conditions meaning that the power may even be de-rated at low line.

Lower cost topologies such as the off line fly-back converter are unable to reach these headline conversion efficiencies but can be very effective in lower power applications.

Achieving high efficiency and high power density across the input and load range requires the highest efficiency in all stages of the converter design and a low noise switching to reduce the losses in EMC filters. Features such as transition mode, bridgeless and interleaved power factor correction circuits, zero current or zero voltage power conversion schemes combined with synchronous rectification will usually yield the best overall efficiency but not the lowest cost.

Topology	Power	Efficiency	Cost
Resonant/LLC	>150 W	90% - 95%	$$$
Forward	>250 W	85% - 90%	$$
Flyback	<150 W	87% - 91%	$

A power supply's topology will affect the maximum efficiency it can achieve.

Summary

When selecting the power supply it is important to understand whether it will perform safely and reliably over the lifetime of the equipment. The best efficiency specified by the power supply manufacturer is not important. The worst case efficiency is the only important performance parameter and the thermal performance of the equipment must be evaluated under the worst case conditions to ensure safe and reliable performance.

• Cooling without a fan

When selecting a power supply for an application, there are many reasons to avoid using a fan to cool it.

The audible noise from a fan can be undesirable. For equipment destined for laboratory or control room environments, where the operator is in close proximity to the equipment at all times, minimal audible noise is a very desirable characteristic. Medical equipment that is used near to the patient, such as patient monitors and infusion pumps that are near the patient for a long period of time, also need to be as quiet as possible.

Another downside of fans is their reliability. The low lifetimes of electro-mechanical fans mean that they can fail in use, causing the system to overheat, or require more frequent maintenance or replacement before the end of their life.

For systems which require a high IP-rating, fans are out of the question since very little ventilation is permitted in order to keep solid and liquid contaminants out. For example, equipment used in food processing areas is required to have a high IP rating as there are solid and liquid contaminants present in the environment. Lower IP ratings, perhaps enough to keep out dust from industrial equipment, may condone use of a fan, but often air filters are required. These filters require scheduled maintenance to clean or replace them periodically, which may be undesirable.

Convection cooling

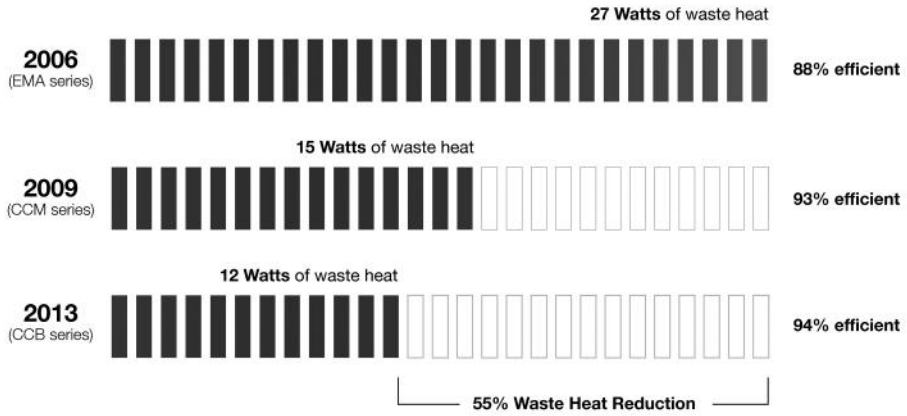
If the application restricts the use of a fan, it is necessary to look at convection or conduction cooled products. Conduction cooling involves fixing the unit to a large heat sink or metal enclosure to transfer the waste heat to the outside of the equipment. This is usually reserved for high power applications with larger levels of waste heat, as it can be complex and expensive to achieve. This editorial focuses on convection cooling as a simple approach for lower power equipment.

Convection cooling means there is enough free air around the power supply that it can dissipate the amount of heat it needs to without excessively raising the ambient temperature. Natural convection currents inside the enclosure cool the unit. As a result, there is a big difference in the power densities offered by power supplies for forced air (fan) cooling and convection cooling, for a given efficiency. A typical 3 x 5” power supply may have a convection cooled rating of up to 200 W while the force cooled version may have a rating as high at 500 W.

It’s important to fully understand the constraints under which a convection cooled power supply operates to ensure the lifetime and reliability of the design.

Efficiency

Efficiency is more important for convection cooled power supplies than for force cooled alternatives. Every efficiency point means less heat dissipated. Technology is constantly improving efficiencies that can be attained (overleaf).



XP's 94% efficient CCB200 dissipates just 12 W from its 3 x 5" footprint

When specifying a convection cooled power supply the most efficient power supply that matches the cost budget is the best starting point. For example, if the application requires the highest efficiency, XP's CCB200 boasts an efficiency of 94%; this 200W supply dissipates just 9.6 W from its 3 x 5" footprint at a load of 150 W. For more cost-sensitive applications, a suitable alternative might be the 150W convection-cooled GCS180, which is 92% efficient.

It's advisable to check that the convection cooled ratings are backed up by the efficiency, otherwise cooling is likely to be a problem. There are several things to bear in mind that may affect the headline efficiency number quoted on the data sheet. This headline efficiency is usually a best-case-scenario and will therefore not be available over the full spec of the unit.

For example, the input voltage used affects efficiency in real-world applications. Most AC-DC supplies on the market have a universal input for worldwide use. However, in the USA, where mains voltage is around half the European equivalent (230V), double the input current is required to produce the same amount of power. Working with higher currents produces a lot more loss in the various components of the power supply and efficiency suffers. Considering the resistive losses alone, the power lost is I^2R, so doubling the input current (from high line voltages to low line) actually multiplies the power lost by a factor of four. Dropping from US voltages (115V) to Japanese mains (90V) increases the input current by a further 28%, creating another 65% more resistive loss. Many data sheets therefore only specify the efficiency at high line voltages.

Convection ratings

The next thing to check on the datasheet is the derating curves for the power supply. It may be a surprise to learn that there is no industry standard way for manufacturers to gather rating information – practices vary widely. Products are generally tested in an environmental chamber, but some chambers use fans to maintain the temperature, inadvertently creating an air flow around the unit. This should be avoided when measuring under strict convection conditions since as even a small amount of air flow can have a significant effect on critical component temperatures.

At XP, products are tested in the environmental chamber inside another box. Ambient temperature based on the temperature inside that box obtains an accurate picture of the product's performance. This creates consistency across design groups and repeatability, which is also a challenge when performing thermal testing. Information relating to how the product is tested is almost never included on the datasheet but nevertheless has an impact on the final ratings.

In order to meet safety requirements, be it industrial, medical or IT, there are maximum temperatures that certain components (like transformers) can be run at. The thing to remember here is that the safety temperatures are the absolute maximum temperatures allowed, not a recommendation for normal use. If the product was to run consistently at the safety temperature, though it might pass agency approvals, the lifetime of sensitive components would suffer. To deliver a long life, the system should run as cool as possible.

Tips and tricks

Other things to remember when designing for convection cooling include that the power supply is designed to be mounted horizontally or vertically. At no time should it be used upside-down. Since heat generated by the power supply will naturally rise, placing the power supply's PCB above the hot components is not recommended.

Consider other parts of the system that are likely to get hot. A CPU, display, motor or pump? These heat-generating components will require cooling and will add to the waste heat inside the product.

In summary, though convection cooling does not permit as much waste heat as forced air cooling, it is a must for certain applications where a fan is not acceptable. Since the waste heat remains inside the enclosure, it helps to choose a power supply whose efficiency is as high as possible, and to check carefully whether the manufacturer's efficiency claims can actually be met in your application.

• Removing heat from sealed enclosures

Demand for power supplies that can withstand harsh environmental conditions does not only come from defense applications. Telecommunications base stations and infrastructure for the smart electricity grid of the future place steep demands on power supplies. These systems are subject to the extremes of temperature, dust and humidity.

Equipment needs to operate continuously as well as reliably, since performing maintenance at remote locations can be difficult, expensive and downtime is unacceptable. Sealed enclosures to prevent dust and moisture ingress are often used to protect the system from its environment, but this poses a problem for thermal management of power supplies.

A common power supply cooling solution when using a sealed enclosure is to use a small convection cooled power supply and over-rate it. For example, if you take a power supply that is rated for full power at 50°C ambient temperature, it might derate by 50% at 70 °C. So for operation at the elevated temperature, a power supply rated for twice the actual output power would be needed.

For the high power levels that are required for smart grid infrastructure or a telecoms base station, it's not feasible – in this example, a system that requires 500 W would need a 1000 W convection cooled power supply, which is impractical from a size and cost point of view. If high power requirements have ruled out convection cooling, another of getting heat out of the box must be considered.

Sealed enclosures prohibit forced air cooling as fans can suck in dirt and dust. Filtering is possible but this cuts down the air flow significantly, meaning a larger fan is needed, and they are susceptible to blockages.

This affects the reliability and maintenance demands of the system. An alternative solution is therefore required to get the heat from the power supply out of the box; using a baseplate cooled unit is a simple and inexpensive way of doing this.

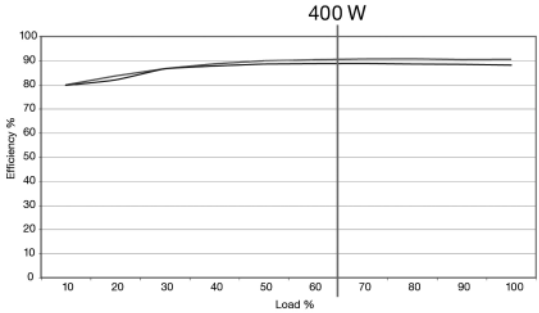
Baseplate basics

A baseplate cooled power supply has most of its heat generating components, such as the switching MOSFETs, diodes and magnetics, mounted in direct contact with the metal baseplate so that heat can be extracted using thermal conduction.

Typically the power supply is then secured to the inside of the sealed box, so that the metal box itself can act as a heat sink, or heat can be transferred from the box to an additional externally mounted heat sink. It's wise to check whether the box can act as a large enough heat sink to conduct the heat out of the unit, or whether an additional external heat sink should be added, because getting this wrong will have a significant impact on the reliability of the power supply.

For example, let's consider the CCH series baseplate cooled power supply from XP Power, which has a maximum baseplate temperature of 85 °C, operating in an ambient air temperature of 40 °C. Operating at 400 W, this power supply is 90% efficient.

Mounting a CCH power supply on the inside of a metal enclosure. The thermal resistance required can be calculated to determine whether an additional external heat sink is required.



In our example, the efficiency of the CCH power supply is 90% at 400W output.

Efficiency = Power out / Power in, so therefore: **Power out / Power in = 0.9**

We know the Power out of the system is 400 W, so: **Power in = 400/0.9 = 444.5 W**.

444.5 - 400 = 44.5 W is therefore dissipated (wasted) as heat.

Assuming a perfect thermal impedance between the baseplate and heatsink, we can use the following formula, where $T_{baseplate}$ and $T_{ambient}$ are the baseplate and ambient temperatures and $\mathbf{0_{ba}}$ is the thermal resistance between the baseplate and the ambient air:

$$T_{baseplate} = T_{ambient} + (0_{ba} \times \text{Power dissipated})$$

$$0_{ba} = (85\text{-}40)℃ / 44.5\ W = 1.0\ ℃/W$$

From this calculation we can deduce that a heatsink with a thermal impedance of 1.0°C/W or less is required to maintain the baseplate temperature at 85°C or below.

Be warned that this is only a basic check, though – heat sink design is a complex process. Once the calculations have been done, tests should be run to check the temperatures of key components, such as the baseplate and capacitors to ensure everything is cooling sufficiently as intended.

Power Supply Design

The design of the power supply unit itself can also have a significant impact on the success of baseplate cooled designs. Clearly, it helps if the power supply is as efficient as possible, and as waste heat generated is directly proportional to the efficiency, higher efficiency means a smaller heat sink can be used. Looking at it the other way around, if you kept the same heat sink and increased the efficiency of the power supply, the temperature inside the case would be lower, which would increase the expected lifetime of the power supply (as a rough yardstick, reducing ambient temperature by 10 °C doubles the lifetime of a capacitor in a power supply). Temperature inside the case is the main contributor to the lifetime of a power supply, so this is especially attractive.

Traditional baseplate cooled power supply designs use power modules. These dc-dc modules, although designed for baseplate cooling, often require external components for filter compliance and power factor correction. It can be challenging to place these parts for optimum EMC compliance and cooling. While the modules themselves have high efficiency, the overall efficiency can be affected by these extra filter components and the discrete PFC stage. Using discrete components instead of relying on modules, like in the CCH series, can alleviate this by allowing the efficiency of each stage to be optimized. All the key heat generating components are placed with optimum circuit flow next to the baseplate and components that are heat sensitive, like the reservoir capacitor, to be placed away from it or even insulated from the (hot) baseplate to extend its life. Heat generating components can also be spaced as evenly as possible around the baseplate to make heat transfer more efficient by avoiding hot spots.

Having design control of the whole circuit means more flexibility is available. It allows the manufacturer to cater for the many modified standard requests which are thrown up by the diversity of applications. It also means that the power supply can be designed with noise requirements and EMC compliance in mind from the start. Protection from mains-borne transients can be added at the front end to make the design extremely robust. As an example, the discretely implemented CCH series meets industrial standard EN55022 Class B as well as MIL-STD-461. MIL-STD-461 for conducted noise covers frequencies down to 10kHz, which even with a low power module would require external components to maintain.

A final argument for an entirely discrete implementation in a baseplate cooled power supply is that modules are bound to the size of that module; in a discrete design the full volume can be utilized by optimizing the physical layout of the components.

In summary, for applications like smart grid infrastructure or telecoms base stations, baseplate cooled designs are a simple and efficient way of keeping power supplies cool. Advances in baseplate cooled power supplies using discrete components can offer more efficient heat transfer, effortless meeting of noise legislation and compact design. These PSUs are designed from the ground up for the special conditions imposed by harsh environments and can be more easily modified to meet individual applications' requirements.

Technology Editorial 4

• Selecting power supplies for LED lighting applications

Traditionally, lighting comprised some form of incandescent, fluorescent or halogen lamp. That has changed with the ever increasing popularity of light emitting diodes (LEDs) which are finding applications in both indoor and outdoor luminaires. The main drivers of this trend are energy savings, long service life, the robustness of solid state devices and the incredible flexibility that an LED luminaire can bring to a lighting application. However, to maximize these the power source needs to be carefully chosen.

An LED will emit light when a voltage is applied across it and a current flows through it. The voltage must be equal to or greater than the LEDs forward voltage drop (typically in the region of 2-3V) and the current for full brightness may be typically 350mA for a 1 W LED which is practically the smallest size used in lighting applications. However, if the voltage applied exceeds the forward voltage of the LED then the current flowing increases exponentially meaning that the LED chip will become too hot and failure will occur.

The power source therefore needs to provide a suitable voltage at the appropriate current. The simplest way to achieve this would be to select a power supply with an output voltage above the forward voltage of the chosen LED and to limit the current to the maximum specified by the LED manufacturer using a current limit resistor. The down-side of this approach is that one of the main benefits of LED lighting – that of high efficiency, is compromised by the power dissipated by the current limiting device.

A further problem with this approach is that the LED junction temperature affects its forward voltage. As a power supply's output voltage is fixed, this in-turn means that the voltage across the current limiting device changes and hence the current will change too. The changing current will affect the amount of light being emitted and decrease the reliability of the LED. The best approach is to drive the LED from a constant current source. This allows the current to be set to the maximum specified by the LED manufacturer to achieve greatest efficiency and reliability, or to achieve the exact brightness required and also to remove the effects of junction temperature as the LED or ambient temperature changes.

One of the benefits of using LEDs in lighting applications is the ease of varying the brightness of the light. This can be achieved by varying the current through the LED which proportionally varies the amount of light emitted, however, running the LED with less than its maximum current reduces the efficiency and may result in slight changes in color. A better way is therefore to pulse the current between zero and maximum to vary the average light emitted. As long as this is done at a high enough frequency to avoid the pulsing being seen as flicker by the human eye this is the optimum way to achieve dimming. Pulsing of the current will usually be done at a fixed frequency with the ratio of zero to full current being changed. This is the pulse width modulation (PWM) method.

Selecting a power supply

The type of power supply selected for a lighting application will be based on several factors. Firstly, the environmental considerations. Is the application for indoor or outdoor use? Does the power supply need to be water-proof or have any special IP rating? Will the power supply be able to use conduction cooling or only convection cooling?

What is the overall power that is required? A single luminaire may only require a small power source but a complex system may need ones supplying hundreds of Watts. Also, will other features be required?

For example, will the power supply require to work in simple constant voltage mode or constant current mode? Will dimming be required?

From a regulation perspective, will the overall system need to operate within certain harmonic current limits? Will it need to conform to the safety standard for lighting or will an ITE power supply be adequate?

In these energy-aware times, how efficienct does the power supply need to be and does it need to comply with any input power requirements when the lamps are turned off?

Safety standards

There are various standards that apply to lighting systems. Internationally there is IEC61347 Part 1 of which covers the general safety requirements of lamp control gear and Part 2 Section 13 which is applicable to power sources for LED modules, the US have UL8750 and Europe has EN61347 following the IEC format of section naming.

Harmonic currents

A lighting application will generally require the harmonic current emissions to meet the requirements of EN61000-3-2 and the class of equipment which covers lighting is class C. Within this class there are one set of limits for above 25W active input power and another set for 25W and below. However, the standard specifically only mentions discharge lighting for 25W and below.

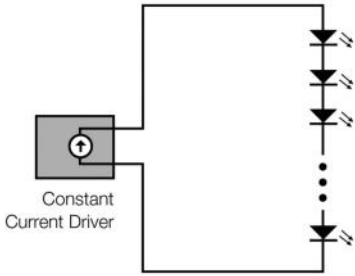
To meet the limits for above 25W will generally require power factor correction and, as the limits are calculated as a percentage of the fundamental rather than as an absolute value of Amps, it may be better to use a power source designed specifically for lighting applications rather than an ITE type power supply. However, an ITE power supply will probably meet the limits as long as the lighting load is above 40-50% of the power supply's full load rating.

An example of an power supply series specifically designed for LED lighting applications is the IP67-rated DLE series from XP Power. The range comprises 15, 25, 35 and 60 Watt models and complies with safety specifications EN61347 and UL8750.

LED configurations

Some lighting applications may use just a single LED. The power used by this will typically be around 1W as the forward voltage is in the range of 2-3V and forward current around 350mA. Although this will produce a bright source of light, it is more probable that LEDs will be used in an array of some kind within a luminaire or group of luminaires to produce a brighter and more even light source. The LEDs will be generally arranged in one of four types of configuration. Placing the LEDs in series, parallel or a matrix (combination of series and parallel) configurations enables them to be driven from a single power source. The fourth configuration utilizes multiple channels which require multiple power sources.

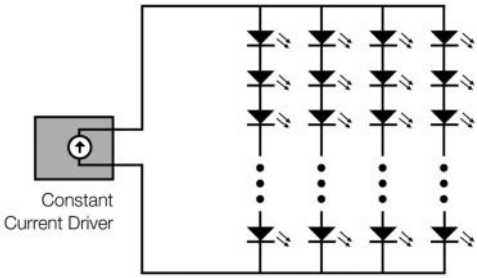
Series configuration



LEDs connected in series

In this configuration the individual LEDS are arranged in series. This gives the advantage that the same current flows through each of them resulting in the same brightness of light given off. Another advantage that if one LED fails in short circuit, the other LEDs are unaffected and hence still lit. A disadvantage is that if one LED fails in open circuit, then current flow is interrupted and all the other LEDs turn off. A further disadvantage is that if many LEDs are needed to produce the amount of light required then the total sum of the forward voltages can necessitate the use of a power source with quite a high output voltage.

Parallel configuration

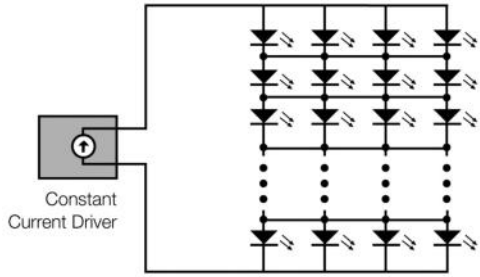


LEDs connected in parallel

When connected in parallel the LEDs may still be arranged in two or more strings of LEDs in series. The advantage is that for the same number of LEDs i.e. the same brightness, the power source could have a lower output voltage as the number of LEDs in each string can be reduced.

Another advantage is that if one of the LEDs becomes open circuit in one string then the other strings are unaffected and the luminaire will still produce light albeit at a reduced brightness. The disadvantage is that the current in each string cannot be precisely controlled from a single power source due to the slightly different forward voltages present in each string and so a current balancing device in each string may be needed which could reduce the overall efficiency.

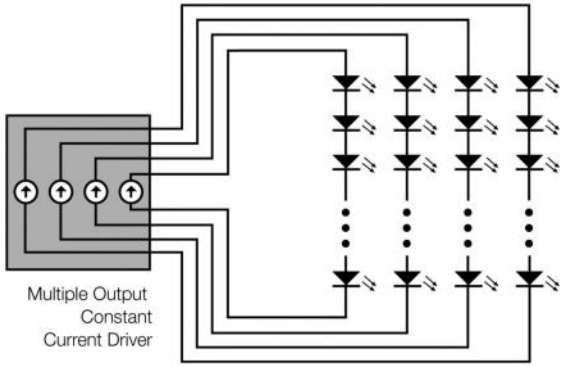
Matrix configuration



LEDs connected in a matrix configuration

In a matrix layout, the LEDs can be arranged in a similar manner to that of parallel configuration but there are links between each LED from string to string. The big advantage of this configuration is that if a single LED becomes open circuit, there is still a path for current to flow through all the other LEDs in that string and so light output is hardly diminished. The main disadvantage is that it is more difficult to control the current in each string as a current balancing device cannot be used. This means that the LEDs used must have a closely matched forward voltage which could add to the cost.

Multiple channel configuration



LEDs connect by the multiple channel method

Using this approach, the LEDs are arranged in series in multiple string arrangements similar to the parallel and matrix configurations. This has the benefit that the total string voltage can be reduced for any given brightness required and as each string is fed from an individual power source the failure of any one string will not affect the other strings in any way. A disadvantage is that the power source will be more costly as each string has an individual output however it does allow for more flexibility in applications where the brightness of one string needs to differ from the others or where individual string dimming is required.

Glossary

Abnormal Failure
An artificially induced failure of a component, usually as a result of 'abnormal' testing for regulatory agency safety compliance.

Ambient Temperature
The still-air temperature in the immediate vicinity of a power supply.

Apparent Power
A value of power for AC circuits which is calculated as the product of RMS current times RMS voltage, without taking the power factor into account.

Autoranging Input
An input voltage sensing circuit in the power supply which automatically switches to the appropriate input voltage range (90-132 VAC or 180-264 VAC).

Balun
A transformer which presents a high impedance to common-mode signals and a low impedance to differential-mode signals. It is commonly used on the input of switching power supplies to suppress common-mode noise. See Figure 1.

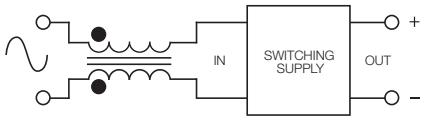


Figure 1

Bandwidth
A range of frequencies over which a certain phenomenon is to be considered.

Basic Insulation
According to international safety standards (e.g. UL60950, EN60950) basic insulation provides basic protection against electric shock i.e. one level of protection, and the test voltage used is 1500 VAC for 300 VAC working voltage. Quite frequently, safety standards call for basic insulation between secondary circuits (e.g. between a telecom network and SELV circuits).

Bode Plot
A graphic plot of gain versus frequency for a control loop, typically used to verify control loop stability, including phase margin.

Breakdown Voltage
The maximum AC or DC voltage which may be applied across an isolation barrier. See Figure 2.

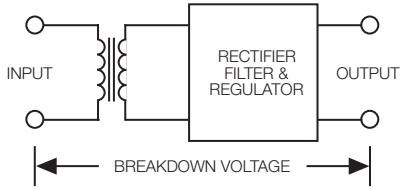


Figure 2

Bridge Rectifier
A full wave rectifier circuit employing four diodes in a bridge configuration.

Brown-out
Condition during peak usage periods when electric utilities reduce their nominal line voltage by 10% to 15%.

BSMI
Bureau of Standards Metrology & Inspection. Certification body for Taiwan.

Burn-in
Operating a newly manufactured power supply, usually at rated load and elevated temperature, for a period of time in order to force component infant mortality failures or other latent defects before the unit is delivered to a customer.

CAN Bus
Controller Area Network Bus is a 2 wire system used for high speed data communication ideally suited to harsh, electrically noisy environments

Capacitive Coupling
Coupling of a signal between two circuits, due to discrete or parasitic capacitance between the circuits.

CCC
China Compulsary Certification. Certification scheme for China for product safety and EMC, issued by China Quality Control (CQC).

Center Tap
An electrical connection made at the center of a transformer or inductor winding, usually so as to result in an equal number of turns on either side of the connection.

Centering
The act of setting the output voltage of a power supply under specified load conditions, usually an auxiliary output of a multiple output power supply with all outputs at half load.

CISPR
Comité International Spécial des Perturbations Radio électriques. (International Special Committee on Radio Interference)

Clearance Distance
The shortest distance (through air) separating two conductors or circuit components.

Common-mode Noise
The component of noise that is common to both the live and neutral conductors with respect to ground, also the component of noise that is common to both the DC output and return lines with respect to input ground.

Compliance Voltage
The output voltage of a constant current power supply.

Conducted Immunity
The immunity of a product to bursts of short duration, fast rise time transients that may be generated by the switching of inductive loads, contactors etc.

Configurable
See *Modular*

Constant Current Limiting Circuit
Current-limiting circuit which holds output current at some maximum value whenever an overload of any magnitude is experienced.

Constant Current Power Supply
A power supply which regulates its output current, within specified limits, against changes in line, load, ambient temperature and time.

Constant Voltage Power Supply
A power supply designed to regulate the output voltage for changes in line, load, ambient temperature and drift resulting from time.

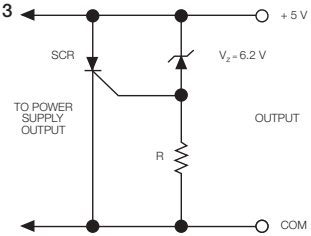
Creepage Distance
The shortest distance between two conducting parts measured along the surface or joints of the insulating material between them.

Crest Factor
In an AC circuit, crest factor is the mathematical ratio of the peak to RMS values of a waveform. Crest factor is sometimes used for describing the current stress in AC mains supply wires for a given amount of power transferred, the RMS value and hence the losses become greater with increasing peak values.

Cross Regulation
In a multiple output power supply, the percentage voltage change at one output caused by the load change on another output.

Crowbar
An overvoltage protection circuit which rapidly places a low resistance shunt across the power supply output terminals if a predetermined voltage is exceeded. See Figure 3.

Figure 3



CSA
Canadian Standards Association. An independent Canadian organization concerned with testing for public safety.

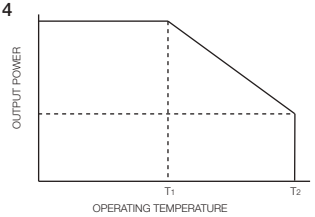
Current Limiting
See *Output Current Limiting.*

Current Limiting Circuit
A circuit designed to prevent overload of a constant-voltage power supply. It can take the form of constant, foldback or cycle-by-cycle current limiting.

Current Share
The accuracy with which two or more power supplies share a load current. An active share control connection is sometimes employed which may be described as a current share or power share connection.

Derating
The specified reduction in an operating parameter to improve reliability. Generally for power supplies it is the reduction in output power at elevated temperatures. See Figure 4.

Figure 4



Differential Mode Noise
The component of noise measured between the live and neutral conductors, and also the component of noise measured between the DC output and output return. See *Ripple and Noise*.

Dips and Interruptions
Short input interruptions to simulate the utility supply under various conditions.

Double Insulation
Insulation comprising both basic insulation and supplementary insulation. Double insulation provides two levels of protection and the test voltage is 3000 VAC for IT and industrial equipment, and 4000 VAC for medical equipment for 300 VAC working voltage.

Distributed Power Architecture (DPA)
This is a power distribution system where the conversion to lower voltages is effected locally, near the load. An interim DC voltage is provided from the AC mains or DC bus by a converter. This is then distributed to smaller DC/DC converters. Some versions of this system are also known as Intermediate Bus Architecture (IBA). See page 16.

Drift
The change in output voltage of a power supply over a specified period of time, following a warmup period, with all other operating parameters such as line, load, and ambient temperature held constant.

Dropout
The lower limit of the AC input voltage where the power supply begins to experience insufficient input voltage to maintain regulation.

Dynamic Current Allocation
A system for dual positive outputs such as 5V & 3.3V where the full amount of current may be taken from either output in whichever combination is required. For instance, in a 6A system any value of current from 0A to 6A may be taken from the 3.3V output and the remainder from the 5V or vice versa.

Dynamic Load Regulation
See *Transient Response.*

Earth Leakage Current
The current that flows through the earth conductor of a piece of equipment under normal conditions. This is limited by legislation. Limits depend upon the application.

Efficiency
The ratio of output power to input power. It is generally measured at full-load and nominal line conditions. In multiple output switching power supplies, efficiency is a function of total output power.

EFT/Burst
See *Conducted Immunity*.

Eighth Brick
An industry standard package size and pin-out for DC/DC converters. The package size is 2.3” x 0.9” with the pins on a 2.0” spacing. The height is typically 0.3”.

Electrostatic Discharge (ESD)
Discharge of static electricity built up when two insulating materials are rubbed together.

Electromagnetic Interference (EMI)
Also called radio frequency interference (RFI), EMI is unwanted high frequency energy caused by the switching transistors, output rectifiers and zener diodes in switching power supplies. EMI can be conducted through the input or output lines or radiated through space.

Enable
Power supply interface signal, often TTL compatible, which commands the power supply to start up one or all outputs.

Equivalent Series Resistance (ESR)
The amount of resistance in series with an ideal capacitor which exactly duplicates the performance of a real capacitor. In high frequency applications low ESR is very important.

ETSI
The European Telecommunications Standards Institute is a non-profit-making organization whose mission is to determine and produce the telecommunications standards that will be used for decades to come.

EU Code of Conduct
Voluntary European energy efficiency standard for external power supplies and adaptors.

FCC
The FCC (Federal Communications Commission) is an independent United States government agency, directly responsible to Congress and charged with regulating interstate and international communications by television, radio, wire, satellite and cable.

Filter
A frequency-sensitive network that attenuates unwanted noise and ripple components of a rectified output.

Floating Output
An output of a power supply that is not connected or referenced to any other output usually denotes full galvanic isolation. They generally can be used as either positive or negative outputs. Non-floating outputs share a common return line and so are referenced to one another.

Fly-back Converter
The fly-back converter is the simplest type of switcher. In most cases, it uses one switch and only needs one magnetic element - the transformer. Practical output power from flyback converters is limited to less than 150W.
See Figure 5 and page 2.

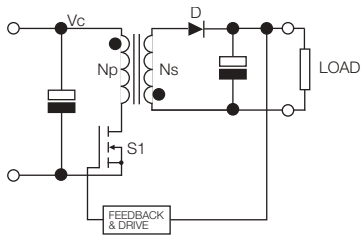


Figure 5

Foldback Current Limiting Circuit
Current limiting circuit that gradually decreases the output current under overload conditions until some minimum current level is reached under a direct short circuit. See Figure 6.

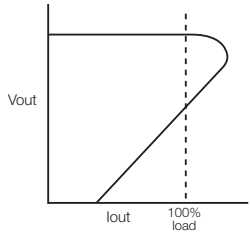


Figure 6

Forward Converter
Similar to a fly-back converter but the forward converter stores energy in the output inductor instead of the transformer. See page 3.

Front End
A particular type of AC/DC converter (usually high power) used in distributed power architecture (DPA) and Intermediate Bus Architecture (IBA) systems which provides the DC voltage that is bussed around the system.

Full Brick
An industry standard package size and pin out for DC/DC converters. The package size is 2.4” x 4.6” with the pins on a 4.2” spacing. The height is typically 0.5” without a heatsink. Four mounting holes are provided for the attachment of heatsinks and to the customer’s board.

Full Bridge Converter
A power switching circuit in which 4 transistors are connected in a bridge configuration to drive a transformer primary. See page 6.

Galvanic Isolation
Two circuits which have no significant ohmic connection are considered to be “galvanically isolated” from each other. Galvanic isolation (separation) is achieved by using a transformer, opto-coupler, etc.

Green Mode Power Supplies
Power supplies designed to minimize no load power consumption and maximize efficiency across the load range. Often used in external power supplies to meet environmental legislation and in component power supplies to enable end equipment to comply with similar legislation.

Ground
An electrical connection to earth or some other conductor that is connected to earth.
Sometimes the term “ground” is used in place of “common”, but such usage is not correct unless the connection is also made to earth.

Ground Loop
An unwanted feedback condition caused by two or more circuits sharing a common electrical ground line.

Half Brick
An industry standard package size and pin-out for DC/DC converters. The package size is 2.40” x 2.28” with the pins on a 1.90” spacing. The height is typically 0.50” without a heatsink. Four mounting holes are provided for the attachment of heatsinks and to the customer’s board.

Half Bridge Converter
A power switching circuit similar to the full bridge converter except that only two transistors (or diodes) are used, with the other two replaced by capacitors. See page 5.

Harmonic Currents
Current distortion generated by non-linear loads such as the input to a switch mode power supply.

Heatsink
Device used to conduct away and disperse the heat generated by electronic components.

Hiccup Mode
See *Trip & Restart Current Limiting*

Hi-Pot Test
High potential test. A test to determine if the breakdown voltage of a transformer or power supply exceeds the minimum requirement. It is performed by applying a high voltage between the two isolated test points.

Hold-up Time
The time during which a power supply's output voltage remains within specification following the loss of input power.

Hot Swap
Redundant units which may be removed and replaced without the need to power down equipment.

I²C Bus
Inter Integrated Circuit BUS is a serial BUS developed by Philips Semiconductor in the 1980s. Widely used in power management systems. See page 71.

IEC
International Electrotechnical Commission.

Induced Noise
Noise generated in a circuit by a varying magnetic field produced by another circuit.

Inhibit
Power supply interface signal, often TTL compatible, which commands the power supply to shut down one or all outputs.

Input Line Filter
A low-pass or band-reject filter at the input of a power supply which reduces line noise fed to the supply. This filter may be external to the power supply.

Input Voltage Range
The high and low input voltage limits within which a power supply or DC/DC converter meets its specifications.

Inrush Current
The peak instantaneous input current drawn by a power supply at turn-on.

Inrush Current Limiting
A circuit which limits the inrush current during turn-on of a power supply.

Intermediate Bus Architecture (IBA)
See *Distributed Power Architecture (DPA)*.

Inverter
A power converter which changes DC input power into AC output power.

Isolation
The electrical separation between input and output of a power supply by means of the power transformer. The isolation resistance (normally in mega ohms) and the isolation capacitance (normally in pico farads) are generally specified and are a function of materials and spacings employed throughout the power supply.

Isolation Voltage
The maximum AC or DC voltage that may be applied for a short, defined duration from input to output and/or chassis of a power supply.

KETI
Korean Electrical Testing Institute. Certification body for safety and EMC in Korea.

Line Frequency Regulation
The variation of an output voltage caused by a change in line input frequency, with all other factors held constant. This effect is negligible in switching and linear power supplies.

Line Regulation
The variation of an output voltage due to a change in the input voltage, with all other factors held constant. Line regulation is expressed as the maximum percentage change in output voltage as the input voltage is varied over its specified range.

Linear Regulator
A common voltage-stabilization technique in which the control device is placed in series or parallel with the power source to regulate the voltage across the load. The term 'linear' is used because the voltage drop across the control device is varied continuously to dissipate unused power.

LLC Half Bridge Converter
A resonant, zero voltage switching power converter enabling the design of high efficiency power supplies. See page 8.

Load Regulation
Variation of the output voltage due to a change in the output load, with all other factors held constant. It is expressed as a percentage of the nominal DC output voltage.

Local Sensing
Using the output terminals of the power supply as sense points for voltage regulation.

Logic Enable
The ability to turn a power supply on and off with a TTL signal. A logic low generally turns the supply off; logic high turns it on.

Long Term Stability
Power supply output voltage change due to time with all other factors held constant. This is expressed in percent and is a function of component ageing.

Magnetic Amplifier
A magnetic device used to improve the cross regulation of multiple output AC/DC converters.

Margining
Adjusting a power supply output voltage up or down from its nominal setting in order to verify system performance. This is usually done electrically by a system-generated control signal.

Minimum Load
The minimum load current/power that must be drawn from the power supply in order for the supply to meet its performance specifications. Less commonly, a minimum load is required to prevent the power supply from failing.

Modular
A physically descriptive term used to describe a power supply made up of a number of separate subsections, such as an input module, power module, or filter module.

MOSFET
Metal Oxide Semiconductor Field Effect Transistor. The device of choice for the main switch in many switch mode power supplies, having much better switching characteristics than bipolar transistors.

MTBF
Mean Time Between Failures. The failure rate of a system or component, expressed in hours, established by the actual operation (demonstrated MTBF) or calculated from a known standard such as MIL-HDBK-217.

Noise
Noise is the aperiodic, random component of undesired deviations in output voltage. Usually specified in combination with ripple. See *PARD and Ripple*.

Nominal Value
The stated or objective value for a quantity, such as output voltage, which may not be the actual value measured.

Off-line Power Supply
A power supply which operates off the AC line directly, without using a power transformer prior to rectification and filtering.

Open Frame
A power supply with no external metal chassis; the power supply is provided to the end user essentially as a printed circuit board which provides mechanical support as well as supporting the components and making electrical connections.

Operational Insulation
Operational insulation is needed for the correct operation of the equipment, but does not protect against electric shock. Operational insulation provides no levels of protection and typically the test voltage is ≤ 500 VDC.

Operating Temperature Range
See *Temperature Range, Operating*.

Operational Power Supply
A power supply with a high open loop gain

regulator which acts like an operational amplifier and can be programmed with passive components.

Output Current Limiting
An output protection feature which limits the output current to a predetermined value in order to prevent damage to the power supply or the load under overload conditions. The supply is automatically restored to normal operation following removal of the overload.

Output Good
A power supply status signal which indicates that the output voltage is within a certain tolerance. An output that is either too high or too low will deactivate the output good signal.

Output Impedance
The ratio of change in output voltage to change in load current.

Output Noise
The AC component which may be present on the DC output of a power supply. Switch-mode power supply output noise has two major components; a lower frequency component at the switching frequency of the converter and a high frequency component due to fast edges of the converter switching transitions. Noise should always be measured directly at the output terminals with a probe having an extremely short grounding lead. See page 55.

Output Voltage
The nominal value of the DC voltage at the output terminals of a power supply.

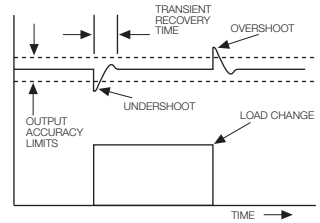
Output Voltage Accuracy
For a fixed output supply, the tolerance in percent of the output voltage with respect to its nominal value under all minimum or maximum conditions.

Output Voltage Trim
The adjustment range of a power supply or DC/DC converter via a potentiometer or external programming of voltage, current or resistance.

Overload Protection
An output protection feature that limits the output current of a power supply under overload conditions so that it will not be damaged.

Overshoot
A transient change in output voltage, in excess of specified output accuracy limits, which can occur when a power supply is turned on or off or when there is a step change in line or load. See Figure 7.

Figure 7



Over Temperature Protection (OTP)
A protection system for converters or power supplies where the converter shuts down if the ambient temperature exceeds the converter's ratings. OTP is intended to save the converter and any downstream equipment in the event of a failure of a fan or such. OTP usually measures the hottest item on board the converter rather than ambient temperature.

Over Voltage Protection (OVP)
A power supply feature which shuts down the supply, or crowbars or clamps the output, when its voltage exceeds a preset level. See Crowbar.

Parallel Operation
The connection of the outputs of two or more power supplies of the same output voltage to obtain a higher output current than from either supply alone. This requires power supplies specifically designed to share the load.

PARD
Periodic And Random Deviation. A term used for the sum of all ripple and noise components measured over a specified bandwidth and stated in either peak-to-peak or RMS values. See Figure 8.

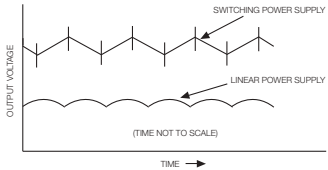


Figure 8

Peak Power
The absolute maximum output power that a power supply can produce without immediate damage. Peak power capability is typically well beyond the continuous reliable output power capability and should only be used within the defined specification.

Pi Filter (π filter)
A commonly-used filter at the input of a switching supply or DC/DC converter to reduce reflected ripple current. The filter usually consists of two parallel capacitors and a series inductor and is generally built into the supply.
See Figure 9.

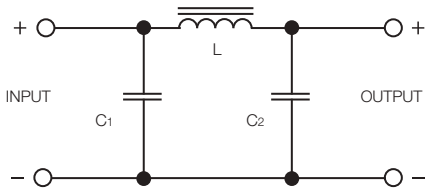


Figure 9

PM Bus
Power Management Bus is an open power system standard used to provide communication between power supplies & converters and other devices utilized in a power system. See page 71.

Post Regulation
A linear regulator used on the output of a switching power supply to improve line and load regulation and reduce output ripple voltage. *See Linear Regulator.*

Power Density
The ratio of output power per unit volume. Typically specified in W/In^3.

Power Factor
The ratio of true power to apparent power in an AC circuit. In power conversion technology, power factor is used in conjunction with describing the AC input current to the power supply. See page 38.

Power Factor Correction (PFC)
Standard AC/DC converters draw line current in pulses around the peaks in line voltage. This may be undesirable for several reasons. PFC circuits ensure that the line current is drawn sinusoidally and in phase with the sinusoidal line voltage. See page 34.

Power Fail Detection
A power supply signal which monitors the input voltage and provides an isolated logic output signal when there is loss of line voltage.

Power Foldback
A power supply feature whereby the input power is reduced to a low value under output overload conditions.

Power Sharing
See *Current Share*.

Pre-load
A small amount of current drawn from a power supply to stabilize its operation. A bleed resistor usually provides a pre-load. See also *Minimum Load*.

Pre-regulation
The regulation at the front-end of a power supply, generally by a type of switching regulator; this is followed by output regulation, usually by a linear type regulator.

PSE
Product Safety Electric Appliances and Materials. Certification for Safety and EMC in Japan.

Primary
The input section of an isolated power supply that is connected to the AC mains and hence has dangerous voltage levels present.

Programmable Power Supply
A power supply with an output controlled by an external resistor, voltage, current or digital code.

Pulse Width Modulation
A method of voltage regulation used in switching supplies whereby the output is controlled by varying the width, but not the height, of a train of pulses that drive a power switch.

Push-Pull Converter
A power switching circuit which uses a center tapped transformer and two power switches which are driven on and off alternately. This circuit does not provide regulation by itself. See page 7.

Quarter Brick
An industry standard package size and pin-out for DC/DC converters. The package size is 1.45" x 2.28" with the pins on a 2.0" pitch. The height is typically 0.50" without a heatsink. Four mounting holes are provided for the attachment of heatsinks and to the customer's board.

Radiated Electromagnetic Interference
Also called radio frequency interference (RFI), EMI is unwanted high-frequency energy caused by the switching transistors, output rectifiers and zener diodes in switching power supplies. The portion that is radiated through space is known as radiated EMI.

Radiated Immunity
The immunity of a product to electromagnetic fields.

Rated Output Current
The maximum load current which a power supply was designed to provide at a specified ambient temperature and input voltage.

Redundancy (N+M)
Power supplies connected in parallel operation so that if one fails, the others will continue delivering enough current to supply the maximum load. This method is used in applications where power supply failure cannot be tolerated. See page 63.

Reference
The stable voltage, generally a zener diode, from which the output voltage of a regulated supply is controlled.

Reflected Ripple Current
The AC current generated at the input of a power supply or DC/DC converter by the switching operation of the converter, stated as peak-to-peak or RMS.

Reinforced Insulation
Single insulation system applied to live parts which provide a degree of protection against electric shock equivalent to double insulation. Reinforced insulation provides two levels of protection and the test voltage used is 3000VAC for IT and industrial equipment, and 4000VAC for medical equipment for 300 VAC working voltage.

Regulation
The ability of a power supply to maintain an output voltage within a specified tolerance as referenced to changing conditions of input voltage and/or load.

Reliability
The ability of a system or component to perform its required functions under stated conditions for a specified amount of time.

Remote Enable
The ability to turn on electrically the output of a power supply via a logic level signal.

Remote Inhibit
The ability to electrically turn off the output of a power supply via a logic level signal.

Remote ON/OFF
One or other of remote enable or remote inhibit, or a combination of both.

Remote Sensing
A technique of regulating the output voltage of a power supply at the load by means of sensing leads which go from the load back to the regulator. This compensates for voltage drops in the load leads.

Resolution
For an adjustable supply, the smallest change in output voltage that can be realized by the adjustment.

Resonant Converter
A class of power converter topology which reduces the level of switching losses by forcing either zero voltage across, or zero current through the switching device when it is turned on or off.

Return
The name for the common terminal of the output of a power supply; it carries the return current for the outputs.

Reverse Voltage Protection
A feature which protects a power supply or DC/DC converter against a reverse voltage applied at the input or output terminals.

RFI
See *Radiated Electromagnetic Interference*.

Ripple and Noise
The magnitude of AC voltage on the output of a power supply, expressed in millivolts peak-to-peak or RMS, at a specified bandwidth. This is the result of feed through of the rectified line frequency, internal switching transients and other random noise. See also PARD & Noise.

Rise Time
The time required for the voltage in a switching electronic circuit to rise from 10% to 90% of its nominal final value.

RoHS
EU directive restricting the use of certain hazardous materials in electrical and electronic equipment

Safety Approvals
Third party or agency approvals to internationally recognized safety standards.

Safety Ground
A conductive path to earth that is designed to protect persons from electrical shock by shunting away any dangerous currents that might occur due to malfunction or accident.

Secondary
The output section of an isolated power supply which is isolated from the AC mains and specially designed for safety of personnel who might be working with power on the system.

SELV
Safety Extra Low Voltage. A term generally defined by the regulatory agencies as the highest voltage that can be contacted by a person and not cause injury. It is often specifically defined as 42.4 VAC or 60 VDC.

Sequencing
The desired order of activation of the outputs of a multiple output power supply.

Shock and Vibration
A specification requirement for which a power supply is designed or tested to withstand, such as 20 g shock for 11 milliseconds and 10 g random vibration for 2 hours over a 2-2000 Hz bandwidth.

Short Circuit Protection
A feature which limits the output current of a power supply under short circuit conditions so that the supply will not be damaged.

Signals
Output interface, often at TTL level, of various operational conditions such as power fail and DC OK.

Sixteenth Brick
An industry standard package size and pin-out for DC/DC converters. The package size is 1.3” x 0.9” with the pins on a 1.1” pitch. The height is typically less than 0.4”.

Soft Start
A technique for gradually activating a power supply circuit when the power supply is first turned on. This technique is generally used to provide a gradual rise in output voltages and to limit inrush current.

Standby Current
The input current drawn by a power supply when shut down by a control input (remote inhibit) or under no load.

Start-up Rise Time
The time between the output voltage starting to rise and reaching the desired level.

Start-up Time (Start-up Delay)
Time between the application of input voltage and the output voltage being within regulation.

Supplementary Insulation
Independent insulation applied in addition to basic insulation in order to provide protection against electric shock in the event of a failure of basic insulation. Supplementary insulation provides one level of protection and has a test voltage of 1500 VAC for 300 VAC working voltage.

Surface Mount Technology (SMT)
A space-saving technique whereby special lead-less components are soldered onto the surface of a PCB rather than into holes in a PCB. The parts are smaller than their leaded versions and PCB area is saved.

Surge
Part of the conducted immunity suite of tests, designed to simulate a nearby lightning strike.

Switching Frequency
The rate at which the DC voltage is switched on and off during the pulse width modulation process in a switching power supply.

Synchronous Rectifiers or Rectification
A circuit arrangement where the output rectifier diodes of a power supply are replaced with active switches such as MOSFETs. The switches are turned on and off under control and act as rectifiers. This results in considerably lower losses in the output stage and subsequently much higher efficiency. They are particularly useful with low voltage outputs.

Temperature Coefficient
The average percent change in output voltage per degree centigrade change in ambient temperature over a specified temperature range.

Temperature Derating
Reducing the output power of a power supply with increasing temperature to maintain reliable operation.

Temperature Range, Operating
The range of ambient or case temperatures within which a power supply may be safely operated and meet its specifications.

Temperature Range, Storage
The range of ambient temperatures within which a non-operating power supply may be safely stored with no degradation of its subsequent operation.

Thermal Protection
See *Over Temperature Protection*.

Topology
The design type of a converter, indicative of the configuration of switching transistors, utilization of the transformer, and type of filtering. Examples of topologies are fly-back, forward, half-bridge, full-bridge, and resonant.

Tracking
A characteristic of a dual or other multiple output power supply whereby one or more outputs follow another output with changes in line, load and temperature, so that each maintains the same proportional output voltage.

Transient Response
The time required for the output voltage of a power supply to settle within specified output accuracy limits following a step change in output load current or a step change in input voltage.

Trip & Restart Current Limiting
Current limiting circuit which switches off the output when an overload condition is reached. The unit will then try to restart periodically until the overload is removed.

TUV
TUV Rheinland Product Safety Group. An independent German organization which tests products for safety.

UL
Underwriter's Laboratories Incorporated. An independent, U.S. organization which tests products for safety.

Undershoot
A transient change in output voltage, below output accuracy limits, which can occur when a power supply is turned on or off, or when there is a step change in line or load. See *Overshoot*.

Universal Input
A power supply's ability to accept a wide input voltage range (90VAC to 264VAC) without the selection of input range, either manually or electronically (as in auto-ranging input).

UPS
Uninterruptible Power Supply. A power supply that continues to supply power during a loss of AC input power. This is accomplished by means of a back-up battery and a DC/AC inverter or DC/DC converter.

Under Voltage Lock Out (UVLO)
A protection system for power converters where the converter is deliberately shut down or prevented from starting if the input voltage drops below a pre-defined level. Some hysteresis is usually present to prevent the converter oscillating on and off. UVLO is usually needed with battery systems where the voltage decreases gradually with time rather than turning off quickly.

VDE
Verband Deutsche Elektrotechniker. A German organization which tests equipment for public safety and emitted noise.

Voltage Balance
The percentage difference in magnitude between the two output voltages of a dual output power supply where the voltages have equal nominal values with opposite polarities.

Warm-up Drift
The initial change in output voltage of a power supply from turn-on until it reaches thermal equilibrium at nominal line, full load, 25°C ambient temperature.

Warm-up Time
The time required, after initial turn-on, for a power supply to meet its performance specifications.

Zero Current Switching (ZCS)
See *Resonant Converter*.

Zero Voltage Switching (ZVS)
See *Resonant Converter*.

• Prefix Codes

Prefix Multipliers

Prefix	Symbol	Multiplier
exa-	E	1,000,000,000,000,000,000
peta-	P	1,000,000,000,000,000
tera-	T	1,000,000,000,000
giga-	G	1,000,000,000
mega-	M	1,000,000
kilo-	k	1,000
hecto-	h	100
deca-	da	10
deci-	d	0.1
centi-	c	0.01
milli-	m	0.001
micro-	µ	0.000 001
nano-	n	0.000 000 001
pico-	p	0.000 000 000 001
femto-	f	0.000 000 000 000 001
atto-	a	0.000 000 000 000 000 001

• SI Unit Codes

SI Base Units

Quantity	Name	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric Current	ampere	A
Thermodynamic Temperature	kelvin	K

SI Derived Units

Quantity	Name	Symbol
Area	square meter	m^2
Volume	cubic meter	m^3
Speed/Velocity	meter per second	m/s
Acceleration	meter per second squared	m/s^2
Current Density	ampere per square meter	A/m^2
Magnetic Field Strength	ampere per meter	A/m

SI Derived Units With Special Names

Quantity	Name	Symbol	Expression in terms of other units	Expression in terms of SI base units
Frequency	Hertz	Hz		s^{-1}
Energy/ Work/ Quantity of heat	Joule	J	Nm	$m^2\ kg\ s^{-2}$
Power/ Radiant Flux	Watt	W	J/s	$m^2\ kg\ s^{-3}$
Electric Potential/ Potential Difference/ Electromotive Force	Volt	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
Capacitance	Farad	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
Electric Resistance	Ohm	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
Magnetic Flux	Weber	Wb	V s	$m^2\ kg\ s^{-2}\ A^{-1}$
Magnetic Flux Density	Tesla	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
Inductance	Henry	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
Celsius Temperature	degree Celsius	°C		K
Electric Field Strength	Volt per meter	V/m		$m\ kg\ s^{-3}\ A^{-1}$

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Gary Bocock

About the Author

Gary is a veteran of the power electronics industry; a spark from within giving him a palpable passion for power from early in his career. He has worked in power electronics for 30 years in design, development, applications and management roles. Gary is a member of the Institution of Engineering and Technology (IET) and holds the position of Technical Director at XP Power, a public company and leading specialist in power electronics.

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