XP Power

Your **Essential Guide** to

Power Supplies

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This easy reference guide provides an invaluable resource for system designers when choosing and integrating power supplies and DC-DC converters.

Your Essential Guide to Power Supplies covers subjects such as safety, electromagnetic compatibility (EMC), thermal management, lifetime, and reliability of power converters. Also considered are energy efficiency, analog and digital control interfaces, the increasing benefits of digital control and intelligent power and much more.

Whether you are experienced or new to designing-in power supplies or DC-DC converters this book offers a wealth of information in one easy reference guide.

Contents

Further technical articles are available online at: www.xppower.com

Written and produced by XP Power

Issue 3

Introduction to Power Conversion

• Introduction

Electronic devices and equipment require AC-DC power supplies and DC-DC converters to power processes, control systems, displays, communications & much more. The DC supplies must be accurately controlled, low noise and present a low output impedance to support load changes. They often include indicators, status signals and signal level controls through analogue or digital interfaces to interact with the equipment or application and for interrogation and communication via appropriate networks.

Power supplies and DC-DC converters also provide protection against fault conditions and input power disturbances protecting both the power converter itself and the end equipment against phenomena such as overload, over temperature, spikes, and surges. They also offer isolation for safety, noise reduction & transient protection.

End applications usually require a combination of AC-DC power supplies, isolated DC-DC converters and/or Non-Isolated Point Of Load (NIPOL or POL) converters to support a variety of power supply, power system and isolation needs for sub-systems to support processes, control electronics, displays, communications and electromechanical or applied parts.

AC-DC power supplies are typically designed to support global market mains supplies offering universal input voltage ranges for single phase or three phase supplies. DC-DC converters commonly offer 2:1 or 4:1 input ranges and in some instances input ranges as wide as 12:1 to cater for a broad range of nominal battery voltages with a single device. These wide or universal input ranges broaden the potential markets for individual products and equipment increasing volumes and reducing cost. Standard power products also incorporate features, EMC certification and safety agency approvals to comply with world-wide requirements.

For very high-volume low-cost applications, it may be advantageous to implement an application specific or custom power solution where the initial risks & costs associated with time to market, design & approvals may be outweighed by reduced unit cost with only the exact electrical, thermal and mechanical properties required for the specific application. The ever growing and extensive range of standard format supplies often means a simple modification with low risk is a better approach.

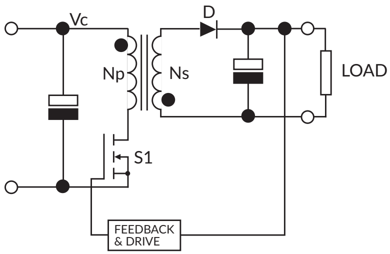
Power supplies and DC-DC converters are available in different mechanical formats, or packages, to suit a wide variety of applications and power ranges. They may be integrated into the equipment in open frame, chassis mount, enclosed or conduction cooled formats. They may be external to the equipment in plug-top, desk-top or rack mount products. They may also be designed for specific applications such as DIN rail mounting power supplies.

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

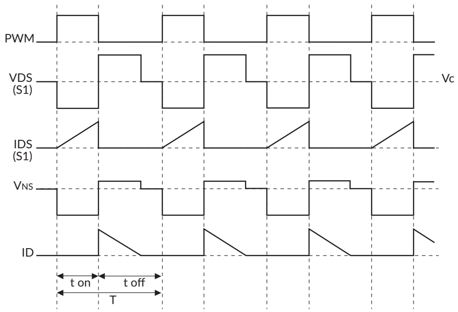
• Common Topologies

Isolated Fly-back Converter

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



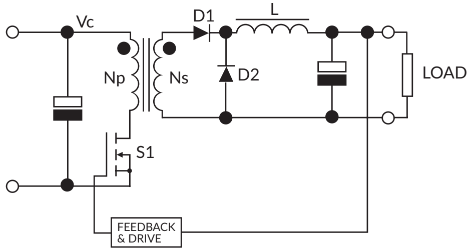
This topology provides a low cost means of converting AC to DC power due to its simplicity and low component count. The power level is restricted by the high levels of ripple current in the output capacitor and the need to store high levels of energy in the coupled inductor in a restricted volume. Flyback converters commonly utilize valley or transition mode controllers, which reduce losses by switching the main power device on at the point of minimum applied voltage, and green mode controllers to maximize efficiency across the load range and minimize no load power consumption.

Flyback converters can be operated in either discontinuous or continuous mode defined by the starting amplitude of the switching current. Waveforms above are for discontinuous mode where the switching current (IDS) starts from zero for each switching cycle.

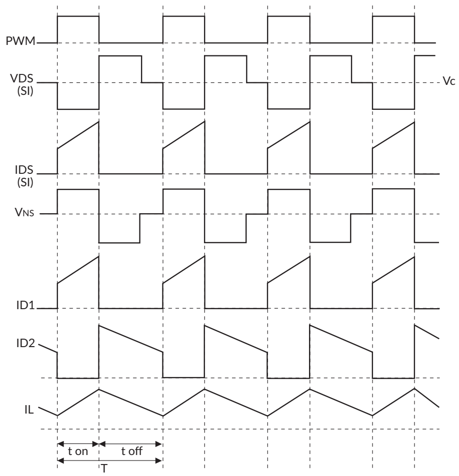
The fly-back converter is used in DC-DC converters but only at low power (<50W) due to the low input voltage and high ripple currents.

Forward Converter

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.



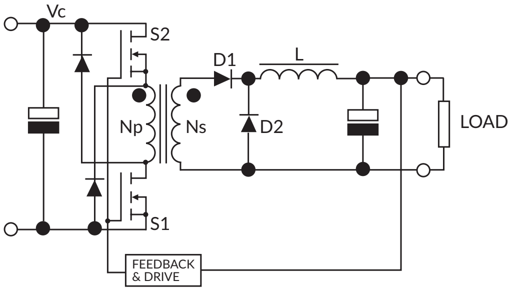
Forward Converter



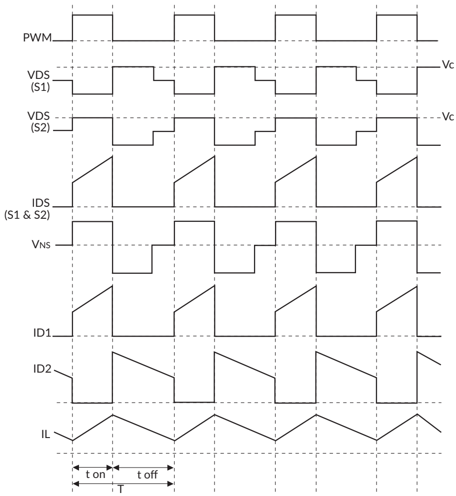
There is no energy stored in the transformer; energy is stored in the output stage of the converter in the inductor and capacitor. The output inductor reduces the ripple currents in the output capacitor and the volume of the transformer is dependent on switching frequency and power dissipation.

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.



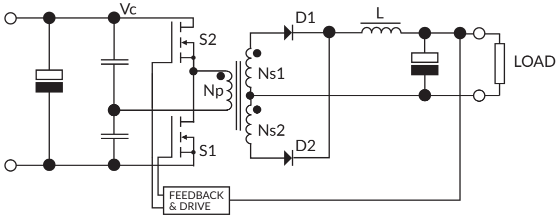
Two Transistor Forward Converter



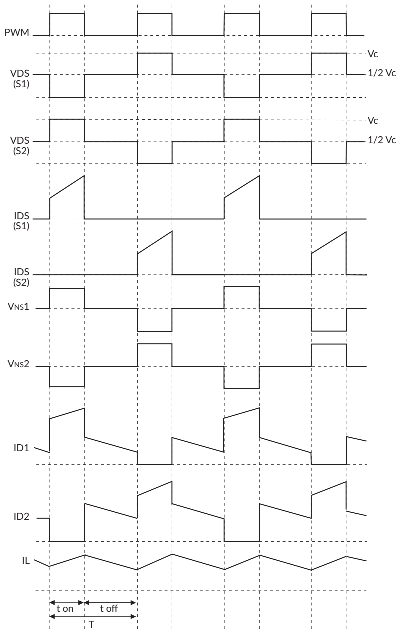
As the power rating increases, it is desirable to utilize the transformer core more efficiently by driving it through two quadrants of its available area of operation, rather than the one utilized in forward converters. This is achieved in half bridge or full bridge converters.

Half Bridge & Full Bridge Converters

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. Like the forward converter there is no energy stored in the transformer.

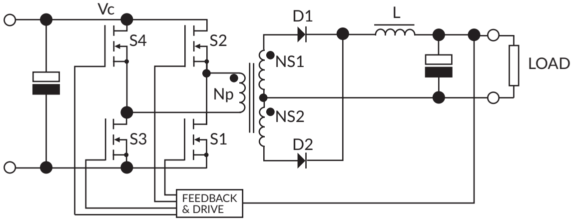


Half Bridge Converter

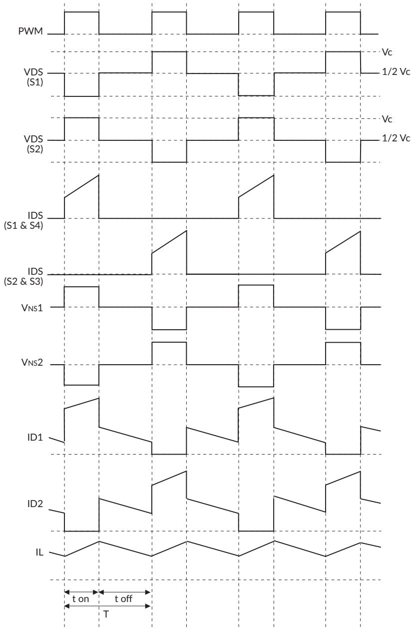


Energy is transferred to the secondary and the load during each switching element on-time by utilizing a split secondary winding. This has the added benefit of doubling the switching frequency seen by the secondary, helping to reduce the volume of the output inductor and capacitor required and halving the voltage seen by each switching element.

In higher power solutions a full bridge converter can be employed (see below).

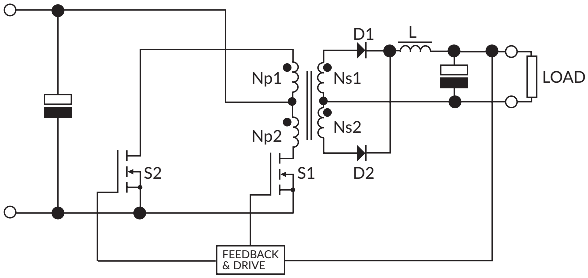


Full Bridge Converter

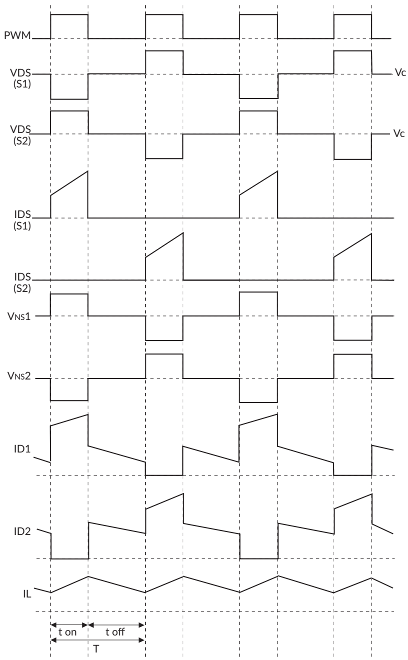


This topology will provide double the output power for the same primary switching current, but increases the complexity of switching element drive circuits, compared to the half bridge.

In DC-DC power supplies 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.

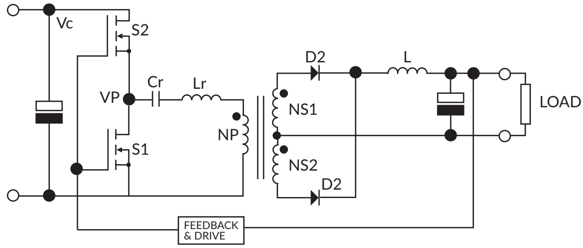


Push-Pull Converter

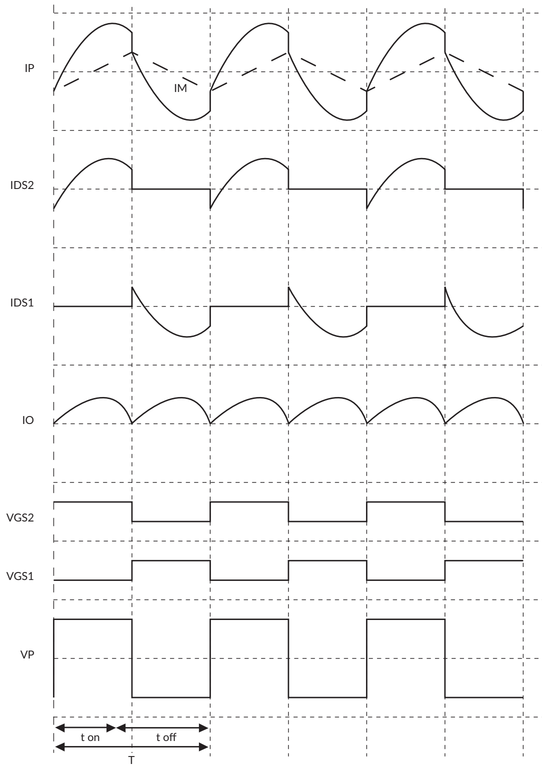


LLC Half Bridge Converter

This resonant topology utilizes Zero Voltage Switching (ZVS) to minimize switching losses and maximize efficiency. The resonant circuit is formed from two inductive elements and one capacitor (LLC). 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 usually paired with a pre-regulator mostly in the form of a PFC boost converter as it has limited ability to compensate for changes in input voltage.

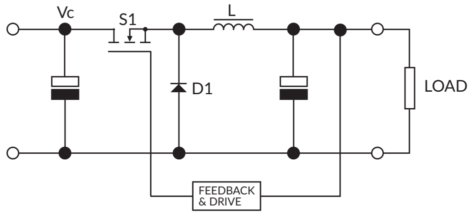


LLC Half Bridge Converter

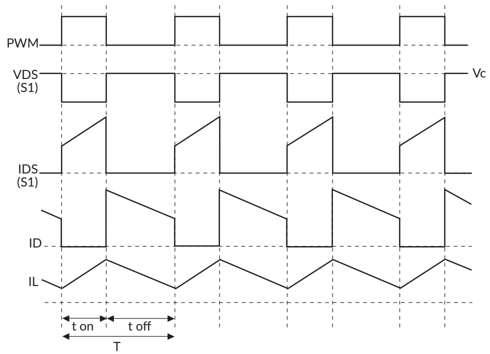


Buck Converter

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 Point Of Load (POL) converters used to produce locally regulated supplies in distributed power architectures.



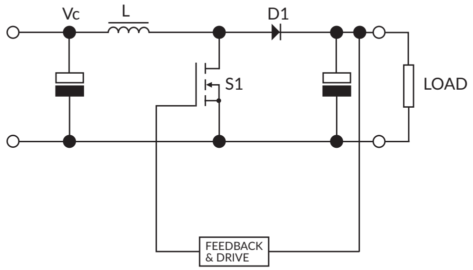
Buck Converter



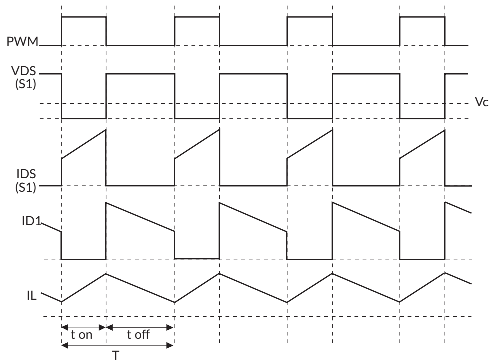
During the switching element on-time the current through the inductor rises as the input voltage is higher than the output voltage and the inductor acquires stored energy. When the switch opens the current freewheels through the diode and supplies energy to the output.

Boost Converter

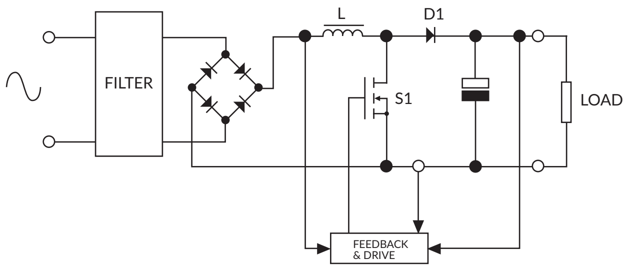
Boost converters are used to step up the input voltage to produce a higher output voltage. They can be used to boost DC supplies but are most commonly used in AC input power supplies configured to provide active Power Factor Correction (PFC). The following are diagrams of a standard boost converter and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

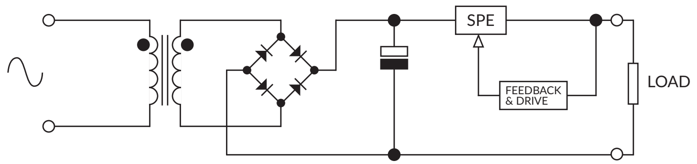


PFC Boost Converter

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 50/60Hz 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.

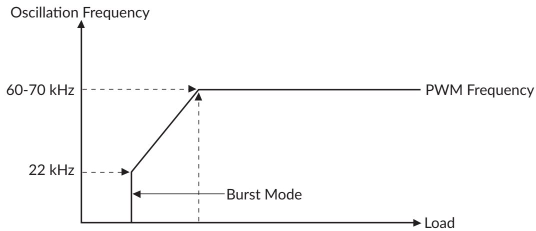
There are multiple pieces of legislation applicable to external power supplies (EPS) including the EU ErP directive (Energy related Products), US DoE (Department of Energy), NRCan (Natural Resources Canada) and the AS-NZS Standard (Australia and New Zealand). Many power supply makers are also marketing component power supplies with similar specifications, designed to enable users to meet green criteria for end applications.

Green Mode Off Line Fly Back Converters

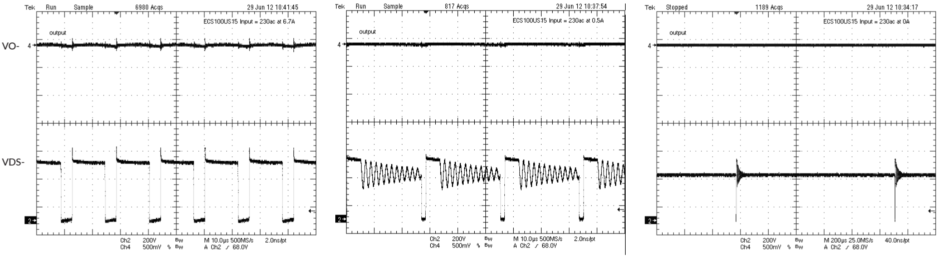
The simplest approach is the green mode off line fly back converter which is suitable for supplies up to around 100W.

At higher loads the switching frequency is typically 60–70kHz. 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 22kHz 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 a typical 100W green mode component power supply at full load (switching at 62kHz) at 10% load (switching at 35kHz) and at zero load when the supply has entered burst mode to reduce the power consumed to <0.5W. Individual bursts occur at a repetition rate of 900Hz.



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.

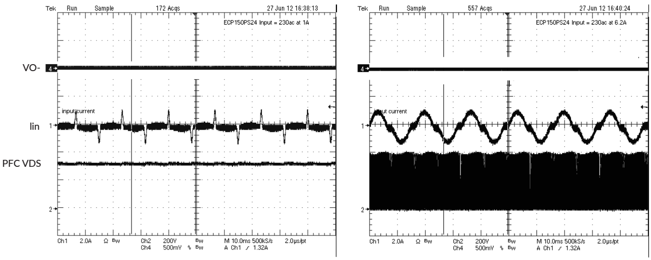
Active Power Factor Correction & Fly Back Converter Combination

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

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 50-60W 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 as described on page 33.

The traces below show the typical operation of the PFC boost converter for a 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.

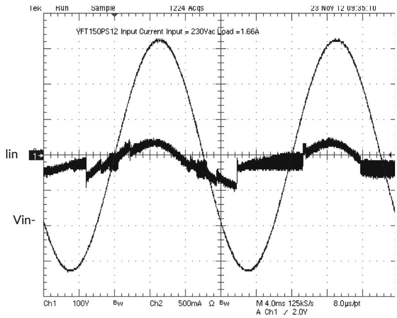
As the load continues to decrease the fly back converter performs in the same manner as the off line fly back converter above reducing the switching frequency with load and entering burst mode at very light or zero load with the same potential side effects.

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 100–1500W range when combined with an active PFC boost converter.

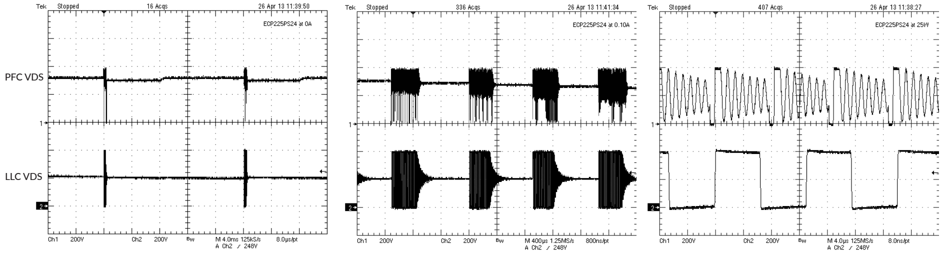
LLC converters are not able to operate over wide input ranges, requiring a stable input supply which is provided by the boost converter stage. This characteristic of the LLC converter means that the PFC boost converter cannot be disabled at lower loads and enters a burst mode to maximize active mode 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.

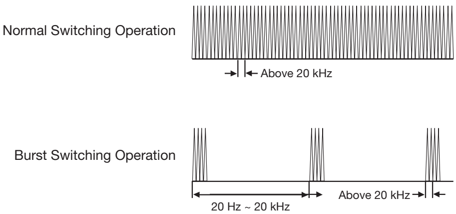


Zero Load | 1% Load | 10% Load

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 20Hz & 20kHz. 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.



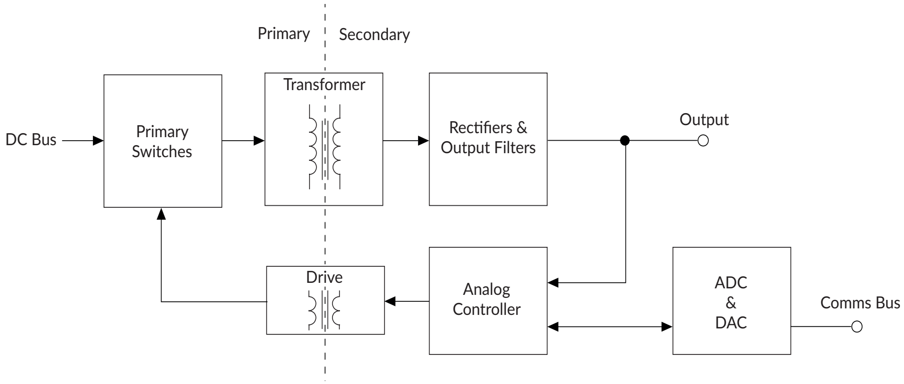
Steps are taken to mitigate audible noise such as varnish impregnation of transformers and other wound components, changing ceramic capacitors to film types in key areas to avoid piezo electric effects and controlling burst mode frequency to avoid the areas most sensitive to the human ear (2kHz–4kHz).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

• Digital Power Supplies

The implementation of digital signal processing (DSP) control in power supplies & power systems brings a wealth of benefits. From communications & control to support networked factories and efficient smart manufacturing, known variously as industry 4.0, the 4th industrial revolution or more broadly as the Internet of Things (IoT), through to flexibility and efficiency in stand-alone applications by communication and control within the end equipment and/or, by tailoring the power supply during the end equipment development phase to ensure efficient integration & optimized performance characteristics.

Background

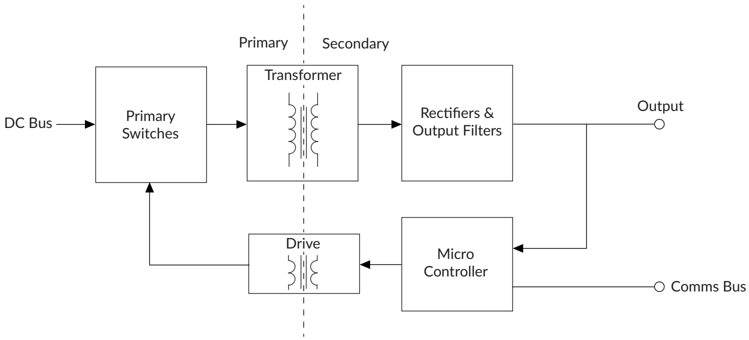
Digital control in power supplies and power systems broadly fits into two implementations. The more common approach is a digital interface between the traditional analog control system and the outside world providing signals & alarms and various levels of control via a communication bus.



Analog power supply with digital interface

Simple, low cost microcontrollers have also been implemented in power applications for many years for functions such as fan speed control, protection functions & alarm detection.

Increasingly, manufacturers are using digital signal processing (DSP) via a micro-controller for power system control bringing more sophisticated functions and greatly enhanced flexibility, allowing user programmable features and characteristics.



DSP controlled digital power supply

DSP is higher cost when compared to an off the shelf analog controller but the cost of a microcontroller capable of implementing full DSP control has decreased over time, making this an increasingly attractive and desirable solution given the significant benefits it provides, especially as the power rating increases. The mixed domain architecture required, combining power analog design principles with efficient code and stabilization of the control loop in the discrete time or z-domain, rather than the frequency or s-domain, is well proven and understood by the product design & development teams within the major power manufacturers.

While the development, documentation, verification and approval of efficient, robust firmware takes significant time and resources to ensure a robust and reliable power supply, once the initial investment has been made the significant benefits of digital power and the ability to reuse the firmware across a broad range of products and platforms with relatively minor changes can be realized.

Digital control loops have the advantage of being insensitive to changes in environment, temperature, ageing and tolerances of components. They can be calibrated at the point of manufacture to further improve accuracy and they enable monitoring of the performance of the power system in real time and adjust parameters to tune for optimal performance at the operating point, increasing efficiency and reducing power losses.

Features & Benefits of Digital Signal Processing (DSP)

Fully digital power supplies offer unparalleled flexibility and adjustability to suit a wide range of applications without the hardware changes and adaptations which traditional analog control systems have historically demanded.

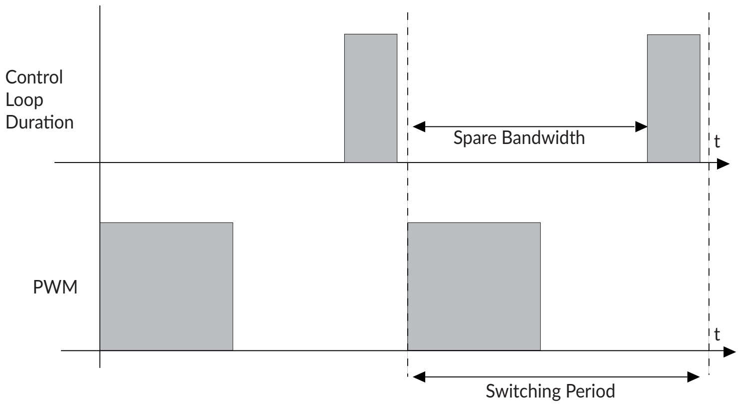
DSP control loops bring the capability of output voltage and current adjustment over ranges as wide as 0 to 105-110% by tailoring the converter operational mode to the demand. They ease the implementation of constant current overload characteristics, which can be complex and costly in modern resonant switching topologies, without the need to compromise efficiency. This entails the employment of multiple switching schemes and control algorithms in the same power conversion stage to achieve optimal performance at the required operational point, an extremely complex, if not impossible task, in a traditional analog control scheme with fixed hardware drive and compensation schemes. This wide range control can be implemented as a continuously variable power supply to maximize system flexibility and efficiency or, exploited during the system development phase, to optimize the supply characteristics to the application without the need for hardware updates.

DSP also enables the user to determine start up ramp times, soft start characteristics and slew rates in software, another feature that would result in hardware changes in traditional control systems. Warning levels and fault conditions such as input over/under voltage, output over/under voltage, output under/over current, temperature warnings & fault conditions can be set by the user to suit the application via software. The use of DSP further allows the response type & delay times applied to individual warning or fault conditions to be user specified. Options, under warning or fault conditions, may be as varied as continuing operation for a short delay & then disable, continuing operation indefinitely, disable & retry (including how many times to retry & time between retries before shutdown) and disable & resume when OK or disable & latch, all user selected.

Digital control systems also allow users to set the polarity of signals, alarms and controls to suit the system demands. A good example is the ability to set the remote on/off control to operate as inhibit or enable simply by toggling a digital switch.

Information from the power system is readily available through the communication interface enabling reporting and status such as model, revision, serial number, run time, operating temperature & fault/event logs.

This level of flexibility and user control is possible as the latest microcontrollers for digital power applications contain DSP functionality that allows the digital control loop to execute within a fraction of one switching period, every switching period. In the simplified example below, the output voltage is sampled once per switching cycle. An ADC conversion time of a few hundred nanoseconds is typical.



Simplified example of control loop & spare bandwidth

The time that the MCU does not spend executing the controller is spare bandwidth and this spare bandwidth can be used to perform other tasks or functions. Low priority tasks are run in a slow loop and are interrupted whenever a high priority task occurs, such as the ADC interrupt to run the control loop code.

The provision for analog control of digital power is usually also provided for systems that use traditional 0-5V or 0-10V control signals by the implementation of an Analog to Digital Converter (ADC) within the power supply and all alarms & controls can usually be accessed through conventional connections as well as digitally through the communications bus.

Connected Systems

Communication and control are increasingly important with the rise of connected, smart factory and IoT applications benefiting from real time status information from power systems as well as adjustment and control inputs, allowing real time adjustments to maximize process efficiency where it benefits from accurate voltage and/or current supplies and the ability to tune these to suit the environment and application.

Digital power products are able to report warnings, fault conditions, power delivery information, run time, thermal data and event logs in addition to enabling the real time adjustments to output voltage, current and power delivery to maximize system efficiency in sensitive processes or test applications. A range of digital interfaces and protocols ranging from the commonly used I²C/PMBus & RS232/RS485 serial buses to DeviceNet & EtherCAT enabled interface solutions are available to suit a wide range of environments, applications and requirements.

While not all end applications require communication to the outside world, the ability to communicate with and adjust the parameters of the power system within an end equipment can enhance features & operating characteristics and has the potential to save cost by replacing the external hardware controls that are required for traditional fixed output supplies. DSP enabled power supplies can support dynamic requirements for output voltage, current and power delivery that are normally associated with far higher cost laboratory supplies, where tolerances are acceptable, and enable complex test, burn-in & process routines directly from a cost-effective power source.

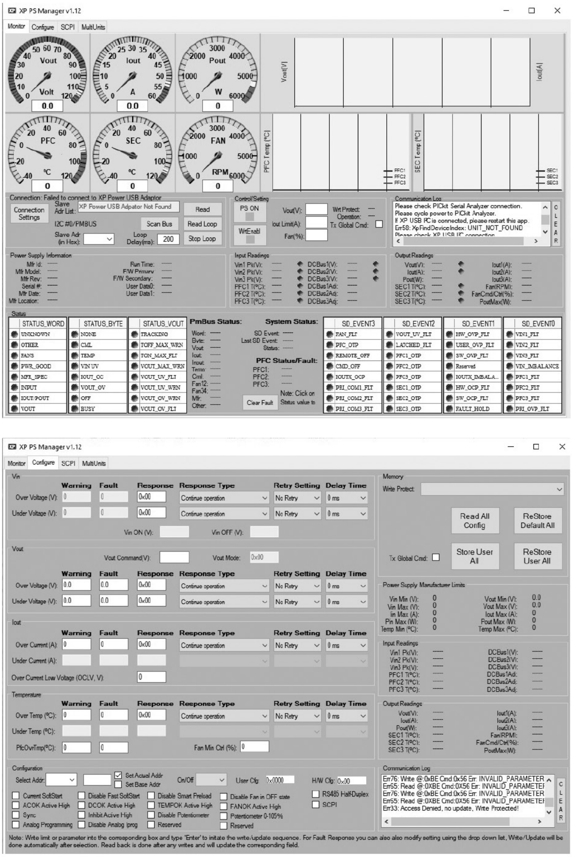
Stand-alone Applications

In end equipment where there is no requirement for communication, either external or internal, there are still benefits to be gained in tailoring the power supply to suit the application, easing integration and removing the need for an application specific solution requiring a modified standard or custom power solution.

Output voltage, output current, power delivery, warnings, alarms, protection & controls can be adjusted, evaluated, amended and finalised during the development stage, creating a set of unique characteristics in firmware which are then implemented by the power supply provider at the point of manufacture for the end equipment production phase. These iterations of characteristics can be implemented on the same standard product saving considerable time and cost compared to the hardware changes required in traditional power products.

End applications employing analog controls for voltage or current adjustment still benefit from the ability to determine the warning and fault condition settings & responses and polarity settings of alarm and control signals again, without resorting to application specific or fully customised power solutions with the time delays, risks and inevitable costs that are involved in development, EMC and safety agency approvals.

Manufacturers of digital power supplies commonly offer a Graphical User Interface (GUI) to enable users to define the requirements for just this purpose as well as enabling speedy evaluation of capabilities for connected applications. A typical example is shown below.



Graphical User Interface (GUI) for XP Power's HPx series digital power supplies

In summary, there are clear and realizable advantages to implementing DSP control in power supplies and power systems in many, usually higher power (1kW+), applications which benefit from the flexibility and the time and cost savings it brings. For simple, lower power applications it is likely to be overly complex and cost prohibitive, with standard off the shelf analog controllers enabling fast time to market combined with low acquisition cost for the commonly used topologies.

Input Considerations

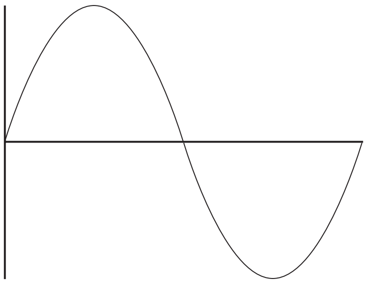
• Power Sources

AC Power Sources

Alternating Current (AC) power sources, from rotary generators or renewable energy source inverters, are the most common form of mains power with a range of nominal voltages and frequencies in different parts of the world. It is delivered to the point of use as either a single-phase or three-phase power supply.

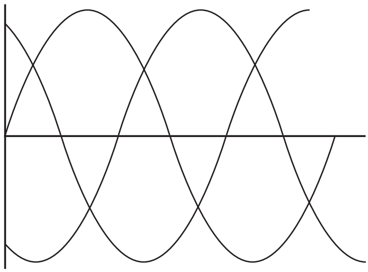
Single-phase AC Power

Single-phase power is a two-wire power circuit comprising a phase conductor and a neutral conductor. Single phase power is generally used in domestic and light industrial settings and is usually derived from one phase of a three-phase AC system configured to supply three single phase supplies. Single-phase power may also be derived from a phase-to-phase connection, providing a higher nominal voltage from the same source system. The power delivered by a single-phase system pulsates and falls to zero during each cycle.



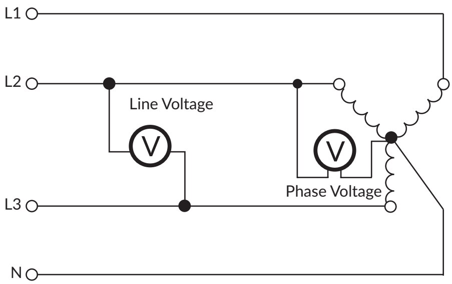
Three-phase AC Power

Three-phase AC power systems use either a three or four conductor arrangement depending on the configuration employed. The three phases are 120 degrees apart providing more consistent power which never pulsates to zero, transmitting 3 times the power of a single-phase system by the addition of one conductor. Three phase power is generally used in commercial and industrial settings which require higher power delivery.



There are two basic three-phase configurations used; star or wye connection and delta connection.

Star or Wye Connection

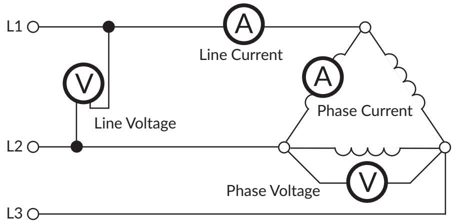


Connecting one end of each of the phases together, as shown on the right, makes a star or wye connection. The phase voltage (or phase to neutral voltage) is the voltage measured across a single coil. The line voltage (phase to phase voltage) is measured across two coils.

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).

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

Delta Connection



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

In this configuration the line voltage and phase voltages are the same. $V_{LINE} = V_{PHASE}$

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 single phase 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. Buildings 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 90-264VAC or 90-305VAC 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.

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

Worldwide nominal voltage

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

DC Power Sources

DC power sources are typically produced by rectifying an AC source, often incorporating power factor correction, or an electrochemical reaction in the form of a battery.

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

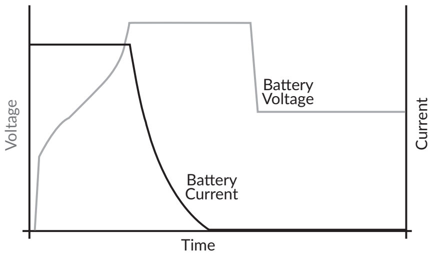
Batteries

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 2.25V/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/°C per cell decreasing above 20°C and increasing below 20°C.

VRLA batteries are often boost or equalize charged at the higher voltage of 2.4V/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

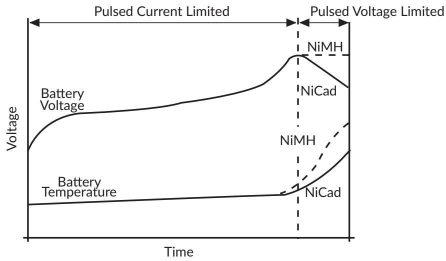
Nickel Cadmium and Nickel Metal Hydride

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.

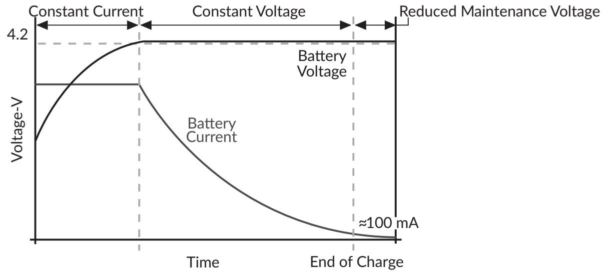
	Li-Ion	NiCad	NiMH
Energy Density Whr/kg	90	90	90
Energy Density Whr/l	210	100	140
Operating Voltage	3.6	1.2	1.2
Lifetime (approx. cycles)	1000	1000	800
Self Discharge	6%/month	15%/month	20%/month

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 0.05V above the battery terminal voltage, current limited to around 100mA.

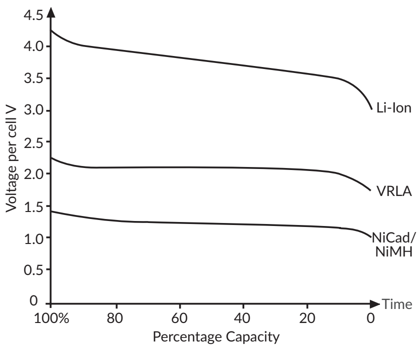


Li-Ion Battery Charging Characteristics

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

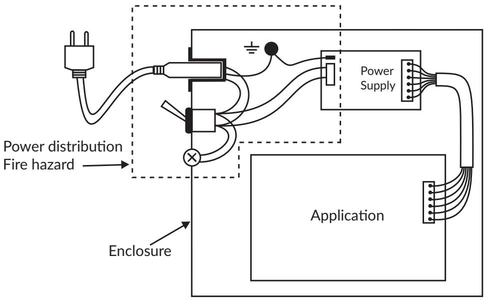
Input Current Protection

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 (or blown) by an overload as the power supply has 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 pose a fire risk 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.

The fuse in the power supply 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 is subjected to abnormal testing to ensure that it will not present a safety or 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

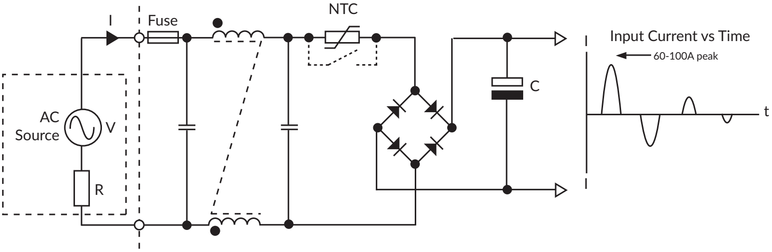
The input of the equipment may be subjected to a number of transient voltage conditions. These differ between AC & DC systems.

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

The AC system transients are outlined 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

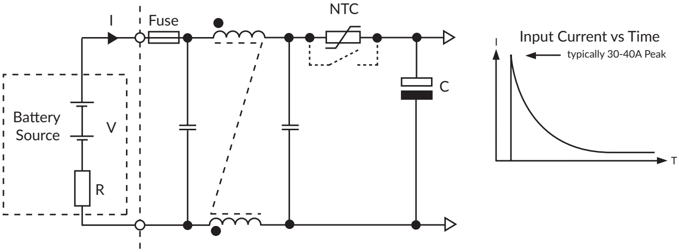
An AC mains system is a low impedance power source that can supply a large amount of current. In a power supply, at the instant of switch-on, the reservoir capacitor is discharged giving the appearance of a short circuit. Without any additional precautions the input current will be very large for a short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



Typical power supply input circuit

Precautions are taken to limit the inrush current as this may 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 40-60A lasting 1-2ms but can it be as high as 90-100A 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, 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.

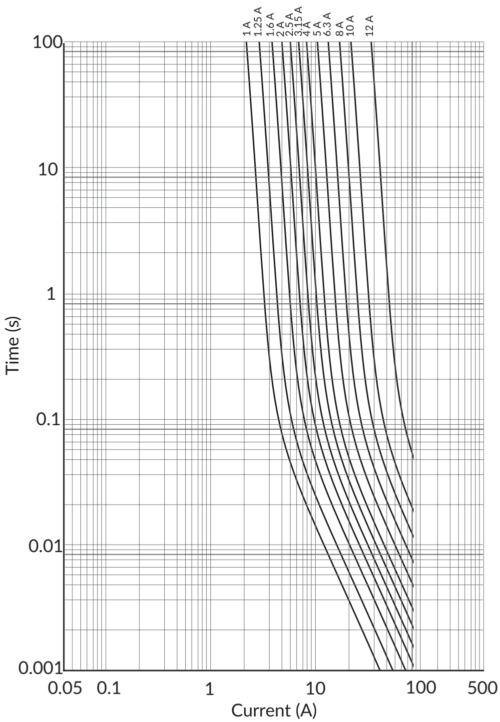
Circuit breakers are A-K (very fast to long time delay). For power supplies, C or above would be recommended.

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

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



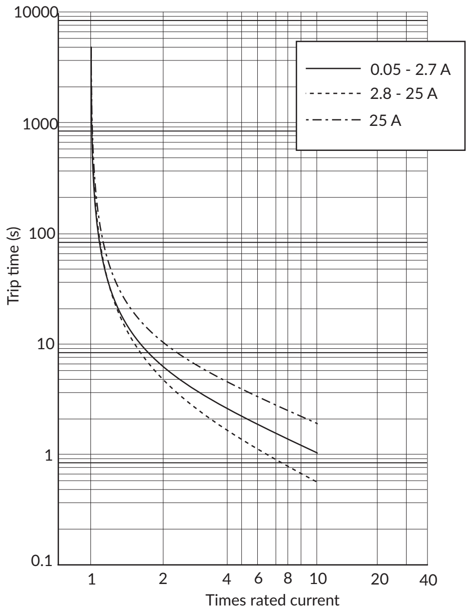
Circuit Breakers - Thermal

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.

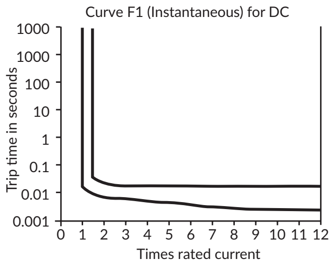
In the case opposite, for the 0.05-2.7A breaker at 10 times the rated current, it would take 1 second for the break to occur. The temperature derating of the device should also be considered to ensure that it complies with the environmental parts of the specification.

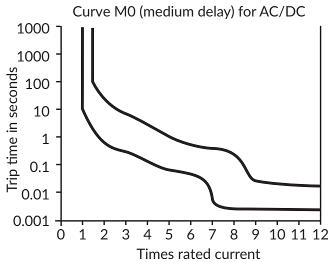
If a battery source is being used, it is also important to check the short circuit rating of the battery and the interrupt capacity of the circuit breaker. Because it has contacts, excessive current may cause it to weld shut rather than break.

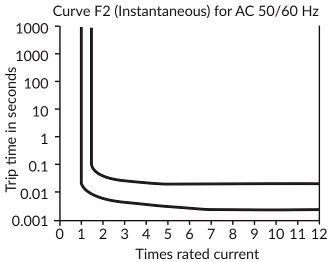


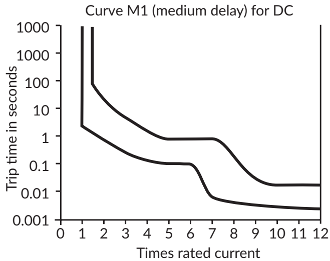
Circuit Breakers – Magnetic

The other type of circuit breaker is a magnetic type, which is 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 by the following standards:

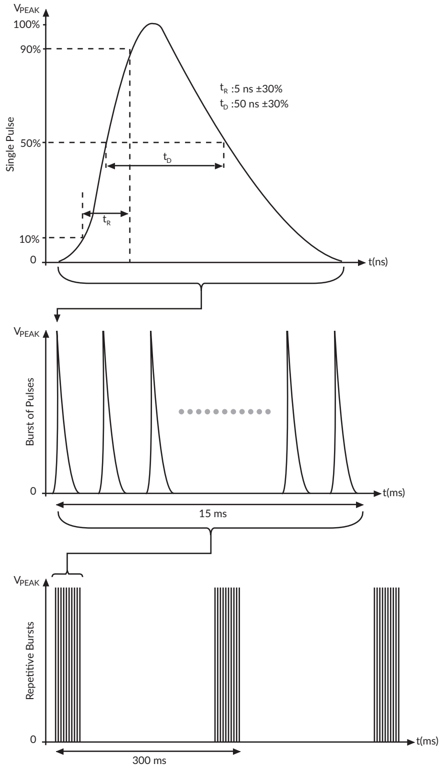
EN61000-4-4	Electrical fast transient (EFT)/burst immunity test	Switching transients
EN61000-4-5	Surge immunity test	Near lightning strikes

There are four levels within the 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.

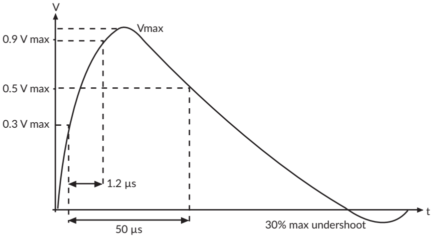
Fast Transient Burst EN61000-4-4	Surge EN61000-4-5	
	Common Mode L/N - ⏚	Differential Mode (L-N)
Level 1, 0.5kV	Installation Class 1, 0.5kV	Installation Class 1, N/A
Level 2, 1kV	Installation Class 2, 1kV	Installation Class 2, 0.5kV
Level 3, 2kV	Installation Class 3, 2kV	Installation Class 3,1kV
Level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

EN61000-4-4 specifies a short pulse with little energy while EN61000-4-5 specifies a longer pulse, which contains substantially more energy.

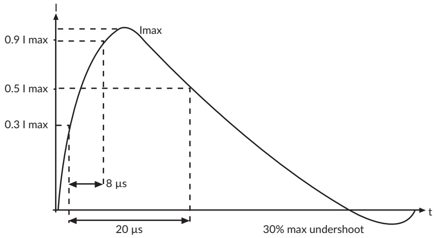
EFT Waveforms



Surge Waveforms



Open Circuit Voltage



Short Circuit Current

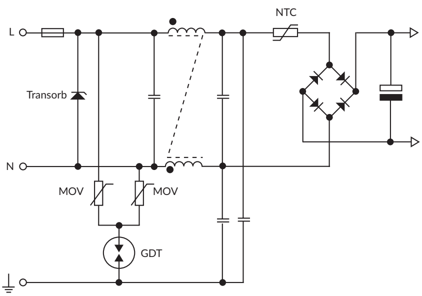
The devices listed below are the major components used to protect electronic equipment from damage caused by these transients. These components have varying response times and energy absorption capabilities and are usually used in combination to provide effective protection.

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 also be added prior to a standard power supply to enhance the protection in harsh environments.

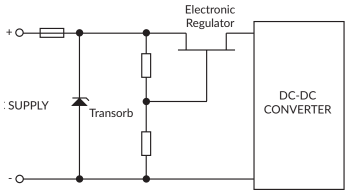


Typical application of GDTs and MOVs

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.

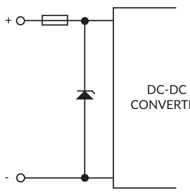


Typical application of DC input surge protection

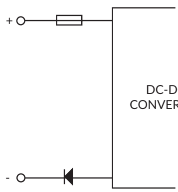
Reverse Polarity Protection

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.

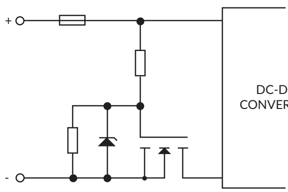
The second option is to implement a series diode or MOSFET which, in the event of reverse connection, will block the current path. The fuse will not blow and no damage will occur. The disadvantage of the method is that the diode or MOSFET is permanently in circuit causing inefficiency and raising the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

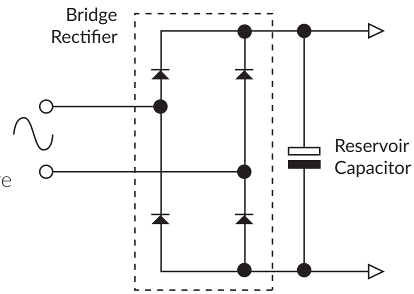
As a result of the peak rectification techniques used in power supplies, harmonic currents are generated. To limit these harmonics, legislation has been introduced. The relevant standard is EN61000-3-2 for equipment with an input current ≤16A per phase.

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

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

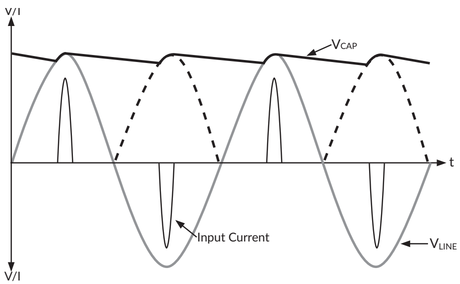
Equipment Classes A & B have absolute limits for harmonics whatever the input power, Class C equipment has limits expressed as a percentage of the 50 Hz current consumed and for Class D equipment the harmonic current limits are proportional to the mains power consumed. Equipment categorized in Classes 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 2-3ms.

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.



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.

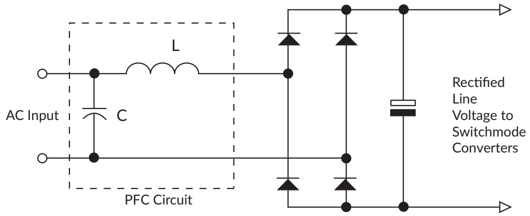
The combined effect of millions of power supplies is to clip the AC voltage because all of the current is drawn at the peak of the sine wave. Power conductors must be sized to carry the extra current caused by the low power factor. Neutral conductors can overheat because they are typically not sized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

Solutions for Power Supplies

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

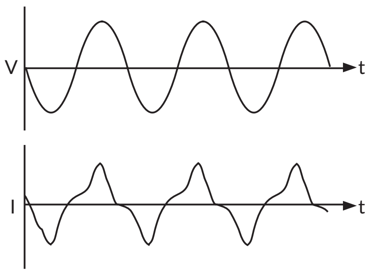
Passive Power Factor Correction

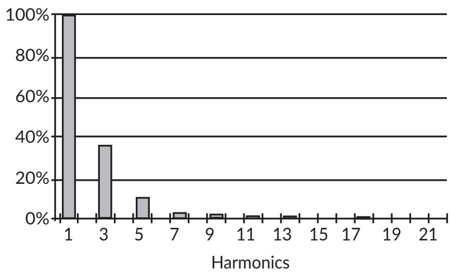
Passive power factor correction involves the addition of a line frequency inductor or resistor into the AC line. The effect of the inductor is to squash the current wave shape as the inductor is a reactive component which resists change in current. The effect of the resistor is to reduce the peak current.



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 300W due to the size of the components required to provide adequate inductance at 50/60Hz 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.

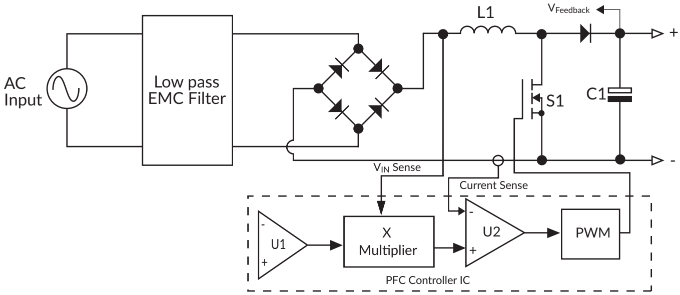




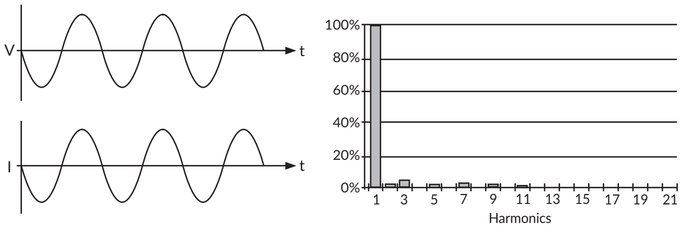
Active Power Factor Correction

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 100kHz 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 400VDC. 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	**Disadvantages**
Simple	Heavy and bulky components
Cost effective	AC range switching required
Rugged and reliable	Low power factor
Noise (EMI)	Cannot use multiple PSUs in a system
Assists filtering	

Active Power Factor Correction

Advantages	**Disadvantages**
High power factor >0.9	Higher cost
Low input current	Higher complexity
Universal input	Higher component count
Regulated high voltage bus	Lower calculated MTBF
Hold up time	
Multiple PSUs can be used	

• 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 simple or 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 $P = V \times I$, 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:

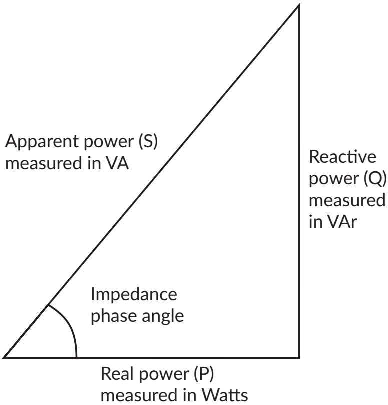
$$P\text{ (W)} = V\text{ (V)} \times A\text{ (I)}$$

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 a 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:

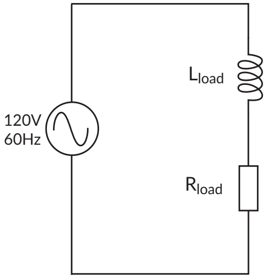
Power (W) = Apparent Power (VA) x Power Factor (PF) or
Apparent Power (VA) = Power (W)/Power Factor (PF)

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 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

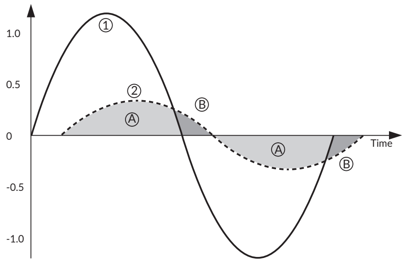


The diagram to the right shows a simple circuit description of a motor load. The load is primarily inductive (motor windings) with a small resistive component (the resistance of the windings).

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

Key:

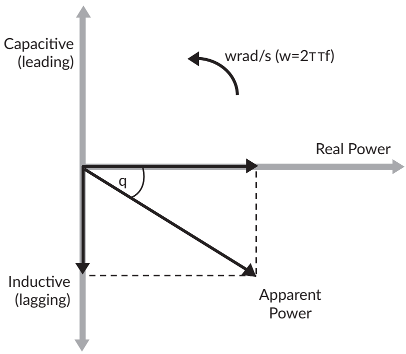
1 Voltage
2 Current
A Real power
B Reactive power



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 A. When voltage and current are out of phase then reactive power is delivered to and returned by the load B.

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

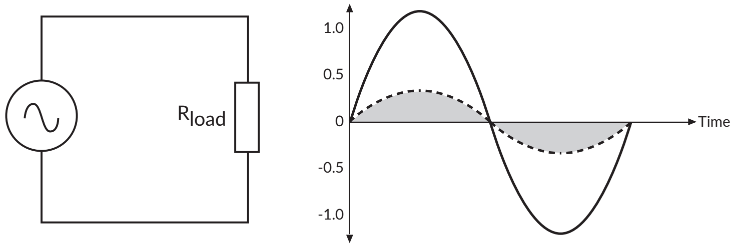
If the triangle has its vertical (reactive portion) positive, then the reactive portion is capacitive. If the vertical is negative then the reactive portion is inductive. If the angle of the opposite is 30 degrees, then the cosine of this angle will give us the power factor of this system:

Cos 30 = 0.87 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.



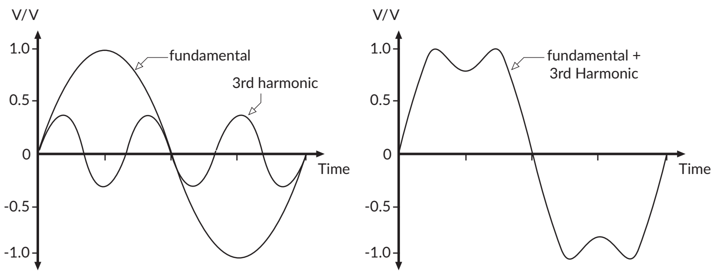
The phase angle between voltage and current is zero, the two elements are in phase.

Cos 0 = 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

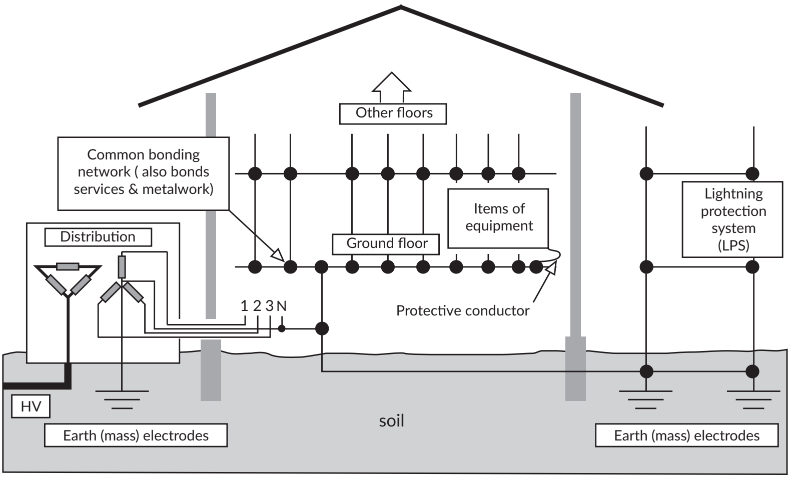
Earth or Ground is a place of zero potential, a place where fault currents can be directed of sufficient capacity to enable fuses to rupture. It is usually the ground beneath our feet and we connect to this in a number of different ways.

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 table below 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	1.5mm	3.2mm
Basic/Supplementary	2.0mm	3.2mm
Double/Reinforced	4.0mm	6.4mm

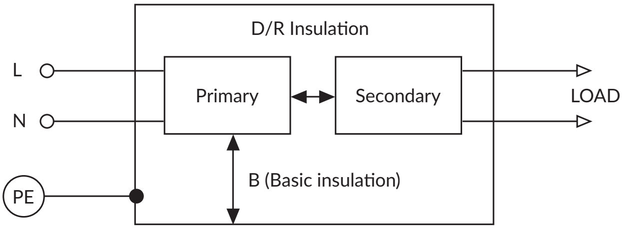
The distances above are based on a 300VAC working voltage. The working voltage is the voltage between the two circuits to be isolated. The lower the working voltage, the lower the creepage and clearance distances required. If the peak working voltage exceeds the peak value of the AC mains supply additional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

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



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

DC Output Considerations

• Output Regulation

Initial Set Accuracy

The initial set accuracy defines the nominal set point of the power supply output, normally under defined conditions such as nominal input and 50% load. Defining the conditions is particularly important in external power supplies when an output cable is employed introducing a voltage drop between the power supply and the connector. A typical tolerance for initial set accuracy is in the range of 0.5% to 1% of the nominal voltage.

Line Regulation

Line regulation is a static performance measure of the change in the power supply output as a result change in the applied input voltage over a specified range, usually the full specified input voltage range from minimum to maximum. Line regulation is normally expressed as a percentage.

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

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

Load Regulation

Load regulation is the static performance measure that defines the ability of a power supply to maintain the output within specified limits over a predetermined load range. Load regulation is normally expressed as a percentage with the load range dependent on the product type and 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
$V_{OUT\,(Max)}$ is the output voltage at maximum output current
$V_{OUT\,(Min)}$ is the output voltage at minimum output current

Cross Regulation

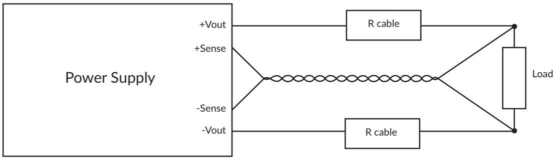
For multiple output power supplies and DC-DC converters a further measure of output accuracy is cross regulation which determines the ability of an output to remain within a specified range for a change in load on another output. It is also expressed as a percentage change but in a different format. E.g., V1 cross regulation = 1% for a 10% change in V2.

Temperature coefficient

The temperature coefficient is a measure of the stability of the output for a change in ambient temperature within the operating temperature range specified for the product. It is generally expressed as a percentage in the form x.xx% / °C

Remote Sense

Remote sense is a feature designed to regulate the output at the load rather than at the terminals of the supply. It is used to compensate for voltage drops between the power supply and the point of use of the output. Power supplies and DC-DC converters with this feature provide two sense connections, one for the positive connection and another for the return, which can be connected at the load, which may be located some distance from the supply itself.



The sense connections monitor and regulate the output at the point of use and adjust the power supply terminal voltage to compensate for variations caused by the impedance of the wiring between the supply and the load. The amount of compensation is typically limited to around 0.5V in total or 0.25V for each of the output & return cables.

Remote sense is normally employed when the load current is variable resulting in an irregular voltage at the point of use. If the load current is constant and therefore the voltage drop is fixed the trim or adjustment feature can be used to compensate for the lead drop. Remote sense connections may also be used to compensate for voltage drops when using ORing diodes or MOSFETS though this may compromise the fault tolerance of redundant systems.

The remote sense leads should be twisted to minimize noise pick up and it may be necessary to employ noise decoupling on the sense connections in noisy environments or where the interconnections are long.

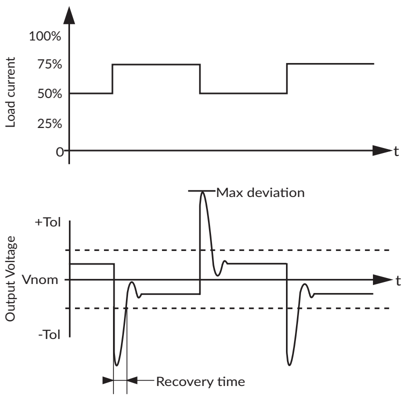
The maximum remote sense voltage compensation is specified in the power supply data sheet and should not be exceeded. Care should be taken to ensure that the maximum power rating is also not exceeded.

Transient Load Response

Transient response is a measure of how quickly and effectively the power supply or DC-DC converter can adjust in response to sudden changes in current demand.

The figure (right) shows the typical response of a power converter to a sudden increase or sudden decrease in load current.

The maximum deviation is a function of the output impedance, and the recovery time a function of the feedback loop speed and compensation. The transient load response is usually specified in these terms following a defined step load change. E.g. 4% maximum deviation, 500µs recovery for a 25% load change.



• Peak Load Applications

Specifying a power converter for systems with peak load requirements that are higher than the normal power requirements for short periods can result in larger, higher power and higher cost product selection. In these applications the average power required is typically significantly lower than the peak demand and, with care, savings in product size and cost can be realized without compromising system reliability or lifetime. Using a power converter that is capable of supporting the peak load but with a lower continuous power rating will result in a physically smaller power supply reducing system size, weight and cost.

For example, in a system that requires 300W for a short duration, using a 200W continuously rated power supply that can support a 300W+ peak load will result in significant savings in volume and cost over a supply rated at 300W continuous output power, provided that the average load is below 200W. The supply must be electrically rated to safely support the peak demand but can be thermally rated at the lower power level.

Applications that require higher peak currents often include some electromechanical elements such as print heads, pumps, motors, and drives. These products are found in factory automation, medical devices, fluid & material handling, robotics, power tools, machining, packaging, test, dispensing systems and printers and have average power demands far lower than the peak power requirements

Some products specify a peak load capability which can be characterized in several different ways outlined below.

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 30% above the continuous current rating. This is essentially a standard design, evaluated and characterized to give short duration headroom over and above the nominal continuous rating. There are applications that where an additional 20-30% of power for short durations is required though electromechanical applications often demand higher peak current for a shorter duration. Taking advantage of these characteristics to support occasional peak power demands results in a smaller lower cost supply but the average power demand must be kept below the maximum continuous rating.

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 200-500µs. This type of peak capability covers a limited range of applications.

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

4. A power supply with the topology and thermal characteristics, designed to support high peak electromechanical loads. Such units may deliver up to twice their nominal power for 10 seconds or more with duty cycles up to 35% for demanding electromechanical applications in industrial process control. XP Power's fleXPower modular power system is one example which allows several standard outputs alongside one that provides a high peak current.

5. Often overlooked when considering peak load applications are power supplies with a convection rating and a higher fan cooled rating. It is not uncommon for such a supply to be rated at up to 50% higher power when fan cooled compared to a naturally cooled environment. These products are generally of open frame or U channel construction and cover power ranges up to 500–600W.

Such products are naturally electrically rated for the fan cooled power rating and thermally rated for the convection cooled power rating, the exact characteristics we need for peak load applications where the peak load is does not exceed the fan cooled rating and the average load is lower than the convection rating, without the noise nuisance of a cooling fan.

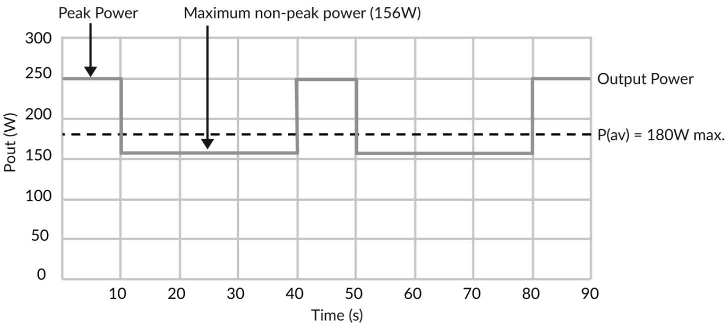
In general the larger the difference between the fan cooled rating and the convection rating the shorter the peak load capability and it is important to ensure that components do not overheat during peak load periods. A benefit for the system designer is that these dual rated products will normally identify key components and their temperature ratings to ensure safe and reliable operation when installed in end applications. This information can be used to ensure that the product will remain safe and reliable in a peak load application by monitoring the temperature of the key parts during the development phase.

The specification will also outline the life time expectations based on key electrolytic capacitor temperatures enabling confirmation of the suitability of the product based on system requirements.

When selecting a power supply for a high peak power application, based on the force cooled and convection cooled ratings, the key parameters are the peak power required, which must not exceed the fan cooled rating, the maximum duration of the peak, the duty cycle and power consumed by the load during the non-peak duration to ensure that the continuous convection ratings of the supply are not exceeded.

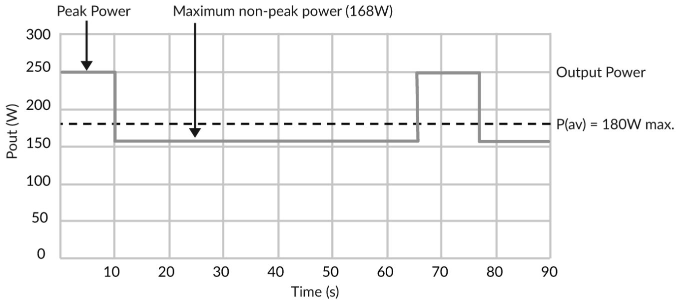
The following example is based on an open frame power supply with a force cooled rating of 250W and a convection or naturally cooled rating of 180W, XP Power's GCS250 series, operating in a convection cooled application where the system requires a peak load of 250W for 10s in every 40s or a duty cycle of 25%. This peak load (Ppk) requirement defines the absolute maximum power consumption during the non-peak period so that the average power does not exceed the convection cooled rating.

In this case the maximum available power during the non-peak duration (Po) will be 156 Watts in order that the convection cooled power rating (Pav) is not exceeded.



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

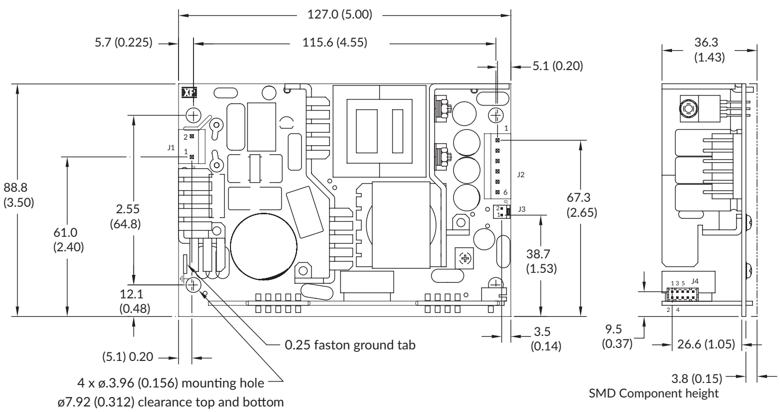
Using the same formula, if the duty cycle is reduced 15%, or 10s in every 67s then the non-peak power can be increased to 168W without exceeding the average continuous convection power rating of 180W.



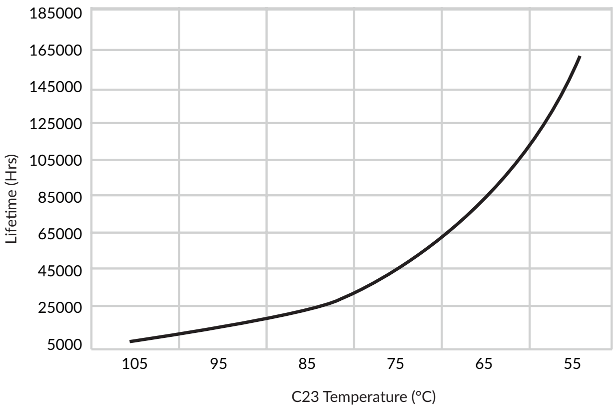
Calculations show that these operating conditions will not exceed the ratings of the power supply. However, we must also consider the key component temperatures of the supply when installed in the unique end equipment to ensure safe, reliable operation over the design life of the end equipment.

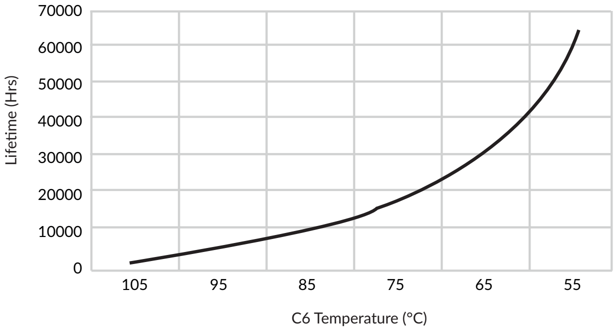
The diagrams below show the maximum temperature of the components for this product to ensure that the safety and reliability requirements are met and the predicted service life of the product based on the average capacitor operating temperature over the life of the equipment can be realized.

In order to ensure safe operation of the PSU in the end-use equipment, the temperature of the components listed in the table below must not be exceeded. Temperature should be monitored using K type thermocouples placed on the hottest part of the component (out of direct air flow).
See below for component locations. (Temperature measurements at ambient 50°C)



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



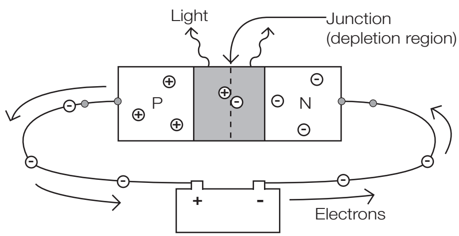


Selecting and evaluating a product such as this, based on the readily available thermal data, rather than one continuously rated for the full peak power results in a smaller, lighter, lower cost solution without compromising the performance, reliability and lifetime of the end application.

• Powering Light Emitting Diodes (LEDs)

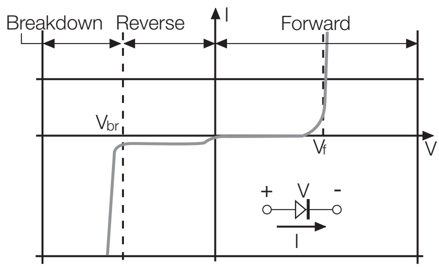
LEDs are used in a wide variety of applications including domestic, street, tunnel, architectural and horticultural lighting, moving signs and traffic signals. Other common applications include data transmission, pulse oximeters, heaters, and ultra-violet curing & sterilisation. They provide more light output per watt than other light sources combined with significantly longer life offering significant reductions in in both running costs and maintenance costs. LEDs are solid state meaning they are also shock resistant.

LEDs function in the same way as a normal diode, current flows from positive to negative, when the junction is forward biased, with electrons flowing from negative to positive. Inside the junction the electrons combine with holes to release light with the color of the light determined by the material employed. The forward volt drop also varies across the color spectrum from around 1.5V, for infrared light, to as high as 3.5V for ultraviolet light.



LED Junction

LEDs have a typical diode characteristic, as shown below, meaning that the LED must be driven from a limited, controlled current source which is most efficiently achieved using a constant or regulated current supply.



Typical Characteristics

Dimming & Control

Many applications require the LED light output to be controlled. This can be achieved by reducing the current through the LED, or LED string, to reduce the light output or by employing a pulsed current from zero to maximum to reduce the average light output at a frequency undetectable by human eye. The current is normally pulsed at a fixed frequency with a variable mark space ratio, known as Pulse Width Modulation (PWM) control.

There are a vast range of power and voltage requirements from a few watts to tens of kilowatts with string voltages from a few volts for a simple light source to hundreds of volts for high power applications such as water treatment, heaters, horticultural lighting, and large format printing & UV curing.

Lower power applications may use simple standard LED drivers, with dimming controls if required, and with either AC or DC input as appropriate.

The higher power applications, which are typically an integral part of a process, require higher voltage power supplies to support string voltages up to 400VDC or more with programmable constant current which can be programmed by the host equipment control system through varying the DC current, or via PWM control to manage the desired power levels employed.

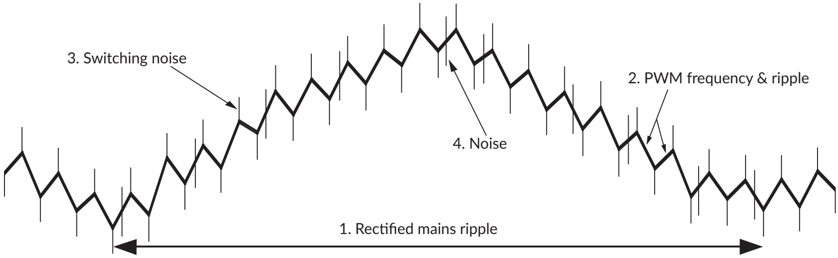
Current Harmonics & Safety

Lighting applications have restrictions on generation of harmonics, due to proliferation, and will need a power supply or driver which complies with the class C limits set out in IEC61000-3-2. Lighting applications also have their own standards for electrical safety such as IEC61347 and UL8750 which applies to LED power sources.

Other applications are typically covered by the class A harmonic limits and the appropriate industrial, ITE or medical safety standards with the power source likely to be approved to IEC62368-1 and/or IEC60601-1.

• 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.

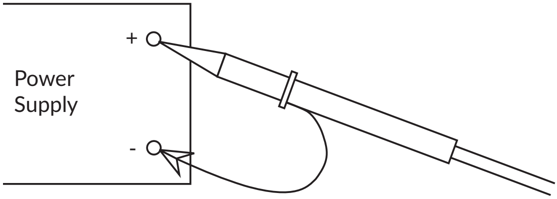
These AC components are normally specified as a peak to peak noise amplitude so that the best method for testing is by an oscilloscope with the bandwidth set as specified in the data sheet, usually 20MHz. Some data sheets also specify a requirement to fit external components to the measurement point,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

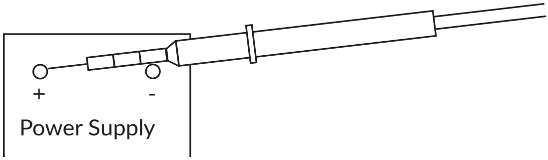
To reduce these measurement errors unshielded leads must be kept as short as possible. The figure below shows the wrong method, because the ground wire of the probe can collect radiated noise and the oscilloscope display is strongly dependent on the probe position and ground lead length.

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 solution and the end equipment. Power converters 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

Fold-back current limit

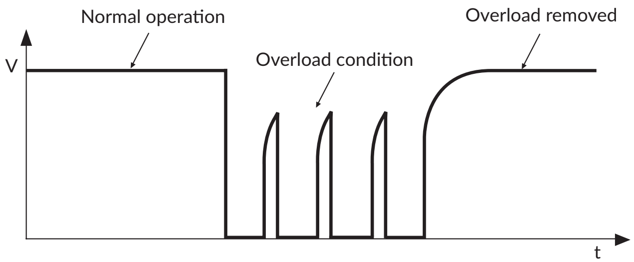
Constant power limit

Constant 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.

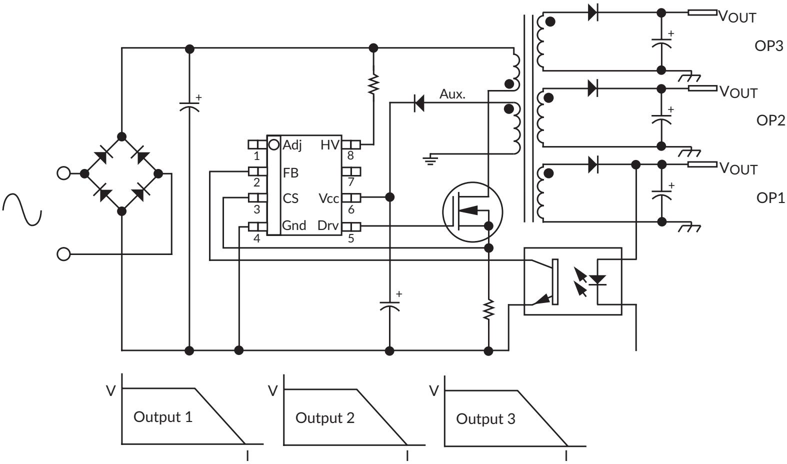


Trip & restart, or 'hiccup' mode

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.

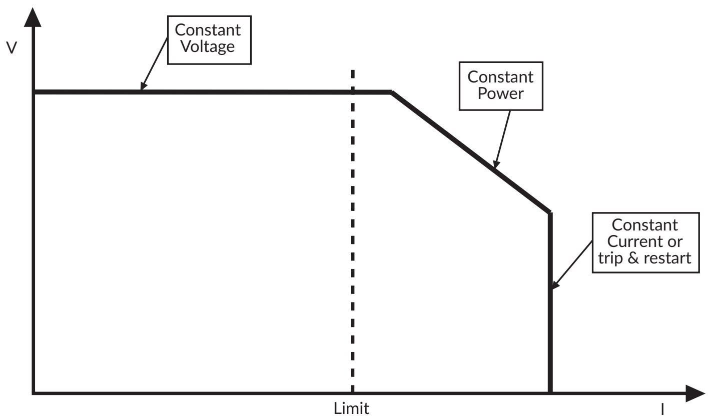
Constant Power Limit

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 power rating is not exceeded.



Multiple output power limit

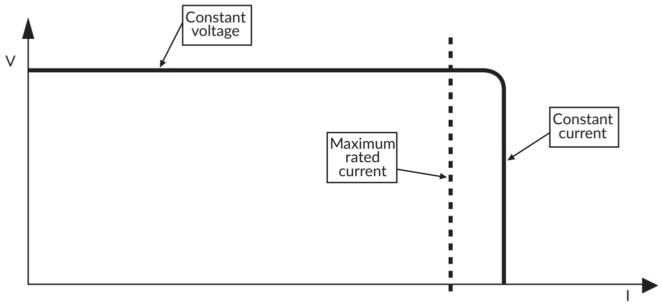
This technique is also used on single output supplies in battery-charging applications as the current is maintained during an overload with the output voltage falling. Normally the constant power output will be maintained until the current reaches a point where damage may be caused, at which point the 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 output current is held constant at a pre-determined level at a point where the maximum load is exceeded. This protection technique accommodates high inrush loads such as large capacitors, lamps, and motors by driving current during the power up phase. The supply will recover to constant voltage mode once the overload condition has been removed.

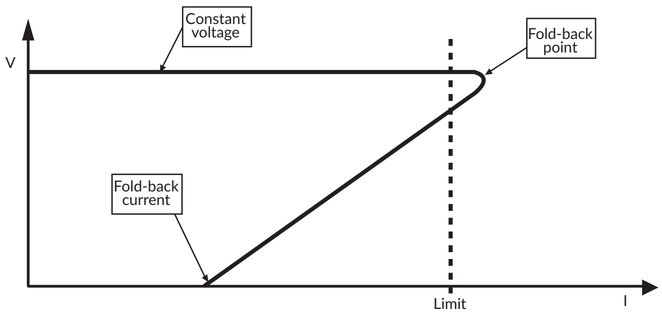


Constant current limit

In programmable power converters, the current limit inception point can be varied over a wide range to create a variable current source to suit applications such as battery charging and management, electrolysis, and LED based systems.

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

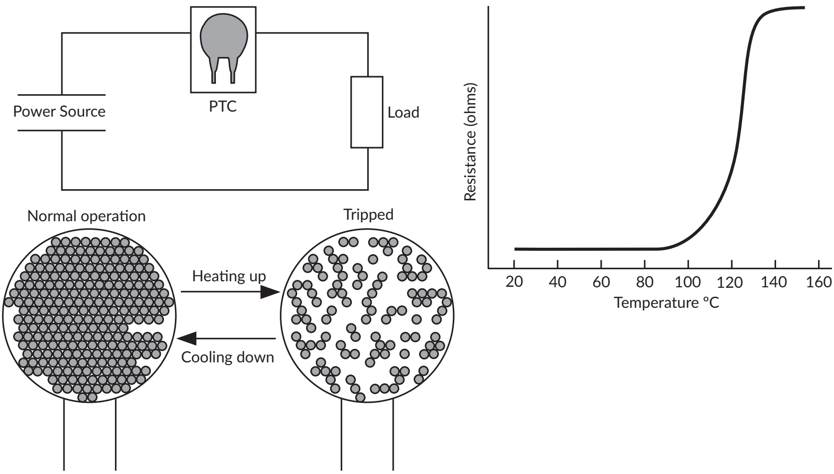
The output voltage will recover once the overload condition is removed, following the overload curve as the load impedance increases.

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.



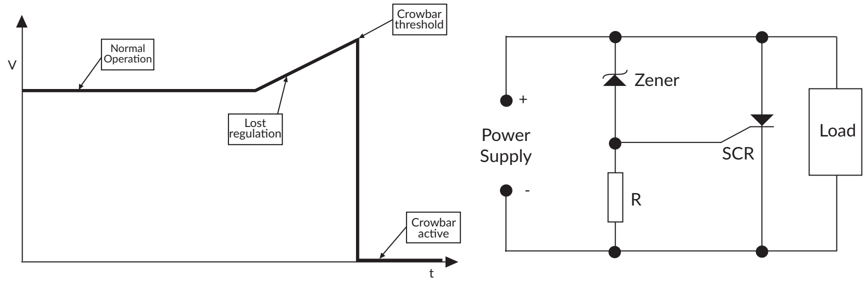
Resetting PTC thermistor fuse characteristics

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 1VDC 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 should 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.

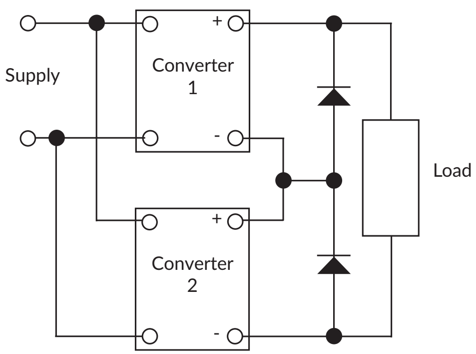
• Series & Parallel Operation

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 and DC-DC converters can be operated with outputs connected in series. Some care is needed to ensure that one 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.



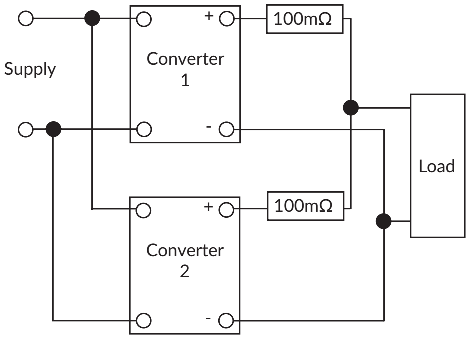
Power supplies with constant current or constant power limit are recommended for series operation. If a power supply with foldback current limit is used, lock-out can occur at switch-on because of the differing ramp-up times of the units. Power supplies with trip and restart or hiccup mode current limits 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 24V, 30V, or 48V 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 or more 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.

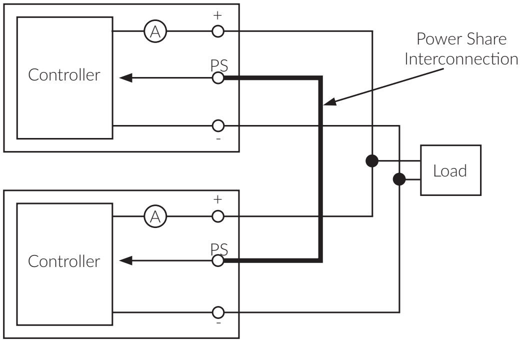
Sharing can be created by adjusting output voltages so that they are as close as possible and matching the impedances of the load cables, i.e. equivalent wire lengths and ring-crimped terminals.



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%.

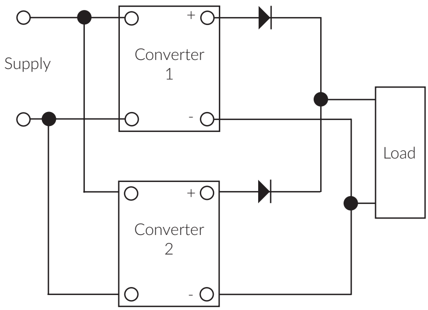
Active Power Sharing

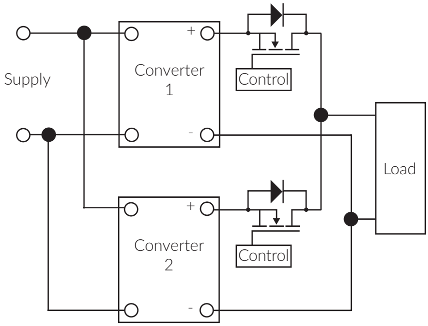
In active power sharing each unit has an additional control terminal through which the power supplies are interconnected. This connection has many different names, the two most common being Power Share and Current Share. This connection enables the control circuits of the two power supplies to communicate 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.



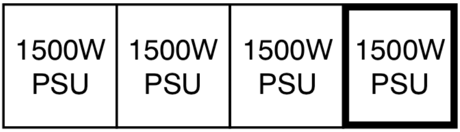


Diodes or MOSFETs can be used in redundant systems so that if one power supply fails the other will continue to operate without the failed power supply pulling down the output rail. Diodes and MOSFETs should always be rated higher than the power supply output current limit.

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 if it is considered to be low enough risk to system fault tolerance.

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 1500W to support the 4500W load and 1 x 1500W unit in redundancy. This solution offers a twenty-fold increase in system reliability.



• Power Supply De-rating

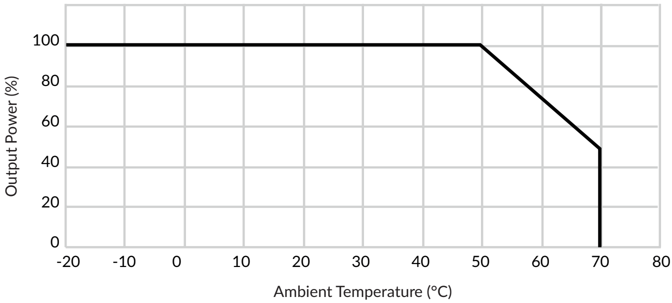
With market pressure on power supply size, power density and cost there are an increasing number of AC-DC power supplies which rely on de-rating specifications to support the headline power rating.

This de-rating information may not be immediately apparent, and the short form or on-line catalogue version of the data may not include this level of detail, so care must be taken when selecting the product to ensure that it is truly suitable for an application.

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

Temperature De-rating

All power supplies have a de-rating curve based on ambient temperature. For embedded products, designed for integration into end equipment, this de-rating typically starts at ambient temperatures in excess of 50°C allowing for an internal temperature rise within the end equipment while maintaining the full specified rating. The output power rating will usually fall to 50% at a maximum of 70°C to support equipment required to operate at particularly high ambient temperature. There can also be de-rating below 0°C based on the ability to start at low ambient temperatures.



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

Some low-cost open frame power supplies 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 power operation at 50°C limited by component specifications, lifetime, and product safety requirements.

While this provides a higher headline power rating and appears to be smaller size or lower cost, when integrated into the end equipment, which itself needs to operate in an ambient temperature of 40°C, the available output power can be reduced by 25% or more. This means that such a product with a headline power rating of 100W is actually a 75W product in practical terms and cannot be considered comparable to other units of the same power that are rated for 50°C operation.

Input Voltage De-rating

Products designed for world-wide operation have a universal input range typically covering 90-264VAC or higher. 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 input voltages down to 85 or 80VAC to cover critical medical device applications and operation in areas where the AC supply is particularly low or prone to brownout.

It has become common place for lower cost and higher power density products to specify de-rating for low line input voltages with de-rating of up to 25% when operating down to 90VAC.

If the end application is required to operate globally, a higher power version of the product could be required. Put another way a power supply with a headline rating of 100W can only be rated at 75W under low line conditions.

Input voltage de-rating is employed to mitigate overheating in the input filter, bridge rectifier & PFC boost converter as the unit input current increases. Some losses increase proportionally to the current but resistive losses in filter inductors 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 may result in reliability and lifetime problems.

Combined De-rating

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

Practical Effects of De-rating

While the specification requires de-rating under certain line voltage and ambient conditions the power supply will not usually 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 isolation barriers are exceeded.

• Status Signals and Controls

Status signals and controls enable remote monitoring and remote control of the power converter via signal level status indicators and inputs and/or through digital interfaces. Where a digital interface is employed, it is usually in addition to the conventional analog interfaces and typically allows the user to determine whether they are active high or active low.

Signals report information from the converter and controls allow for changes in parameters or function.

Common status signal outputs include power fail or AC OK, DC OK, power good, fan fail, fan speed and over temperature. Controls include remote on/off (inhibit or enable), voltage & current programming, voltage trimming, current share, and remote sense. Remote sense is discussed separately in the output regulation section.

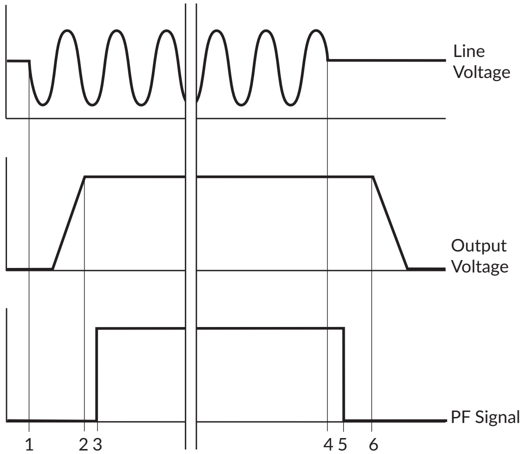
Separate standby supplies are provided in many higher power & more sophisticated products providing an output which is always present when the input supply is present. This supply is available for powering system standby & logic circuits and for configuring signals and controls.

Power Fail (PF) or AC OK

Power Fail and AC OK are typically the same thing. In most cases, they are a measure of the internal DC bus voltage rather than the actual AC supply and may require the converter to be running, due to measurement on the converter secondary side via the power transformer.

Measuring the internal DC bus voltage is advantageous as it negates nuisance alarms due to short mains interruptions and is set to change status several milliseconds before the output falls, allowing time for data saving routines to be implemented in the end equipment.

It is unusual for this to be an actual measurement of the AC input voltage as fault detection is likely to be too slow, though some digital power supplies have the facility to report the input voltage via the communications interface.



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 & Power OK

DC OK signals indicate that the DC output is within the specified tolerance. A typical application is to ensure that the DC output is present and correct prior to enabling the load or to detect unit/ output failure in a redundant system. The DC OK signal will also change state if the converter is in an overload condition, has shut down due to overvoltage protection or has been disabled by a remote signal.

When combined with a power fail signal, controlled start-up & shut down routines can be readily applied in the end application and these two signals are sometimes combined within the power converter to provide a single Power OK or Power Good signal to the user.

Fan Fail, Fan speed and Overtemperature

Products that employ an integral fan often provide information regarding the status of the cooling fan and/or internal temperature warnings & shutdown. The most sophisticated may be able to warn of impending fan failure and report actual fan speed and internal temperatures, usually via a digital interface, while others may simply detect the internal temperature of key components & shut down the supply in the event of an excessive temperature being detected.

With power products increasingly providing variable speed fans, to reduce audible noise and extend lifetime, understanding the fan(s) status has clear advantages in terms of system reliability and service or maintenance requirements.

Remote On/Off

This interface is used to switch the output supply of a power converter on and off via a signal level control, without the need to switch either the input or output power lines.

By using Remote On/Off control, input inrush current is limited to first switch on, the DC output supply is managed via signal level components and the power up response time is reduced from 1 – 2 seconds to just tens of milliseconds.

When using multiple output configurable power supplies, the outputs can be switched on and off independently enabling output sequencing control where desired.

Remote On/Off interfaces are categorized as remote inhibit or remote enable. In remote inhibit configuration the user intervenes to switch the output off. When configured as remote enable, the output is not present when input power is applied until the user intervenes. Remote enable is advantageous in systems requiring fail safe operation of the output.

Where digital control and interfaces are employed, it is usually possible for the user to select the Remote On/Off configuration via software control. It is also possible for the output to be controlled via software command though this is normally overridden by the signal level control to ensure fail safe operation in the event of a communication error.

Voltage & Current Programming

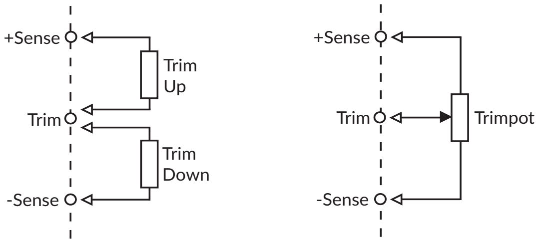
Output programming allows the user to adjust the output voltage and current limit through signal level analog controls, external variable resistance or via software where a digital interface is employed. In products with a constant current overload characteristic, programming can be used to create a programmable, variable current source to suit applications such as battery charging & management, electrolysis, and LED based systems.

Typical analog controls employ 0-5V, 0-10V or 4-20mA inputs for a specified full-scale change in output voltage or current with ranges as wide as 0-110% available in the most sophisticated products. Power converters employing digital control can be programmed through software and can also report back the voltage and current level via the digital interface for closed loop control systems. Additionally, they allow the user to set appropriate alarms, protection levels and responses for the end application.

Output Voltage Adjustment & Trimming

The most common means of adjusting the output of a power converter is via an available adjustment potentiometer which allows the user to adjust the output by a few percent to as much as ±10% depending on the topology employed. In general, high efficiency resonant designs are less tolerant of output adjustment.

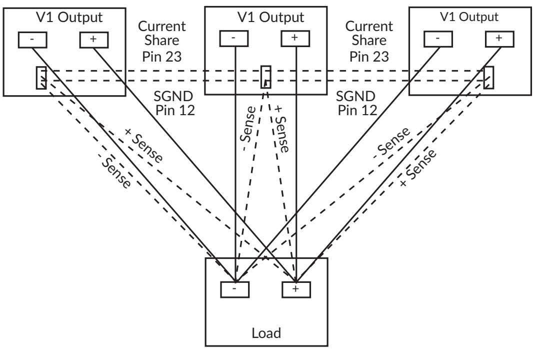
Another common method of output voltage adjustment, often used in encapsulated DC-DC converts is voltage trimming, via an external potentiometer or resistor(s) connected via the trim interface, an example of which is shown below.



Current Share, Power Share or Single Wire Parallel

Current, power, or Single Wire Parallel (SWP) connections have a common function. The interface is used for parallel power converters to communicate to distribute the load among the available resources within a specified tolerance, typically between ±3% and ±10%. The total power drawn from the parallel supplies should be de-rated by the sharing tolerance to ensure that no individual power supply can be overloaded.

The power converter data sheet or application notes will specify the actual connections needed, the sharing tolerance and often a maximum number of parallel units. Additional connections are likely to be a signal ground, to improve accuracy, and, in more sophisticated systems, a connection to synchronise power up of parallel units to avoid circulating currents. An example is shown below.



The current share connection interfaces with each power supply comparing the output current and adjusting the output voltage of individual until the current is equally distributed. This sharing interface is ideal for scalable power systems and may be deployed in redundant power systems if it is considered a low enough risk to system fault tolerance.

Common Topologies For Signal & Control Interfaces

Signal outputs and control inputs are presented to the user in a number of topologies varying from converter to converter and manufacturer to manufacturer.

Analog signal interfaces may employ internal pull up resistors to 5V or 3.3V, they may be open collector or open drain referenced to a signal ground, and they may be isolated, uncommitted opto-coupler transistors providing an isolated output connection.

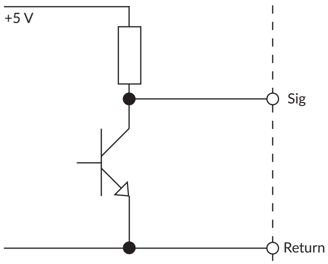
Analog control interfaces may require simple pull-up or pull-down connections referenced to a signal ground, they may require the application of an external voltage or current, and they may be uncommitted opto-coupler diodes providing an isolated input connection.

Common digital control interfaces include serial buses such as I^{2}C, RS485, RS232 and UART with protocols such as PMBus, Modbus, CANopen and SCPI, which may be isolated or referenced to a signal ground. Network interfaces such as EtherCAT & DeviceNet are also commonplace in some applications, such as semiconductor fabrication.

Signals With Internal Pull Up

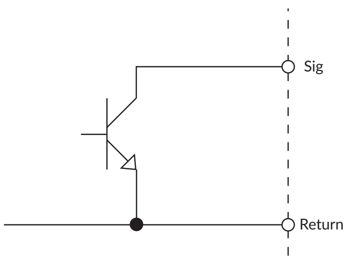
These signal interfaces are designed to work with 3.3V or 5V logic systems and can be active high or active low.

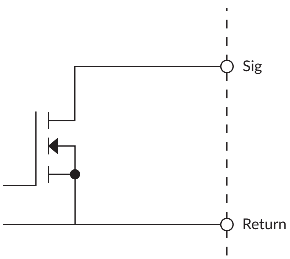
They are typically formed from bipolar transistor or MOSFET with a pull up resistor to an internal 3.3V or 5V internally generated supply and referenced to an internal signal ground. Right is an example of a 5V signal interface.



Open Collector or Open Drain Signals

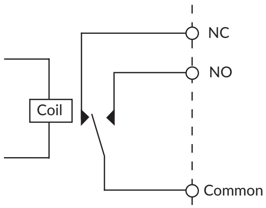
Open collector or drain signal interfaces comprise a bipolar or MOSFET signal transistor with the emitter or source connected to an internal signal ground and the collector or drain floating. This configuration enables the user to connect the signal to an external reference using external components to suit the application demands, the limit being the voltage and current rating of the signal device. Signals may be active high or active low.



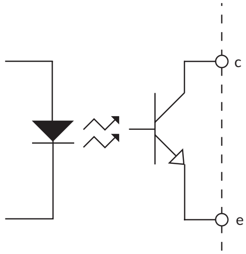


Isolated Signals

Isolated signal outputs are generally provided as opto-coupler transistors, allowing the user to configure as either high or low as the application demands. They may also be provided as volt free relay contacts. They are generally small signal relays able to switch up to 1A at 24VDC or 0.5A at up to 120VDC.



Relay signal output



Opto-coupler signal output

A benefit of isolated signals is that they can be combined into a single warning when using multiple converters in series or parallel combinations and can be referenced to a common signal ground for the end equipment interface, regardless of positive or negative output configuration.

• Digital Communication Interfaces

PMBus

One of the most commonly used power supply interfaces is PMBus (Power Management Bus) is an open power system protocol with a defined language, used to provide programming, control, monitoring and communications between power converters and other devices in a system over an I^2C (inter-integrated circuit) serial bus. The PMBus protocol is implemented using SMBus (System Management Bus), an industry standard serial interface for system management communications. It is a standard protocol in XP Power's digital power solutions.

Modbus

Modbus is an open data communication protocol used for connecting industrial electronic devices transmitted over a serial bus, such as RS485 or RS232 which define the signal levels employed. Originally designed for use with programmable logic controllers it has become a standard protocol for industrial electronics applications and is widely supported in XP Power's digital power products.

CANopen

CANopen is a communication protocol and device profile specification largely used in automation applications and is supported in XP Power's digital power solutions. It uses the Controller Area Network Bus (CANBus) serial bus designed for industrial environments and is also used in transportation applications.

SCPI

Standard Commands for Programmable Instruments (SCPI) is designed for controlling test and measurement instruments and devices and can be used with RS232 & RS485 serial communication buses. It is used for programmable electronic test equipment and automated test equipment and is supported by both laboratory power supplies and XP Power's embedded programmable products.

DeviceNet

DeviceNet is an open network protocol, managed by ODVA, used for data exchange between interconnected industrial devices on a Controller Area Network (CAN), using the Common Industrial Protocol (CIP). It has been standardized in IEC62026-3 and is optional in XP Power solutions

EtherCAT

EtherCAT (Ethernet for Control Automation Technology) is an ethernet based fieldbus protocol. Used for automation systems that require short data cycle times in real time distributed control, it is standardized in IEC61158 and is an option in XP Power solutions.

Digital Signals, Controls, And Status Information

Depending on the individual implementation, digital communication allows the user to access information such as the manufacturer's build data, serial numbers, firmware revisions, run times and event logs. It may also allow some, or all of the following features: -

- Voltage, current & temperature monitoring
- Voltage and current control
- Fan speed control & monitoring
- Fault & status monitoring
- Fault and warning limit setting such as Overvoltage Protection (OVP), overcurrent protection (OCP), overtemperature protection (OTP) and input over and undervoltage protection
- Fault response setting
- Output on/off control
- Setting of ramp-up times & soft start configurations
- Active high or low alarm setting

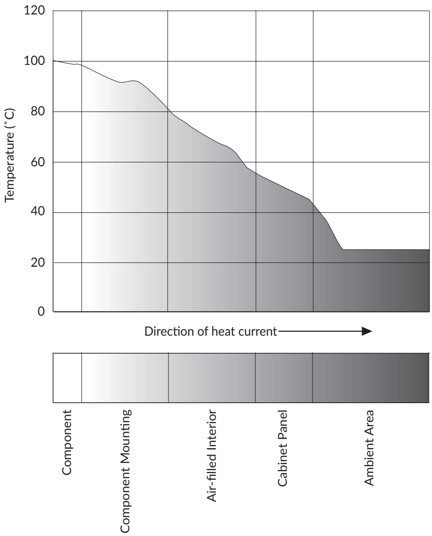
Manufacturers will typically provide a Graphical User Interface (GUI), for development purposes and configuration of application specific requirements, along with comprehensive communication, control, and status specifications for the development of interface software.

The provision for analogcontrol of digital power is usually also provided for systems that use traditional 0-5V or 0-10V control signals by the implementation of an Analog to Digital Converter (ADC) within the power supply and all alarms & controls can usually be accessed through conventional connections as well as digitally through the communications bus.

Thermal Management

Power losses occur in all electronic components, sub-assemblies, and equipment. The effect of the power losses is greater as size is reduced and more components are used in tighter spaces for miniaturization. This leads to more power dissipation and waste heat per volume of space, offset by enhanced component performance and improved efficiency.

Power losses are typically in the form of heat and are expressed in Watts. The heat generated by component losses is passed into the surrounding environment and is also absorbed by surrounding components, printed circuit boards and equipment enclosures. The waste heat affects the performance of the adjacent components raising their operating temperature and reducing their reliability and service life.



Temperature gradient of a device to ambient

In some applications convection or conduction cooling are employed, to minimize nuisance audible noise or to prevent pollution ingress, in others the use of a cooling fan, or cooling fans, is employed at the power supply and/or system level.

• System Cooling Fan Selection

Allowable Temperature Rise

The maximum temperature in which the power supply and/or system electronics can safely operate and the specified maximum ambient temperature for the system, determine the allowable temperature rise within the system enclosure. Typically, power converters are specified to a maximum ambient temperature of 50°C, when operated at full load with derating for higher temperatures. If the system is to be operated in a non-air-conditioned environment, where the ambient temperature could be up to 40°C, then the maximum allowable internal temperature rise would be 10°C.

Power Dissipation

If the system has all of the load within the enclosure, then the power dissipated will be the system load dissipation and the power dissipated by the power converter due to its inefficiency. For example, If the load dissipates 260W supplied by an 85% efficient power converter then the total power dissipation would be: -

260 + [(260/0.85) – 260] = 260 + 46 = 306W

Once the allowable temperature and power dissipation have been established, the airflow required through the system can be estimated by

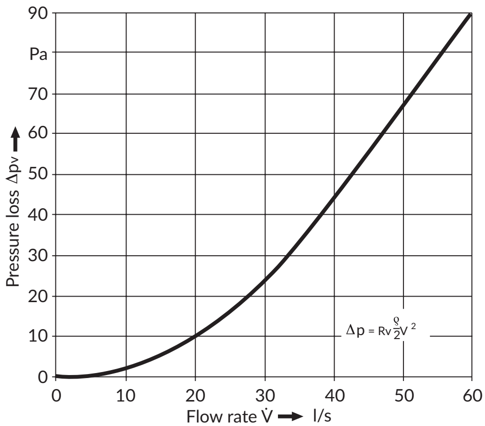
$$\textbf{Airflow (m}^3\textbf{/hr)} = 2.6 \times \frac{\textbf{Power dissipation (W)}}{\textbf{Allowable temp. rise (°C)}}$$

Fan suppliers often specify the airflow in Cubic Feet per Minute (CFM). To convert m^3/hr to CFM we need to multiply by 0.589. In the example above this would be: -

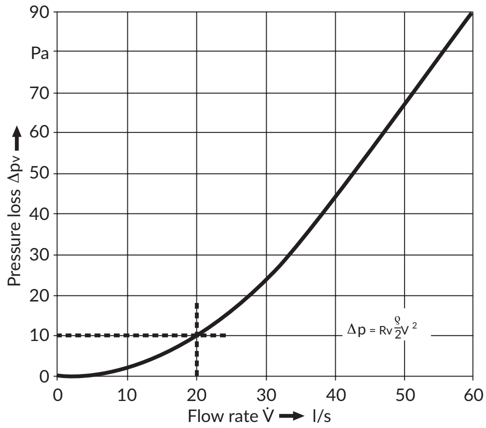
$$\textbf{Airflow} = 2.6 \times \frac{306}{10} = 79.56\,m^3/hr \text{ or } 46.86\,CFM$$

Characterization of Equipment Pressure Drop

Specified airflow for equipment fans is given in free air. The system components, sub-assemblies and enclosure present resistance or back pressure to air movement which changes with each unique design due to the positions & size of the internal construction. There is an approximation to back pressure which can be applied which is an average based on accumulated historical data from fan manufacturers applicable to most electronic equipment, as shown in the graph below. The graph plots the flow rate in liters per second against the back pressure in pascals.

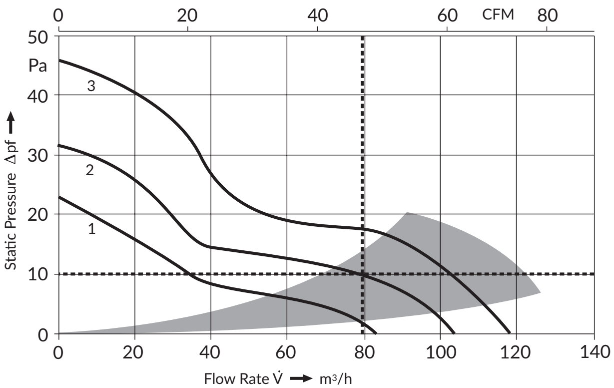


This can be used to estimate the system back pressure, where $1m^3/hr = 0.278 l/s$ or for the example above approximately 10 Pascals.



Fan Characteristic Curves

Using 10Pa as the back pressure with a required flow rate of 79.56m³/hr and the fan characteristic graph below, which shows the optimum performance in the shaded area, we would select fan 2 as the suitable system cooling 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. Force 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 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 250W while the force cooled version may have a rating as high as 500W.

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.

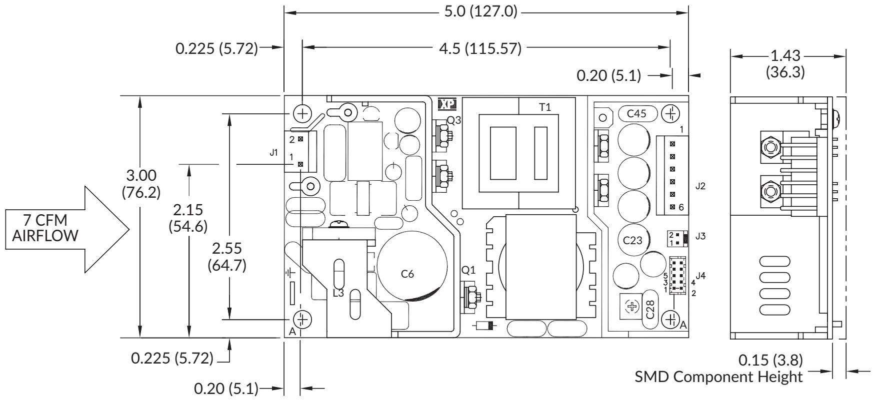
Forced Cooling

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 a 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 7CFM 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 = 236LFM or 1.2m/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

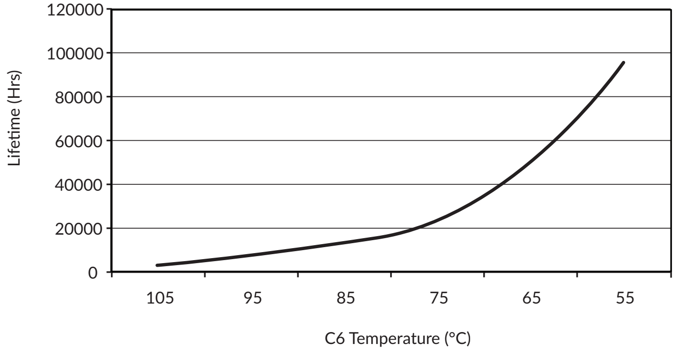
The object is to maintain the components used within the power supply at a safe operating temperature and to ensure adequate service life. Given the huge potential for variation between one application and another, the only real test is measurement of the temperature of the critical components within 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.

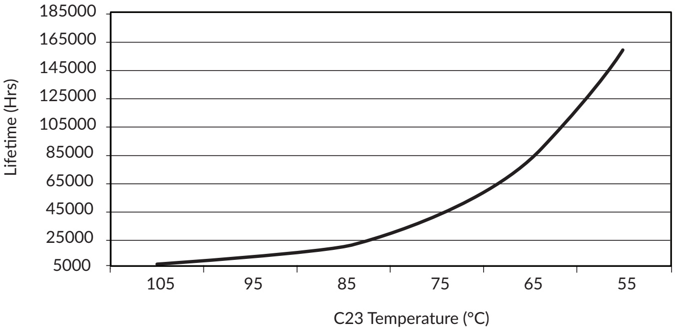
The criteria for safe operation will be specified for the power supply in question or can be obtained from the manufacturer. For the example above, the specific component temperatures for safe operation are given on the next page; these are typical for a power supply of this type.

Component	Max Temperature
T1 Coil	120°C
L3 Coil	
Q1 Body	
Q3 Body	
C6	105°C
C23	

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.

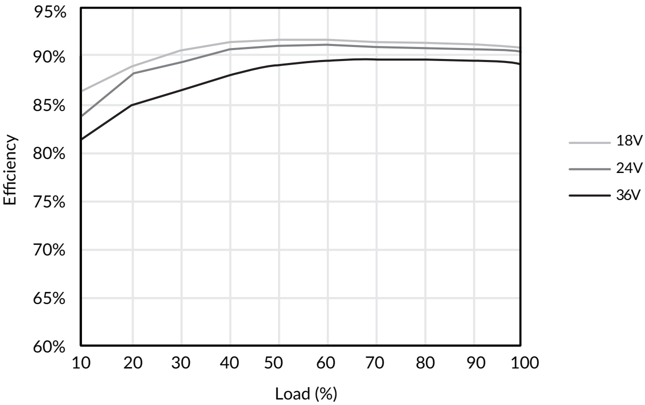




• Cooling Power Modules

Thermal management is a key element in the integration of baseplate cooled AC-DC or DC-DC power modules which are designed to be baseplate cooled. The power module is designed with the power dissipating components thermally bonded to the baseplate, which must then be maintained below the maximum operating temperature under the worst-case conditions of the end system. The thermal resistance of the cooling scheme must be matched to the power required by the load or end equipment, the efficiency of the module and the maximum temperature in which it is expected to operate.

The power dissipated, in Watts, can be determined from the power module efficiency specification under the worst-case operating system conditions. It is important to consider the actual operating load and lowest input voltage applied rather than the data sheet headline efficiency. An example of the variation in efficiency with input voltage and load is given below: -



Once the efficiency at the worst-case operating point is established the waste power to be dissipated as heat is calculated as below: -

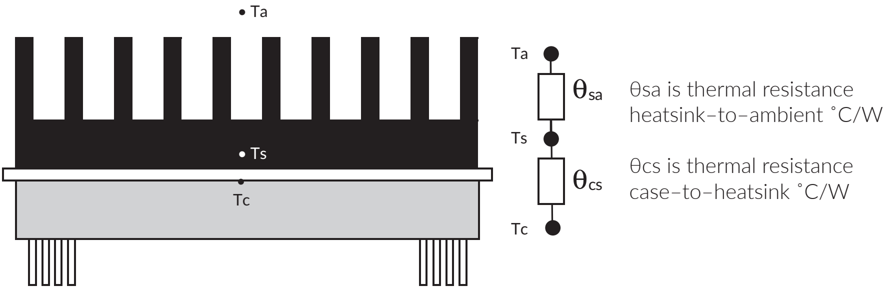
$$\text{Waste Heat} = \left(\frac{1 - \text{Eff\%}}{\text{Eff\%}} \times \text{Pout}\right) \text{Or} \left(\frac{1}{\text{Eff\%}} - 1\right) \times \text{Pout}$$

Having determined the waste heat/power, the simple model overleaf determines the thermal resistance required for operation with ΔT defined as the difference between the maximum operating temperature of the equipment and the maximum baseplate temperature of the power module. The thermal resistance from the case to heatsink is typically 0.1°C/W when using a thermal pad or grease.

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

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:



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 θca.

$T_C = T_A + P_D\,(\theta CA)$

where	T_C =	maximum power supply temperature
	T_A =	ambient temperature
	P_D =	power dissipation
	θca =	case to ambient thermal resistance

The thermal resistance of the heatsink to ambient is heavily dependent on available airflow meaning that in convection cooled applications it’s physical size will be greater than in a comparable power system with forced air or liquid cooling.

When utilising multiple bricks connected to a common heatsink or cold wall the sum of the dissipated power from each brick in the system under worst case conditions determines the overall thermal resistance required.

• 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.

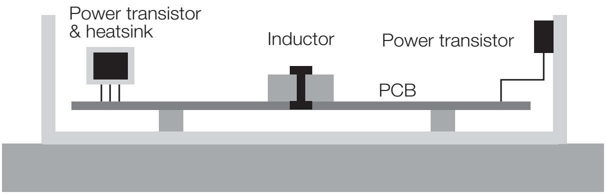
Under these conditions, it is generally accepted that electronic systems must be sealed against the elements making the removal of unwanted heat particularly difficult. The use of forced-air cooling is undesirable as it increases system size, adds the maintenance issues of cleaning or replacing filters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

Remote 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.

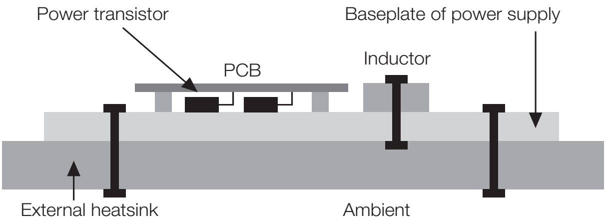
Conventional power supplies dissipate heat into small on-board heatsinks or onto a chassis. The basic construction is shown in below. Most of the heat is dissipated within the enclosure in which the power supply is used. Such units typically have to be derated from 50°C, delivering 50% of their full 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

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 EMC filter inductions the power FET diode 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 baseplate that in turn can be affixed to a heatsink, rather than on to the PCB. 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 increasing manufacturing complexity and cost.

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:

$$\text{Waste Heat} = \left(\frac{1 - \text{Eff\%}}{\text{Eff\%}}\right) \text{x Pout} \text{ or } \left(\frac{1}{\text{Eff\%}} - 1\right) \text{x Pout}$$

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 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.

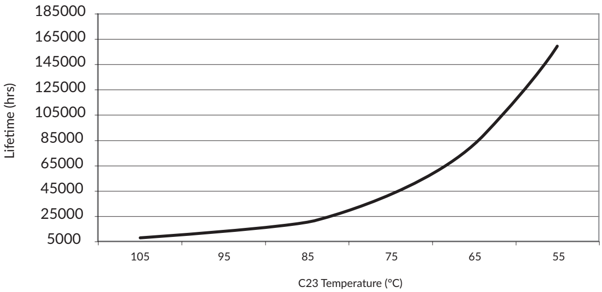
Ambient Temperature And Local Heating Effects

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 mission profile, 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 assuming operation is 24hrs per day, 7 days per week. 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°C	2000hrs (0.23 years)	5000hrs (0.57 years)
95°C	4000hrs (0.46 years)	10000hrs (1.14 years)
85°C	8000hrs (0.91 years)	20000hrs (2.28 years)
75°C	16000hrs (1.82 years)	40000hrs (4.56 years)
65°C	32000hrs (3.65 years)	80000hrs (9.31 years)
55°C	64000hrs (7.30 years)	160000hrs (18.2 years)*

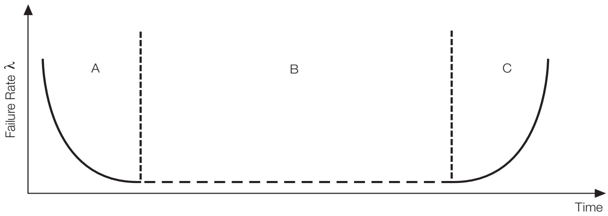
*Lifetime calculations above 15 years should be considered as 15 years maximum

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.to a capacitor rated at five thousand hours at various temperatures assuming operation is 24hrs per day, 7 days per week. If the lifetime is calculated or indicated to be in excess of fifteen years then it should be assumed as fifteen years.



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

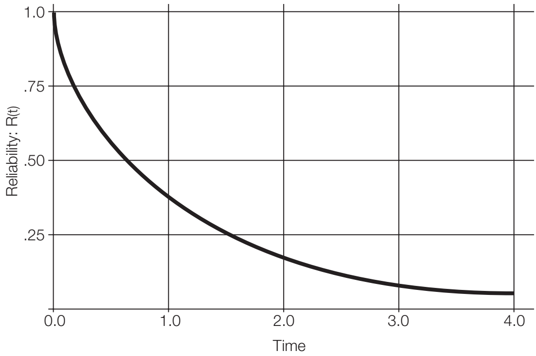
$R_{(t)}$ = e-1 = 0.37

This equation can be interpreted in a number of ways:

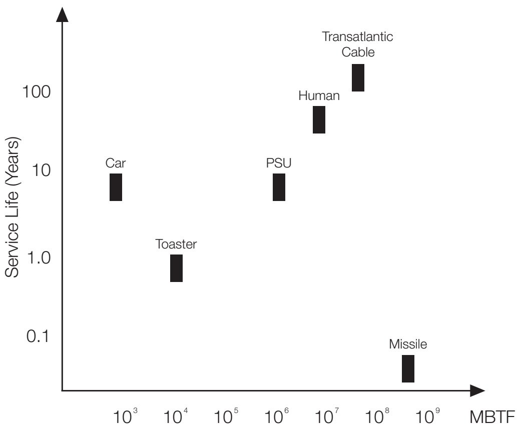
a) If a large number of units are considered, only 37% of them will survive for as long as the MTBF figure.

b) For a single unit, the probability that it will work for as long as its MTBF figure is 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 500,000hrs (or a failure rate of 0.002 failures per 1000hrs), Using the above equation, $R_{(t)}$ for 26,280hrs (three years) is approximately 0.95 and if such a unit is used 24hrs 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 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 increase with 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 two databases in common use: MIL-HDBK-217F for the defence industry and Telcordia for telecommuncation and commercial products.

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 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, Telcordia gives the most favourable result, 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. 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 61 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 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 200,000hrs and another states 3,000,000hrs 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 or DC-DC converter 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, 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 and DC-DC converters for building in to end equipment. However, most power supplies and DC-DC converters use one or more of the following standards to demonstrate compliance for safety:

IEC/EN/UL62368-1 - Audiovisual and information technology equipment

IEC/EN/UL60355-1 - Household and similar electrical appliances

IEC/EN/ES60601-1 - Medical electrical equipment

IEC/EN/UL61010-1 - Measurement, control & laboratory equipment

UL508 - Industrial control equipment, often used for DIN rail power supplies

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 J55032 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 KN32 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

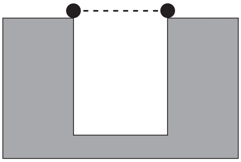
An electrically safe system relies on the use of safety earthing, the insulation of hazardous voltages and the control of leakage currents.

Insulation

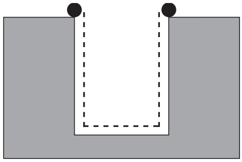
The five different types of insulation grades are listed below.

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

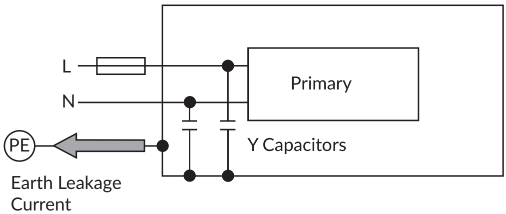
Earthing/Grounding

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.

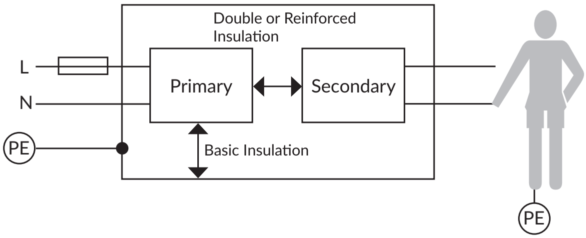
Earth Leakage Current

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 specific safety standard. Within the power supply the main contributors to the earth leakage current are the EMC filter Y capacitors.



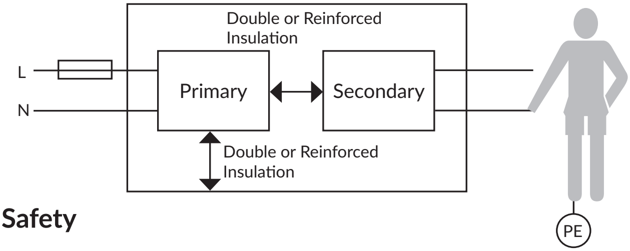
Class I Systems

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 devices and IEC60601-1 is the cornerstone standard addressing the risks and requirements for medical device safety. The standard covers equipment, provided with not more than one connection to a particular mains supply and intended to diagnose, treat, or monitor patients or for compensation, alleviation of disease, injury, or disability. It also covers applied parts, the part of the medical device which, in order for the medical device to perform its function, deliberately comes into direct contact with a patient or has parts which are likely to come into contact with the patient during normal use.

Applied Parts

The 60601-1 suite of standards defines Applied Parts according to the type of patient contact and the type or nature of the medical device. The current version of 60601-1 is the 3rd edition which was first published in December 2005 has been adopted in all major countries and regions of the world as the following latest versions:

IEC 60601-1: Edition 3.1, 2012-08
Europe : EN 60601-1: 2006 + CORR: 2010+A1 (2013)
USA: ANSI/AAMI ES60601-1 (2005 + C1:09 + A2:10+A1(R2012))
Canada CAN/CSA-C22.2 No. 60601-1 (2008)+A1 (2014)

Each classification within the standard has requirements for protection against electric shock. The three classifications are detailed below, in order of the least stringent to the most stringent:

Type B (Body)

Type B classification is given to applied parts with are generally not conductive and may be connected to Earth.

Type BF (Body Floating)

Type BF classification is given to applied parts which are electrically connected to the patient and must be floating and separated from Earth. This classification does not include applied parts which are in direct contact to the heart.

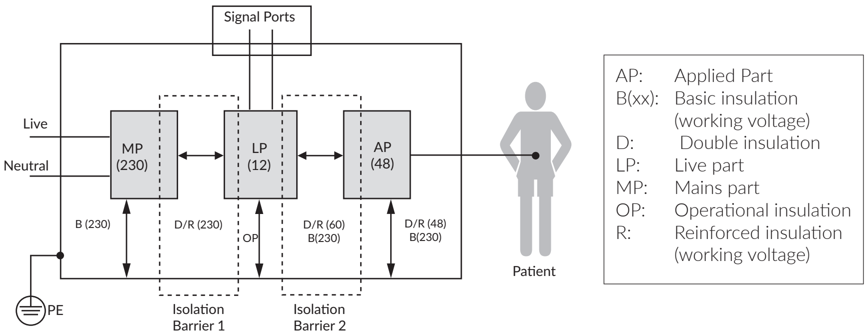
Type CF (Cardiac Floating)

Type CF classification is given to applied parts suitable for direct cardiac connection. This means connection to the heart of the patient including intravenous connection such as dialysis. These applied parts must be floating and separated from Earth.

Isolation Requirements

Patient connected medical devices are required to provide two Means Of Protection (MOP) to prevent applied parts and other accessible parts from exceeding the limitations of voltage, current or energy. A compliant protective earth connection provides 1 x MOP, basic isolation also provides 1 x MOP & Reinforced isolation provides 2 x MOP. Means of protection can be categorized as Means of Operator Protection (MOOP) or Means of Patient Protection (MOPP). In devices intended for patient connection 2 x MOPP are required. Power architectures for use in medical devices with type BF & CF classification are required to provide 2 x MOPP from primary to secondary, 1 x MOPP from primary to earth and additional safety isolation from the secondary output of the power system to earth also rated at 1 x MOPP, all at the (highest rated) incoming AC line voltage.

Once the type of medical device has been defined an isolation diagram can be constructed identifying the main primary circuits, secondary circuits and applied parts allowing different concepts to be analyzed to achieve the required means of protection. Following is a typical isolation diagram for a power system meeting the requirements for a BF & CF applied part. Isolation barrier 1 is contained within a standard, medically approved, 230VAC to 12VDC power supply. Isolation barrier 2 is contained within a 12VDC to 48VDC medically approved DC-DC converter.



Typical medical device with patient connection

The table below outlines the creepage & clearance distances required for both MOOP and MOPP and the test voltages to be applied based on 250VAC working voltage.

Insulation	**MOOP**			**MOPP**		
	Air Clearance	**Creepage Distance**	**Test Voltage**	**Air Clearance**	**Creepage Distance**	**Test Voltage**
Basic (1 x MOP)	2.0mm	3.2mm	1500VAC	2.5mm	4.0mm	1500VAC
Double or Reinforced (2 x MOP)	4.0mm	6.4mm	3000VAC	5.0mm	8.0mm	4000VAC

Insulation test voltages based on 250VAC working voltage

KEY: MOP: Means of Protection, **MOOP**: Means of Operation Protection, **MOPP**: Means of Patient Protection

Leakage Currents

Additionally, the power system must be designed to limit the touch current, patient auxiliary current and patient leakage current. For example, in BF applications the maximum allowable values for the touch current are 100µA in normal conditions and 500µA in a Single Fault Condition (SFC), which effectively limits the system earth leakage current to 500µA in normal operation. The maximum allowable patient auxiliary current and patient leakage currents are defined in the table below.

Insulation	Description		Type B Applied Part		Type BF Applied Part		Type C Applied Part	
			NC	SFC	NC	SFC	NC	SFC
Patient Auxilliary Current		d.c.	10	50	10	50	10	50
		a.c.	100	500	100	500	10	500
Patient Leakage Current	From PATIENT connection to earth	d.c.	10	50	10	50	10	50
		a.c.	100	500	100	500	10	500
	Caused by an external voltage on a SIP/SOP	d.c.	10	50	10	50	10	50
		a.c.	100	500	100	500	10	500
Total Patient Leakage Current*	With the same types of APPLIED PART connected together	d.c.	50	100	50	100	50	100
		a.c.	500	1000	500	1000	50	1000
	Caused by an external voltage on a SIP/SOP	d.c.	50	100	50	100	50	100
		a.c.	500	1000	500	1000	50	1000

Current in µA **KEY: NC:** Normal condition, **SFC:** Single Fault Condition

* Total PATIENT LEAKAGE CURRENT values are only applicable to equipment having multiple APPLIED PARTS.
The individual APPLIED PARTS shall comply with the PATIENT LEAKAGE CURRENT values.

The use of approved AC-DC power supplies and approved DC-DC converters, which provide the necessary isolation combined with low isolation capacitance and leakage currents, provide an easy to integrate, low risk power system architecture for medical equipment.

Safety for Home Healthcare and Non-Hospital Environments

For medical devices to be used in home healthcare and non-hospital environments there are additional requirements for the power system.

The AC input voltage operating range is extended down to 85VAC or 80VAC, depending on the criticality of the device, and the insulation system must be class II due to the uncertainty of the integrity of the earth or ground connection at the point of use.

Medical devices designed for use in the home or non-hospital environments often employ external power supplies which are required to comply with a minimum ingress protection rating of IP21 in addition to the AC voltage and insulation system requirements above.

Plug top and desktop external power supplies with safety agency approval to IEC/EN/ES 60601-1-11 (requirements for medical electrical equipment and medical electrical systems used in the home healthcare environment) are readily available, simplifying the safety approval process for home healthcare medical devices.

• Safety for Household and Similar Electrical Appliances

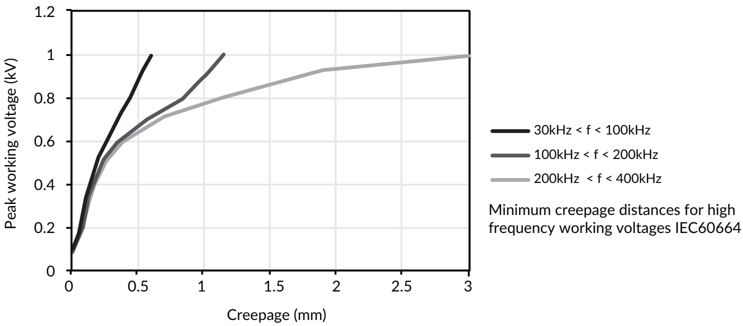
Scope

IEC 60335 Part 1 is a safety standard for household and similar electrical appliances that defines how products in this category can meet the overall requirements of the Low Voltage Directive and others such as the Machinery Directive or the Construction Products Directive, as relevant, in recognition of a typical household having electrical equipment intended for many different uses.

Because products vary in type and use the standard includes over 100 Part 2 standards which relate to the requirements of specific products. The relevant Part 2 document must be consulted and takes precedence over the general requirements of Part 1. IEC 60664-1, Insulation coordination for equipment within low-voltage systems, principles, requirements, and tests is also often referenced. A modern kitchen might have professional grade appliances which are covered by the standard. Equally, commercial premises have equipment intended for the domestic market; examples would be hotels, restaurants, shops, offices and anywhere with a house-keeping function such as care homes. The standard covers all these areas with the increasingly blurred distinction between office, home and medical. IEC 60335 covers rated input voltage not more than 250VAC single-phase and 480VAC 3-phase as well as battery operated equipment but some specific household products such as power tools are covered by their own separate standards. The standard specifically does not apply to audio, video and similar electronic apparatus, appliances for medical purposes, hand-held motor-operated electric tools, personal computers and similar equipment or transportable motor-operated electric tools.

Implications For Power Supply Design

IEC 62368 is the common standard applied to information technology and audiovisual equipment. IEC 60601 is the equivalent for medical. Power products meeting these standards would not necessarily meet the requirements of IEC 60335 though in some areas it is less stringent. Attention must be paid to creepage & clearance distances which are related to switching frequency in IEC60664, in addition to working voltage, as shown below for a pollution degree 1 environment. The values are multiplied by 1.2 and 1.4 for pollution degree 2 and 3 respectively



Creepage distances depend on frequency, not just voltage

Attention must also be paid to Protective Electronic Circuits (PECs) and the standard requires two bridging capacitors rather than the one required for information technology.

In the latest edition, the 60335 standard embraces the realities of modern household equipment. It is likely to be smart, have electronic controls and may be internet connected. The electronics may be part of the safety provisions of the equipment, for example many ON/OFF controls are now digital inputs to a processor putting the product into a 'standby' mode. If the electronics is monitoring temperature and relies on that ON/OFF control to disconnect the device, the electronics is part of safety. The standard therefore considers failures in the electronics in conjunction with another single fault elsewhere, effectively two faults. This contrasts with the IT and medical safety standards which look for safe operation only after imposed single faults.

EMC

IT & medical equipment must meet the provisions of the EMC directive which mandates compliance with the appropriate standard defining severity in the EN 61000-4 series. The product is categorised as to whether it continues to function, interrupts, or fails. However, failing in a way that compromises other safety protection features in the equipment is not evaluated. In IEC 60335 this is considered in recognition that the environment is not well controlled, and equipment may not be routinely maintained. Consequently, a failure is imposed in any PECs and then the EMC tests conducted to check for safety hazards. The severity levels of susceptibility are typically set high and significantly, surge arrestors on mains power supply inputs are disconnected during the tests. The rationale for this is that these components can have wear-out mechanisms and cannot be assumed to be effective after periods in service. Consequently, there are three abnormal conditions, a failed PEC, a worn-out surge arrestor and an EMI surge or transient.

Integral power supply products have to be designed to withstand these stress levels without surge arrestors and not fail or induce failures in a hazardous way. They must not respond to the stimulus and PEC failure by switching into an operating condition from a safe standby or off condition set by the first PEC failure.

Software and Firmware

A specific requirement in household equipment is that any software or firmware control of the product should be robust under single fault conditions and with external EMC stimulus applied. The software should not have any systematic bugs and is subject to a program of verification and validation during development to ensure that safety is not compromised. The hardware comprising the program electronics needs to be evaluated with Failure Mode and Effect Analysis (FMEA). All this with an existing first fault and electromagnetic interference and at any identified critical point in the program execution. For comprehensive protection, redundant hardware may need to be added or effective self-test and reporting schemes. Power supplies may include digital signal processing and control via firmware which is affected by these requirements.

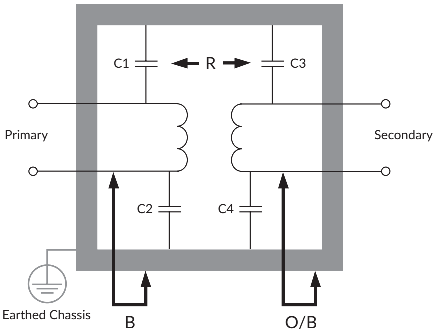
• High Voltage Safety Testing

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 implemented.
Between primary and earth basic insulation is implemented.
Between secondary and earth operational insulation or basic insulation may be implemented depending on the target application.

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 single phase input IT/Industrial products and medical products the type test requirements are as follows:

IT/Industrial	Primary to secondary	3000VAC, 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 42.4VAC or 60VDC for operational insulation 1500VAC or the DC equivalent for basic insulation
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 42.4VAC or 60VDC for operational insulation 1500VAC or the DC equivalent for basic insulation

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 1500VAC can be applied from primary or secondary to earth. If the primary to secondary insulation is to be verified consideration must be made to how the test is performed.

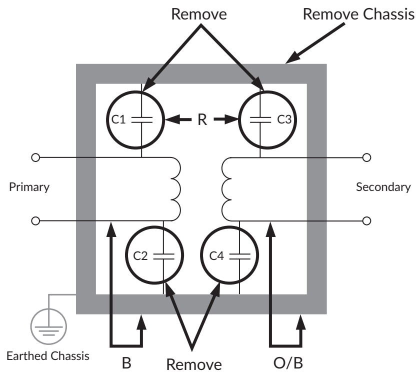
For products employing operational insulation between output and earth, basic insulation exists between primary and earth and operational insulation exists between secondary and earth. Applying 3000VAC directly from primary to secondary on the finished product will over stress the primary to earth and secondary to earth insulation which may result in an apparent failure.

For products employing basic insulation from output to earth a different problem can occur where the input common mode capacitance is much lower volume than the output common mode capacitance. This also results in overstressing of the primary to earth isolation being overstressed as these two capacitance act as a potential divider dropping more of the applied voltage across the lower capacitance which has higher impedance.

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 which can lead to component failure and render the power supply inoperable. This does not indicate a failure of the reinforced insulation between primary and secondary that is the focus of the test.

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.



Power supply disassembly may be required for type testing

• Electromagnetic Compatibility (EMC)

EMC describes how items 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 DC-DC converter or its electronic load and transmitted along the input and output cables as conducted noise or from the outer casing & cables as radiated noise. Electrical noise is generated at the switching frequency and harmonics of the switching frequency. Higher frequency noise is generated at frequencies associated with the rise and fall times of the switching edges and their harmonics. 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. In particularly sensitive applications careful cable routing, screened cables and external filtering may need to be employed.

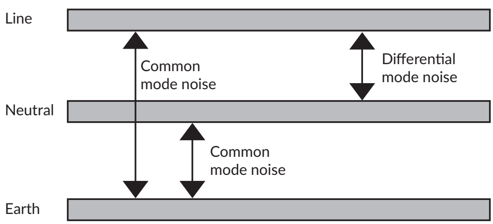
The European Union 2014/30/EU EMC directive imposes limits on the amount of noise that equipment can emit. In the USA, the limits are set by the FCC (Federal Communications Commission). In Asia the CISPR and FCC standards are widely accepted by the various approval bodies.

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.



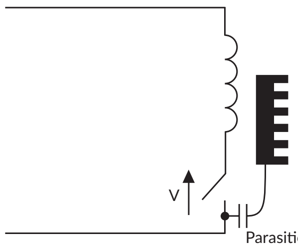
Differential Mode Noise

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 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 50ns, and if the primary current was in the order of 1A, the change would be 1A in 50ns 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 switching a voltage. The voltage could be as high as 600V and this may be being interrupted in the order of 50ns meaning that there could be a voltage change rate of 12V/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 30MHz, radiated emissions are typically measured up to 1GHz.

Standards

In the US, EMC standards are written and enforced by the FCC covering both radiated and conducted emissions for all commercial and non milatary sources. 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 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 are not relevant or 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 (dBµV)

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

Class B limits (dBµV)

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

*Limit reduces with log frequency

Class A limits (dBµV)

Frequency (MHz)	CISPR Limit	
	3m	10m
30 - 230	50.5 Quasi Peak	40 Quasi Peak
230 - 1000	57.5 Quasi Peak	47 Quasi Peak
1000 - 3000	76 Peak	
	56 Average	
3000 - 6000	80 Peak	
	60 Average	

Class B limits (dBµV)

Frequency (MHz)	CISPR Limit	
	3m	10m
30 - 230	40.5 Quasi Peak	30 Quasi Peak
230 - 1000	47.5 Quasi Peak	37 Quasi Peak
1000 - 3000	70 Peak	
	50 Average	
3000 - 6000	74 Peak	
	54 Average	

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

CISPR32 for conducted emissions (maximum of level B)
CISPR32 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 applicable to end user equipment.

Conducted Noise

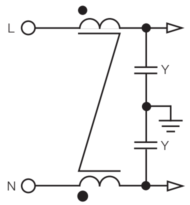
Conducted noise values are dependent upon the local impedance of the mains system at the location at which the measurement is being done. Mains impedances vary throughout a network and they could be vastly different throughout the world. A Line Impedance Stabilization Network (LISN), also known as an Artificial Mains Network (AMN) is used to give a defined mains impedance to the measurement system of 50Ω In the case of CISPR32, the noise is measured from 150kHz to 30MHz 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

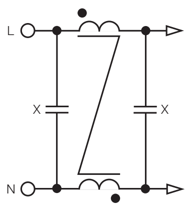
The services of a dedicated test house is normally required to measure radiated noise. The test should be performed on a large area known as an Open Area Test Site (OATS), using the 10m limits which is free from reflecting surfaces and calibrated so that the influence of any reflections from far away is known. The reflections will either add to the original signal, or detract from it depending upon the phase shift of the reflection. 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, the antenna will be positioned with its elements alternately horizontal and vertical, again to obtain the worst case reading. Measurements can also be made in a callibrated screened room, usually using the 3m limits.

EMC Filtering

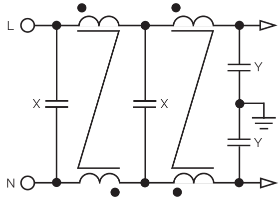
Power supplies and DC-DC converters typically incorporate an in-built input filter to reduce the conducted emissions. High density DC-DC and AC-DC power modules may not include a filter and require it to be integrated into the end application, using data provided by the manufacturer. In either case, it will have two parts; one to attenuate the common mode noise, the other to attenuate the differential mode noise. Common mode noise can be attenuated by use of Y capacitors between line or positive and ground and between neutral or negative and ground in conjunction with a common mode inductor.



Differential mode noise is attenuated by use of an X capacitor between the line or positive and the neutral or negative in conjunction with a differential mode inductor. Sometimes 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 attenuation is not adequate for application. This may be because 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 an external filter is required.

Filter Selection

There are some basic steps to follow when choosing a filter.

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 fuse holders. They can be mounted by either screw fixings or by use of self locking lugs. Generally, for metal chassis equipment, the screw fixing 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 attenuation.
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 attenuation and, for a given current rating, the higher the attenuation the larger the filter. Higher levels of attenuation will require the use of multi-stage filters.

Immunity

Immunity is concerned with how a piece of equipment behaves when subjected to external electrical or magnetic influences, either conducted or radiated noise 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 is subject to conducted noise 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.

While the standard allows criteria C for some of the immunity phenomena, products are designed to comply with criteria A or criteria B as user intervention is undesierable and may be impractical. The test severity levels applied are determined by the end application product or product family standard, e.g. multimedia equipment, household appliances, medical devices. Where there is no relevant product specific standard the generic standards are used, e.g. industrial environments/non industrial environments.

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.

RF Electromagnetic Field: IEC61000-4-3

This test simulates the fields given off by mobile phones. The field is generated by a sweeping signal generator with a 1kHz modulation function. The signal is amplified and radiated using an antenna. The field strengths are high enough and in the frequency band 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.

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.

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 50µs with a 1.2µs rise time. The pulse is applied between each line and earth and also between lines themselves.

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.

Power Frequency Magnetic Field: IEC61000-4-8

This test represents magnetic disturbances at the power frequencies of 50Hz and 60Hz.

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.

CE Marking

CE marking within Europe is 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.

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) 2014/35/EU

The LVD is applicable to equipment designed for use with a voltage rating of between 50 and 1000VAC and between 75 and 1500VDC. The directive itself does not define how to comply with it but by conforming to one of the relevant standards, such as EN62368-1 compliance is demonstrated.

Electromagnetic Compatibility (EMC) Directive 2014/30/EU

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 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 209/1782 implements the directive for external power supplies with regard to no load power consumption and active efficiency.

Restriction of Hazardous Substances (RoHS) 2011/65/EU and Amending Directive 2015/863

The Restriction of Hazardous Substances Directive 2011/65/EU 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) 2012/19/EU 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 include:

- Product identification number
- The name and address of the manufacturer or authorised representative
- Sole responsibility declaration
- Description of the merchant or equipment
- Reference to harmonized product standards used
- Date of issue
- Name of signatory and position

The LVD and RoHS directives relate to open frame, U channel, chassis mount and component embedded products. The LVD, RoHS, EMC and ErP directives relate to external plug top and desktop products.

UKCA Marking

Since the UK left the EU customs union, the CE mark is no longer valid for products sold in the UK to denote conformity with the required legislation. An alternative mark has been introduced to take its place, the UKCA mark. Products intended to be sold into both Europe and the UK bear both marks.

The UKCA mark is applied to a product on a self-declaration basis in the same way as the CE mark. A UK self-declaration of conformity (UK DofC) is required for each product to identify the UK legislation the product conforms to. The legislation follows the EU requirements meaning that for each European Directive there is a corresponding piece of UK legislation. For power supplies and DC-DC converters the equivalent legislation is as follows: -

European Directive	UK Legislation
Low Voltage Directive 2014/35/EU	The Electrical Equipement (Safety) Regulation 2016, SI 2016 No.1101
EMC Directive 2014/30/EU	Electromagnetic Compatibility Regulations 2016, SI 2016 No.1091
RoHS Directive 2011/65/EU as amended by 2015	The Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment Regulations 2012, SI 2012 No.3032
Ecodesign Directive 2009/125/EC and amending Directives implemented by Comission Regulations (EU) 2019/1782	The Ecodesign for Energy-Related Products and Energy Information (Amendment) (EU Exit) Regulations 2019, SI 2019 No.539

Conformity to the UK regulations is demonstrated by meeting the same existing international or EN standards that are used for EU conformity. Although the UK does not recognise the EU Official Journal (OJ), it is expected that a UK equivalent will be published in time. In line with the CE marking requirements, the Electrical Equipment (Safety) Regulations 2016, SI 2016 No. 1101, and the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment Regulations 2012, SI 2012 No. 3032 apply to open frame, u-channel, chassis mount and component embedded products.

The Electromagnetic Compatibility Regulations 2016, SI 2016 No1091 an the Ecodesign for Energy-Related Products and Energy Information Regulations 2019, SI 2019 apply to external plug top and desktop products in addition.

• Energy Efficiency Legislation for External Power Supplies (EPS)

With the global concerns over carbon emissions, most countries have introduced legislation to regulate the energy efficiency of external power supplies (EPS), so that as little as possible of our natural resource is wasted. This legislation encourages power supply manufacturers to introduce EPS models with higher efficiency and lower no-load power consumption and, by gradually tightening the limits on these figures, governments and regulatory bodies around the world are effectively driving the power supply industry to produce more energy efficient products.

In the USA there are a number of bodies legislating on energy efficiency; the California Energy Commission (CEC), US Congress with its Energy Independence and Security Act (EISA) and the United States Department of Energy (DoE). There is also Energy Star that sets limits for electrical and electronic equipment.

In Europe there is the Energy related Products (ErP) Directive with its latest Commission Regulation No 2019/1782 and the UK Ecodesign for Energy-Related Products and Energy Information Regulations 2019, SI 2019 No. 539 which s based on the ErP directive. Other examples are Natural Resources Canada (NRCan) and Australia's Minimum Energy Performance Standard (MEPS).
The standards are broadly similar describing levels of energy efficiency in Roman numerals (level I to VI), where level I means, an EPS doesn't conform to any standard, and VI means the EPS conforms to the most stringent standard.

Of the legislation produced by these bodies, the US DoE and EU/UK rules are of primary interest to power supply manufacturers because they represent the most stringent requirements. Products designed for global markets are designed to comply with the most stringent requirements in mind, since it's more straightforward to produce one product for all markets than to continue producing older designs that can only be sold in one particular territory.

Energy Efficiency Limits

The legislation focuses on two things: the average active mode efficiency, and the no-load power consumption. The average active mode efficiency is calculated by taking the efficiency of the EPS at 25%, 50%, 75% and 100% of full load and averaging the four figures. The no-load power consumption is simply defined as any power the EPS consumes when it is plugged in to the mains but disconnected from the equipment it is powering.

The legislation applies to EPS for household and office equipment and the ErP limits the legislation to 250W while the DoE level VI has no maximum power rating. The scope of the legislation in both the USA and Europe has been extended to include multiple output EPS.

The limits for energy efficiency level VI are broadly the same and are given in the table overleaf for single output EPS, which are by far the most common. For multiple out EPS the efficiency limits are lower, and the maximum no load power consumption limit is increased to 0.3W.

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

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

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

Effects on the Industry

The effects of this new legislation have been to encourage power supply manufacturers to develop new EPS products with better energy efficiency, aided by developments in control ICs and power semiconductors. This new generation of higher quality EPS products comes at a cost but this is outweighed by reduced emissions and savings for consumers using less energy. As energy tariffs continue to significantly increase year on year, this saving becomes more pronounced. Combined with energy awareness initiatives, it means consumers and business buyers alike have energy efficiency as a primary selection criterion.

• 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 component 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, ingress, reliability or service concerns, conversion efficiency becomes a primary concern.

Power supplies with efficiencies in the 90-95% range are commonly available and, by considering efficiency as a key criterion, 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

Component power supply designs minimize no load power consumption and maximize active efficiency by utilizing green mode control and resonant topologies combined with the latest component innovations to provide OEMs with the best possible starting point and enabling the design and manufacture of Energy Efficiency compliant products.

• Integrating Power Converters

Understanding Efficiency

Overview

Efficiency is a key consideration when selecting the best power converter 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 critical applications, drives equipment designers to look for ever more efficient power supplies.

Higher efficiency results in less power dissipation, less waste heat and lower temperatures in a given form factor. Increasing efficiency has a direct impact 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 allows the equipment to be designed with significantly reduced fan cooling, or may allow the removal of cooling fans altogether, reducing or eliminating audible noise and pollution Ingress.

Miniaturization of power converters requires increased switching frequency to reduce the size of transformers, inductors, and capacitors. Increasing the switching frequency has the effect of decreasing efficiency due to increased switching losses in semiconductors and magnetic materials and reducing the available surface area for dissipation significantly increasing temperatures.

These increased losses can be mitigated by topology and controller advancements, material improvements and component innovation. The introduction of affordable controllers to support resonant LLC converters to reduce switching losses, improved magnetic materials with lower losses at higher frequencies, higher speed micro controllers and more recently Wide Band Gap (WBG) semiconductors (SiC & GaN) are all enabling technologies for more compact, higher power density, power converters with a trade-off of increased cost. Switching power converters use a switching element which is traditionally a silicon-based semiconductor. WBG GaN semiconductor switches allow operation at higher voltages, higher temperatures and higher frequencies while reducing on resistance by up to 10 times and reducing reverse recovery time and recovery current. These benefits mean significantly reduced power losses and allow switching frequencies to increase by 2 to 3 times resulting in volume reduction of up to 50% for a given power level. GaN devices are significantly more expensive than traditional silicon-based devices due to the small wafer size and lower yields though this cost is likely to decrease over time

Power Converter Selection

Having determined that higher efficiency is a desirable feature for the equipment power system, the equipment designer turns to the power supply manufacturer's website and datasheets 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 favorable input voltage and load conditions. The efficiency under the conditions required for the end equipment may be quite different. If, as is commonly the case, the equipment is to be supplied to the world-wide market the low line efficiency is crucial. The system design must be based around the worst efficiency not the headline efficiency. The headline efficiency at high line (230VAC) will be different from the efficiency at low line (100VAC), "universal input" does not mean that the efficiency is maintained across the input range.

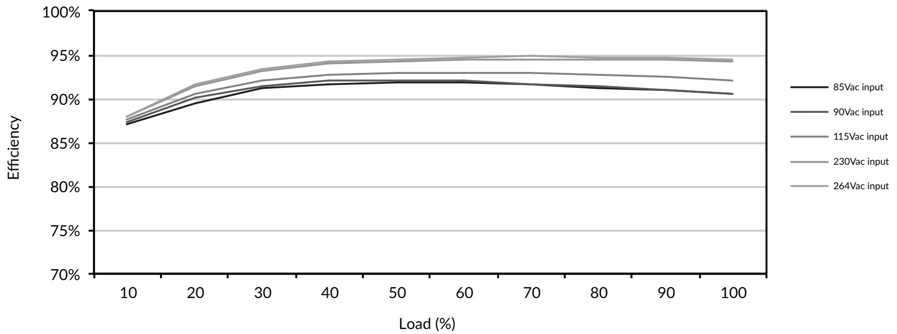
Finding the worst case efficiency requires some investigation into the real data for the selected power product. While some manufacturers make this clear in their product datasheets this is not always the case. Selecting a product with good headline efficiency, perhaps with an attractive price, may result 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, the reason for low input voltage derating in lower cost products.

Comparing the efficiency of what may appear to be comparable products, gives an insight into the efficiency that can be expected over the operating range specified in the data sheet. The graph below shows the relative efficiency of a typical power supply with changes in input voltage and load. The example power supply is rated at 150W.



At high line and maximum load, the efficiency is 95% meaning that the power dissipated is approximately 8W. Changing the input to 90VAC under the same load condition results in a drop in efficiency to 91% which means that the power dissipated increases to 15W or put another way the power dissipated increases by 87%. 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.

Output

The actual load drawn by the application is also a consideration. Power supply efficiency typically peaks at around 80 - 90% of full load as can be seen from the curves on the previous page. 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.

Summary

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

• Installation of Open Frame and U channel AC-DC Power Supplies

AC-DC power supplies are commonly supplied in what is known by the industry as an open frame format. Open frame generally describes a product which is a PCB only construction, component power supply designed to be installed into an end equipment application which provides the enclosure for the entire product.

Another common format for power supplies for integration into end equipment is the U channel where the power supply PCB is installed in a U shaped, usually aluminium, chassis which is used as a part of the thermal management of power semiconductors as well as providing multiple fixing options for the equipment manufacturer to install the supply into the final assembly.

There are several considerations when installing open frame and U channel power supplies, principally these are related to safety, electromagnetic compatibility (EMC) and thermal management and these areas of concern are discussed here.

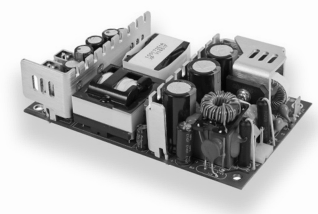
Another important consideration is the detailed specification of the power supply, especially with regard to temperature and input voltage de-rating, when compared to the data sheet headline power rating. The best products maintain the rated power to 50°C ambient temperature and down to 90VAC input, while some products advertise a headline power rating with derating of up to 20% at low line and de-rate the available power at ambient temperatures as low as 40°C, which may make these products unsuitable for the end application.

Safety

When mounting an open frame power supply into the equipment enclosure, it is necessary to observe the required creepage and clearance distances to the equipment enclosure to all faces of the supply. In a class I system this will usually mean ensuring 3 or 4mm between any earthed metal part and any primary part of the power supply, depending on whether the end application is industrial or medical, which may necessitate the use of insulators around the power supply assembly.

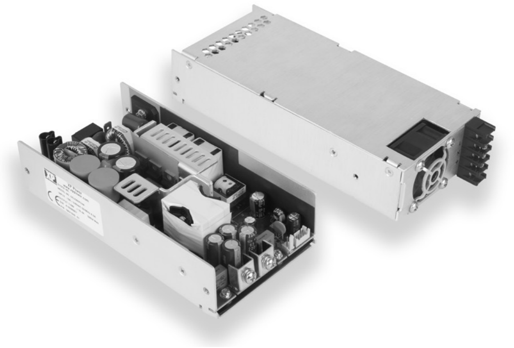
Where a class I power supply is employed the safety ground connection to the power supply is an integral part of the electrical safety system and must be securely connected to the equipment safety ground. This connection is generally made available via one of the mounting holes, via the AC input connector or via a faston style tab on the power supply PCB. There is likely to be more than one earth connection to the assembly required which affects the electrical emissions and susceptibility performance and is discussed later.

Where a class II power supply is employed the creepage and clearance distances may be required to be larger in metal enclosures though often the equipment enclosure is non-conductive where these units are employed.



Open frame power supply

U channel construction eases the issues surrounding safety as the U channel chassis is connected to the supply's safety ground and can be bonded directly to the equipment enclosure along with the power supply safety ground connection. The requirements for safety clearances between the PCB and the surrounding U channel are catered for in the design. However, the ends of the U channel and the top face of the assembly are usually still open, and care must be taken in these areas to ensure adequate creepage and clearances distances are maintained.



U channel power supply with and without cover

U channel construction has the additional benefits of ease of handling and ease of installation. The U chassis provides a more rugged construction and incorporates threaded mounting holes for use by the installer, reducing the mounting hardware to a simple screw fixing. Care must be taken to observe any maximum screw insertion penetration depth to maintain safety creepage and clearance distances.

Another U channel construction benefit is the potential for additional cooling of the power components by conduction cooling to the equipment enclosure reducing both the temperature of the bonded components and consequently the general temperature within the U channel construction.

Both open frame and U channel power supplies include one or sometimes two, in the case of products designed for medical equipment applications, input fuses which are also integral to the overall product safety system design and protect against fire hazard in the event of catastrophic failure. This fuse is usually permanently installed in the power supply and is not designed for replacement as the only reason for clearing of the fuse is failure of the power supply assembly.

As both constructions require input cabling, the end equipment also requires additional fusing to protect against potential fire hazard issues created by the incorporation of connectors, indicators, switches, and the cabling itself.

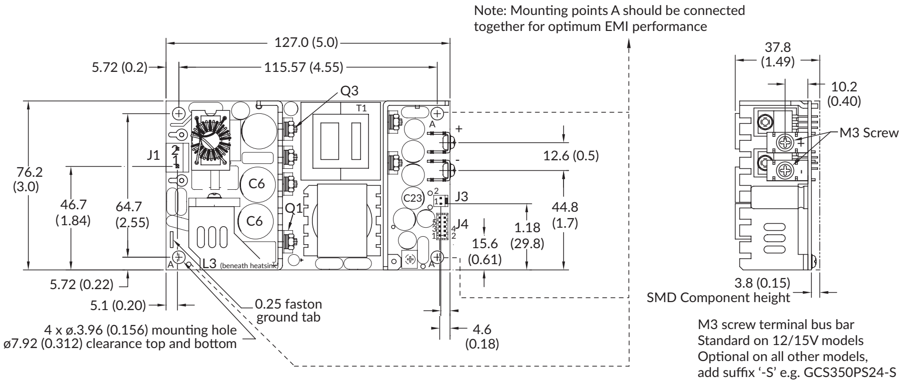
Output cables must be sized to accommodate the maximum power capability of the power supply including the maximum tolerances for its overload protection specification to ensure safe operation in the event of a fault in the equipment itself.

There are also thermal considerations to take into account as some safety critical components have a maximum temperature rating, this is discussed in more detail later under thermal management.

Electromagnetic Compatibility (EMC)

Open frame power supplies normally require two and sometimes three mounting points to be connected to ground. As discussed above, in a class I system usually one of these connections is required for safety ground and is located on the input side of the assembly, this connection will also connect the line to ground and neutral to ground common mode filter capacitors, also known as Y capacitors. These Y capacitors work in conjunction with the common mode inductors within the power supply assembly to attenuate noise associated with rapid changes in voltage in the supply's power stage. The other or others are usually on the secondary side and connect the output common mode filter capacitor(s) to ground. The differential element of the filter which is designed to attenuate the noise associated with rapid changes in current is contained within the supply in the line and neutral connections.

This output common mode capacitor is integral to the EMC performance of the power supply and must be connected for optimum EMC performance. Where the equipment uses a metal enclosure this is rarely an issue. In plastic enclosures, either in class I or class II configurations, it is necessary to make other provision to connect these points together to ensure EMC compliance. The points which require connection to ground or together are usually identified in the power supply data sheet as in the following example.



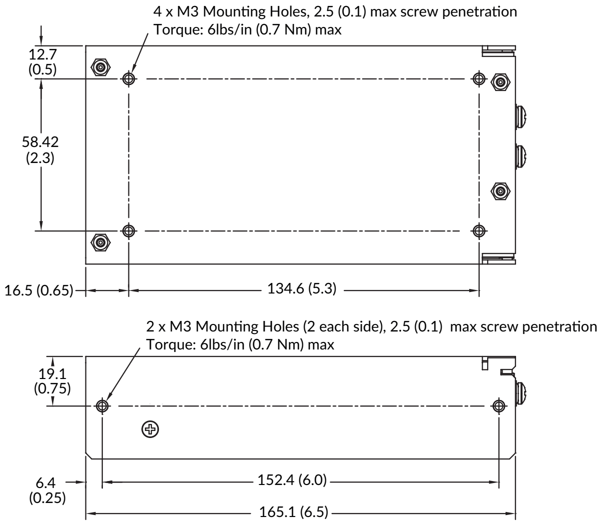
Mechanical drawing of open frame supply showing mounting point ground connections

The optimal way to connect these points is by mounting the open frame supply on a metal plate which need not be connected to anything else but provides a low impedance path with low parasitic elements for the filter capacitors to be connected.

Where this type of mounting is impractical then other methods must be employed to connect these mounting points such as a multi-strand cable.

In a U channel construction, all ground connections are made within the U channel enclosure simplifying the installation of power supply from an EMC perspective. Good electrical bonding from the U channel chassis to the equipment enclosure via multiple fixing points is also beneficial, minimising parasitic elements.

In both cases the input and output cables should be kept well apart and avoid proximity to the open assembly to avoid potential issues with radiation from the switching components and magnetic assemblies within the power supply being induced into the system creating potential conducted and radiated emissions issues for the end equipment.



Typical mechanical details of a U channel power supply detailing fixings and connections

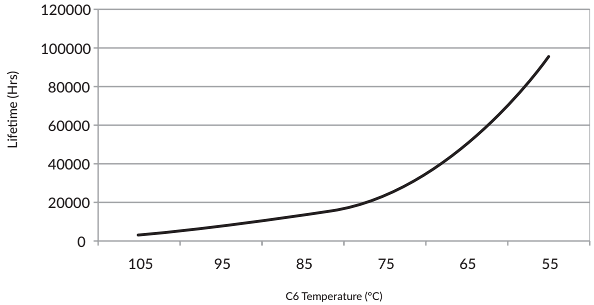
Thermal Management

Open frame power supplies may have a power rating when convection cooled, force air cooled or both. In the case of U channel supplies there may also be a conduction cooled rating utilizing the equipment enclosure or external heatsinking for further cooling of the assembly.

The mounting position, orientation, available surrounding space, applied load and surrounding parts along with any system air cooling are unique to each application. It is important to check the operating temperature of key components within the power supply assembly once installed to ensure that the safety critical components do not exceed their maximum ratings as specified in the safety approval reports and that the reliability and service life of the supply are not impaired.

Data sheets for both open frame and U channel power supplies designed for integration into end equipment, commonly identify the key safety components & their maximum temperature ratings which vary from one supply to another depending on the class of insulation system employed. They typically also provide an estimated service life curve based on the temperature of key electrolytic capacitors, which are the only parts with a wear out mechanism within the power supply.

Temperature Measurements	
Component	**Maximum Temperature**
T1 Coil	120°C
L3 Coil	
Q1 Body	
Q3 Body	
C6	105°C
C23	



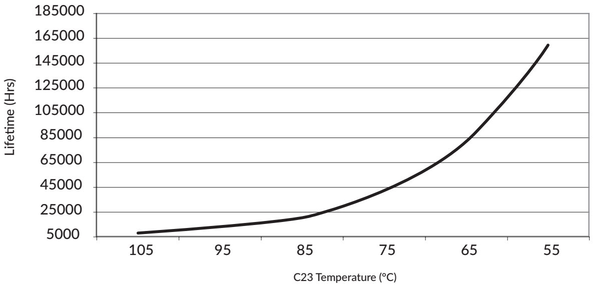


Table and graphs showing safety limits and estimated service life for 24/7 operation

Service life predictions are based on the electrolytic capacitor design lifetime at its maximum temperature rating and the average temperature experienced in the end application over its mission profile. Clearly the maximum temperature rating cannot be exceeded under any circumstances or extremes of operation.

All electrolytic capacitor lifetime calculations are based on the Arrhenius equation, where the rate of reaction halves and hence the lifetime doubles for every ten Degree Celsius reduction in temperature, making this a critical element in the service life or service interval of the entire end application. Lifetime calculations undertaken by the power supply manufacturer will include elements based on the applied ripple current but, as this is impractical in the finished power supply assembly, a good indication of service life can be determined by measurement of the component case temperature and application of the Arrhenius equation to the to the specified temperature and design lifetime.

Summary

Careful application and attention to safety, EMC and thermal management considerations, when integrating component power supplies, enables trouble free certification for safety and EMC and, in combination with the system mission profile, the expected service lifetime and reliability.

• System Integration Of Baseplate Cooled Converter Modules or "Bricks"

Baseplate cooled power converter modules, also known as bricks, provide building block power solutions for integration into end equipment. These high-density power solutions are ideal for sealed enclosures, transportation, and defence applications, where their rugged construction and conduction cooled properties are beneficial, and in high density force cooled applications where the benefits of the compact size can be realised.

They also provide the building blocks for low-risk bespoke power solutions designed either by the end equipment designer using support and application notes from the manufacturer or by the module manufacturer itself using the proven, reliable module as a base for low development cost, low risk, custom solutions with accelerated time to market.

Baseplate cooled converters are component level power solutions rather than drop-in products which generally require additional design resources and components for correct operation, electrical safety, thermal management, and electromagnetic compatibility (EMC). They are designed for both DC and AC input applications with input ranges designed to cover battery and DC vehicle supplies as well as higher voltage, rectified or Power Factor Corrected (PFC), AC supplies.

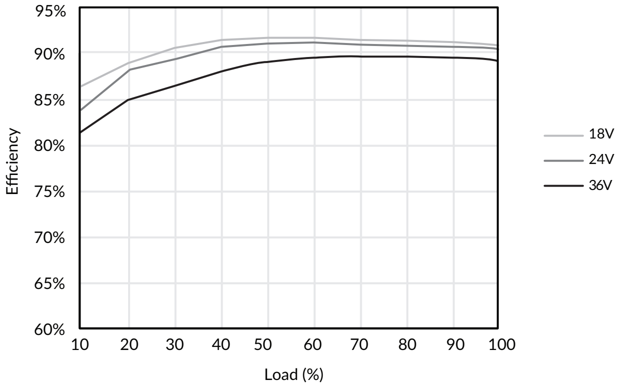
The industry has developed standard sizes for these parts described as ¼ bricks, ½ bricks and full bricks with standard dimensions. Power ratings up to 600 or 700W can be achieved in a standard 2:1 input full brick though power density reduces as the input range is widened to 4:1, 8:1 or even 12:1 to accommodate multiple nominal battery supplies in a drive to standardize system design for multiple voltage platforms.

Baseplate cooled converters with AC input are also available either as a more complete solution providing AC to low voltage DC conversion or as PFC modules with high voltage outputs (usually around 400VDC) to drive downstream high input voltage DC-DC bricks. Most of these AC input products also require additional design and components including high voltage electrolytic capacitors and components for EMC with one or two exceptions such as the ASB series of 75W, 110W and 160W complete AC-DC brick solutions from XP Power, which only require thermal management and include all other parts.

Thermal Management

Thermal management is a key element in the integration of power bricks which are designed to be baseplate cooled. The brick is designed so that the power dissipating components, such as the power semiconductors and power magnetics, are thermally bonded to the baseplate which must then be maintained below a maximum operating temperature under the worst-case conditions of the end application. The thermal resistance of the cooling scheme must be matched to the power required by the load or end equipment and the efficiency of the module, which determines the power dissipated in the brick converter, and the maximum temperature in which the equipment is expected to operate.

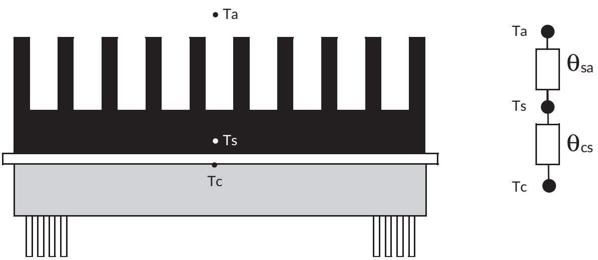
The power dissipated in Watts can be determined from the module efficiency specification under the worst-case operating conditions though it is important to consider the actual operating load and lowest input voltage applied rather than the data sheet headline efficiency. An example of the variation in efficiency with input voltage and load is given below: -



Once the efficiency at the worst-case operating point is established the waste power to be dissipated as heat is calculated as below: -

$$\text{Waste Heat} = \left(\frac{1 - \text{Eff\%}}{\text{Eff\%}} \times \text{Pout}\right) \text{ Or } \left(\frac{1}{\text{Eff\%}} - 1\right) \times \text{Pout}$$

Having determined the waste heat/power, the simple model below determines the thermal resistance required for operation with ΔT defined as the difference between the maximum operating temperature of the equipment and the maximum baseplate temperature of the power brick. The thermal resistance from the case to heatsink is typically 0.1°C/W when using a thermal pad or grease.



θsa is thermal resistance heatsink–to–ambient ˚C/W

θcs 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 θca.

TC = TA + PD (θca)

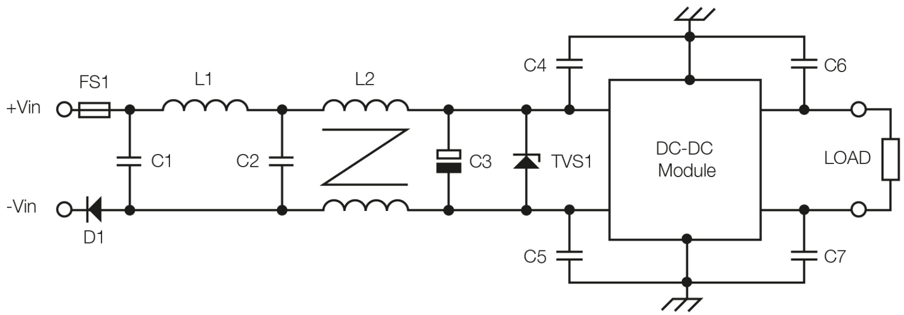
where	TC =	maximum power supply temperature
	TA =	ambient temperature
	PD =	power dissipation
	θca =	case to ambient thermal resistance

The thermal resistance of the heatsink to ambient is heavily dependent on available airflow meaning that in convection cooled applications it's physical size will be far greater than in a comparable power system with forced air or liquid cooling. When utilising multiple bricks connected to a common heatsink or cold wall the sum of the dissipated power from each brick in the system under worst case conditions determines the overall thermal resistance required.

Electromagnetic Compatibility

In addition to the thermal management outlined above, baseplate cooled modules require additional external components for correct operation, reverse polarity protection, control of noise emissions and for protection against spikes and surges defined in the susceptibility requirements of the application. This means that a network of capacitors, for both noise mitigation and to reduce source impedance, inductors and surge suppressing components must be installed within the end application. Fusing must also be implemented for safety in the event of catastrophic failure presenting a short circuit to the supply.

The power module data sheet and application notes will specify the values of the components required though it is up to the design engineer to implement following good design practices for any creepage & clearance requirements and minimizing parasitics for EMC compliance.

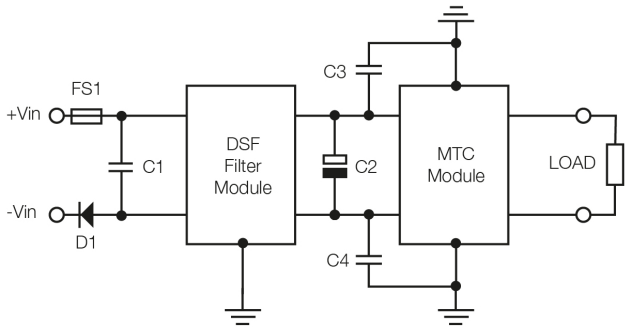


Example: schematic for DC input systems

FS1 provides protection against an input short circuit failure and D1 provides reverse polarity protection L1, C1 & C2 form a pi filter to mitigate differential noise created by rapid changes in current in the power switching stage and L2, C4 & C5 form a common mode filter to mitigate noise created by the rapid changes in voltage in the power stage. C3 presents a low impedance source for the power converter switching current demand and TVS1 is a bi-directional transient surge suppressor to protect against spikes & surges. C6 & C7 reduce output common mode noise and an additional differential filter may be added at the output for applications that require very low noise.

In general, the decoupling capacitors (C4, 5, 6 & 7) should be as close as possible to the pins and chassis connection to the baseplate to keep the loop as short as possible. The input electrolytic capacitor (C3) and Transient Voltage Suppressor (TVS1) should be physically close to the input pins of the module with the loop as small as possible and tracks beneath the power module should be avoided.

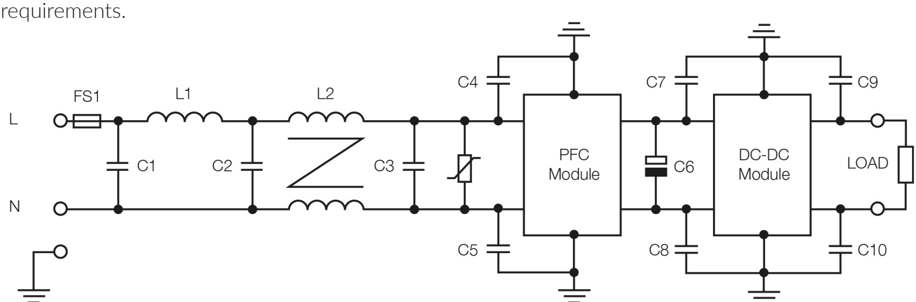
There are a number of application specific filter modules available for the abnormal surges found in DC input transportation and defense applications. These generally also require a few additional components for full compliance.



Example: schematic for DC input defense application

In this case the DSF filter module contains all the necessary active surge protection circuits to comply with the requirements of a 28V nominal military vehicle supply and the filter inductors. C1 completes the differential filter stage and C3 & C4 the common mode filter stage. C2 provides a low impedance source for the MTC series DC-DC converter.

When using a PFC module solution for an AC input power systems similar EMC components are required and additional a high voltage (450VDC) electrolytic bulk capacitor (C6) is also required as shown. The value of the bulk capacitor is determined by the system hold up, or ride through requirements.



Example: schematic for AC input systems

Some AC input solutions combine the PFC and DC-DC sections into one brick with connections made available for the bulk capacitor. There are additional requirements for AC input systems regarding creepage and clearance distances between Line & Neutral and between Line & Neutral and earth which must be adhered to during the power system implementation. These creepage and clearance distances are outlined in the relevant safety standard for the end application.

The additional components outlined above also need careful selection and thermal management to stay within the thermal safety limits for inductors and filter capacitors and to ensure that the electrolytic capacitors employed have the desired service life over the mission profile of the end equipment. It is possible to conduct heat away from the inductors to the equipment cold wall using suitable insulting thermal pads and other components are often mounted on the reverse side of the PCB and kept away from any higher temperature parts.

Summary

Manufacturers of these high-density base plate cooled brick converters have supporting applications information and EMC data to support design-in. They also have experienced applications engineers on hand to support the user during the design & compliance testing phases and offer pre-compliance testing against common industrial, communications, transportation, and defence EMC standards.

The manufacturer will also have utilised the modules in a myriad of application specific custom designs and gained invaluable experience in their application and compliance with safety and EMC standards. Using the module manufacturer to design and produce a bespoke brick-based power system remains a popular choice, negating the need for the additional design & test resources in house and allowing the OEM to focus on the core system design.

• Power Architectures for Patient Connected Medical Devices

When considering power architectures within medical devices for patient connected applications there are several key elements to consider; isolation, leakage/touch currents, electromagnetic compatibility (EMC), number of power outputs required and environment for use.

Applied Parts

The element of the medical device which comes into contact with the patient is known as the applied part. The applied part is defined as the part of the medical device which, in order for the medical device to perform its function, deliberately comes into direct contact with a patient or has parts which are likely to come into contact with the patient during normal use.

The 60601-1 suite of standards defines Applied Parts according to the type of patient contact and the type or nature of the medical device. The current version of 60601-1 is the 3rd edition which was first published in December 2005 has been adopted in all major countries and regions of the world as the following latest versions:

IEC-60601-1: Edition 3.1, 2012-08
Europe : EN 60601-1: 2006 + CORR: 2010+A1 (2013)
USA: ANSI/AAMI ES60601-1 (2005 + C1:09 + A2:10+A1(R2012))
Canada CAN/CSA-C22.2 No. 60601-1 (2008)+A1 (2014)

Each classification within the standard has requirements for protection against electric shock. The three classifications are detailed below, in order of the least stringent to the most stringent.

Type B (Body)

Type B classification is given to applied parts with are generally not conductive and may be connected to Earth.

Type BF (Body Floating)

Type BF classification is given to applied parts which are electrically connected to the patient and must be floating and separated from Earth. This classification does not include applied parts which are in direct contact to the heart.

Type CF (Cardiac Floating)

Type CF classification is given to applied parts suitable for direct cardiac connection. This means connection to the heart of the patient including intravenous connection such as dialysis. These applied parts must be floating and separated from Earth.

Isolation Requirements

Patient connected medical devices are required to provide two Means Of Protection (MOP) to prevent applied parts and other accessible parts from exceeding the limitations of voltage, current or energy. A compliant protective earth connection provides 1 x MOP, basic isolation also provides
1 x MOP & Reinforced insulation provides 2 x MOP. Means of protection can be categorised as Means Of Operator Protection (MOOP) or Means Of Patient Protection (MOPP). In devices intended for patient connection 2 x MOPP are required. Power architectures for use in medical devices with type BF & CF classification are required to provide 2 x MOPP from primary to secondary, 1 x MOPP from primary to earth and additional safety isolation from the secondary output of the power system to earth also rated at 1 x MOPP, all at the (highest rated) incoming AC line voltage.

Insulation		MOOP		MOPP		
	Air Clearance	Creepage Distance	Test Voltage			
Basic (1 x MOP)	2.0mm	3.2mm	1500VAC	2.5mm	4.0mm	1500VAC
Double of Reinforced (2 x MOP)	4.0mm	6.4mm	3000VAC	5.0mm	8.0mm	4000VAC

Insulation test voltages based on 250VAC working voltage

Key: MOP: Means of Protection
MOOP: Means of Operation Protection
MOPP: Means of Patient Protection

Insulation	Description		Type B Applied Part		Type BF Applied Part		Type BC Applied Part	
			NC	SFC	NC	SFC	NC	SFC
Patient Auxiliary Current		DC	10	50	10	50	10	50
		AC	100	500	100	500	10	500
Patient Leakage Current	From PATIENT connection to earth	DC	10	50	10	50	10	50
		AC	100	500	100	500	10	500
	Caused by an external voltage on a SIP/SOP	DC	10	50	10	50	10	50
		AC	100	500	100	500	10	500
Total Patient Leakage Current*	With the same types of APPLIED PART connected together	DC	50	100	50	100	50	100
		AC	500	1000	500	1000	50	1000
	Caused by an external voltage on SIP/SOP	DC	50	100	50	100	50	100
		AC	500	1000	500	1000	50	1000

Current in µA

Key: NC: Normal Condition
SFC: Single Fault Condition

*Total PATIENT LEAKAGE CURRENT values are only applicable to equipment having multiple APPLIED PARTS. The individual APPLIED PARTS shall comply with the PATIENT LEAKAGE CURRENT values.

The challenge for the power system architecture designer in patient contact medical devices, where an electrical connection is required, is to ensure that the power system provides the required safety isolation while minimizing the leakage currents under normal operation and protecting under fault conditions, by isolating the patient from ground.

Electromagnetic Compatibility (EMC)

The medical device must also comply with the EMC requirements outlined in 60601-1-2. An updated version of the medical EMC standard IEC60601-1-2 was published in 2014, widely referred to as the 4th Edition. There are two main aims of the 4th Edition revisions.

The first is to improve immunity of equipment partly due to the proliferation of wireless communication devices operating within the local proximity of what may essentially be life critical equipment. These wireless devices may take the form of mobile phones, blue-tooth, WiFi, Tetra, RFID or paging system products.

The second aim is to introduce an element of risk analysis into deciding which levels of immunity are suitable for the equipment, its intended operating environment and foreseeable levels of disturbances. This is due to the inclusion into the standard of equipment intended to operate outside of hospital or professional healthcare environments in which there is less supervision of equipment and less control over the electromagnetic phenomena present. Part of the risk approach is that manufacturers must be clear about the essential operation of their product and mitigate the risk of failure or abnormal or unexpected operation by choosing the appropriate immunity levels.

The 4th Edition considers three environments: professional health care facility, home health care and special environments, examples of which could include heavy industry or medical equipment intentionally generating high power fields. As the required immunity levels now relate to these environments rather than to the product, the term 'life supporting equipment' is no longer used.

Power Solutions

In BF & CF rated medical devices, the power system is a critical factor in complying with isolation, leakage current and EMC requirements.

For home healthcare environments, it is mandated to select an isolation scheme where there is no earth required, by implementing a class II isolation system which is naturally floating, but importantly, must still comply with requirements for enclosure and patient leakage currents to earth. This is a practical solution up to around 500Watts, above which the EMC requirements become increasingly difficult to manage.

The majority of standard medically approved AC-DC power supplies are not suitable for direct connection to the patient for a number of reasons:

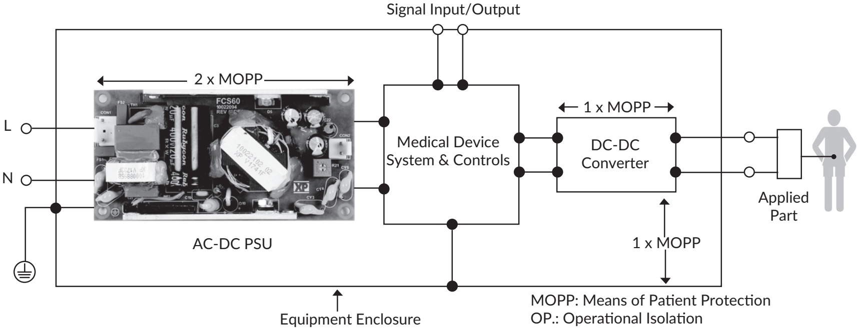
1. They do not have the required isolation from output to ground.

2. They do not meet the requirements for patient leakage current.

3. While they may offer the required 2 x MOPP from input to output and 1 x MOPP from input to ground, most of these units employ operational isolation from output to ground, often rated around 500VAC/VDC, when patient connect applications require a minimum of basic insulation at mains voltage, where the test voltage required is 1500VAC and the creepage and clearance distances must be adhered to.

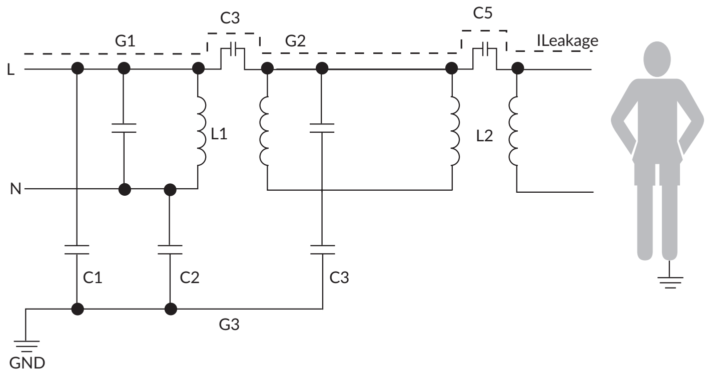
4. The isolation capacitance from input to output is too high, resulting in excessive leakage current from output to ground.

A simple and low-cost solution, for low power patient connected medical devices, is to employ a second isolation stage in the form of a medically approved DC-DC converter which provides both basic isolation at AC line voltage and minimises input to output capacitance (20 – 50pF) reducing the potential patient leakage current to single digit µA. This solution also accounts for potentially low integrity system input and output signals which may be connected to uncontrolled external equipment such as a computer or monitor.



Medical power system with secondary DC-DC.

In the simplified model of the power system below the path for patient leakage current is shown with C4 & C5 in series. C5 represents the DC-DC converter input to output capacitance which is very small and presents a high impedance to reduce the leakage current regardless of the typically higher value of C4.



Simplified model for power system with secondary DC-DC isolation.

Medically approved DC-DC converters with output ratings from 1W up to 30W are readily available, with the required input to output isolation and very low internal capacitance, designed specifically for these applications at a competitive cost and carrying agency approvals to the 60601 standards. When used in conjunction with a standard medically approved mains input power supply, patient leakage current can be reduced to levels as low as 2µA suitable for use in both BF & CF applications. Where the supply to the DC-DC converter is from a regulated AC-DC power supply and the power required is less than 2-3W, a fixed input, non-regulated output device can be used resulting in a very cost-effective solution.

Wide range input DC-DC products, offering a tightly controlled output over a wide DC input and output load range, with up to 2 x MOPP isolation and equally low internal capacitance are also readily available for DC input or battery powered portable devices.

XP Power's medically approved DC-DC converters from 1 Watt to 30 Watts.

Power Solutions For Multiple Outputs

In medical devices requiring multiple outputs for patient contact, the low leakage current provided by the additional DC-DC converter which may be as low as 2µA provides an easy to implement robust solution to both patient auxiliary and patient leakage current requirements.

Where multiple outputs are required in the AC-DC stage the complication becomes the earth leakage current which is limited by the SFC touch current and makes the use of multiple power supplies impractical. In this instance a multiple output AC-DC supply may be required.

For lower power systems, up to 2-300W, there are multiple output medically approved units available in open frame or U-channel formats or, alternatively, extra voltage rails may be created using isolated or non-isolated off the shelf DC-DC converters running from a single output AC-DC power supply.

For higher power applications there are readily available configurable solutions providing high power multiple output power solutions with medical safety agency approvals as standard, such as the fleXPower series pictured below.

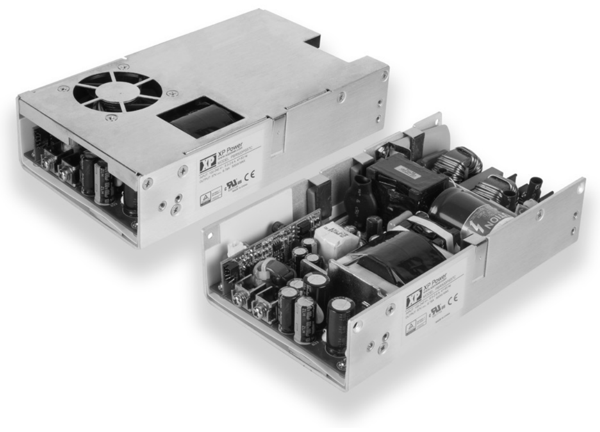
Medically approved fleXPower series offers from 400 Watts to 2500 Watts with up to 20 outputs

Motor Driven Applications

In higher power devices and motor driven applications, such as bone shavers, surgical tools and electrically powered tables, beds & chairs, it is not desirable to employ an additional isolation stage due to both the lack of suitably isolated DC-DC devices with higher power ratings and the inherent inefficiency of dual conversion of the power. In these applications a power supply designed with the necessary isolation, spacing and patient leakage current is required.

This combination of high isolation and low leakage currents presents its own design challenges in an AC-DC supply. The internal spacing requirement on the secondary side is greatly increased and must be implemented with system integration in mind. The requirements for low emissions and low leakage current are in conflict, requiring a low noise topology and care in minimising differential and common mode noise throughout the product while minimising the line frequency ripple in primary circuits to reduce patient leakage current for the same input to output capacitance.

These higher power applications are usually BF rated, rather than CF rated, meaning that the patient leakage current requirement, while challenging, is less severe at 100µA rather than 10µA and there are increasing numbers of standard AC-DC power supplies available which suit BF rated applications. XP Power’s 500W, BF rated, PBR500 series for example, comes with the isolation, leakage current and 4th edition EMC requirements catered for with the added benefit of a convection cooling rating of up to 400W to eliminate noisy system fans making it ideally suited to motor driven applications.



• 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:

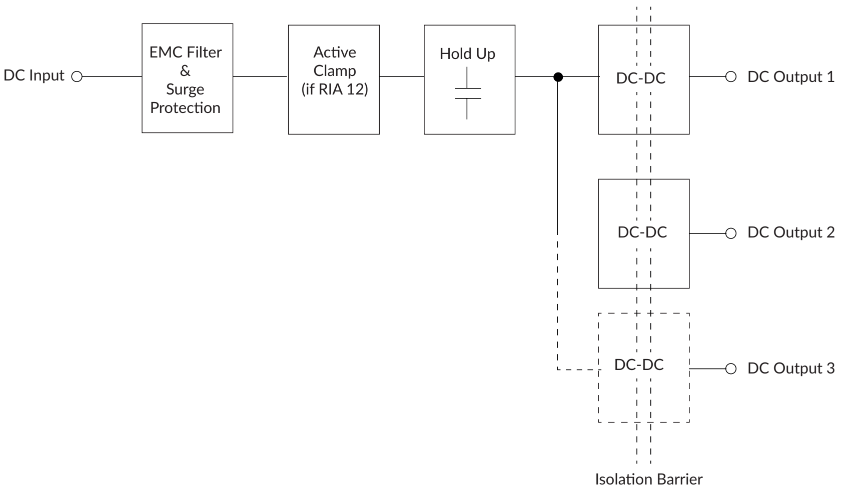
• Power Supply

- 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 shown below.



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 10ms 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 20ms 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)					Specificaion
	110	96	72	48	24	
EN50155	77.0-137.5V	67.2-120.0V	50.5-90.0V	33.6-60.0V	16.6-30.0V	Continous range 0.7-1.25 x Vnom
	66.0 V	57.6 V	43.2V	28.8V	14.4V	Brownout 100ms 0.6 x Vnom
	154.0 V	134.4 V	100.8V	67.2V	33.6V	Transient 1s 1.4 x Vnom
NF F 05-5110	77.0-137.5V		50.0-90.0V		18.0-34.0V	Continuous range
	55.0V		36.0V		12.0V	Brownout 100ms 0.5 x Vnom
	176.0V		115.0V		40.0V	Transient 100ms
BRB/RIA12	77.0-137.5V	67.2-120.0V	50.4-90.0V	33.6-60.0V	16.6-30.0V	Continuous range 0.7-1.25 x Vnom
	66.0V	57.6V	43.2V	28.8V	14.4V	Brownout 100ms 0.6 x Vnom
	165.0V	144.0V	112.5V	72.0V	36.0V	Transient 1s 1.5V x nom
	385.0V	336.0V	252.0V	168.0V	84.0V	Transient 20ms 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**
9kHz-150kHz	No limit
150kHz-500kHz	99dBuV quasi peak
500kHz-30MHz	93dBuV quasi peak

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

Power Solutions For Rail Applications

XP Power has a long and successful history of supplying power solutions into the railway industry from individual DC-DC converter modules to complete power assemblies. We have a clear understanding of the specification requirements and challenges encountered in developing electrical & electronic systems for train borne & trackside applications. When comparing EN50155 and the older BRB/RIA & NF F standards, the input ranges and surge requirements differ. XP Power has developed solutions to comply with all of these standards over a number of nominal input voltages and successfully deployed these solutions in partnership with our customers.

Our latest DC-DC module product introductions are fully evaluated and certified to the railway standards with full EMC reports for integration into end system assemblies or for integration into complete power system sub-assemblies in our engineered solutions groups around the world to provide turnkey solutions for system designers.

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 (90-132VAC or 180-264VAC).

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.

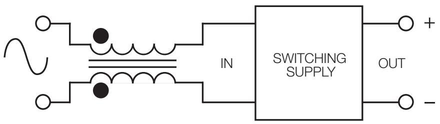


Figure 1

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

Basic Insulation
According to international safety standards (e.g. IEC62368-1) basic insulation provides basic protection against electric shock i.e. one level of protection, and the test voltage used is 1500VAC for 300VAC working voltage.

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

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

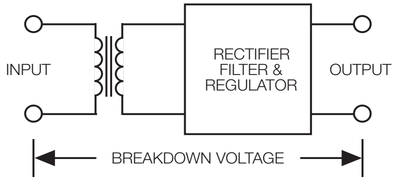


Figure 2

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 data communication ideally suited to harsh, electrically noisy environments

CANopen
CANopen is a communication protocol and device profile specification largely used in automation applications. It uses the Controller Area Network Bus (CANBus) serial bus designed for industrial environments

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

CE Mark
A means of identifying a product as meeting all of the relevant European directives developed to allow free trade between member states.

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,.

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.

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.

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.

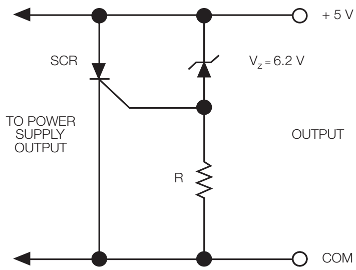


Figure 3

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 converters it is the reduction in output power at elevated temperatures or low input voltages.

DeviceNet
DeviceNet is an open network protocol, managed by ODVA, used for data exchange between interconnected industrial devices on a Controller Area Network (CAN).

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.

Digital Signal Processing (DSP)
The mathematical manipulation and processing of a signal in real time using a digital algorithm. Used to control digital power supplies and DC-DC converters.

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 3000VAC for ITE and industrial equipment, and 4000VAC for medical equipment for 300VAC 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.

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. EMI can be conducted through the input or output lines or radiated through space.

Enable
Power supply interface signal 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.

EtherCAT
EtherCAT (Ethernet for Control Automation Technology) is an ethernet based fieldbus protocol.

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.

Floating Output
An output of a power supply that is not connected or referenced to any other output. 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 switching power supply. 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 4.

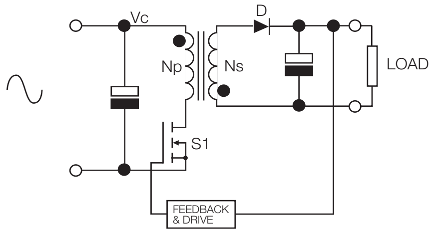


Figure 4

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 5.

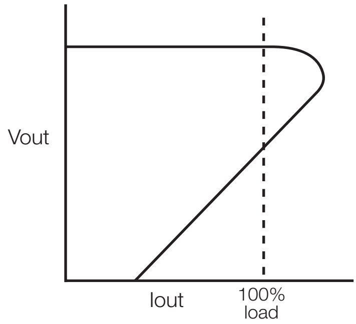


Figure 5

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.

Graphical User Interface (GUI)
A user interface that enables interaction with digitally enabled electronic devices, such as a power supply or DC-DC converter, using a computer.

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.

I^{2}C Bus
Inter Integrated Circuit BUS is a serial BUS widely used in power management systems.

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 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 or DC-DC converters at turn-on.

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 or DC-DC converters 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 converter.

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 converter as sense points for voltage regulation.

Logic Enable
The ability to turn a power supply or DC-DC converters on and off with signal level control.

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.

Modbus
Modbus is an open data communication protocol used for connecting industrial electronic devices transmitted over a serial bus, such as RS485 or RS232 which define the signal levels employed.

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 converters.

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-217F.

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 ≤500VDC.

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 converter. Switch-mode power converter 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 53.

Output Voltage
The nominal value of the DC voltage at the output terminals of a power converter.

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 6.

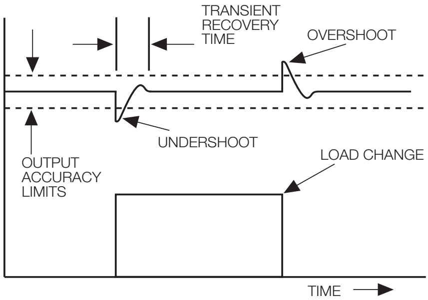


Figure 6

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 a temperature within 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 7.

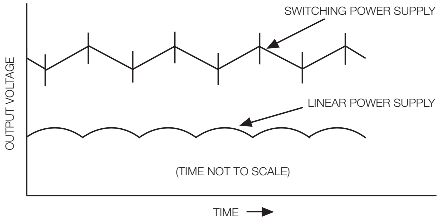


Figure 7

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 8.

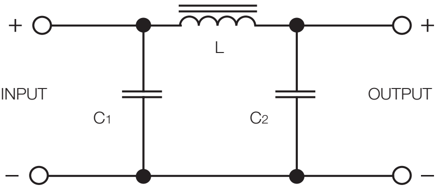


Figure 8

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.

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.

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.

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 20g shock for 11 milliseconds and 10g random vibration for 2 hours over a 2-2000Hz 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 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 converter circuit when the power supply is first turned on. This technique is generally used to provide a gradual rise in output voltage or current, 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 1500VAC for 300VAC 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 switching rate at which the power stage(s) of a power supply or DC-DC converter operates.

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.

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 37.

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 36.

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.

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 interface.

Pulse Width Modulation
A method of voltage regulation used in switching supplies whereby the output is controlled by varying the width 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. 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. 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 failure cannot be tolerated. See page 61.

Reference
The stable voltage from which the output voltage/current 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 ITE and industrial equipment, and 4000VAC for medical equipment for 300VAC 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 derating any dangerous currents that might occur due to malfunction or accident.

SCPI
Standard Commands for Programmable Instruments (SCPI) is designed for controlling test and measurement instruments and devices and can be used with RS232 & RS485 serial communication buses. It is used for programmable electronic test equipment and automated test equipment.

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.

TÜV
TÜV Rheinland Product Safety Group. An independent German organization which tests products for safety.

UKCA Mark
The CE mark is no longer valid for products sold in the UK to denote conformity with the required legislation. An alternative mark has been introduced to take its place, the UKCA mark.

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 without the selection of input range, either manually or electronically (as in auto-ranging input).

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 used 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.

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.

Index

Index

Your **Essential Guide** to

Power Supplies

This easy reference guide provides an invaluable resource for system designers when choosing and integrating power supplies and DC-DC converters.

Your Essential Guide to Power Supplies covers subjects such as safety, electromagnetic compatibility (EMC), thermal management, lifetime, and reliability of power converters. Also considered are energy efficiency, analog and digital control interfaces, the increasing benefits of digital control and intelligent power and much more.

Whether you are experienced or new to designing-in power supplies or DC-DC converters this book offers a wealth of information in one easy reference guide.

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