INTRODUCTION

One of the first questions one should ask themselves when selecting an appropriate AC/DC power supply for a given application is what sort of environment that device will be expected to operate in. A power supply that is intended to spend its operational life on the floor of an office cubical will clearly be subject to a different set of design considerations than one that is intended to be potted into an enclosure and mounted to the side of an industrial irrigator for instance. Many physical properties of circuit elements and the media that surround them are functions of environmental factors such as ambient temperature, air pressure, humidity, pollution degree, etc. Accordingly, the behavior of a given power electronics network is expected to change as its surrounding environment changes.

This month’s Technical Bulletin will provide a basic overview of how changes in ambient temperature can be expected to affect the behavior, performance, and reliability of power supplies. We will examine what determines a power supply’s operational temperature range, how to interpret thermal derating curves, and what one might expect if thermal limits are exceeded. An overview of some temperature related industry conventions and of popular cooling methods is also provided.

CONVENTIONAL OPERATING RANGES AND DERATING CURVES

Before diving into the implications of operating power supplies at extreme temperatures, it will be useful to define some basic expected operating ranges for two common types of power conversion products. It should be noted that there is not one single standard for operational temperature range, nor for thermal derating. The following ranges are intended to be a basic rule of thumb in lieu of a formal specification from the power supply manufacturer. Further, the scope of these generic ranges is limited to the industrial, commercial, and medical markets. Other markets may be expected to observe different generic ranges.

AC/DC Power Adaptors (Wall Mounts and Desktops)

The typical AC/DC power adaptor, enclosed in a plastic case, can be expected to offer its full nameplate-rated output power in ambient temperatures between 0°C and 40°C (32°F and 104°F). This range spawns from the assumption that the devices are being used indoors in an office, home, or similar environment where people work or live. Most people are not interacting with electrical office equipment or hospital equipment in environments outside of this range. These types of power converters can usually operate safely and reliably in environments between 40°C and 60°C with appropriate derating considerations. These converters can also be used safely and reliably below 0°C, if they start. More on that later. In general, the power in Watts drawn from an adaptor by a piece of equipment should not exceed the output of the function of temperature (T) given in [1] and displayed graphically in Figure 1.

$$P_{AVAILABLE} = \begin{cases} P_{RATED} & ; 0°C < T \leq 40°C \\ P_{RATED} (2 - 0.025T) & ; 40°C < T \leq 60°C \\ 0 & ; T > 60°C \end{cases}$$ [1]

Internal AC/DC Power Supplies (Open Frame and Enclosed):

The typical internal AC/DC power supply can be expected to offer its full nameplate-rated power output in ambient temperatures between 0°C and 50°C (32°F and 122°F). It is also rather common to see open frame converters with lower temperature reaches well below 0°C. This range spawns from the assumption that the devices are being operated in some enclosed end device that may house other dissipative elements and may offer limited means for generated heat to escape. Further, the possibility exists that the internal supply may be used in an end device designed for use outdoors or in more extreme environments than a home or office. These types of power converters can usually operate safely and reliably in environments between 50°C and 70°C with appropriate derating considerations. In general, the power in Watts drawn from an adaptor by a piece of equipment should not exceed the output of the function of temperature (T) given in [2] and displayed graphically in Figure 2.

$$P_{AVAILABLE} = \begin{cases} P_{RATED} & ; 0°C < T \leq 50°C \\ P_{RATED} (2.25 - 0.025T) & ; 50°C < T \leq 70°C \\ 0 & ; T > 70°C \end{cases}$$ [2]
CONVENTIONAL OPERATING RANGES AND DERATING CURVES CONTINUED

Open frame power supply thermal derating curves often carry one additional caveat, especially when dealing with super-100W systems. That caveat is the presence of a conduction or convection based cooling mechanism. It is not uncommon to see open frame derating curves with multiple traces, each for different cooling considerations, and/or different output voltages. Lower voltages represent higher currents and higher currents translate to greater dissipation. Most higher-power open frame power supplies are rated under the assumption that a prescribed volume (usually between 20 and 40 CFM) of forced air will be provided to push hot air away from the surface of dissipative elements. Without this airflow, the available output power can be expected to suffer by as much as 40 or 50%. Further discussion on convection cooling will be provided later in this article.

It warrants reiteration that these functions are generic, and are presented to further this articles discussion on environmental factors, but that manufacturer datasheets should always be consulted before making formal design decisions.

LOW TEMPERATURE OPERATION

There are two primary mechanisms by which power supply performance is degraded at sub-specified temperatures: “self-removing” inrush current limiting devices may lose their ability to “self-remove”, and electrolytic capacitors may begin to act more like resistors than energy storage devices.

Inrush Current Limiting Devices

All switch mode power conversion topologies include a bulk capacitor just downstream of the primary rectifier. When the rectified high voltage rail rises rapidly from 0VDC to √2•Line upon application of AC, the bulk capacitor acts almost like a short circuit, drawing extremely large amounts of current, known as inrush current, as the capacitor begins to charge. Excessive inrush current is undesirable for a number of reasons, and so efforts are made to mitigate it. One of the most common strategies it to place a negative-temperature-coefficient thermistor (NTC) in series with the bulk capacitor. At rated storage temperatures, the thermistor exhibits a high impedance, effectively limiting the amount current allowed to flow into the bulk capacitor during start-up. As the limited current flows through the impedance, I²R losses in the thermistor are dissipated as heat. That heat raises the temperature of the thermistor and quickly decreases its impedance accordingly. In this manner, the NTC acts as a self-removing impedance, present during start-up and negligible shortly thereafter.
LOW TEMPERATURE OPERATION CONTINUED

The fact that these current limiting devices have a negative temperature coefficient means that there is an inverse relationship between the device temperature and its impedance, and that relationship is exponential in nature. A representative NTC impedance curve is shown in Figure 3.

![Representative NTC Impedance Curve](image)

Figure 3. Representative NTC Impedance Curve

There are many different types of thermistor materials and constructions, attributing to a vast array of nominal impedances, and rates of impedance change across given temperature spectrums. Accordingly, great care is taken by the PSU design engineer to ensure that the chosen thermistor maintains an appropriately high impedance at the upper limits of the PSUs rated temperature range to properly mitigate inrush currents, while still maintaining an appropriately low impedance during steady state, light load operation at the lower limits of the PSUs rated temperature range.

Most off-the-shelf pulse width modulation controllers utilize a start-up circuit that pulls a small amount of current from the rectified HV rail to energize the chip, allowing it to effectively begin steady state power conversion. As ambient temperatures decrease below the PSUs rated values, the NTCs impedance continues to rise exponentially. For a given design, there exists a temperature below which the input impedance will be too large for the converters start-up circuit to pull the needed amount of current off the HV rail to initiate a successful start-up. If the device does not start up, current is not pulled through the thermistor quickly enough to raise its temperature and lower its impedance. The device is effectively stalled.

Electrolytic Capacitors

Discounting the above described low temperature fault mechanism, there still remains another concern for the low temperature operation of switch mode power supplies: electrolytic capacitance. As was mentioned in the last section, all converters have at least one bulk capacitor needed for storing energy within an electric field on the primary side of the converter according to [3].
LOW TEMPERATURE OPERATION CONTINUED

\[ E = \frac{CV^2}{2} \]  

[3]

Where \( C \) is the bulk capacitance and \( V \) is the voltage on the HV bus. This local energy store is a fundamental requirement for the stable operation of any switching converter. The switching frequency of such a converter varies widely from design to design but is always much higher than the AC line frequency (tens to hundreds of kHz). At these high frequencies, the inductive nature of the mains lines effectively limits the available current that can be supplied to the converter. Accordingly, a local energy store with low HF impedance can receive and store the incoming 50 or 60Hz energy, while simultaneously providing energy to the downstream conversion network at a much higher frequency. One of the earliest PSU design determinations is just how much energy actually need to be stored in this bulk capacitor to support stable operation.

As the temperature of the electrolyte within an electrolytic capacitor decreases, its viscosity increases, resulting in a degradation in electrical conductivity. This drop in electrolyte conductivity ultimately manifests itself as a decrease in capacitance of the structure. In examining [3], one can see that as the temperature decreases, and the bulk capacitance decreases in turn, less energy can be stored on the primary side of the converter. Accordingly, there exists a temperature below which the available HF energy is insufficient for stable operation of the converter. Further, most power supplies incorporate a good deal more than a single electrolytic capacitor. E-caps are also used widely in the output filter to reduce voltage ripple. As the capacitance in the output filter decreases with temperature, the ripple will increase and may become unsuitable for the application at hand.

HIGH TEMPERATURE OPERATION

Heat is a power converter’s foremost nemesis. At high operational temperatures, thermal runaway can cause semiconductors to overheat and burn out, component temperatures may exceed those permitted by applicable safety standards, and a devices operational lifetime can be rapidly degraded as chemical processes are accelerated (we will provide future technical bulletins on each of these topics as they can each easily warrant a full article). Further complicating this matter is the fact that power supplies generate heat as a byproduct of normal operation. This occurs when functional currents pass through any element with a real impedance such as diodes and transistors, and even PCB traces and transformer windings. Heat is also generated when non-functional currents move through real impedances, such as eddy currents in the cores of magnetic elements. The heat generated by a power supply is related to its operational efficiency according to [4].

\[ Q_d = P_{OUT} \left( \frac{1}{\eta} - 1 \right) \]  

[4]

Where \( Q_d \) is the heat dissipated in Watts, \( P_{OUT} \) is the output power in Watts, and \( \eta \) is the efficiency. \( P_{OUT} \) and \( \eta \) have been assigned like subscripts to make clear the fact that the operational efficiency varies with output power and is not just some fixed value.

If 100% of the heat generated by a given component is transferred to its environment (indicative of a [hypothetical] junction to ambient thermal impedance of 0°C/W), that components temperature will not rise. On the other hand, if there is a disparity between the heat generated and the heat transferred, the devices temperature will rise according to its thermal impedance. To prevent component temperatures from rising to levels that adversely affect their reliabilities or safe operation, the power supply must be designed in manner that allows generated heat to escape (by reducing the thermal impedance between heat sources and the ambient environment), and also perhaps in a manner that minimizes the amount of heat generated in the first place.

Heat is transferred out of a power supply through a combination of all three heat transfer mechanisms: radiation, conduction, and convection, but primarily via the latter two. Any mass that is at least warmer than absolute zero (0°K) will radiate some amount of heat based on its temperature, but the mechanisms that truly shed light on PSU environmental constraints are conduction and convection.
HIGH TEMPERATURE OPERATION CONTINUED

Conduction Heat Transfer and the Origin of Thermal Derating

Conduction is the transfer of heat via the physical contact of objects of different temperatures or through a single solid object with opposing surfaces of different temperatures. The dependence on a temperature difference is the key to understanding why power supplies must be derated at higher ambient temperatures. The rate at which heat is transferred via conduction is given by Fourier’s Law, given in [5].

\[ Q = \frac{A}{\theta \cdot d} (T_1 - T_2) \]  

Where \( Q \) is the heat transferred in Watts, \( A \) is the equivalent surface area of the conducting medium orthogonal to the transfer of heat in squared meters, \( \theta \) is the thermal resistance of the medium in meters Kelvin per Watt, \( d \) is the length of the heat transfer path through the medium in meters, \( T_1 \) is the temperature of the warmer surface in Kelvin, and \( T_2 \) is the temperature of the cooler surface in Kelvin. Notice that the thermal resistance appears in the denominator of the expression on the right-hand side of [5]. This supports the claim that if the thermal resistance is zero, infinite heat is transferred (or can be transferred) and accordingly, the device temperature rise is zero as it retains no heat.

Now, assuming the conduction heat transfer paths are already designed, and the materials are real (such that \( A, d, \) and \( \theta \) are fixed and are non-zero) one can assert that the rise in temperature of a given component is proportional to the heat it generates less the heat transferred away from it via conduction, or \( \Delta T_C \propto Q_d - Q \). Substituting in [4] for \( Q_d, [5] \) for \( Q \) and assigning a constant, \( k \), to the material properties in [5] for a given conduction heat transfer path, one obtains [6].

\[ \Delta T_C \propto P_{OUT} \left( \frac{1}{\eta_o} - 1 \right) - k(T_1 - T_2) \]

Equation [6] tells us exactly why we must derate the output power of a power supply as the ambient temperature surrounding it increases. Notice that as \( T_2 \) approaches the value of \( T_1 \), \( \Delta T_C \) rises. That is, as the ambient temperature of a power supply approaches its internal temperature, the ability of the components to transfer their self-generated heat out to the ambient environment diminishes.

To exemplify this point, we will make a number of simplifying assumptions. First, assume that component \( c \) is some arbitrary component within the PSU that must not exceed a particular temperature in order to ensure proper operation, such that if \( \Delta T_C \) exceeds a given value the device as a whole will fail. We will arbitrarily assign \( \Delta T_C\text{MAX} \) a value of 50 for demonstrative purposes. Similarly, we will arbitrarily assign \( \eta_o \) a proportionality constant of 1, and \( k \) a value of 1. To further simplify, we assert that \( \eta_o \) is fixed (which we already explained is not true in practice) and will assign it a value of 80%. Assume that the power supply in question is rated to deliver 380W maximum. The final simplifying assumption will be to assume that \( T_2 \), the internal temperature of the power supply, is a fixed constant assigned a value of 85. In reality, the internal temperature will of course rise as more heat is dissipated. All of these simplifications remove some of the scientific value of [6], but in return, allow us to very simply and graphically detail how ambient temperature and output power are exchanged in an effort to prevent the overheating of internal components. If one works equation [6] with the above given assignments, they can obtain the traces shown in Figure 4.

Figure 4 should make clear why power supply derating curves take the shape that they do. Full rated power is available up until the point where ambient temperatures are high enough to diminish the rate of heat transfer to the point that the temperature rise of internal components exceeds a set threshold. Beyond this point, if we wish to continue to raise the ambient temperature, there is no choice but to draw less power so as to decrease the internal dissipation.
HIGH TEMPERATURE OPERATION CONTINUED

Figure 4. Affect of Derating on Internal Component Temperature Rise

Convection Heat Transfer and the Origin of Convection vs. Forced Air Ratings:

Convection is the transfer of heat via the movement of fluids, including air, across the surface of an object with a temperature different than that of the fluid. Convection heat transfer can get a good deal more complex than conduction in the context of power supply cooling. The key take-away is to understand that conduction does not work alone to remove heat from inside a power supply, conduction simply brings the internally generated heat out to the surface of the power supply. From there, we depend on convection to “carry” the heat away from the supply into the ambient environment.

Consider for a moment a situation whereby the air directly abutting the surface of a power supply were somehow disallowed from moving. As the air stays in proximity with the hot power supply surface, its temperature will rise. Eventually, the temperature will become equal to the temperature of the power supply surface. Going back to the first sentence of this section, notice that there is once again a dependence on a temperature differential between the two media. If the fluid (air) and the power supply (the hot object) are the exact same temperature, then no heat will be transferred. Without allowing heat to transfer away from the outside of the power supply, its temperature will begin to rise as well, further impeding the effects of conduction. Luckily, air is not naturally inclined to stay in one static location, particularly in the presence of temperature gradients throughout the fluid. It is common knowledge that “warm air rises”. Indeed, as the temperature of the air nearest the warm power supply increases the density of the air decreases, causing cooler, denser air to “sink in” and take its place.
HIGH TEMPERATURE OPERATION CONTINUED

For some power supplies, the natural process of convection (cool, dense air sinking and replacing warmer less dense air) is sufficient for maintaining an adequate temperature differential between the power supply’s outer surfaces and the air for appropriate heat transfer. However, the rate of heat transfer via convection, not unlike conduction has a dependence on interface area, or how much surface in squared meters is actually in contact with the fluid. The power supply industry, alongside many of the industries it supports, strives to achieve greater functional densities. One of the strongest ongoing industry trends is to develop technologies that allow us to put more and more power into smaller and smaller packages. Recall that in general, as output power increases, the amount of heat generated increases as well. Combining this with the fact that the ability of convection to remove heat from the surface of a power supply is dependent on the size of the power supply and its effective contact area reveals the need for forced air cooling in many of today’s modern, high density power converters. The natural process simply isn’t fast enough to maintain adequate heat transfer rates and prevent internal components from overheating.

This is why you will sometimes see a family of curves on a power supply thermal derating plot for different volumes of forced air, like those in shown for the PDAM240 series in Figure 5, and also why power supply ratings are offered for both natural convection and forced air cooling configurations. The faster the user removes heat from the surface, the more heat they are allowed to dissipate, and the more power they can draw.

![Figure 5. Example of a Family of Derating Curves (PDAM240 Series)](image-url)

THERMAL MANAGEMENT FOR YOUR NEXT DESIGN

Power supply thermal management is an enormous topic that we’ve only just scraped the surface of in this technical bulletin. Expect to see future bulletins that focus entirely on even just one of the topics touched upon in this article. Proper power supply selection, cooling strategy implementation, and derating observation are fundamental elements of ensuring PSU longevity, reliability, and performance. The team at Power Partners Inc. can help you solve your next thermally challenging power converter design in.