Electronics

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Specification Demystification III: Understanding Power Supply Operating Altitude

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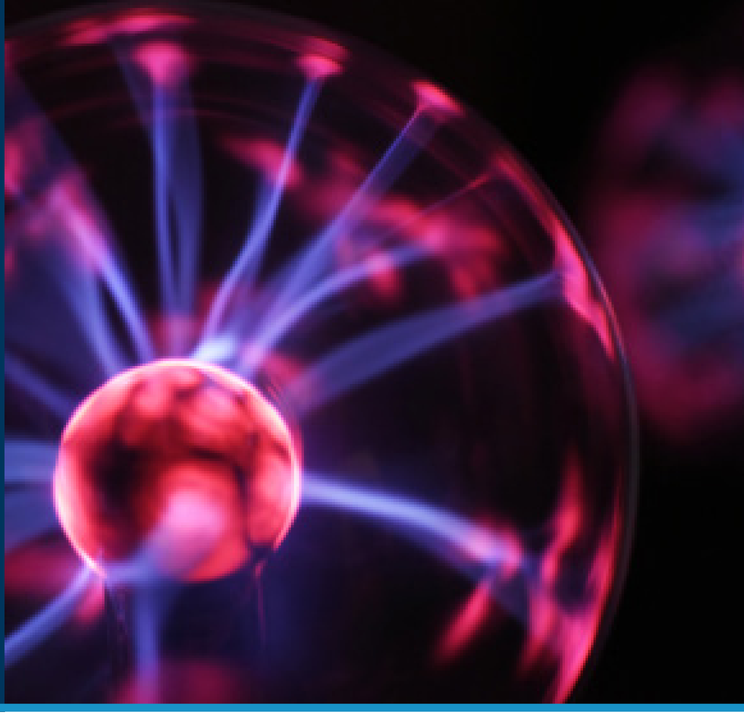
Introduction

From the capital of Tibet, to the once-bustling mining town of Leadville, Colorado, our planet's mountainous terrain has not stopped mankind from settling down in some pretty altitudinous places. Residents of the world's highest cities have acclimated to the decrease in pO_2 , but design engineers need to ensure that their electronic devices are up to the same challenge. The decrease in air pressure as altitude rises away from sea level has some interesting effects on the operation of electronic devices. These effects are particularly pronounced for power electronics circuits such as switch mode power supplies (SMPS) which dissipate considerable amounts of heat, and often contain high voltage networks. This month's bulletin will provide an introduction to the physical phenomena that spawn power converter design challenges for high altitude applications.



Increasing altitude has interesting effects on the dielectric properties of air and on the effectiveness of air as a cooling agent.

UNDERLYING CAUSE OF CHANGE

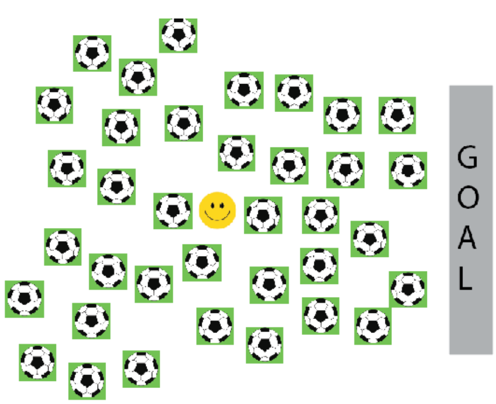
The decreasing effectiveness of air as a coolant and as a dielectric with increasing altitude both stem from the same fundamental force: gravity. Newton's law of universal gravitation tells us that the attractive force between any two objects is inversely proportional the square of their distance from one another. Accordingly, the molecules in a gas (such as air) are pulled towards the Earth's surface with ever greater force the closer they are to it's center of mass. Further, air below any given horizontal cross section of the atmosphere is compressed by the weight of all the air above that cross section. Thus, a density gradient is developed through the atmosphere with the highest concentration of air molecules per unit volume occurring at sea-level, and the lowest concentration occurring at edge of the vacuum of space. The density of a gas is key parameter in the determination of both its thermal and electrical material properties.

DENSITY VS. DIELECTRIC STRENGTH

Picture several isolated patches of tall grass spread about an otherwise smooth concrete surface in front of a net. In each patch of tall grass there is kickball. If you lightly tap one of these balls, the tall grass will impede it from rolling onto the concrete. If you kick the ball with a good deal of force however, you can dislodge it from the tall grass and set it rolling toward the net. Along the way, it may bump into another kickball nested in another grassy patch. If you kicked the ball hard enough, it might even have enough kinetic energy left by the time it reaches the next ball to dislodge that one as well, setting both balls rolling toward the net. Suppose your goal is to get as many balls as possible into the net with one single kick. You can start as close or as far from the net as you please for your first kick, and you can choose the density of balls present. How can you optimize your odds of scoring the most goals?

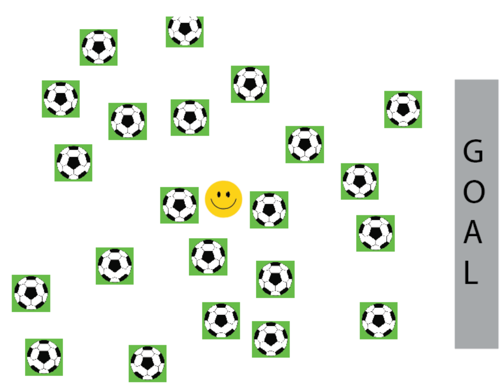
Your first thought is that to score a lot of goals, you'll need a lot of balls between you and the net, and so you opt for a high density, and you stand far back from the net for your one and only kick. This is illustrated below. You are represented by the happy face.

You kick with all your might, but to your dismay, you are unable to score any goals. There are simply too many balls in the way and all of the energy of your kick is lost dislodging the first few balls from their patches. If you could kick a good deal harder, you might stand a chance, but you can't, so instead you decide to move a bit closer.



Once again, you kick with all of your might, and now with less balls in the way, the last collision has just enough energy to set one ball slowly rolling into the net. Success. But you can do better. Moving closer worked well, so you move even closer still.

This might not be your brightest moment. You wind up for a strong kick but as your foot goes flying freely through the air, never making contact with a ball, you realize that you've stepped too close to the net, and now there aren't any balls in front of you at all. You remember that you've been given two parameters to play with and so you step back again but ask to have the density reduced.



The fourth time's a charm and your swift kick in this optimized playing field sends three balls hurdling into the net. You're pleased with your performance but can't help but wonder if you could still do better. Decreasing the density did wonders, so you consider decreasing it further, but you won't be fooled again. If you decrease the density too much, you'll be left kicking at the wind again with no kickballs in sight. Perhaps it is best to stop here. What has been learned?

It turns out that your success isn't dependent on your distance or the density alone. Increase either too much and your energy will all be spent dislodging balls from grassy patches. Decrease either too much and you'll be left kicking the breeze. Both of these parameters effectively determine the total number of kickballs between you and the net. In fact, if you kick with the same force everytime, it is the product of your distance and the density of the balls that determines how many will go into the net, and neither a very large product nor a very small product benefits your success. Instead, there appears to be a magic number somewhere in between that yields the highest number of goals.

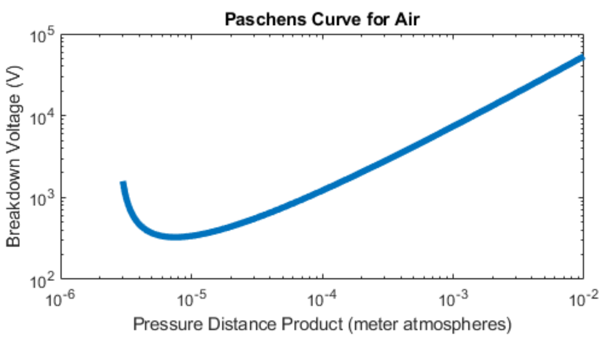
This is the fundamental concept behind Paschen's law, which was first published in 1889. Paschen's law provides a model for the voltage at which dielectric breakdown of a gas will occur as a function of the product of the gasses pressure and the distance between opposite polarity conductors. Paschen's law is given below:

$$V_{BREAKDOWN} = \frac{B\rho RT\Delta s}{ln\left(\frac{A\rho RT\Delta s}{ln\left(\frac{1}{\gamma}\right)}\right)}$$

Where B and A are constants determined by the material properties of the gas. Paschen's law is actually expressed as a fucntion of gas pressure, but we've taken the liberty of expressing the pressure is terms of density according to the ideal gas law so as to draw a clear relationship to the kickball analogy. Gamma represents the secondary electron emission probability, and delta-s represents the distance between conductors of opposite polarity within the gas.

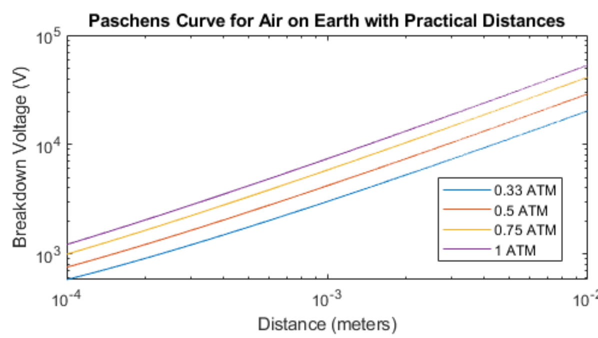
The density-distance product essentially determines the probability of a collision between a charge carrier which has been accelerated by the electric field, and any neutral molecule in the gas. When the charge carrier collides with a neutral molecule with enough kinetic energy, it can ionize that molecule. The ionzied molecule, no longer charge neutral, will also begin accelerating in the electric field. Every time a collision occurs, energy is lost in ionizing the molecule that was collided with (just like energy was lost everytime a new kickball needed to be dislodged from a grassy patch) and the charge carriers can only gain more kinetic energy as they are being accelerated by the field between collisions. Of course, the charge carriers can gain more kinetic energy over a shorter distance if the electrical field is stronger. A stronger electric field is the same as a harder kick to the first kickball. The only major difference between our kickball analogy and Paschen's law, is that in reality the force of the "kick" is always present and not just an initial impact. Because of this, there exists a condition whereby the dislodging of balls (ionizing of neutral molecules) can take on a multiplicative effect.

One rolling ball dislodges two other balls, each of which go on to dislodge another two and so on. This is known as avalanche and it is the condition under which the gas ceases to act as an insulator, and instead allows electrical current to flow freely. This is observed as an electric arc, sort of like lightening, a large amount of current flowing freely through a low impedance path in air. For a given density-distance product, there is an associated voltage that is high enough to set off this avalanche action. That voltage is called the breakdown voltage. A simplified Paschen's curve for air is shown below.



Notice that the general trend is for breakdown voltage to increase rapidly with increasing density-distance product. This is the situation where you are getting further from the net and/or the density of the balls on the field is increasing. More and more energy (harder and harder kicks) would be required to make anything interesting happen. We also see the condition however, where for very small density-distance products, it quickly gets difficult to make anything interesting happen. This is the situation where you are kicking at the wind with no kickballs in sight.

For the purposes of designing safe power converters, we can fairly quickly dispel the left-hand portion of the curve. The air pressure on top of Mount Everest, the highest point on our planet, is approximately 0.33ATM. This means that in an absolute worst-case situation, designing a power supply for use on Everest's summit, we'd only need to start considering the left-hand portion of the curve for high-potential node separations of less than about 30μm. This is clearly a moot condition for practical power supply design on planet earth. So for our purposes, it is safe to say blanketly that as air density decreases, breakdown voltage rapidly decreases as well. This is illustrated by the family of curves below, where we have plotted breakdown voltage versus separation distance (from 0.1mm to 10mm) for a a few different air pressures between 1ATM (sea level) and 0.33ATM (summit of Everest)



Looking at Paschen's curve for air through this lens, one can see clearly how as we increase altitude, we must also increase the distance between conductors of opposite polarity in order to maintain an equal value for breakdown votlage, and this is one of the main reasons power converters have altitude ratings. When a power supply is designed, special care must be taken to ensure that conductors with high potential product of your distance and the density of the balls that determines how many will go into the differences are kept at appropriate distances from one another. If by chance a high enough potential were to appear across two close conductors, the impedance of the air between them could rapidly deplete as avalanche begins, and mains current could flow freely onto the secondary side of the converter where users may be interfacing with the equipment. Safety standards that mandate how far two such conductors must be kept from one another typically include tables of distance multiplication factors for different altitude ratings. If a PSU manufacturer wants to certify their design for 5,000 meter operation, those conductor distances are going to need to be much greater than if they are certifying for only 2,000 meter operation.

DENSITY VS. CONVECTIVE HEAT TRANSFER COEFICIENT

Due to the vast number of variables at play, the effect of air density on convective heat transfer is not as readily depicted by kickballs and smiley faces as the relationship between density and dielectric strength. For simplicity, we can vaugely conceptualize each individual molecule of a gas as a "heat carrier" with some limited capacity for storing thermal energy. The more dense the gas, the higher the number of individual heat carriers per unit volume. Cooling fans are designed and specified to push or pull some volume of air through a cross section per unit time. So for a given fan operating at a fixed speed, there is some fixed volume of air passing through a given cross section in a given amount of time. The more "heat carriers" that exist in that volume of air, the more heat the air can take with it as it leaves the area. This again is a rather drastic simplification, but it is sufficient to recognize that the convective heat transfer coefficient in a cooling system is a function of, amongst many other things, the density of the cooling gas:

$$Q = hA\Delta T$$

and

$$h \propto \rho$$

where Q is the rate of heat transfer in Watts per unit time, A is the surface area of contact between the dissipater and the gas, delta-T is the temperature difference between the surface and the gas, h is the heat transfer coefficient and rho is the density of the gas.

So as altitude rises, and density falls, the rate at which heat can be convectively transferred away from a power supply falls as well. As the rate of heat transfer falls, component temperatures rise. Hotter components live shorter lives. The heat generated by the power supply is proportional to the amount of power it is processing. So there are really only a few variables one can play with in an effort to prevent temperature rise if the device is to operate under the same thermal conditions (same delta-T) at high altitude as it is at sea level. The surface area can be increased by using larger heat sinks, and/or the volume flow rate of the cooling fan can be increased. Otherwise, one would have no choice but to derate the PSU throughput so that less heat is generated to begin with.

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Dylan Howes is a Power Electronics Applications Engineer at TT Electronics. Dylan manages all technical aspects of power converter design-in efforts, and authors technical content featuring power conversion trends and technologies. He has past experience is in acoustics engineering and communications hardware engineering and spends much of his free time teaching science/mathematics to college and high school students in the Central Massachusetts area. Dylan holds a B.S. in Electrical Engineering from the University of Massachusetts at Lowell and continues his post-graduate studies in Power Electronics Engineering at the Worcester Polytechnic Institute in Worcester, MA.

Previous Bulletins:

- Specification Demystification II
- Power Supplies for Home Healthcare Applications
- Specification Demystification
- Installation Considerations for Internal Power Supplies
- Burst-Mode Operation