WHITE PAPER

How to Specify High Voltage Connectors

JULY
2020

HOW TO MOST EFFECTIVELY SPECIFY HIGH VOLTAGE CONNECTORS FOR YOUR APPLICATION

Experienced insights for superior results

Specifying the right connector can have an enormous impact on the ultimate quality of your product or research equipment, both in the efficacy and longevity of its performance as well as the ongoing safety of its operation. This is true, of course, with any connectors, but with high voltage connectors the necessity is more urgent still. Indeed, the carrying of higher voltages and/or the tendency for more sensitive operations can not only bring with it increased safety concerns for operators, patients, technicians, manufacturers, surrounding communities and other stakeholders, but also often presupposes the increasing threat of generating arcs or coronas, which can lead to reduced reliability and premature failure of the equipment.

While most equipment manufacturers understand that the engineering capabilities, advanced materials knowledge and other experience needed to develop effective high voltage connectors is far more extensive than that needed for their lower voltage cousins, and thus seek out proven expertise accordingly, many do not realize the value of forming an informational alliance with their selected high voltage connector partners. Indeed, optimum selection can involve much more than merely selecting a part number; there can be numerous other aspects to understand, consider and discuss in order to benefit from optimum results for the long term. These might include defining the impact of operating conditions, appreciating the various voltage levels that may be involved, selection of safety mechanisms to be built in, and more.

If application specific information is not provided, it is incumbent upon the equipment manufacturer to at least determine and communicate the appropriate technical regulations and standards that will impact the application. This will provide the experienced high voltage connector supplier with valuable information for appropriate design specifications. Providing this information is a vital first step, and you and your supplier can work together to communicate additional details from there.

Regulations we often see, for example, originate from the International Electrotechnical Commission (IEC) and can include 60601-1, 60664-1 and 61010-1. Industry specific standards from automotive or medical organizations or specialized research institutes often impact operation and salability or legal usability and should also be identified and communicated. If the final product needs to meet Underwriters' Laboratory (UL), Canadian Standardization Association (CSA) or International Organization for Standardization (ISO) testing requirements, this would be useful information to impart as well.

Figure 1
IEC building based in Geneva Switzerland

In this white paper, LEMO engineers and designers specializing in high voltage connectors will work to provide readers with an insider perspective, and take some of the mystery out of high voltage connector specification. With this understanding, manufacturers and operators will be able to better specify the high voltage connector that will allow them to design equipment that will deliver maximum performance, optimum longevity, long-term reliability and ultimate safety for all stakeholders.

WHAT IS “HIGH VOLTAGE” ANYWAY?

It is important to understand—and then not worry too much about—that there is no particular specific voltage “number” at which the “high voltage” category begins. What constitutes “high” varies by industry and application, and, more importantly, high voltage connectors in some cases are vital in applications where there is, almost inarguably, fairly low voltages involved.

For example, there is an old rule of thumb amongst industrial manufacturers that anything above 50 volts can be potentially hazardous for humans to handle or to come into contact with under certain circumstances, so over 50 volts might be considered “high” in that context. And, indeed many manufacturers of medical devices that may go inside the body often specify high voltage connectors—with the extra protections inherent to them—for their products even though the voltage involved may be even less. On the other hand, in an industry such as power transmission, which is accustomed to handling extremely electrified equipment and infrastructure, the word “high” might not even be applied until 30,000 volts or more are involved.

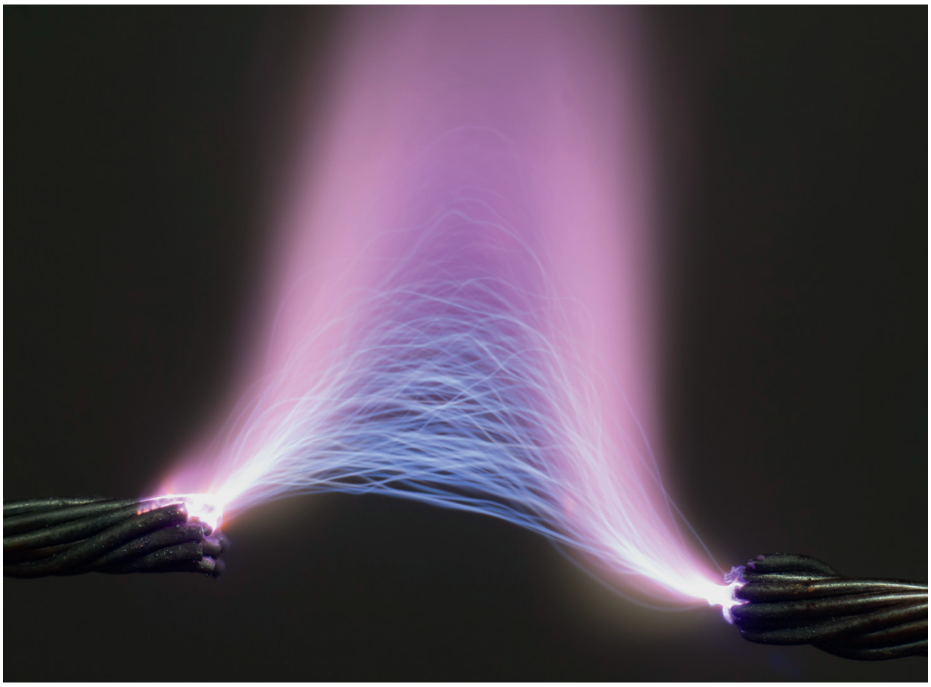

Figure 2
Electrical arc, due to the flow of electric current through the air gap between two conductors, causing plasma

Experienced high voltage connector manufacturers find that for every extremely "high number" voltage application in medical and research-driven instrumentation such as supercolliders, plasma technology, electron beams, nuclear physics, photolithography, x-ray imaging, neutron microscopy and similar applications, there are always "low number" applications such in-body electronics like LVAD (Left Ventricular Assist Device) devices and electrophysiology catheters, as well as microelectronic and circuit board applications that demand the extra degree of protection against arcs, coronas and other dangers and so use only high voltage connectors.

For some additional context, the IEC has a working rule of thumb setting the threshold of "high voltage" at 1000 volts. We at LEMO, based on where we observe clusters of requests for "high voltage" connectors from our customers, often think of the high voltage segment of the connector market as starting at equipment at about 500 volts.

However, the key message in this regard is that, while it is vital to correctly understand and quantify the voltage(s) relating to your product or piece of research or testing equipment, it is not this number alone which should determine whether a "high voltage" connector is right for your application. The ultimate designation should be based upon the function of the end product, and, especially, the relative need to avoid the dangers of arcing or corona generation in use. This is a vital discussion which will be pursued later in this white paper, after some more fundamental concepts are presented.

VOLTAGE IS NOT ONLY ONE NUMBER

When designing components for customers, experienced high voltage connector manufacturers often think of the voltage requirements as at least three distinct numbers, not just one. This is an important concept for product manufacturers to understand in order to get the most effective connectors for their needs, and it should be food for discussions with their chosen high voltage connector manufacturer partner. Certainly, the more the high voltage connector manufacturer understands the specific real world needs of the application, the more on target their connector design will be, and the more reliable and effective their customer's product or equipment will be. So, let's look into this concept.

Often, the default meaning of voltage is **operating** voltage or **working** voltage—the typical voltage used when the equipment is new and operating under "optimum," "pristine" conditions. This is the number that, at a minimum, might be supplied by a product or equipment manufacturer to their high voltage connector partner when they are determining the requirements of a new design.

Perhaps more useful—and practical—is the concept of **test** voltage. Test voltage assumes the demand of the device under the theoretical **poorest** conditions. These detrimental conditions—sometime called **pollutants**—can include:

- **Altitude**
  Air density is impacted by the lower pressures found at higher altitudes, so the elevation at which the product will be used can have significant impact on its voltage requirements.

As a rule of thumb, requirements are assumed at sea level, but designs should be provided with enough threshold to encompass up to 2000m above sea level. If, for example, a piece of test equipment will be used in a mountainous area at an even higher altitude, this fact should be shared with the high voltage connector manufacturer. Impacts on design to ensure efficacy can be substantial; for example, usage at an elevation of 5000m requires an adjustment of 48% in a crucial design specification. The impact can be even more critical in aviation and aerospace applications—usage at 20,000 meters, for example, might demand a correction of 14x or more.

Altitude (m)	Coefficient
2000	1.00
3000	1.14
4000	1.29
5000	1.48

Figure 3
Correction factor for high altitude applications

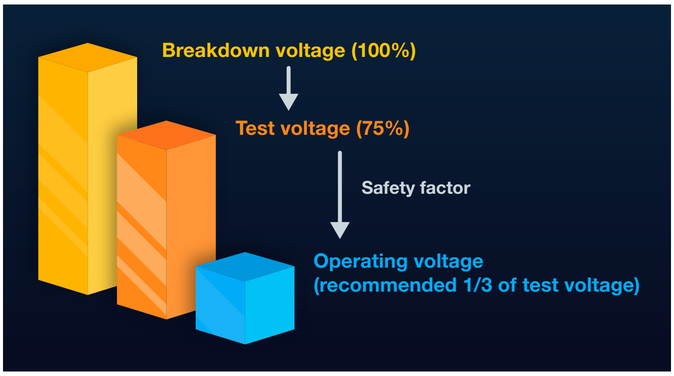

Figure 4
Illustration Breakdown voltage & test voltage

- **Humidity**
  Usage in tropical areas with especially high humidity, use outdoors, or under conditions where wide and frequent temperature fluctuations could create condensation, could impact the voltage needs of the connector.

- **Grit/Dust**
  Equipment usage where there are commonly fine particles in the air—such as in a sawmill or wheat mill or similar processing facility—create conditions that can allow an arc or corona effect to be created inside or around the connector at lower voltages than would otherwise be expected. The high voltage connector design needs to compensate accordingly.

- **Temperature**
  All materials have temperature limits—limits that will be tested as the current passing through it heats it significantly. If ambient temperatures are much higher than typical room temperatures—in an industrial environment in a tropical climate, for example—limits could be reached at lower relative voltages and design would need to be modified accordingly.

As a default, test voltage might be assumed to be 3x operating voltage to provide ample headroom; however, if the machinery will be used during especially challenging conditions—such as those described above—then this fact should be shared with the connector manufacturer so that even more headroom can be built in. These can sometimes be communicated in pollution **degrees**, relative measures with “degree 1” meaning extremely low up to “degree 4” meaning an extreme level of the particular pollutant. As suggested, the optimum span differences in each case could be significant.

Finally, responsive high voltage connector manufacturers will often test or extrapolate to determine **breakdown** voltage, the absolute limit voltage at which arcing or corona will occur and the product will irrevocably fail. In the absence of specific information, the test voltage is assumed to be 75% of the breakdown voltage. However, in some industries this can vary considerably. For example, in some experimental work air is removed from the test environment and instruments are operated at very low pressure. This can have great impact on breakdown voltage and should be communicated to the high voltage connector manufacturer.

Figure 5
Corona effect visible between two electrical contacts at the surface of the connector insulator

In addition, determining these voltage numbers might be more complex still. Also important for the high voltage connector manufacturer to know is if the voltage levels will be constant or intermittent, such as pulsing in short duration bursts of high power operation. Some applications, for example, require millisecond bursts of power. This type of duty cycle could impact design needs as well.

Another potential pitfall that a product manufacturer might also fall into is not realizing—and not communicating to their high voltage connector manufacturer—that voltages might actually fluctuate substantially—albeit briefly—at start up.

We have seen sensitive test equipment where voltage experienced can spike 2x, 3x or more for an instant, and tax the limits of components and possibly cause failure. The potential for this operating characteristic should be communicated to the high voltage connector manufacturer so that modifications can be made to avoid the threat of arcing and other damaging events.

THE DANGERS—ARCING AND CORONAS

Although the full extent of the complex physics involved may be beyond the scope of this white paper, it is important for device manufacturers to at least have a basic working knowledge of the threats facing high voltage and electronic equipment in use.

In general, the threats fall into two categories—arcs and coronas. Arcs are the most common failure mode in this industry and what you will likely hear the most about. In simple terms, an arc is basically a spark that forms and jumps between two pieces of metal or other conductive materials due to a combination of “too high” voltage and “too close” proximity of the components relative to that voltage. When an arc occurs, it leaves a trace of carbon deposit—a burned, ashed, charcoal-like material on the components, which significantly reduces their voltage handling capability at every level. With the breakdown voltage threshold now significantly lower, any subsequent flow of electricity will likely cause immediate product failure.

A corona discharge is a phenomenon that occurs when electricity unintentionally flows off of the components and into the surrounding air, especially under conditions of high frequency. As the air becomes ionized, it heats up, creating a blue glow, often an audible buzz and an ozone smell, and can cause damage or failure to components around such as insulators.

THE INTRICACIES OF HIGH VOLTAGE CONNECTOR DESIGN

To help protect equipment manufacturers and their customers against the devastating effects of arcing and coronas, high voltage connector manufacturers must develop an expertise in specialized engineering design as well as create and continually maintain a cutting edge portfolio of advanced materials to select from.

For example, depending upon the application, helping guard against the threat of a corona occurring often involves developing an expertise in creating components with smoothly rounded edges rather than sharp, perpendicular, 90° edges. This is due to the fact that, like a car racing around a track, sharp curves can, in layman’s terms, cause speeding electrons to veer off the conductor or insulator and into the surrounding ambient air.

Another design concept that may be called upon is minimizing or eliminating the air surrounding the connector components—such as replacing air gaps between conductors with additional insulation material—so that coronas cannot form. Key in this regard is the ability to create a tight tolerance mating interface and the expert use of self-sealing materials such as fluorosilicone to help keep air out of the system. It is vital to let your high voltage connector manufacturer partner know about the details of your application such as if high frequencies will be utilized so that these or other proper design precautions can be taken.

When it comes to engineering in protections against the dangers of arcing, the main concept becomes maximizing the distance between conductor pins and other metal parts inside the connector. In fact, the distance between conductors in large part determines the voltage rating of the connector, and the closer they are to each other the lower the voltage capabilities will be. Since connectors are by nature relatively small components—and marketplace demands are driving ever-smaller shell profiles—the engineering challenge becomes enlarging the distances by artificial rather than spatial means.

Figure 6
Design with increased creepage distance between electrical contacts

This is done through engineering concepts such as creating insulative sleeves around components to create an artificially longer path and make the electrons "think" they are further apart than they really are since they have to travel further distances to go from contact to contact. These created distances are carefully constructed and precisely measured to ensure efficacy, and are usually reported in two ways. **Creepage distance** is the distance along surfaces between the two conductors; **air clearance** is the distance in a straight line between them. It is these specifications that are often codified by IEC and similar regulations to ensure adequate voltage performance—and that's why it is vital that your high voltage connector manufacturer know what regulations are pertinent to the application. And, as suggested above, the distances that need to be created are determined not only by the different voltage demands, but also the mitigating factors mentioned above such as the altitude, temperature, humidity and pollution degree in the operating environments.

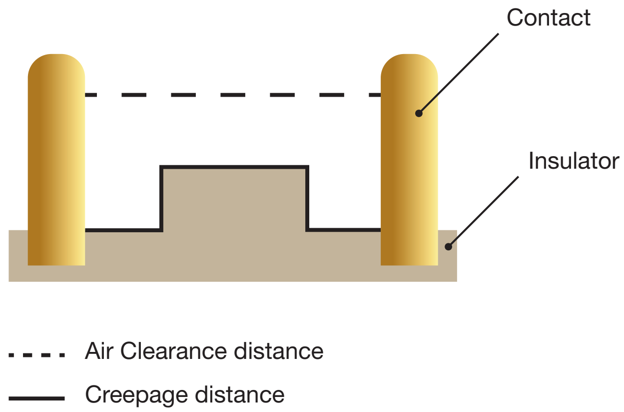

Figure 7
Creepage and clearance distance

Determining the best way to create the creepage distance and air clearance to optimize performance is predicated on possessing a working knowledge of the performance characteristics of insulative materials that have high dielectric strength such as polyoxymethylene (POM), Teflons, polyether ether ketones (PEEK), polyphenylene sulfides (PPS), fluorosilicones and silicones. In addition, if high temperatures will also be involved in the application, then ceramics or even glass will likely be specified as well. Many of these materials are not often utilized in the construction of lower voltage connectors, and effective high voltage connector manufacturers must cultivate ongoing partnerships with materials suppliers as well as understand and be able to effectively deploy this more advanced esoteric knowledge and experience on behalf of their customers.

One such area of knowledge is understanding the concept and pertinence of the comparative tracking index (CTI), a measurement of the electrical breakdown over the surface of an insulating material, measured in volts. Specifying materials with high CTIs helps improve creepage distances; however all materials also have tradeoffs such as relative temperature performance or resistance to radiation and steam sterilization, vital performance characteristics for medical devices and other equipment. It is here where the strategic selection of advanced materials becomes both an art and a science.

It is also worth noting that there are a number of design subspecialty niches within the high voltage connector specialty itself. These include high voltage hermetically sealed connectors for environments that not only have the challenge of high voltage, but vacuum environments as well. In these applications, additional engineering and materials knowledge is required to provide effective connectors. For example, in LEMO's case, these connectors make use of ceramic to metal construction with materials including alumina ceramic, moly-manganese and nickel plating. Further, knowledge of sealing techniques and their relation to ambient temperatures is vital in the deployment of O-rings, welds or ultra-low leakage bonded ceramic or glass seals.

In addition, high voltage applications tend to be relatively low current, but some applications in high end research facilities and power generation facilities might require connectors that can operate effectively in both high voltage and high current environments. This would call for "high power" rather than "high voltage" connectors, a separate line that requires additional design expertise still.

As important as this knowledge and expertise is, perhaps the most important aspect of high voltage connector manufacture has yet to be explored. This is another huge difference between design criteria unique to high voltage connectors and can be literally the difference between life and death for users of the ultimate device. This is the safety engineering.

THE SPECIAL ENGINEERING OF SAFETY DEVICES IN HIGH VOLTAGE CONNECTORS

Unlike standard connectors, high voltage connectors are built with additional safety protections to help ensure that the connector will not be disconnected while it is live, protecting operators, patients and other stakeholders from the risk of burns or electric shock.

High voltage connector manufacturers should be well versed on the engineering options available when selecting a strategy for a particular application. They include the addition of a safety ring, a screw type mechanism which must be unloosened—disconnecting power—before the connector can be unmated. Another strategy is the addition of a microswitch, which, similarly, disables power with a flick before the connector can be decoupled. A simple Safety Interlock (SIL) strategy is to make one pin longer than the others, so the shorter ones disengage while the longer one stays grounded, protecting the handler. Danger warning and directional stickers or tags are often affixed as well.

Figure 8
The safety ring (in red), a mechanical feature can prevent unmating when powered

In addition, special attention may be given to ensure that the connector is “scoop proof” to not only protect the pin or pins, but also ensure that live pins are unlikely to be touched during mating and unmating. Connectors are designed so that parts carrying current are further away from the opening, and openings are tapered so that fingers would be unlikely to be accidently inserted.

ASSEMBLY AND REPAIR ISSUES AND FINAL WORDS

For all the added security and sophisticated engineering they deliver, most device manufacturers find that the modest additional investment that may be necessary in specifying high voltage connectors over standard connectors represent high value and good business sense. Nevertheless, longevity of components—and their relationship to the efficacy of the overall system—should be a concern for every manufacturer. Here again, selecting the right high voltage connector partner—and providing them with detailed, accurate information—can go a long way in this regard.

For example, even though many device manufacturers have the high voltage connectors and cable produced separately and attached remotely, it behooves them to inform the connector manufacturer of the type of cable that will be specified, with specifications provided such as inner and outer dimensions, insulation type and conductor interface. Better yet, provide a sample if necessary. In the high voltage space, high quality manufacturers will often work to produce the connector very close to the dimensions of the cable conductor in order to ensure that when they are bonded together a very central fit can be readily achieved—even by a less-skilled assembler. They can even suggest the best cable choices if it has not yet been specified. Sometimes the cable and connector can be produced in tandem to ensure a perfect match.

For high voltage connector manufacturers, precision is even more vital than with regular connectors. Small bits of metal or debris that may be harmless in a regular connector could increase the danger of arcing or corona in a high voltage environment and must be cleaned out carefully and completely. For this reason, these parts are more often injection molded rather than machined; indeed, residues of machining oils add impurities to the system that can impact performance and must be carefully cleaned or eliminated. Assembly tolerances need to be even more precise; heat shrink might be added to confine metallic parts together or podding installed to isolate wires to the electrical parts.

Customer-focused high voltage manufacturers will work to ensure maximum ease of assembly in other ways as well—designing so that no special tools are required for example. In addition, they might work to ensure that in the case of a failure of the cable, or wear of a pin or other single component, the high voltage connector can be field repaired rather than need to be discarded and replaced. LEMO connectors, for example, are often constructed in modular fashion, with replaceable contacts and key components nutted and threaded rather than welded on, making field disassembly possible to remove debris if needed.

Getting the most effective high voltage connectors produced is not difficult, but it does take a higher level of communication than with many types of components, and it does take knowledge and specialization that not every connector manufacturer can offer. By selecting an experienced and proven high voltage connector partner, and working together with detailed application information every step of the way, manufacturers can ensure that their devices and equipment operate effectively and safely from day one—and for many years to come.

LEMO is the acknowledged leader in the design and manufacture of precision custom connection and cable solutions.
LEMO's high quality Push-Pull connectors are found in a variety of challenging application environments including medical, industrial control, test and measurement, audio-video and telecommunications.

LEMO has been designing precision connectors for seven decades. Offering more than 75,000 combinations of product that continue to grow through custom specific designs, LEMO and its affiliated sister companies REDEL, NORTHWIRE and COELVER currently serve more than 100,000 customers in over 80 countries around the world.

HEADQUARTERS
Ch. des Champs Courbes 28
1024 Ecublens
www.lemo.com