Chapter 9

High Voltage Design Guidelines

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Introduction

The use of high voltage transformers in power converters in space, for power processing, require special attention, in regards to insulation. These transformers usually operate with a square wave voltage on the primary, and boost the voltage from 1 to 10 kv, or even higher. At this voltage level, corona degradation becomes a serious limitation on reliability. Corona is a particularly serious problem in all solid dielectric high voltage transformers. In order to assure the success of high voltage encapsulated transformers, the design must follow proven guidelines. There are many unusual problems that arise when high voltage is operating at critical pressure, and not all of the basic mechanisms are well-understood. The art of building high voltage transformers has developed to the point where guidelines can be given to help the new designer avoid old problems. (See Terms Used at the end of this chapter).

High Voltage Design Guidelines

All electronic equipment to be exposed to the critical pressure region and employing voltages above the minimum require special attention to avoid failures, caused by corona and arcing. The intent of this chapter is to provide guidelines for high voltage fabrication.

High Voltage Limits

Guidelines presented here are on constructing and fabricating hi-rel, high voltage electronic equipment with circuit conductors having instantaneous voltage, (with respect to other circuit conductors to the common ground, or to the subchassis), in excess of 250 volts peak. This limit is applicable to frequencies, from dc to 60 Hz, and shall be reduced, in accordance with Figure 9-1, for frequencies above 60 Hz.

At voltages, lower than that specified in Figure 1, compliance may be desirable for one or more of the following reasons:

Number 1

The conductive plasmas generated by a corona or arc, or other mechanisms, such as passage of equipment through, low pressure gaseous environments, can drift across bare conductors carrying much lower voltages, (e.g., 24 volts), initiating arcing in these circuits, also.

Number 2

The theoretical, breakdown voltage minimum of 270 volts peak is for air; other gases, especially the noble ones, even in trace quantities, can cause breakdown to occur at much lower voltages.

Number 3

Other conditions being the same, reduction of large voltage gradients, by suitable gradient control techniques, will markedly improve the long-term reliability of high voltage circuits.

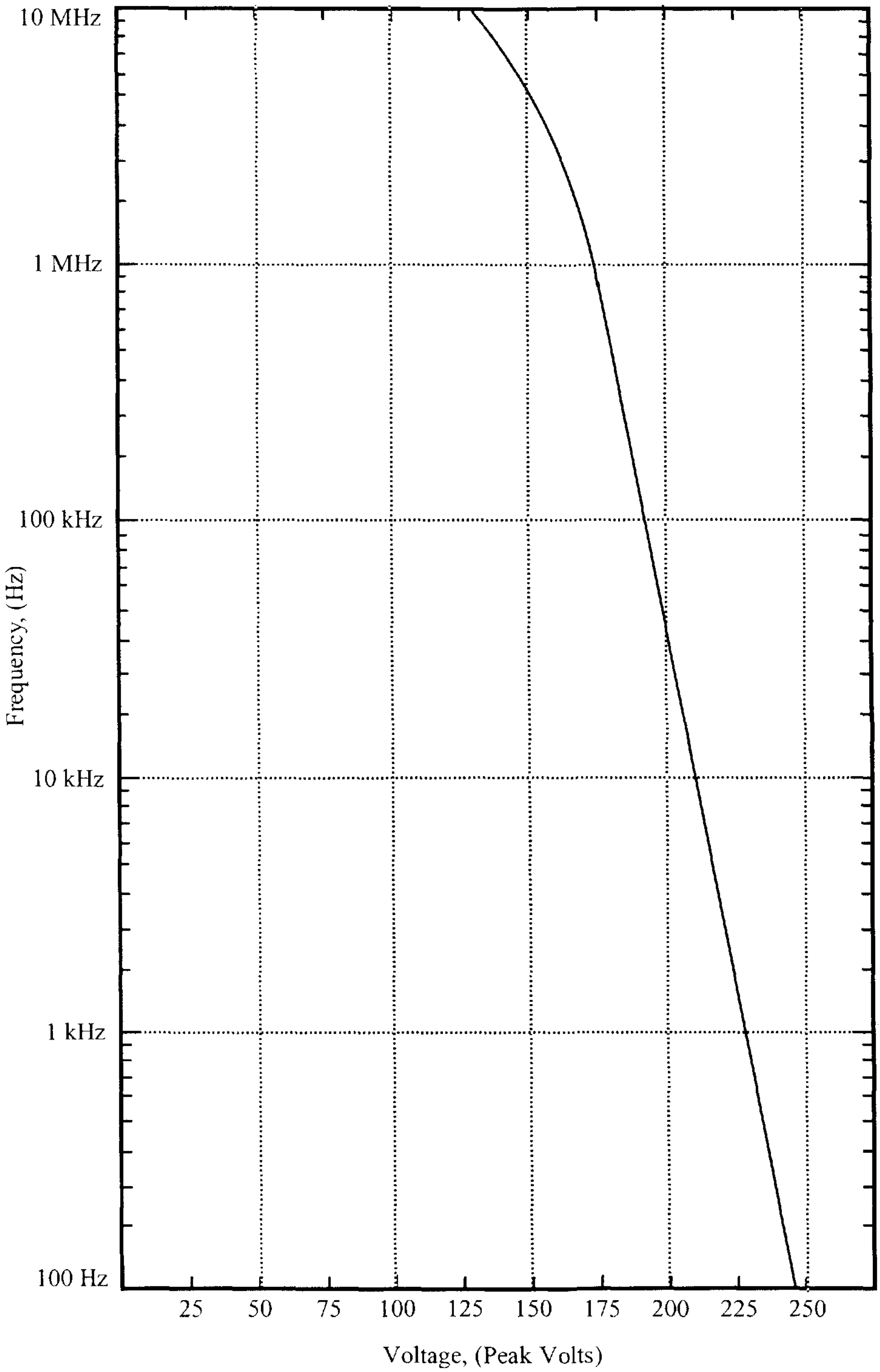


Figure 9-1. Lower Voltage Breakdown Limit versus Frequency.

High Voltage Problem Areas

The design of high voltage equipment, is heavily influenced by the following problem area:

Means of Reducing High Field Density

Field Density

Field lines should be spread out as evenly as possible to minimize the local field density, and not allow the field lines to concentrate, as is the case at sharp points. The field density can be improved by having smooth, round surfaces compared to a sharp point, as shown in Figure 9-2.

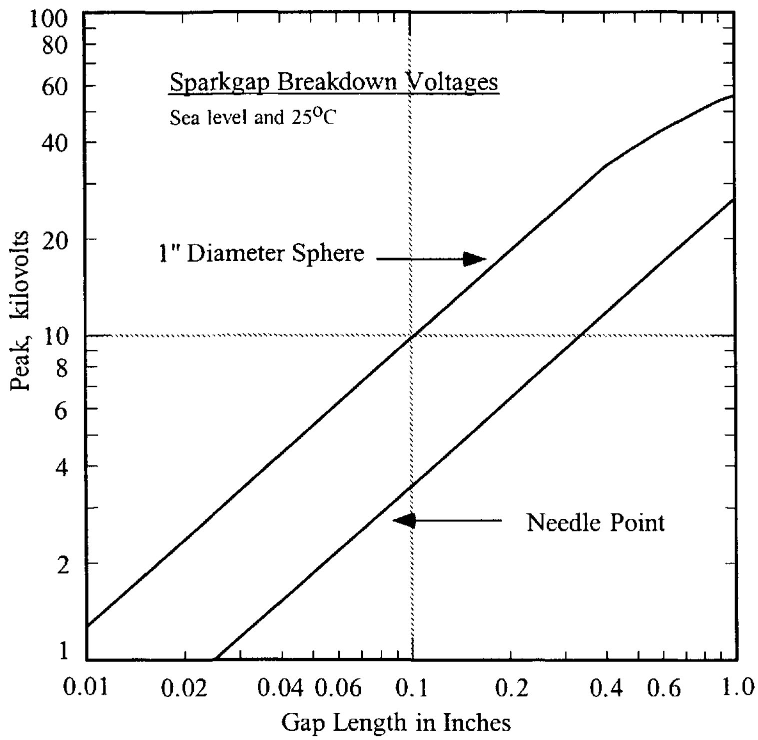


Figure 9-2. Comparing Sparkgap, Breakdown Voltage with a Sphere and Needle Point.

High Voltage Solder Connections

Terminals

Terminals used, for high voltage will be a smooth, rounded swage mount, as shown in Figure 9-3.

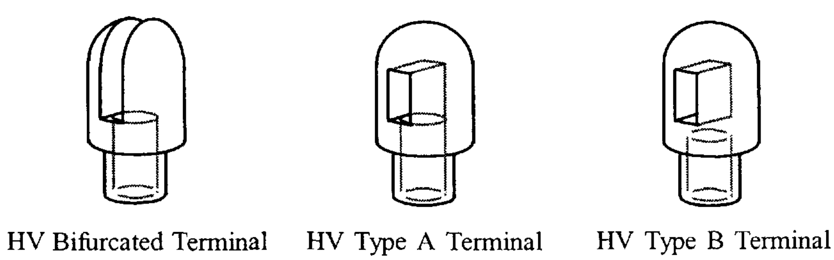


Figure 9-3. Hemispherical High Voltage Terminals.

Flush Leads

The ends of the component leads shall be flush with the edge of the terminal. After part leads are installed, the terminals, at voltages above 1.0 kv, will have excess length of the bifurcated terminal trimmed off, as shown in Figure 9-4. A smooth solder joint will be made to enclose all cut ends of the component leads and trimmed tines of the bifurcated terminal to reduce the voltage gradient. A smooth solder ball or other conductive material, shown in Figure 9-4, is allowable for high voltage terminals. For circuits above 1.0 kv, the terminals will have a hemispherical conducting cap to reduce the voltage gradient at the edge of the swage, as shown in Figure 9-4.

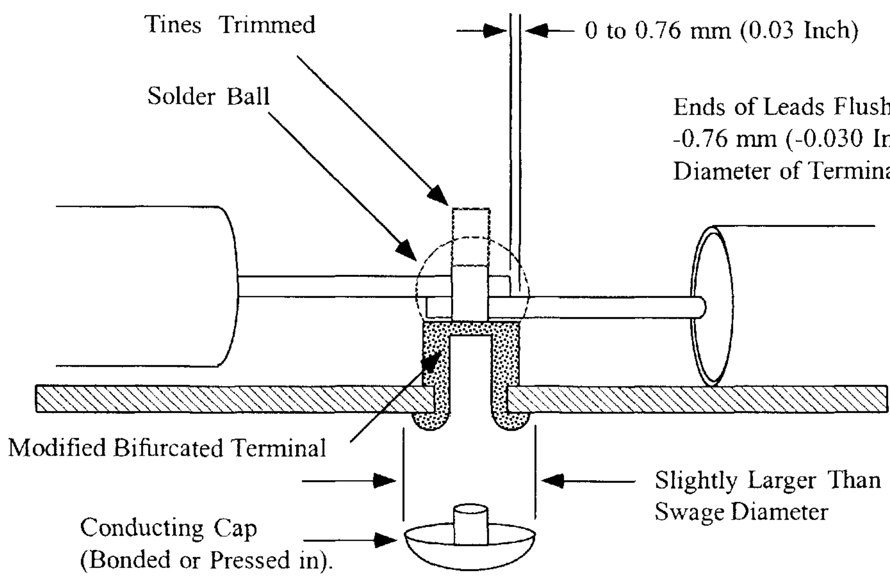


Figure 9-4. High voltage Solder Terminal.

Minimum Terminals

The use of terminals will be kept to a minimum in high voltage circuits.

Sharp Points

Circuit conductors, electronic parts and mechanical parts, either in the high voltage circuit, grounded, or insulated electrically but located at a distance that is less than twice conductor spacing (CS), from the high voltage conductors, will be designed or laid out in a manner that avoids sharp points, sharps corners, and abrupt changes in dimensions.

Smooth Conductors

Smooth curves, rather than sharp corners, will be used for changes in directions of all conductors, both in printed circuit (PC) traces and wire.

High Voltage Solder Joints

Inline Solder Joint

Inline solder connections shall be assembled using a tinned or soldered-plated, thin wall metal sleeve, (ferrule), as shown in Figure 9.5.

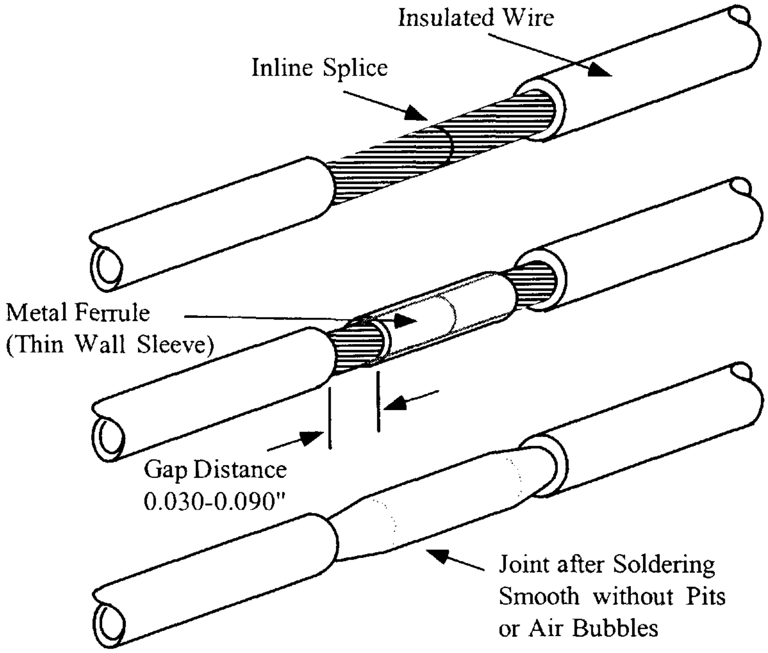


Figure 9-5. Inline Solder Connection.

Parallel Solder Joint

Parallel solder connections shall be assembled using a tinned or soldered-plated thin, wall metal sleeve (ferrule), as shown in Figure 9.6.

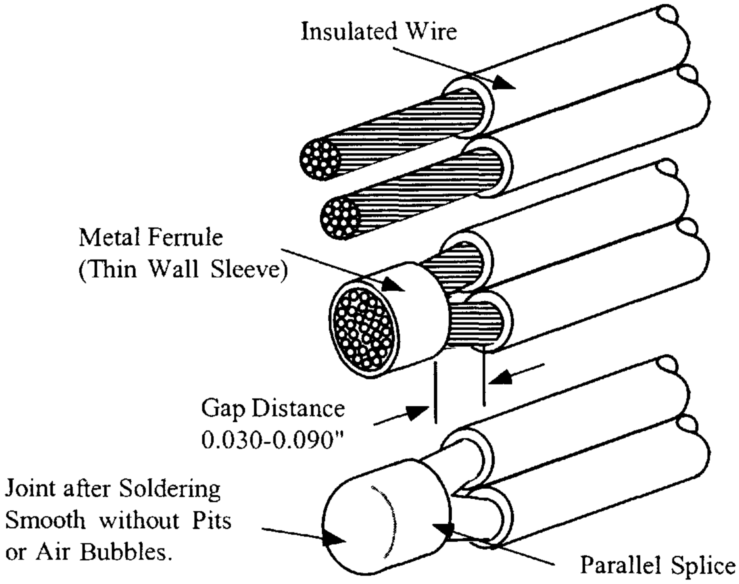


Figure 9-6. Parallel Solder Connection.

Assembly of Solder Joint

Teflon sleeving shall be used over each required terminal to assist in forming a spherical, shaped solder joint. Each length of sleeving shall be notched, as shown in Figure 9-7, to allow clearance for the wire being soldered to the terminal. Only newly cut, Teflon sleeving will be used.

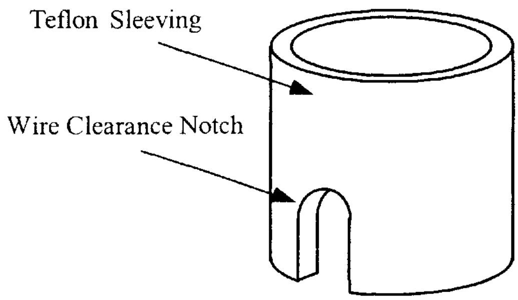


Figure 9-7. Teflon Sleeving, Soldering Mold.

Modified Holding Tweezers

Specially modified tweezers, as shown in Figure 9-8, are designed to help to hold the Teflon sleeving during soldering. The tweezers are used to secure the Teflon mold in place, while soldering.

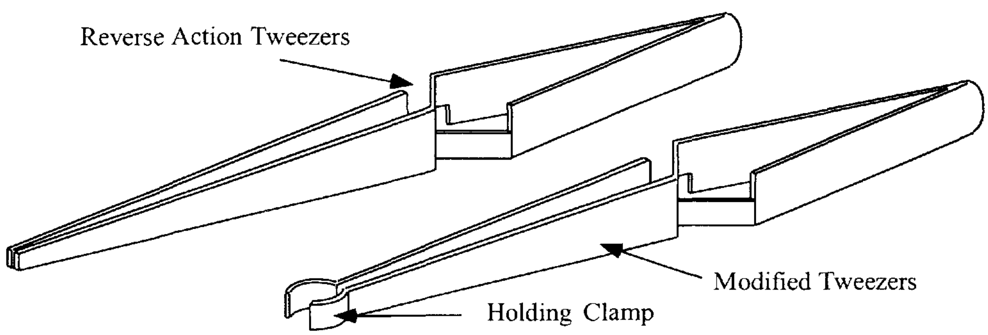


Figure 9-8. Modified Tweezers, Used as a Holding Clamp.

Assembly of HV Solder Joints

Prior to assembly, all parts of the connection shall be cleaned with ethyl alcohol. Wire insulation shall be removed from the ends of wires to provide a gap of 0.76 to 2.3 mm (0.03 to 0.09 inch), between the insulation and the terminal shoulder. In order to minimize the amount of solder in the high voltage solder joint, unused sections of the turret shall be filled with tinned copper wire. Wire ends shall not protrude past the terminal. The soldering tip shall be kept as short as possible, and small enough to fit inside the Teflon sleeving surrounding the high voltage solder joint. The solder on top of the terminal should appear round, or approximately round, but not flat, as shown in Figures 9-9 through Figures 9-11. The finished high voltage terminal assembly is shown in Figure 9-12.

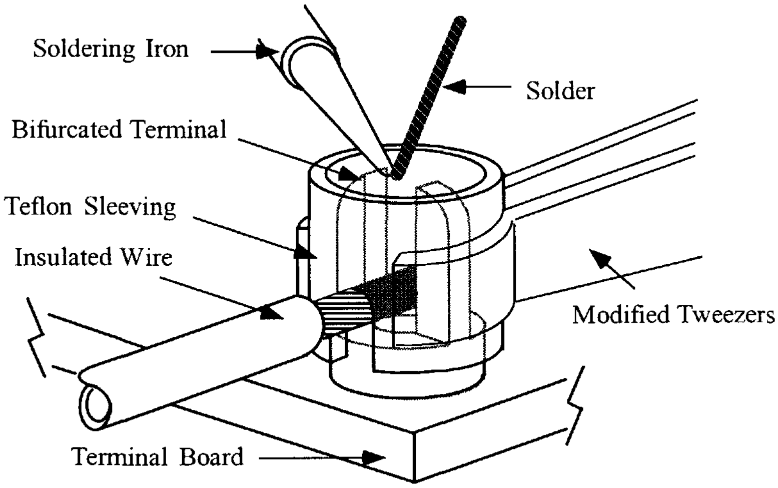


Figure 9-9. Standard, Bifurcated Terminal in a High Voltage Assembly.

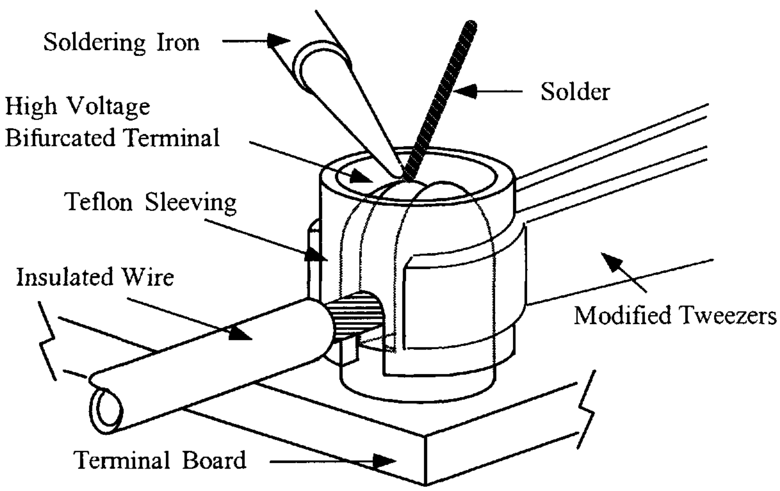


Figure 9-10. High Voltage, Bifurcated Terminal Assembly.

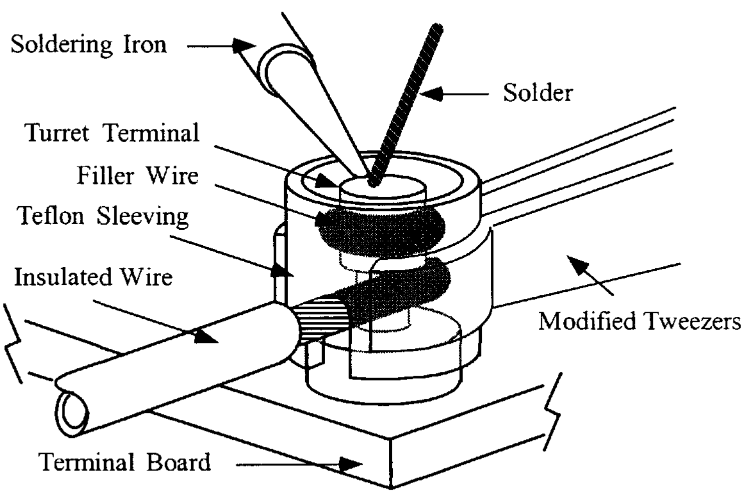


Figure 9-11. Turret Terminal in a High Voltage Assembly.

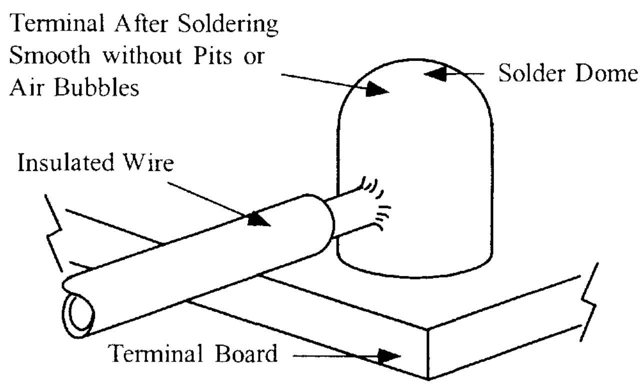


Figure 9-12. A Finished, High Voltage Terminal Assembly.

Means of Reducing Voltage Gradients

Voltage gradient should be as low as possible. Attempt to spread the applied voltage to minimize the unit voltage gradient linearly over, or within, the total available insulating media. Increase the insulating distance, when possible, or utilize insulating media with a greater dielectric strength, or both.

Determination of Voltage Gradient

The distance or thickness between high voltage conductors shall be measured in a straight line from the point of closest approach, including worst tolerance buildup. Then the voltage gradient will be calculated by dividing the peak voltage by the insulating distance thickness in mm, or (mils).

Voltage Gradient Limits

The thickness of insulation provided as a function of the voltage, shall be 40 volts/mil or ten percent of the actual breakdown voltage for the thickness of the insulation used in the design, whichever voltage gradient is less. This is the linear gradient, calculated by dividing the peak volts by the distance in mils. If the geometry is one in which calculation of the maximum gradient is possible, the maximum gradient allowable shall be 100 volts/mil, or 25 percent of the actual breakdown voltage for the same thickness, whichever is less.

Conductor Spacing (CS)

The minimum high voltage carrying conductor separation, (CS), on the same side of the printed wiring or terminal boards shall be as calculated by:

$$\mathrm{CS} = 6.35\sqrt{kv_{(pk)}} = [\mathrm{mm}]$$

$$\mathrm{CS} = 0.25\sqrt{kv_{(pk)}} = [\mathrm{inches}]$$

The minimum separation shall be 3 mm (0.125 inch). Distances shall be measured along the surface between the conductor and shall be the minimum distance possible. Layout of the high voltage circuitry should consider gradient reduction by placing conductors in order of decreasing voltages, if such locations do not cause adverse effects on the performance of the circuit.

High Voltage Pulse Circuit

The minimum conductor separation (CS), as specified in the above equation, can be reduced when the conductor is carrying pulses. The conductor separation (CS), can be reduced by a multiplying factor K. The pulse duty cycle shall be less than five percent for this reduction to apply, where t is the pulse width in microseconds.

$$K = \frac{t}{t + 0.8}$$

Separation of High Voltage and Low Voltage Circuits

Separation of High Voltage Circuits

Circuits employing high voltage shall be physically separated from low voltage circuits with a minimum common boundary, when located on the same printed wiring or terminal board, as shown in Figure 9-13 through Figure 9-15.

Low Voltage Circuit Protection

A ground bus shall be located between high and low voltage circuitry to prevent possible creepage currents or arcs causing premature damage of failure to the low voltage circuits, as shown in Figure 9-13 through Figure 9-15. Where the high voltage circuit is physically separated from the low voltage circuit board, a ground bus around the perimeter of the high voltage board shall be used to prevent a possible arcing to the low voltage circuits. Where high voltage exists on both sides of the printed wiring or terminal board, the ground bus shall be on both sides, preferably superimposed one above the other, as shown in Figure 9-16. This ground bus should about a 4 mm (0.15 inch) conductor to provide a low impedance return path in case of an arc. A ground bus shall be used in each layer of a multilayer circuit board to isolate the high voltage circuit from the low voltage circuit. In selected areas, the ground buses may be staggered instead of superimposed to allow conductors to pass between the high and low voltage areas by transferring from one layer to an adjacent one; or a ground bus on a given layer may be interrupted to allow passage of such conductors. The connection to the ground point for this bus shall be so that the currents from a possible arc will not be coupled into the ground returns of any other circuits.

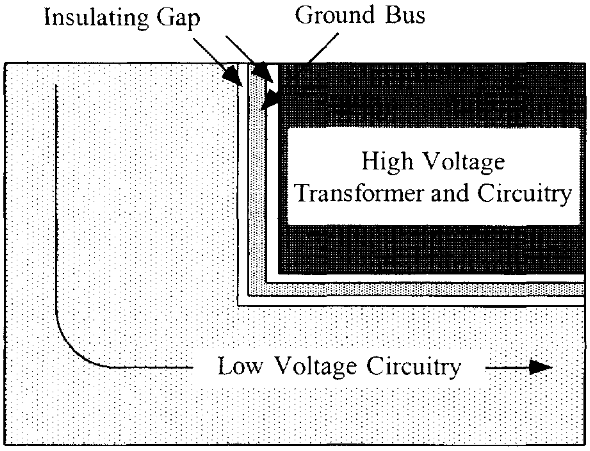


Figure 9-13. Preferred Combine Layout, High and Low Voltage Circuitry.

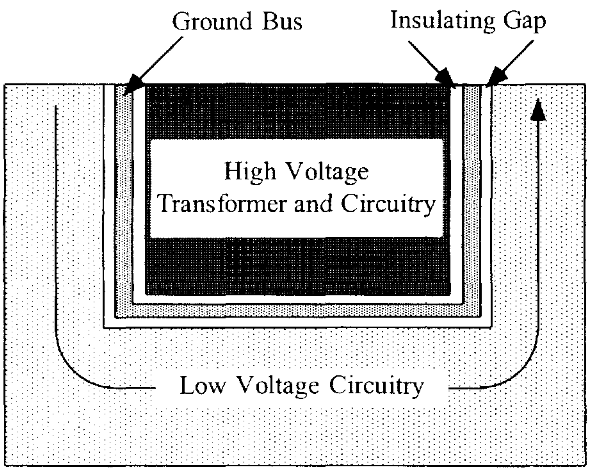


Figure 9-14. Acceptable Combine Layout, High and Low Voltage Circuitry.

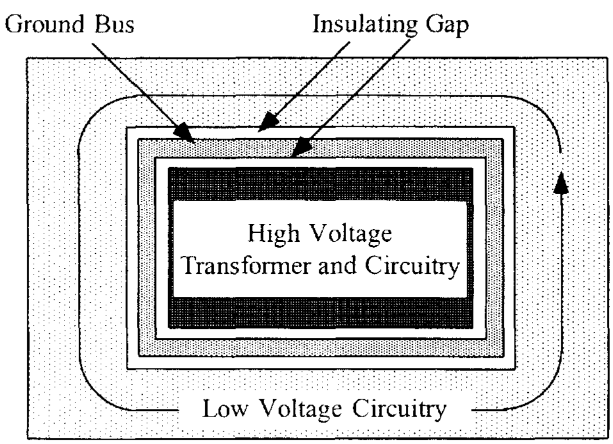


Figure 9-15. Unacceptable Combine Layout, High and Low Voltage Circuitry.

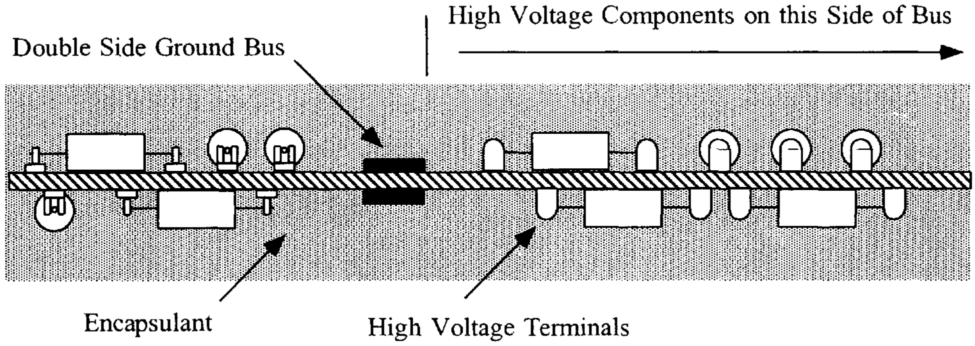
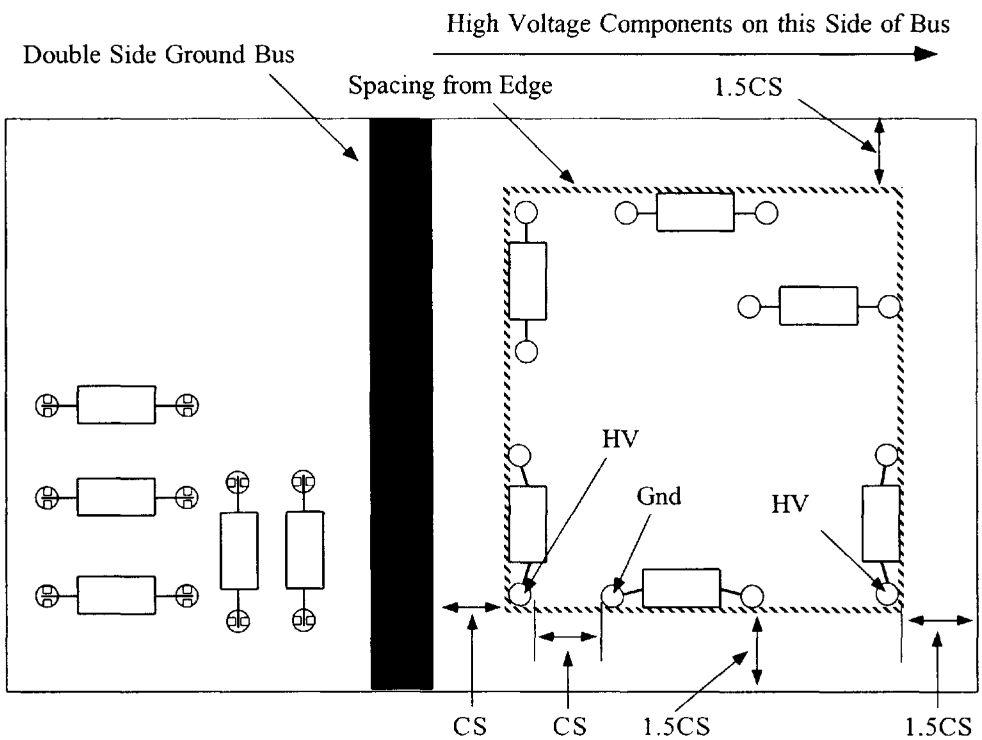


Figure 9-16. Circuit Board with Double Sided Ground Bus.

Component Spacing

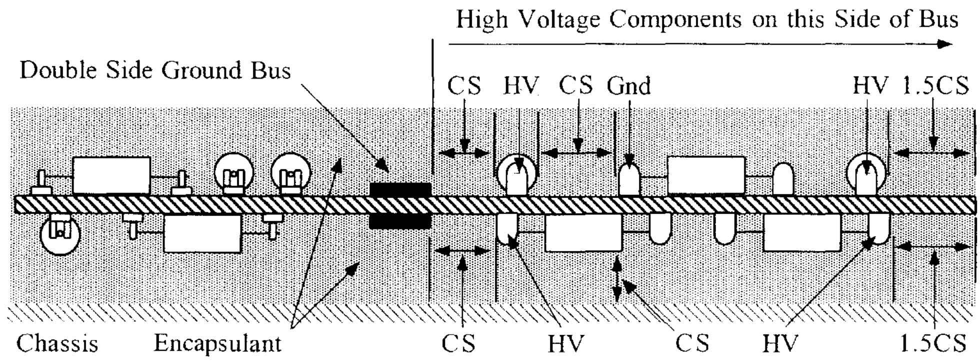
<u>Spacing from Edge</u>

The minimum distance of the conductor from the edge of the printed wiring or terminal board shall be 1.5 times conductor spacing (CS), as shown in Figure 9-17 and Figure 9-18. See page 9-10 for an explanation.



CS = Conductor or Component Spacing, HV = High Voltage, Gnd = Ground

Figure 9-17. Minimum Distance for High Voltage Circuitry from Board Edge.



CS = Conductor or Component Spacing, HV = High Voltage, Gnd = Ground

Figure 9-18. Minimum Distance for High Voltage Circuitry Between Terminal and Ground.

Grounding

Chassis ground leads shall be separate from signal and power returns leads to prevent corona or arc currents from adversely affecting or damaging other circuits. The connection to the ground point for this bus shall be so that currents from a possible arc will not be coupled into the ground returns of any other circuits. The random grounding, shown in Figure 9-19, is not recommended. The recommended grounding is shown in Figure 9-20. Ground leads shall be such that ground loops are not permitted.

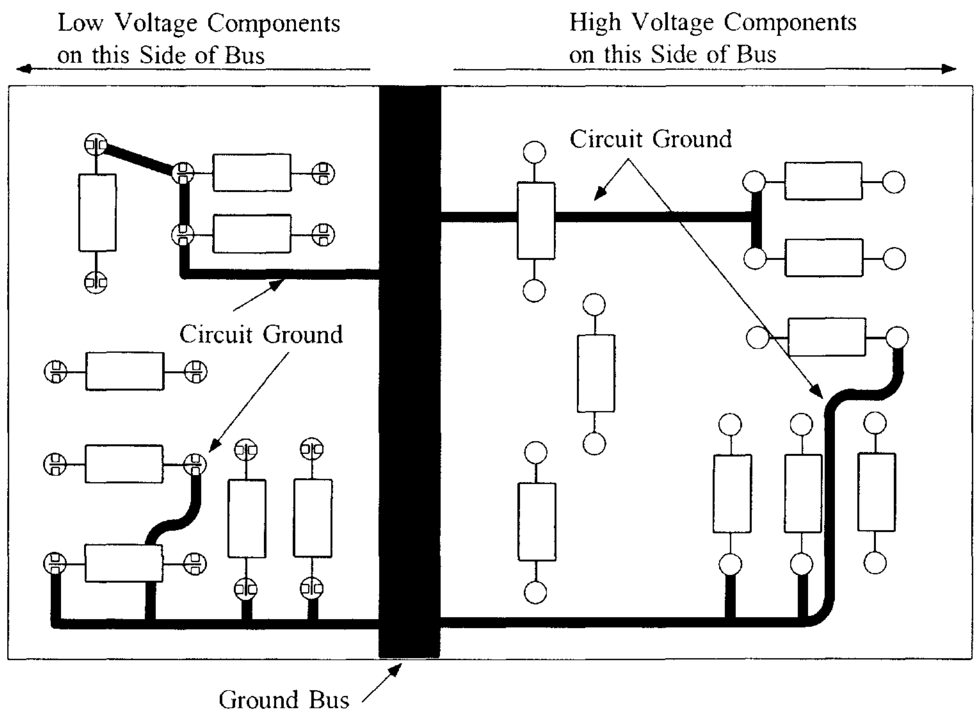


Figure 9-19. Circuit Grounding to the Ground Bus.

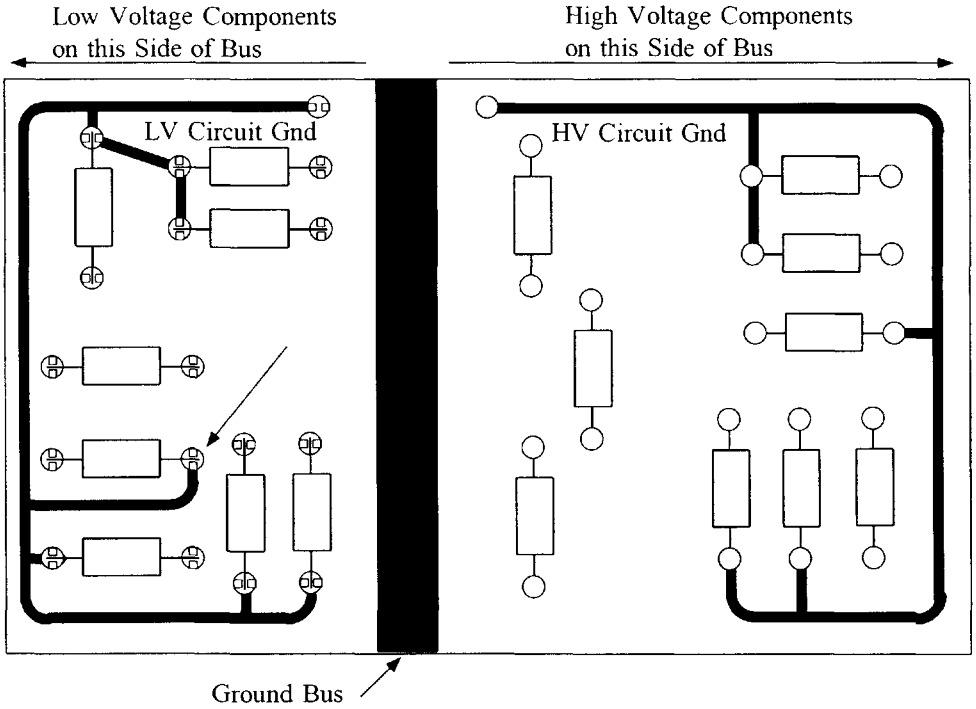


Figure 9-20. Isolated Circuit Grounds from the Ground Bus.

High Voltage Transformer Insulating Materials

Dielectric Strength

Insulating materials, having the higher dielectric strengths, shall be used in high voltage applications when other properties or characteristics pertinent to the application are similar. Materials, with dielectric strength of less 400 volts/mil measured between parallel plates at the thickness required, should be avoided.

Dielectric Constant

Insulating materials with low dielectric constants shall be selected for insulation of ac voltages. Where two different insulating materials are in contact, they should be selected so that the difference in their dielectric constant is minimal. Materials, with dielectric constant greater than five shall be avoided.

Air Dielectric Strength

For the purpose of equipment design, in accordance with this chapter, air shall be assumed to have zero dielectric strength in the critical pressure region.

High Frequency Applications

Insulating materials, selected for use in the high frequency, (nominally above 1 MHz), application, shall have the dielectric constant and dielectric losses small enough, so that blistering, delamination, or other internal damage caused by internal heating, will not occur during normal operation.

Foams

Expanded or syntactic foam materials, or materials that are porous, shall not be used for high voltage, insulation applications.

Low Arc Resistant Materials

Organic insulating materials, which have a tendency to sustain arcing under any pressure condition, or which deteriorate, or outgas under arcing conditions, shall not be used in contact with bare conductors emerging from the insulating material, and exposed to the ambient pressure. Inorganic insulating materials, which do not sustain arcing, shall be used to provide the interface of an emerging bare conductor from the encapsulent or conformal coating, as shown in Figure 9-21.

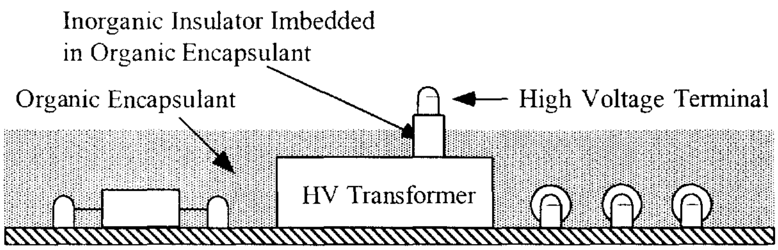


Figure 9-21. Using Inorganic Insulators in Organic Encapsulating Material.

Magnet Wire Insulation

The thickness of the magnet wire insulation coat and winding technique shall be such that the maximum possible voltage gradient between any two adjacent wires in a winding shall be, in accordance with the voltage gradient limit, and, in no case, greater than 40 volts peak, as shown in Figure 9-22. Voltage, at termination of winding, and between wires in excess of this value, shall employ additional insulation in accordance with the voltage gradient limit requirements for high voltage equipment. In high voltage pulse transformers, with pulse widths of 10 μs or less, the allowable voltage limit between wires can be 200 volts peak.

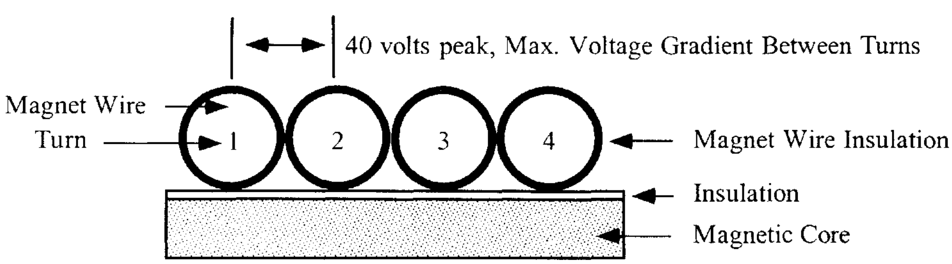


Figure 9-22. Maximum Voltage Gradient Between Turns.

Magnetic Core Connection

Electrically conductive cores, insulated from the mounting base of the transformer or inductor, shall have an auxiliary lead brought out to facilitate hi-pot testing between core and the windings, as shown in Figure 9-23.

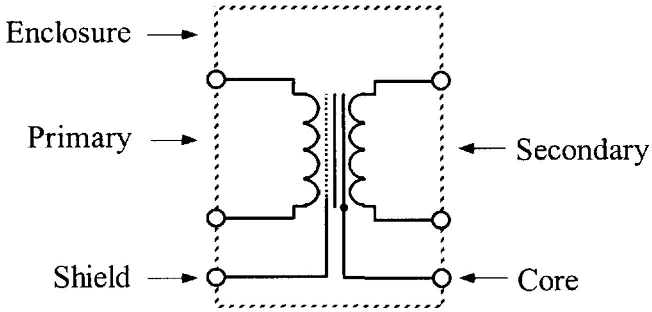


Figure 9-23. Transformer with External Lead Attached to the Core.

Cores, that are exempt from this requirement, are toroidal powder cores, toroidal ferrites and tape toroidal cased cores, providing that they are wrapped with an insulating material that meets the high voltage insulation material requirements, and that the low voltage winding is located between the high voltage windings and the core.

Interwinding Insulation

Insulation between windings shall meet the high voltage, insulation material requirements and shall be capable of withstanding, without damage, the equipment test requirements.

Winding Embedment

Windings shall be impregnated, and then, encapsulated with materials that meet the high voltage insulation material requirements so that all the wires are securely anchored and no voids are present.

Winding Termination

Winding termination into insulated lead wires shall be embedded with materials that meet the high voltage insulation material requirements. Terminals employed for termination of transformer or inductor windings shall meet the same requirements as the high voltage printed circuit boards terminals. The conformal coating, or encapsulant material, shall be compatible with the lead wire insulation and achieve a thorough bond, so that creepage paths from the conductor to the outside of the module will not occur. The length of the path from the conductor to the outside shall be 6.35 mm (0.25 inch), for voltage less than 1.0 kv. Voltages, greater than 1.0 kv, use the equation that is used for component spacing (CS):

$$\text{CS} = 6.35\sqrt{kv_{(pk)}} = [\text{mm}]$$

$$\text{CS} = 0.25\sqrt{kv_{(pk)}} = [\text{inches}]$$

Provisions shall be made to anchor the wire as it emerges from the encapsulant, or other precautions shall be taken so that subsequent handling does not mechanically stress the bond between the encapsulant and the wire insulation.

Terms Used

High Voltage

Circuit conductors having instantaneous voltages, (with respect to other circuit conductors, to the common ground, or to the subchassis), in excess of 250 volt peak ac. This limit is applicable to frequencies from dc to 60 Hz.

Critical Pressure

The range of pressure through which the dielectric strength of the air reduces to 20 percent or less of the dielectric strength of 20°C (68°F) and at sea level pressure, will be the critical pressure for the purpose of this chapter. Nominal limits of the critical pressure region in air are 50 torr 18.3 kilometers, (60,000 feet altitude), to 5×10^{-4} torr 94.5 kilometers (310,000 feet altitude).

Arcing

A complete voltage breakdown of dielectric between two conductors, with currents on the order of milliamperes or higher, limited only by power supply impedance, or the total number of ionized gas molecules or atoms available.

Corona

An incomplete or partial voltage breakdown of the air or gas adjacent to one or both electrodes or conductors resulting in a current flow of the order of 10^{-7} to 10^{-6} amperes rms.

Voltage Breakdown

As used in this chapter, voltage breakdown refers to either arcing or corona.

Noble

Noble refers to a group of chemically inert gases, such as helium, neon, argon, krypton, and xenon.

torr

It is a unit of pressure that is equal to approximately 1.316×10^{-3} atmosphere. 1 atmosphere = 14.7 pounds per square inch.

Conductor Separation (CS)

The distance between conductors and terminals is:

$$\mathrm{CS} = 6.35\sqrt{kv_{(pk)}} = [\mathrm{mm}]$$

$$\mathrm{CS} = 0.25\sqrt{kv_{(pk)}} = [\mathrm{inches}]$$

Plasma

Plasma is the electrical discharge generated by a corona or arc that has ionized gas, that is electrically neutral.

CDN

Corona Detection Network is used in testing the presence of corona.