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OPTIMAL DIMENSIONING OF COMPONENTS FOR A HIGH VOLTAGE FEEDTHROUGH

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Key words: components for power delivery, dielectric materials, dielectric strength, dissipation constant, feedthrough, high voltage applications, high voltage breakdown, RF power, RF power equipment, unbalanced load impedance

Abstract: The design of high voltage feedthrough components needs to satisfy mutually contradictory requirements. Selected geometries, dimensions, and materials of a high voltage feedthrough need to prevent voltage breakdown under worst case conditions, while size and weight are often constrained. The compact size requirement is less important in massive systems (distribution of electric energy), but it becomes critical with requirements of limited space and/or low mass. Both constraints, on size and weight, are crucial in RF power delivery systems for plasma processing in the semiconductor industry and in satellite-mounted instruments for space exploration, such as instruments for solar wind measurements. Expressions for optimal dimensioning of a high voltage feedthrough are derived in this paper for the case of delivering RF energy to a plasma chamber via an impedance matching network. Derived geometries and expressions are useful in design of high voltage feedthrougs in RF and other engineering areas (instruments for space exploration, instruments for high-energy physics experiments, X ray systems, systems for distribution of electric energy).

Določitev optimalne geometrije in izpeljava izrazov za dimenzioniranje komponent visokonapetostnega prehoda

Kjučne besede: dielektrični materiali, dimenzijska optimizacija, močnostne komponente, RF energija, RF močnostna oprema, neuglašena impedanca bremena, visokonapetostne komponente, visokonapetostni preboj

Izvleček: Konstruiranje komponent visokonapetostnih prehodov mora zadovoljiti izključujoče se zahteve. Velikosti in materiali komponent visokonapetostnega prehoda morajo preprečiti napetostni preboj pri najneugodnejših pogojih delovanja, in sistemske zahteve pogosto omejujejo velikost in maso visokonapetostnih komponent. Zahteva po majhnih dimenzijah in masah visokonapetostnih prehodov je manj pomembna v velikih sistemih, kot na primer pri distribuciji električne energije. Zahteva po majhnosti pa je kritična, kadar so dimenzije in masa celotne naprave vnaprej omejene. Kompaktne izmere in majhna masa visokonapetostnih sistemov sta elementarni zahtevi v a) konstrukciji sistemov za generiranje in dovajanje elektromagnetne energije v radijskem frekvenčnem (RF) območju za vzbujanje RF plazme za prizvodne procese v izdelavi mikroelektronskih vezij, in b) v konstrukciji satelitskih sistemov in instrumentov.

V tem prispevku so določene optimalne geometrije in so izvedeni izrazi, potrebni za optimalno konstruiranje visokonapetostnega prehoda pri dovajanju RF energije v plazemsko komoro preko sistema za impedančno prilagajanje. Izvedene geometrije in izrazi so uporabni za načrtovanje visokonapetostnih prehodov v RF tehniki in na drugih področjih (instrumenti za raziskovanje vesolja, instrumenti za eksperimentalno delo v visoko-energetski fiziki, rentgenski sistemi, distribucija električne energije).

1. Introduction

A universal problem in the design of RF power equipment is the transfer of RF power across equipment walls. Typical examples are energy transfer out of RF generators, into and out of matching networks, and into loads. At high powers, the physical design of such feedthroughs runs into the difficulty of satisfying mutually contradictory requirements. One requirement, related to voltage, is that there be sufficient separation between the center conductor and the wall. The other requirement, not fundamental but quite common, is that of over-all size reduction - which may limit the space available for the feedthrough. When the impedance is controlled, as out of a generator and into a matching network (the two being connected by a 50 Ohm cable), tested commercial solutions exist for different power ranges. It is at the interface of the loads (e.g., the RF plasma chamber) and matching networks /1,4/, that the RF and mechanical designers face the challenge of geometric optimization /3/. What makes this interface critical is the uncontrolled impedance of the load /2, 5/. For a given power, whose *maximal* value is known as the power rating of the generator P_{gen_rated}, and for variable load impedance, the voltages that may appear at the feedthrough can reach extremely high values. Hence, the feedthrough design voltages are not those expected in steady state operation, but those that may be generated by the worst transients, however short.

Thus, for a generator power rating P_{gen_rated} and maximal transient load impedance Z_{max} is

$$P_{gen\_rated} > \frac{V_{eff\_load}^{\ \ 2}}{|Z_{max}|},$$

and the feedthrough *design* voltage (peak value) is

$$V_{max} = K\sqrt{2P_{gen\_rated}\,|Z_{max}|}\,, \qquad (1)$$

where K is the designer's safety factor.

Fortunately, the feedthrough design problem naturally splits into two parts. One is the optimization of conductor shapes, regardless of the required maximal voltage rating; the other is the selection of its overall dimension. The first part, which is pure physics, can be solved once for all for any type of feedthrough geometry - which is done in the present paper for an easily manufactured feedthrough. The second part depends on the application. Here, we only suggest guidelines.

2. Derivation of expressions for optimization of shapes and dimensions of conductors

We state the problem as follows:

For a given round hole opening of diameter D in a cabinet wall determine the feedthrough shape that withstands the highest RF voltage if the dielectric is air.

Here, D is the variable that characterizes the physical size of the solution (second part of the problem). As we shall see, it is proportional to V_{max}.

The mechanical feedthrough model is that of a cylindrical conductor (usually made of copper tubing) of diameter d passing at a right angle through the center of the hole. The support issue is irrelevant in principle, provided the corona paths along insulator surfaces are sufficiently long.

The voltage limit for this model is defined by the onset of arcing, which would take place between the center conductor and the wall over a distance (D - d)/2. As arcing begins at local ionization spots[1] when the dielectric field exceeds the medium's characteristic breakdown value, (about 1000 V/mm for dry air), the often quoted computation of electric fields as voltage divided by distance regularly leads to grossly under-designed feedthroughs. This is because the voltage over distance expression is valid only between parallel capacitor plates. In all other cases, we must use the exact definition of the electric field, which is the gradient of the potential function. This is particularly true near all edges. The edge of the window in a cabinet wall is the critical one for feedthroughs. It thus follows that all radii of curvature must be maximized, not only the distances between conductors. This is why we install into the window a tube of outer diameter D and wall thickness w, as shown in Figure 1. The length of this tube is not important. It can be optimized with respect to other considerations (e.g., mechanical structure). The optimal wall thickness w of the tube will be determined below.

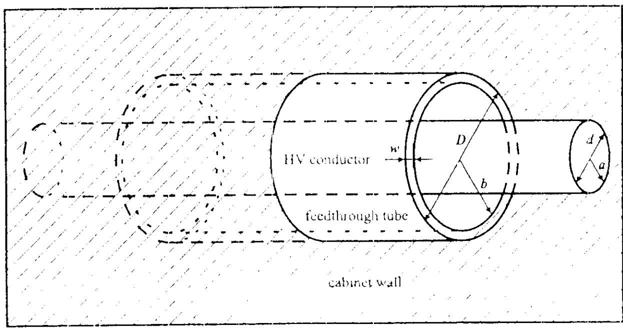

Figure 1 Tube-type high voltage feedthrough.

Disregarding for the time being the edge effects at the end of this tube, our first task is to determine the optimal diameter of the inner conductor in terms of hole opening of diameter D in a cabinet wall. To this end, we view the geometry as a cylindrical capacitor, whose inner electrode is of outer radius a = d/2 and outer electrode of inner radius b = (D - 2w)/2. Solving the Laplace equation for the space within the capacitor, i.e., $\nabla^2\Phi = 0$, the potential function $\Phi = \Phi(r)$ between the two conductors is

$$\Phi(r) = \frac{V}{\ln\left(\frac{b}{a}\right)}\ln\left(\frac{b}{r}\right).$$

The magnitude of the electric field is then $E = |\nabla\Phi|$, i.e.,

$$E = \left|\frac{\partial\Phi}{dr}\right| = \frac{-V}{r\ln\left(\frac{a}{b}\right)}.$$

Clearly, its maximal value is at the minimum value of r, which is $r = a$:

$$E_{max} = \frac{-V}{a\ln\left(\frac{a}{b}\right)}. \qquad (2)$$

This value is to be minimized by properly selecting the ratio a/b. For a given b, we thus require $\partial E_{max}/\partial a = 0$.

1 *If the medium is not air, but a dielectric, the language may change from "arcing" to "punch through", but the arguments and the calculations are identical.*

$$\frac{dE_{\max}}{\partial a} = \frac{V}{\left(a^2 \ln\left(\frac{a}{b}\right)\right)^2}\left(\ln\left(\frac{a}{b}\right) + a\frac{b}{a}\frac{1}{b}\right) = 0 \ ,$$

which implies

$$\ln\left(\frac{a}{b}\right) + 1 = 0.$$

Hence, the solution is

$$a = b/e.$$

This establishes one relationship between D, d, and w:

$$d = \frac{D - 2w}{e} \ .$$

The next task is to determine the optimal value of w.

The following intuitive arguments give us a starting point: To minimize the field inside the capacitor, it is better to have a small value of w, as this leaves a greater spacing between the conductors. A thin wall, however, implies a small radius of curvature at the edge, namely w/2, as it is shown in case C in Figure 2. Hence, from the point of view of edge effects, it is better to have a thicker wall.

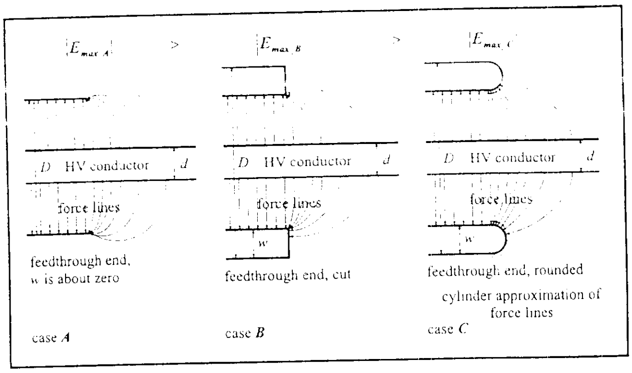

Figure 2 *Ends of tube-type high voltage feedthroughs.*

An exact solution to the problem of optimal wall thickness would also give us the optimal shape according to which the edge should be formed. Such a shape is not present in cases A and B in Figure 2 that are simple to manufacture. From the standpoint of machining, one would easily decide for either case A or case B in Figure 2.

Figure 2, case C is quite close to an exact solution. Additional computational and machining efforts of an exact solution of the optimal edge shape would hardly be justified by the marginal improvement. We thus assume that the edges terminate in a semicircular profile of radius w/2. For a heuristic estimation of the minimal value of w/2, we note that the density of force lines near the edge (but inside the cylinder) is equal to the density at the inner conductor divided by e. Hence, in a good approximation, we may increase the density of lines at the edge of the cylinder by a factor of e without degrading the voltage rating of the device, as suggest the geometries and force lines shown in dashed lines in Figure 2, case C. This occurs if we take the radius of curvature at the edge to be the radius of the inner conductor divided by e, i.e.,

$$w = d/e.$$

With the previous equation, this gives us the complete solution:

$$w = \frac{D}{e^2 + 2} \ ,$$
$$d = ew.$$

Numerically,

$$w = \frac{D}{9.39} \ , \qquad (3)$$

$$d = \frac{D}{3.45} \ . \qquad (4)$$

The next task is to relate the window's diameter D to the absolute maximum of peak RF voltage, V_{max}, (1) that could possibly appear on the conductor. The governing equation is (2). Combining it with relation (1), we get

$$E_{\max} = \frac{-V_{\max}}{a \ln\left(\frac{a}{b}\right)} = \frac{-K\sqrt{2P_{gen\_rated}\left|Z_{\max}\right|}}{a \ln\left(\frac{a}{b}\right)} \ .$$

Substitution of $a/b = 1/e$ and

$$a = \frac{d}{2} = \frac{D - 2w}{2e} = \frac{e^2}{2e\left(e^2 + 2\right)} D$$

yields

$$E_{\max} = K\frac{2e\left(e^2 + 2\right)\sqrt{2P_{gen\_rated}\left|Z_{\max}\right|}}{e^2 D} \ .$$

Expressing power in kW, all dimensions in meters, and taking E_{max} = 10^6 V/m, we finally get

$$D = K\frac{2\left(e^2 + 2\right)}{1000\, e}\sqrt{2P_{gen\_rated}\left|Z_{\max}\right|} =$$
$$= 6.91 \times 10^{-3} K\sqrt{2P_{gen}\left|Z_{\max}\right|} \ .$$

Numerically,

$$D[\mathrm{cm}] = 0.7K\sqrt{2P_{gen\_rated}[kW]\left|Z_{\max}[\Omega]\right|} \ ,$$

or

$$D[\mathrm{cm}] = 0.7K\, V_{\max}[\mathrm{kV}] \ .$$

The safety factor K remains to be selected. For a 50 percent safety margin, for example, we would have K = 1.5, and hence, the simple rule of thumb

$$D[\mathrm{cm}] = V_{\max}[\mathrm{kV}]\,. \tag{5}$$

If V_{max} has already been estimated with a reasonable safety margin, one can take $K = 1$, which yields

$$D[\mathrm{cm}] = 0.7\,V_{\max}[\mathrm{kV}] \tag{6}$$

Thus, at least one centimeter of window diameter opening is required for every seven hundred volts of peak RF voltage. This assumes that the edge of the window is mechanically terminated with a tube that leads through the window in the equipment wall, Figure 1. The tube is to be made according to the optimal dimensions derived above. Any other dimensioning makes matters worse.

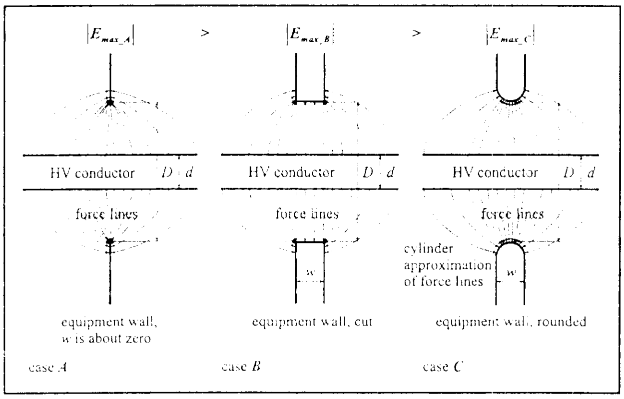

Figure 3 High voltage feedthrough without a built-in tube.

These results are for framed feedthroughs, which are often a natural mechanical solution regardless of voltage rating considerations. If the frame is not needed, however, its length may be reduced to the minimum, which is its wall thickness, *w*. It may then be implemented as an integral part of the housing wall, provided its edges are machined to a semi-circular profile, as illustrated in Figure 3, case *C*. The required opening *D* is then smaller, since it does not have to accommodate the frame. Geometries and force lines shown dashed in Figure 3 are identical to those in Figure 2, and so is the analysis. Results, i.e., modified design equations are:

$$d = \frac{D}{e}, \tag{7}$$

$$w = \frac{d}{e} = \frac{D}{e^2}, \tag{8}$$

$$D[\mathrm{cm}] = 0.6\,K\,V_{\max}[\mathrm{kV}]. \tag{9}$$

Cases *A* and *B* in Figure 3 would be simple to manufacture, but such geometries are inadequate for optimization of feedthrough dimensioning, since sharp edges imply intense local peaks in force line densities.

3. Worked out examples

Let us assume that the RMS voltage at full generator power in a matched condition is 2 kV. The peak voltage is then $2\times\sqrt{2}$, which can be conservatively rounded to 3 kV. Let us further assume that experience and computations indicate that in the case of worst transient mismatch the steady state voltage gets doubled, at most. Then, we may take V_{max} = 6 kV. Equations (6), (4), and (3) then yield

$$D = 0.7 * 6 = 4.2 \text{ cm},$$

$$d = \frac{4.2}{3.4} = 1.24 \text{ cm},$$

$$w = \frac{4.2}{9.4} = 0.45 \text{ cm}.$$

Hence, the smallest possible robust feedthrough requires a window opening of 4.2 centimeters, a center conductor 1.24 cm in diameter and a window frame of wall thickness 0.45 cm. Figure 1 shows the general appearance. Both ends of the tube are rounded as shown in Figure 2, case *C*. The length of the tube is arbitrary, and may be very short.

For a straight feedthrough, case *C* in Figure 3 (no separate tube), equations (9), (7) and (8) yield the solution

$$D = 0.6 * 6 = 3.6 \text{ cm},$$

$$d = \frac{D}{e} = 1.32 \text{ cm},$$

$$w = \frac{1.32}{e} = 0.49 \text{ cm}.$$

We see that the diameter of the center conductor and the thickness of the wall are essentially the same, but a much smaller opening is required. The trade-off is in the thickness of the housing wall, which must be 0.5 cm. It is also essential that the hole be smoothly milled to a semi-circular profile.

Finally, we must emphasize that this entire analysis refers to air as a dielectric. The supporting insulators are also assumed to be designed for a sufficiently long surface corona path. Clearly, a substantially more compact feedthrough is possible if the window and central conductor can be completely and tightly potted (no air gaps) in some appropriate structural dielectric. The relative geometry of the optimal solution remains the same, i.e., relations (7) and (8) are still valid, but equation (9) becomes

$$D[\mathrm{cm}] = 0.6\frac{\varepsilon'}{r}K\,V_{\max}[\mathrm{kV}], \tag{10}$$

where ε' is the dielectric's relative dielectric constant, and *r* its dielectric strength relative to air. We see that the dielectric constant ε' works against us, while the dielectric strength r is in our favor.

Example:

We consider the same problem as above, but with Teflon encapsulation. We have $\varepsilon' = 2.5$, and let us take $r = 50$ (which corresponds to a dielectric strength of 50 kV per millimeter). Then,

$$D = 0.6\frac{2.5}{50}V_{\max} = 0.03V_{\max} = 0.03 * 6 = 0.18\,\text{cm}\,,$$

$$d = \frac{0.18}{e} = 0.066\text{cm}.$$

The minimal wall thickness (w = 0.024 cm) is irrelevant in this case, as any realistic housing wall would substantially exceed it in any event.

This example points to two issues not considered above:

1. The current carrying capability of the conductor. Clearly, the wire with a diameter of 0.6 mm in this example is probably unrealistic (unless the minimal impedance of the load is so high that the RF current is very small). However, it is the lesson that counts: Once a feedthrough design is completed, the conductor diameter, d, must be reviewed for its current carrying capability. At RF frequencies, the resistance must be computed accurately by taking the skin effect into account. If a larger diameter is called for, the window diameter D must be increased accordingly – either by redoing the mathematical analysis under the assumption of a given d, or, overconservatively, by preserving the geometric relations derived above (i.e., by taking $D = ed$).
2. The dissipation in the dielectric. If the dielectric were ideal, i.e., if its dissipation constant ε'' were zero, (as it is in air), the design equation (10) would suffice. With realistic dissipation constants, it is not. The reason is that at sufficiently high field strengths and frequencies, even for the smallest available ε'' (as in Teflon and Ultem), enough power is dissipated in the dielectric to heat it faster than it can cool. As the dielectric strength decreases with temperature /6/, thermal runaway and catastrophic failure immediately follow.

We extract the following lesson from these considerations:

In selecting a potting dielectric, aim at a minimal dielectric constant ε' and minimal dissipation constant ε'' It is a mistake to search for maximal dielectric strength r, as it is most unlikely that the dielectric strength of the cold dielectric will ever be a limiting design parameter.

4. Conclusion

At high voltages, the physical design of feedthroughs runs into the difficulty of satisfying mutually contradictory requirements. One requirement, related to voltage, is that there be sufficient separation between the center conductor and the wall. The other requirement is saving the equipment volume. The feedthrough design problem splits into optimization of shapes, in selection of materials and into calculation of dimensions.

Optimal feedthrough shapes and expressions for optimal dimensioning are derived in this paper. Our optimization suggests selection of materials with a low dielectric constant and with a low dissipation constant for potting dielectrics. It is most unlikely that the dielectric strength of the cold dielectric would be a limiting design parameter.

Acknowledgments

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