

An Overview of Lapp Insulator High Voltage Bushing Design

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INTRODUCTION

High voltage bushings are devices designed to transmit electric energy through a grounded barrier. The barrier could be a wall, a floor, or most commonly, a transformer or circuit breaker tank.

In the simplest case, a piece of insulated wire could be inserted through a hole and provide the required insulation. If the apparatus inside the grounded enclosure needs to be sealed to protect it from the environment, then the wire has to pass through some device to provide a seal around the entrance. This device becomes a bushing.

DRY-TYPE BUSHINGS

The simplest bushings consist of a conductor with a porcelain or

composite hollow shell (See Figure 1). The assembly is held together by the hardware to position the conductor in the

center of the insulator. The dielectric consists of porcelain (or an organic material such as epoxy) and air. Sometimes the air is replaced by transformer oil or another filler such as asphalt. In some cases, the entire bushing consists of a molded epoxy insulator with the conductor embedded in the epoxy.

These bushings are called Dry-Type bushings, or Bulk bushings (See Figure 2).

Dry-Type bushings can provide excellent service, particularly at low voltages (up through 35kV).

The advantages are low cost, the absence of oil (in most cases), and the ability to operate at higher temperatures. They can operate at high temperatures because they have little or no organic components. Gasket and o-ring seals can be made with high temperature materials.

The limitations of dry-type bushings are the inability to provide partial discharge free service because of the air around the conductor, and limited impulse performance, particularly at higher voltage classes. Because of the very low capacitance between the mounting flange and the center conductor, power factor and capacitance measurements are not meaningful. Often the results are high due to leakage currents across the porcelain.

Another limitation of dry-type bushings is the seal between the mounting flange and the porcelain. In many designs, the mounting flange is cemented to the porcelain. The cement provides a strong mechanical attachment, but it does not provide a moisture-proof seal. Various methods have been employed to provide better seals, but many methods have limited sealing ability, or have limited life. The differential thermal expansion between the aluminum flange and the porcelain body makes it necessary to provide a flexible membrane at the interface. It is usually this membrane that is the weak point in the design.

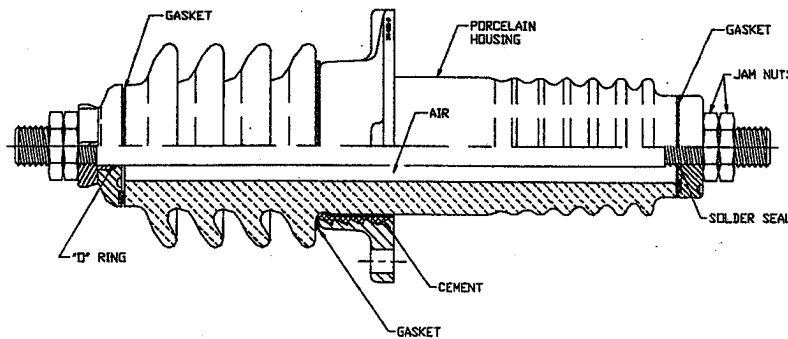
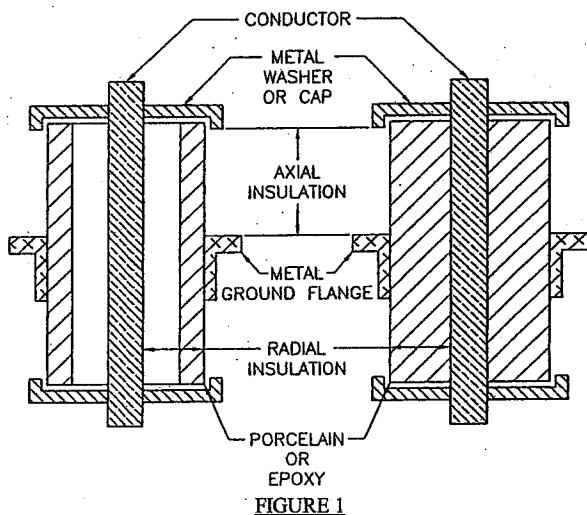


FIGURE 2

VOLTAGE STRESS

At low voltages, the insulation around the conductor does not need to be very thick to provide enough insulation between the conductor and ground. As the voltage is increased, the insulation thickness must also be increased. The voltage stress is not distributed evenly throughout the insulation thickness however.

Figure 3 shows the voltage stress distribution versus the radial distance from a conductor insulated with a homogeneous dielectric. The stress is very non-uniform. In order to keep the maximum stress below the partial discharge inception voltage, the insulation must be very thick. At high voltages, the thickness required is so large that it becomes impractical.

The capacitance between layers is equal, and thus the voltage between layers is uniform. This causes the radial stress to be much more evenly distributed throughout the dielectric. The result is a bushing that is smaller in diameter than would be necessary without capacitance grading.

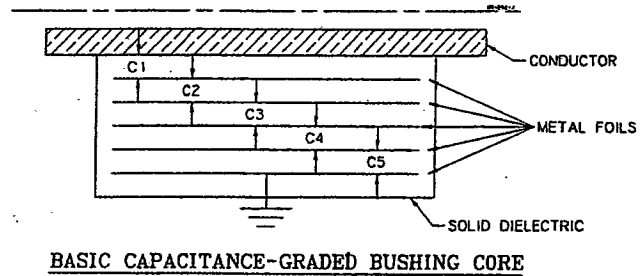
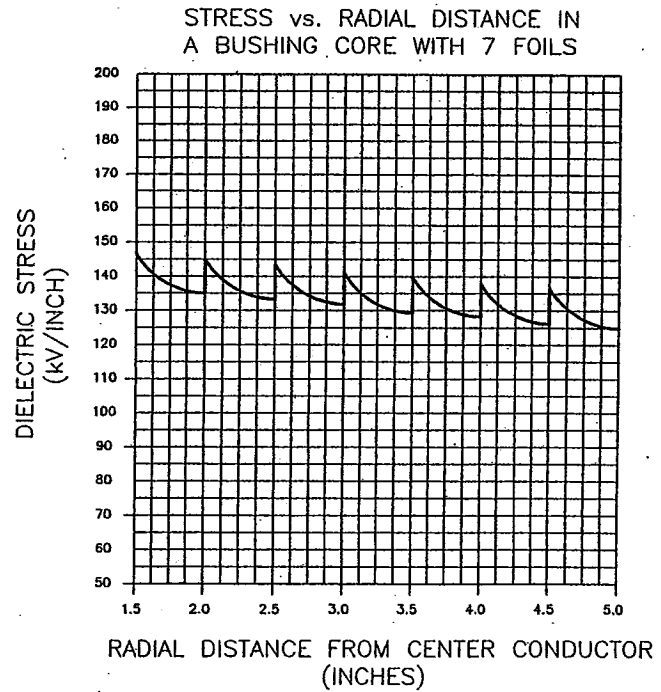
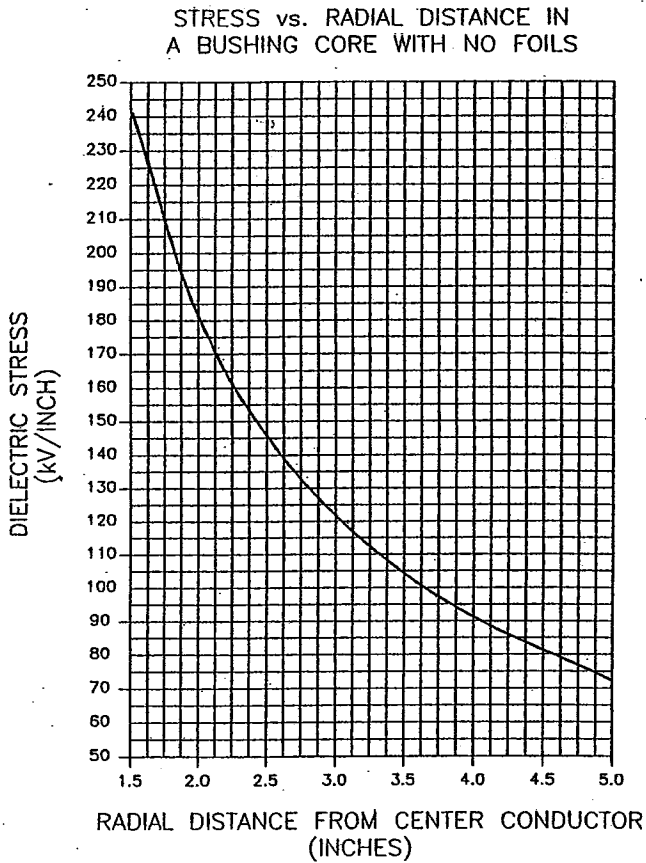


FIGURE 4

Figure 5 shows the radial voltage stress distribution of a typical capacitance-graded bushing.



The curve in Figure 3 shows that the insulation is not being used efficiently. The stress close to the conductor is very high, while the center of the insulation is under much lower stress.

In order to provide more uniform stress distribution, capacitive-graded bushings (often called condenser bushings) are constructed with two or more capacitance layers imbedded in the bushing structure to force the voltage distribution to be more uniform. A cross section of a simple capacitance graded bushing is shown in Figure 4.

The above discussion deals with radial stress; there is another concern that must be considered in high voltage bushing design, that is the axial stress. Figure 1 shows that each end of the bushing is comprised of hardware that holds the bushing assembly together. This hardware, along with the terminal connections, is at the high voltage potential. The mounting flange is at ground potential, which means the line-to-ground voltage is applied across the length of both the upper and lower porcelains.

The surface of the top and bottom housings (usually porcelain) can be weak electrically. Normally, a boundary between two dielectric materials is weaker than the surrounding materials, and can provide a path for disruptive discharges (flashovers). The path can become even more conducive to discharges if it becomes contaminated from airborne pollution. The contamination is often conducive, or can become conducive when wet.

The same non-uniform voltage distribution occurs axially as it does radially. The same capacitance grading used to make the radial stress more uniform can also improve the axial stress distribution. The capacitance layers are designed so the ends of the foils are located with uniform spacing along the top and bottom ends of the bushing. This forces the voltage to be distributed more uniformly along the outside surface of the top and bottom porcelains. The capacitive grading improves the contamination performance of bushing, and allows the bushing to be shorter than a similar non-graded

bushing. Condenser bushings are often shorter than station posts of the same voltage class. Condenser bushings have been produced for many years using various designs and dielectric materials. .

POC BUSHINGS

The most common type of capacitance-graded bushing is the paper-oil-condenser bushing. Lapp calls this design a POC bushing (See Figures 6 and 7).

POC bushings are constructed by wrapping a conductor with an electrical grade of kraft paper and inserting the capacitance layers between the paper layers at locations throughout the diameter. The capacitance layers are often made of aluminum foil, but can be copper, or conductive ink.. The paper is dried under heat and vacuum to remove the moisture, then it is impregnated with transformer oil.

The resultant dielectric structure with many layers of oil impregnated paper is very strong electrically, and can

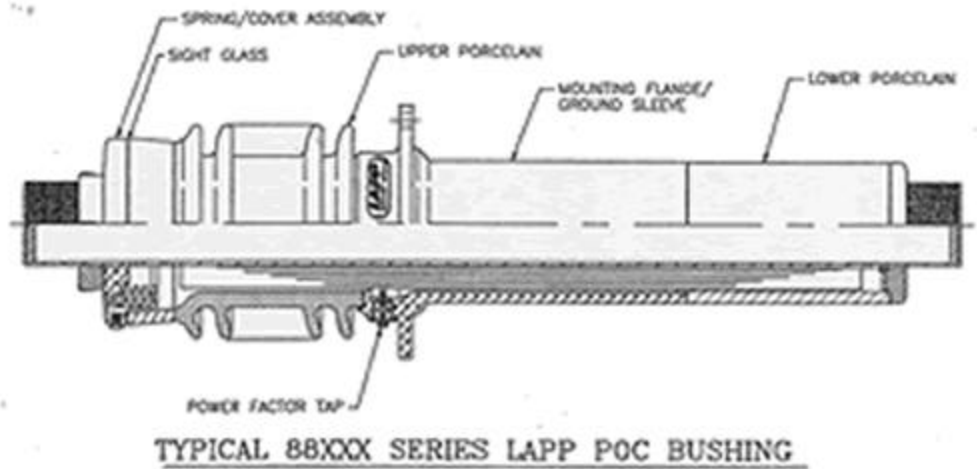


FIGURE 6

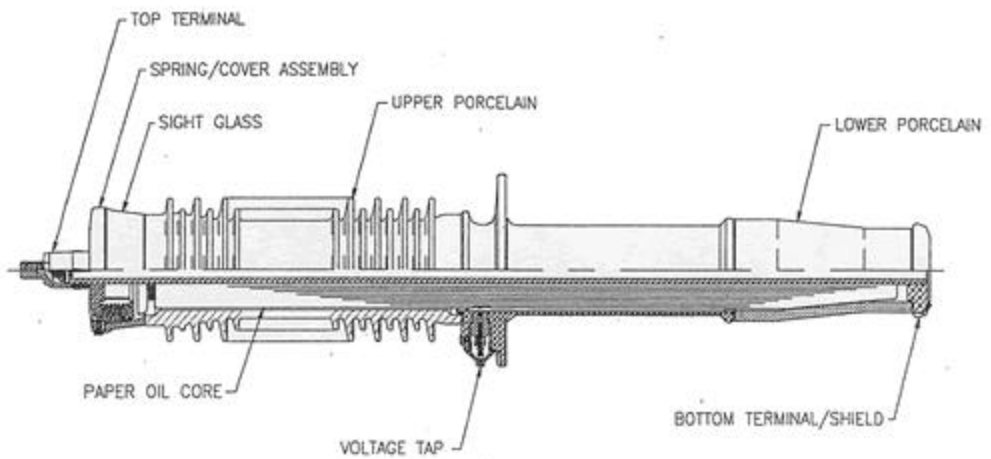


FIGURE 7

withstand 60 Hz electrical stresses up to about 300 kV per inch. Like all high voltage dielectric systems, the geometry and the thickness of the dielectric determine the actual maximum stress. In order for a POC bushing core to maintain its high dielectric strength, the paper must be totally impregnated with transformer oil at all times. Any air pockets or incompletely impregnated areas will have a higher stress due to the lower dielectric constant, and lower dielectric strength due to the absence of oil. The void will most likely ionize at a voltage stress significantly lower than the rest of the core. The result will be corona, or partial discharges, which could damage the paper, create carbon and lead to failure of the bushing. Depending on the voltage stress, as well as the size and location of the void, the failure could occur almost immediately upon energization, or it may take several years.

To keep the paper fully covered with oil at all times, the core is assembled inside of a shell (usually made of porcelain) to contain the transformer oil. A metal mounting flange is usually fixed in the center, to provide a means of mounting the bushing to the equipment, or structure. A reservoir is usually included at the top of the bushing to accommodate the expansion and contraction of the oil due to temperature variations.

There are many tens of thousands of paper-oil-condenser bushings in operation worldwide.

PRC BUSHINGS

While most bushings in use are of POC type construction, there are also a significant number of bushings in use that are constructed with solid cores that have been impregnated with resin. Many different resins have been used to produce solid core bushings including phenolics and epoxies.

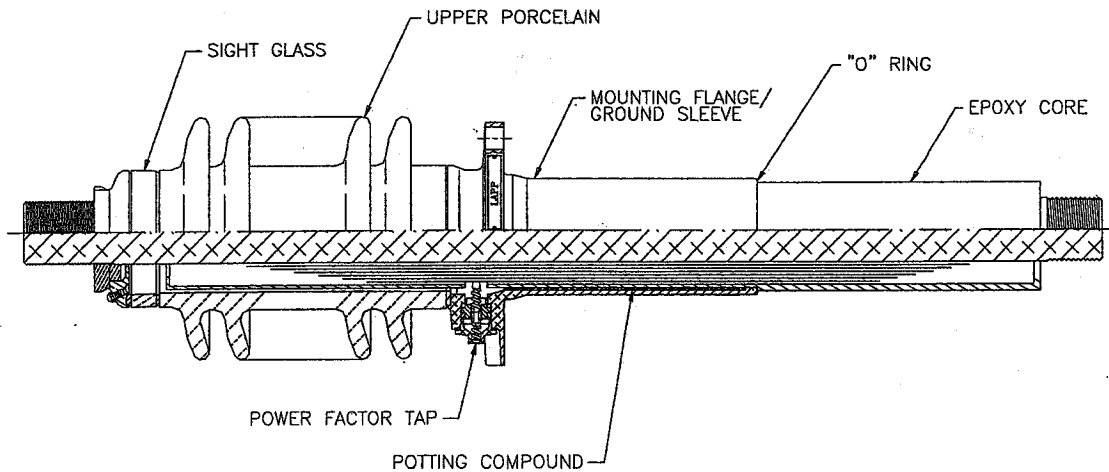
Early solid core bushings were inferior because they were manufactured by impregnating the paper with resin, then while still wet, the core was wound and the foils were

inserted. The wet paper/foil assembly was put into an oven to cure the resin. Bushings made in this manner are called resinbonded bushings. Resin bonded bushings often have voids between the paper layers. They are prone to delamination, partial discharges, and moisture ingress. The voids produce low levels of partial discharges, which often slowly increase in magnitude. Moisture is a common problem in resin bonded cores. The moisture often causes the power factor to slowly increase. The power factor can be reduced by baking the cores in an oven, but this is only a temporary solution, as the moisture level eventually increases again. Many coatings have been used to reduce the amount of moisture ingress, but most coatings only form an imperfect barrier, which slows the speed of moisture absorption; they cannot stop it completely.

Resin bonded bushings are often used in less demanding applications such as switchgear. The poor power factor and partial discharge performance make them unsuitable for use in most transformers.

A process was developed in Europe in the 1950's and 1960's that produced a solid epoxy resin core without the drawbacks of the resin bonded core process. This process is similar to the paper-oil process except that the paper is impregnated with epoxy resin rather than transformer oil. Several European manufacturers produce bushings up through 765kV using this process. Lapp is the only manufacturer using this process in the United States. Bushings produced by Lapp using this process are called Paper-Resin-Condenser bushings, or PRC bushings.

Lapp PRC bushings meet or exceed all IEEE, CSA, and IEC standards for high voltage bushings. PRC bushings are designed in the exact same manner as POC bushings. The manufacturing process is very similar, except for some important differences that are necessary to produce a voidfree dielectric structure. The following are some of the design features and process steps taken to insure Lapp PRC bushings provide long and trouble free service.



TYPICAL 89XXX SERIES LAPP PRC BUSHING

FIGURE 8

Like POC bushings, PRC bushings are wound with an electrical grade of paper, but unlike POC bushings, the paper is creped instead of smooth. Creped paper is used because the epoxy resin shrinks when it gels (changes from liquid to solid).

The paper is creped in the cross direction, much like the rolls of colored streamers used as party decorations. As the bushing cores are wound around the conductor, or stud, some of the stretch is removed. This allows the entire core to shrink in a controllable manner with the resin as it gels, and still maintain a cylindrical shape. The foil pattern, which defines the capacitive grading and determines the stress distribution in the bushing, is identical to that used in POC bushings. PRC bushings are constructed using specially coated aluminum foils. The foils are coated with a primer that promotes bonding of the epoxy to the foil surface. The bond between the resin and the foils is critical. Maximum stress is located at the foil surfaces, so care must be taken to ensure that no voids occur at the foil-resin interface.

In a POC bushing many layers of oil impregnated paper provide the high dielectric strength. Because all paper has many microscopic holes, it takes several layers to ensure that there is no through path between adjacent foil layers. In a PRC core; the epoxy resin has a dielectric strength of about 500 kV per inch. The paper does not provide the dielectric strength, it acts as a means to position the foils, and the paper fibers add mechanical strength to the epoxy resin.

Because every bushing is a composite structure made up of several widely different materials, the design must take into consideration the reaction of those materials to changes in temperature. The following is a table of the coefficients of thermal expansion for several materials used in bushing construction:

MATERIAL	EXPANSION COEFFICIENT.
Aluminum	$23.6 \times 10^{-6} / ^\circ\text{C}$
Copper	$17.6 \times 10^{-6} / ^\circ\text{C}$
Porcelain	$5.8 \times 10^{-6} / ^\circ\text{C}$
Epoxy	$\approx 55.0 \times 10^{-6} / ^\circ\text{C}$

From the table above, you can see that the epoxy resin core has two to three times the thermal coefficient as the conductor. - Since the rated operating temperature range for Lapp PRC bushings is -50°C to +120°C, the differential movement between the core and conductor can be as much as % inch!

To allow the solid epoxy core to move relative to the conductor, the core is designed to adhere to the conductor in the center, and slip on the conductor on the ends. To accomplish this, special coatings are applied to the conductor before winding. Since the voltage stress is normally high on the conductor surface, the void that is formed along the interface would cause partial discharges to occur. To prevent partial discharges, an extra foil layer is wound in the core just

one paper layer out from the conductor. This layer is electrically attached to the conductor, and completely eliminates the voltage stress on the core-conductor interface.

The resin used to impregnate Lapp PR C bushing cores is a proprietary bisphenol -A based epoxy. The components were selected to have excellent electrical, mechanical, and thermal properties. Two of the most important properties are the viscosity and surface tension of the liquid epoxy during impregnation.

It is imperative that the resin completely impregnate the paper so no voids remain that can cause partial discharges. For that reason, no fillers are added to the mix. Fillers would increase the viscosity and impede impregnation.

Because there are no fillers, the UV stability and track resistance of PRC cores is limited. A pigment is added to the epoxy that improves the UV resistance without significantly increasing the viscosity. In most applications, the resin is completely surrounded by transformer oil, either from the transformer (or circuit breaker) or from the oil filling in the bushing. For applications where the resin will be immersed in air, a protective coating is applied to improve the track resistance of the surface. The coating is a Teflon® filled epoxy that forms a barrier to moisture and provides a smoother surface.

A unique feature of PRC bushings is the elimination of the lower housing. Because the core is a solid structure that does not use transformer oil as a dielectric, the inboard side of the bushing does not require a housing to contain the oil. Instead, the epoxy core itself is all that forms the oil, or indoor air, end of the bushing. This has two significant advantages: First, the diameter can be much smaller than a paper-oil-impregnated bushing. Second, there is a significant reduction in the amount of oil required in the bushing.

PRC bushings can be stored outdoors as long as the exposed resin is protected from the sun and weather. The bushings are shipped in black plastic sleeves that will provide the necessary protection.

Like Lapp POC bushings, Lapp PRC bushings are designed to be interchangeable for use with transformers and circuit breakers. To provide superior shock resistance, the aluminum mounting flanges are bonded to the epoxy cores with a proprietary potting compound. This material has been formulated to provide bonding between the flange and core while providing shock protection.

The potting compound fills almost the entire space between the flange and the core. The only oil in the bushing is that between the upper porcelain and the core. In most bushings, there is no more than a cupful of oil. The oil is between the core and the porcelain to provide a higher dielectric fluid than air. This forces any electrical activity due to overvoltages to be on the outside of the bushing where it will do little or no damage. A Lapp PRC bushing can function in air without any oil filling, or even without an upper porcelain housing; although it would lose any weatherability characteristics, it would operate as long as the operating conditions were not too severe.

Lapp has been producing PRC bushings since the early 60's. The designs and processes have been improved over the years to take advantage of new technologies. The reliability of Lapp PRC bushings is outstanding. Lapp PRC bushings are among the most reliable bushings ever produced.

C1 POWER FACTOR

The epoxy resin used in Lapp PRC bushings has a higher power factor than paper-oil insulation does. The power factor of PRC bushings is typically in the 0.6% to 0.8% range compared to 0.2% to 0.3% for POC bushings.

It is important to note that the power factor of paper-oil insulation is very dependent on the moisture content of the paper at the time of impregnation. It is well known in the electric industry that thoroughly dried paper-oil bushings (using cellulose, not synthetic paper) should have power factors between 0.2% and 0.3%. The upper limit in the IEEE standards for paper-oil bushings is 0.5%. -It is widely known that moisture is typically the cause of power factors above this range (on new bushings). For that reason, it is important to require low power factors when specifying paper-oil bushings.

The higher C₁ power factors for paper-resin bushings are a function of the epoxy resin used. The epoxy-hardener combination used for Lapp PRC bushings has an intrinsic dissipation factor at 60 Hz of 0.57% (per the resin manufacturers specifications). The IEEE limit for paper-resin bushings is 0.85%.

The C₁ power factor of Lapp PRC bushings is very stable. It does however have a much higher temperature coefficient than paper-oil insulation. It is important to correct the power factor readings taken in the field using correction factors supplied by Lapp Insulator. These correction factors can be found in the manuals supplied with the test equipment from The Doble Engineering Company. The nameplate readings are corrected to 20° C as required by IEEE C57.19.00-1991.

C2 POWER FACTOR

High voltage bushings for voltage classes above 69kV (350kV BIL) are designed with voltage taps (also called capacitance taps, or potential taps). These bushings have an extra foil wound in the core that can provide a voltage for use with a potential device. The capacitance formed by the last two foils is called the C₂ capacitance. Because the capacitor is part of the core, it is well controlled and has a power factor similar to the C₁ (overall core capacitance). Normally the innermost of the two foils is grounded in service, unless the bushing is connected to a potential device. The outermost foil is permanently connected to the flange; thus, it is always at ground potential.

In low voltage POC bushings (69kV and below), the capacitor that is formed by the outer foil in the core and the aluminum flange is also commonly called the C₂ capacitance of the bushing. The outer foil is only grounded when the test tap cover is in place. The C₂ capacitance and power factor are not controlled.

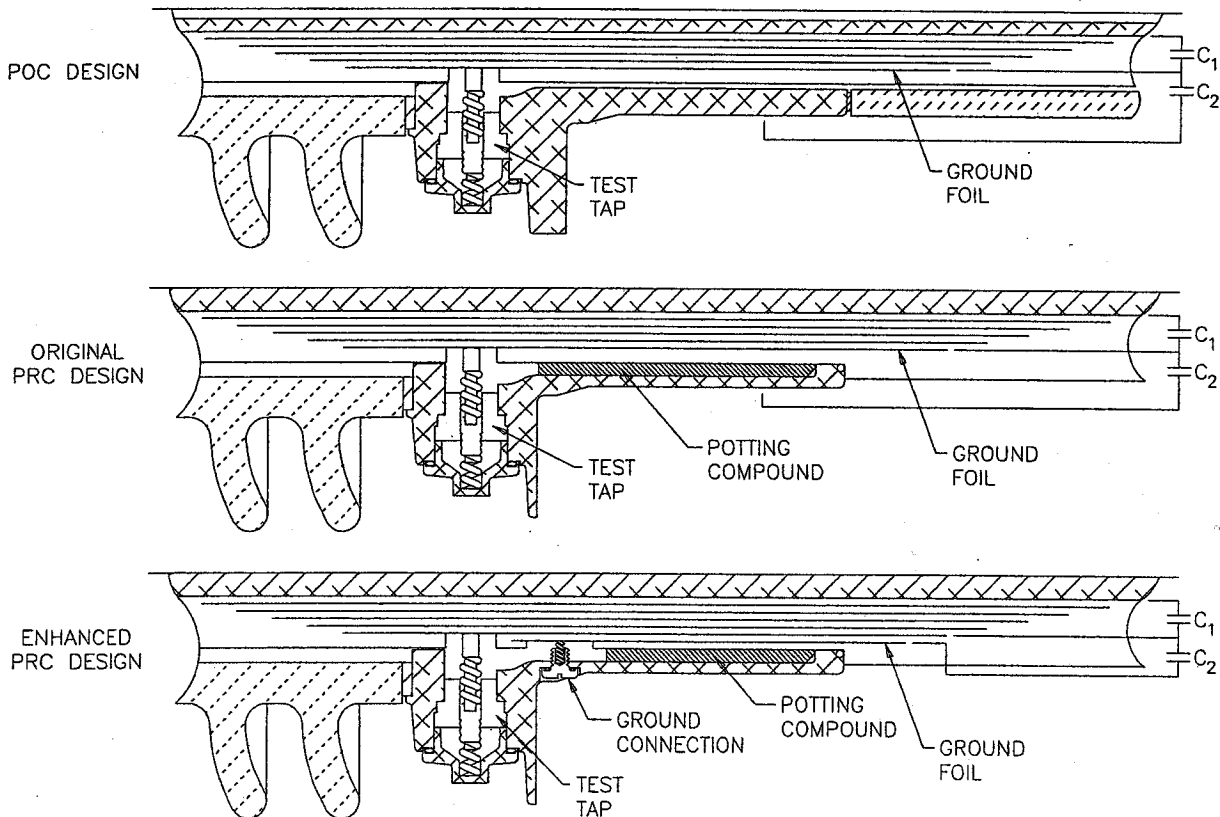


FIGURE 9

Figure 9 shows the cross section of the flange and core of a Lapp low voltage POC bushing and of the two Lapp PRC bushing designs. -You can see that the dielectric -between the last foil in the core and the flange in the POC bushing is comprised of a few layers of paper, but is mostly transformer oil. In the PRC bushings there is very little oil in this area, it is mostly filled with the epoxy potting compound.

This compound was formulated for its mechanical properties and has a high power factor. Since the potting compound is shorted in service, the electrical properties of the material have NO EFFECT on the operation of the bushings.

All PRC bushings manufactured before May 2000 were designed as shown in the center view of Figure 9. This design placed the potting compound in the cz test circuit. Because the power factor tap must be grounded in service, the potting compound is not under any voltage stress in operation.

Lapp PRC bushings being made today have been redesigned to eliminate the effects of the potting compound. Before the change was made, the test tap was connected to the last foil in the core. The cz capacitor was formed between the core and the aluminum flange casting. A significant part of the dielectric of this capacitor was the

epoxy potting compound that was placed between the flange and the core.

Lapp PRC bushings with the enhanced core designs have an extra foil which is permanently connected to the flange. The test tap is connected to a second foil at a slightly smaller diameter. (bottom view of Figure 9) The cz capacitor on these bushings is formed between two foils within the resin impregnated core.

The result is a much lower cz power factor, in the same range as the Cl power factor.

Bushings with the enhanced design began shipping in May of 2000. They can be identified by the higher cz capacitance values. Typically, they will be double or more than the capacitance of the original designs.

The enhancement was made to address field questions regarding the cz power factors on Lapp PRC bushings. THE QUALITY AND PERFORMANCE OF THE TWO DESIGNS ARE IDENTICAL. The change in cz power factor does not effect the C, power factor, nor does it have any effect on the operation or reliability of the bushing, The performance of the material has been proven in the more than 180,000 PRC bushings that have been produced.