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HIGH-VOLTAGE AIR-CORE PULSE TRANSFORMERS

G. J. ROHWEIN

Sandia National Laboratories

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HIGH-VOLTAGE AIR-CORE PULSE TRANSFORMERS*

G. J. Rohwein
Sandia National Laboratories, Albuquerque, NM 87185

Introduction

Air core transformers basically consist of two or more inductively coupled coils and, in principle, function the same as magnetic core transformers. They differ from iron or ferrite core transformers in that no ferromagnetic core materials are used to channel the magnetic flux through the windings to assure flux linkage. With air core transformers, flux linkage is strongly dependent upon the physical proximity of all turns of one winding with respect to all turns of the other winding. Consequently, the mutual coupling of air core windings tends to be lower than magnetic core transformers, particularly with high gain transformers which have thick windings. However, since air core transformers do not have magnetic cores, they are not limited in current handling capacity, by saturation of the magnetic materials or frequency limited by the composition of the core. Not having core saturation and frequency limits are two of the most significant advantages of air core pulse transformers. They are limited in power and energy handling capacity primarily by the resistance of the windings and the mechanical strength of the composite materials and structure from which they are made. They are, therefore, best suited for use with large, high current energy sources such as parallel capacitor banks which often generate peak power levels over 10^{11} watts or to lower energy fast pulse applications involving voltage step up in the nanosecond time regime. In the high energy category air core pulse transformers systems are well adapted to charging pulse forming lines (PFL) up to the multi-megavolt range. In the low energy fast pulse category, air core

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transformers have proven useful in spark gap triggering applications where the pulse rises to several hundred kV in 10 ns or less. Fast pulse transformers may also be used to direct drive higher impedance electron guns.

Other devices could be included in a discussion of air core pulse transformers. This paper will cover only the general types designed for high voltage pulse generation and energy transfer applications. Special emphasis will be given to pulse charging systems which operate up to the multi-megavolt range.

Discussion

There are two basic types of high voltage air core pulse transformers which can be operated in the megavolt range. The first and most common is the single layer helical wound transformer (Figure 1). The second is the spiral strip type (Figure 2). These transformers differ from each other primarily in the configuration of the secondary windings which, as will later be shown, accounts for a significant difference in their resistance to insulation failure from fast pulses. The primary windings for either type, whether single or multiple turn, may be designed in a variety of ways without affecting electrical breakdown characteristics of the transformers. For reasons of high voltage isolation, the low voltage primary winding is typically placed outside the secondary in either type transformer so that the high voltage output of the secondary may be led out through the center of the assembly.

With helical transformers high voltage standoff between the primary and secondary windings is provided by an insulated space between the windings. The space may be uniform or tapered in the longitudinal direction. When tapered, the insulation thickness (usually oil) increases with the voltage along the length of the coils. With spiral strip transformers voltage standoff is largely a function of the radial thickness of the secondary winding since the turns directly overlay each other. The winding stack therefore has a pure radial voltage gradient between

the high voltage inner turns and the low voltage outer turns. Like helical type transformers, the open volume in spiral strip transformers is usually insulated with oil. However, because of the high winding density, spiral strip windings must ordinarily be vacuum impregnated to displace air from the secondary winding.

Two problems are common to both types of transformers. These are electrical breakdown turn to turn or between windings and partial shorting from eddy currents induced in voltage grading devices and structural components which are necessarily present in high voltage transformers. Turn-to-turn breakdown is common with helical transformers when used in charging systems for pulse forming lines (PFL). This problem arises from fast rising voltage transients (usually less than 10 ns) generated by the discharge of the PFL which are fed into the output of a direct coupled transformer. The turns of a helical winding are inductively and transit time isolated from each other and the capacitance components between turns and from each turn to ground (Figure 3) are not sufficient to grade fast rising transients. Consequently, a voltage pulse approaching the full amplitude of the transient can momentarily appear across the final turns of the secondary and cause breakdown. This problem was corrected in the FRIZZ¹ transformer design by adding a capacitive voltage grading dish across the output turns of the transformer as shown in Figure 4. Spiral strip transformers are inherently less prone to breakdown from fast voltage transients because the interturn capacitance components are all directly in series to ground as shown in Figure 5. These capacitance components are comparatively large because of the large surface area and close spacing between turns of the spiral strip. Consequently, a fast voltage pulse is capacitively graded through the thickness of the winding. The principal weakness of simple spiral strip windings, however, is their tendency to break down from the thin edges of the strip. An arc breakdown typically originates from the edge of one of the final turns, flashes across the insulation margin and closes with the

low voltage primary. Such breakdowns usually damage the insulating film in the margin and leave a heavy carbon path through the oil.

These edge breakdowns result from highly enhanced electric fields associated with equipotentials which emerge from between the high voltage turns and bend sharply around the edges toward the low voltage turns (Figure 6). The high fields can be reduced and edge breakdown eliminated by placing a coaxial shield across the margins to shape the equipotentials into a coaxial distribution which is nearly parallel to the uniform field through the thickness of the winding, Figure 7.

Adding the voltage grading structures to either type of transformer can lead to the second major difficulty with air core transformers which is eddy current shorting of the transformer by the grading structures. Although these structures may be slotted, eddy currents can be induced in cylindrical shields as illustrated in Figure 8. Eddy current shorting decreases the gain and energy transfer efficiency of the transformer by an amount roughly proportional to the magnitude of the currents. In one instance, cylindrical shielding reduced the gain of a spiral strip transformer by 58%² compared to an equivalent unshielded transformer.

The problem of electrostatic shielding and grading structure design must therefore be concerned with making these devices transparent to magnetic fields. One grading technique that has been employed successfully with transformers used in single shot service consists of filling the open volume of the transformer with a resistive liquid such as water or a solution of water and copper sulfate.^{3,4} In these cases, voltages are resistively graded but the resistivity of the solution is high enough to prevent large eddy currents. Resistive solution grading is adequate for single shot transformers but less satisfactory for repetitive pulse applications because of resistive losses in the grading solution.

The most successful method developed for grading spiral strip transformer is concentric ring cage shielding across the margins⁵ as shown in Figure 9. Magnetic

fields diffuse freely through the ring cage without inducing eddy currents in the elements and yet maintain the proper electric field distribution in the margins. Each ring, of course, must have at least one circumferential gap to prevent current from flowing in the hoop direction of the rings. Spiral strip transformers shielded in this manner have been operated successfully in PFL charging applications to 3 MV with over 90% energy transfer efficiency from the primary to secondary capacitor.^{5,9} Figure 10 is a diagram of a ring shielded transformer which operates with high efficiency in the multimegavolt range.

At lower voltages, in the few hundred kilovolt range, ring shielding is often not necessary. Adequate electric field shaping along the edges of the high voltage winding can be provided by the primary turn and center coil form if they are made wider than the secondary winding strip. The maximum distance that the primary and coil form should extend beyond the winding strip edges should be limited to an amount equal to the secondary winding thickness. Otherwise, eddy currents in the edges of the wider elements will begin to cause measurable degradation of transformer performance. This method of winding edge grading is illustrated in Figure 11 which is a diagram of a small 200 kV fast pulse trigger transformer.

Transformer Circuit Analysis

For transformers with perfect coupling, no winding resistance and negligible interturn capacitance (Figure 12), a simple set of relations may be derived which relate the primary and secondary current (I_p , I_s) and voltage (V_p , V_s) to the primary and secondary turns (N_p , N_s) of the transformer:

$$I_p N_p = I_s N_s \quad (1)$$

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \quad (2)$$

The primary and secondary impedances (Z_p , Z_s) are:

$$Z_P = \frac{V_P}{I_P} \quad (3)$$

$$Z_S = \frac{V_S}{I_S} \quad (4)$$

from which

$$\frac{Z_P}{Z_S} = \left(\frac{N_P}{N_S}\right)^2 \quad (5)$$

From these ideal relations it can be seen that a transformer can be used to change current, voltage or impedance. However, since no transformer is perfect and often both the primary and secondary sections of the circuit have resonant characteristics, the analysis of such circuits is somewhat more complex.

An analysis of various pulse transformer circuits by W. H. Bostick may be found in Glasoe and Lebacqz.⁶ However, the pulse charging circuit is of particular interest to a discussion of air core transformers since they are often used in conjunction with low voltage capacitor banks to charge high voltage pulse forming transmission lines. A basic transformer charging circuit is shown in Figure 13. Neglecting stray parameters such as winding resistance, capacitance and eddy current losses, the voltage loop equations are,

$$\frac{1}{C_1} \int_0^t I_1 dt + L_1 \frac{dI_1}{dt} - M \frac{dI_2}{dt} = 0 \quad (4)$$

$$\frac{1}{C_2} \int_0^t I_2 dt + L_2 \frac{dI_2}{dt} - M \frac{dI_1}{dt} = 0 \quad (5)$$

where

$$L_1 = (L_B + L_P)$$

$$L_2 = (L_G + L_S)$$

The equations have been solved for the general case⁷ where the primary and secondary frequencies may not be matched and the coupling coefficient (K) is less than one.

$$\frac{V_2(t)}{V_o} = \frac{K\omega_2^2 \left(\frac{L_2}{L_1}\right)^{1/2} [\cos S_2 t - \cos S_1 t]}{[\omega_1^4 + \omega_2^4 - 2(1 - 2K^2)\omega_1^2\omega_2^2]^{1/2}} \quad (6)$$

where

$$S_1^2, S_2^2 = \frac{\omega_1^2 + \omega_2^2 \pm \sqrt{\omega_1^4 + \omega_2^4 - 2(1 - 2K^2)\omega_1^2\omega_2^2}}{2(1 - K^2)}$$

Pulse charging circuits may be operated in matched or off resonance modes, but are generally matched as nearly as possible to maximize energy transfer efficiency. In the matched frequency mode--that is, with the open circuit frequencies of primary and secondary sections of the circuit equal ($L_1C_1 = L_2C_2$), two cases are of practical interest: 1) first swing charging where maximum secondary voltage is reached on the first excursion (Figure 14a), and 2) dual resonance charging where maximum voltage occurs on the second or reverse voltage excursion of the secondary (Figure 14b). The secondary voltage (V_2) as a function of time for a matched frequency circuit with damping is given by:

$$V_2(t) = \frac{V_o}{2} \sqrt{\frac{L_2}{L_1}} e^{-t/T} \left[\cos \frac{\omega t}{\sqrt{1-K}} - \cos \frac{\omega t}{\sqrt{1+K}} \right] \quad (7)$$

where

$$T = \frac{4L_1L_2}{R_2L_1 + R_1L_2} (1 - K^2) \text{ damping time constant}$$

V_o = Charge voltage on primary capacitor

L_1 is the inductance of the transformer primary circuit

L_2 is the inductance of the transformer secondary circuit

ω is the radian frequency of primary and secondary circuits

$$K = \frac{M}{\sqrt{L_1L_2}}$$

M is the mutual inductance.

With Eq. 7 it can be shown that the second or reverse voltage peak exceeds the first for all values of $K < 0.8$.⁷ This implies that energy transfer efficiency decreases for first-swing charging as the coupling coefficient decreases but tends to increase with lower coupling at the second peak. Transfer efficiency at the second peak increases to a theoretical maximum of 100% when $K = 0.6$ which is the most common coupling condition for the so called dual resonance charge cycle. This and other discrete coupling coefficients which satisfy requirements for 100% energy transfer are given by:⁸

$$K = \frac{2n - 1}{2n^2 - 2n + 1} \quad (9)$$

for $n = 1, 2, 3, 4, \dots$

$K = 1, 0.6, 0.385, 0.28, \dots$

The case of K exactly equal to one is, of course, impossible but for K approaching one, the secondary voltage maximum is reached on the first voltage excursion. With air core transformers having a gain of ten or more, this operating condition is unrealistic because of the practical difficulty of constructing high voltage transformers with coupling coefficients greater than about 0.85 to 0.9. Within the range 0.6 to 0.85 it is possible to produce a wide variety of transformer designs. For this reason dual resonance transformers having the lower coupling coefficients of 0.385, 0.28 which reach maximum voltage on the third or fourth voltage excursions are of little practical interest.

In a dual resonance transformer circuit operating with $K = 0.6$, it is desirable to use a transformer which by itself has a coupling coefficient greater than 0.6.⁵ This permits exact resonant matching with the primary and secondary capacitors by adding small tuning inductors to both sections of the circuit (Figure 15). The values for primary and secondary tuning inductances (L_{t-1} and L_{t-2}) may be found if the primary and secondary capacitances (C_1 and C_2) and the inductances

(L_p , L_s and M) of the transformer are known. From the relation for coupling coefficient set $K = 0.6$.

$$K = \frac{M}{\sqrt{L_1 L_2}} = 0.6 \quad (10)$$

The values of total primary and secondary circuit inductance, L_1 and L_2 , become,

$$L_1 = \frac{1}{L_2} \left(\frac{M}{0.6} \right)^2 \quad (11)$$

$$L_2 = \frac{1}{L_1} \left(\frac{M}{0.6} \right)^2 \quad (12)$$

Since $L_1 C_1 = L_2 C_2$, substitution gives,

$$L_1 = \frac{M}{0.6} \sqrt{\frac{C_2}{C_1}} \quad (13)$$

and

$$L_2 = \frac{M}{0.6} \sqrt{\frac{C_1}{C_2}} \quad (14)$$

and the tuning inductances are

$$L_{t-1} = L_1 - (L_p + L_b)$$

$$L_{t-2} = L_2 - L_s$$

where L_b is inductance of the primary capacitor bank.

From the foregoing it can be seen that any transformer with a coupling coefficient greater than 0.6 can be adapted to a dual resonance circuit. As previously indicated, unless the circuit coupling is close to 1.0, it is more advantageous from the standpoint of transfer efficiency to operate in the dual resonance mode with $K = 0.6$. With repetitive pulse systems, high transfer efficiency is essential to preventing excessive energy dissipation in the system components from residual energy ringing through the system after discharge of the secondary capacitor. When properly tuned, a dual resonance charging system will operate with an overall efficiency between 90 and 95%.^{5,9}

Transformer Insulation

Proper application of insulating materials is an essential consideration in high voltage transformers design. As a minimum, it is necessary to know the dielectric strength of the materials and the voltage stresses that they will be subjected to in service. In reality, these two aspects are a complex of many factors, the details of which are beyond the scope of this paper. It is useful, however, to summarize some of the general characteristics and modes of failure of dielectric materials.

For pulse transformers, the types of materials most commonly used are liquids and film or cast solids, usually in combination. Failure in one invariably leads to failure of both. The initiating mechanism can be prompt in nature such as bulk breakdown from over stressing or gradual as a result of deterioration of dielectric strength from partial discharges. The process of dielectric deterioration from partial discharges includes gas production in the liquid which leads to ionization in the gaseous inclusions and erosion of solids in contact with the liquids.

Three characteristics common to liquid and solid dielectrics used in pulsed voltage applications include time dependent breakdown in the approximate range of 10^{-6} to 10^{-9} s, breakdown strength which decreases with a weak dependence on increased stressed area in the range of a few square centimeters to several thousand square centimeters and breakdown strength which decreases with increasing insulator thickness below 1 cm. Data also exists that shows the dielectric strength of liquids such as transformer oil and n-Hexane decrease by a factor of three with increases in pulse voltage rate of rise in the range of 10^2 to 10^4 kV/cm- μ s.¹³ Figures 16 and 17 illustrate pulse time and electrode gap dependence on breakdown for several oils. Figure 18 is a plot of dielectric strength as a function of thickness for Mylar polyester film. Although the trends for liquids and solids are similar, the actual strength levels for given pulse

times and thicknesses may be very much different. With few exceptions, liquid dielectrics tend to be weaker than solids, particularly solid films.

Various theoretical models have been developed to explain dielectric breakdown phenomena. Some authors consider liquids and solids to be homogeneous dielectrics while others ascribe breakdown to the presence of various impurities or faults in the media. For practical purposes, any theory which considers liquids or solids totally homogenous can have only limited application. However, the effects of impurities and faults are inclined to neglect the fact that eventually it is the insulator itself which breaks down.¹⁴ Thus there is no single theory which is generally accepted for all cases.

A model for time dependent breakdown of solids by Kuffel and Abdullah¹⁵ is illustrated in Figure 19. Breakdown strength which decreases as a function of time is described as resulting from four different initiating mechanisms which operate in different time regimes. The highest strength a material can have, its intrinsic strength, can only be obtained experimentally under the best of conditions when all extraneous effects are removed so that breakdown is dependent on only the material and temperature. Intrinsic breakdown occurs in times of 10^{-8} s or less at stress levels in excess of 10^6 V/cm. Intrinsic breakdown is postulated to be electronic in nature and assumed to occur when dielectric electrons gain enough energy from the applied field to cross the forbidden energy gap from the valency to the conduction band. The criterion condition is formulated by solving an equation for energy balance between the gain of energy by conduction electrons from the applied field and their loss to the lattice.

The second and next lower initiating mechanism is streamer breakdown which, with electrodes embedded in the material to avoid external effects, occurs from an electron entering the conduction band of the insulator at the cathode. As it drifts toward the anode under the influence of the electric field, the electrons gain energy

between collisions and lose it on collisions. On occasions when the path is long enough to exceed the lattice ionizing energy an additional electron is produced by collision. The process may lead to the formation of an electron avalanche which, if a critical size is exceeded according to Seltz,¹⁶ will result in a streamer being formed. The fields at the streamer tip, estimated to be in the order of 10^7 V/cm, exceed the intrinsic electric strength and complete breakdown ensues. The concept is similar to the streamer theory developed by Loeb and Meek¹⁶ for gas breakdown and collisional ionization leading to electron avalanches and streamer formation in liquids by Goodwin and MacFadyen.¹⁸

Thermal breakdown of a solid is associated with a decrease in electric strength with increasing temperature. The temperature rise in a solid may occur as a result of heat transferred from an external source or direct dissipation in the solid from electric stressing. When a DC field is applied to a dielectric at room temperature the conduction current is generally very low. The conduction current increases rapidly with increasing temperature if the heat is not conducted away, causing a thermal run away condition. The electric stress simply exceeds the dielectric strength of the material at the elevated temperature. In the case of AC voltages, heat is generated inside the dielectric as a result of dipole relaxation. The losses associated with AC fields are usually much greater than DC fields because the loss in relaxation phenomena such as dipolar motions depend upon the rate of change of the field. Consequently, thermal breakdown strength is generally lower for AC fields and decreases with increasing frequency.

Erosion breakdown, as the name implies, involves long term degradation of a solid from arcs, or partial discharges generated within or at the boundaries of the solid and an electrode surface or another insulating medium. Repeated surface discharges across a solid insulator surface can gradually remove enough material along preferential paths until breakdown occurs. Cavities, voids or particle

inclusions which have lower breakdown strengths than the solid dielectric result in corona generation and eventual failure from within the volume of the material. The problem of breakdown from gas filled voids is aggravated by the fact that the gas usually has a lower dielectric constant than the solid and the electric field in the void is correspondingly increased according to:¹⁹

$$E_b = \frac{3\varepsilon_1 E_0}{2\varepsilon_1 + 1}$$

where E_0 is the field in the solid in the absence of the void and ε_1 is the permittivity of the solid. The same relation applies to bubbles in a liquid.

In addition to the foregoing failure modes, solids, particularly soft ones may be subject to electromechanical failure. This type of failure is the result of electrostatic pressure produced by the electric field. A two-dimensional mechanical stress is thereby produced in the insulator with compression through the thickness and tension in the lateral direction. Should the stresses exceed the tensile or compressive strength of the material it will fail mechanically.

Liquid dielectrics exhibit the same general characteristics as solids with respect to failure modes and dielectric strength dependence on temperature, pulse time, stressed area and thickness in the short gap ranges (< 1 cm). They differ from solids in their sensitivity to particle and chemical contamination, absorbed gases and increased strength at high hydrostatic pressures.

Probably the most widely used relationship for impulse breakdown of liquid dielectrics is the empirical formula developed by J. C. Martin²⁰ for gaps greater than 1 cm:

$$Et^{1/3} A^{0.1} = K$$

where

E is the field strength in MV/cm

t is effective pulse time, the time the voltage is greater than 0.63 of its maximum value

A is electrode area in cm^2

$K = 0.5$ for transformer oil.

The expression has been experimentally verified for areas up to 10^6 cm^2 and pulse times from less than 20 ns to at least 1.0 μs . For small electrode spacings a gap dependence of $d^{-1/4}$ in the expression gives a better fit to breakdown data:²¹

$$Et^{1/3} A^{0.1} d^{-1/4} = K$$

Martin's liquid breakdown formula applies specifically to bulk breakdown conditions with comparatively long time intervals (at least minutes) between shots so that the effects of any disturbances in the liquid such as partial discharges or streamers that do not completely cross the electrode gap have time to heal.

Gas generated by partial discharges and streamers in the captive oil volume of a transformer can not generally be tolerated because of shot to shot buildup. The transformer designer must therefore be more concerned with the corona inception voltage (CIV) than with dielectric strength. Corona or partial discharge damage in transformers has been a well known problem in AC power transformers and low voltage pulse transformers for over 50 years. It has only recently received attention as a major problem with high voltage pulse transformers. The primary reason is that high voltage pulse transformers were used in single shot applications where mild corona discharges had little or no effect over a life of five to ten thousand shots. However, with repetitive pulse systems which have life expectancies of at least 10^9 shots, corona damage has become a dominant consideration in pulse transformer design. Figure 20 is a photograph of damage to Mylar film produced by repetitive pulsing with partial discharges for several thousand shots.

This type of failure is common in spiral strip transformers when partial discharges occur in the oil adjacent to the film surface.

Clark²² gives a brief description of the products of corona in mineral insulating oils. He shows that the products of ionization associated with corona bear a strong resemblance to those produced by controlled heat treatment (heat cracking). The primary gaseous products include:

Hydrogen	H ₂
Carbon Monoxide	CO
Carbon Dioxide	CO ₂
Methane	CH ₄
Ethane	C ₂ H ₆
Ethylene	C ₂ H ₄
Acetylene	C ₂ H ₂

In addition to the gaseous products, carbon particles and unsaturated liquid hydrocarbons are formed. The liquids have poor oxidation stability and in general lower dielectric strength. Thus corona discharges over a long period of time result in the buildup of low strength liquids which eventually render the oil useless as a dielectric.

It is well known that moderate carbon particle, dust and moisture contamination in many insulating oils does not decrease the dielectric strength appreciably under fast pulse conditions in the range of nanoseconds to at least 10 μ s. These contaminants do, however, lower the CIV which is not as sensitive to pulse time.²³ With silicone oils, for example, a reduction of nearly 30% has been measured between dry oil samples and ones with a moisture content of 170 ppm²⁴ (Figure 21). The CIV reduction is linear over that range and fits the equation:

$$\text{CIV} = - 0.55 \text{ x } + 3610 \text{ kV/cm}$$

$$\text{X} = \text{water content (ppm)}$$

Other experiments with oil impregnated mylar-copper disk laminates sandwiched between flat plate electrodes (Figure 22) showed similar results with respect to partial discharge effects. A variety of oils were pulse tested in both "barrel fresh" condition and in the dry degassed condition. In some cases breakdown of the laminate from repetitive partial discharges differed by as much as 30%. Table I summarizes the oils tested and the nominal breakdown levels.

Table I
Onset of Partial Discharges in Various Oils
Tested in Laminate Structures

	Dry Degassed Condition kV/cm	Barrel Fresh Condition kV/cm
Transformer Oil, Inhibited	325	250
X-ray Oil (Marcol 2930)	590	510
Silicone Oil (Dow Corning 200)	360	305
MIPB (Mansanto 1238)	620	410
DAA (HISOL SAS 10 E)	460	390
Paraffin Oil (RTEmp)	650	380

Voltage stresses are mean values and are intended to illustrate comparative properties of the oils in two conditions. To determine the actual stress in the oil and mylar film it is necessary to compute the stress distribution in the two dielectric system according to the relation:

$$E_1 = \frac{V_O}{d_1 + d_2 (\epsilon_1/\epsilon_2)} \text{ kV/cm}$$

$$E_2 = \frac{V_O}{d_1 (\epsilon_2/\epsilon_1) + d_2} \text{ kV/cm}$$

where

V_O is the total voltage across the electrodes, kV

E_1 and E_2 are the voltage stresses in materials 1 and 2

ϵ_1 and ϵ_2 are the dielectric constants of materials 1 and 2

d_1 and d_2 are the thicknesses of materials 1 and 2 in cm.

Considerable caution must be exercised in interpreting dielectric strength and partial discharge data because of differences in test conditions. Factors already mentioned such as pulse time, sample thickness and area can give results which differ by as much as an order of magnitude. This can be seen by comparing the CIV for silicone and mineral oil reported by Kuwahara et al.²³ with that obtained in the laminate tests. In the first case, measurements were made using close spaced needle-plane electrodes with applied voltages between 15 kV and 20 kV. This resulted in a CIV of 3370 kV/cm for silicone oil and 3520 kV/cm for mineral oil. With the laminates, which were one cm thick and tested above 300 kV, the onset of partial discharges were observed at 360 kV/cm for silicone oil and 325 kV/cm for mineral oil with both oils in the dry degassed condition. These two sets of results emphasize the necessity of searching for data or conducting tests as near as possible to the actual service conditions that dielectrics will experience. Lacking such specific data, most common insulating liquids such as mineral oils, paraffin base oils, and silicone oils can be repetitively stressed at at least 150 kV/cm without encountering bulk breakdown or partial discharge problems. If the oils are carefully filtered to remove particle matter above 1 micron and degassed before use, the margin of safety will be increased by at least 50%. When the highest possible performance must be obtained from an insulation system there is no alternative to conducting tests as near as possible to anticipated service conditions.

Conclusions

High voltage air core pulse transformers are best suited to applications outside the normal ranges of conventional magnetic core transformers. In general these include charge transfer at high power levels and fast pulse generation with comparatively low energy. When properly designed and constructed, they are capable of delivering high energy transfer efficiency and have demonstrated superior high

voltage endurance. The principal disadvantage of high voltage air core transformers is that they are not generally available from commercial sources. Consequently, the potential user must become thoroughly familiar with all aspects of design, fabrication and system application before he can produce a high performance transformer system.

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Fig. 1. Simple helical wire transformer.

Fig. 2. Simple spiral strip transformer.

Fig. 3. Equivalent circuit along the length of a helical wound transformer.

Fig. 4. FRIZZ, helical transformer.

Fig. 5. Equivalent circuit through the thickness of a spiral strip winding.

Fig. 6. Equipotential profile at the edge of an unshielded and ungraded spiral winding.

Fig. 7. Coaxial shield across spiral strip transformer margin.

Fig. 8. Eddy current pattern in solid concentric shields.

Fig. 9. Ring cage shield for spiral strip transformer.

Fig. 10. 3 MV transformer.

Fig. 11. 200 kV trigger transformer.

Fig. 12. Simple transformer circuit with perfect coupling.

Fig. 13. Basic transformer charging circuit.

(a)

(b)

Fig. 14. a. First-swing charge cycle.
b. Dual resonance charge cycle.

Fig. 15. Transformer circuit with tuning inductors.

Fig. 16. Breakdown strength of n-Hexane as a function of electrode gap and pulse duration.

Fig. 17. Impulse breakdown strength of various oil as a function of electrode gap with a 1.5 μs dual resonance pulse shape and 10 cm² electrodes.

Fig. 18. Dielectric strength of mylar polyester film as a function of thickness.

Fig. 19. Solid Dielectric breakdown model.

Fig. 20. Damage to mylar film from partial discharges.

Fig. 21. Relation between water content and mode value of CIV in silicone liquid.

Fig. 22. Mylar-copper disk laminate test.

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