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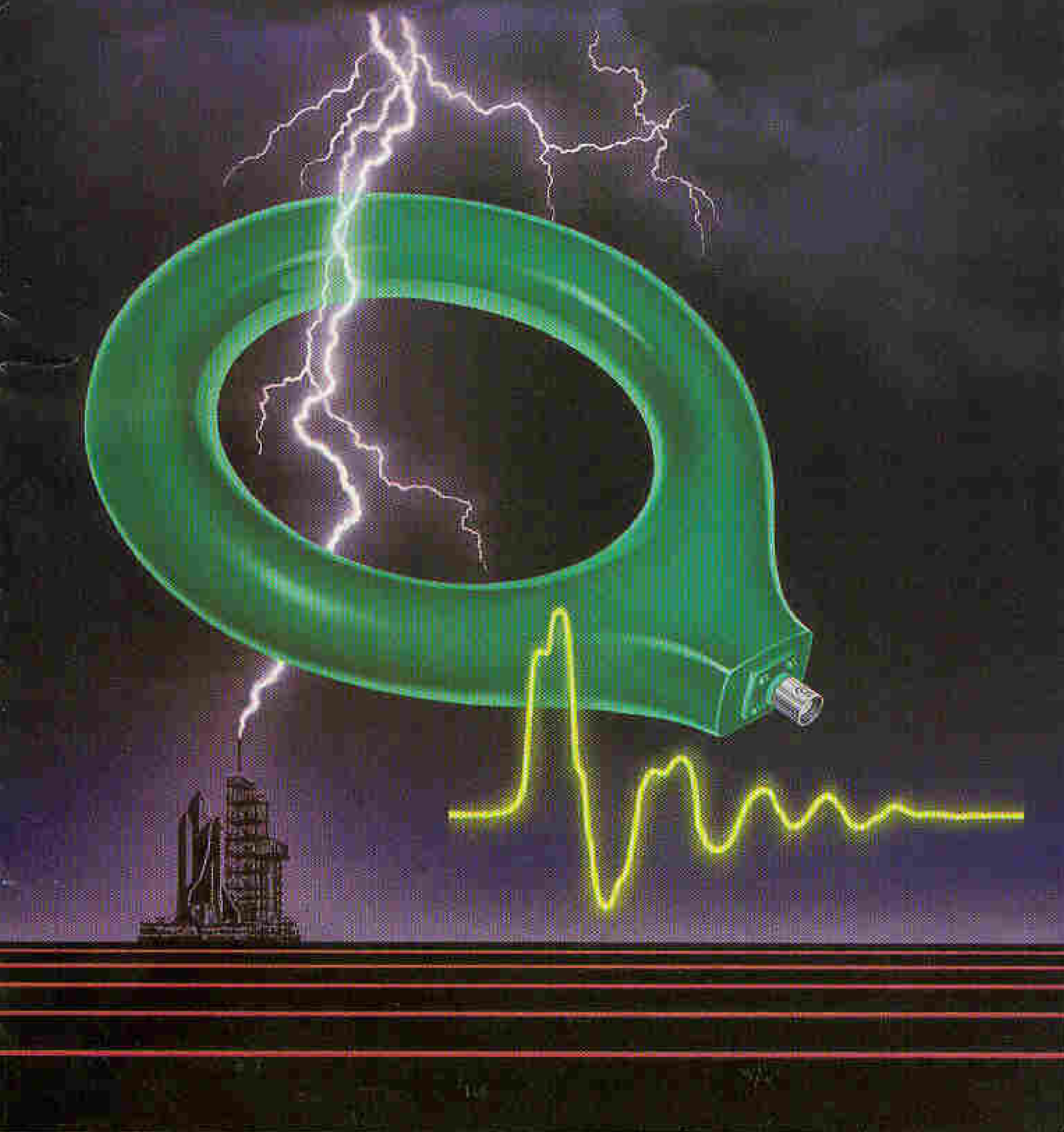

Current Transformers Provide Accurate, Isolated Measurements

by
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The theory and applications of current transformers are explained along with the design considerations of biasing, pulsed and continuous wave operation, sensitivity, high voltage use and shielding.

Accurate measurement of the amplitude and waveform of AC current is required in many electronic and electrical applications. The most obvious way to make such measurements is to insert a resistor into the circuit to be measured and observe the voltage developed across it. It is often more advantageous to determine the current flowing in a conductor by means of its associated magnetic field. This provides isolation between the measuring equipment and the circuit being measured.

Several devices measure current by means of magnetic coupling. These include DC current probes based on the flux-gate and Hall Effect principles, and various AC measuring transformers such as air core Rogowski coils, or transformers with high permeability cores. The terminated current transformer, or current monitor, will be discussed in detail. This device is capable of broadband response and is linear over a wide current range. It can be used as a current-to-voltage converter for a voltmeter, oscilloscope, or analog-to-digital converter.

Current monitors differ from conventional current transformers because they are internally terminated and give an output voltage proportional to the current being measured. Also, they are generally one-winding devices that surround the conductor under test and use it as the primary winding. The current monitor has a built in, factory calibrated current-to-voltage termination that permits easy connection to standard voltage-measuring test equipment.

Applications

Current monitors are being used for measuring and characterizing current waveforms from the microampere range to above 500 kiloamperes. Compared to series resistors, they are well-suited for measurements where ground-loop noise, lack of high-voltage isolation, or voltage drop and power dissipation would cause problems.

An application where isolation, fast rise-time and high peak current capabilities of the current monitor are used to advantage is in the characterization of lightning strike currents. They can also be used in the evaluation of devices for protection from lightning-produced transients. Current monitors have been in use for 15 years at the Kennedy Space Center for charting the history and character of lightning strikes received by space vehicle service towers. Current monitors are also used in research on transient protection devices. Lightning simulators and strikes triggered by small rockets are used to test these devices. A large monitor measures the test discharge current, whereas smaller units monitor the currents entering the protected equipment.

In the power industry uses include measurement of transients in switch gear and observation of harmonics and phase relationships on power lines. Current monitoring can be combined with voltage measurement to obtain power factor. A manufacturer of power apparatus monitors leakage current in high voltage impulse testing. In another application, the conductivity of grounds, neutrals and guy-wires is investigated by using an injected signal voltage and current monitoring.

Because of its geometry, the current monitor is uniquely suited to measure current in charged-particle beams and in electrolytic solutions. Standard models are fully impregnated and can be used in vacuum and in most liquids. Models built for use in a proton accelerator allow beam current measurement with minimal beam disturbance. Current monitors are often used in high voltage pulse modulators that drive microwave tubes. Applications are found both in development and in the routine monitoring of performance. Such modulators are found in radar systems and high energy particle accelerators.

In manufacturing, current monitors are used in development and testing. One maker of microwave ovens uses current monitors as an alternative to viewing resistors to evaluate the transients produced on the power line during the various states of operation of the product.

The welding industry uses dedicated monitors to view output currents in induction and spot welding equipment. Current monitors can measure pulse shapes in switch-mode power supplies and stepper motor drivers, and can detect EMI in signal and control circuits. Some units are used to monitor automotive ignition systems, and others look at flash-lamp and laser pulse currents.

Theory of Operation

The current monitor consists of four main elements. These are the magnetic core, the secondary winding, the resistive termination and the electromagnetic shield. Careful choice and assembly of these items produces a current-to-voltage converter of wide bandwidth, high linearity and low insertion resistance.

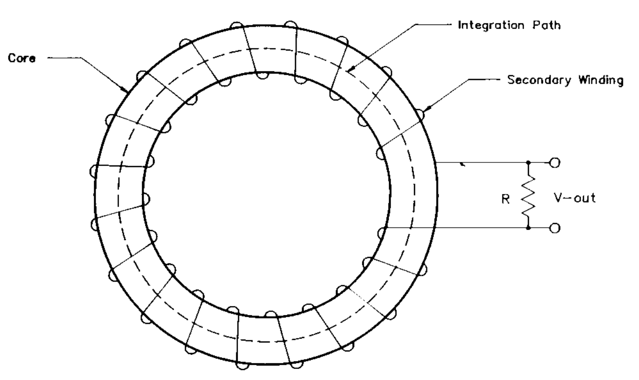

Figure 1. Terminated Current Transformer

To understand the operation of the current monitor, consider *Figure 1*, which depicts a simplified terminated current transformer. A toroidal magnetic core of high permeability has been wound with a coil of n evenly distributed turns. The primary circuit, not shown, consists of a long wire, or path of current flow, along the axis of the toroid. The magnetic field produced by current flowing in these conductors is nearly radially symmetric, and is treated as such for this derivation. We obtain from Ampere's Law:

$$\oint H \bullet d\ell = i_P - n i_S \qquad (1)$$

If the cross-section of the core is small compared to the radius, the field in the core due to the primary current is nearly uniform, as is that due to the secondary current. We can then integrate around a closed path inside the core and obtain:

$$H = (i_P - n i_S)/\ell \qquad (2)$$

where ℓ is the mean path length around the core. We now introduce the permeability $\mu = B/H$, where B is the magnetic flux density inside the core of permeability μ. If the effective cross-sectional area of the core is A then the flux Φ in the core is

$$\Phi = BA = \mu HA = \mu A(i_P - n i_S)/\ell \qquad (3)$$

By Faraday's Law,

$$V = n\, d\Phi/dt = i_S\, R \qquad (4)$$

Therefore, combining these we obtain the differential equation for the secondary current

$$i_S R = (n^2 \mu A/\ell)\, d/dt(i_P/n - i_S) \qquad (5)$$

Note that $L = n^2\mu A/\ell$ is the inductance of the n turn coil wound on the core. Therefore,

$$di_S/dt + i_S R/L = (1/n)\, di_P/dt \qquad (6)$$

Using the Laplace Transform, we find that

$$I_S(s) = (s/n)[\, I_P(s)/(s+a)\,] \qquad (7)$$

where $a = R/L$ and $I_S(s)$ and $I_P(s)$ are the respective transforms of $i_P(t)$ and $i_P(t)$. The transfer function, $G(s) = s/n(s+a)$, is that of a simple high pass filter with a cutoff frequency of $a/2\pi$.

To see what secondary voltage is produced by a unit current step at $t = 0$, we set $I_P = 1/s$. Then $I_S(s) = 1/n(s+a)$, which corresponds to $i_S(t) = (1/n)\, e^{-at}$. This is a jump from zero to 1/n followed by an exponential decay back to zero with a time constant of L/R.

For a rectangular pulse, in which the current returns to zero after a time $T \ll 1/a$, the output voltage is a pulse with a tilted top. The rate of droop of the top is simply a.

The response of the transformer at high frequency is determined by the inductance, resistance and stray capacitance of the winding. These elements interact to create resonances, and a roll-off of response at high frequency. Pearson current monitors employ a system of distributed terminations which extend the usable high frequency limit well beyond that of the simple transformer of *Figure 1*.

The presence of a high permeability magnetic core is very important to the extension of flat response to low frequency. However, the core also causes a limitation on the product of current and time for a unidirectional pulse. To see why this is so, recall that the voltage developed in the winding is proportional to the rate of change of flux in the core. If we integrate equation (4) we obtain

$$\int V(t)\, dt = n\, \Delta\Phi \qquad (8)$$

where $\Delta\oint$ is the change in flux in the core. Since the maximum flux is limited by core saturation, there is a corresponding limit on I•t. In terms of the design parameters,

$$\int I(t)\, dt \leqslant n^2 B_{MAX} A/R \qquad (9)$$

In addition, the core can be saturated by the DC component of the current being measured. As discussed below, properly applied DC bias current can overcome these problems in many cases.

In summary, we have shown that the frequency response of the terminated current transformer is flat between a low frequency limit set by the secondary inductance and the terminating resistance, and high frequency limit due to stray capacitances. Current signals with spectra within the pass band are faithfully displayed in the output voltage. This is in contrast to the operation of a Rogowski coil, or I-dot coil, in which the output voltage is proportional to the rate of change of the current being measured.

Design and Specifications

So far we have considered an abstract current monitor without mentioning any specific performance characteristics or design parameters. The ideal current monitor would have unlimited current handling ability, unlimited bandwidth, would be small, light weight, and inexpensive. As you might imagine, satisfying all these wishes at once is impossible, and it falls to the transformer designer to achieve a balance among these areas suitable to a particular application.

Pearson Electronics makes a series of general purpose current monitors which combine the above properties in different ways to address a wide range of applications. We will use the Model 110 as an example as we relate application requirements to performance specifications and design parameters. The specifications of this model are found in Table 1.

Applications can generally be divided into the pulse or transient type, with emphasis on the peak current capability, droop, rise-time, and $I \bullet t$ product, or the continuous type where the RMS current limit, bandwidth, and I/f figure are of primary interest. Examples of the former would be pulsed cathode current for high power klystron tubes and lightning strike currents. The latter would include observation of harmonics on power lines, and the current part of a power-factor measurement. Let us first look at the pulse specifications and then show how they relate to the continuous specifications.

Pulses

The maximum peak current is of course the highest permissible current in the circuit being measured by the current monitor. This specification is closely related to the maximum current time product $(I \bullet t)_{MAX}$. If the maximum allowable pulse energy in the internal termination is known to be W, then, since $W = I^2Rt$,

$$I_{MAX} = W/R \ (I \bullet t)_{MAX} \qquad (10)$$

I_{MAX} is then a safe limit for all unidirectional flat-top pulses.

The $I \bullet t$ product is limited by saturation of the core. If a current pulse exceeds this limit, the output drops suddenly to zero, and does not follow the input current until its polarity reverses and brings the core out of saturation.

If the pulse to be measured falls within the limits of peak current and $I \bullet t$, then the droop rate should be multiplied by the pulse duration to see whether sufficient accuracy is maintained throughout the pulse.

At high frequencies, the current monitor has roll-off and resonances that limit high frequency response and may cause overshoot and ringing on a fast-rising pulse. The usable rise-time is defined as that 10% to 90% rise-time that causes less than 10% overshoot or ringing. When pulse rise-time is below about 100 nsec, or if a long connecting cable is being used, it is advisable to terminate the cable with a 50 ohm resistance to obtain the best waveshape fidelity. The standard current monitors have a 50 ohm source impedance, and if a matched load is applied at the oscilloscope end of the cable, the sensitivity in volts/ampere must be divided by 2. The accuracy, in this case, is affected by the accuracy of the external terminating resistance, and the cable attenuation. External loads greater that 5000 ohms affect the nominal sensitivity by less than 1%.

Continuous Waves

When current monitors are to be used for measuring continuous-wave currents, the specifications of maximum RMS current, low and high frequency band limits, and the saturation limit on I/f are relevant.

The RMS limit is determined by the allowable temperature rise of the unit, and depends on case area as well as secondary current and internal termination resistance. If the power per unit case area that gives the maximum acceptable temperature rise is P, and the case area is A_C, then the maximum RMS current is:

$$I_{RMS} = n\,(P\,A_C\,/\,R)^{1/2} \qquad (11)$$

In this case R is the sum of the winding and termination resistances.

For AC transients, a time range exists for which the safe current maximum is greater than the continuous RMS value above, but less than the peak limit for pulses. The derating from the peak value for longer transients requires that I^2t for the transient be less than $I_{MAX}\ (I \bullet t)_{MAX}$ from equation (10). The curve for Model 110 transformer is shown in *Figure 2.*

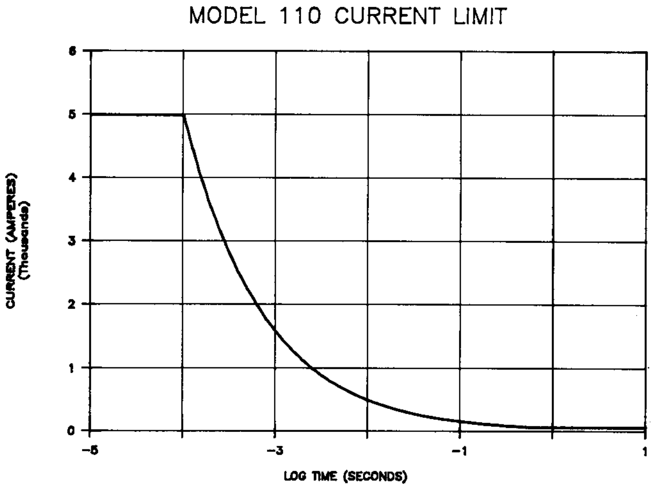

Figure 2. Current Limit as a Function of Time

The upper and lower bandwidth limits correspond respectively to the usable rise-time and droop. Below the low frequency cut-off, response rolls off at 20 dB/decade. The high frequency response is within ±3 dB up to the specified upper limit. For signals at least one decade inside the band limits, amplitude error is typically less than 1% and the phase shift is less than 6°.

The I/f limit corresponds to the $(I \bullet t)_{MAX}$, but it is based on the flux swing from negative to positive saturation since the current is bi-directional. The zero-to-peak value of the sine wave is given. For example, at 60Hz the maximum sine wave current that can be followed without core saturation is 90A, peak.

Biasing

Current monitors often need to work with a DC component of current present, or at the maximum possible $I \bullet t$ product. The use of DC bias improves performance in such situations. The objective here is to cancel the DC component and to obtain flux excursions from negative to positive saturation, resulting in the highest $I \bullet t$ product.

Bias may be applied either through an additional primary conductor passing through the monitor, or by injecting current into the secondary winding via the output connector. In both cases the current source should have a high impedance. The objective is to cancel the DC ampere-turns of the primary circuit. If the secondary is to be biased, the current value to be used is approximately equal to the DC component to be nulled divided by the number of secondary turns. If the secondary winding resistance is significant relative to the internal termination, some of the applied current will flow in the termination, and a larger bias current will be needed to obtain the correct ampere-turns.

The ability of a current monitor to work in the presence of a DC component depends on the core material and whether or not the core is constructed with an air gap. A high permeability gap-less core is used in the Model 110, and it will be saturated at about 0.3A primary current. On the other hand, the same design incorporating a core with a small air gap can measure AC current on top of a DC current many times higher. A side effect of the gap is to lower the apparent permeability, and therefore increase the droop rate. The gap increases the H field needed to saturate the core, and a similar effect is obtained by using a core material with a high value of H at saturation. Monitors made with gapped cores seldom require biasing.

Sensitivity

The mid-band transfer resistance, or sensitivity, G, is equal to R/n, where R is the termination resistance. Designs used for high pulse current usually have sensitivities in the range of 0.001 to 0.01V/A. R is small and n is large, which gives low droop and high I•t product. Rise-time, however, is greater for these units. When the terminating resistance is less than 50 ohms, a resistor is added in series with the output connector to bring the source resistance up to 50 ohms.

For small currents, a sensitivity of 1V/A is more appropriate. Rise-time is short, with small units having usable rise-times as low as 2 nsec, but droop is large and I•t product is small. A low noise amplifier should be used with the monitor, since the noise of the amplifier usually dominates that of the monitor. It is impractical to arbitrarily increase the sensitivity of a passive current monitor to overcome amplifier noise. To increase G one would increase R, which increases the thermal noise, or decrease n, which would increase the low cut-off frequency. The thermal noise voltage may be calculated as:

$$V_N = (4kTbR)^{1/2} \tag{12}$$

where k is Boltzman's constant, T the absolute temperature and b the bandwidth. As a point of reference, the equivalent primary current noise for the Model 110, over its usable bandwidth, is 40μA.

TABLE 1
Performance Specifications for Model 110

Dimensions:	
Inner diameter	2 inches
Outer diameter	4 inches
Thickness	1 inch
Weight	20 ounces
Sensitivity:	
Transfer Resistance	0.1 Volt/Ampere
Accuracy	+1 / −0 %
Pulse:	
Maximum Peak Current	5000 Amperes
Droop Rate	0.8%/millisecond
Usable Rise-time	20 nanoseconds
Maximum I•t	0.5 Ampere-seconds
Continuous:	
Maximum RMS Current	65 Amperes
Low-frequency Cut-off	1 Hz
High-frequency limit	20 megaHz
Maximum I/f	1.5 peak Amperes/Hz
Other:	
Maximum DC Current	0.3 Amperes
Voltage in Air	15 kVolts

High Voltage and Shielding

The fact that the current monitor makes no ohmic contact with the circuit being measured is very useful when monitoring current in a conductor at high voltage. Monitors designed for high voltage service feature large holes to accommodate insulation, radiused hole edges to reduce electric field, and double electrostatic shielding to reduce capacitively coupled noise and safeguard external equipment. To maximize the working voltage for a given hole size, the primary conductor should be centered and have a diameter of 1/e times the hole diameter. This arrangement creates the ideal coaxial geometry. Standard models are available with hole diameters of 3.5 and 10.75 inches. These can operate respectively at pulse voltages of 50 and 150kV in air, or 300 and 900kV in transformer oil. Solid dielectric insulation is recommended for high DC potentials.

Double-shielded models are connected so that the outer shield, which is the protective case, is isolated from the winding and termination. It may be grounded through the mounting feet to provide a safe path to ground for accidental discharges from the primary conductor. The outer shell of the connector is attached to the low end of the secondary, and to the inner shield. The instrument ground is then isolated from the primary circuit ground, which may be beneficial in eliminating ground-loop noise. All shields are gapped to prevent their acting as a shorted turn around the core.

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