SOME OBSERVATIONS ON THE PERFORMANCE OF MODERN WIDEBAND CURRENT TRANSFORMERS IN PULSE CURRENT MEASUREMENT APPLICATIONS

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Abstract

In this paper the analysis of the performance of both internally- and externally-terminated current transformers (ct's) is presented. Factors limiting the I-t, droop, peak pulse current, frequency response and mean dc current performance of these instruments are discussed and the trade-offs examined. Experimental results which demonstrate the behaviour of inexpensive ring-type designs over a broad spectrum of frequencies are examined and compared with those achieved with internally-terminated structures. It is shown that some unterminated ring-type designs can produce a good and versatile performance in the measurement of pulse currents with frequency components below 0.1Hz and to several 100kHz. Internally-terminated designs extend the performance by two to three decades of frequency for applications where high-frequency harmonics are to be measured accurately.

INTRODUCTION

Terminated current transformers have been used to measure pulse currents in power electronics for several decades. Arguably their greatest attribute is that they permit the measurement of current without the need for direct electrical connection to the circuit under test. This quality greatly facilitates the concurrent measurement of other electrical parameters [1]. These instruments can record currents measured in milliamps to pulse currents of several hundred thousand amps whilst imposing little burden on the system under test. Terminated current transformers combine this broad dynamic range with an impressive bandwidth. There are commercially-available instruments that can measure pulse currents with harmonic components in the range 0.1Hz to 100MHz. They have the ability to replicate a high-current waveshape with good fidelity for capture by a data recorder or display on an oscilloscope. Indeed, where the highest frequency components are to be measured it is difficult to envisage an alternative system of measurement.

The performance of a ct is governed in some measure by the properties of the magnetic materials employed in its construction. For the magnetic circuit, the strip-wound toroidal structure is preferred. Materials used in commercial products include grain-orientated steel (GOS), nickel-iron alloys such as mumetal and, more recently, nanocrystalline and amorphous iron alloys. Some of the properties of these materials are examined and compared in this contribution.

In pulse applications, both low-frequency characteristics, such as I-t capability and droop performance, and high-frequency characteristics, such as rise-time and stray signal pick up, are important. In this paper we employ the appropriate equivalent circuits to explore the nature these characteristics.

The construction of transformers designed for the measurement of the high-frequency components in very high current pulses can cause some difficulties to the transformer manufacturer. In the latter part of this paper we illustrate how characteristics of cascaded transformers can be combined to produce a high-frequency performance that is difficult to match in a single instrument.

EQUIVALENT CIRCUITS

In analysing the performance of a broadband current transformer it is convenient to refer to both the low-frequency and high-frequency transformer equivalent circuits.

Low-frequency equivalent circuit

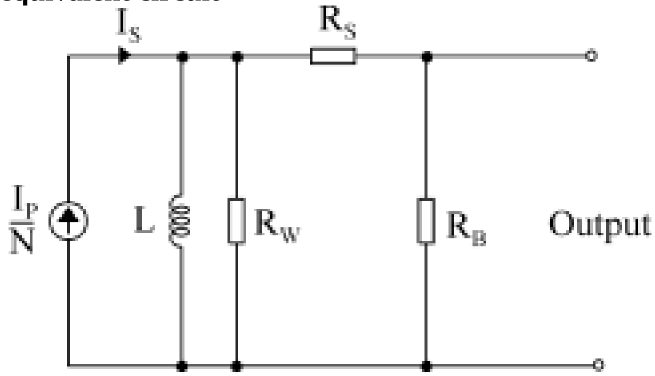

Fig.1 Low-frequency equivalent circuit

In Fig. 1

I_s is the secondary current. This is essentially a constant current equal to I_p/N where N is the transformer turns ratio and I_p the primary current

L is the inductance of the secondary winding,

R_W is the core watts loss,

R_s is the resistance of the secondary winding and

R_B is the burden or sense resistor.

The instrument is essentially a transducer which converts primary current to a voltage signal. Its sensitivity is equal to R_B/N volts per primary amp. In transformers designed for pulse measurement, R_W can be made sufficiently small for it to be ignored. It can be seen, that for faithful reproduction of the primary current waveform, the current flowing in L must be significantly less that that flowing in R_s and R_B. The low frequency 3dB cut-off point f_{lfco} is given by:

$$f_{lfco} \cong (R_W + R_B)/2\pi L \qquad (1)$$

Where $$L=(\mu_r\mu_0 N_s^2 A_{fe})/l_{fe} \qquad (2)$$

μ_r is the relative permeability of the core material,
μ_0 is the permeability of free space,
N_s the number of secondary turns which is equal to N when, as often is the case, a single-turn primary is employed,
A_{fe} is the effective area of cross section of the core and
L_{fe} is the mean length of the magnetic path.

The ability of the instrument to display a rectangular waveform without saturation is known as I-t capability. It is given by:

$$\text{I-t} \cong. (B_s A_{fe} Ns^2)/(R_W + R_B) \qquad (3)$$

Where B_s is the saturation flux density for the core material. This equation is valid where droop is small over the period of the pulse. See Refs [2] and [3].

When a rectangular waveform is measured the output signal deviates from the true value with time. This deviation or droop is caused by the increase in the current flowing into L in the presence of a constant output voltage. It can be shown that

$$\text{Droop} = 0.1(R_s + R_B)/L \ \%/\text{ms} \tag{4}$$

Droop is a measure of the rate of exponential decay of the recorded value of current from its true value. The flow of current in L also results in a phase shift between input and output signals. For more information on this and droop see Ref [3].

In some pulsed applications there can be a significant dc component of current present. The primary dc current that can saturate the transformers core can be found from

$$I_p = B_s I_{fe}/\mu_r \, \mu_0 \tag{5}$$

Though this relationship is for guidance only as μ_r is often a strong function of flux density.

High-frequency equivalent circuit

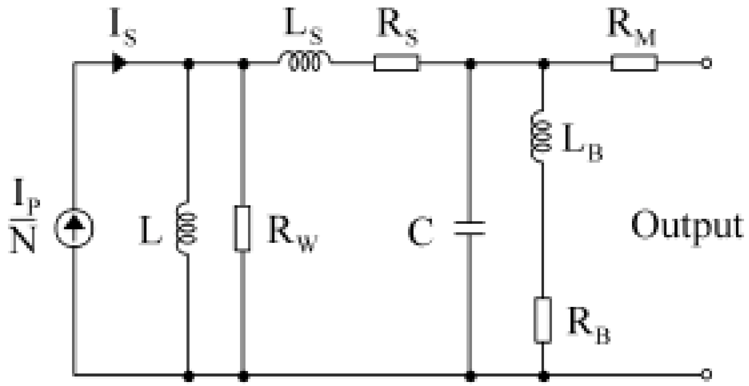

Fig. 2 High-frequency equivalent circuit

At high frequency, parasitic inductance and capacitance limits the performance of the transformer.

L_s represents the parasitic inductance caused by leakage flux.

C represents the parasitic capacitance.

L_B is the parasitic series inductance associated with the sense resistor.

R_M is the resistor used to match the output impedance of the instrument to its connecting cable.

The positioning of the capacitance C in Fig. 2 is more symbolic than to assist with analysis. It represents the distributed stray winding-to-winding, winding-to-shield and winding-to-core capacitances.

Unlike low-frequency characteristics which lend themselves to determination by calculation, the high-frequency design depends more on the experience of the designer. For internally-terminated transformers the effect of stay inductance and capacitance is reduced by essentially constructing multiple series-connected transformers to form a single unit. By this means pulse power transformers can be constructed with a high-frequency cut-off point that is beyond 100MHz.

Factors can limit effective high-frequency performance include:

(1) The stray inductive and capacitive components can cause oscillation, attenuation or overshoot of the output at a limiting frequency.

(2) Loss of core permeability at high frequency can make the instrument over-sensitive to magnetic pick up.

(3) The stray inductance, L_B associated with resistor $R_{B,}$ can cause distortion of the output signal. For high pulse currents, a low-sensitivity and high I-t capability are required. These attributes are achieved in part by selecting a low value for R_B. L_B tends to have a constant value for a particular resistor design and its inductive reactance can limit hf performance as its value approaches that of R_B. Ironically, the employment of multiple stages in internally-terminated transformers tends to exacerbate the problem as effectively the total value of R_B has to be achieved by the series connection of several discrete resistors each with its associated L_B. The cascade arrangement illustrated later in this paper can mitigate this limitation.

MAGNETIC PROPERTIES OF SOME STRIP-WOUND MATERIALS

The lowest-cost core material suited for pulse transformer core manufacture is grain orientated silicon steel. Its cost makes its use attractive where a large volume of core material is required. Other materials that are used include Ni-Fe alloys and modern materials such as nanocrystalline iron alloys. The latter material is somewhat more expensive than the former though its magnetic properties can often justify the price differential. In Figs 3 and 4 curves illustrating two important magnetic properties of these materials with regard to their use in wideband current transformers are illustrated. The curves are for M4 grade GOS, the Ni-Fe alloy mumetal and a high-permeability nanocrystalline material.

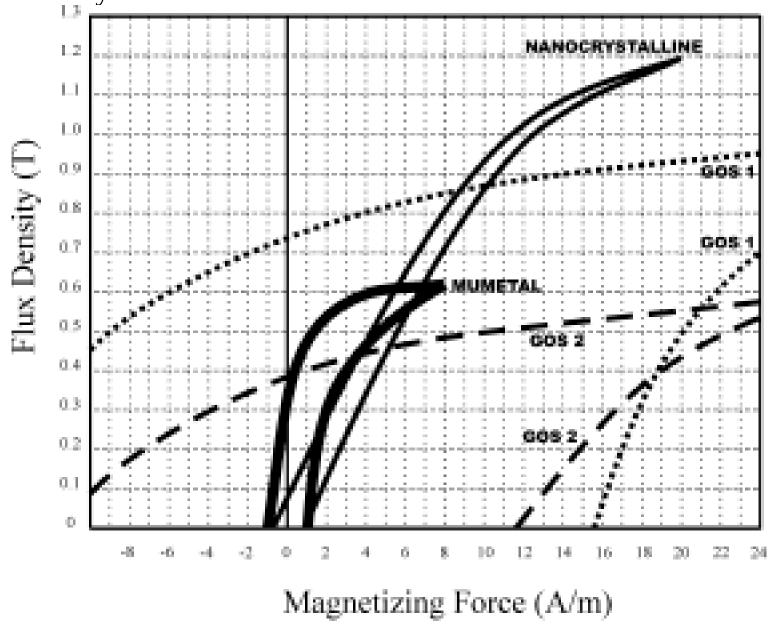

Fig.3 B-H loops for some core materials

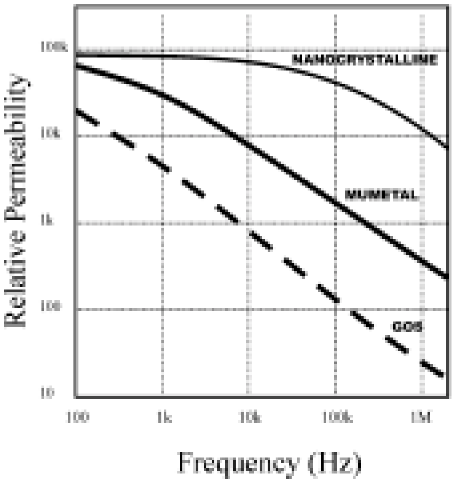

Fig 4 Permeability against frequency

When a ct experiences a primary current pulse there is a tendency for the core to remain magnetised to some extent, a property referred to a remanence. Fig. 3 illustrates this effect. The flux density, B, present in the core once the magnetising force, H, is reduced to zero is a measure of remanence. A high remanence has the effect of temporarily reducing a transformer's I-t capability with successive pulses until eventually a limiting value is reached. It can be seen from Fig 3 that GOS material suffers greatly from this effect, the effect is also noticeable in mumetal but in the nanocrystalline material the effect can be ignored for many practical purposes. The remanent flux density in a core can be reduced to zero or set at a negative value by applying a compensating pulse to the core after the signal of interest has passed. A similar effect can be achieved by the application of an appropriate dc reverse bias current via an auxiliary winding The level of this should be sufficient to reset the core but not so great as to put the core into near reverse saturation.

Application of a resetting pulse can be practical in production equipment where the advantages of lower-cost materials can be exploited. It is less attractive for general laboratory use.

In Fig. 4 the effect of frequency on core permeability is illustrated. Reduction in permeability with frequency reduces L in Figs 1 and 2. This reduced inductance is not of itself a problem as increasing frequency increases the reactance of L to more than compensate for this effect. Low permeability at high frequency, however, greatly increases the flux leakage in the cores. The limitation is most apparent in cores of large diameter. At low frequency the output of a transformer will be found to be independent of the position of the primary conductor. As frequency is increased the position of the primary inductor starts to have an effect on the recorded current waveform. It is this loss of permeability with frequency that effectively limits the use of GOS material. In large transformers that contain distributed windings, sensitivity to stray magnetic fields and primary conductor position can limit performance rather than the effects of parasitic inductance and capacitance. To a lesser extent the effect can also be seen in ct's that utilise cores containing nanocrystalline materials.

PULSE PERFORMANCE OF TWO PULSE TRANSFORMERS EMPLOYING GOS CORES

In Table 1 the performance of two large diameter current transformers is illustrated. These ct's were manufactured with cores made from GOS material. The instruments were terminated externally with an effective value of R_B of 25R. The high-frequency cut-off value was somewhat arbitrarily determined. In both units A and B it was the frequency at which the positioning of the primary conductor at any point within the central aperture of the toroid caused a 3dB deviation in output from the true reading. The lf cut-off value was the frequency at which the output was 3dB down on the true value. I-t capability with no reset was recorded after the application of several successive 1000A pulses. Reset was achieved by following each pulse with the momentarily application of a 12AT pulse to an auxiliary reset winding.

Table 1
Performance of two externally terminated ct's with GOS cores

Trans-former	Inner Diameter	Afe	Ratio	Sensitivity	Lf cut-off	Hf cut-off	I-t Reset	I-t No reset
	cm	cm^2		V/A	Hz	kHz	As	As
A	13	1.3	3000:1	0.00833	0.2	100	17.4	4.5
B	6	2.7	500:1	0.05	6.0	500	6.0	0.67

The results illustrate that low-cost GOS cores with simple termination can be used to monitor pulse currents where frequency components measured in tens of kilohertz are present. The application of a reset pulse compensates for the material's high remanence. The lf and I-t capabilities of the test pieces could be extended by reducing the value of effective R_B as indicated in Eqs. (1) and (3) with an accompanying reduction in sensitivity.

Internally-terminated transformers of similar size would have greater bandwidth with the upper frequency cut-off point being extended to several megahertz.. I-t capability would be similar to that achieved with the application of a reset pulse, although with a nanocrystalline core the use of a reset pulse would not be necessary.

MEASUREMENT OF HIGH PULSE CURRENTS WITH CASCADED TRANSFORMERS

In some applications it is necessary to monitor current with an instrument that combines a bandwidth that extends well into the megahertz region with an ability to monitor pulses measured in tens of kiloamps. A core with good high-frequency permeability is required and distributed internal termination. A high transformation ratio is attractive, as, in addition to enhancing I-t capability, Eq. (3), it would reduce the current in the measurement resistors R_B. However, a large number of turns dictates that a high number of series-connected stages would be required to satisfy the frequency response demand thus increasing production costs. The number of stages also reduces the resistance value of the individual sense resistors that form R_B so increasing the effect of parasitic inductance L_B in Fig. 2. Under these circumstances there can be some merit in using two cascaded transformers [4] as illustrated in Fig. 5.

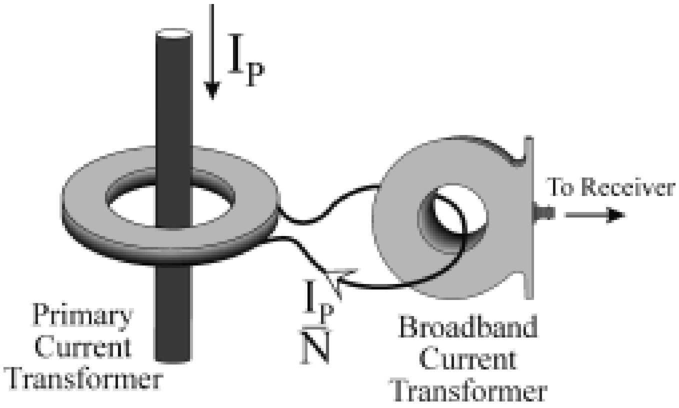

Fig. 5

In this arrangement a relatively simple transformer construction is used to reduce the effective magnitude of primary current whilst preserving its waveshape. This attenuated signal is fed into a standard internally-terminated broadband current transformer for monitoring. It is unlikely that a ratio in excess of 100:1 will be required for the first transformer. The I-t capability of the unit is upheld by ensuring the value of $R_W + R_B$ in Eq. (3) is kept low. R_W is reduced by the appropriate choice of wire and R_B is eliminated. The value of L and its associated low-frequency characteristics are less good than if the system transformation ratio were to be achieved in a single unit although the high-frequency performance is likely to be much better. In this arrangement, low-frequency performance is effectively traded for improved high frequency response.

CONCLUSION

1. The high-frequency performance of broadband current transformers can be limited either by internal parasitic components or the hf permeability of the core material.
2. Cores manufactured from nanocrystalline material can be employed in instruments requiring maximum bandwidth and I-t capability without recourse to reset pulses.
3. Low-cost GOS material core material can be employed in the manufacture of current transformers with bandwidths to several hundred kilohertz.
4. Cascading of transformers can be considered where both high-frequency response is required and high pulse currents are to be measured.

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