THE HYDRO-ELECTRIC POWER COMMISSION OF ONTARIO
RESEARCH DIVISION REPORT

To Mr. J.H. Waghorne
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SATURATION CONTROL IN RELAYING CURRENT TRANSFORMERS

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The loss of output from current transformers, operating under fault conditions, may be due to saturation caused by transients, residual magnetism or stray flux. The loss of output may result in a delay of operation of protective relays or indeed in the maloperation of protective relays. Current transformers with high accuracy ratings, air gaps and shield windings are suggested as solutions to overcoming saturation and the loss of output.

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Introduction

When a relaying current transformer saturates in service, the performance of the associated protection scheme can be affected because of the false current transformer output. The causes of current transformer saturation under system fault conditions are presented below, and means of preventing or controlling saturation are discussed.

A previous paper/2/ revealed that current transformer saturation can cause undesirable delays in the performance of line relaying, for example. Possibly some of the unexplained relay maloperations could be due to current transformer saturation. For these reasons, the control of current transformer saturation merits consideration. The saturation may be due to any one or combination of (a) offset fault currents, (b) stray magnetic fields, and (c) remanent flux in the current transformer core. Saturation can be controlled by the use of higher accuracy ratings, air gaps in the core, and shield windings on the core.

For the purpose of this paper the current transformer can be considered as a null-balancing system where the primary ampere turns on a core are equal and opposite to the secondary ampere turns plus any losses. The motive force in this system is magnetic flux. As long as the flux density in the core is below the saturation flux density the losses are small and the output is therefore very nearly equal to the input. When the flux density in the core approaches the saturation flux density where the losses are high, the output is not equal to the input.

Loss of Output During Transient Fault Conditions

Consider a circuit composed of a current transformer, loaded with resistive burden as shown in Figure 1. Under steady state conditions the current in the secondary circuit, the voltage developed in the secondary winding, and the flux in the core are represented by the waveforms in Figure 2. The peak values of each of these waveforms are 1.0 per unit. Under all other than steady state conditions, the flux requirements of the core are always higher than the steady state requirements. Thus shown in Figure 3 are the waveforms of the same three variables for a starting condition where the current follows the cosine function. Under this condition the peak flux requirement is twice that for the steady state condition, or 2 per unit.

Under transient fault conditions the flux requirement increases rapidly. Shown in Figure 4 is a current of 1.0 per unit peak amplitude with a 1.0 per unit exponential transient having a time constant of 0.04 seconds. The flux required of the transformer to reproduce this current climbs rapidly until it reaches a value of approximately 16 pu.

Let us now examine the output of a current transformer for the three cases of primary current illustrated in Figures 2, 3 and 4. Shown plotted in Figure 5 are the input and output current waveforms of a current transformer having a knee-point flux of 1.0 per unit. The output current waveforms clearly indicate the loss of output due to magnetizing losses when the flux enters the low permeability, or saturated region.

Loss of Output Due to Remanent Flux

Remanent flux can be set up in the core of a current transformer under operating or test conditions. Under operating conditions remanent flux can be left in the core when the primary current is interrupted while the flux density in the core of the transformer is high. This usually occurs when clearing fault currents. Test conditions where direct current is applied to the secondary winding, as in resistance or continuity measurements, will also leave almost maximum possible remanence.

Once remanent flux is set up in a core it is very difficult to remove. It can be shown that a voltage in the order of 60 per cent of saturation voltage must be applied to reduce the remanent flux to less than 10 per cent of saturation flux. Such high voltages are not induced in the windings of a current transformer under normal operating conditions, and the remanent flux, therefore, stays in the core until the next occurrence of fault current or transient condition.

To substantiate the fact that remanence persists a survey was conducted on 141 transformers in service. The survey revealed that indeed large remanence can be present in a large percentage of current transformers. The results of the survey appear in Table I below.

TABLE I

Remanent Flux (per cent of Saturation Flux)	Per Cent of Transformers
0 - 20	39
20 - 40	18
40 - 60	16
60 - 80	27
80 - 100	0
	100

Remanent flux in a current transformer core affects the burden and current capabilities of that transformer. The important case to be considered is when the capability of the transformer is reduced. Shown in Figure 6 is the input and output current waveforms for a current transformer with 0, 50 per cent, and 75 per cent remanence. The input current has a 1.0 per unit peak amplitude and an exponential transient of an 0.04 second time constant. The transformer has a flux capability of 16.0 per unit and is loaded with a resistive burden of 1.0 per unit. The loss of output due to remanent flux can be seen in Figure 6. Figure 7 represents the same curves, but for a transformer with a flux capability of only 8.0 per unit. This is a more realistic representation of conditions presently prevailing in the industry.

Loss of Output due to Stray Flux

Under many circumstances the core of the current transformer is subjected to magnetic fields other than due to the current in the conductor that is to be measured. These stray magnetic fields are mostly due to the current in the return conductor or the current in conductors of adjacent phases of an installation. The stray flux in the transformer core that is due to the stray magnetic field will add to the working flux. Due to the addition of these fluxes the saturation density is reached faster, resulting in an early loss of output.

Figure 8 shows a current transformer located on a hair-pin primary conductor. This transformer is subjected to the stray magnetic field of the return conductor. The stray flux in the core depends on many factors which include the current, the width of the hair-pin - D, and the geometry of the core - r, R, and W. Pfuntner/1/ in his paper presented equations that make the calculation of flux due to the return possible. Assuming values for the various dimensions as shown in Figure 8, and using Pfuntner's equations one can calculate the stray flux to be approximately 0.03 volts (rms) per turn per thousand amperes in the conductor. Assuming a core of two square inches with a saturation flux of 0.6 volts (rms) per turn at 60 Hz, it will become saturated when the current in the hair-pin reaches 20,000 amperes. If Figure 8 represents a 230 kv, 1200 to 5 ampere, relaying current transformer, one may assume that at 20 times rated current (24,000 amperes) the core of the transformer will be saturated by the stray flux due to the current in the return conductor. There will be a premature loss of output from the transformer under such circumstances.

Consequences due to Loss of Output

Loss of current transformer output may cause a delay or a maloperation of protective relays. The delay is usually associated with overcurrent and with line relays. It depends on the time the transformer requires to revert to the unsaturated operating condition, and may last many cycles. In the past, slow clearing times for line faults have been attributed to many different causes but seldom to the delay of relay operation caused by saturation of current transformers. The assurance of fast clearing times by eliminating delays in relay operation, gives stability to a power system.

A more serious consequence of current transformer saturation and the associated loss of output is the possibility of differential relay operation for faults outside of their zone of protection. This type of maloperation has been known to occur when current transformers of different accuracy ratings are used in a differential circuit. Remanence in one transformer of a differential scheme has the same effect as different accuracy ratings and therefore may cause more than sufficient unbalance to operate differential relays.

Improving Transient Performance

The most obvious solutions to guard against the loss of output under transient fault conditions are a larger transformer, a larger ratio or a combination of the two. Thus one could obtain a transformer having the core cross-section increased 16 times to handle the transient current waveform shown in Figure 4. This oversized transformer would reproduce the primary waveform without distortion as shown in Figure 6 curve A. Another solution may be to use a ratio that is four times as large as the original. Assuming that the internal and external burdens remain the same, this current transformer will also reproduce the current of Figure 4 without distortion.

The method of improving transient performance by increasing size and ratio of transformer may not be too practical for situations where the system time constants are large. To cope with transients in situations where the time constant is 0.1 seconds, the transformers have to be about 40 times as large as transformers designed to cope with fault currents on the steady state basis. Such a transformer may be too large to accommodate.

A not so obvious solution to guard against saturation under transient fault conditions is to reduce the time constant of the secondary circuit of the current transformer by inserting air gaps in the magnetic circuit. The time constant of the secondary circuit is defined as the inductance of the circuit, with the primary open circuited, divided by the resistance of the circuit. By inserting air gaps in the magnetic circuit of the transformer, the inductance and therefore the time constant are reduced. A short time constant has the effect of depressing the flux requirement of the transformer, and acts opposite to the increase in the flux requirement needed to cope with the time constants of the transients.

This phenomena is represented by the family of curves in Figure 9 which shows the flux requirement for the current of Figure 4 and computed for various time constants of the secondary circuit. The reduction in the flux requirement can be easily seen in Figure 9, as the time constant, that is the inductance of the current transformer, is reduced. There is a practical low limit to the current transformer inductance that can be tolerated since the errors of the current transformer climb rapidly as the inductance is reduced. Figure 10 shows the relationship between the secondary time constant of a current transformer and its composite error under steady state conditions. Under transient conditions the percentage error is always larger than shown in Figure 10.

Figure 11 shows the input and output curves for a current transformer that has a 8.0 per unit flux capability, and a secondary circuit time constant of 0.08 seconds. Figure 11 shows that although saturation does not occur, there is a distortion present that is due to the short time constant of the secondary circuit of the current transformer.

The advantage of a current transformer with a short time constant is that it guards against saturation without making the transformer very large. The distortion this type of transformer introduces may not affect the operation of overcurrent or line relays. The disadvantage is that these transformers should not be used together with conventional current transformers in differential schemes.

Reducing Remanence

The most effective means of reducing remanence is by inserting a small air gap in the magnetic circuit of the transformer. To reduce the maximum possible remanence to less than 10 per cent, an air gap of only 0.0001 inches per inch of circumference is required. This size of the air gap, say 5 to 10 mils for a 230 kv current transformer, will increase the magnetizing current by only a small factor and will therefore not significantly influence other parameters of the transformer.

Under special circumstances, where this increase in magnetizing current cannot be tolerated a special bias arrangement can be used. A diagram of a biased core current transformer appears in Figure 12. In this arrangement the core is divided into two equal halves, with a bias winding applied in opposite directions on each half. A small power supply is used to supply direct biasing current through a choke, and biases one core to about +75 per cent and the other core to -75 per cent flux. Except for the flux resetting action of the bias windings, this arrangement operates in the same manner as an ordinary current transformer.

Reducing Flux Due to Stray Fields

There are two methods available for reducing stray flux. The first method of shielding consists of creating an approximately equal and opposite field to the stray field. This is accomplished with the aid of a short circuited winding placed around the transformer core. The stray flux that enters the transformer core induces a voltage and therefore a circulating current in the shorted winding. This circulating current causes a flux in the core that is opposite to the stray flux, thus reducing the stray flux. This short circuited winding must be applied in such a way that it does not represent a shorted winding to the primary and the current that is to be measured. Shown in Figure 13 is a transformer with a shield winding. As can be seen the shield winding consists of a large number of sections, each with the same number of turns, all paralleled together on a common buss. As long as the number of turns in each section is the same, the shield winding does not represent a shorted path for the primary ampere turns. One can also visualize this type of shield as a hollow toroidal case made of conductive material and with the core located inside.

The effectiveness and efficiency of the shield depends primarily on the impedance of the shield winding. As the impedance is reduced the shield becomes more effective and more efficient. Approximate formulas for designing a shield of this type can be found in "Shielding Electrical Apparatus from Stray Flux" by S. Seeley (Electrical Review, September 1964).

Figure 14 shows the performance of a toroidal current transformer with and without a shield. As can be seen there is a ten fold improvement in the dynamic range of the transformer, all due to the shield.

The second method consists of shielding the current transformer from stray magnetic flux with magnetic material. This method is seldom used because it adds to the weight and bulk of an installation.

Conclusions

The conventional relaying current transformers have some serious shortcomings with respect to the reproduction of transients, residual magnetism and the influence of stray magnetic fields. All of these problems can be cured if good performance is necessary and the physical size and cost is not too important. The important thing is to realize that relaying current transformers that are required to perform properly under transient fault conditions must have much more capability than the size of the burden, the magnitude of the fault current and their ratio would dictate.

References

1. R.A. Pfuntner, The Accuracy of Current Transformers Adjacent to High-Current Busses. Trans. AIEE, Vol 70 1951, p 1656.

2. Hans Bay, Walter Hamala, Johannes H. Noeller and Rudolf Zahorka, "The Response of Current Transformers and Protective Distance Relays to Short-Circuit Currents with a Direct-Current Component", ETZ-A, Vol 88, No 5, March 3, 1967.

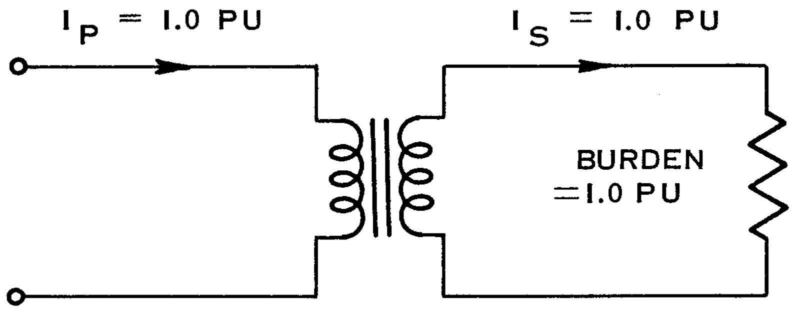


FIGURE I

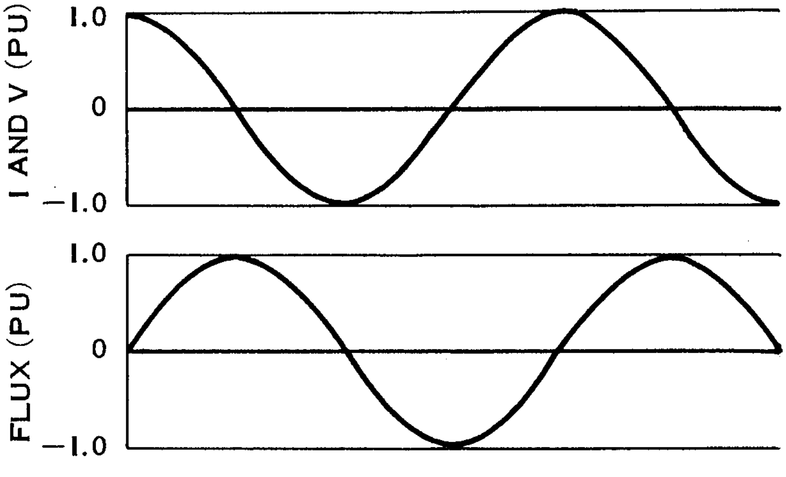


FIGURE 2

CURRENT, VOLTAGE AND FLUX IN A CURRENT TRANSFORMER

STEADY STATE CONDITIONS

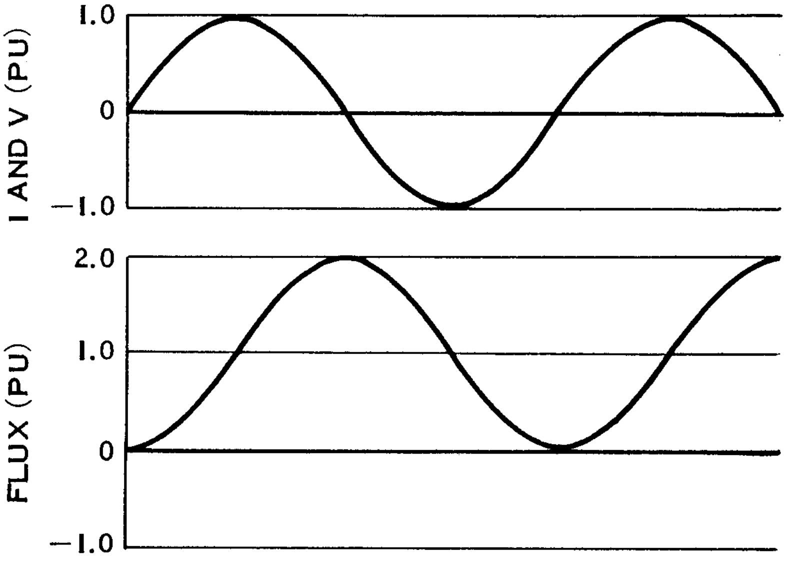


FIGURE 3

CURRENT, VOLTAGE AND FLUX IN A CURRENT TRANSFORMER
STARTING CONDITIONS

122008—RD

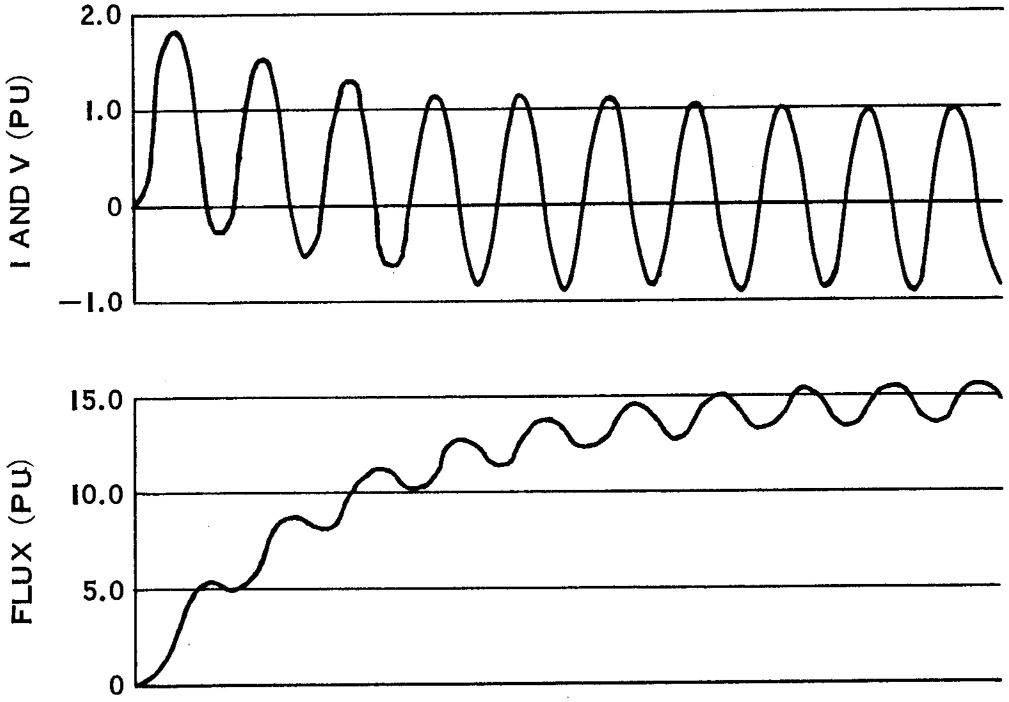


FIGURE 4

CURRENT, VOLTAGE AND FLUX IN A CURRENT TRANSFORMER
TRANSIENT CONDITIONS

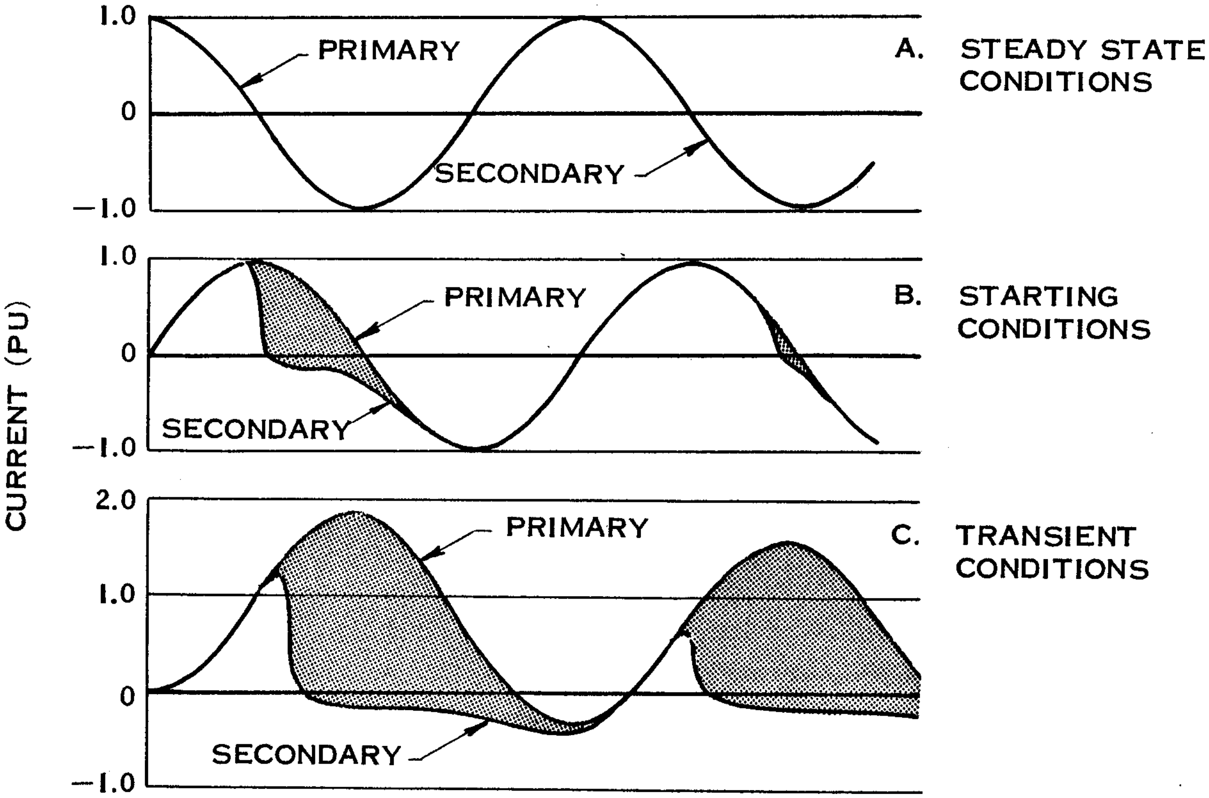


FIGURE 5

INPUT AND OUTPUT WAVEFORMS FOR A CURRENT TRANSFORMER
CURRENT = 1.0 PU; BURDEN = 1.0 PU; FLUX = 1.0 PU

122009—R

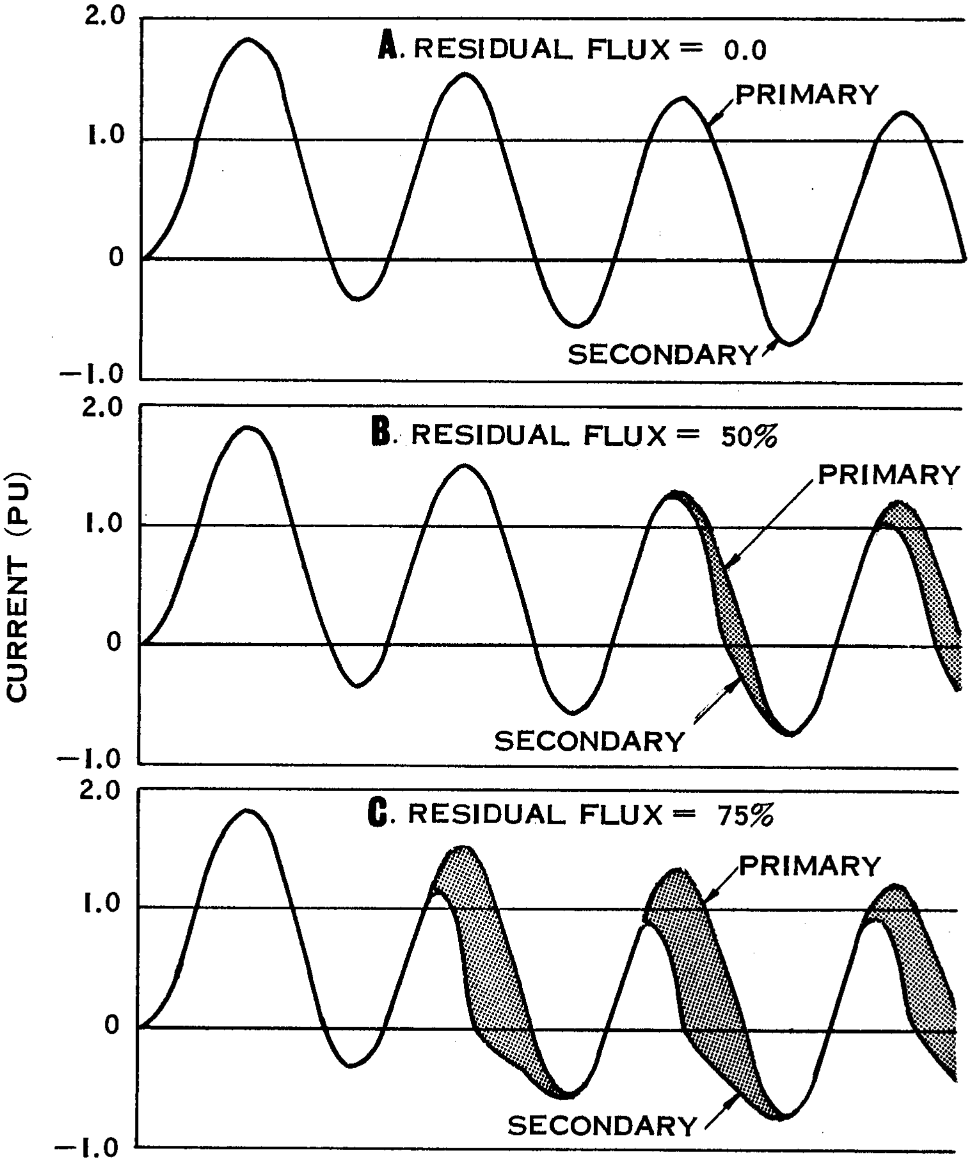


FIGURE 6

INPUT AND OUTPUT WAVEFORMS FOR A CURRENT TRANSFORMER OPERATING UNDER TRANSIENT CONDITIONS AND RESIDUAL FLUX

CURRENT = 1.0 PU; BURDEN = 1.0 PU; FLUX = 16.0 PU; TRANSIENT T.C. = 0.04 S

122010—RD

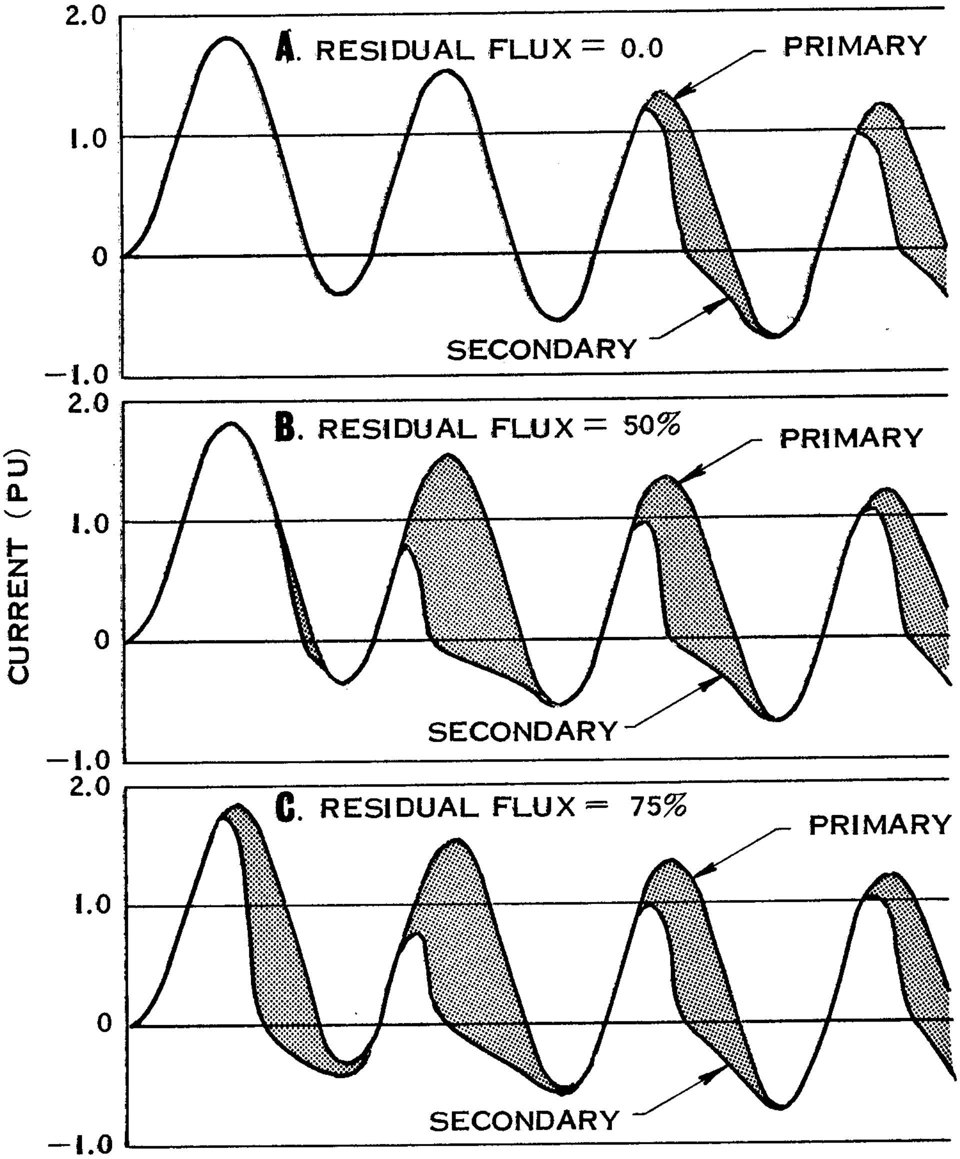


FIGURE 7

INPUT AND OUTPUT WAVEFORMS FOR A CURRENT TRANSFORMER OPERATING UNDER TRANSIENT CONDITIONS AND RESIDUAL FLUX

CURRENT = 1.0 PU; BURDEN = 1.0 PU; FLUX = 8.0 PU;
TRANSIENT T.C. = 0.04 S

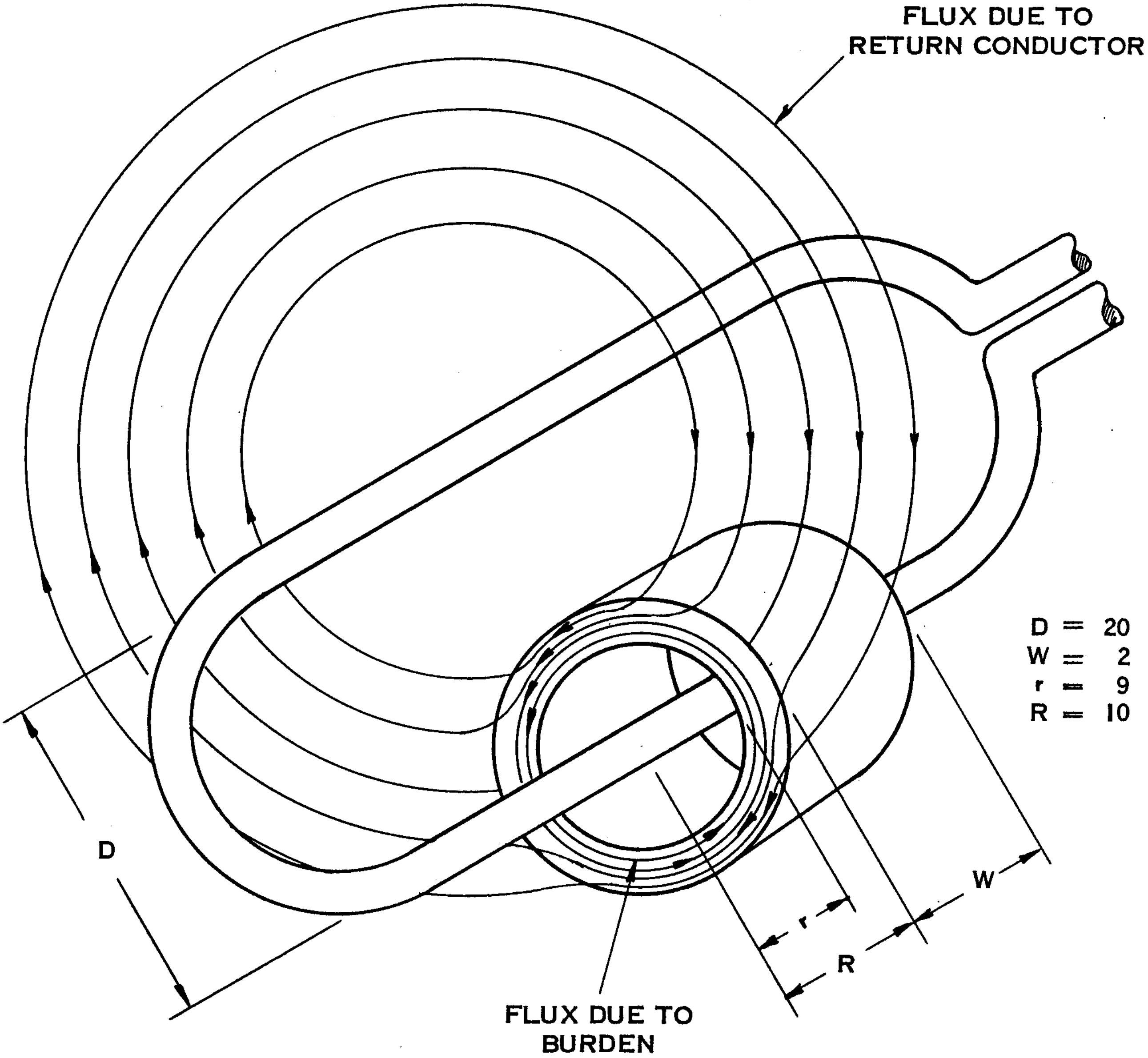


FIGURE 8

STRAY FLUX DUE TO CURRENT IN THE RETURN CONDUCTOR

122012—RD

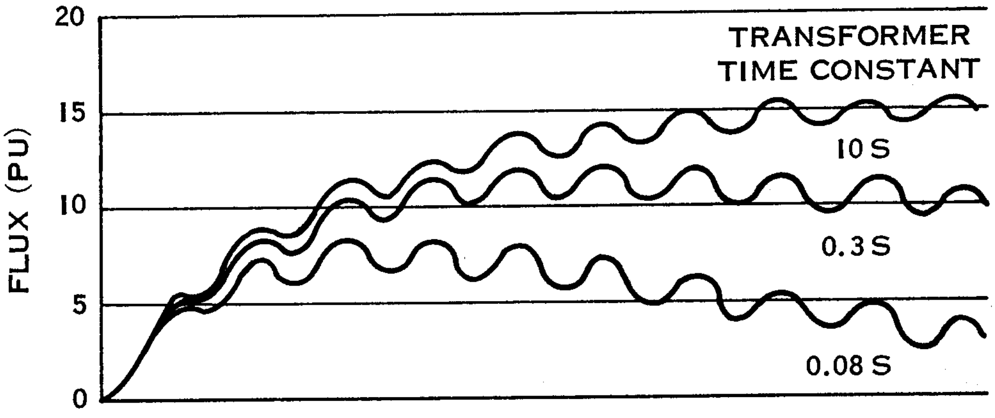


FIGURE 9

FLUX REQUIREMENT FOR CURRENT TRANSFORMERS WITH DIFFERENT TIME CONSTANTS

TRANSIENT TIME CONSTANT = 0.04 SECOND

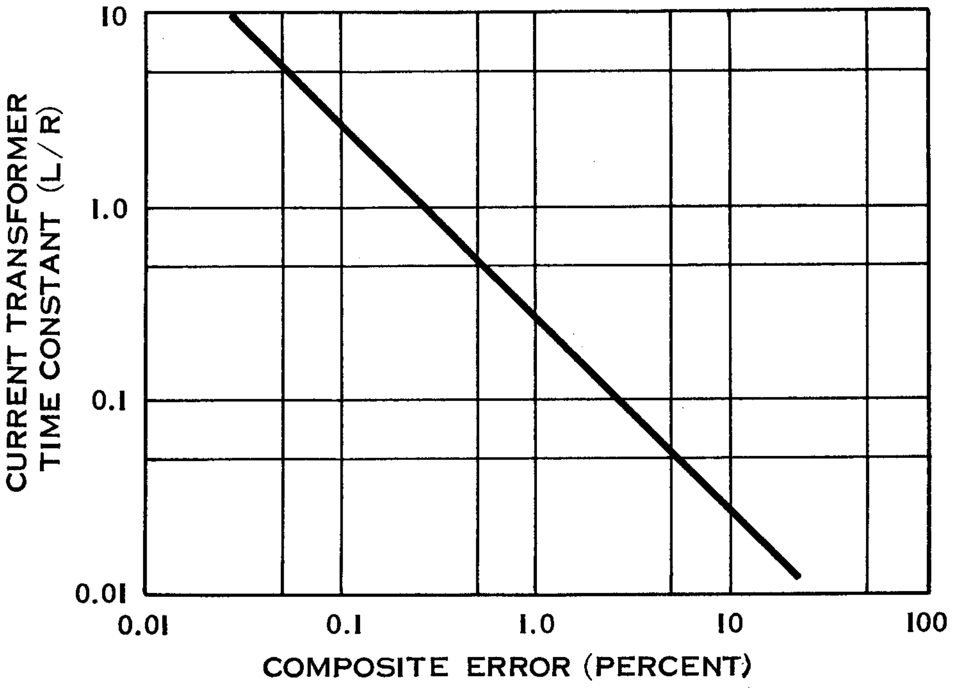


FIGURE 10

COMPOSITE ERROR AS A FUNCTION OF CURRENT TRANSFORMER TIME CONSTANT

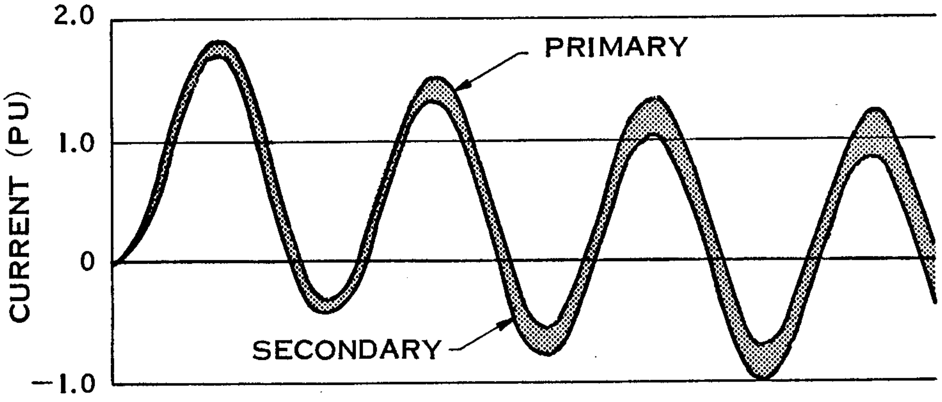


FIGURE 11

INPUT AND OUTPUT WAVEFORMS FOR A CURRENT TRANSFORMER WITH A SHORT TIME CONSTANT

CURRENT = 1.0 PU; BURDEN = 1.0 PU; FLUX = 8.0 PU,

TRANSIENT T.C. = 0.04 S; TRANSFORMER T.C. = 0.08 S

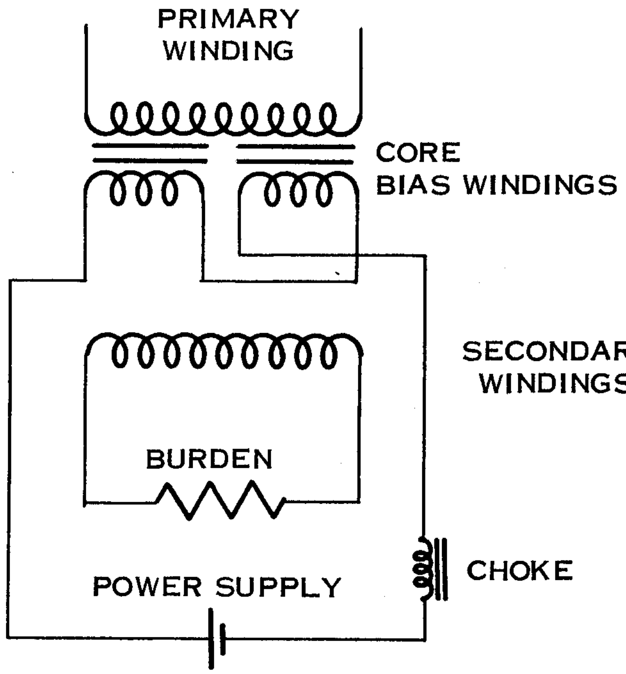
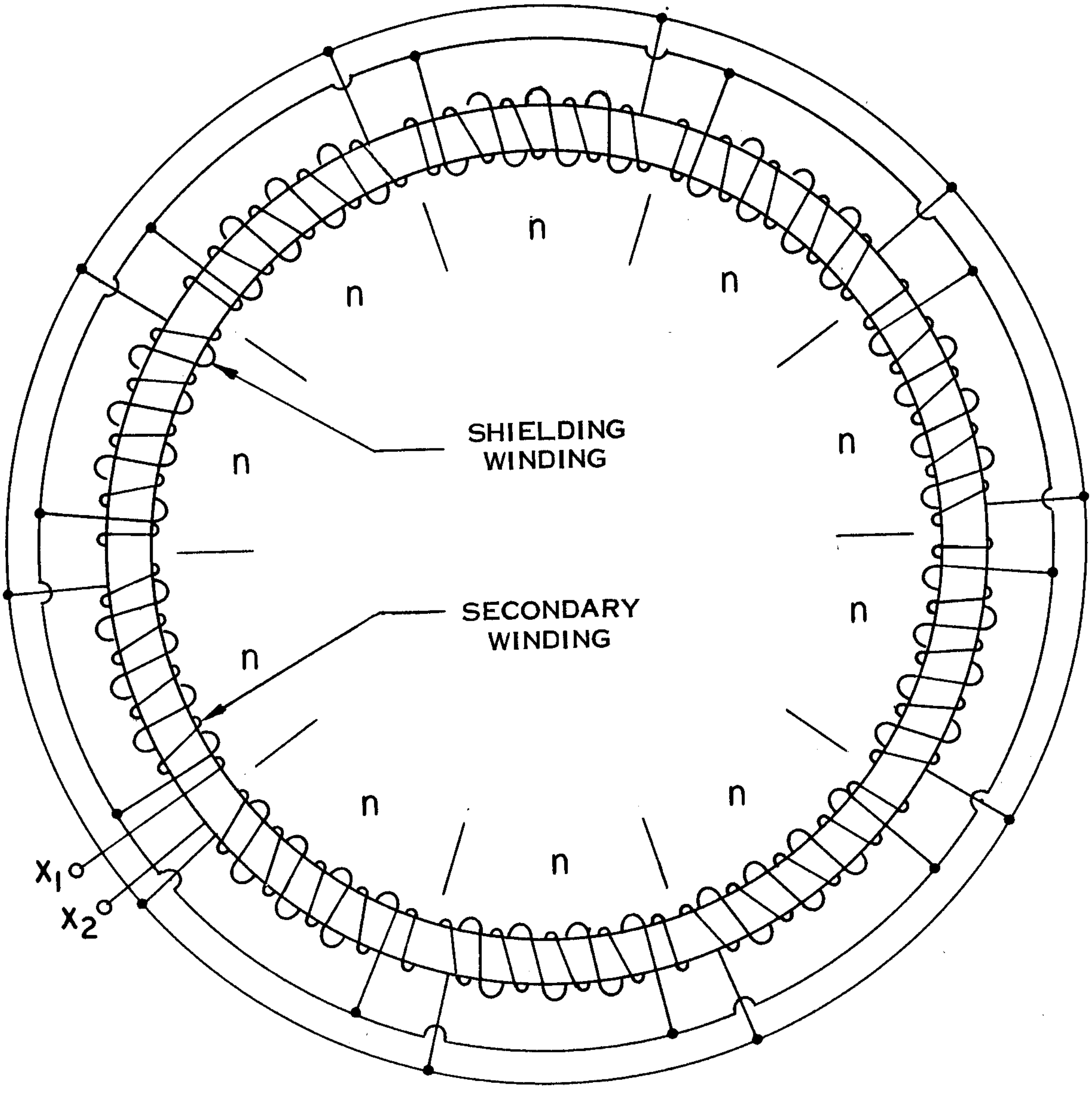


FIGURE 12

DIAGRAM OF A BIASED CORE CURRENT TRANSFORMER



N = 49 TURNS OF NO 10 COPPER WIRE

FIGURE 13

DIAGRAM OF A CURRENT TRANSFORMER WITH A SHIELD WINDING

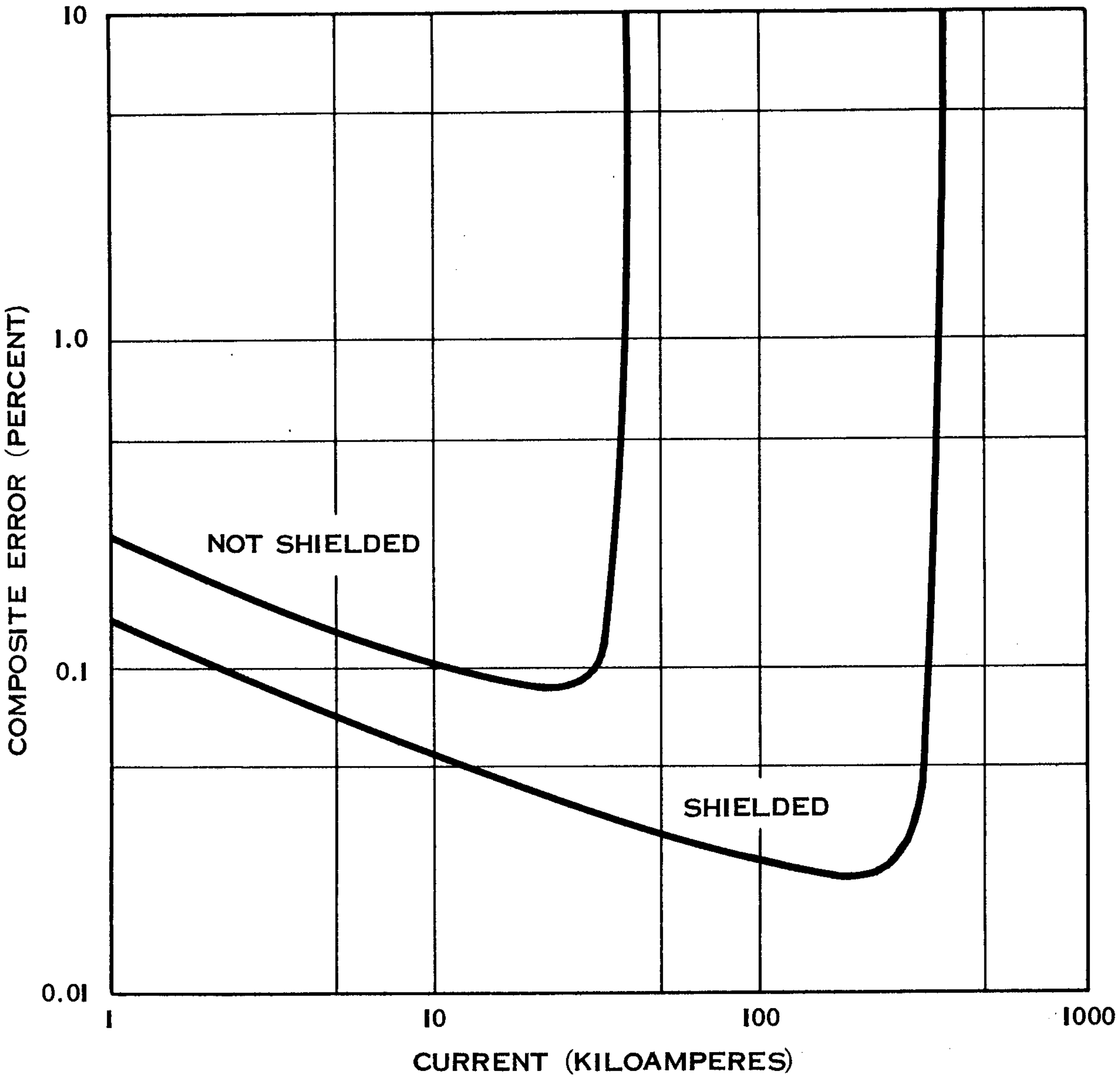


FIGURE 14

PERFORMANCE OF SHIELDED AND NOT SHIELDED TOROIDAL CURRENT TRANSFORMER