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DESIGN FUNDAMENTALS OF CURRENT TRANSDUCTORS FOR LARGE DC CURRENTS *

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Introduction

The efficacy of the transductor as a magnetically isolated, wide bandwidth, large signal means of measuring direct currents is well known and documented, but the basic operating principal is not. The alternating current transformer is accepted as a current-driven, volt-second constrained device with wide bandwidth. The direct current transductor has the same basis of operation, with the addition of an alternating voltage constraint in the secondary. This paper will describe transductors from the current driven point of view, starting with the basic single core device and developing the multi-core units from it. A new Feedback-Transductor will then be described.

Single Core Transductor

The basic transductor which must be thoroughly appreciated is the single transformer device as shown in Figure 1. First assume that the source of alternating voltage is reduced to zero volts, and that the core was previously set to saturation at one end of the B-H loop. If the direct current source is now applied to the primary winding in the sense to drive the core out of saturation, the primary and secondary windings will now be coupled together by the changing flux in the core. Assuming equal turns, a secondary current will flow which is equal to the primary current minus the magnetizing current until the core saturates at the opposite end of the B-H loop. The rate of change of flux in the core, and therefore the time it takes to reach opposite saturation, is by Faraday's Law equal to the voltage seen by the core. The core voltage is here constrained to be the magnitude of the current source times the resistive drop in the secondary circuit. As an example of the kind of time involved in the $-B_s$ to $+B_s$ excursion, solve the integral form of Faraday's Law with some possible core and winding parameters:

$$e_{core}\, t = 2B_{sat} A_{core} N 10^{-8},$$

Where B_{sat} = 16,000 gauss, n = 200 turns (#20 AWG)

$e_{core} = IR_{secondary} = 1$ volt, $A_{core} = 1.25$ cm^2,

therefore t = 80 ms.

During this period of time before saturation the secondary current faithfully reproduces the primary current with a bandwidth from dc to hundreds of kilohertz (wherever the distributed inductance and capacitance of the transformer resonate). The magnetizing current will typically be from 0.1 to 1% of the maximum secondary current depending on the type of core material used. It should be emphasized again that the transductor described is driven from a current source.

If the alternating voltage source shown in Fig. 1 is now increased from zero to an appropriate magnitude, with the direct current source still applied to the saturated core, the core will be driven out of saturation during the half-cycle when the source polarity is as shown. When the secondary current rises to become equal to the primary current, the core unsaturates, and the voltage applied to the core is the difference between the source voltage and the IR drop. The first half-cycle of Fig. 2 shows this condition for a square-wave voltage source. The core is driven out of saturation to some flux determined by the volt-seconds applied during this half-cycle. On the next half-cycle with the reverse polarity source, the two voltages add and the core again saturates at the time when the volt-seconds equal those applied during the previous half-cycle. Every subsequent cycle will now repeat because this is the steady-state condition for a given value of direct current, i.e., where the volt-seconds are equal on every half-cycle and therefore the flux excursion repeats cycle-to-cycle. The addiition of the alternating source has made possible many repeated periods when there is coupling between primary and secondary through the changing flux just as there was for one time only in the case where the alternating source was zero. And when there is coupling the current in the primary is faithfully reproduced in the secondary. But it must be emphasized that the role of the alternating supply is as a means of determining the voltage applied to the core, and not as a source of power as such. Note that with direct current flowing in the secondary while there is coupling, power flows both ways in the source.

After the core saturates a current equal to the source voltage divided by the secondary circuit resistance flows. For monitoring applications a diode is added in series to the circuit to cut-off the current after the core saturates. Here again the current-driven aspect of the circuit is revealed, because as long as the core is unsaturated, the diode remains conducting, power being inverted back into the alternating source, rather than the diode blocking at the beginning of the negative half-cycle.

To complete the transductor description for a single core let us use the same parameters employed in the first example for the case of a 60 Hz square-wave source. A supply voltage of 10 volts will drive the core from positive to negative saturation in 8 ms. With a winding resistance of approximately 1.0 ohms for a 3-in. window-diameter core, a 9 ohm load resistor would give a total secondary drop of 10 volts at 1 amp. This is the limiting voltage because at this maximum value of current the IR drop cancels out the supply voltage on one half-cycle, and therefore no flux excursion occurs.

Before discussing transductors with multiple transformers in series or parallel arrangements, which solve the obvious failing of the single transformer in not providing coupling at all times, it is important to discuss core characteristics and their effect on linearity, voltage and temperature sensitivity, and range.

Core Characteristics

The preceding analysis of the single core transductor was done assuming an "ideal transformer" characteristic, with only passing reference made to the fact that the secondary current differed from the reflected primary current by the core exciting current. The transformer is characterized by the proper application of Ampere's and Faraday's Laws as follows:

$$\oint_{\ell c} \bar{H} \cdot \overline{d\ell} = \sum_{j=1}^{n} N_j \bar{I}_j \,, \quad \oint \bar{E} \cdot \overline{ds} = -\frac{\partial}{\partial t} \int \bar{B} \cdot \overline{dA}$$

$$\Rightarrow e_j = -N_j \frac{d\Phi}{dt} \,, \quad j = 1 \text{ to } n.$$

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For the two winding case, assuming that the exciting current is zero, the governing equations are then:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}, \quad \frac{i_1}{i_2} = \frac{N_2}{N_1}.$$

The product indicates that the net power into the ideal transformer is zero, as it should be.

With the continual improvements in core materials over the last 30 years the "ideal transformer" approximation is far more valid today than every before. Materials available today have magnetizing forces at 60 Hz that range from electrical silicon steels at 1 to 10 oersteds, down to 50% nickel-iron alloys like Deltamax at 0.2 oersted, on down to the 80% nickel-iron alloy, Supermalloy, at 0.005 oersted. (Supermalloy has a B_S of less than half the 16 kG of Deltamax, however, which means proportionately more core cross-section for a given voltage.)

In order to clarify how the "core function" enters into the transductor operation, let us insert a generalized equivalent circuit into the single core diagram as redrawn in Fig. 3. The equation of the exciting current, i_m, as a function of the core voltage is

$$i_m = I_{co} \text{ sign } e + Ge + \Gamma \int e dt \quad (1),$$

for the B-H loops shown in Fig. 4, when the core is unsaturated. When the core saturates and the core voltage collapses the switch closes. The equation separates the magnetizing current into its three dominant components: the static I_{co}, shown as a current sink in Fig. 4; the dynamic loss term G which makes the current a function of the core voltage, and the inductive term traditionally used in circuit theory for coupled circuits, $\Gamma = \frac{1}{L}$.

The inductive term is associated with domain rotation of the ferromagnetic material, where increased magnetization requires increasing applied H. Removal of the applied field returns the magnetization to zero without any loss in the material. In the "soft" ferrous materials this term is more predominant. Without the inductive term the sides of the B-H loop are vertical and represent domain-wall motion. Wall motion once started in a uniform specimen with well-defined wall boundaries is maintained by a constant applied field. The "hard"nickel-iron alloys approximate this vertical characteristic, Deltamax being representative. This is a loss term to the circuit. The applied voltage determines the rate of domain wall motion through the material (which in turn determines the rate of change of flux), and faster motion produces greater losses and hence greater exciting current. Note that in presenting B-H loops in the literature the implication is that the increased width between the 60 and 400 Hz loop is due to the increased frequency, where in reality it is the increased voltage applied to the core to drive it from + to - saturation at 400 Hz that causes the change. This voltage sensitive term is one of the main causes of errors in high performance transductors.

Applying the core model to the single core transductor it is seen that with the alternating voltage reduced to zero the load current is always less than the current source by the exciting current. With voltage applied in the first half cycle of Fig. 2, the load current is the sum of the current source and the exciting current. On the second half cycle the core voltage is reversed and the exciting current is subtracted. Note that the core voltage magnitude is greater on the second half cycle and the exciting current will be correspondingly different.

The single core transductor makes a bipolar monitoring device approaching 0.01% when used in conjunction with a sample-and-hold circuit. The only constraint is that the transductor output can only be sampled at the zero crossing of the core voltage between the first and second half cycle of Fig. 2. At the time of the zero crossing the exciting current is very close to zero while moving from above to below the measured current, and with Supermalloy and greater than 1000 turns the exciting current is already less than 0.1% of the maximum current.

Multi-Core Transductors

The correct basis for comparison between the series and parallel connected multi-core circuits are shown in Fig. 5 and 6 (Waveshapes - Fig. 7 and 8). Both of these circuits provide an output current which is continuously coupled to the current bus with a superimposed magnetizing current cycling above and below the correct value.

The parallel connected circuit has two halves which are identical in their operation to the single core circuit already studied. The two halves drive a common output resistor with the result that during the time when one side is saturated and uncoupled the other side is doing the job. As a result the magnetizing current only dips below the reflected bus current for a short period at the transition from one half cycle to the next.

This parallel-connected circuit is identical to the Bridge Magnetic Amplifier circuit, except of course, that the transductor is driven from a current source rather than a voltage source. As the source impedance is raised from zero ohms, the mode sequence of operation transitions when $N^2 Z_c >> R_L$. The circuit goes from the time quantized operation of the mag-amp with its time-delayed, phased-back, average controlled output, to the continuously coupled mode of the transductor. It is also a transition from a device with power amplification and carrier-limited type bandwidth to one with no power gain but very wide bandwidth.

The Hingorani circuit[2] is the same basic device with a diagramatic interchange of diodes 1 and 2 with cores 1 and 2. Then only one resistor is added across the two diodes D1 and D2 to prevent saturation at zero primary current rather than 2 resistors as in Fig. 5. Additionally, a zener diode is placed in series with the load resistor to assure that with no primary current flowing the volt-seconds seen by a core will be less on the half-cycle when it is coupled to the load than on the half-cycle when it is not. By this means when the core goes slightly into saturation at the end of a half-cycle because of unbalanced volt-seconds, it will occur through the auxiliary resistors and not the load resistor R_L.

At first glance it does not appear that the three-core series circuit could be economically compared to the two core parallel circuit. Because of the series-opposed nature of the series circuit, only one core at a time is coupled to the primary. During the 180° coupled period the core is driven out of saturation down to some point on the active portion of the B-H loop and then back up into saturation with equal volt-seconds of the opposite polarity. The sine wave from $\pi/2$ to $3\pi/2$ supplies the varying polarity voltage, with maximum volt-seconds of a 1/4 period at zero current; whereas in the parallel circuit each core sees a full period sine wave, with a maximum volt-seconds of a 1/2

period. As a result the series circuit cores need only half the core-area of those of the parallel circuit, the decrease in cost covering the addition of the third core. As the direct current increases, the point of maximum flux excursion advances in time due to the addition and subtraction of the load voltage from the alternating supply voltage (the parallel circuit operates similarly as shown in their respective diagrams). But where in the parallel circuit the end points of a cycle of core operation move toward each other with increasing direct current (and ultimately determine the maximum range), in the series circuit each core must always couple for 180°, so the end point of a core cycle both advance along the sine wave.

A square wave of current flows through the series cores as they alternately couple and must be rectified with a corresponding loss of coupling during the transition from one polarity current to the other. Here the third core operates in exactly the same way as in the single-core transductor circuit with no alternating supply voltage in the circuit. It is connected directly across the load resistor through the bridge rectifier and the resistive and diode drops determine how far the core comes out of saturation before one of the series cores is again coupled and takes over operation. With the addition of 2 extra turns on the third core it is reset back into saturation during the first part of the next cycle of cores 1 and 2 operation. The added turns on core 3 cause it to be excited earlier than the upper two cores from the alternating source; after being reset to saturation its secondary current is determined by the current provided by one of the upper two cores.

The parallel transductor has received the most attention in recent literature through the careful work of Brentford Electric Limited[3,4]. There Mr. Michael G. J. Fry and his associates have taken the Hingorani circuit and with careful attention to detail have developed a package which is basically a 0.001% device over normal operating conditions. They have done an excellent job of providing a heater and temperature regulator to maintain the thermal environment, a constant voltage transformer with a frequency coefficient matched to each transductor, and,of course, a highly stable load resistor. Mr. Fry's most recent development work, reported on at the last Magnet Conference[4], senses the maximum flux excursion away from saturation in each of the cores by an integrator and sample-and-hold circuit; compares this with a reference and adds in a correction to the alternating supply voltage. Higher order harmonics in the supply voltage are also sensed and cancelled to reduce the current circulating through the inter-winding capacitance.

The series circuit described was developed at the Lawrence Berkeley Laboratory by Alfred Windsor 12 years ago[5]. The design also incorporates a fourth core coupled to the bus in the circuit shown in Fig. 9. This circuit replaces the load resistor of Fig. 6 and acts as a low-pass filter to frequencies contained in the current signal (coming from the three cores) because of the substantial self-inductance of the Supermalloy fourth core in series with the load resistor, and the shunt capacitor path. Thus both the real high frequency information and the unwanted magnetizing current waveshape are filtered out. But the coupled fourth core also acts as an alternating current transformer, with balanced direct current-turns on primary and secondary, and thereby restores the desired frequency information from the bus. The resistor in series with the capacitor is a compromise to achieve reasonable large-signal response without having the fourth core move into saturation transiently due to capacitor charging current, with the corresponding appearance of magnetizing current in the output. The resistor unfortunately also reduces the filtering action on the magnetizing current waveshape. Transductors of this type with a regulated supply voltage and no resistor in series with the capacitor are being used at 0.001% error in steady-state operation in regulated supplies at LASL.

Mr. Fry of Brentford has proposed an alternative to the filter scheme just described[4]. In the circuit three wide-band amplifiers are employed, one of some power capability to drive a winding on a third core coupled to the bus, with a signal from the transductor output resistor (containing the magnetizing components). A second amplifier senses the error compared to the bus current from a second winding, and drives a third winding to minimize the error. This driving signal is ac coupled into a summing amplifier along with the original output voltage for cancellation of the unwanted magnetizing component.

A major source of linearity and repeatability errors in both the described circuits is due to the sensitivity of the magnetizing current to the core voltage (which was described under core characteristics). Increasing direct current and resistive drop in the circuit causes an increasing difference to exist between the decreased voltage driving the core out of saturation and the increased voltage returning it to saturation. The magnetizing current during these periods varies accordingly. In the parallel circuit each core is coupled to the load during the half-cycle when the magnetizing current is added to the reflected current, except for a short period at the crossover between half-cycles. Therefore, there is a positive error which decreases with increased direct current. In the series circuit the magnetizing current appears in the output both above and below the reflected current, and therefore some cancellation occurs in the average error.

Temperature affects repeatibility in two ways: the first being the direct effect on the magnetization current. Here again the parallel circuit is more affected because of the partial cancellation afforded by the series circuit. The second effect is through the variation of the resistance of the copper windings with temperature and the corresponding change in the core voltage and hence the exciting current. Supply voltage variations similarily affect the magnetizing current.

The Feedback Transductor

Having decided to submit this transductor paper to the conference committee last August, the possibility of a new approach to providing continuous coupling between a primary direct current source and a secondary load was of interest to me. Anyone who has excited a winding on a core from a Variac and observed the waveform of the associated magnetizing current is aware of the symmetry of the flux excursions about the center of the B-H loop. Any tendency toward saturation at one end of the B-H characteristic is conteracted by a diminished voltage of that polarity due to the dc and even harmonic current flowing through the source impedance.

If a core could be kept cycling symmetrically around the B-H loop in the above fashion and never saturate there would always be coupling from primary to secondary. But with an uncontrolled source of alternating voltage, direct current flowing through resistive drops unbalances the core voltage and saturation occurs. The solution is to provide an

active voltage source which senses the core voltage only (no resistive drop) by an auxiliary winding on the core, compares it through a high resistance to an alternating reference, and maintains it by closed-loop action. Such a system is shown in Fig. 10. As direct current is introduced in the primary and coupled to the secondary, the flux excursions move away from the center of the B-H characteristic due to the IR voltage drop. The second harmonic content of the magnetizing current on top of the direct current is sensed and a dc correcting signal applied through the same closed-loop amplifier, keeping the amplifier output approximately "in step" with the ac and dc requirements. Because the alternating voltage now has to be only large enough to provide coupling between primary and secondary and is not related to the resistive drop as in previous transductors, the normal excursion about the center of the B-H loop can be an arbitrary part of the available core capacity. The remainder of the B-H loop is then available to handle the voltage transients caused by changes in current before the second-harmonic loop restores equilibrium. The reflected voltage in the primary is also proportionately reduced.

The production of even-harmonics as a non-linear core material is biased off-center by a direct current has been known as a useful, polarity-sensitive means of detection for many years. Current monitors employing this technique utilize an amplifier sensing the second-harmonic term to drive an auxiliary winding to amp-turn balance with the bus current being measured. The output of the amplifier at null is then proportional to the bus current, with the bandwidth somewhat less than half the carrier frequency. In the new Feedback Transductor the second harmonic is being used as a feedback term to keep the voltage loop in balance; the output voltage itself is taken directly from a resistor in series with the secondary winding and thus is wideband and not directly related to the second-harmonic frequency. The combination of the available excess core capacity and the second-harmonic detector bandwidth determine the large signal transient and slewing rate capability of the device, the limit being where the core saturates because the loops cannot keep up. For instance, if the core previously used for the single core transductor is now driven with an alternating wave to only 10% of its capacity, the system could handle a 40% I_{max} step without saturating. With the reference frequency now arbitrary this range could be increased to 100% with a modest frequency change. The second harmonic loop also removes any offsets caused by dc drift in the system.

In addition to substituting active, integrated circuit devices for cores and providing bipolar operation, the Feedback Transductor will be immune to supply voltage induced variations. By cycling around a minor loop about the center of the B-H characteristic in steady state, the magnetizing current is reduced and is symmetrical with a zero average. With the variation in time and magnitude gone as a function of direct current level, it is possible to cancel the magnetizing current waveshape using a current source from the reference summed-in to either a buffer amplifier in a monitor, or the loop amplifier in a current regulator. The series element from the reference would be either a resistor or a small (1" diameter) core cycling about the same part of the B-H loop. The cores must be reasonably shielded from external magnetic fields.

Conclusion

As greater demands are placed on the transductor in terms of repeatability, linearity, range, bandwidth (both large and small signal), and immunity to environmental effects, the traditional multi-cored device is hard-pressed to strike a compromise between the various requirements. A new approach is required which utilizes the basic concept of maintaining coupling between primary and secondary by cycling around the B-H loop with a controlled core voltage. The Feedback-Transductor frees the device from the traditional constraints while imposing new ones in the realm of feedback theory.

References:

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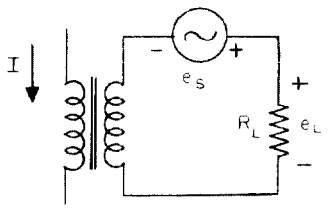


Fig. 1 - Single Core Transductor

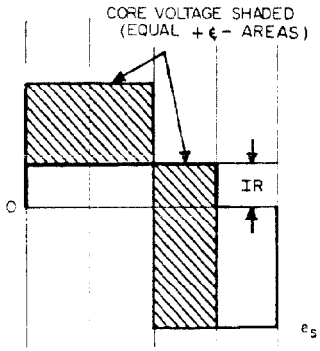


Fig. 2 - Single Core Transductor Waveshapes

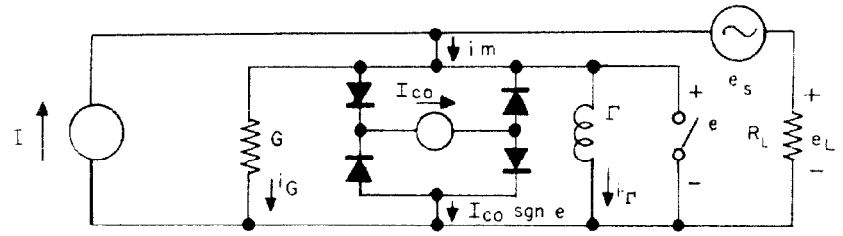
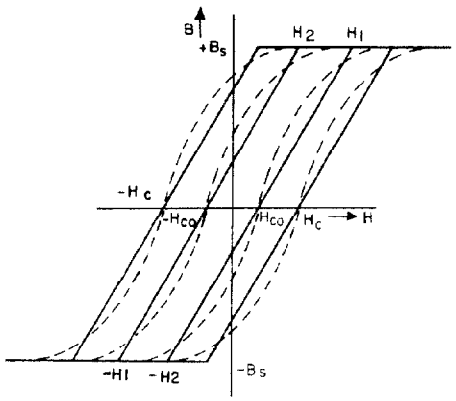


Fig. 3 - Single Core Transductor with Core Model



$$I_{co} = \frac{H_{co}\, l_c}{N} \qquad e = N \frac{d\phi}{dt}$$

$$G = \frac{(H_c - H_{co})\, l_c}{N^2 A_c \frac{dB}{dt}} \qquad \Gamma = \frac{(H_1 + H_2)\, l_c}{2N^2 A_c B_s}$$

Fig. 4 - B-H Loops & Linearization

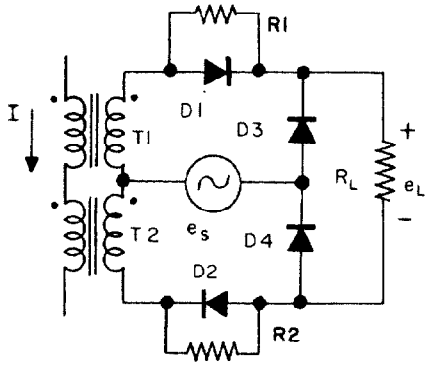


Fig. 5 - Parallel Transductor

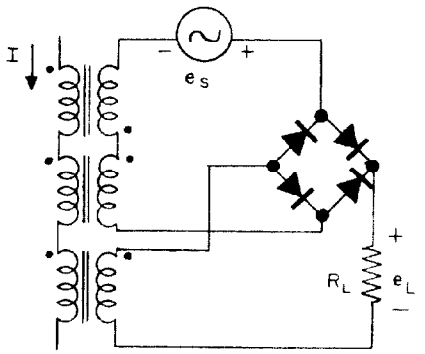


Fig. 6 - Series Transductor

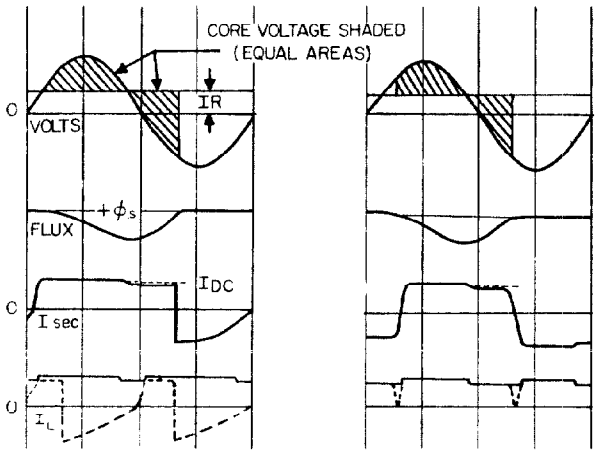


Fig. 7 - Parallel Transductor Waveshapes

Fig. 8 - Series Transductor Waveshapes

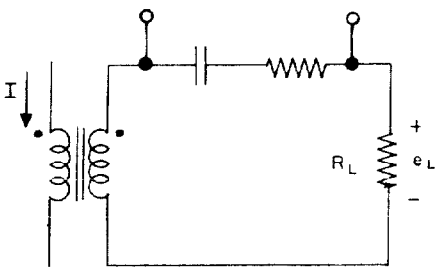


Fig. 9 - Additional Core Filter (replaces R_L)

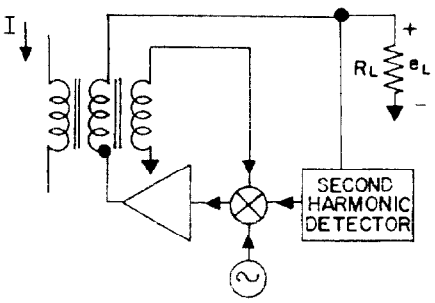


Fig. 10 - Feedback Transductor