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A NEW SATURABLE TRANSFORMER MEASURES  
DIRECT CURRENT THROUGH CONDUCTORS  
IN THE VICINITY OF LARGE STRAY  
MAGNETIC FIELDS

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Alfred Windsor

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ABSTRACT

An improved dc transformer operates with its accuracy not impaired by stray magnetic fields because the ampere-turn balance is continuous. Applications are especially useful in physics research.

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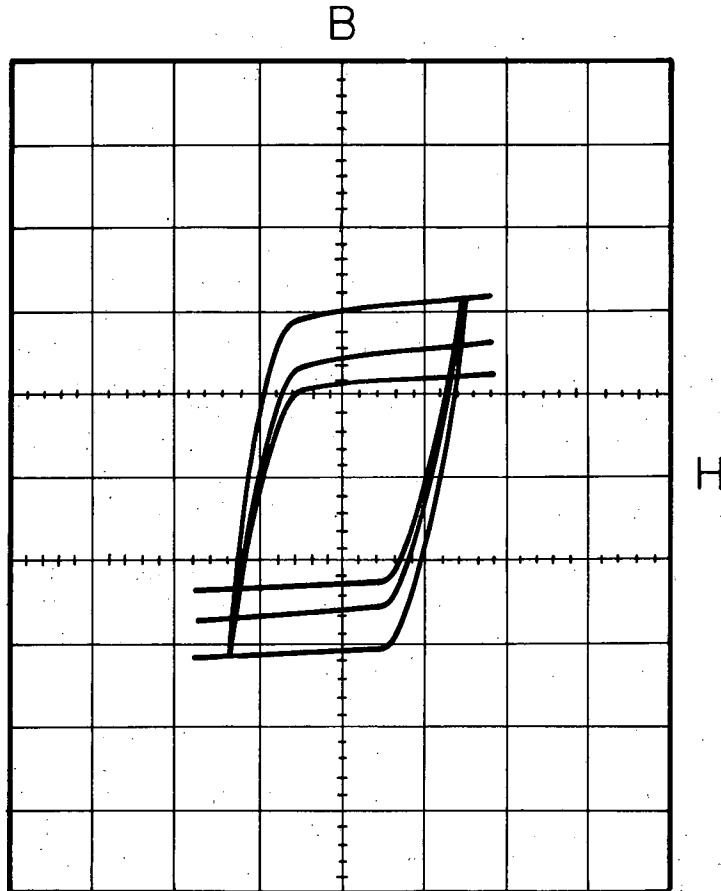
Stable current transducers have many applications in physics research. Particle accelerators and their auxiliary equipment usually require large direct currents, for example. The dc transformer has certain general advantages and limitations. Advantages are: (a) isolation between the current bus and burden resistance, (b) low power dissipation, (c) low temperature coefficient, and (d) high output voltage. Limitations to be considered are: (a) loss of accuracy at low currents, (b) dependence on source voltage and frequency, (c) transfer of source voltage to the current bus, and (d) accuracy affected by stray magnetic fields.

A transverse field has the effect of lowering the saturation flux or  $B_{\max}$  of square loop core material, while the average of positive and negative coercive forces for an alternating wave of equal positive and negative flux remains nearly zero (see Fig. 1).

This saturable transformer makes use of the basic symmetry of the hysteresis loop without being affected by the saturated inductance which varies with stray magnetic fields. Figure 2 illustrates the principle of operation. Here an ac current transformer with a vertical hysteresis loop is supplied a negative volt-second area in the primary, and an equal and opposite volt-second area in the secondary.  $E_s$  is adjusted until  $a_1 = a_2$  and then is continuously adjusted to maintain an ampere-turn balance between  $I_C$  and  $N_2 I_L$ . The secondary voltage of  $T_2$  is  $I_L (R_{T2} + R_L)$  as long as  $D_2$  conducts.  $D_1$  conducts and blocks  $D_2$  when  $E_s$  reverses and reaches the value of  $I_L R_{T1}$ . The voltage of  $T_2$  reverses from  $\phi_2$  to  $(\pi - \phi_2)$  to form area  $a_1$ .  $E_s$  is set just large enough to maintain zero net flux in core 2. Equating the areas and solving for  $E_s$  yields  $E_s \cos \phi_1 = \pi I_L (R_{T2} + R_L)$ . If  $R_{T1}$  is small,  $\cos \phi_1 = 1$ , and

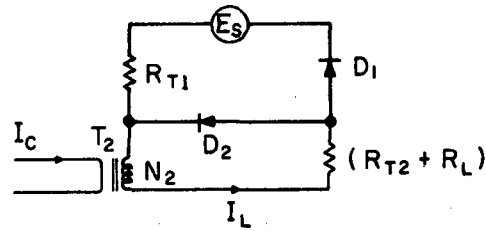
$$E_s (\text{RMS}) = 2.22 I_L (R_{T2} + R_L). \quad (1)$$

When  $E_s$  is low  $a_1$  is low, and the core saturates on each cycle from current in the primary. When  $E_s$  is high, the core saturates during the interval of excess  $a_1$ .



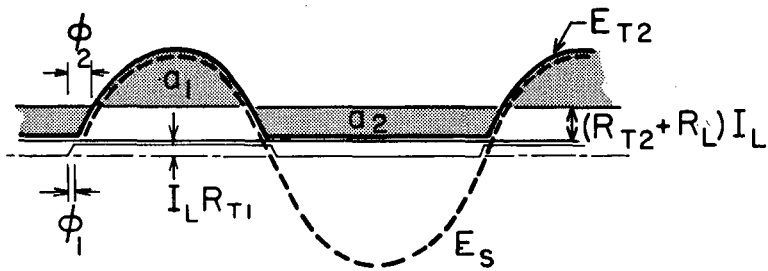
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Fig. 1. A family of B - H loops for delta-max or Orthonol core material shows reduced  $B_{max}$  when a transverse field is applied.



$$E_S \cos \phi_1 = \pi I_L (R_{T2} + R_L)$$

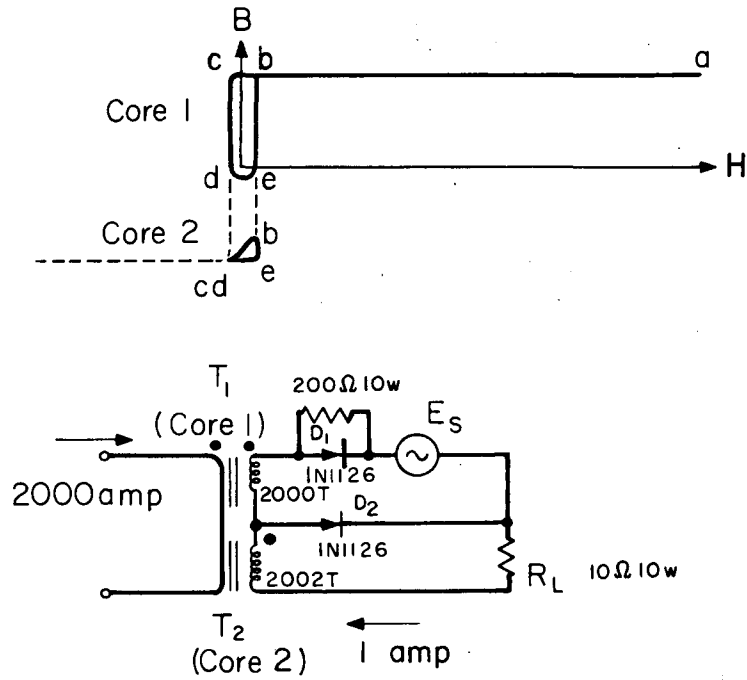
when  $\alpha_1 = \alpha_2$



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Fig. 2. Basic circuit and principle of operation.





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Fig. 3a. A practical circuit with B - H loops for low control current.

Since it is not practical to regulate and adjust  $E_s$  to every current,  $E_s$  is made higher than  $2.22 (R_{T2} + R_L)$  and the excess volt-seconds are absorbed in another transformer connected in series with  $R_{T1}$ . Thus an ampere-turn balance is maintained by  $T_1$  and  $T_2$  in series during the interval of excess  $a_1$ .

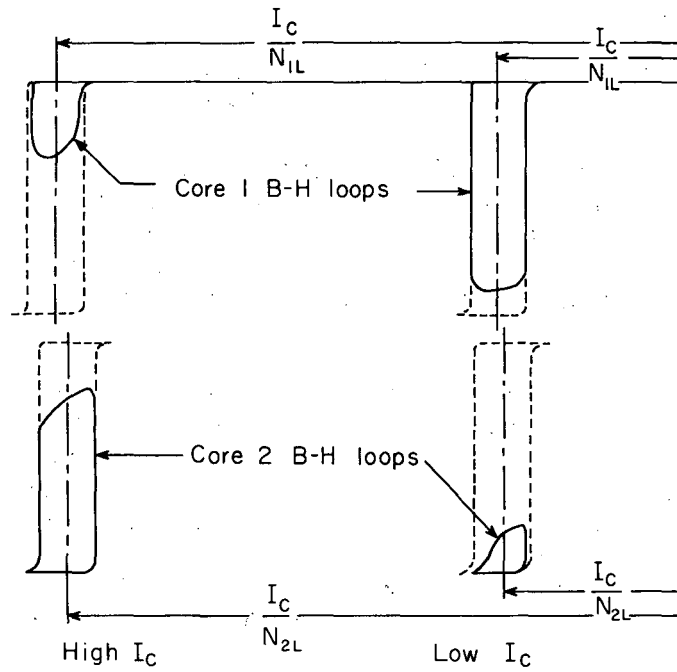
The current transformer of Fig. 3 is superior to the conventional series-connected saturable reactor, which has a negative stray-field coefficient, because of changes in the saturated inductance with transverse fields. It responds faithfully to high-frequency components of currents because of close coupling between primary and secondary during the full cycle. The series-connected saturable reactor was used in Germany for telemetering direct current before 1919.<sup>2</sup> The same circuit is in use today but suffers the disadvantage of momentary interruptions of the ampere-turn balance while the twin cores are switching.

The dc transformer of Fig. 3a is designed to be unbalanced in order to assure a reset for  $T_2$  before the excess volt-seconds are absorbed in  $T_1$ . A fully excited core has a wider hysteresis loop than a partially excited one, thus  $T_1$  may be identical with  $T_2$  as long as the excess of volt-seconds for  $T_1$  is greater than the volt-seconds required to reset  $T_2$ . A better utilization of core cross section results from adding secondary turns to  $T_2$  over  $T_1$  or using a core material for core 1 of wider hysteresis loop or making the diameter of core 2 smaller than that of core 1.

Figure 3b shows the shift in volt-seconds from core 1 to core 2 from low to high currents.  $N_2$  is made a little larger than  $N_1$  to permit the smaller loop of core 1 to reset core 2. Another method of reset would be to use orthonol core material for core 1 and Hy Mu 80 for core 2.

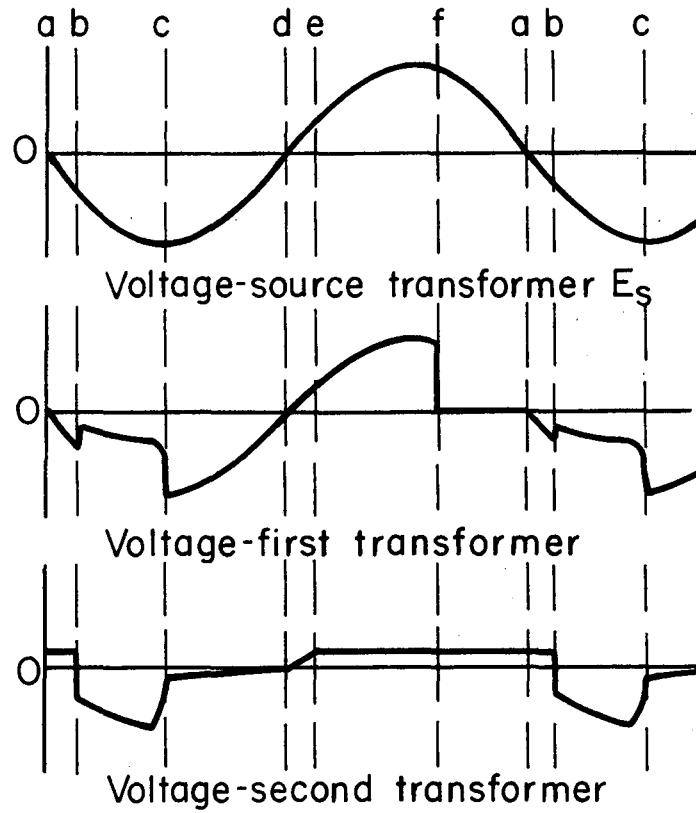
To understand the cycle of operation refer to Fig. 4. Starting at "a," core 1 is saturated and core 2 is in a high  $\mu$  region. An ampere-turn balance is maintained by  $T_2$  as current circulates through  $D_2$  and  $R_L$ . Also,  $E_s$  blocks  $D_1$  while the core of  $T_1$  is saturated. At point "b," core 2 is still in a high- $\mu$  region with established domain walls, while core 1 is just coming out of saturation and starting nucleation centers.<sup>3</sup> Current shifts from  $D_2$  to  $D_1$  at point "b," and the difference in excitation requirements between core 1 and core 2 results in an unbalanced distribution of voltages between  $T_1$  and  $T_2$  until core 2 approaches saturation at point "c." When core 2 reaches the limit of its flux change, voltage shifts to  $T_1$ , since core 1 has now established domain walls.  $T_1$  continues to absorb volt-seconds until it resets to saturation at "f." Meanwhile, the ampere-turn balance has shifted to  $D_2$  at "e," when  $E_s$  reverses.  $D_2$  maintains the current in the same direction through the load. The switching of current from  $D_1$  to  $D_2$  and back again is done so smoothly that the output current is a true representation of the input plus a small square wave of ripple current equal to the width of the hysteresis loop and of the same frequency as  $E_s$ .

At zero control current, core 1 fails to get reset unless reverse volt-seconds are fed back around  $D_1$ .  $R_1$  prevents  $T_1$  from going into the magnetic amplifier mode at zero control current and turns  $D_2$  "on" a little bit better at other currents. Core 1 must have enough cross-section



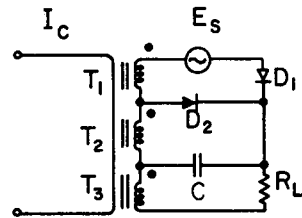
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Fig. 3b. Hysteresis loops showing how core 1 resets core 2 when  $N_2$  is greater than  $N_1$ .

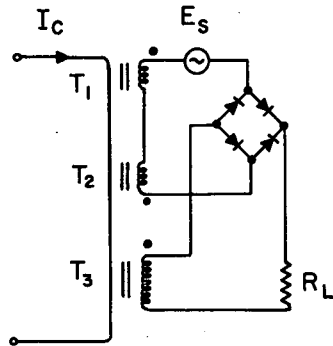


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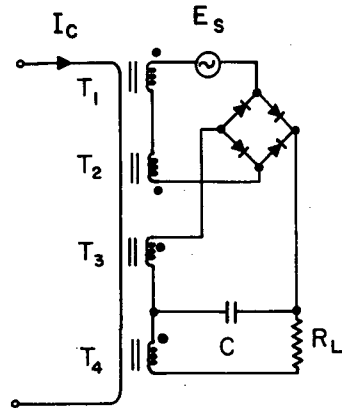
Fig. 4. Principle of operation -- 2000-amp saturable transformer.



Coercive current flows in C



Conventional dc transformer maintains constant ampere turn balance.



Second harmonic ripple is removed in four-core saturable transformer.

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Fig. 5. Coercive current ripple removed.

area to absorb all of  $E_s$  plus a safety factor and, as seen from Eq. (1), core 2 requires about half as much, since it can not absorb more than  $I_L (R_L + R_{T2})$  for a little more than half a cycle.

This mode of operation makes the dc error approximately equal to the average of positive and negative magnetizing forces for core 2. The ripple current may be removed without loss of frequency response by filtering the output and biasing an ac current transformer.<sup>4</sup> The ac current transformer  $T_3$  in Fig. 5 (upper) should have a low-frequency response that includes the frequency of  $E_s$  and crosses over with the frequency response of the saturable transformer so that ripple-frequency components are filtered out by capacitor  $C$  and the inductance of  $T_3$ .

The conventional dc transformer can be modified to obtain a constant ampere turn balance by adding a third transformer as in Fig. 5 (middle). The ripple amplitude is equal to the width of the hysteresis loop, but the frequency is twice that of  $E_s$ . In Fig. 5 (lower), the ripple is removed in the same manner as Fig. 5 (upper) by adding a fourth transformer.

In magnetic fields up to 50 gauss, this transformer is approx a factor of 10 more stable than the conventional one. It is recommended for applications where stray fields are difficult to remove by shielding.

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