The Forgotten Use of Saturable-Core Inductors (Transductors)

The tunable reactive components available for RF circuits include more than variable capacitors, varactors and slug-tuned inductors.

By Christopher Trask
ATG Design Services

The transductor, more widely known as a saturable reactor, is an inductor whose electrical properties are varied by superimposing a steady magnetic field in the core material. Actually it is an extension of the method of controlling the reactance of a filter choke ("swinging" chokes), and has been used in practice for a considerable time [1]. Although the basic principles are understood easily, the applications in RF circuit design have diminished, mostly because of the availability of less-expensive varactors. What is not readily obvious, and poorly documented, is the distinct advantage that transductors offer in terms of linearity, a highly desirable feature in the design of communications equipment.

The term "transductor" initially was applied to small-signal saturated reactors by E.C. Snelling in his comprehensive work on soft ferrites [2]. His work contains a significant amount of information on the details of the principles of the magnetic and electrical circuits involved, as well as a variety of applications, including variable filters [3], oscillators and attenuators [4]. Additional literature provides further insight on various methods of construction [5, 6, 7 and 8], as well as a more basic presentation of the principles [9 and 10].

In general, a transductor is composed of three elements: the core material itself, properly chosen for the application at hand; the controlled, which is the inductance that we wish to control and the control winding, through which we will apply the controlling current. The controlled and control windings must be constructed on the core material in a way that will prevent them from coupling with each other, as illustrated in the referenced literature.

In designing a transductor, the quantity that we become concerned with is immediately the incremental permeability, known by the designation $\mu\Delta$.

Figure 1 shows a B-H curve, with hysteresis, for a typical ferrite core material. Here, H_0 is the steady-state magnetic field strength, measured in Oersteds, and is the result of a field generated by a DC current passing through the control winding. This, in turn, results in a flux density within the core, B_0, which is measured in Gauss. With no alternating field applied, the reversible permeability μ_{rev} is found by the relationship. The initial permeability μ_i is:

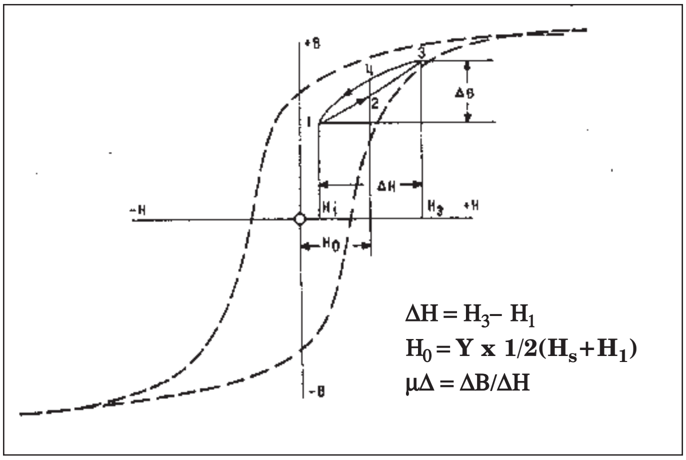
$$\mu_{rev} = \frac{\left(\dfrac{B_0}{H_0}\right)}{\mu_0} \qquad (1)$$

where $\mu_0 = 4\pi 10^{-7}$ H/μ. The initial permeability μ_i is that of (1) above where there is no steady-state magnetic field.

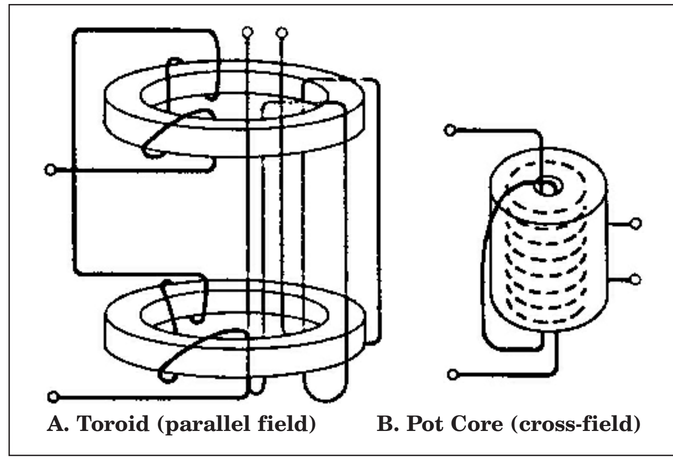
$$\mu_i = \frac{\left(\dfrac{B_0}{H_0}\right)}{\mu_0} \qquad (H_0 = 0) \qquad (2)$$

By superimposing a varying magnetic field ΔH on this steady-state magnetic field, the result of a small-signal current passing through the controlled winding, we create an incremental flux density ΔB, from which we can derive the incremental permeability:

$$\mu\Delta = \frac{\left(\dfrac{\Delta B}{\Delta B}\right)}{\mu_0} \qquad (3)$$



■ **Figure 1. Definitions of magnetic parameters (used with permission of [9]).**

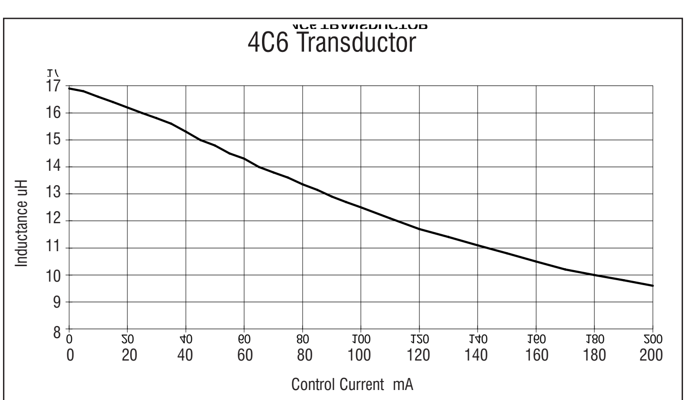


■ **Figure 2. Transductor realization methocs (used with permission of [11]).**

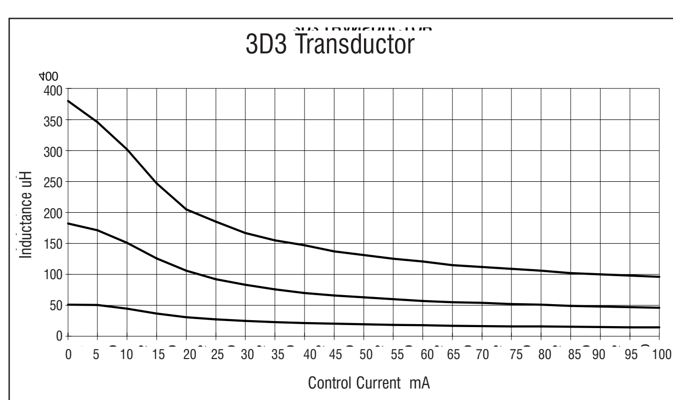
Most manufacturers of ferrite core material will publish graphs showing the initial and incremental permeability with respect to applied magnetic field strength. Theoretically, it should be possible to operate the transductor through the entire range of incremental permeability from a value where the steady field is close to zero to where the steady field is large enough that the initial permeability approaches unity. However, this latter condition is impractical.

With the essential basics in hand, let's now examine two of the many realizations available. Figure 2A illustrates a form known as a parallel-field reactor [11], so called as the steady-state magnetizing field is parallel to the signal field in the core material. This type is commonly found in magnetic amplifiers and consists of a pair of ferrite (or tape-wound) toroids, each with an identical inductive winding that is wound in opposite directions on the two cores. The control winding is then wound around both cores simultaneously. This construction requires both inductive windings to be identical to prevent inductive coupling to the common control winding. Figure 2B illustrates a form that is referred to as a cross-field inductor [11], so called because the magnetizing field is perpendicular to the signal field in the core material. In this construction, the control winding is placed on a bobbin, or coil former, which is part of a ferrite pot core assembly. This is very convenient, as a large number of turns can be placed on the bobbin using automated machinery. The bobbin is then assembled between two pot core halves of suitable material, and the controlled inductor winding is formed on the outside of the pot core, through the center hole normally used for a tuning slug, in effect turning the pot core into a toroid of sorts. This latter form of construction ensures a high degree of isolation between the two windings, and at the same time is easy to reproduce and manufacture.

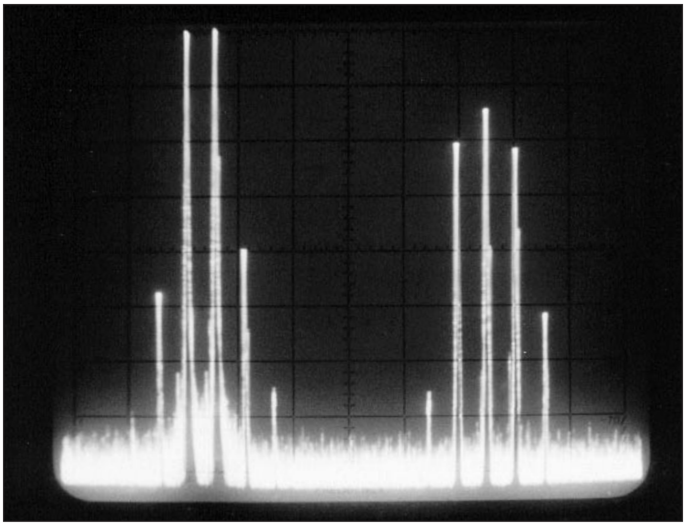
To demonstrate the tuning capabilities of this latter form, four transductors were constructed, using two different ferrite mixes. The first device consists of a Philips P18/11-4C6 pot core with no gap. The control winding is 200 turns of #36 enameled wire on a CPV-P18/11-1S-6PDL coil former. The inductive winding is eight turns of #30 enameled wire, wound as described earlier. The results are shown in Figure 3, where the control current was varied from 0 to 200 μA. Measurements were made at 1 MHz using an HP 4271B automatic LCR meter.



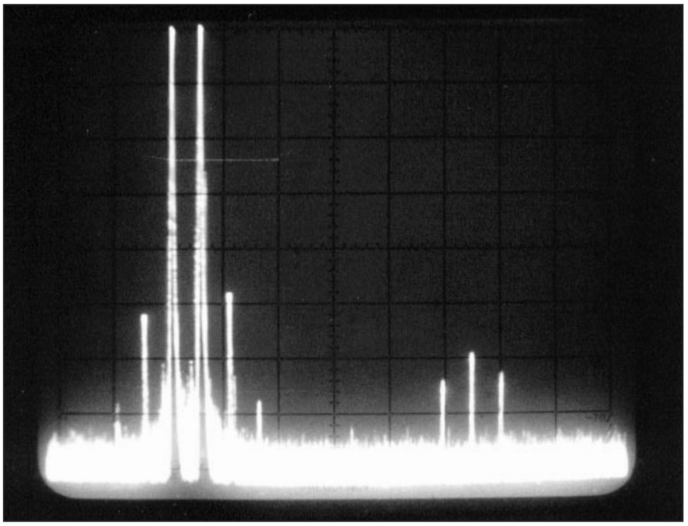
■ **Figure 3. 4C6 Transductor test results (see text for details).**



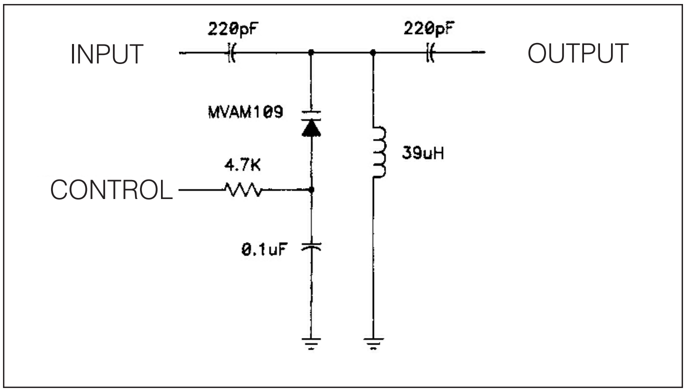
■ **Figure 4. 3D3 Transductor test results (see text for details).**



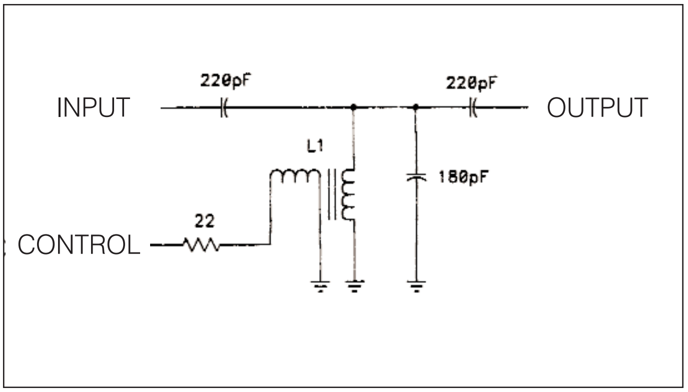
■ **Figure 5B. Varactor-tuned bandpass filter distortion products.**



■ **Figure 6B. Transductor-tuned bandpass filter distortion products.**



■ **Figure 5A. Schematic for varactor-tuned bandpass filter.**



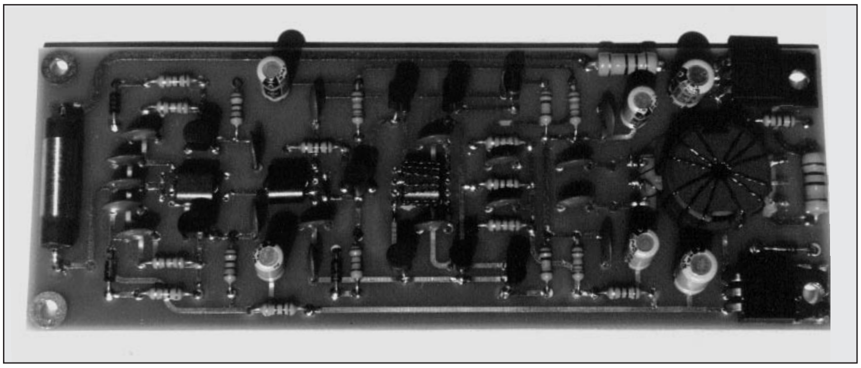
■ **Figure 6A. Transductor-tuned bandpass filter schematic.**

Next, a similar transductor was made, this time using a Philips P18/11-3D3 pot core. The control winding was increased to 400 turns of #36 enameled wire, and the unit was tested with an inductive winding of 4, 8 and 12 turns, in order. The results are shown in Figure 4, the 12-turn transductor being the upper-most curve and the 4-turn unit being the lowest. Note here, that an inductance range of 4:1 is achieved with approximately 100 µA, whereas the previous example achieved less than 2:1 with 200 µA of control current. This is attributed to the higher number of control winding turns in the second example, as well as the considerably higher initial permeability of the 3D3 material (750 H/µ) *vs.* the 4C6 material (120 H/μ), more readily recognized in terms of the inductance factor A_L, which is 910 nH/N^2 and 265 nH/N^2, respectively.

Although the use of transductors as RF tuning elements has been well-documented, little has been said about their distortion properties, particularly in comparison with varactors. One author's work with ferrite toroids [12] may be extended to pot cores, as the magnetic materials are similar in nature, but overall the literature appears to be very limited [13].

Two circuits were constructed to demonstrate the linearity advantages of transductors over varactors, both of which were centered around a one-pole coupled resonator bandpass filter having a center frequency of 1.0 MHz and a 3 dB bandwidth of 100 kHz. In the first circuit, shown in Figure 5A, the variable element for the resonator is an MVAM109 varactor diode, chosen because it delivers a similar tuning range as that of the transductor to be used later. Here, the applied signals are at 950 kHz and 1050 kHz, with an arbitrary signal level of –10 dBm. Figure 5B shows the results of this experiment. Note that the third-order intermodulation (IM) products are not equal, because the signal levels are arithmetically symmetrical, whereas the filter is geometrically symmetrical. Of particular interest are the second-order products, to the left side of the display, showing second harmonic levels at –21 and –22 dBc, as well as a mixing product at 2.0 MHz at a level of –14.5 dBc. The varactor is still operating in its linear range, so forward biasing is not a factor.

Next, a similar circuit was constructed, this time using a fixed capacitor and a transductor for the tuned resonator, shown schematically in Figure 6A. The trans-



■ **Figure 7. Remotely-tuned active antenna transductor application.**

ductor whose test results are shown in Figure 4 was used, which is 400 control winding turns and four inductive turns on a Philips P18/11-3D3 pot core. These results are shown in Figure 6B. Note that the third order products have decreased approximately 10 dB, giving a 5 dB increase in the third-order intercept point (IP_3). Of particular interest, though, is the remarkable 45 dBc decrease in the second-order products.

In respect to this simple demonstration, the transductor posesses superior linearity properties, especially in terms of second-order distortion, over its varactor conterpart. This feature may well override the disadvantages of cost and physical size when designing critical system functions, such as a remotely-tuned receiver preselector, where harmonic and intermodulation distortion performance are important considerations. Figure 7 shows such an application, where a transductor, seen on the far left-hand end of the PCB assembly, is used as a remotely-controlled tuning element in a high dynamic range HF loop antenna. This particular application required that the inductive (controlled) winding be center-tapped to provide both a ground reference for the antenna, as well as initial balancing for common-mode EMI cancellation, and therefore is made of a bifilar winding. ■

Acknowledgements

I would like to express my appreciation to Eastern Components, a nationwide distributor of ferrite magnetic materials, for supplying samples of the Philips pot cores and coil forms used here.

References

1. de Kramolin, L., "Magnetic Tuning Devices," *Wireless World*, February 1938.

2. Snelling, E.C., *Soft Ferrites: Properties and Applications,* Iliffe Books, Ltd., 1969, chapter 6 (High Frequency Transductors).

3. Beskorovainyi, B.M., V.M. Vol'f, V.S. Gorbenko, M.I. Karoskii, B.I. Shotskii, and A.A. Iur'ev, "Variable Ferrite Filters," *Radio Engineering* (Radiotekhnika), Vol. 15, No. 9, 1960.

4. Jackson, R.C. and Simpson, A.W. "A High Frequency Ferrimagnetic Attenuator," *Electronic Engineering*, April 1962.

5. Katz, Harold W. (ed), *Solid State Magnetic and Dielectric Devices*, Wiley, 1959, chapter 6 (Small Signal Applications).

6. Newall, E. P. Gomard and Ainlay, A. "Saturable Reactors as RF Tuning Elements," *Electronics,* September 1952.

7. Stiber, Samuel, "Use of Ferromagnetic Materials in Electronic Tuning of Radiofrequency Components," *Proceedings of the National Electronics Conference*, 1952.

8. Kiser, J.L., "The Electrically Variable Inductor," *Electronic Industries*, June 1996.

9. Stiber, Samuel, "Electronically Tunable Circuit Elements," *IRE Transactions on Military Electronics*, October 1960.

10. Polydoroff, W.J., *High-Frequency Magnetic Materials*, Wiley, 1960, chapter 12 (Incremental Permeability and Incremental Permeability Tuning).

11. Gross, T.A.O., "Revisiting the Cross-Field Inductor," *Electronic Design*, March 15, 1977.

12. Watson, J. Kenneth, "On the Nonlinearities of Inductors using Linear Ferrite Toroidal Cores," *IEEE Transactions on Magnetics*, Vol. MAG-17, No. 3, May 1981.

13. Hopf, J.F. and H.K. Lindenmeier, "Extremely Linear Electrically Tunable Active Receiving Antenna," *Proceedings of the Second International Conference on Antennas and Propagation*, 1981.

Author information

Christopher Trask is a designer of analog, RF and microwave circuitry and is the author of ALMOND, a PC compatible RF design program. He received his BSEE and MSEE degrees from Pennsylvania State University in 1973 and 1979 respectively, taking time in between to fly C-130 transports for the U.S. Air Force. He currently is a technical editor for *QRP Quarterly* magazine. He may be reached at P.O. Box 25240, Tempe, AZ 85285-5240 or by e-mail at ctrask@primenet.com.

"The Forgotten Use of Saturable-Core Inductors (Transductors)," Applied Microwaves and Wireless, Sep/Oct 1997, pp. 76-82. "Lossless Feedback Amplifiers," QRP Quarterly, January 1998, pp. 40-41. "A Wide-Band Low-Distortion Ferrimagnetic Attenuator," Proceedings of the 1998 IEEE International Symposium on Microwave Theory and Techniques, Baltimore, Maryland, June 1998, pp. 1847-1850. "A Linearized Active Mixer," Proceedings of the RF Design '98 Conference, San Jose, California, October 1998, pp. 13-24. A saturable-core reactor is a magnetic-core coil whose reactance is controlled by changing the permeability of the core.Â Applications range from the use of large inductors in power supplies, which in conjunction with filter capacitors remove residual hums known as the mains hum or other fluctuations from the direct current output, to the small inductance of the ferrite bead or torus installed around a cable to prevent radio frequency interference from being transmitted down the wire.Â A ferrite core inductor with two 47mH windings. An inductor usually consists of a coil of conducting material, typically insulated copper wire, wrapped around a core either of plastic or of a ferromagnetic (or ferrimagnetic) material; the latter is called an "iron core" inductor. A saturable reactor in electrical engineering is a special form of inductor where the magnetic core can be deliberately saturated by a direct electric current in a control winding. Once saturated, the inductance of the saturable reactor drops dramatically. This decreases inductive reactance and allows increased flow of the alternating current (AC). Saturable reactors provide a very simple means to remotely and proportionally control the AC through a load such as an incandescent lamp; the AC current is