Increductor® Notes #6

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Designing for Stability

Part 1: General Consideration of Compensation Circuits

This issue of INCREDUCTOR NOTES and the next one will, in two parts, discuss circuits that give stable operation. The circuits to be discussed are readily designed and follow acknowledged engineering practices. Most are economical enough to be easily incorporated into commercial equipment. All use readily available components.

Introduction

The questions design engineers most frequently ask about controllable inductors are: "How much hysteresis do they exhibit?" and "How sensitive are they to changes in ambient temperature?" The answers to these questions depend partly on the characteristics of the specific INCREDUCTOR unit, but mostly on the circuit in which it is operated. Control circuits play a significant part in determining the stability of the design. For example, a circuit in which a controllable inductor is operated "wide open" (i.e., with no effort made to minimize the effects of hysteresis and temperature variation) can exhibit as much as 10% frequency error. Operating the same INCREDUCTOR unit in a properly designed closed-loop circuit reduces these effects to 0.1% or less. (A consideration of how the choice of operating point affects hysteresis and temperature coefficient appears in INCREDUCTOR NOTES #5.)

Temperature Coefficient

Ferrite-core components are affected by changes in the surrounding temperature and by changes in the core due to changes in control current. These changes appear as variations in the inductance of the unit for given control and bias currents. The sensitivity of a particular INCREDUCTOR controllable inductor to these changes in temperature is indicated by the temperature coefficient or the percentage of change of inductance per degree change of temperature. The temperature coefficient varies with the control current. It is usually positive at low values of control current and negative at large values of control current. There is a point at which the coefficient changes from negative to positive; this is the zero temperature coefficient point. Typical change in inductance with temperature is from .01% to 2% per degree C. The temperature characteristic is uniform in controllable inductors using the same materials.

Temperature coefficient depends upon core material, core configuration, and on use of air gaps. A controllable inductor can be so constructed, as in the case of the AP series, that the temperature coefficient is remarkably low.

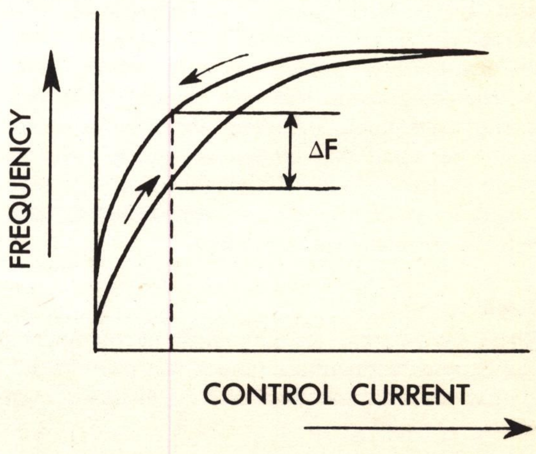


FIGURE 6-1.

Hysteresis

Hysteresis is a property of all known magnetic materials and results in the materials having a magnetic memory. With iron-core materials operating at power-line frequencies, the principal effect of hysteresis is the heating of the core and the consequent loss of efficiency. At the radio frequencies at which INCREDUCTOR units operate, the major effect of hysteresis is a difference of signal winding inductance when the control current approaches a specific current from a different starting value. This occurs because the inductance of the core at any instant is the result of (1) the control current induced magnetism at that instant, and (2) the remanent magnetism of the core. In tuned circuits, this means that a different apparent resonant frequency will be produced for the same value of control current depending on the direction from which the point is reached. See Figure 6 - 1.

Compensation Circuits

Two types of compensation are in common use: open-loop and closed-loop circuits. The open-loop circuit utilizes a device such as an air-core inductor in parallel with the INCREDUCTOR unit. The closed-loop circuit involves a feedback system, with the INCREDUCTOR control winding usually becoming part of a feedback circuit.

Open-Loop Compensation Methods

Previous issues of INCREDUCTOR NOTES have discussed open-loop compensation to a certain extent. The reader is referred to pages 6 and 7 of Number 2 and pages 17 and 18 of Number 5. Other open-loop methods are considered below.

"Swamping" Effect

Where the controllable inductor has greater range than required, both the effects of hysteresis and temperature variation can be reduced by placing an external inductor (usually an air-core unit) either in parallel or in series with the signal winding of the INCREDUCTOR unit. This "swamping" inductor then becomes the dominant inductive element and the tuned circuit will tend to possess its characteristics. If this "swamping" inductor is stable, then the combination will approach its stability. The combination will have higher Q than that of the controllable inductor alone. However, it should be noted that while "swamping" can increase Q and stability, the combination will have a smaller inductance (or frequency) change ratio than the INCREDUCTOR unit alone.

Oven

Where temperature stability must be maintained over extreme temperature ranges, it is recommended that the INCREDUCTOR unit be enclosed in a thermostatically controlled oven. Such a thermostatically controlled oven is inside the packaging can and does not add appreciably to the over-all size of the unit. The type 61BT1, described on the back of this issue of INCREDUCTOR NOTES, is supplied with such a thermostatically controlled oven. Other units can be so supplied on special order.

Temperature Compensating Resistance

Figure 6 - 2 shows a temperature-sensitive resistor network (R1 and R2) associated with the bias winding. These resistors could also be used with the control winding. The temperature coefficient of the network should be equal and opposite to that of the controllable inductor over the range of operation.

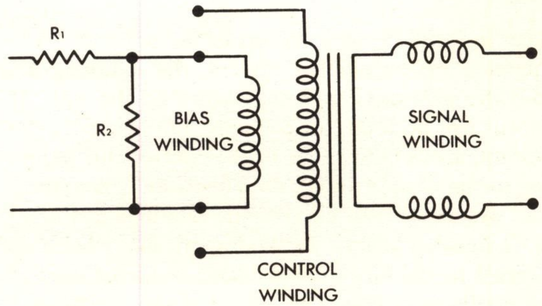


FIGURE 6-2. TEMPERATURE COMPENSATING NETWORK WITH TEMPERATURE SENSITIVE RESISTORS.

Tuned Circuits

In a panoramic receiver in which the INCREDUCTOR inductor-tuned local oscillator's frequency sweeps alternately up and down, it may be desired to generate frequency marker pulses precisely as the sweep starts and as it stops. Hysteresis effects would ordinarily shift the start and end of the sweep. This problem can be solved by using two bandpass filters connected to the local oscillator. As the local oscillator sweeps to the lowest frequency, one of the filters will conduct and trigger a flip-flop which will start the upsweep. The other filter will trigger a second flip-flop at the maximum frequency, thus starting the downsweep at that point.

Precycling

Since hysteresis is a function of the past magnetic history of a component, a circuit can be stabilized by insuring that the past magnetic history remains uniform. One method of achieving this is to return the core to some point, usually close to saturation, before adjusting the control current to some new value.

Compensating Hysteresis

It is sometimes possible to introduce a second source of hysteresis which will compensate for the controllable inductor's hysteresis. A case in point involved an INCREDUCTOR inductor-tuned receiver. A meter measured the control current. Since control current is related to inductance and hence to the frequency being tuned, it was possible to calibrate this meter in kilocycles. By choosing a meter with a hysteresis characteristic which resembled that of the controllable inductor, the meter would stay in step with the hysteresis of the inductor and hence would read relatively accurately.

Closed-Loop Methods of Compensation

Block Diagram

The inductance of a controllable inductor is a function of the control current, the temperature, and the previous magnetic history of the unit. If means can be found to compare automatically the instantaneous inductance of the controllable inductor to the desired value, the effects of temperature and hysteresis may be virtually eliminated. Figure 6 - 3 shows a general method applicable when it is desired to stabilize a controllable inductor used in an oscillator circuit. The output of the oscillator is fed into a discriminator. The discriminator voltage output is proportional in amplitude to any discrepancy in frequency between the oscillator and the discriminator, while the polarity of the discriminator output depends upon whether the oscillator has drifted above or below the desired frequency. This error voltage can be fed through the current driver to the control winding, retuning the INCREDUCTOR-controlled oscillator to the correct frequency. Thus, a circuit not subject to hysteresis or temperature variation, i.e., the discriminator, becomes the frequency-determining element. With this circuit, it is possible to reduce hysteresis to as low as 1/3 of 1 per cent.

Because controllable inductors wound on cores of the same material exhibit similar temperature coefficients and similar hysteresis loops, it is possible to apply the advantages of the closed-loop type of circuit to groups of INCREDUCTOR units. Thus, if we insert in series with the control winding of the INCREDUCTOR unit in Figure 6 - 3, one or more additional INCREDUCTOR unit control windings of the same type, it is found that the signal inductances of these units are always very nearly equal to that of the controlled unit. The additional inductances thus follow the frequency of the controlled unit, hence the term "bellwether" to describe schemes of this type. (The following definition is found in Webster's New Collegiate Dictionary: "Bellwether. 1. A wether or male sheep, which leads the flock, with a bell on its neck.")

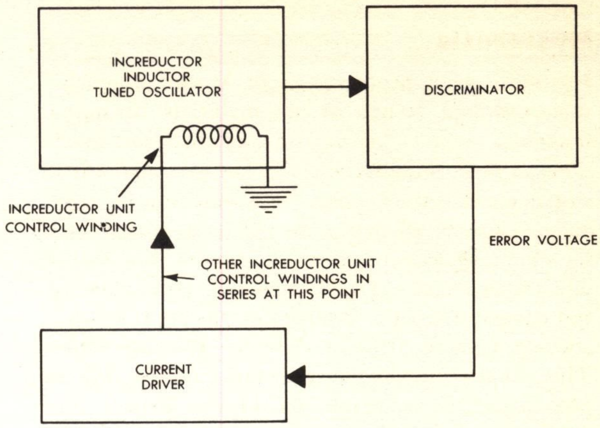


FIGURE 6—3. SIMPLIFIED CLOSED-LOOP OSCILLATOR CONTROL CIRCUIT

General Considerations

The amount of correction provided by a given closed-loop bellwether circuit depends upon the accuracy of the reference, the gain of the loop, and the tracking between controllable inductors. Where extreme precision is required, precision components should be used and the gain of the feedback should be as high as possible without danger of oscillation. As is the case with any servo system, this feedback loop must be carefully designed to control phase shift from output to input because of the danger of oscillation.

The speed with which the circuit corrects for frequency drift depends principally upon the time constants of its components. In general, the less inductance and capacitance used in the circuit, the faster the speed of response. Sometimes filtering must be employed to remove ripple from the error voltage. Such filters may tend to slow the response, but the principal danger is that they will introduce unwanted phase shift.

Specific Circuits

INCREDUCTOR NOTES #7 will describe specific circuits employing closed-loop methods of compensation.

Type 61BT1 INCREDUCTOR® Controllable Inductor

Oven enclosed — Megacycle Operation — FM & AFC

This unit was developed specifically for use in frequency modulating the RF oscillator in an airborne drone-control transmitter. A separate winding is provided for automatic frequency control of the transmitter center frequency. To assure satisfactory performance over the temperature extremes encountered in airborne applications, the Type 61BT1 INCREDUCTOR unit is provided with a thermostat and heater winding inside the can to maintain constant operating temperature.

The core is formed of two slotted ferrite rings, each carrying a balanced signal winding. The two signal windings are connected in series. Each ring core carries a separate control winding: control winding No. 1 for FM and No. 2 for use in an AFC circuit. The unit is hermetically sealed in a can providing terminals for the signal winding, the two control windings, and the heater winding. With a heater supply of 24 volts, an internal temperature of +65°C is reached in not less than 15 minutes at −55°C ambient.

Best adapted for use at a few megacycles, the unit is particularly suitable for use in frequency modulation circuits and the data given here are based on an FM application. Linearity of modulation is better than 1% at frequencies up to 80 kc. Frequency deviations of 1% of the carrier frequency are attained with phase distortion over this range on the order of 1 degree and harmonic distortion of less than 1.3%.

Signal Winding

Min. Effective Inductance (with control current and nominal current as specified in control windings No.'s 1 and 2, below)	12 μh
External Capacity	7 to 45 μμf
Stray Capacity	12 μμf
Center Frequency	5.1 mc
Maximum Deviation	±100 kc

Control Winding No. 1 (FM Winding)

Inductance	1.5 h
DC Resistance	230 Ohms
RF Frequency Change Effected	100 kc/ma
Control Frequency	300 cps to 100 kc, nominally 10 kc
Control Current	9 to 13 ma

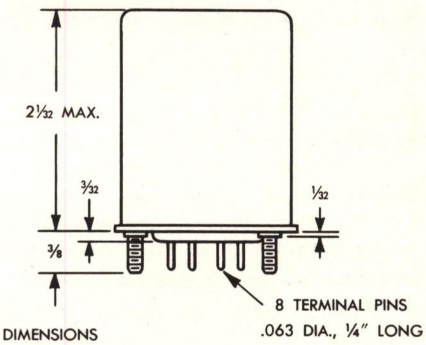
Control Winding No. 2 (AFC Winding)

Inductance	0.04 h
DC Resistance	18 ohms
RF Frequency Change Effected	400 to 800 kc/ma
Maximum Rate of Change	200 cps/sec
Nominal Current	2.5 ma

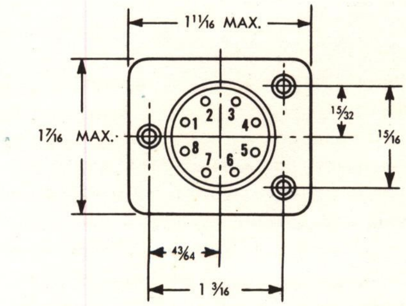
Temperature Control

Internal Temperature	+65°C (+10°C, −0°C)
Ambient Temperature Range	−55°C to +65°C
Heater Voltage	27.5 VDC, nominal

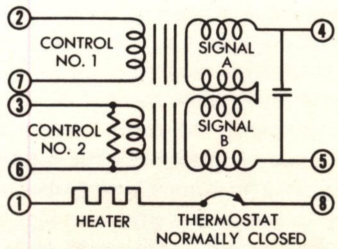
(Frequency modulation caused by an AC heater supply does not exceed 1.0 kc.)



EXTERIOR DIMENSIONS



BASE DIAGRAM



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