Testing Inductors at Application Frequencies

Introduction

The accurate measurement of an inductor has always been more difficult than the measurement of other passive components. The primary difficulty with coil measurements lies in the fact that coil inductance and Q are frequency dependent; similarly, coil parasitics vary dramatically with frequency. The measurement of coils at application frequencies, so-called “use frequency testing,” is more accurate than testing at typical traditional frequencies.

Often, the value of a measurement frequency is specified for measurement convenience alone. If the measurement frequency is not the circuit (or “use”) frequency, the result of testing will generally not yield the same inductance value seen by the intended circuit. Given that recent developments of equipment and methods now allow more flexibility in test frequency selection, particularly if tight tolerances are required, inductors should be tested at the actual frequency of use.

Inductor Parameters

The primary electrical parameters of a coil are inductance, Q, self resonant frequency (SRF) and the direct current resistance (DCR). All primary electrical parameters are design controlled, although not independently. The inductance and Q are highly dependent on both the frequency and instrumentation of a test.

Inductance is expressed in Henries (and sometimes as its capacitance corollary in Farads) with a tolerance, at a specific frequency. The Q parameter is unitless as a figure of merit which is specified as a minimum. The SRF is stated in Hertz as a minimum and the DCR is expressed in Ohms as a maximum.

Other parameters such as current carrying capability and impedance are sometimes specified but are not necessary; they are reflected in the primary parameters. For example, the wire gauge determines both the DCR and current carrying ability. The DCR is easier to measure than the current density (or the temperature rise) and both parameters are indicated in the Q.

Test Equipment

The appropriate selection of a method of test largely determines the accuracy of a measurement. Instrumentation and test methods vary for individual electrical parameters, and every instrument has further limitations in terms of range, frequency and error. Parasitics and their effects associated with test fixturing is a significant consideration in a measurement. In all cases, the instrument, fixturing, frequency, and current (if applicable) must be specified in order to have a repeatable and reliable test.

A Q meter or impedance analyzer is generally used for inductance and the Q measurements. There have also been some recent efforts in measuring Q on a network analyzer. The SRF can be measured on a grid dip meter or a network analyzer. The DCR is usually measured on a low Ohm meter or a wheatstone bridge.

The choice of equipment may establish the measurement units for inductance. For example, when coils are measured on a Q meter, the affected units for inductance are picofarads (pF). A Q meter resonates the coil under test with a variable capacitor; the meter indicates this value of capacitance. In most cases, the measurements are not converted to Henries, but left as picofarads.

The selection of instrumentation also influences measured values. The influence an instrument has is a result of the various measurement methods and frequencies employed by each piece of equipment. In the case of inductance, the following table shows the typical variations that can be expected, for the same coil, when measured on different instruments, at different frequencies.

INSTRUMENT	FREQUENCY	INDUCTANCE
HP4342A	25 MHz	682.3 nH (59.4 pF)
MEGURO MQ-171	25 MHz	580.6 nH (69.8 pF)
MEGURO MQ-171	50 MHz	603.1 nH (16.8 pF)
HP4192A	0.130 MHz	607.0 nH
HP4192A	10 MHz	592.7 nH
BOONTON 62AD	1 MHz	594.0 nH
TEKTRONIX LC130	0.130 MHz	1300.0 nH
HP4191A	100 MHz	1065.0 nH

As we can see from the table above, an inductance value can vary considerably, depending upon how the inductor has been measured. Part of the discrepancy can be attributed to the different instruments, but the majority is due to the different frequencies. In general, the proper instrument to specify is one that is accurate and repeatable at the frequency required.

The Hewlett Packard HP4191A is emerging as the new standard for inductance measurements of RF coils. The HP4191A has an accuracy that can be better than 1%

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for impedances near 50 ohms, and a machine to machine repeatability of approximately 1%. The significant feature of the HP4191A as a coil tester, with a frequency range of 1 MHz to 1000 MHz, is that it allows the actual application frequency to be used in a measurement.

Traditional Method of Specifying and Testing Inductors

Q meter measurements have been the conventional method of specifying L and Q parameter values. However, a Q meter requires a test frequency that is both within the range of its oscillator and within the limits of its tuning capacitor. Also, a Q meter measurement yields an inductance that is in terms of capacitance (pF). Q meters also have specific frequencies (called blue lines) that are easier to use than intermediate frequencies because an alternate scale on the tuning capacitor allows direct inductance readings.

Commercially available Q meters have accuracies of no better than 3% and typically much worse than this. Q meter inaccuracy requires the use of setup “standards” (correlation pieces). Correlation pieces are deemed to be the standard for a particular component part and are used to setup each instrument every time a test is performed. Correlation is still the traditional method and results in very little error, excellent repeatability and is applicable at any frequency. However, the method of correlation has significant logistical disadvantages: the establishment and accountability of specific correlation pieces between the manufacturer and the customer, as well as the task of adjusting every instrument for each test.

The other electrical parameters, SRF and DCR are generally specified along with L and Q but there is rarely any reference to the test method used. The lack of a specific method of testing SRF and DCR reflects the fact that the inductance is the dominant parameter and one which requires the most diligent control.

Application Frequency Testing

The basic complication with the traditional testing method is that the coils are tested at one frequency and used at another frequency. The graphs at right show the fundamental problem with the traditional testing method.

Inductance vs Frequency

Fig. 1 shows a log sweep of inductance vs. frequency for three different inductors. When these parts are tested at a typical Q meter frequency, they appear to be identical in terms of inductance. At the actual circuit frequency, these coils are quite different. These three coils can represent three different designs or three different coils of the same design. If the use frequency is the point where all three converge, then these coils are effectively the same. If the circuit frequency is significantly different from the test frequency, then the inductance at the use frequency cannot generally be implied from the test frequency.

Even if these coils had not deviated from each other, there is still a change in inductance. The consequence of an inductance shift with frequency is generally observed when a design requires a specific inductance and the particular coil does not perform as expected. The shift is generally attributed to fixturing differences and circuit parasitics and the specified value is compensated accordingly.

Figure 1—Inductance vs Frequency

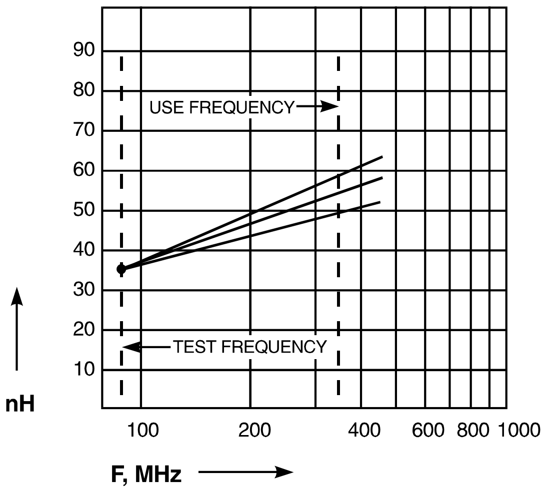
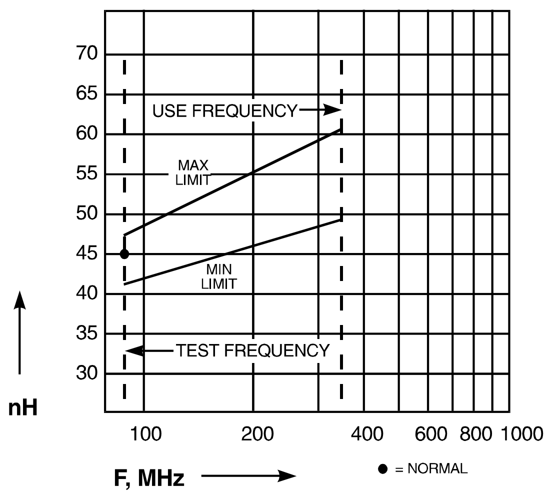


Figure 2—Inductance vs Frequency



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Inductance vs Frequency

Figure 2 shows another consequence of testing at a frequency other than the application frequency. It displays an inductance vs. frequency sweep for a particular coil. The normal inductance is indicated at both frequencies along with their tolerances. If this coil had been specified as a 5% inductor at the test frequency, it would have resulted in a 10% tolerance at the application frequency. These limits could have compressed over frequency or spread even farther, depending on the design. The fact that the limits are not constant with respect to each other results in a loss of tolerance control over frequency.

In all cases where the inductance changes with frequency, testing at the application frequency results in better specification control. Although correlation is still the most expedient method of reducing testing error, it is almost always applied at some frequency other than the application frequency. Testing at the application frequency, without correlation, can be an extremely effective and superior method of determining the application suitability of a coil.

Specifying Inductor Tests at Application Frequencies

The procedure to specify and the electrical test for an inductor at use frequencies is as follows:

1) Inductance

1.1) Specify the nominal inductance.

1.2) Specify the test instrument, fixture and frequency.

1.3) Specify the inductance tolerances.

1.3.1) Determine the allowable tolerance as a % using 6 sigma or other appropriate methods. The customer should test to this tolerance without correlation.

1.3.2) Evaluate the instrument error for the nominal impedance at the test frequency. Subtract this error % from the allowable tolerance found in step 1.3.1.

1.3.3) Establish the instrument and fixture repeatability. Subtract this error % from the result of step 1.3.2. This result is the tolerance to specify. The manufacturer should test to the specified tolerance without correlation as all errors have been accounted for.

2) Q

2.1) Specify the absolute minimum Q (allowable minimum).

2.1.1) Determine the allowable minimum using 6 sigma or other appropriate methods. The customer should test to this tolerance.

2.2) Specify the test instrument, fixture and frequency.

2.3) Specify the Q minimum for manufacture.

2.3.1) Evaluate the instrument error for the nominal impedance at the test frequency. Adjust the allowable minimum found in step 2.1.1 (i.e., increase the minimum Q by an amount equal to the instrument error).

2.3.2) Establish the instrument and fixture repeatability. Adjust the new allowable minimum found in step 2.3.1 (i.e., increase the minimum Q by an amount equal to the test repeatability). This result is the tolerance to specify. The manufacturer should test to the specified tolerance without correlation because all errors have been incorporated into the final adjustment of the Q specification.

3)DCR

3.1) Specify the absolute maximum DCR (allowable maximum).

3.1.1) Determine the allowable maximum using 6 sigma or other appropriate methods. The customer should test to this tolerance without correlation.

3.2) Specify the test instrument and fixture.

3.3) Specify the DCR maximum for manufacture.

3.3.1) Evaluate the instrument error for the nominal resistance. Adjust the allowable maximum found in step 3.1.1(i.e., decrease the maximum DCR by an amount equal to the instrument error).

3.3.2) Establish the instrument and fixture repeatability. Adjust the new allowable maximum found in step 3.3.1 (i.e., decrease the maximum DCR by an amount equal to the test repeatability). This result is the tolerance to specify. The manufacturer should test to the specified tolerance without correlation because all errors have been incorporated into the final adjustment of the DCR specification.

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4) SRF

4.1) Specify the absolute minimum SRF (allowable minimum).

4.1.1) See SPECIFICATION EXAMPLE below.

Component prints should indicate that inductance is the critical parameter. Assuming the need exists for a sorted population, only inductance needs to be 100% tested. The other parameters will track inductance and should only be qualified.

Specification Example

As an example, we will specify the aforementioned parameters for a chip inductor.

The coil in question was measured at 300 MHz, the use frequency of the circuit for which the component was designed.

INDUCTANCE

The coil was measured to have an average inductance of 53.8 nH with a standard deviation of 1.1 nH. We will use the average as the nominal.

A six sigma specification for the indicated coil would be 53.8 nH $\pm$ (6 $\times$ 1.1 nH), or $\pm$ 12.3% of a nominal 53.8 nH. We have then satisfied steps 1.1 and 1.3.1, the specification of the nominal inductance and its tolerance.

We will choose the HP4191A as the tester, and the Coilcraft SMD-A as the test fixturing. We will specify the component to be tested at the 300 MHz use frequency. We have now satisfied step 1.2, the identification of test instrumentation and frequency.

The basic measurement error associated with the HP4191A, testing at 300 MHz for a 53.8 nH inductance is approximately 0.5%. We subtract the measurement error from 6 sigma tolerance of 12.3% and obtain nominal $\pm$11.8% tolerance to compensate for instrumentation accuracy. We have then satisfied step 1.3.2.

The HP4191A/SMD-A testing setup has an overall session to session repeatability of 1.0%. We adjust the resultant tolerance of 11.8% given above by an additional repeatability error of 1.0%. We have the final manufacturing tolerance (print specification) of 10.8%, thus satisfying step 1.3.3.

Q

The Q parameter tracks the inductance parameter very closely, that is given the same designed coil the Q will not deviate without a noticeable change in L. For example, a shorted turn will affect both the Q and L parameters simultaneously. Because of the dependency of Q on L, reliable Q measurements can be made on Q-meters which cannot support high application frequencies and which are most accurate at lower frequencies,

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although application frequency Q measurements are ideal whenever possible.

The average Q of the coil was measured to be 42.2 on a Meguro MQ0171 Q-meter at 150 MHz with a standard deviation of 0.8. Using the average again as the nominal we obtain a six sigma minimum of 42.2 – (6 × 0.8), or an allowable minimum Q of 37.4 (nominal - 11.4%). Step 2.1.1 is completed.

We will specify an MQ-171 Q-meter, the Coilcraft CCF-764 test fixture, and a 150 MHz test frequency (Step 2.2).

The instrument error of the MQ-171 at 150 MHz is 7.5%. We adjust the minimum Q specification to compensate for instrument error and obtain a new minimum Q of 40.6 (nominal - 3.9%). Step 2.3.1 is completed.

The session to session repeatability of the MQ-171/CCF-764 is 2.0%. We make our final adjustment to the Q minimum specification by subtracting the repeatability error from the last adjustment. The adjustment is 3.9% - 2.0% = 1.9%, which brings the manufacturing Q minimum (print specification) to 41.4 (Step 2.3.2).

DCR

The average DCR of the coil was measured to be 1.97 Ohms with a standard deviation of 0.05 Ohms. Using the average as the nominal we obtain a six sigma maximum of 1.97 + (6 × 0.05), or an allowable maximum DCR of 2.27 Ohms (nominal + 15.2%). Step 3.1.1 is completed.

We will specify model 510A Micro-Ohm meter from Cambridge Technology, Inc. and the Coilcraft SMD-C chip fixture to perform the DCR tests. (Step 3.2).

The instrument error of the 510A is 0.25% for a 2.0 Ohm measurement. We adjust the maximum DCR specification to compensate for instrument error and obtain a new maximum DCR of 2.26 (nominal + 14.95%). Step 3.3.1 is completed.

The session to session repeatability of the 510A is 0.5%. We make our final adjustment to the DCR maximum specification by subtracting the repeatability error from the last adjustment. The adjustment is 14.95% - 0.5% = 14.45%, which brings the maximum specification (print specification) to 2.25 Ohms. Step 3.3.2 is completed.

SRF

The SRF is not an independent parameter, given that the other parameters of L, Q, and DCR are specified. The SRF should generally be specified as at least twice the application frequency. The manufacturer can indicate the expected SRF of particular coils and coil constructions.

Specifications With Correlation

Each of the primary coil parameters in the above example are specified without the use of correlation. In this technique, each of the individual measurement errors are reflected in the specifications. The use of correlation in conjunction with use frequency testing can eliminate these errors and allow the specifications to be tightened. Correlation can be used with any of the inductor parameters but is most often applied to inductance and Q.

Conclusion

Coil inductance and Q are frequency dependent and testing methods have further influence on these parameters. Specifying and testing at the factual circuit frequency is an appropriate method of controlling inductor parameters. Use frequency testing assures components consistent with their intended application.

The primary inductor parameters are interrelated design functions of the coil and the print should reflect that the inductance is the dominant test parameter. The inductor specification should also take into account the component variations and instrumentation errors.

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