DATATRONICS

MEASURING TRANSFORMER DISTRIBUTED CAPACITANCE

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This article is a general discussion of distributed capacitance, Cd, in transformers with emphasis on measurement. We will discuss how capacitance occurs, references to formula for calculating, how capacitance is modeled, how Cd is measured (with three cautionary notes) and guidelines to aid in evaluating / measuring Cd.

Capacitance in a transformer winding cannot be avoided. The voltage difference between turns, between winding layers and between windings to core create these parasitic elements. In general, part of the designers' task is to keep capacitance to a minimum. On rare occasions winding capacitance is increased to reduce ringing in switching transformers.

There are several capacitive elements in a transformer. Capacitance occurs winding to winding, turn to turn, windings to core and stray capacitances between terminals and case. To better understand the capacitance phenomenon in transformers, see REF [1, 2 & 3]. Reference [6] is an article aimed at Cd of coils for higher frequency applications with several test methods. This discussion will be aimed at the measured capacitance that appears across a winding in a transformer. Each winding in a transformer will add capacitance to this total. Transformer action will cause the sum of reflected capacitances to appear at the terminals of each winding.

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by Kirby Creel

In the literature, the capacitance appearing across the terminals of an inductor are almost universally identified as the distributed capacitance "Cd". Authors identify the parasitic capacitive elements of a transformer with various symbols. For this discussion, distributed capacitance "Cd" will be the total capacitance. The total is the winding capacitance of a winding used as the reference plus the sum of capacitances of all other windings reflected by the square of the turns ratio. See (Equation 1) below.

$$Cd = C_{(REF)} + C_{(A)}\left(\frac{N_{(a)}}{N_{(REF)}}\right)^2 + C_{(B)}\left(\frac{N_{(B)}}{N_{(REF)}}\right)^2 + \dots \qquad \left[EQ.1\;\right]$$

To illustrate with an example, consider the transformer schematically shown in Figure 1. The example was made by testing SRF (Self Resonant Frequency) after each winding was added and the capacitance increase by each winding was calculated. Each winding has the turns and the related capacitance identified. If this transformer were to be modeled in one of the circuit analysis programs, the transformer as shown would be acceptable.
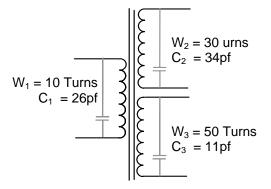

$W_2 = 30$ urns
$C_2 = 34$pf

$W_1 = 10$ Turns
$C_1 = 26$pf

$W_3 = 50$ Turns
$C_3 = 11$pf

FIGURE 1

Table 1 illustrates how each capacitance reflected to a reference winding creates the Cd "total". (see EQ.1) Note that in the last column of the table, the SRF is calculated from the reference winding inductance and Cd. The transformer action causes the reflected capacitances to appear in a ratio that makes the SRF the same with different turns. The fact that all windings will have the same SRF is not intuitive. Transformers with poor coupling between windings or a strong drive sensitivity will have differences in SRF.

Reference Winding	Effective Capacitance Reflected to reference winding (pF)			Cd (pF) Total	L(mH)	SRF MHZ
	C_1	C_2	C_3			
W_1	**26.00**	306.00	275.00	607.00	**.04**	1.0214
W_2	2.89	**34.00**	30.56	67.45	**.36**	1.0214
W_3	1.04	12.24	**11.00**	24.28	**1.00**	1.0214

NOTE: VALUES SHOWN IN (**BOLD**) ARE GIVEN. ALL OTHERS ARE CALCULATED.
TABLE 1

MEASURING TRANSFORMER DISTRIBUTED CAPACITANCE
by Kirby Creel

When modeling a transformer, the capacitance can be included with one of the total values rather than the three individual values. See Figure 2.

$W_2 = 30$ Turns

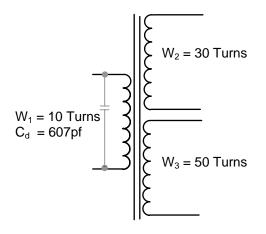$W_1 = 10$ Turns
$C_d = 607$pf

$W_3 = 50$ Turns

FIGURE 2

Having an accurate value for Cd is important in circuit modeling. As the frequency of operation increases the capacitance effects play a larger role in the operation of the circuit and a correct value for the model becomes more important.

The measurement of Cd is a complex operation that requires care. Cd cannot be measured directly. The "standard" method is to measure the SRF of a transformer (or inductor) and calculate the Cd, see EQ. 2.
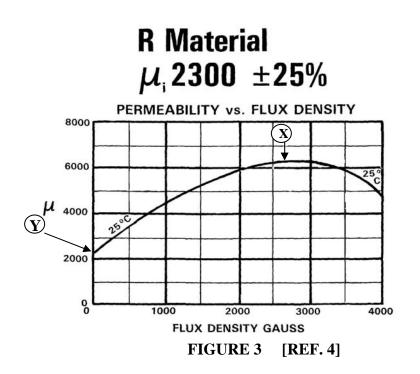

$$Cd = \dfrac{\left(\dfrac{1}{2\pi(SRF)}\right)^2}{L}$$

SRF is in Hertz
Inductance is in Henries $\qquad [EQ.2\ ]$
 Cd in Farads

The total capacitance of the device that resonates with the inductance of the winding tested is the Cd. Experience shows that this result is considered axiomatic by many Engineers. In a majority of devices this method will provide the correct value of Cd. This article describes three factors that can cause the measured value to be in considerable error. To demonstrate each of these factors, an example is provided to give the reader a better understanding of the problem.

In each of the example coils, a toroid core was selected. Toroids most closely demonstrate the material characteristic curves provided by manufacturers. Any gap in a core structure will effect the material characteristics. In a gapped core, the following factors will still cause error in the readings but the effect will be reduced.

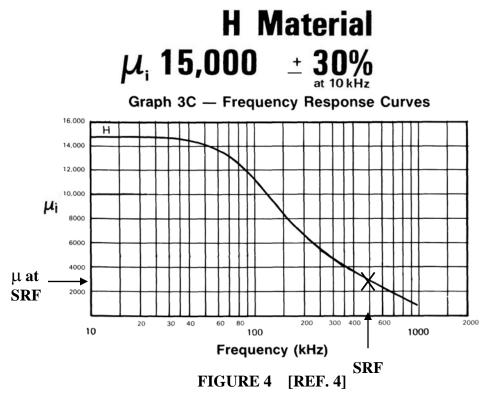MEASURING TRANSFORMER DISTRIBUTED CAPACITANCE
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1) The first error factor is caused by measuring the inductance of the device at a drive level that exaggerates the inductance at SRF.   A coil was wound on an "R" material core and the inductance was tested with 1.0 volt at 1.0 kHz. (The 1 volt at 1 kHz is a typical specified value.) The same coil was tested with .01 volts at 10 kHz. Table 2 shows the calculation of the Cd based on the two measured inductance values. Most ferrite materials have inductance values that are sensitive to the drive level. In this case, Magnetics Incorporated "R" material was selected. The material permeability varies with drive level. See Figure 3 below. The possible error as shown in the curve is greater than 2:1. The solution to this factor is to measure the inductance at a low flux level. As a guideline use 10 gauss maximum.

FIGURE 3   [REF. 4]

TEST VOLTAGE	INDUCTANCE	SRF	CALCULATED Cd pF
1.0V at 1.0 kHz	7.60 mH (POINT X)	703 kHz	6.74
0.01V at 10 kHz	4.16 mH (POINT Y)		12.32

TABLE 2

MEASURING TRANSFORMER DISTRIBUTED CAPACITANCE
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2) The second error factor is more subtle. The error is caused by the drop in permeability as the frequency of the applied signal is increased. See Figure 4. Note that the "H" Material curve is typical of a production lot and does not constitute a guaranteed response. Experience has shown that individual lots will vary widely.   A coil was wound using "H" material and the inductance tested at a low flux level at 10 kHz.
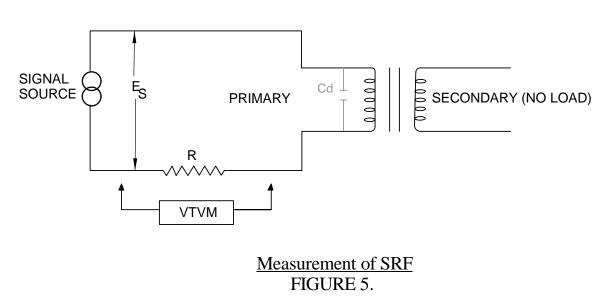

FIGURE 4   [REF. 4]

The SRF was measured and Cd calculated. The question becomes what is the "true" Cd ? The answer can be "measured" by winding an identical coil on a core that is not subject to the drop in permeability with increased frequency. A second coil was wound on a core made from Magnetics "A" material using the identical winding technique. Table 3 shows readings and calculations. The calculated error is about 46%. Figure 4 shows the possibility of errors approaching 5:1.

FERRITE MATERIAL	INDUCTANCE	SRF	CALCULATED Cd pF
H	38.5 mH	499 kHz	2.64
A	1.734 mH	1.565 MHz	5.96

TABLE 3
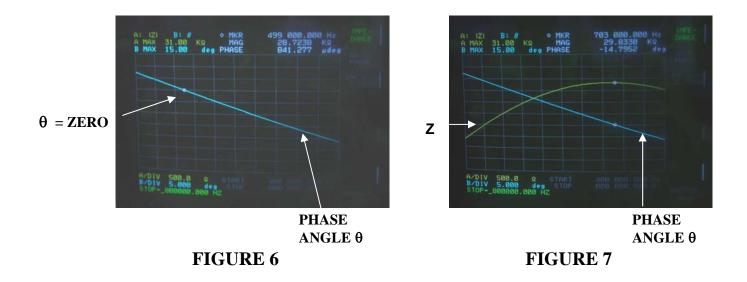
MEASURING TRANSFORMER DISTRIBUTED CAPACITANCE
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3) The third error factor has to do with the SRF measurement method. The generally accepted method is to find the maximum impedance point of the device. The impedance of a parallel resonant circuit reaches a maximum at the resonant frequency. By measuring the "line" current using the voltage across a series element the maximum impedance point can be determined. One source of the test method is shown in Figure 5 from military specification MIL-PRF-27. Paragraph 4.7.12.9 of the Military Specification defines the SRF as the frequency that the minimum dip in voltage occurs on the VTVM. The definition of SRF is the frequency at which the distributed capacitance resonances with the self inductance and the reactive components cancel. The maximum impedance point and the SRF can be quite different.

MIL-PRF-27F

Measurement of SRF
FIGURE 5.

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Figure 6 shows the phase angle of current plotted against frequency, using a Hewlett Packard HP-4194A. The plot is the same coil as discussed in (2). The resonant frequency is 499 KHz (zero in this case is actually +0.00084°). Figure 7 is the exact same display with the impedance included. The impedance maximum occurs at 703 KHz. The point where the phase angle is zero (resonance) does not coincide with the maximum impedance point.

θ = ZERO

PHASE
ANGLE θ

FIGURE 6

Z

PHASE
ANGLE θ

FIGURE 7

The Cd is calculated in table 4. Results of the "A" material from Table 3 are included. Note the large difference in the calculated values. Selection of the test method (SRF or maximum "Z") may give very different results.

FERRITE MATERIAL	INDUCTANCE	SRF θ = 0	MAX "Z"	CALCULATED Cd (pF)
H	38.5 mH	---	703 KHz	1.33
H	38.5 mH	499 KHz	---	2.64
A	1.734 mH	1.565 MHz	1.565 MHz	5.96

TABLE 4

MEASURING TRANSFORMER DISTRIBUTED CAPACITANCE
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All three of the errors noted will give Cd values lower than the actual. In a worst case scenario, the total error may be greater than a factor of 10. Below are some guidelines to help the reader to anticipate when to expect errors and how to avoid them in determining Cd.

Problem indicators
a) High permeability cores (includes nickel laminations)
b) Toroid cores (includes nickel strip)
c) Ferrite cores
d) High perm MPP
e) Cores that are permeability sensitive with level or frequency
f)   High turns ratios (error effects are multiplied)
g) Applications where the Cd is a critical parameter
Indicators of fewer problems
h) Low perm cores
i) Gapped core structure
j) Bobbin style windings (measurements can be made on the
     wound bobbin before core is installed)
Measurement guidelines
k) Take inductance measurement at a low level
l)   Review the core characteristics to anticipate whether frequency
      or test level will effect the readings.
m) Determine the measurement method (impedance or frequency)
n) Calculate a predicted value. Reconcile any significant difference.
o) Wind / test another core that is not as sensitive to level or frequency.
p) Because the results may be in pF, extra care must be exercised
      in zeroing out errors in fixtures or test leads.
q) If the individual capacitances are of interest, test SRF after each winding. The
      capacitance added by each winding can be calculated.
r)   The following ESTIMATED Cd for toroids with a single winding is
      provided as a "sanity" check. See REF [5] . For more than one winding,
       (all windings with a ratio of 1:1) multiply the estimated capacitance by the
        number of windings -
           Small (less than .25" OD) = 6 to 10 pF
           Medium (.25" to 1" OD)   = 10 to 25 pF
           Large (greater than 1" OD) = 25 to 75 pF

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