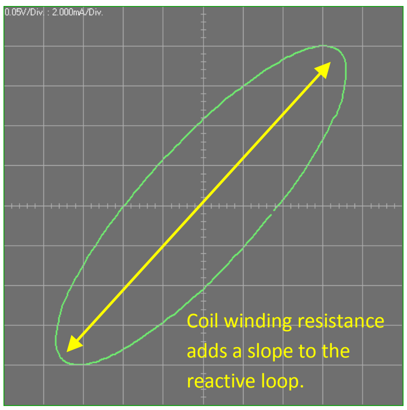
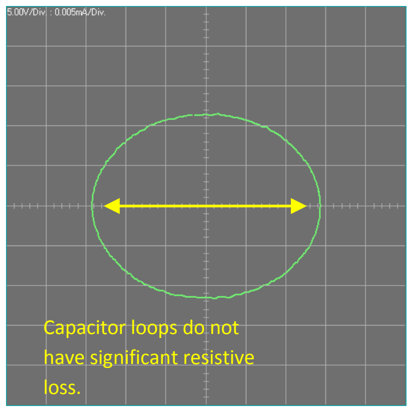
Inductors and Transformers

The question is: Can Mini_CT measure inductance and test transformers? The answer is: Sometimes. Passive components that use magnetic cores are more frequency dependent than ones without cores. In addition the core has hysteresis, losses and it may saturate at high drive levels. All this can make measurements difficult.

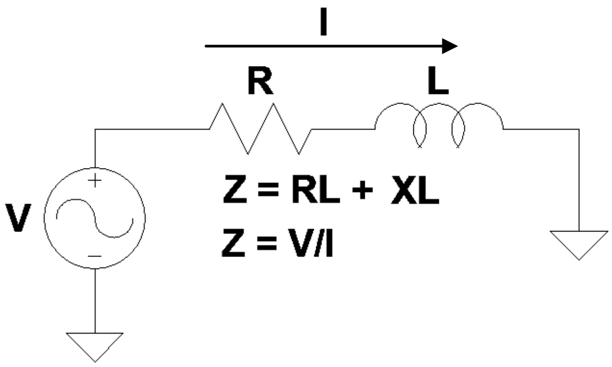
Air core inductors do not have the non-linear limitations of magnetic core devices. Unfortunately, at 60Hz the inductor needs a lot of windings to have a minimum reactance. A minimum reactance of 10 ohms or inductance around 25mH will allow a reasonable measurement. The measurement is also associated with a high winding resistance. Winding resistance may dominate the measurement as it can be about or higher than the reactance. The perfect reactance ellipse no longer exists.

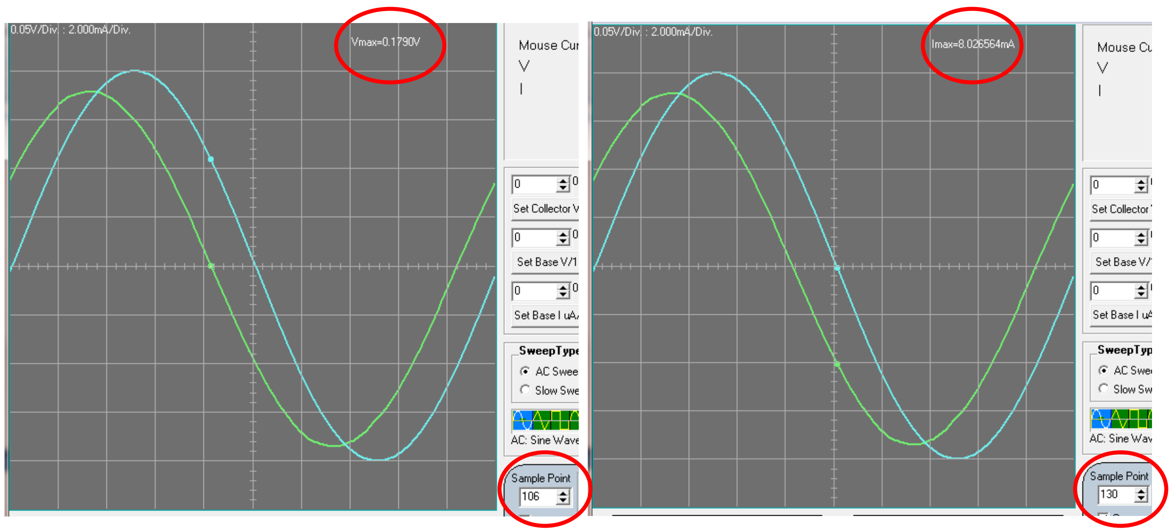




At 60Hz, capacitors have a very high reactance as compared to their losses. The main capacitor loss is typically the equivalent series resistance or ESR. A 10uF capacitor has a reactance of 265 ohms while the ESR is generally an ohm or less. The reactance dominates and the measurement is simplified to finding peak voltage and peak current of the reactance ellipse.

The basic inductor can be modeled as an inductor in series with a resistance. Resistance includes winding resistance and core loss. To measure inductance, two values are needed: The magnitude of the impedance and the phase of the impedance. The magnitude is the peak voltage divided by the peak current. Phase is the separation between the voltage and current sinusoidal waveforms. Both can be obtained in the X-t plot mode.

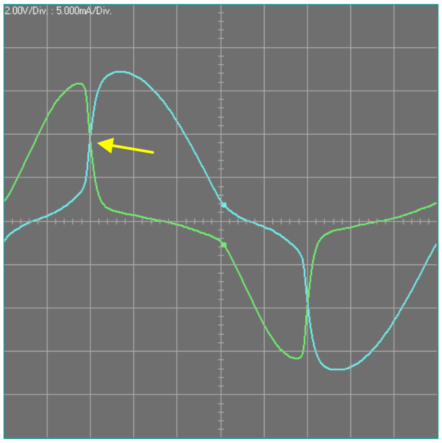




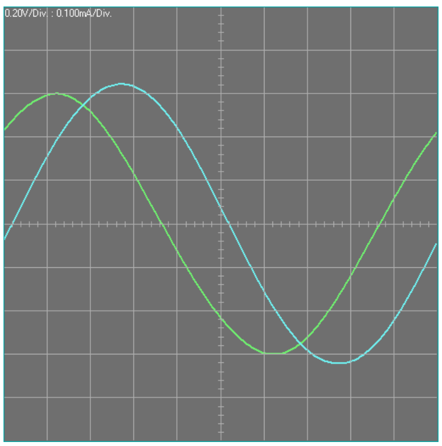
Measuring the Sample Point locations for the voltage and current zero crossing is all that is needed to identify phase. There are 256 sample points. If the voltage is at Sample Point 106 and the current is at Sample Point 130 then the phase is 360*(130-106)/256 = 33.75°. With the peak voltage at 0.179V and the peak current at 8.03mA, the impedance magnitude is 22.29Ω.

R_L = Mag * cos(33.75°) = 22.29 * 0.831 = 18.53Ω
X_L = Mag * sin(33.75°) = 22.29 * 0.556 = 12.38Ω
L = X_L/(2*π*60) = 12.38/377 = 33mH

The above example is the winding resistance and inductance of a small motor. The core does not saturate at the low test frequency. Transformers designed for high frequency switching and even small audio transformers may show core saturation at 60Hz. Good low frequency response requires a lot of inductance without core saturation. Keeping the drive level low may avoid core saturation but it adds more noise to the test.

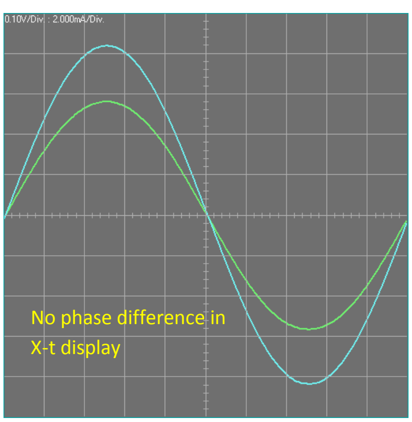


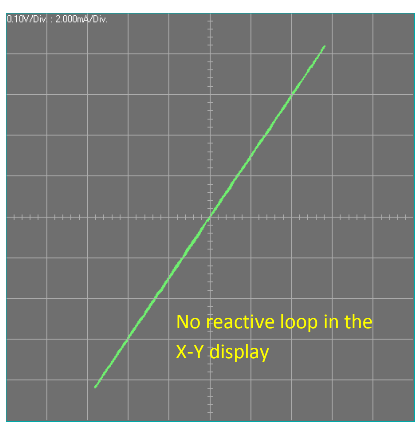
When the core saturates, the voltage drops and the current rises. This audio transformer is good to 30Hz but only at low drive levels.



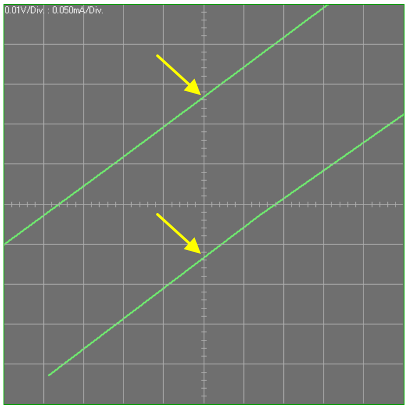
The same audio transformer with a lower drive has no saturation. The winding resistance plus core loss is 1865Ω and the inductive reactance is 1525Ω. For good low frequency response, the secondary winding inductance is 4.04H.

High frequency response of audio transformers relies on low leakage inductance. This can be evaluated by measuring one winding pair while shorting the other winding pair. If the leakage inductance is low, the winding will be a pure resistance with little or no reactance.





With the secondary shorted on the audio transformer, the primary has almost no inductance (no phase shift). The input appears resistive as the X-Y plot shows.



Expansion of the current in the X-Y mode can reveal small phase differences. See the following example on how to measure phase using Lissajous figures.

This primary winding leakage inductance is 8.89mH while the secondary winding leakage inductance is 1.08mH. The resistive part for the primary is 271Ω and the resistive part for the secondary measured 33.7Ω.

Winding capacitance is measured either between primary and secondary or from each winding to shield. The audio transformer in this example has 80pF of primary winding capacitance to shield and 60pF of secondary winding capacitance to shield.

To model the transformer in SPICE, the following parameters would be used:

L1: Inductance = 4.04H, Series Resistance= 33.8Ω, Capacitance = 60pF
L2: Inductance = 32.26H, Series Resistance= 271Ω, Capacitance = 80pF
K = 0.99987

Where $K = \sqrt{1 - (L_{Leakage}/L)}$. The inductance L is for the winding and the leakage inductance is for the same winding.

You might be wondering if there is a way to get a higher test frequency. The answer is yes. The following script file generates a sine wave 16X as fast or 960Hz. At this frequency 2πf = 6032.

```
rem 16x sine wave
custom 8192
for 16
 custom 2048
 custom 1265
 custom 601
 custom 157
 custom 1
 custom 157
 custom 601
 custom 1265
 custom 2048
 custom 2831
 custom 3495
 custom 3939
 custom 4095
 custom 3939
 custom 3495
 custom 2831
next
stop
```

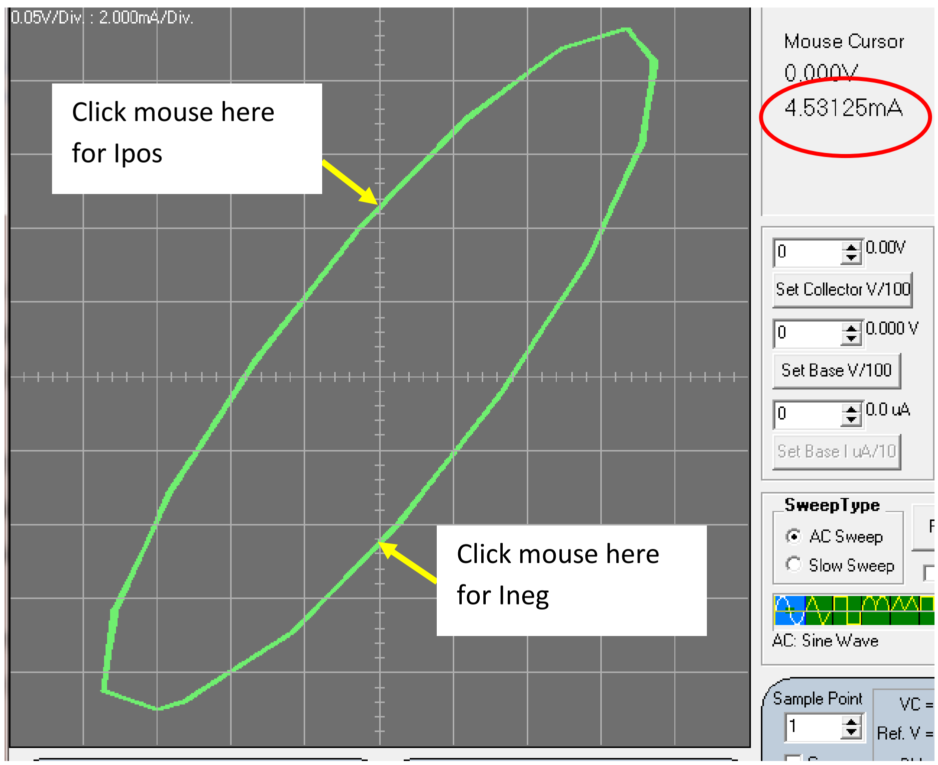
Note: Clicking any other waveform type on the Mini_CT application will overwrite the 16X sine waveform. You will need to run the script program to restore it. You can increase the sensitivity of not only inductor testing but also capacitor testing. Divide the capacitance measurement by 16 to obtain the correct result.

The X-t display cannot be used to find phase at 960Hz. Nor can small phase differences at 60Hz be measured. Instead, the Lissajous figure in the X-Y display and the Mouse Cursor can extract phase.

First acquire a trace with the ***Avg 8*** button. Find the maximum current and minimum current using the ***Value*** list box. Imag = Imax - Imin. Next find the maximum voltage and minimum voltage using the ***Value*** list box. Vmag = Vmax – Vmin. Calculate the impedance magnitude Z = Vmag/Imag.

Using the mouse cursor, find the current at the zero voltage crossing points. Izero = Ipos – Ineg. The phase angle is ϕ = arcsin(Izero/Imag).

Inductor resistance is R_L = Z * cos(ϕ) and inductor reactance is X_L = Z * sin(ϕ)



The test voltage is low so the gain switch was set to 4.5X for more resolution. The part above had an impedance magnitude Z= 19.9 ohms and a phase angle of 29.58°. Therefore Z = 17.31 + j9.83Ω. At 960Hz, the inductance calculates to 1.63mH.

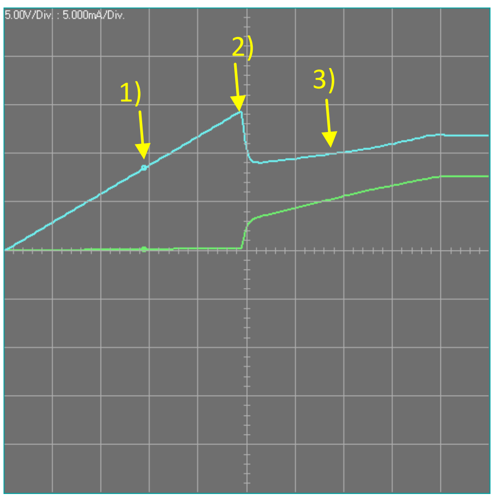
To simplify measuring impedance magnitude, phase and inductance, functions to extract these values are available in the Cursor Functions ***Value*** List Box. The phase algorithm searches for the voltage zero crossing and interpolates the current values to correct for sampling spacing. Be careful about the result. If the trace is not noise free around zero, incorrect phase measurement may occur from multiple crossing points. Also, series inductance and parallel capacitance values are for 60Hz only. Divide the value by 16 if using 960Hz.

As you can see, it is possible to characterize some inductive devices. Mini_CT is limited to measuring large value inductors commonly found in audio circuits. As noted earlier, small motors also have inductor properties.

If you have a small motor that will rotate unloaded at less than 20mA, then you might be able to obtain some estimates of additional characteristics. For example, motor starting and running torque are related to the torque constant K_T (N-m/amp) and current. The motor speed is related to a voltage constant K_E (V/RPM) and generated armature voltage. Calculating the back electromotive force is simply the applied voltage minus the motor current times the winding resistance.

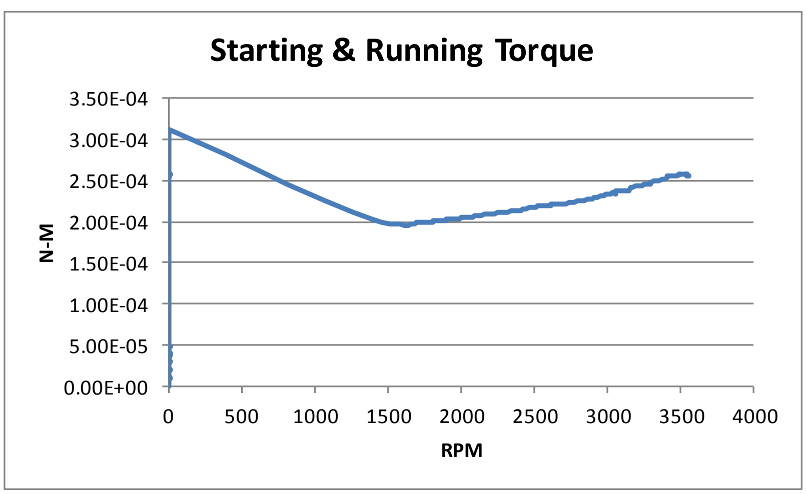
Formulas for motors:

$$\text{Torque} = K_T * I$$
$$\text{RPM} = (V - I * R) / K_E$$



Applying a ramp voltage to the armature of a small DC motor yields:

1) Motor winding resistance = V/I
2) Starting torque = $I*K_T$
3)Running torque = $I*K_T$.



Data exported to a spreadsheet allows calculation of torque and motor speed.

$K_T = 3.12 \times 10^{-4}$ N-m/A
$K_E = 2.10 \times 10^{-3}$ V/RPM
R = 19.3Ω

A script program to step the motor voltage using the Collector source with a 500 ohm series resistance.

```
rem small motor example
setcollector 0
voffset 0
ioffset 0
vperdiv 8
iperdiv 11
sweepstep 1
traceno 1
notodisp 1
plottype 1
samplepoint 0
live 0
cursor 0
update 0
baseuav 0
setcollector 0
setbasei 0
startcollector 0
stepcollector 10
setsweepvalues
autoinc 0
filteron 0
wave 0
sweeptype 0
show 0
hide 1
hide 2
hide 3
hide 4
hide 5
hide 6
comparestep 1
comparetrace 1
compare 0
baseat 128
rem voltage gain x1
rem sense R 500
setcollector 0
plotreset
name dcmotordata
open n
storerem CV CI BV BI
for 256
 readvoltages
 plotcvic
 storeread
 addcollv 6
next
setcollector 0
cursor 1
samplepoint 0
mark
samplepoint 74
value 0
storerem Winding Resistance
storevalue
stop
```