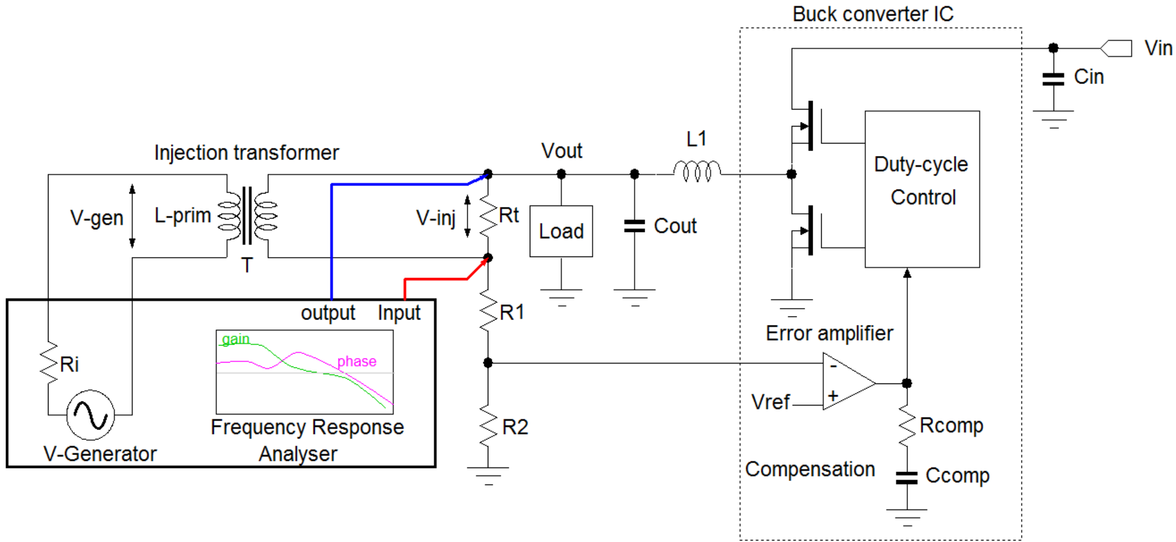
Roland van Roy Feb 13, 2018

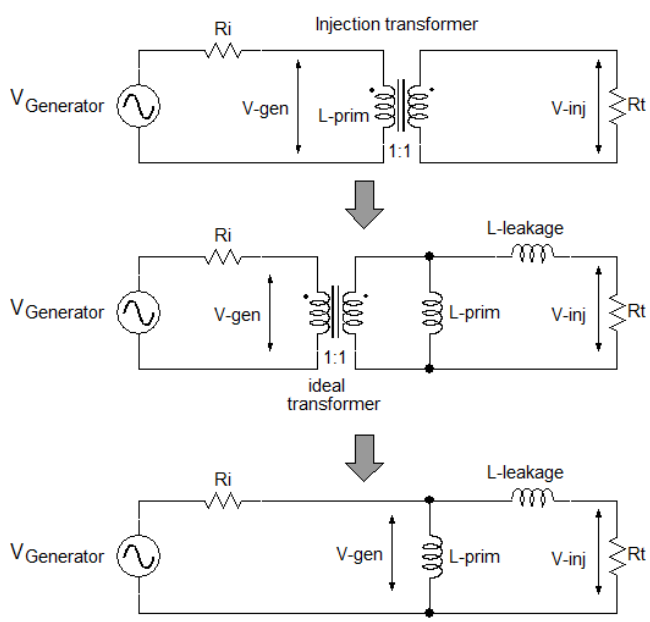
Make your own insertion transformer for measuring loop gain-phase of power converters

Below figure shows the basic measurement setup for measuring the loop gain of power converters (a buck step-down converter in this example).
The feedback loop (consisting of R1, R2 and the error amplifier) is opened at the top of R1.
A small sine-wave signal is injected into the loop via the generator and an injection transformer which is terminated with a resistor Rt. (Rt normally ranges from 10Ω ~ 50Ω, it should be small with respect to R1).
The small injected signal travels through the converter feedback loop, and by measuring the loop input and converter output with a Frequency Response Analyzer (FRA), the converter control loop gain and phase can be calculated and shown as a Bode plot.



Important criteria for the signal injection transformer:

- The transformer must be able to provide sufficient injection voltage V-inj over a wide frequency range
- Minimize generator signal attenuation at low frequencies 10~100Hz (related to generator Ri, Injection transformer primary inductance L-Prim and termination resistor Rt).
- Maintain flat response up to around 1MHz (related to the transformer leakage inductance and Rt)



The transformer can be seen as an ideal transformer, and two separate inductors for the primary inductance and the leakage inductance.

At low frequencies, leakage inductance can be neglected. The impedance due the primary inductance will drop and attenuate the V-gen voltage according:

$$V_{INJ} = \frac{\omega L_{PRIM} // R_t}{R_i + \omega L_{PRIM} // R_t} \cdot V_{GENERATOR}$$

At high frequencies, the leakage inductance will form a low pass filter with Rt:

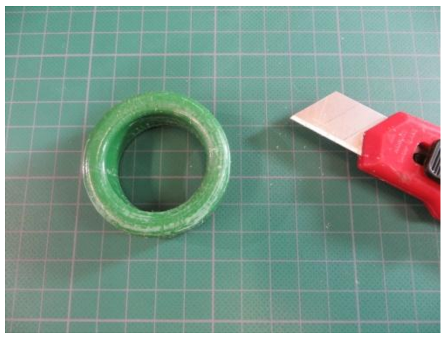
$$V_{INJ} = \frac{R_t}{R_i + \omega L_{LEAKAGE} + R_t} \cdot V_{GENERATOR}$$

So when designing the injection transformer a high primary inductance and low leakage inductance are desirable.

Selection of materials for the DIY signal insertion transformer:

High primary inductance and low leakage inductance means selecting a core with high permeability and shape & winding structure for highest winding coupling. Ring cores which are used in high current common mode chokes are quite suitable in this respect: These provide high inductance per winding and have no airgap. The primary and secondary windings should be wound bifilar for optimal coupling. Due to the high permeability and non-gapped core, the transformer may easily saturate at already moderate current levels. A larger core cross section will be better to achieve higher current capability without saturation.

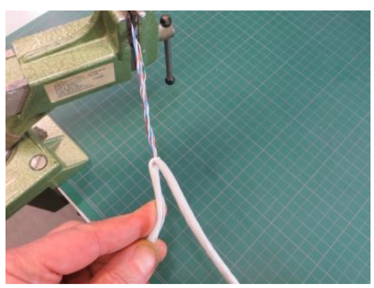
After searching various common-mode vendors, I selected the largest toroid core common mode choke from CoilCraft: CMT4-10-15L; see https://www.coilcraft.com/cmt.cfm
(Note we only need the green core. Most likely all parts from the CMT4 series will be OK, as I guess they all use the same core)

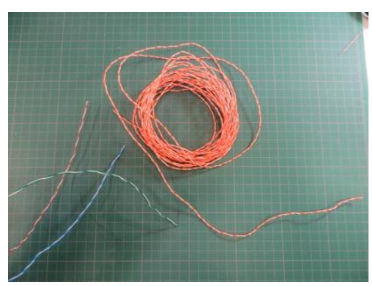


Preparing the core: Remove the plastic parts and glue. Then remove the copper windings from the core. For easier winding, carefully remove most of the core's varnish with a knife.

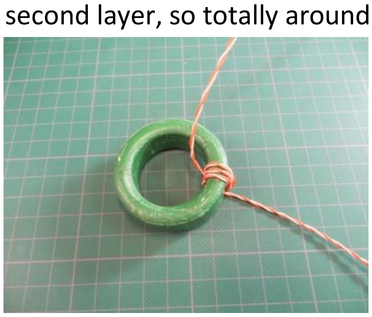
For the windings, good coupling and easy winding can be achieved by using twisted isolated wire. You could use any thin isolated wire for this, but an easy solution for this is to take a twisted pair out of a CAT5 Ethernet cable, which has 4 twisted pairs inside the main isolation sleeve.

You need around 6.5 meters of cable: Remove the outer isolation and remove one twisted pair from the other pairs.

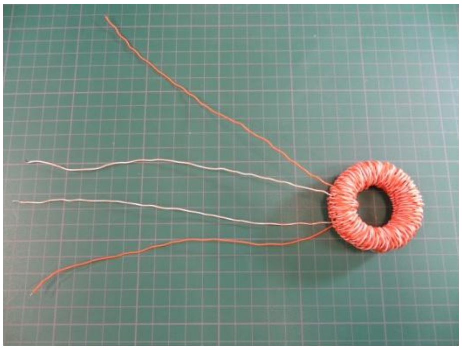


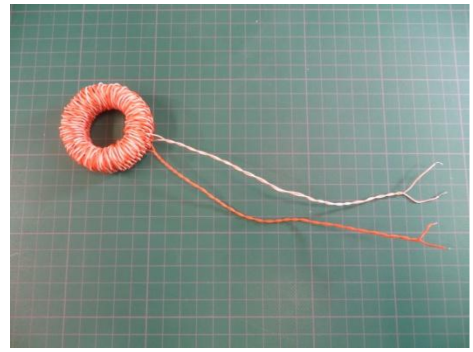


Winding the transformer: Start in the middle of the wire and start winding one end to fill the complete core.
Place the windings tight, you should be able to get around 70 windings on the first layer. Then start with the other wire end and wind the second layer, finishing close to the previous finished winding end. I got around 66 windings on the second layer, so totally around 136 windings.

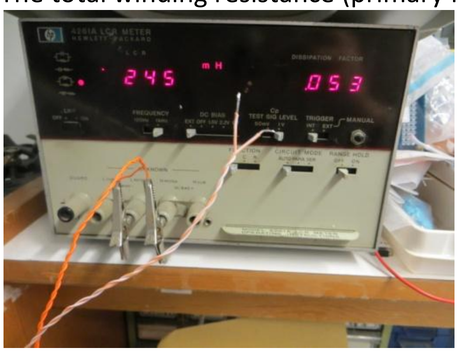


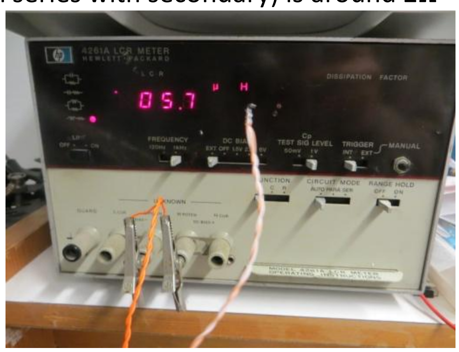
Now separate the twisted wire ends. Then twist the wires with the same color, to form the primary and secondary winding.

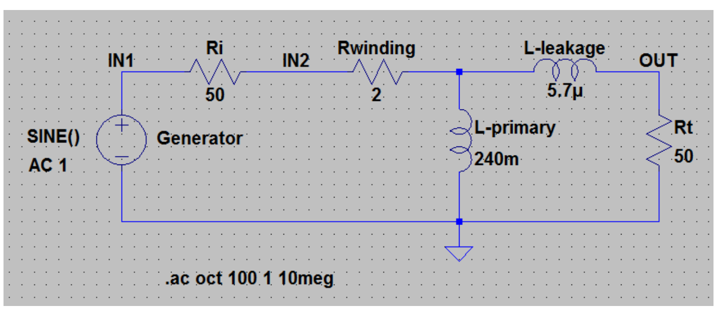




To measure the primary inductance, measure one winding with an LCR meter and keep the other winding open.
I got 245mH primary inductance.
Then measure the winding inductance with the other winding in short-circuits. I got 5.7uH leakage inductance.
The total winding resistance (primary in series with secondary) is around 2Ω

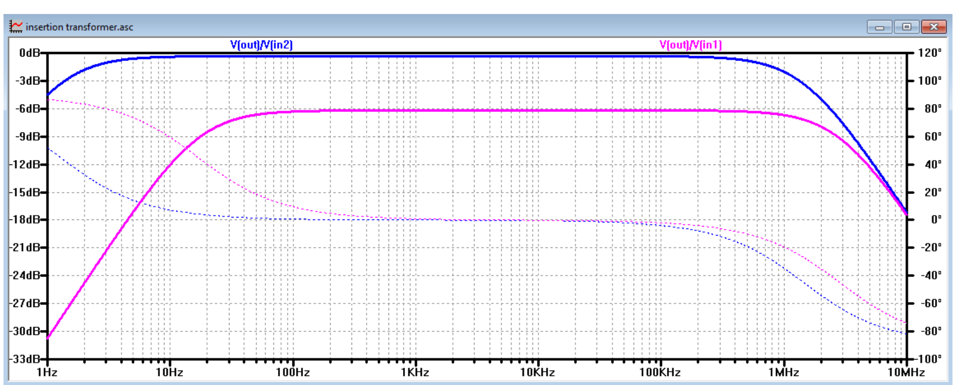






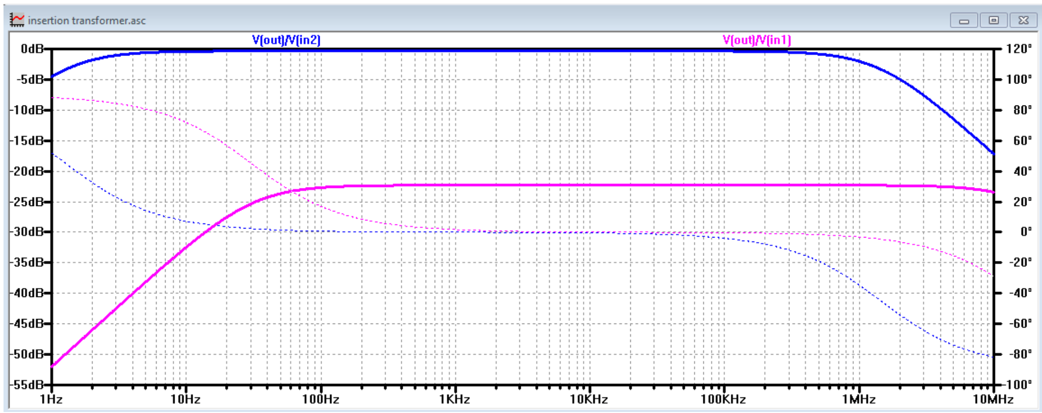
With these values, you can make some calculations (or do a simulation):
I used LTSpice in AC analysis to check the circuit with 50Ω generator impedance and 50Ω termination impedance.

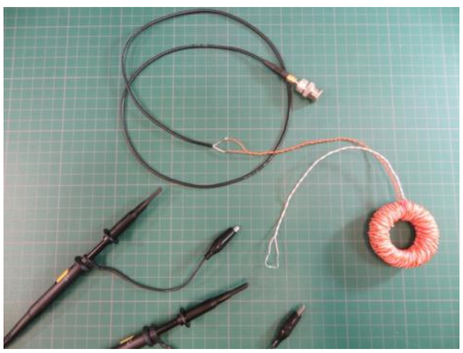
The pink curve is the transfer from generator before its internal resistance to termination resistor, the blue curve is the transfer from the generator after its internal resistance to termination resistor. The blue curve has a low frequency roll-off due to winding resistance, primary inductance and termination resistance, and a high frequency roll-off due to the leakage inductance. The pink curve transfer includes the generator internal impedance now has a low frequency roll-off due to the generator resistance, primary inductance and termination resistance. (See previous formulas).

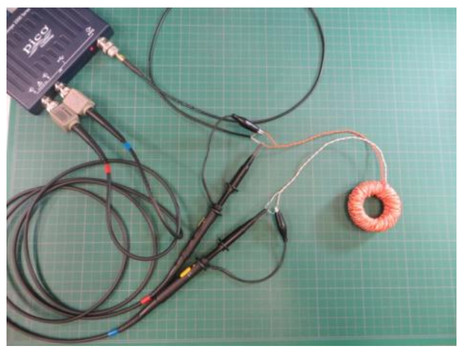


You can see that the signal attenuation is quite flat from 50Hz to 1MHz. Note that the curves will be different for different generator internal resistance and termination resistance.

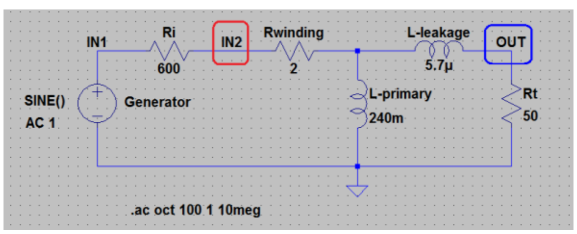
Below is a simulation where I changed the generator internal impedance to 600Ω, which matches my PicoScope 2208B generator output impedance. The total signal to output attenuation (pink curve) is increased. But the response is still quite flat over a wide frequency range.



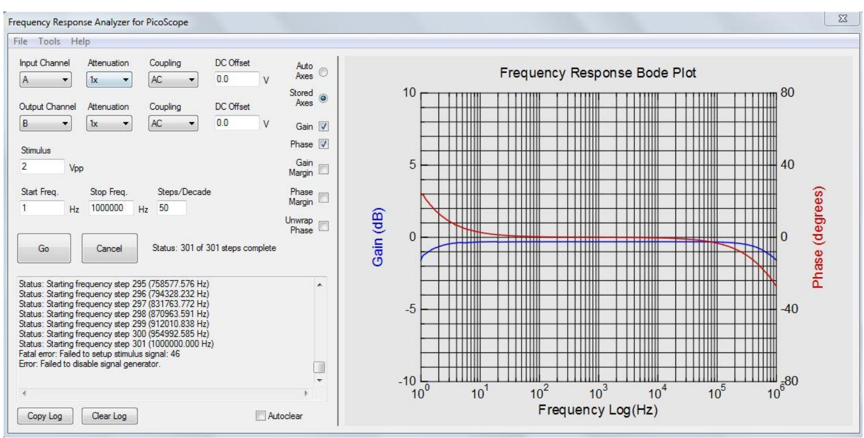


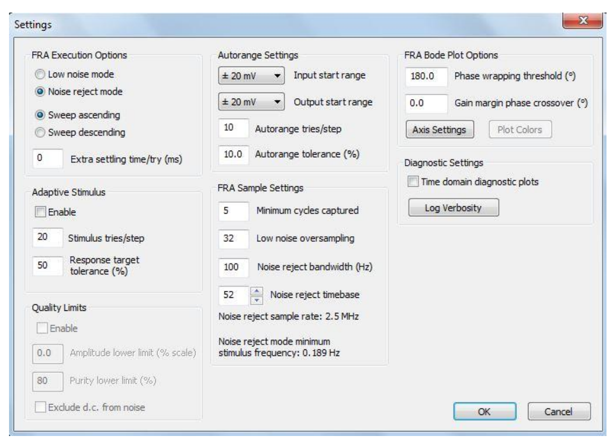


For testing the transformer transfer with the PicoScope 2208B, I soldered a thin coaxial cable to one winding, and 51Ω termination resistor to the other winding. Then connect the probes with 1:1 setting to the input winding connection and the output (51Ω resistor). Input winding to CHA, and 51Ω resistor output to CHB.

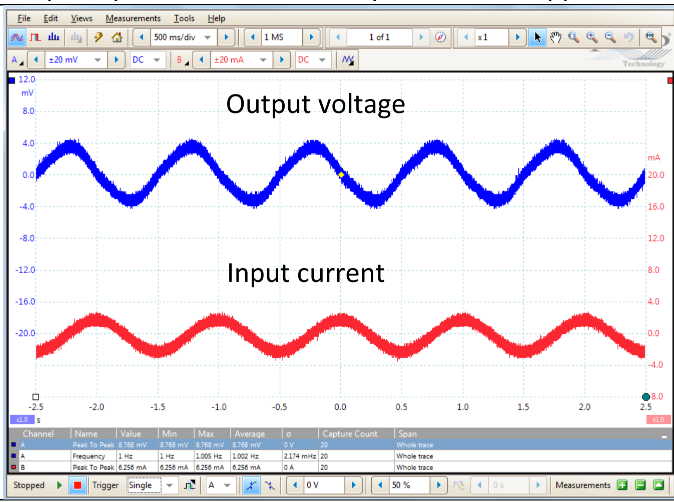
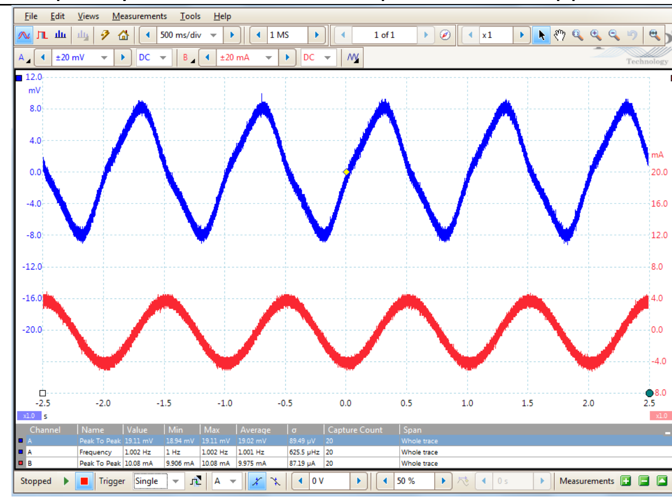
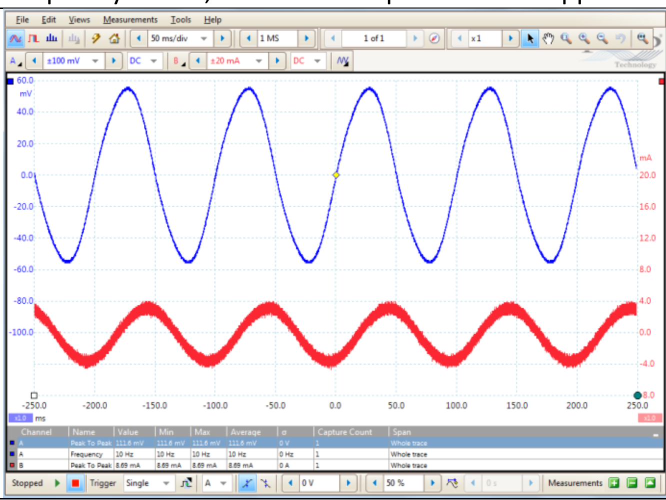
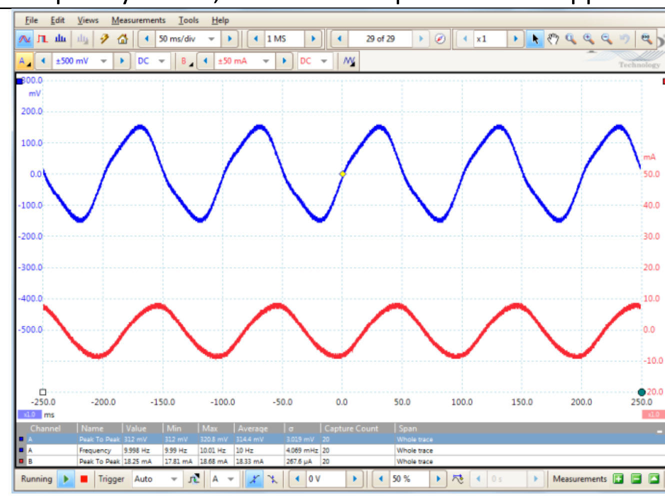
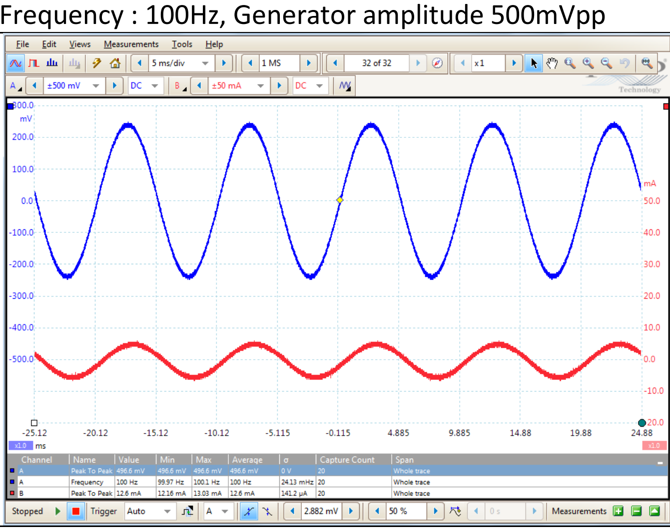
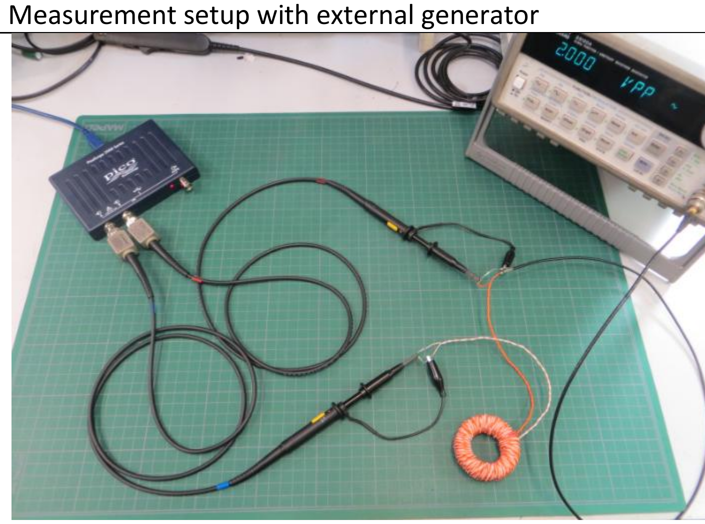


Below is the result of the Generator output to transformer output frequency response, measured with PicoScope 2208B and the FRA freeware utility developed by Aaron Hexamer.
https://bitbucket.org/hexamer/fra4picoscope/wiki/Home
Note that we measure the transfer from IN2 to OUT node, which is the blue gain curve in the simulation and the blue gain curve in the below FRA result.





To get clean graphs in the low frequency area, you need to select noise reject mode. The measurement results from the FRA utility match the simulated results quite well. The stimulus amplitude of 2Vpp will result in maximum current of 2V/600Ω = 3.3mApp in the transformer at lowest frequency, which will not lead to core saturation. But when you are using a Picoscope with 50Ω generator output impedance, a 2Vpp stimulus will result in 40mApp current. This will result in core saturation. The next page shows some input current and output voltage measurements with a 50Ω generator output impedance and different generator frequency and amplitude settings.

Frequency : 1Hz, Generator amplitude 100mVpp	Frequency : 1Hz, Generator amplitude 200mVpp
	
I_{IN}: 6.2mApp, $I_{51\Omega}$: 8.7mVpp/51=0.17mApp. Transformer magnetization current ≈ 6mApp. Just no core saturation.	I_{IN}: 10mApp, $I_{51\Omega}$: 19mVpp/51=0.37mApp. Transformer magnetization current ≈ 9.6mApp: Core saturation
Frequency : 10Hz, Generator amplitude 200mVpp	Frequency : 10Hz, Generator amplitude 500mVpp
	
I_{IN}: 8.6mApp, $I_{51\Omega}$: 111mVpp/51=2.2mApp. Transformer magnetization current ≈ 6.4mApp. Just no core saturation	I_{IN}: 18.3mApp, $I_{51\Omega}$: 314mVpp/51=6.15mApp. Transformer magnetization current ≈ 12.1mApp: Core saturation
Frequency : 100Hz, Generator amplitude 500mVpp	Measurement setup with external generator
	
I_{IN}: 12.6mApp, $I_{51\Omega}$: 497mVpp/51=9.7mApp. Transformer magnetization current ≈ 2.9mApp. No core saturation	1:1 probe setting and measure current via 1Ω resistor in generator ground.

At low frequency (1 ~ 50Hz) too high generator amplitude settings can cause core saturation and lead to output signal distortion. This can influence the FRA measurement results.