# Progress Report on the Magnetic Delay Transformer (MDT)

**Cyril Smith, 7th February 2012**

## 1. Introduction

This report details the progress made into the investigation of the MDT. The transformer consists of a large ferrite toroidal core that has small windings of only 6 turns each placed on opposite sides of the ring. This layout provides the maximum time delay through the ferrite between primary and secondary. Math modelling had shown that if the secondary were loaded with a capacitor the primary input resistance could go negative at a frequency slightly above the LC resonance. Unfortunately this negative excursion has failed to show up, but fortunately Graham took his measurements to frequencies well above the area of interest. That produced some anomalous results where the input resistance did indeed go negative, indicating the possibility of self-oscillation. At first it was thought these high frequency excursions were just a measurement artefact, but a more detailed analysis has shown the possibility that this could be a real effect. This report presents that analysis. Graham has measured a bare MDT, a MDT where the core is encased within a conductive shield (but arranged so as to not be a shorted turn), and a MDT with the core biased by the presence of a permanent magnet (called PMAG).

## 2. Input Impedance

Figure 1 shows the input impedances (plotted as Rin and Xin) for the BARE and PMAG versions, with a load resistor of 1K shunted by 2000pF. The small kink near 500KHz is the LC resonance. Note the zero crossing near 14MHz.

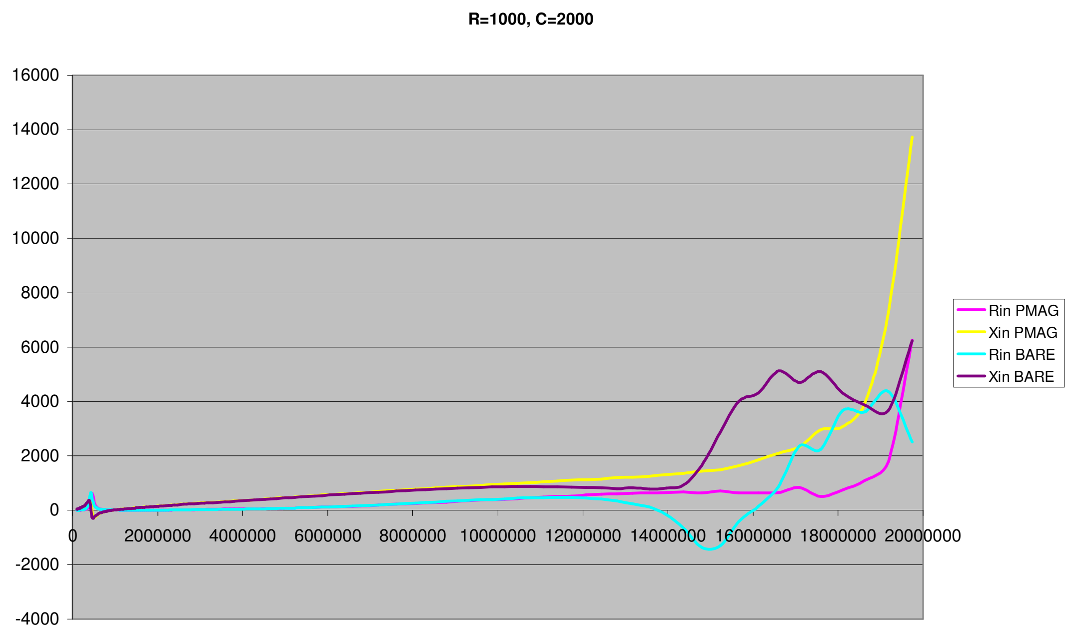


**Figure 1. Measured Input Impedance**

### 3. COP and CONP

The presence of a zero input resistance causes the COP to reach infinity at that crossing point. However the measurements were taken at spot frequencies, so the actual COP values depended on where the spot occurred. This led to an ill-behaved COP chart like that in Figure 2. Note the tiny blips around 14 and 16MHz, no sign of infinite COP there.

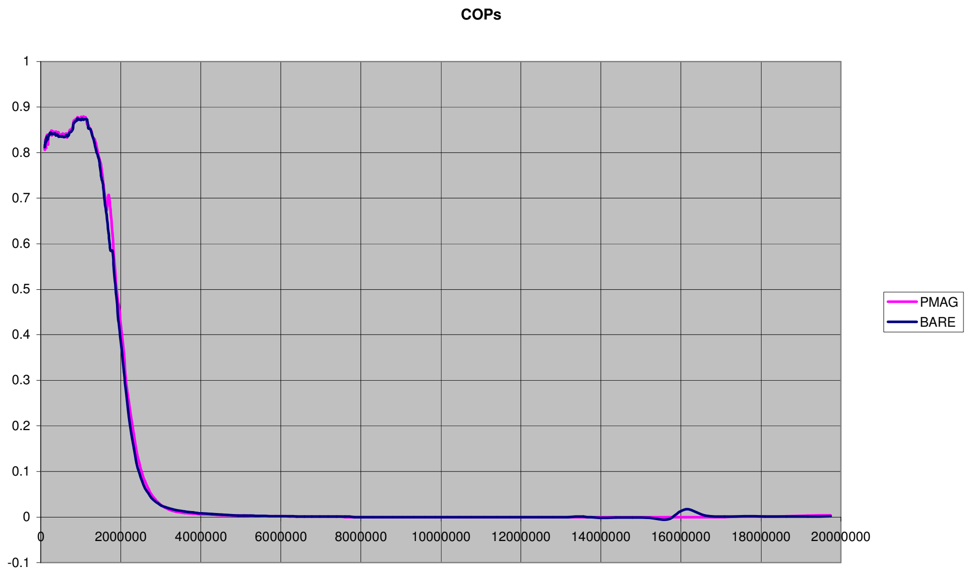


**Figure 2. COPs, R=1000, C=2000**

Compare that with the COPs for other load values such as that shown in Figure 3. Here we see large COP spikes as the frequency points get closer to the zero crossing.

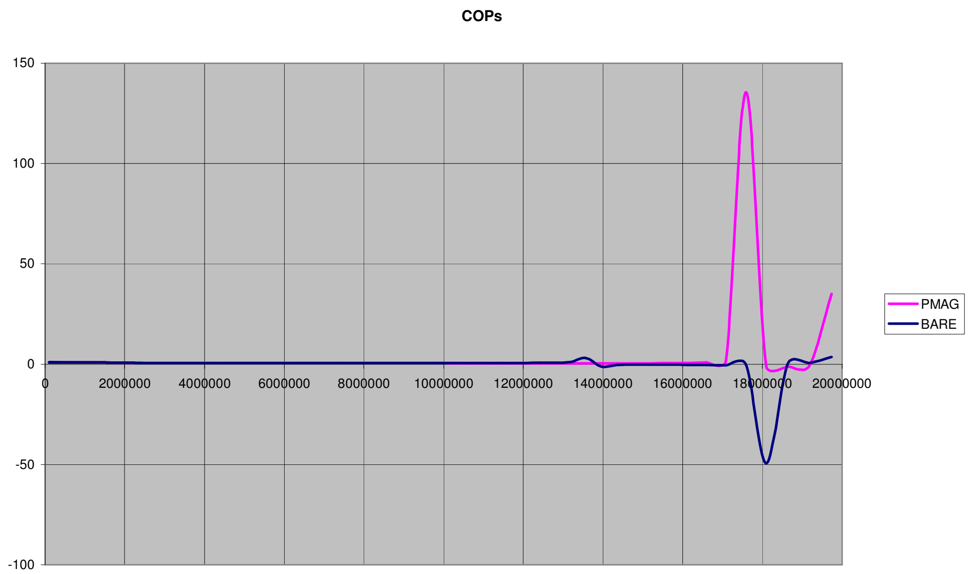


**Figure 3. COPs, R=1000, C=20**

The zero crossing catastrophe can be avoided if instead of plotting COP (power-out/power-in) we plot the inverse. It is convenient to call this CONP, coefficient of non-performance. The value of this approach is seen in Figure 4 where we can plot and compare CONPs for a wide range of conditions.

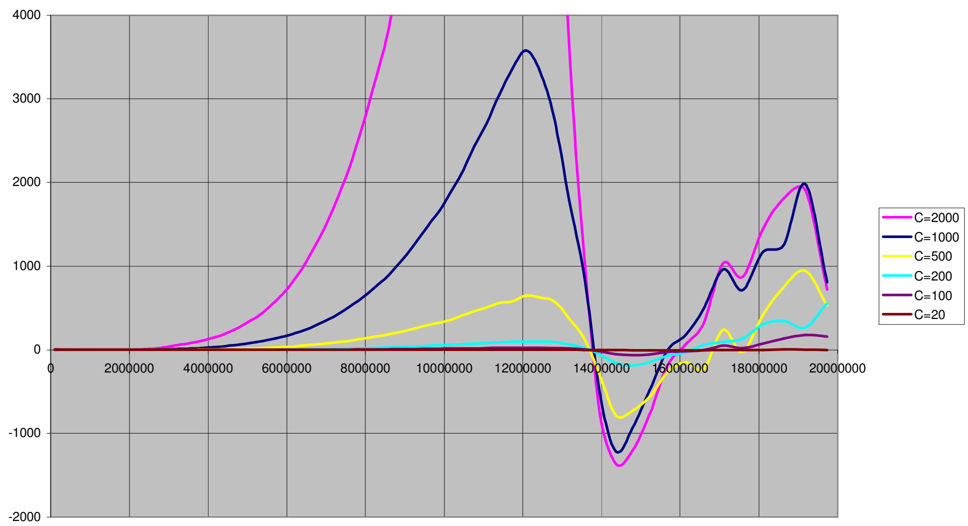


**Figure 4. BARE CONP's for R=1000 and a range of capacitor values.**

This tells us that the first zero crossing occurs at just below 14MHz for all capacitor values. All the curves have a similar shape varying only in magnitude, and this consistency suggests that the anomaly has a cause that is worth further investigation.

The PM biased PMAG shows a different set of CONP's at this 1K load resistor value as seen in Figure 5.

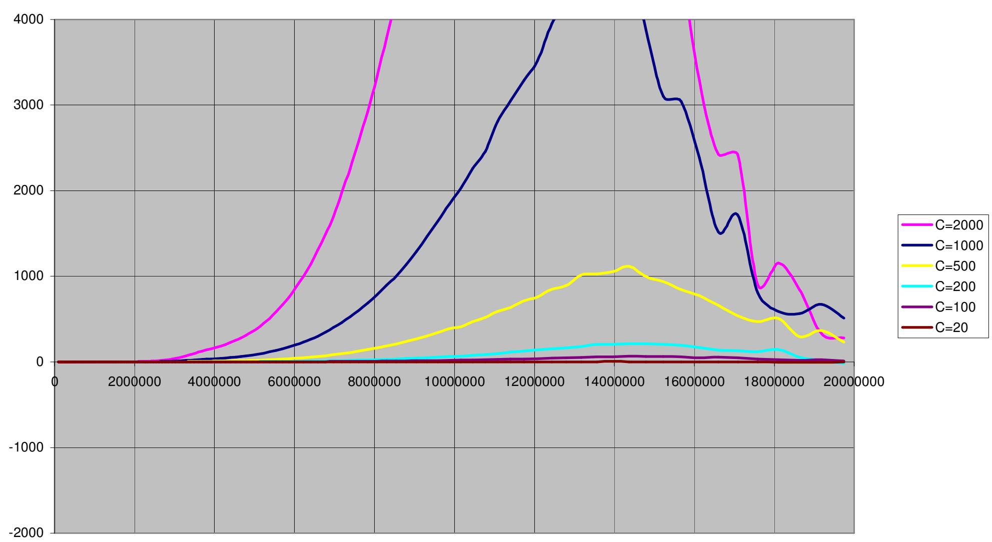


**Figure 5. PMAG CONP's for R=1000 and a range of capacitor values**

## 4. Phase Delay Considerations

The theoretical model based on transmission-line formula has been extended to cover the higher frequencies and it does predict a negative input resistance where the phase delay along the transmission-line is large. For the earlier work (that predicted an effect slightly above the LC resonance) the phase delay was small, only a few degrees. So attention was given to the phase delay from the measurements. Figure 6 shows the BARE phase from input voltage to output voltage for 1K load and various capacitors.

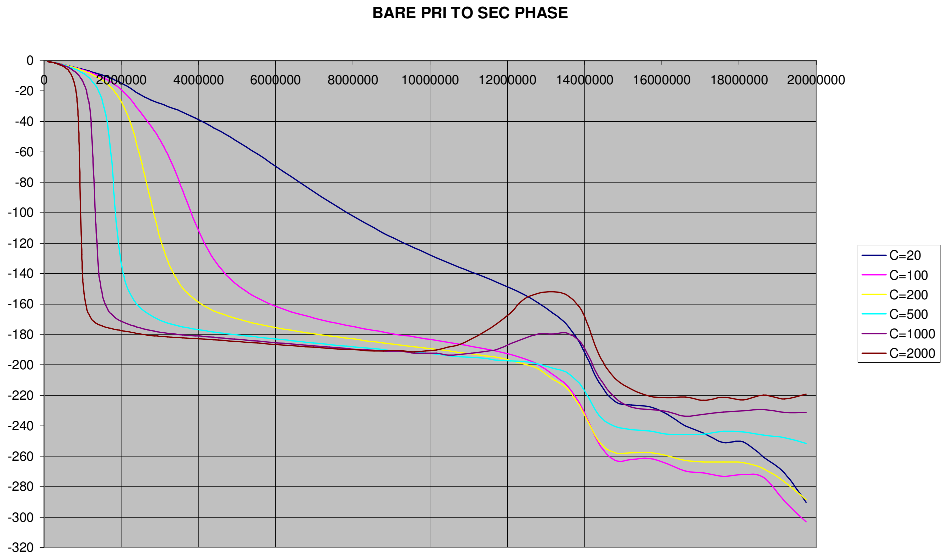


**Figure 6. Phase Delay**

It can be seen that the capacitor value alters the measured phase dramatically, but the curve of interest is the one for 20pF, which is just the scope probe. This is almost a straight line against frequency at the lower end (before the 20pF capacitor takes effect) indicating a fixed time delay of about 34.8 nS that can be taken as the delay through the core. From this and the known physical length of 0.135m we can establish the propagation velocity as $3.88\times10^{6}$ m/s. Assuming the velocity follows $v = c/\sqrt{K\mu_R}$ where $K$ is the dielectric constant of the ferrite and $\mu_R$ its relative permeability we get a value for $K$ of 6.64. This seems reasonable. The interesting feature of this propagation velocity is that the phase delay across the transformer reaches 180 degrees at a frequency of 14.36 MHz, which is close to the frequency where the input resistance goes negative (Figure 1) and the CONP goes negative (Figure 4).

The PMOD shows the same phase delay (Figure 7) but doesn't have the same impedance characteristics and doesn't offer the same negative CONP excursions.

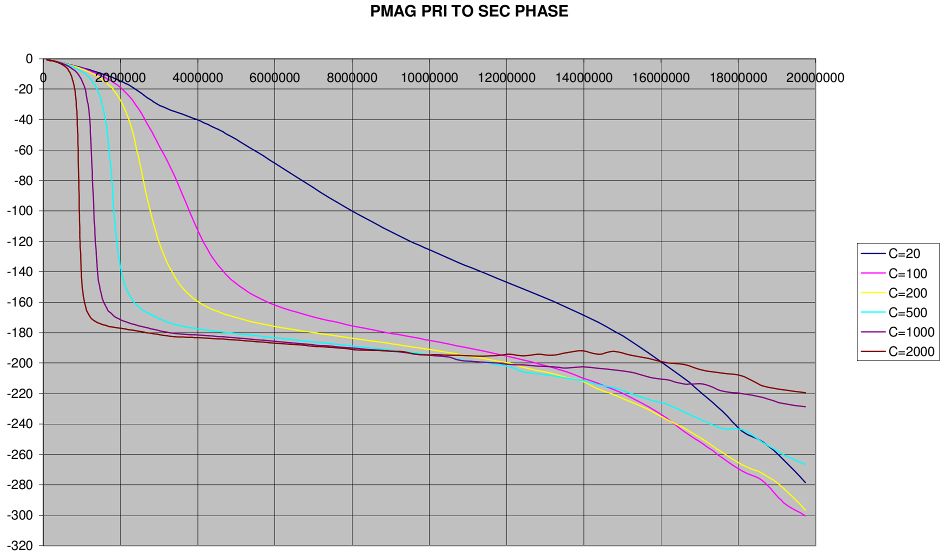


**Figure 7. PMOD Phase Delay**

## 5. Results with 33 Ohm Load

Turning to the measurements with a 33 Ohm load we get the same shapes to the CONP values but different magnitudes. The zero crossing near 14MHz remains, see Figure 8.

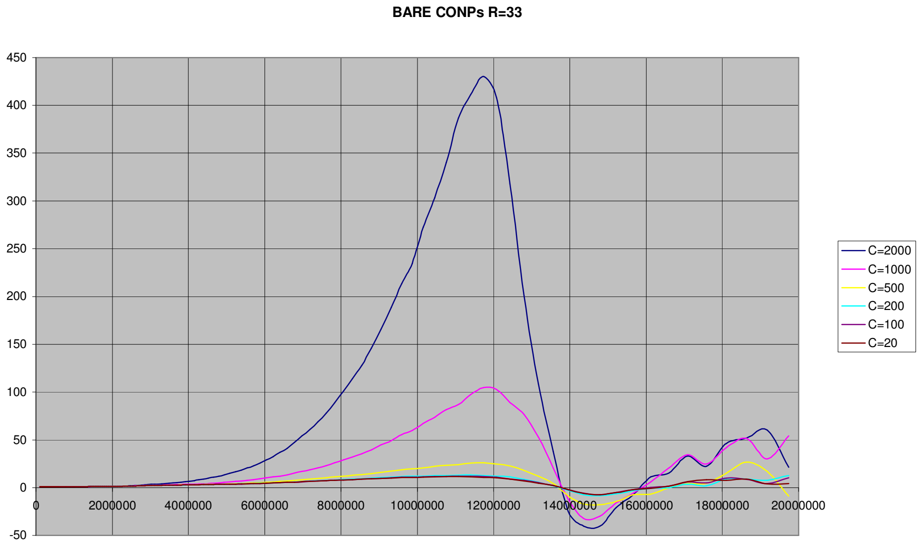


**Figure 8. BARE CONPs with 33 Ohm**

Interestingly the PMAG CONPs are very similar, see Figure 9, whereas with the 1K load they weren't.

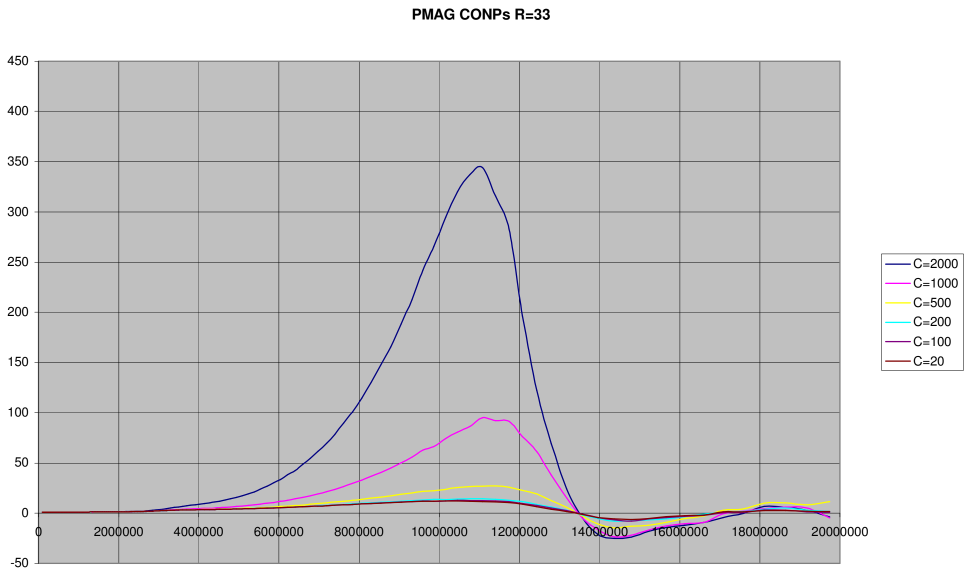


**Figure 9. PMAG CONPs with 33 Ohm**

## 6. Discussion of Results

Anyone familiar with transmission lines will know that their behaviour when the electrical length of the line is an integer number of quarter wavelengths yields impedance values that are not necessarily the load values but are related to them. Odd numbers of quarter-wave lines are used as (non OU) impedance matching networks, while even numbers of quarter-waves reflect the load impedance directly (only modified by the line losses). But that classical non-OU behaviour applies to practical transmission lines that have real characteristic impedance, there doesn't appear to be any consideration given to imaginary characteristic impedance. It is the latter that offers anomalous behaviour, and a transformer core acting as a transmission-line most certainly has imaginary impedance. Those familiar with the EM wave impedance for antenna you will know that the near-field has an imaginary ratio of E to H, another example of imaginary impedance. A transformer core may be looked upon as a means for channelling that EM wave from one magnetic loop antenna (the primary) to another (the secondary). Surprisingly the half-wave line with imaginary impedance reflects a resistive load, not as a resistance of equal value as would be the case for a classical line, but as a negative resistance. And it seems that Graham's measurement of negative input resistance occurs at the frequency where the one-way phase delay through the core is 180 degrees, although this has yet to be fully confirmed. It would support this conclusion if the phase delay across the transformer could be measured using a higher value load resistor and a lower value shunt capacitor than 20pF (e.g. by using a low capacity 'scope probe).