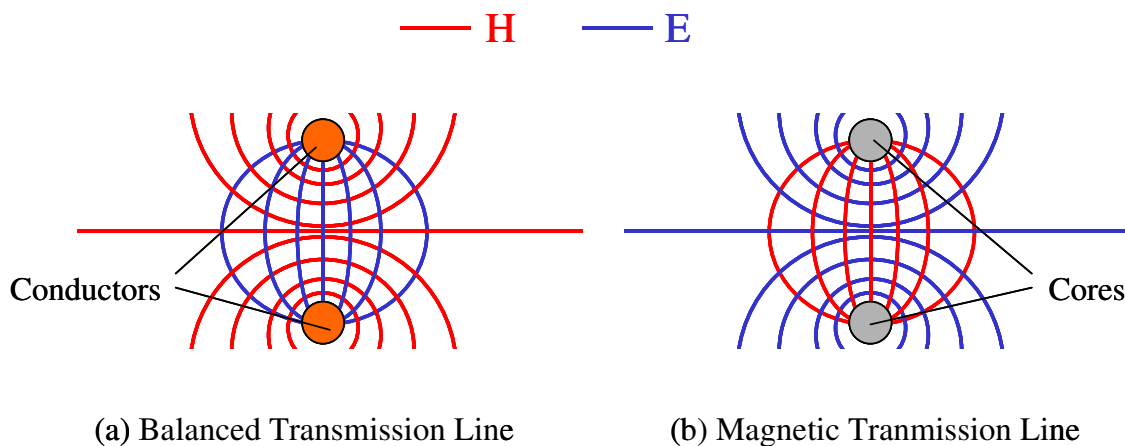


# On Magnetic Delay Lines

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## 1. Introduction

Figure 1 shows the magnetic and electric field lines around two types of transmission lines where the propagation direction is into the paper. Figure 1(a) is a cross section of the classical balanced line with parallel copper conductors in air. Electric field lines run from one conductor to the other while the magnetic field lines form closed contours around each conductor. The E and H fields form a transverse electromagnetic (TEM) wave propagating through the paper, and although there are arguments about whether the energy actually propagates through the air as this TEM wave or travels within the conductor as voltage and current, the net power transfer is the same whichever way it is calculated. Figure 1 (b) shows a cross section of a magnetic line (this could be the cross section of a ring core where the primary and secondary windings are above and below the paper). The H field lines would normally be considered as flux leakage, and the closed E fields are what actually drives the conduction electrons within coils. The similarity to the electrical line (a) is obvious, one difference being that the E and H fields are interchanged. These fields still create a TEM wave transporting energy to the load.



**Figure 1. Comparison between Electric and Magnetic Transmission Lines**

It is known that the electrical line (a) has a characteristic impedance determined by the geometry (conductor diameter and separation) so it can be expected that the magnetic line would have a similar characteristic. However there is one more significant difference between these two lines; whereas the characteristic impedance of the electrical line is resistive because E and H are in phase, in the magnetic case the impedance is reactive because E and H are at in phase quadrature. Now reactive impedance lines are not generally recognized or used for transporting energy, but classical transmission line theory does cover such lines. In view of the recent discovery that a transformer having magnetic delay between primary and secondary might exhibit anomalous characteristics, examination of the theory applied to reactive impedance lines would seem worthwhile.

## 2. Transmission Line Theory

The impedance  $Z_{in}$  looking into a line of characteristic impedance  $Z_0$ , of length  $x$  (m) and terminated in an impedance  $Z_{load}$  is given by

$$Z_{in} = Z_0 \frac{Z_{load} \cosh \gamma x + Z_0 \sinh \gamma x}{Z_0 \cosh \gamma x + Z_{load} \sinh \gamma x} \quad (1)$$

where  $\gamma$  is the propagation constant

$$\lambda = \alpha + j\beta \quad (2)$$

$\alpha$  is the attenuation constant (nepers/m) and  $\beta$  is the phase constant (radians/m). If attenuation is ignored (1) reduces to

$$Z_{in} = Z_0 \frac{Z_{load} + jZ_0 \tan \theta}{Z_0 + jZ_{load} \tan \theta} \quad (3)$$

where  $\theta$  is the line length  $\beta x$  expressed electrically in radians. We are interested in the case where  $Z_0$  is purely reactive (say  $jX_0$ ) and where the line is terminated in a reactive "load" (say  $jX_{load}$ ). Putting these into (3) yields

$$Z_{in} = \frac{X_0 \tan \theta (X_{load}^2 - X_0^2) + jX_0^2 X_{load} (1 + \tan^2 \theta)}{X_0^2 + (X_{load} \tan \theta)^2} \quad (4)$$

Note that if  $X_0 > X_{load}$  then the real part of this impedance is negative.

$$R_{in} = \frac{X_0 \tan \theta (X_{load}^2 - X_0^2)}{X_0^2 + (X_{load} \tan \theta)^2} \quad (5)$$

*Classical theory allows some passive components to create negative resistance.* Negative resistance is an energy source, so the question must be asked where does this anomalous energy come from? Perhaps the answer to that is found in Prof. Turtur's assertion that field propagation involves an interchange of energy with the zpe. The magnetic delay line not only involves a reactive TEM field propagating in air, but also a longitudinal magnetic field propagating within the core material.

For small attenuation (1) becomes

$$Z_{in} = Z_0 \frac{Z_{load} + \alpha x Z_0 + j(Z_0 + \alpha x Z_{load}) \tan \theta}{Z_0 + \alpha x Z_{load} + j(Z_{load} + \alpha x Z_0) \tan \theta} \quad (6)$$

Applying the reactances  $jX_0$  and  $jX_{load}$  as before yields

$$R_{in} = \frac{X_0 \tan \theta ([X_{load} + \alpha x X_0]^2 - [X_0 + \alpha x X_{load}]^2)}{[X_0 + \alpha x X_{load}]^2 + [X_{load} + \alpha x X_0]^2 \tan^2 \theta} \quad (7)$$

which reduces to (5) when  $\alpha=0$ . The condition for  $R_{in}$  to be negative is the same,  $X_0 > X_{load}$ .

## 3. Actual impedance of lines

The classical balanced line in air, figure 1(a), has a characteristic impedance  $Z_0$  given by

$$Z_0 = \frac{377}{\pi} \cosh^{-1} \frac{D}{d}$$

where 377 is free space impedance,  $d$  is the conductor diameter and  $D$  is the centre-to-centre separation distance. For  $D \gg d$  this becomes

$$Z_0 \approx \frac{377}{\pi} \log_e \frac{2D}{d}$$

The propagation velocity is  $c$  hence we can deduce the distributed capacitance  $C_l$  and inductance  $L_l$  as

$$C_l = \frac{1}{Z_0 c} = \frac{\pi \epsilon_0}{\cosh^{-1}\left(\frac{D}{d}\right)} \approx \frac{\pi \epsilon_0}{\log_e\left(\frac{2D}{d}\right)} \text{ Farads/m}$$

$$L_l = \frac{Z_0}{c} = \frac{\mu_0}{\pi} \cosh^{-1}\left(\frac{D}{d}\right) \approx \frac{\mu_0}{\pi} \log_e\left(\frac{2D}{d}\right) \text{ Henry/m}$$

where  $\epsilon_0$  is permittivity and  $\mu_0$  is permeability of free space and  $\sqrt{\frac{\mu_0}{\epsilon_0}} = 377$ , the impedance of free space.

Since the geometry of the fields in the magnetic line, figure 1(b), are identical save for the interchange between E and H we can deduce that the magnetic line will exhibit interchanged distributed values, e.g.

$$L_l = \frac{\pi \mu_0}{\cosh^{-1}\left(\frac{D}{d}\right)} \approx \frac{\pi \mu_0}{\log_e\left(\frac{2D}{d}\right)} \text{ Henry/m}$$

$$C_l = \frac{\epsilon_0}{\pi} \cosh^{-1}\left(\frac{D}{d}\right) \approx \frac{\epsilon_0}{\pi} \log_e\left(\frac{2D}{d}\right) \text{ Farads/m}$$

Yielding an impedance  $Z_0$  as  $Z_0 = \sqrt{\frac{L_l}{C_l}}$ , but note that this is really a reactance since in the magnetic line the E and the H fields are 90 degrees out of phase. Hence

$$X_0 = \sqrt{\frac{L_l}{C_l}} = \frac{377\pi}{\cosh^{-1}\left(\frac{D}{d}\right)} \approx \frac{377\pi}{\log_e\left(\frac{2D}{d}\right)}$$

#### 4. Practical device

A practical device can be built around a Ferroxcube Ring Core (Toroid) T107/65/18 using Grade 3F4 Ferrite. This is a large ring core having a 107mm OD, 65mm ID and 18mm depth. The ferrite is a high frequency power material for use in power and general purpose transformers at frequencies of 1-2MHz. The effective length of the core is about 260mm which is the mean circumference. When used as a delay element it requires small windings that are diametrically opposite each other so the delay length is about 130mm. Without some deliberate means of lengthening the delay the surface wave delay time through air is only 0.433nS. One method of slowing the surface wave is to immerse the transformer in a material having high permittivity and/or high permeability. Composite dielectrics can be made offering these features, one such example is soft-iron filings embedded in a plastic binder. There is some anecdotal evidence that this type of construction might give anomalous results. However the approach offered here is somewhat different. A series of coils placed along the core, with each coil shorted by a capacitor, can offer the same effect as immersing the toroid in a very high K dielectric. It is proposed that each coil is a single turn and that the turns are packed tightly so as to get a large number in place along the core. Figure XX shows the construction of each single-turn soldered to its capacitor with minimum lead length so as to minimise lead inductance. Figure XX shows the completed transformer. Using 1mm magnet wire one can get about 180 single-turns in the gap between the primary and secondary coils, and since there are two gaps that is 360 in total. If each single-turn is shorted by a 100pF capacitor, that represents a distributed capacitance of 100pF every mm, or 100nF per metre.

To achieve that by immersion in a high K dielectric would require a dielectric constant of YYY.

## **5. Conclusion**

Classical theory does not prohibit the use of passive components to create an energy source in the guise of a negative resistance. It is shown that a delay line with reactive characteristic impedance, when terminated in a reactance, can exhibit such a negative resistance at its input. Normally such reactive delay lines are not found, but magnetic delay lines *are* reactive and it is perhaps surprising that this feature has not been exploited in the past. This work should offer credence to the possibility of a magnetic delay transformer (MDT) producing overunity performance.