1. Magnetic Domain Model.

Figure 2 shows the simple magnetic domain circuit for a transformer that is loaded by a capacitor C in parallel with a resistor R. These reflect into the magnetic circuit as magnetic components, the resistor appearing as a magnetic inductor $\mathcal{L}$=N^2/R while the capacitor reflects as a negative reluctance $\mathcal{R}$=-ω^{2}N^{2}C where N is the secondary turns. These are in series with the core reluctance where flux Φ is driven via the primary current i_{drive} which appears as an mmf generator U=Ni_{drive}. In the modification to this model the core appears as a form of transmission line where account can be taken of the propagation time from primary to secondary and vice versa, Figure 3.

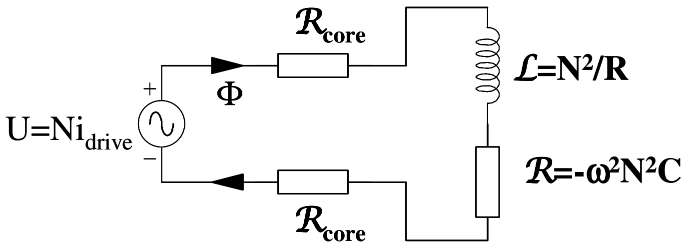


Figure 2.

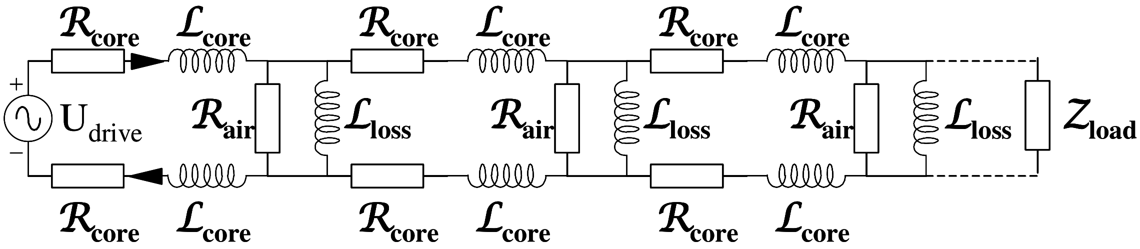
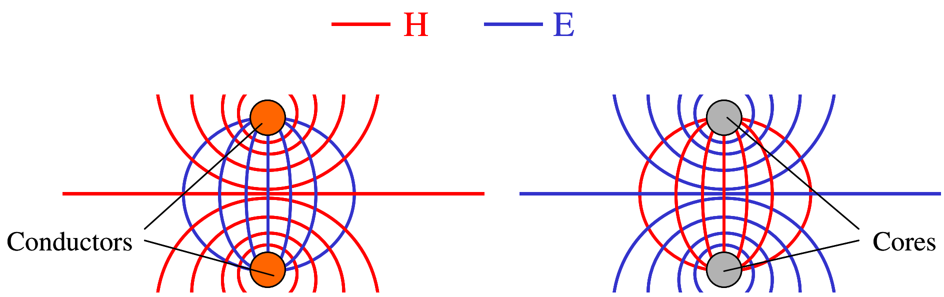


Figure 3.

Here the core reluctance appears as a distributed parameter, along with a distributed magnetic inductor representing the core losses. Also included is the leakage flux shown as distributed shunt air reluctance (actually modelled as distributed inverse reluctance, permeance or magnetic conductance $\mathcal{G}$). Losses in the flux leakage are shown as distributed magnetic inductors (actually modelled as distributed inverse magnetic reactance, magnetic susceptance $\mathcal{B}$). Then, just as the characteristic impedance of an electrical transmission line would be $Z_0 = \sqrt{\dfrac{R + jX}{G + jB}}$ so the *magnetic* impedance of this line is $\mathcal{Z}_0 = \sqrt{\dfrac{\mathcal{R} + j\mathcal{X}}{\mathcal{G} + j\mathcal{B}}}$. The propagation velocity is taken as that which pertains at microwave frequency, i.e. $c \big/ \sqrt{\mu_R K}$ where *c* is light velocity, μ_R is the relative permeability (900 for 3F4 ferrite) and *K* is dielectric constant. Since the dielectric constant is not published, this value is input as a control variable which conveniently allows a quick change to zero propagation delay when *K*=0. Losses in the core are accounted for using the published complex permeability for the 3F4 ferrite (see Annex 1 for method), which is used to calculate a distributed series reluctance and "magnetic inductive reactance". Since the complex reluctance (expressed as a magnetic impedance $\mathcal{Z} = \mathcal{R} + j\mathcal{X}$) for core length *l* and area *A* is $\mathcal{Z} = \dfrac{l}{\mu_R \mu_0 A}$, and $\mu_R = \mu' - j\mu''$, we find that the distributed reluctance is $\mathcal{R} = \dfrac{\mu'}{\mu_0 A(\mu'^2 + \mu''^2)}$ and the distributed magnetic reactance is

$$\mathcal{X} = \frac{\mu''}{\mu_0 A(\mu'^2 + \mu''^2)}.$$

For the distributed shunt permeance (magnetic conductance $\mathcal{G}$) we can use known data on electric transmission lines. The similarity between a balanced line of conductors and one of magnetic conductors is illustrated in Figure 5.



(a) Balanced Transmission Line (b) Magnetic Tranmission Line

Figure 5.

The equations describing the capacitance between the electric balanced line (a) will be of identical form to those describing the permeance between the magnetic cores in (b). Hence we arrive at the distributed permeance as $\mathcal{G} = \dfrac{3.14\mu_0}{\log_e\left(\dfrac{2D}{d}\right)}$ where d is the core diameter and D is the centre-to-centre distance.

The current model really covers a long thin rectangular core where the impedance is constant along the transmission path, Figure 4.

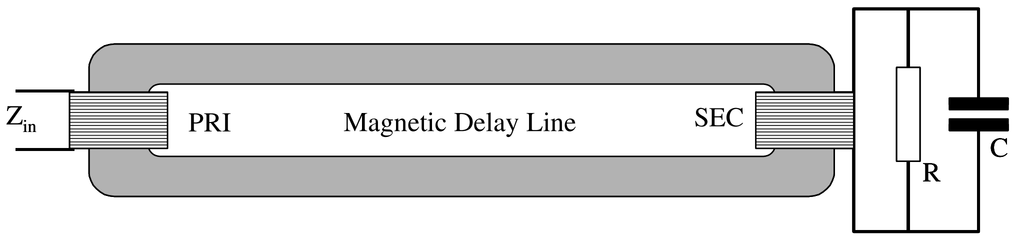


Figure 4.

The circular core can be modelled by multiple sections having different line spacings, but this has not been done yet (the existing model uses 54 spreadsheet columns, extending that to say 10 sections would take the column count to 540!!).

2. Transmission Line Formula

The model uses classical transmission-line formula but applied to magnetic parameters instead of the usual electrical ones. Taking $\mathcal{Z}_2$ as the load impedance, $\mathcal{U}_2$ as the load mmf and Φ_2 as the load flux, the input mmf $\mathcal{U}_1$ is given by

$$\mathcal{U}_1 = \mathcal{U}_2 \cosh(\gamma x) + \Phi_2 \mathcal{Z}_0 \sinh(\gamma x)$$

and the input flux Φ_1 by

$$\Phi_1 = \Phi_2 \cosh(\gamma x) + \mathcal{U}_2 \mathcal{Y}_0 \sinh(\gamma x)$$

where γ is the propagation constant $\gamma = \alpha + j\beta$. The phase constant β is determined from the magnetic propagation velocity, while the attenuation constant α is obtained from the ladder network Figure 3. Note that the attenuation constant (which here is a flux or mmf ratio expressed in Nepers), unlike that for electrical lines, here in the magnetic domain does not represent power loss. Power loss is represented by the magnetic inductors.

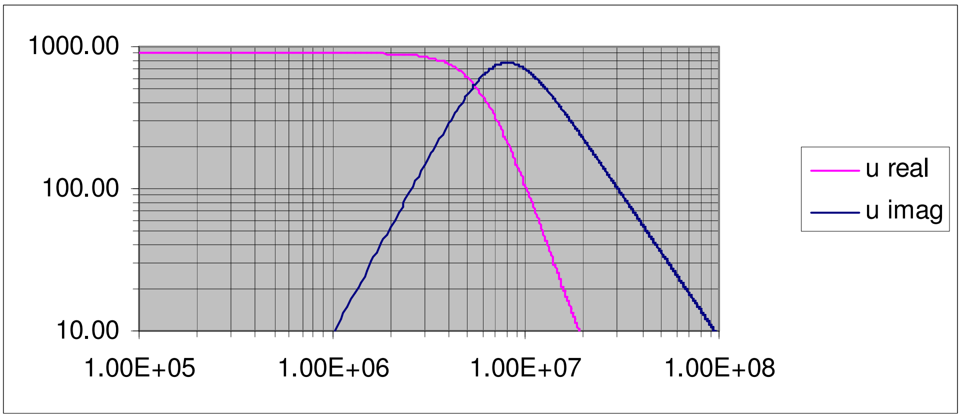
Annex 1. 3F4 Ferrite Data.

For inclusion in the model the 3F4 complex permeability data has been entered as formula.

$$\mu' = 1 + \frac{\mu_S - 1}{1 + \left(\frac{f}{f_1}\right)^4} \quad \text{where } \mu_S = 900 \text{ and } f_1 = 6MHz$$

$$\mu'' = \frac{(\mu_S - 1)\left(\frac{f}{f_2}\right)^{2.5}}{0.3 + \left(\frac{f}{f_2}\right)^{4.5}} \quad \text{where } f_2 = 10MHz$$

This produces the characteristic shown in the following chart.



This may be compared with the published data.