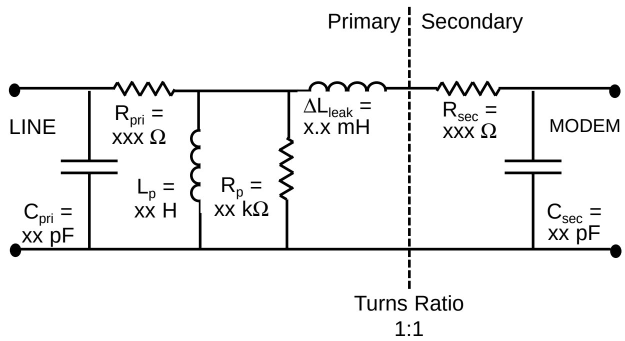
INTRODUCTION

The purpose of this application note is to explain the equivalent schematic for modem couplers like the REMtech DataLink™ product family. Let's start with the schematic provided as Fig. 4 on Page 2 of every DataLink™ data sheet, and see in simplest terms what the schematic model represents ...

SCHEMATIC EQUIVALENT (Fig. 4)

(Typical Transformer Model @ 1 V, 1 kHz)



First, let's eliminate some variables that are generally unimportant to modem line interfaces. C_{pri} and C_{sec} represent parasitic capacitances among the coils. The values are generally of such low value, 30 pF typically, that these capacitances do not significantly impact overall impedance of the transformer. Therefore, REMtech™ engineers generally omit C_{pri} and C_{sec} from SPICE models unless specifically requested.

R_p is commonly called Shunt Loss, or Core Loss, and represents energy lost in the soft magnetic core materials. The unfortunate use of the word "Loss" in "Shunt Loss" can really confuse people at first, because higher Shunt Loss (R_p) really infers lower energy loss. Basic power formulas such as $P = V^2 / R$ reveal that a higher R_p value really results in lower energy "loss". From a plumbing perspective, R_p offers very high impedance compared to other SPICE variables (multiple-tens of kilo-ohms compared to tens of ohms). Because the signal will follow the path of least impedance, and R_p is a path of high impedance, the signal almost entirely moves in the series direction through R_{pri}, ΔL_{leak}, and R_{sec}, a path directly from line to modem electronics. Higher R_p improves high-end frequency response, so it is quite convenient that R_p does increase with frequency. Measured mean minus two standard deviations conservatively appears on DataLink™'s Fig.4 schematic.

R_{pri} and R_{sec} represent the DC resistance of the coils wound about the transformer core. These resistance values do not change with signal frequency. They are important variables in that they affect Insertion Loss, and thus the signal level delivered to the system implementation. More coil means more resistance and more Insertion Loss. So why add coils? Answer: Because more coils means lower cost, as will be explained shortly.

L_p, known as Shunt Inductance, represents the bulk of the inductance in the transformer as current courses through the coil windings. Inductance is primarily affected by number of coil turns, amount of soft magnetic material within the coil space, and the type of soft magnetic alloy itself. Shunt Inductance increases as frequency decreases, which is very convenient since higher L_p improves low-end frequency response. Measured mean minus two standard deviations conservatively appears on DataLink™'s Fig.4 schematic.

Methods of increasing L_p also increase R_p. Whereas competitors rightly point out the need for flat frequency response even to low frequencies for 56K modems, this is commonly accomplished easily as a by-product of choices in other areas to be explored next.

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A key performance parameter for modem couplers is Distortion (or, said the opposite way, "Fidelity") because a damaged signal conveys less discernible data in a modem system implementation. Improvement (i.e. lowering) of Distortion correlates with increasing Shunt Inductance (L_p). (There are bounds on Shunt Inductance where core saturation must be considered, but this issue applies only to special types of modem transformer designs.) However, Shunt Inductance does not fully explain differences in Distortion performance. Distortion is also affected by the geometry of the transformer.

In practice, the soft magnetic core material constitutes a very expensive part of transformer costs, so manufacturers strive to achieve acceptable Distortion ratings using less core material. Remember that Shunt Inductance (L_p) partially explains Distortion ratings, and that it is possible to achieve a given Shunt Inductance using less core material and more coil turns to save costs. But as the number of coil turns increase, so does Insertion Loss. There is a limit to cost-reduction via added coil turns, before finally an inadequately low signal level remains delivered to the modem system implementation.

Optimal transformer geometry also impacts Distortion results. So, REMtech™ engineers also focus design choices on optimal transformer geometry patterns, resulting in lower costs while maintaining desirable Distortion ratings. Geometry decisions do not adversely impact other electrical characteristics --- in this sense, optimizing geometry provides "free" benefits.

Another key performance parameter is Return Loss, which is a measurement indicating good transfer of signal through the telephone interface due to effective impedance matching. Because of the word "Loss", measures of Return Loss are expressed as positive values; for example, 20 dB. But actually this example would mean -20 dB (note the *minus* sign) of signal returning back toward the source of the signal rather than passing to its destination. By providing optimal impedance matching in the system implementation, the Return Loss can be improved (as for example, from 20 dB to 25 dB). Thus more of the signal passes through the transformer-based telephone interface.

REMtech DataLink™ presents lumped application circuit models for 600-ohm telephone lines as Fig. 3 on Page 2 of each product data sheet. Fig. 10 on Page 3 presents a lumped application circuit model for pan-European CTR-21 telephone lines (when applicable to the safety class of the coupler). These circuit models recommend resistances and capacitances around the modem transformer in order to achieve best Return Loss.

All variables including Leakage Inductance (DL_{leak}) factor into electrical network analysis when designing good application circuits for good Return Loss. However, only Leakage Inductance (DL_{leak}) remains as a transformer design choice, once the other variables (R_{pri}, R_{sec}, L_p, R_p, C_{pri}, C_{sec}) have been established according to the other performance characteristics already discussed above. Discussion next focuses on Leakage Inductance (DL_{leak}) because of its key impact on Return Loss circuit designs.

Where does Leakage Inductance (DL_{leak}) come from? In non-technical terms, the primary coil puts energy into a magnetic field, and the secondary coil recovers most of that magnetic energy. The energy that is not recovered is stored in the magnetic field. Well, that is also what inductors do, and so the SPICE model shows an inductor called Leakage Inductance (DL_{leak}).

What happens to the signal because of Leakage Inductance ((DL_{leak})? Well, now the SPICE model boils down to R_{pri}, R_{sec}, and DL_{leak} in series from the line side to the modem side, all affecting the signals applied through the telephone interface. Now, consider the inductor (Leakage Inductance DL_{leak}) behavior as the signal moves through the circuit with a frequency (f). The inductor stores energy as current moves from zero and releases energy as the current moves back to zero. These "energy storage" effects somewhat "impede" normal signal flow, in that the signal "reacts" to the energy storage --- a reactance that varies with frequency, and impacts high frequencies most. Because modem data is encoded in the the shape of the waveform, only low values of Leakage Inductance (DL_{leak}) can be tolerated before data loss arises from waveform changes.

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What is the objective of the application circuits (Figs. 3 and 10 on data sheets)? Basic electrical network theory says Impedance (Z) may consist of a resistive element (R) and a reactive element (X). The basic definition of Impedance (Z) is:

$Z = R + jX$

where R = DC resistance

j = square root of "-1" (an imaginary number, which enables complex number mathematics to manipulate R and X impedance effects simultaneously during network analysis)

$X = +X_L - X_C$

X_L = reactance caused by inductances (L) $= 2 \pi f L$

X_C = reactance caused by capacitances (C) $= 1 / (2 \pi f C)$

f = signal frequency (ranging to 4000 Hz)

π = constant of about 3.1416.

In the application circuit models (Figs. 3 and 10 of data sheets), capacitors provide X_C to offset the X_L arising from inductances, and emerge necessary where Leakage Inductance is high. The actual network analysis math for the circuits is a more detailed matter, but the objective is to match either a straight Z = R = 600 ohms (Fig. 3), or a complex Z = R + jX according to CTR-21 (Fig 10). Thus the telephone interface will comply with telecommunications standards.

Since high Leakage Inductance (ΔL_{leak}) is the concern, what causes high Leakage Inductance? The minor factor affecting the exact amount of Leakage Inductance (ΔL_{leak}) is essentially the Shunt Inductance (L_p). Simply stated, the transformer will show more Leakage Inductance when there is a more intense magnetic field, which comes with higher Shunt Inductance (L_p) as set according to Distortion and Insertion Loss considerations. But by far the major factor is the internal construction of the transformer.

What are the various kinds of internal transformer constructions affecting Leakage Inductance (ΔL_{leak})? See now horizontal cross-sectional drawings, Figs. A through D, which depict various coil winding methods.

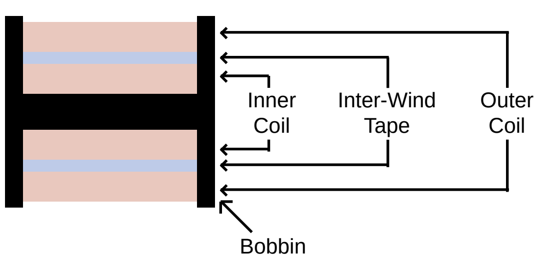

Figure A. Concentric

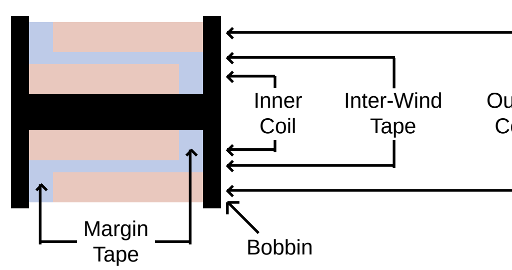

Figure C. Concentric / Margin

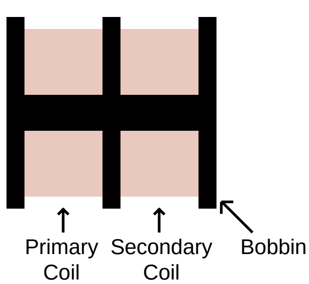

Figure B. Adjacent

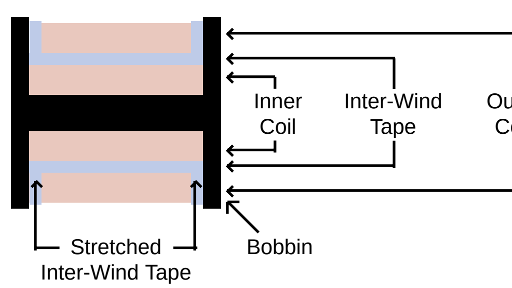

Figure B. Concentric / Stretch

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Fig. A depicts “Concentric” winding construction. One coil lies directly within the other coil. Magnetic field can be almost perfectly coupled by the coils. Typical Leakage Inductance (DL_{leak}) is lowest at around 2 or 3 mH, requiring no external components for 600-ohm impedance match countries such as the U.S. This construction is adequate for UL1459 safety, but does not meet IEC60950 safety because inter-winding tape edges cannot be sealed to the bobbin, and the tape is too thin to maintain creepage/clearance dimensions between the coils along that unsealed tape edge. UL1459 is being upgraded to IEC60950 (US names UL1950), so this method is becoming obsolete.

Fig. B depicts “Adjacent” winding construction. This method provides lowest winding cost because coils can be wound simultaneously. But the coils do not couple magnetic field well. So typical Leakage Inductance (DL_{leak}) is highest at up to around 25 mH, and requires external components. The center bobbin flange between coils can remain high enough above coils to meet minimum applicable IEC60950 creepage/clearance safety requirements, and greater safety comes with potting insulation around the entire assembly. This design has historically been appropriate for European modems which require external components regardless of construction.

Fig. C depicts “Concentric / Margin” winding construction. Magnetic field couples almost as well as Fig. A. Typical Leakage Inductance (DL_{leak}) is low at around 6 mH, a level which for which Return Loss improvement via external components may sometimes be optional. The addition of margin tape provides insulation to meet IEC60950 creepage/clearance dimensions. This method incurs highest winding cost because of greatest number of winding operations. This design has historically been appropriate for very thin transformers facing space constraints when conforming to IEC60950 safety requirements.

Fig. D depicts “Concentric / Stretch” winding construction. With this method, inter-winding tape is stretched up the sides of the bobbin. Generally, the tape cannot be stretched far enough to meet IEC60950 creepage/clearance dimensions, but can stretch far enough to the outside of the outer coil. The transformer is then potted with insulating material that seals to the tape and bobbin, such that the outer coil is entirely enclosed with insulation. Now enclosed, the insulation provisions of IEC60950 take precedence over creepage/clearance rules, and the device passes IEC60950 safety norms. Typical Leakage Inductance (DL_{leak}) is under 3 mH like Fig. A, resulting in no external components for 600-ohm telephone lines. And since the device passes all IEC60950 safety norms taking effect worldwide, the transformer serves as a universal coupler. However, the potting process adds cost.

New methods of construction are being investigated to improve the cost-effectiveness of acceptable constructions.

Here are some general rules applicable to DataLink™ SPICE models:

1. Distortion is not directly predicted by Shunt Inductance (L_p). The Schematic Equivalent (Fig. 4) on data sheets conservatively presents two standard deviations below the mean of measured values, and even much lower values do not significantly impact Distortion results measured for DataLink™ transformers.

2. Insertion Loss is most predicted by DC resistance arising from wire gauges and coil turns. Insertion Loss specifications on data sheets are measured according to recommended load resistance. This is more consistent with application circuits than competitors’ habits of simply measuring with 600-ohm load. Very small transformers often need more Insertion Loss, but otherwise the trade-off is transformer cost against signal requirements of other (ex. IC) electronics.

3. Just about any IEC60950 transformer can be used universally. But tranformers with low Leakage Inductance (DL_{leak}) often provide very good Return Loss on 600-ohm telephone lines without external capacitors and resistors. On pan-European CTR-21 telephone lines, external components are required anyway.

4. Substituting transformers of similar construction (identical DC resistances (R_{pri}, R_{sec}, R_{load}) and Leakage Inductance (DL_{leak}) often will not create system issues. SPICE (Fig. 4) and application circuit (Fig. 3, 10) component tolerances affect Return Loss by only a few dB. New DataLink™ couplers often support upwardly compatible Distortion with cost improvement, without electrical design consequences in high-speed modems.

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