CEETUS ENTERPRISE CORPORATION
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Function of Ethernet Magnetics

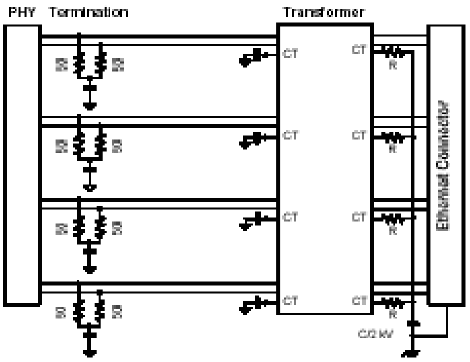
- Electrical isolation per IEEE 802.3
- Transfer of Ethernet signals without distortion
- EMI suppression

EMI properties are directly related to CM properties
Relevant information never found in data sheets
Significantly affected by parasitic elements in the construction
Hand-wound – affects CM performance and consistency
Physical layout in the package extremely important
Limited package size and HV requirement limit available options
Extremely price sensitive business

Ingredients

- Pulse (Isolation) Transformers
- Common Mode Chokes
- Autotransformers
- Capacitors
- Resistors
- Package/Mechanical (+ connector pins and leads in ICMs)

Typical Ethernet Port



First part deals with:
Transformer Differential Mode (DM) Properties
(Functional Characteristics)

- This section treats the subject in a way not yet found in transformer data sheets or related Application Notes and literature.
- The material covers basic considerations essential for understanding EMI suppression function of Ethernet magnetics.

Second part deals with:
Transformer Common Mode (CM) Properties
(EMI Suppression Characteristics)

Introduction to Functional Properties

- DM parameters are main factors to consider for functional properties. The frequency range to consider is from 1 MHz up to 100 MHz (CAT5e) and 250 MHz (CAT6)

- Some idealistic assumptions about transformer properties must be made to simplify initial analysis

Assumptions

- 1) Permeability is high enough to be considered infinite (μ ! ∞)
- 2) Core magnetization is small enough to be considered zero (R ! 0)
- 3) Negligible core losses

- 4) Negligibly small winding resistance
- 5) All magnetics flux is contained within the windings (no leakage, perfect coupling, *k*=1)
- 6) Winding capacitances are negligible

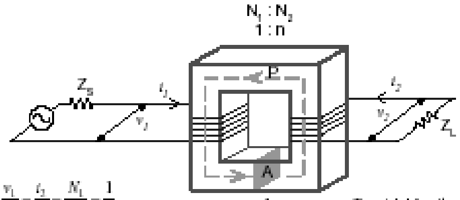
Faraday's Law

Induced electromotive force in a closed loop is proportional to the rate of change of magnetics flux with time.

Magnetic flux, Wb

$$e = -\frac{d\Psi}{dt} = -N\frac{d\Phi}{dt}$$

Relation between Voltage, Current, and Turn Ratio in Ideal Transformer



$$\frac{v_1}{v_2} = \frac{i_2}{i_1} = \frac{N_1}{N_2} = \frac{1}{n}$$

core area A
flux path length P

Toroidal ferrite cores are used in Ethernet magnetics

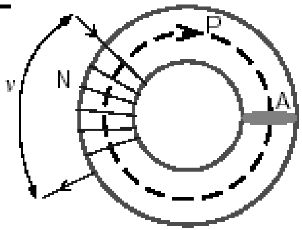
Self Inductance on a Toroidal Core

Flux density

$$L = \frac{d\Phi}{di} = \frac{\oint B ds}{di}$$

$$v = -L\frac{di}{dt}$$

$$L = \frac{N^2 A\mu_0\mu_R}{P}$$



P – path length

A – cross-section area

Mutual Inductance

$$M = \frac{d\Phi_{21}}{di_1} = \frac{d\Phi_{12}}{di_2} = \sqrt{L_1L_2}$$

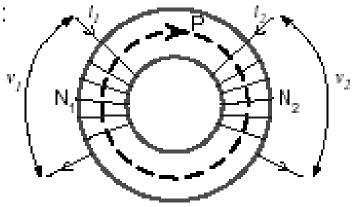
Because current in one coil induces flux in the other coil

In non-ideal transformers:

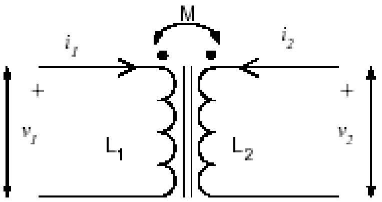
$$M = k\sqrt{L_1L_2}$$

$$0 \le k \le 1$$

Flux linkage losses



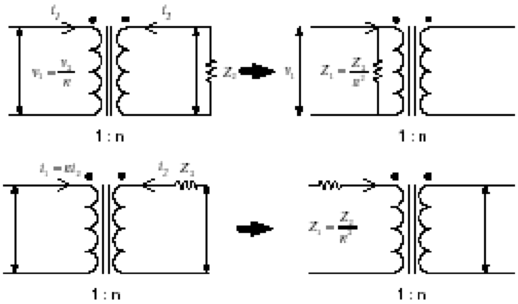
Circuit Symbol of Transformer



N1 : N2
1 : n

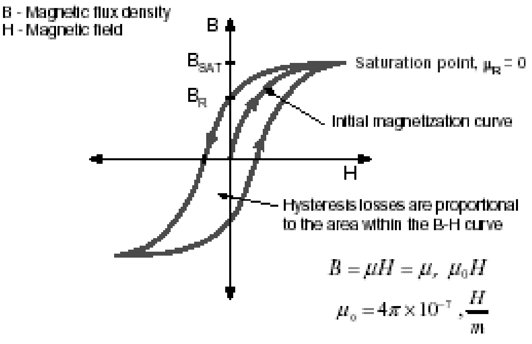
$$v_1 = L_1\frac{di_1}{dt} + M\frac{di_2}{dt} \qquad v_2 = L_2\frac{di_2}{dt} + M\frac{di_1}{dt}$$

Transformation of Impedance



Proportional to 1/n²

Core Permeability and Saturation

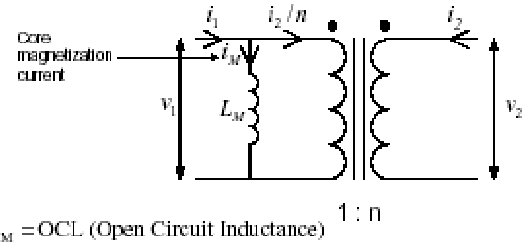


$$B = \mu H = \mu_r \mu_0 H$$

$$\mu_o = 4\pi \times 10^{-7}, \frac{H}{m}$$

Non-Ideal Parameters

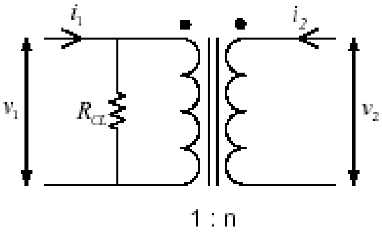
Finite permeability



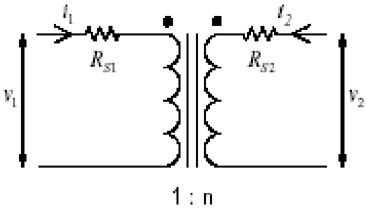
L_M = OCL (Open Circuit Inductance)
Minimum L_M for Ethernet transformers = 350 μH
@100 kHz with 8 mA DC bias

Core losses

Hysteresis and eddy current losses can be approximated by a resistance R_{CL} in parallel to the winding. Core losses can be reduced by using high-resistivity materials (e.g. ferrites) and core construction that impedes the flow of eddy currents (e.g. laminated cores).

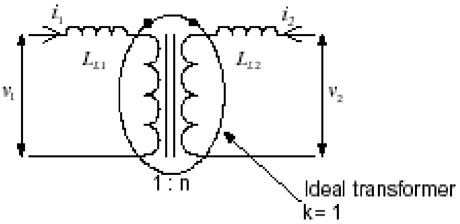


Winding (wire) resistances



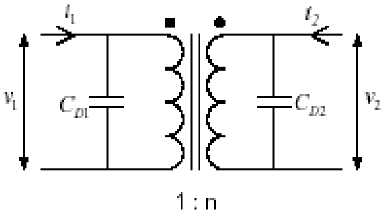
Flux leakage

A portion of the magnetic flux is not linked between the two windings, described by the coupling coefficient k, $0 \le k \le 1$.



Leakage is determined by the winding technique and core geometry.

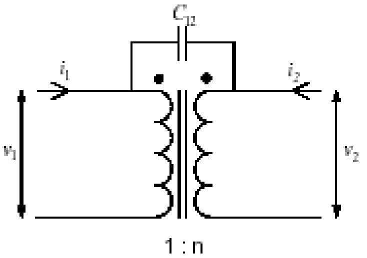
Distributed capacitance



Primarily determined by:

- Coupling between the winding and the transformer core
- Coupling between the adjacent turns, distributed in nature.

Inter-winding capacitance

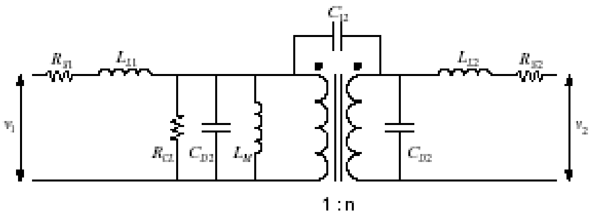


Due to the proximity coupling between the primary and secondary windings.

Small enough to have no effects on the intentional signals through the transformer.

High enough to provide low-impedance path for the unintentional common-mode signals that significantly affect the EMI-related characteristics.

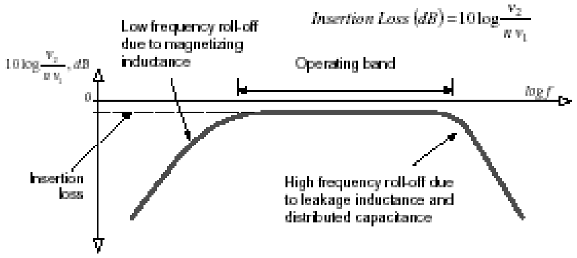
Transformer Equivalent Circuit



Bandpass filter

Good transformer design optimizes the bandpass frequencies and the losses in the transformer for maximum efficiency of the signal transfer.

Frequency-Domain Response



Lowering magnetizing and leakage inductances and distributed capacitance increases frequency range.

Lowering core losses and wire resistance reduces insertion loss.

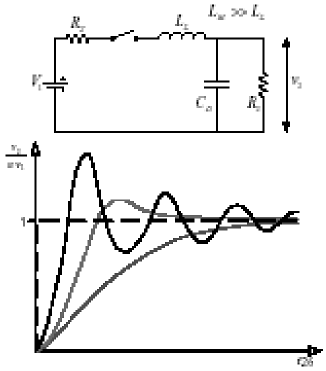
Time Domain Response to Pulse

Rising edge

The parallel magnetizing inductance L_M is effectively large impedance for the rising edge, and can be omitted.

Damped (exponentially decreasing) oscillations.

The magnitude of the oscillation and damping factor depend on L_L, C_D, and R_2 (assuming the source impedance R_S is negligible).



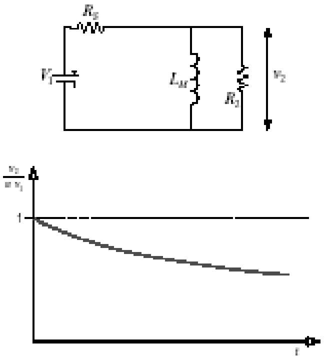
Pulse peak/plateau

The response is primarily determined by magnetizing inductance and (transformed) load impedance.

Leakage inductance is much smaller than the magnetizing inductance so it can be neglected.

Distributed capacitance can be omitted because current doesn't flow through it.

The load (secondary) voltage decreases exponentially with time.

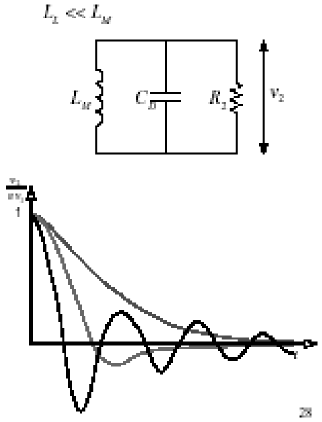


Falling edge

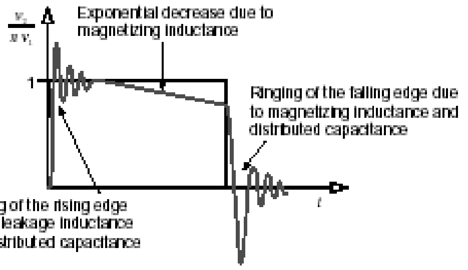
Leakage inductance can be ignored because it is much smaller than the magnetizing inductance.

Damped (exponentially decreasing) oscillations.

The magnitude of the oscillations and damping factor depend on magnetizing inductance, distributed capacitance and (transformed) load impedance.



Combined Response to a Pulse



Exponential decrease due to magnetizing inductance

Ringing of the falling edge due to magnetizing inductance and distributed capacitance

Ringing of the rising edge due to leakage inductance and distributed capacitance

Ringing and exponential decrease exaggerated for clarity

- The following section discusses magnetics properties that are instrumental in EMI suppression.

These properties mostly affect CM attenuation and CM-DM conversion by the magnetics.

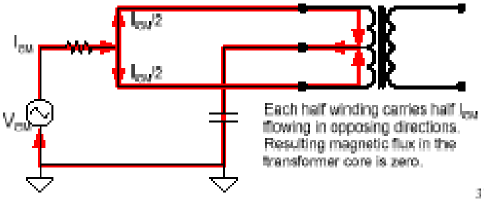
Transformer with Ideal Center Tap

All CM current flows through center tap back to the source.

Center taps provide:

a) Attenuation of CM currents and voltages on cables, by providing low-impedance return path to the source for CM currents on differential pairs.

b) DC bias for differential pairs or power source for Tx output in some transceivers.



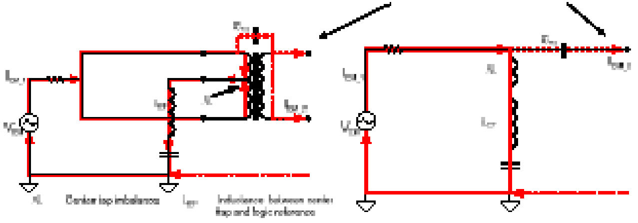
Each half winding carries half I_{CM} flowing in opposing directions. Resulting magnetic flux in the transformer core is zero.

Non-Ideal Center-Tapped Transformer

L_{CT}, ΔL, C_{12} decrease CM attenuation

ΔL creates DM-CM conversion

Equivalent CM model



CM current flows on the connected cable

CM voltage exists on the center tap, because $\Delta L + L_{CT} \neq 0$

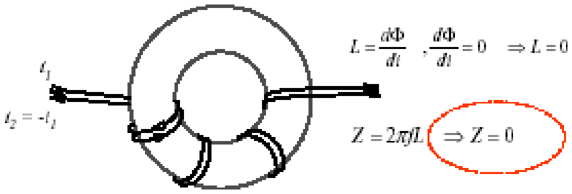
CT voltage drives CM current on the cable, which causes emission.

CM Choke – DM Transmission

- Transmission of intentional (DM) signal

Wires carry all signal currents, including the "return" currents

Net current = 0 (current cancellation) ⇒ net flux = 0



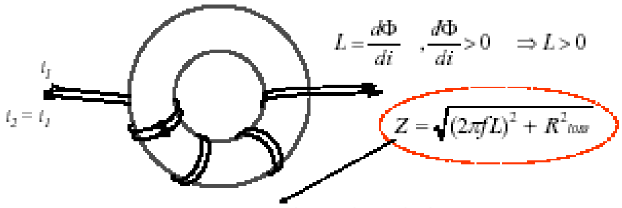
CM choke presents no impedance (attenuation) to the signal that is contained within the wires wound on the ferrite core

CM Choke – CM Suppression

- Suppression of unintentional (CM) "noise"

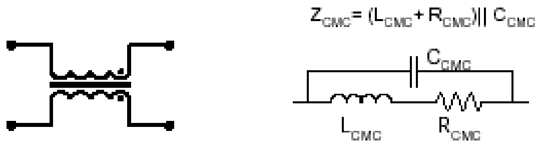
Wires carry CM currents i_1 and i_2.

Net flux in the core is produced by i_1+i_2



Considerable impedance (attenuation) to the CM "noise" that flows on the cable (wires) wound on the ferrite core.

CM Choke – Symbol and Model



Distributed capacitance C_{CMC} reduces CM choke impedance at high frequencies.

Lossy ferrites ("soft ferrites") are advantageous because the dissipate energy.

Significant part of Z_{CMC} is resistive rather than reactive.

Tradeoff between:

- high impedance provided by L_{CMC} and R_{CMC}
- low distributed capacitance C_{CMC}

Summary of Transformer Elements

Main Functional (DM) parameters:	Parasitics influence DM parameters:
• Turn ratio • Magnetizing inductance (OCL) • Insertion loss • Return loss (reflection coeff. in dB) (related to all funct./DM parameters)	• Leakage inductance • Distributed and interwinding C

CM noise suppression affected by:
- Center tap balance
- Series impedance in the connection between the center tap and reference (imbalance + CT inductance + center tap C)
- Interwinding capacitance
- CM choke impedance

Ethernet Magnetics CM Properties

EMI suppression result of each component AND parasitics properties AS WELL AS THEIR INTERACTION
Performance cannot be judged based on the schematic-level configuration as given in data sheets. Currentl
available data sheets are more-less USELESS regarding EMI suppression characteristics
Measuring performance is not simple
- Intended environment
- Test jig

Jigs may not model all system aspects properly, especially "GND" and cable impedance

As with any filters, the source and load impedance (CM in this case) and the impedance to the reference ("GND" are critical to the magnetics CM rejection

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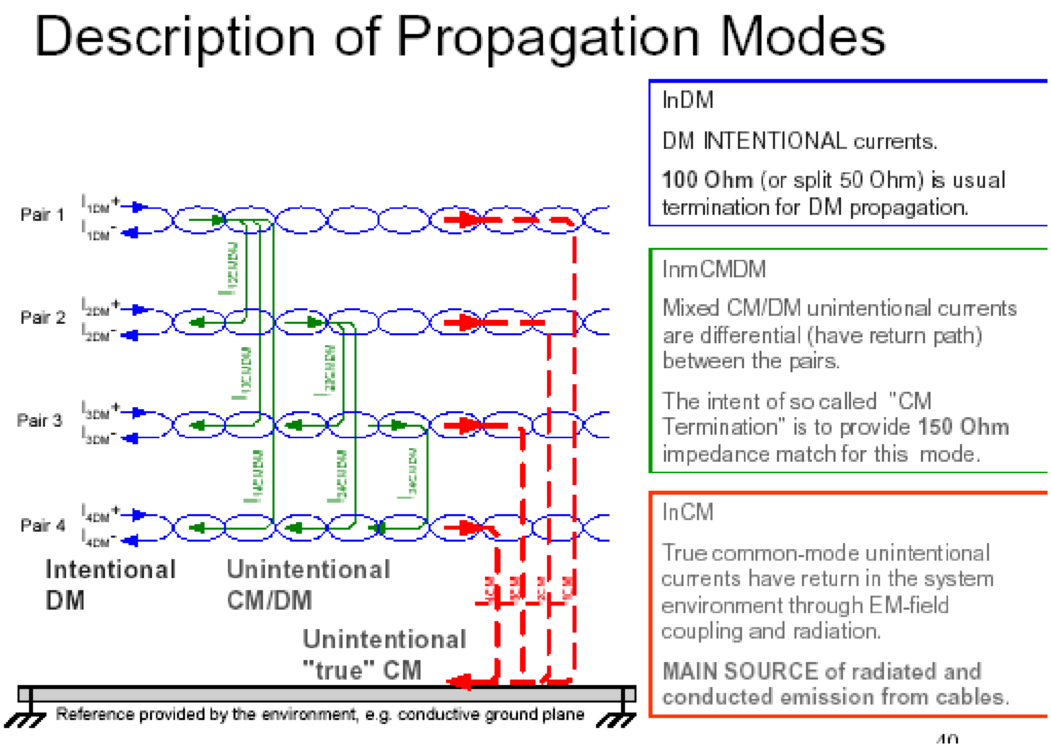
Understanding propagation modes on (Ethernet) cable is essential for understanding magnetics function as EMI suppression devices

Modes of Propagation on UTP

Typical UTP and the conductive environment (e.g. conductive ground) is a multi(9)-conductor T-line
Intentional and unintentional modes propagate at the same time

- Intentional propagation: DM propagation between two wires of each pair
- Unintentional propagation: Mixed CM/DM propagation between pairs
CM propagation between pairs and environment



Description of Propagation Modes

InDM

DM INTENTIONAL currents.

100 Ohm (or split 50 Ohm) is usual termination for DM propagation.

InmCMDM

Mixed CM/DM unintentional currents are differential (have return path) between the pairs.

The intent of so called "CM Termination" is to provide 150 Ohm impedance match for this mode.

InCM

True common-mode unintentional currents have return in the system environment through EM-field coupling and radiation.

MAIN SOURCE of radiated and conducted emission from cables.

Propagation Modes and EMI

- Intentional DM propagation on each pair

Opposing currents mostly cancel EM field à low EMI

- Unintentional mixed CM/DM propagation

It is different from pure CM propagation because CM/DM propagation is contained within the cable

Thus, it doesn’t have major impact on EMI

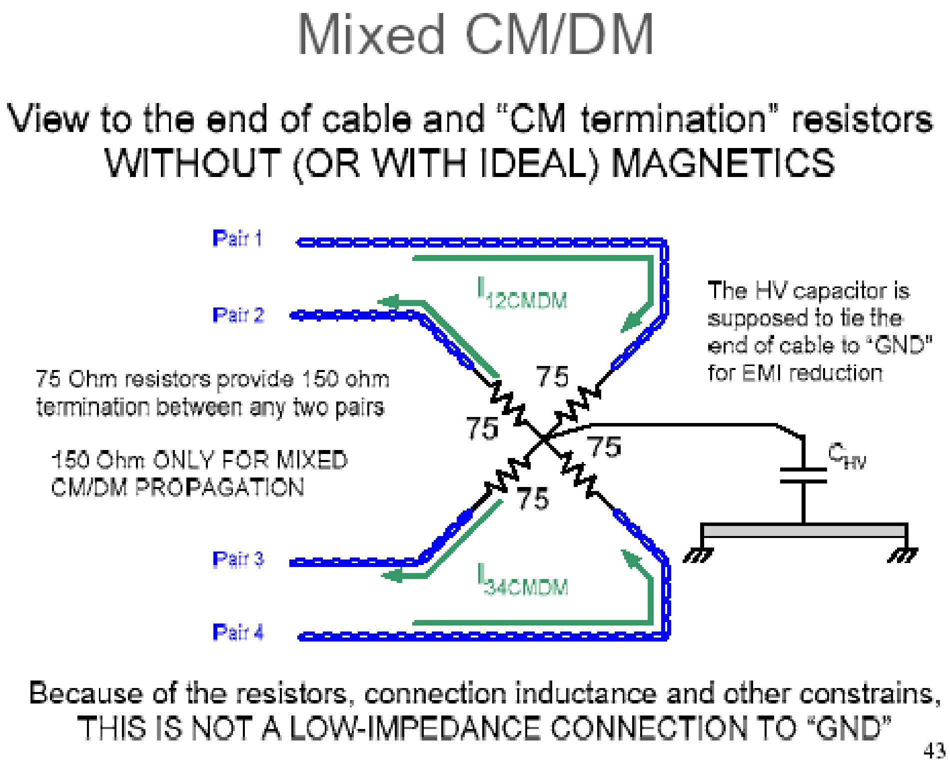
- Pure CM propagation – main source of EMI

Highest potential to cause EMI, because propagation is between the cable AND the environment

The main EMI-related function of magnetics is to suppress this mode of propagation

Differential-Mode

- Not a direct contributor to EMI.
- However, it is a SOURCE of emission, by the mechanism of mode conversion, which converts a part of DM propagation into CM propagation.
- Important to keep balance, symmetry, constant impedance and proper termination. E.g. a fraction of pF of imbalance can cause significant level of DM-CM conversion. Conversion increases crosstalk and EMI.



Mixed CM/DM

View to the end of cable and “CM termination” resistors
WITHOUT (OR WITH IDEAL) MAGNETICS

Because of the resistors, connection inductance and other constrains,
THIS IS NOT A LOW-IMPEDANCE CONNECTION TO “GND”

True CM

- Most significant contributor to EMI, because radiation and coupling from external EM fields is dominantly CM
- Caused by effects such as:

– Imbalance (impedance, amplitude, timing, dv/dt)
– Crosstalk
– Non-ideal reference (“ground bounce”, RF voltage shift across planes and in relation to “chassis”)

75 Ohm resistors terminate true CM with this impedance:

$$Z = \sqrt{(75/4)^2 + j(\omega L - 1/\omega C_{HV})^2}$$

1nF@100MHz ≅ 1.6 Ω
10 nH@100MHz ≅ 6.3 Ω

Z@100MHz ≅ 19 Ω

Is this really “good” impedance to terminate CM propagation?

Is it better to “terminate” or to suppress CM?

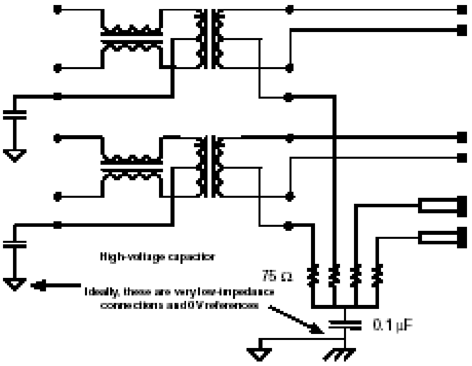
- For EMI reduction, it may be better to connect the CM-end of a cable through low impedance (meaning LOW INDUCTANCE) to chassis.

Common Magnetics Configurations

2-line CMC on the PHY side

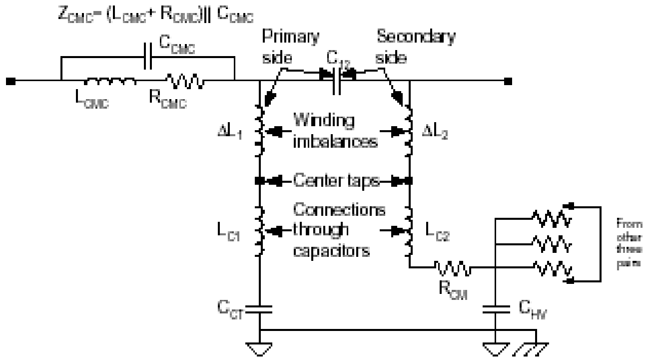
This configuration is good to start discussion. However, it is not recommended with “current drive” transceivers, in which the Tx output power is supplied from the center tap connected to Vcc.

“GND” ≠ 0 V



CM Model of One Channel (Pair)

CM coupling between channels and CM-DM conversion not included



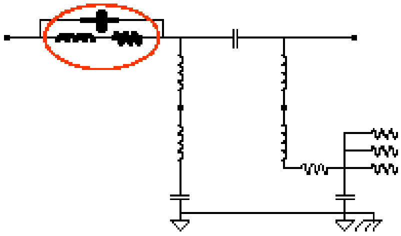
Elements of the CM Model

Z_{CMC}

Impedance of the CM choke reduces EMI by impeding flow of CM current. The design goal for the CM choke is to maximize the L_{CMC} and R_{CMC}.

C_{CMC}

Distributed capacitance of the CM choke, reduces efficiency of the CM choke at high frequency. Decrease in C_{CMC} can be achieved by minimizing overlapping of the windings on the ferrite core, especially at the two ends of the entire winding. Proximity to conductive structures can strongly affect this capacitance.



Typical CM Choke Impedance in Ethernet Magnetics

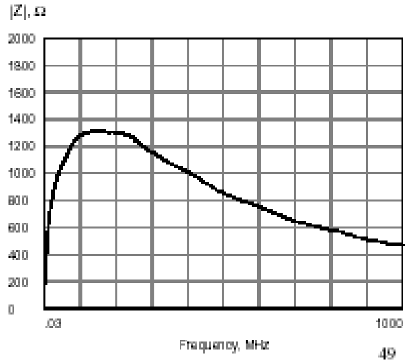
Z_{CMC} is a function of the core material, size, number of turns, and C_{CMC}.

In order to maximize the CM impedance in a particular frequency range, it is usually necessary to trade-off the impedance at other frequencies.

Z_{CMC} decreases with saturation. This is especially important in two cases:

- POE, where DC current may bias and saturate the core

- Exposure of UTP to relatively strong voltages and currents, e.g., exposure to high-intensity EMI.



Center tap imbalance (PHY-side)

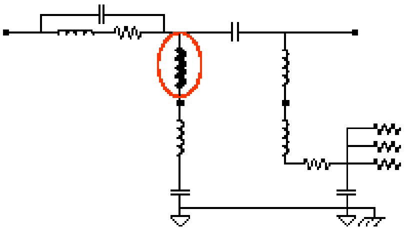
ΔL_1

Imbalance between the two halves of the winding. An ideal transformer with the center tap exactly at the midpoint in the winding would have $\Delta L_1 = 0$.

Two effects of the center tap imbalance:

- Impedance of ΔL_1 increases with frequency, limiting the CM rejection by reducing the efficiency of the center tap to bypass/shunt the CM current.

- ΔL_1 presents an imbalance to the differential signal, which causes DM-CM and CM-DM conversion. This increases emission and susceptibility.



Inductance in center tap connection

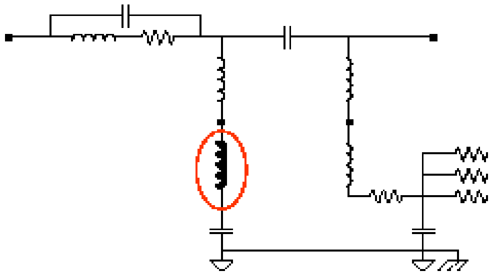
L_1

Adds significant impedance in center-tap connection.

Highly dependent on physical layout of the wires.

Does not create conversion at the center tap, but significantly decreases CM-CM rejection above ~ 100 MHz.

Typically about 10 nH.



Center tap capacitor

C_{CT}

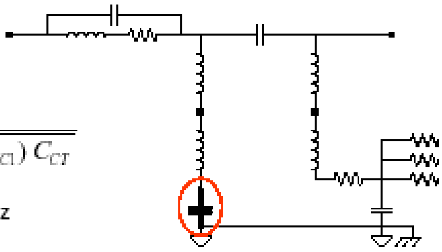
Impedance through center-tap connection resonates:

Typical resonance with 0.1uF capacitor and 10 nH series inductance is at 5 MHz. Above the resonance, the impedance of the center tap connection is inductive.

Fres can be changed by using different C_{CT} value, but it is best to keep L low.

$$fres = \frac{1}{2\pi\sqrt{(\Delta L_1 + L_{C1})\, C_{CT}}}$$

Typically 5-50 MHz



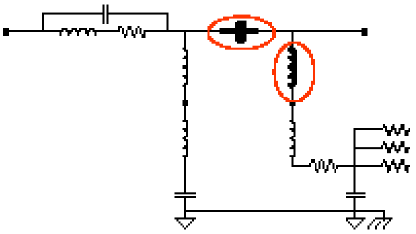
Interwinding capacitance and imbalance in cable-side center tap

C_{12}

Interwinding capacitance of the transformer. To attenuate CM transfer across the transformer, this capacitance should be low. Unfortunately, it is hard to keep this capacitance low enough to provide any significant CM rejection at the frequencies of interest for EMC.

ΔL_1

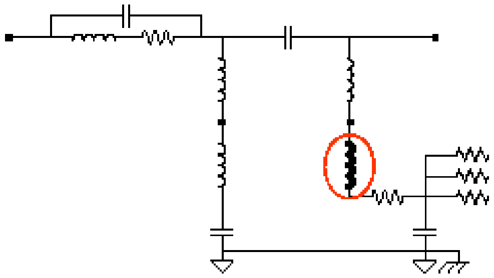
Similar considerations regarding the CM-DM conversion and effect of the increased impedance apply as to ΔL_1 .



Inductance in center tap connection on the cable-side

L_{C2}

Inductance in the center tap through R_{CM} and high-voltage capacitor C_{HV}. Similar considerations as for L_{C1} apply, but it is more difficult to keep the L_{C2} low.



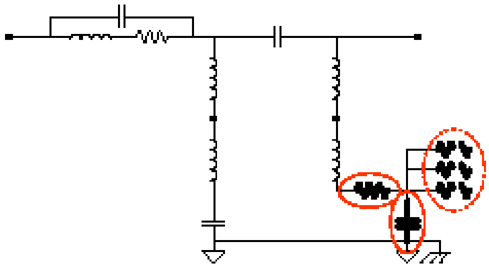
High-voltage capacitor and CM/DM termination resistors

C_{HV}

High voltage capacitor, shared by four resistors R_{CM}. The high-voltage requirement limits the available capacitance range in the acceptable SMD sizes. Typical capacitor is 1 nF/2000V ceramic type.

R_{CM}

One of four 75Ω resistors used to terminate mixed CM/DM propagation.
It also increases the impedance in the center-tap connection on the cable-side.



Summary of the Model with 2-Line CMC on the PHY-Side

- The configuration can be excellent for suppressing low-frequency CM noise originating in the PHY
- The CM choke and the center-tap together provide efficient low-pass filter
- At the frequencies where impedances of parasitic CCMC, L1, and LC1 are significant, EMI suppression by the magnetics is significantly reduced