Common Mode Chokes, design techniques with applications

20 May 2026

Presented by

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Contents:

Review: Common Mode Choke (CMC)

Wurth Elektronik
744282010 Common Mode
Chokes / Filters

Wurth Elektronik 100 µH 14A
Common Mode Choke 6 mΩ
250 V ac 744844101

Würth Elektronik 7448640398 Choke,
Common Mode, 3.3Mh 1.1A

Würth Elektronik 744834310
Common Mode Choke, 0.01H, 3A

Wurth Elektronik 744238102 Common
Mode Choke 12.5µH 3A

Wurth Elektronik 744228
Line-Filter SMD Common
Mode 25µH

Figure 1: Various CMCs

Review: Magnetically Coupled Coils (MCC)

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Examples of MCCs

CMCs are used to improve circuit immunity and meet EMC guidelines

Figure 2: Voltage transformers (top left), current transformers (top right), Common Mode Chokes (CMC) (bottom centre)

Review: Magnetically Coupled Coils (MCC)

Consider a current passing through coil N_1 with N_2 left open. The flux generated by coil N_1 is given by

$$\phi_1 = \phi_{11} + \phi_{12} \ldots (1a)$$

ϕ_{11}: links only coil N_1; and
ϕ_{12}: links coils N_1 and coil N_2.

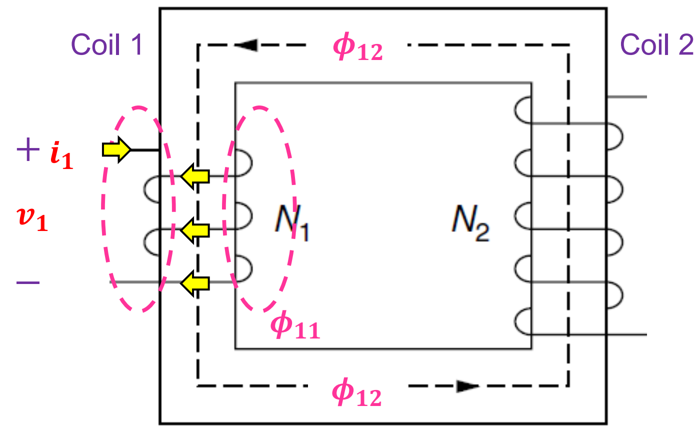

Figure 3a: Single energised coil, N_1

The coefficient of coupling k is the fraction of total flux from one coil linking another coil.

$$k = \frac{\phi_{12}}{\phi_1} = \frac{\phi_{12}}{\phi_{11} + \phi_{12}} \ldots (2a)$$

Maximising the flux linking both coils requires $\phi_{11} = 0$; and is termed perfect coupling.

The voltage developed across coil N_1 is given by

$$v_1 = N_1 \frac{d\phi_1}{dt} \equiv L_1 \frac{di_1}{dt} \ldots (3a)$$

← The inductance connects voltage and current without the need to know the flux

Review: Magnetically Coupled Coils (MCC)

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Consider a current passing through coil N_2 with N_1 left open. The flux generated by coil N_2 is given by

$$\phi_2 = \phi_{22} + \phi_{21} \ldots (1\text{b})$$

ϕ_{22}: links only coil N_2; and
ϕ_{21}: links coils N_2 and coil N_1.

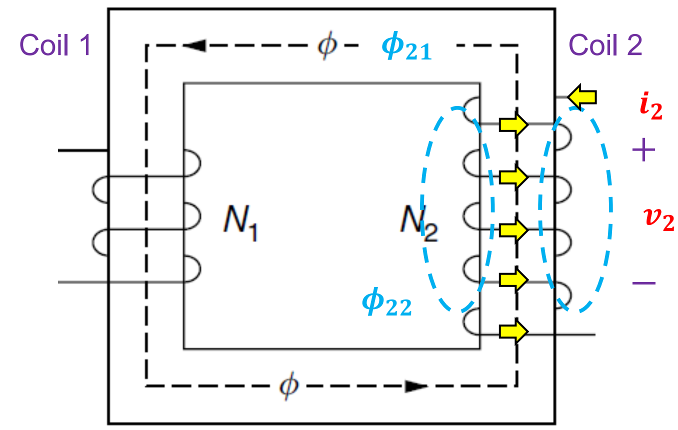

Figure 3b: Single energised coil, N_2

The coefficient of coupling k is the fraction of total flux from one coil linking another coil.

$$k = \frac{\phi_{21}}{\phi_2} = \frac{\phi_{21}}{\phi_{22} + \phi_{21}} \ldots (2\text{b})$$

Maximising the flux linking both coils requires $\phi_{22} = 0$; and is termed perfect coupling.

The voltage developed across coil N_2 is given by

$$v_2 = N_2 \frac{d\phi_2}{dt} \equiv L_2 \frac{di_2}{dt} \ldots (3\text{b})$$

← **The inductance connects voltage and current without the need to know the flux**

The analysis is extended to include the two energised coils.

Review: Magnetically Coupled Coils (MCC)

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The flux linking coils N_1 and N_2 are given by (4) and voltage across coils N_1 and N_2 are given by (5)

Fluxes flowing in the same direction:

$$\lambda_1 = \phi_1 + \phi_{21} = \phi_{11} + \phi_{12} + \phi_{21} \ldots (4a)$$
$$\lambda_2 = \phi_2 + \phi_{12} = \phi_{22} + \phi_{21} + \phi_{12} \ldots (4b)$$

$$v_1 = N_1 \frac{d\lambda_1}{dt} = N_1 \frac{d\phi_1}{dt} + N_1 \frac{d\phi_{21}}{dt} \equiv L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \ldots (5a)$$
$$v_2 = N_2 \frac{d\lambda_2}{dt} = N_2 \frac{d\phi_2}{dt} + N_2 \frac{d\phi_{12}}{dt} \equiv L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} \ldots (5b)$$

Fluxes flowing in opposite direction:

$$\lambda_1 = \phi_1 - \phi_{21} = \phi_{11} + \phi_{12} - \phi_{21} \ldots (4c)$$
$$\lambda_2 = \phi_2 - \phi_{12} = \phi_{22} + \phi_{21} - \phi_{12} \ldots (4d)$$

$$v_1 = N_1 \frac{d\lambda_1}{dt} = N_1 \frac{d\phi_1}{dt} - N_1 \frac{d\phi_{21}}{dt} \equiv L_1 \frac{di_1}{dt} - M \frac{di_2}{dt} \ldots (5c)$$
$$v_2 = N_2 \frac{d\lambda_2}{dt} = N_2 \frac{d\phi_2}{dt} - N_2 \frac{d\phi_{12}}{dt} \equiv L_2 \frac{di_2}{dt} - M \frac{di_1}{dt} \ldots (5d)$$

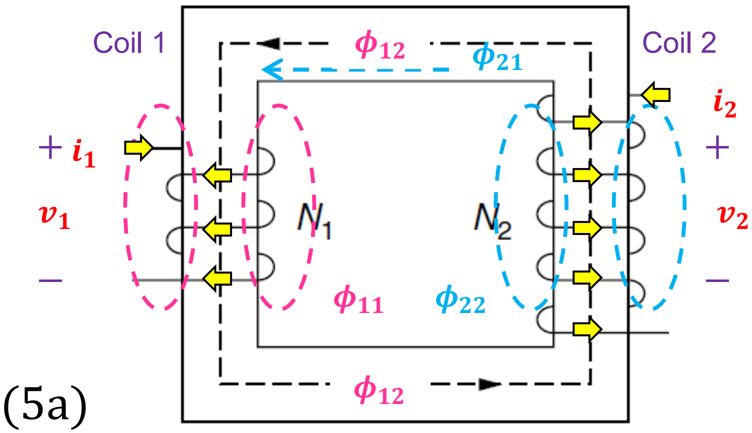

Figure 4a: Coupled coils, fluxes flowing in the same direction

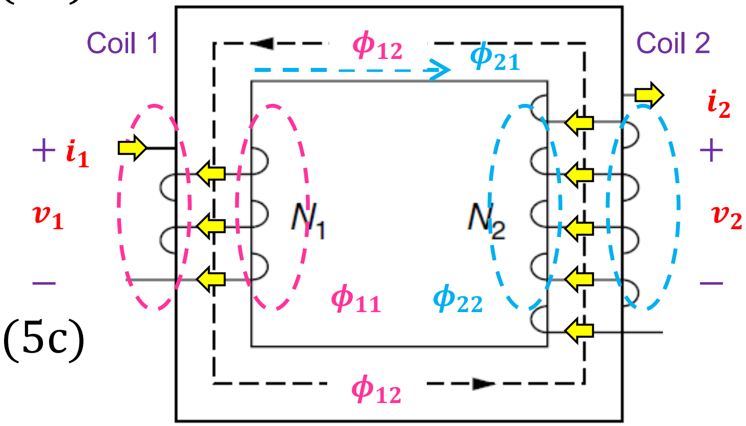

Figure 4b: Coupled coils, fluxes flowing in opposite direction

Electrical models of CMC: Low frequency lossless

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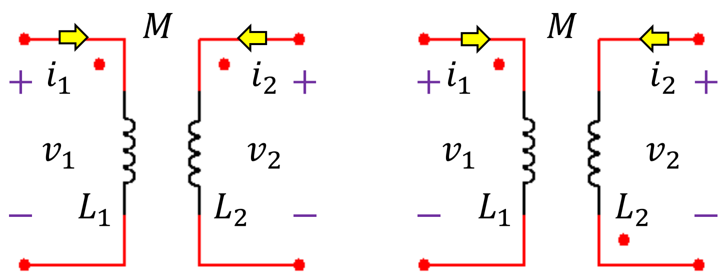
Substituting exponential time varying terms in (5) yields the compact steady state equations of coupled coils.

$$v_1 = sL_1 i_1 \pm sMi_2 \text{ ... (6a)}$$

$$v_2 = \pm sMi_1 + sL_2 i_2 \text{ ... (6b)}$$

Low Frequency (LF) electrical equivalent circuits for the coupled coils are shown.

Dot convention:
a current entering a dot produces a positive voltage at the dotted terminal of the other coil.



← **CMCs are transformers**

← **Note the change in the dot**

Figure 5a: Electrical equivalent circuit of Figure 4a and Figure 4b

The coefficient of coupling is given by (7a) and approximately given by (7b).

$$k = \frac{M}{\sqrt{L_1 L_2}} \text{ ... (7a)}$$

$$k \approx \left.\frac{M}{L}\right|_{L=L_1=L_2} \text{ ... (7b)}$$

$$M \cong L\Big|_{k=1,\, L=L_1=L_2} \text{ ... (7c)}$$

These equations are readily applied to analyse a CMC.

Electrical models of CMC: Low frequency lossless

Worked example 1:

For the following circuits, determine the polarity of the induced voltage.

Figure 5b: Magnetically Coupled Coils MCC, top left (i), top right (ii), bottom left (iii), bottom right (iv)

Electrical models of CMC: Low frequency lossless

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Worked example 1:

For the following circuits, determine the polarity of the induced voltage.

Figure 5c: Magnetically Coupled Coils MCC, top left (i), top right (ii), bottom left (iii), bottom right (iv)

Electrical models of CMC: Low frequency lossless

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Common mode configuration

Assumptions: $L = L_1 = L_2$.

Applying equations (6) yields.

$$2v_{i\,CM} = s(L_1 + M)i_1 + s(L_2 + M)i_2 \ldots (8a)$$

$$0 = s(L_1 - M)i_1 - s(L_2 - M)i_2 \ldots (8b)$$

Employing assumptions yields

$$i_1 = i_2 \ldots (8c)$$

$$v_{i\,CM} = s(L + M)i_1 = s(L + M)i_2 \ldots (8d)$$

$$v_{i\,CM} = sL(1 + k)i_1 = sL(1 + k)i_2, M = kL \ldots (8e)$$

Noting that $i_3 = 2i_1 = 2i_2 \ldots$

$$v_{i\,CM} = \{s(L + M)/2\}i_3 \ldots (8f)$$

$$v_{i\,CM} = \{sL(1 + k)/2\}i_3, M = kL \ldots (8g)$$

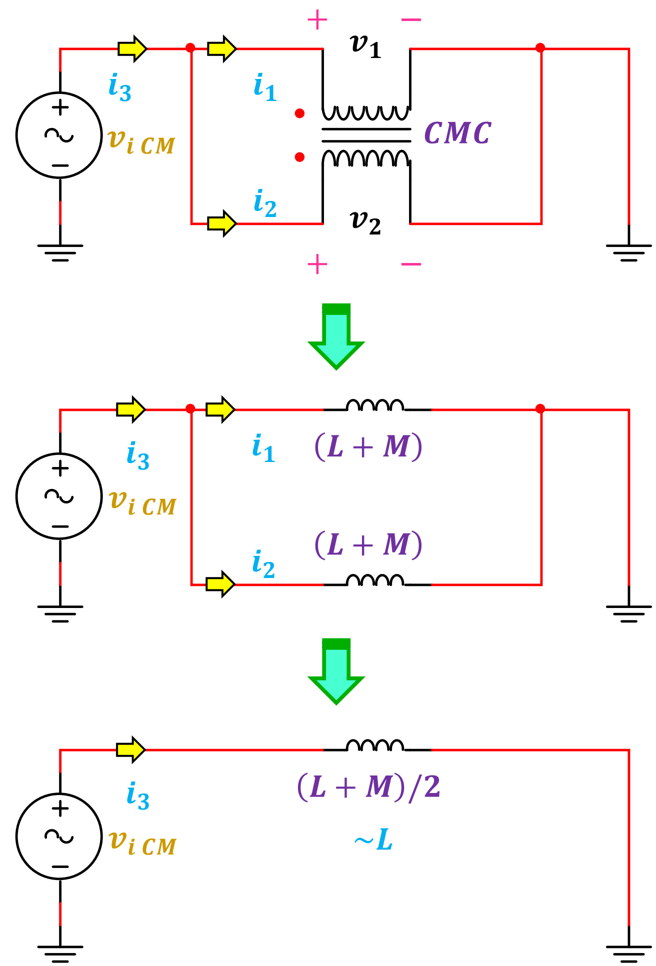

Figure 6: In-phase CM configuration (top), branch and single ended equivalent circuits (middle) and (bottom)

Electrical models of CMC: Low frequency lossless

Differential mode configuration

Assumptions: $L = L_1 = L_2$.

Applying equations (6) yields.

$$v_{i\,DM} = v_1 - v_2 \rightarrow sL_1 i_1 + sM i_2 - sL_2 i_2 - sM i_1 \ldots (9a)$$

Simplifying

$$v_{i\,DM} = s(L_1 - M)i_1 + s(M - L_2)i_2 \ldots (9b)$$

Noting that $i_2 = -i_1$ and taking i_1 as the reference

$$v_{i\,DM} = s(L_1 - M)i_1 + s(L_2 - M)i_{\mathrm{i}} \ldots (9c)$$

Employing assumptions yields

$$v_{i\,DM} = s(L - M)i_1 + s(L - M)i_{\mathrm{i}} \ldots (9d)$$

$$v_{i\,DM} = s2(L - M)i_1 \ldots (9e)$$

$$v_{i\,DM} = s2L(1 - k)i_1, M = kL \ldots (9f)$$

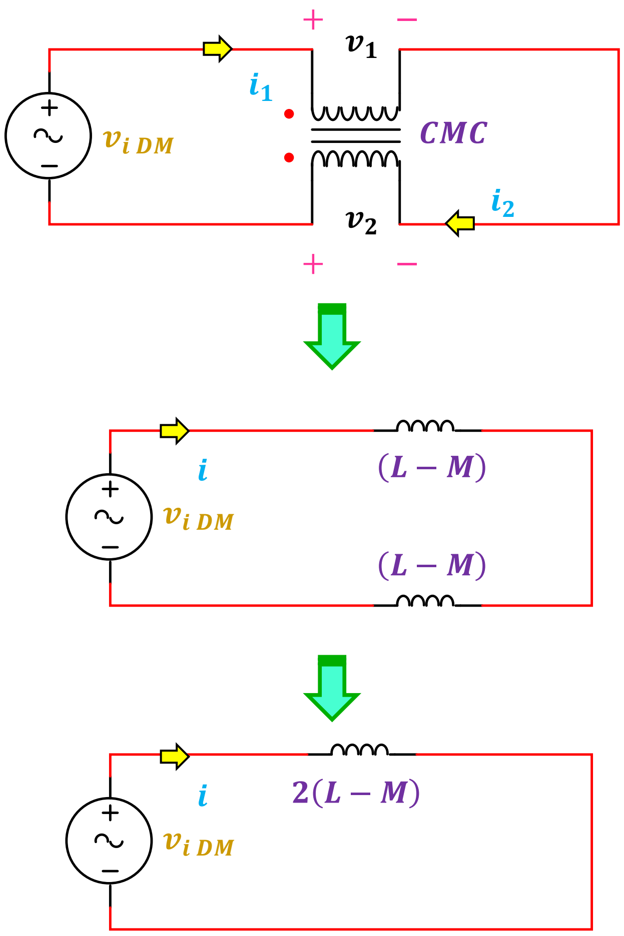

Figure 7: In-phase DM configuration (top), single element and consolidated equivalent circuits (middle) and (bottom)

Electrical models of CMC: Low frequency lossless

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Worked example 2:

With the help of Figure 8, which modes of current are impeded by the CMC in Figure 9.

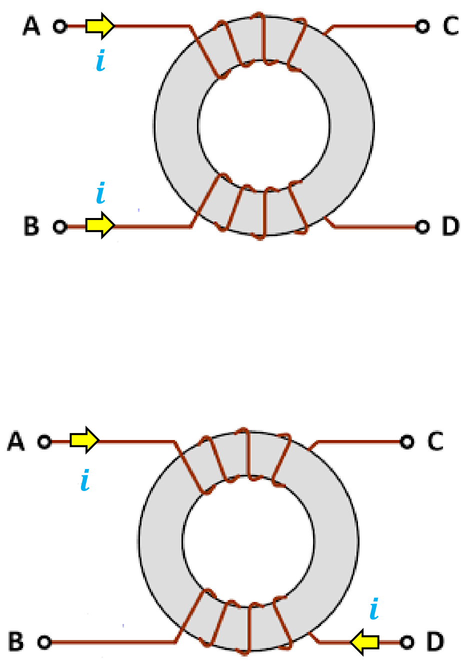


Figure 9: Current modes

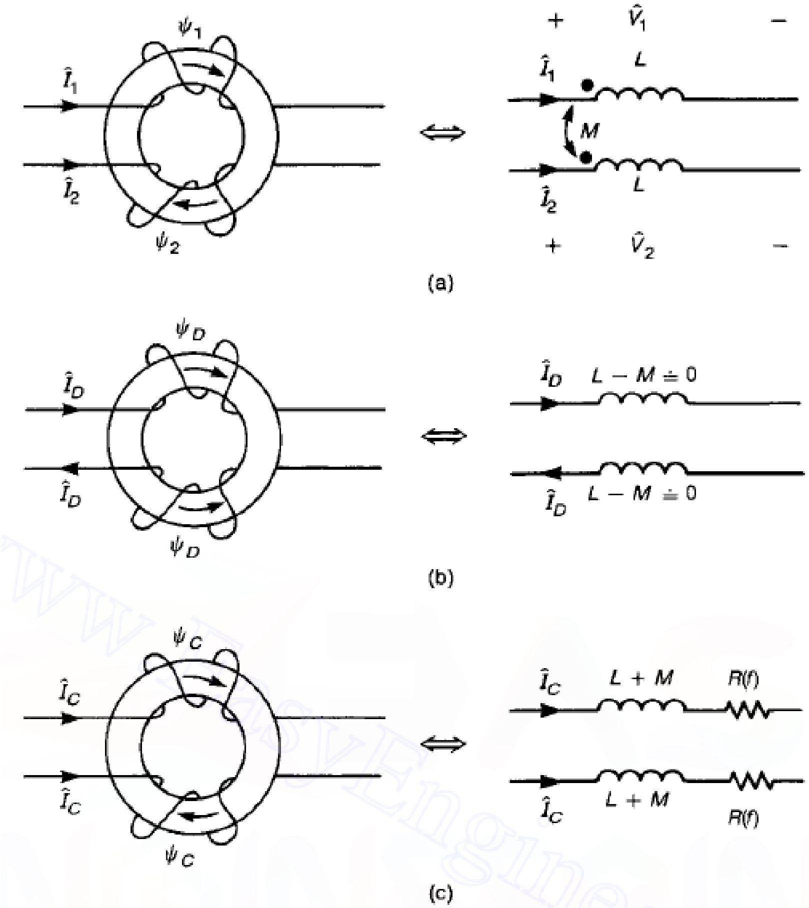
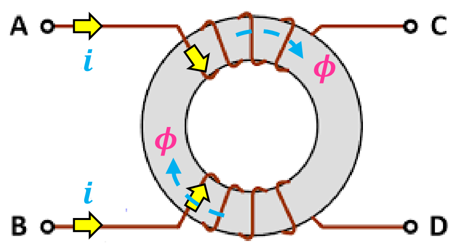


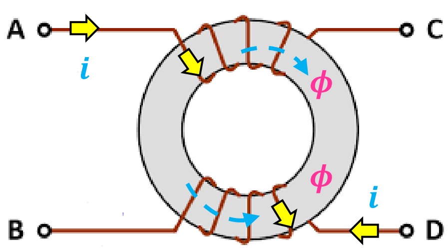
Figure 8: Currents flowing through a CMC (a), DM components (b), and CM components (c)

Electrical models of CMC: Low frequency lossless

Worked example 2:
With the help of Figure 8, which modes of current are impeded by the CMC in Figure 9.



Flux aiding, therefore CM



Flux opposing, therefore DM

Figure 9: Current modes for aiding (top) [CM (c)], currents opposing (bottom) [DM (b)]

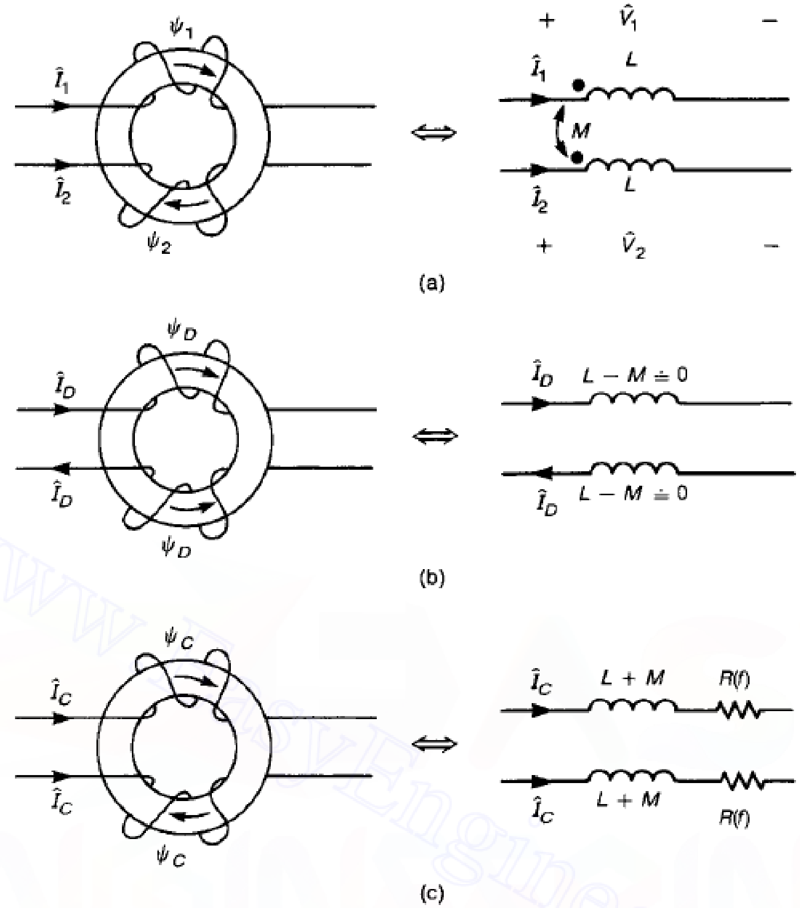


Figure 8: Currents flowing through a CMC (a), DM components (b), and CM components (c)

Electrical models of CMC: Low frequency lossless

Worked example 3:

What is the voltage across the 1kΩ resistor?

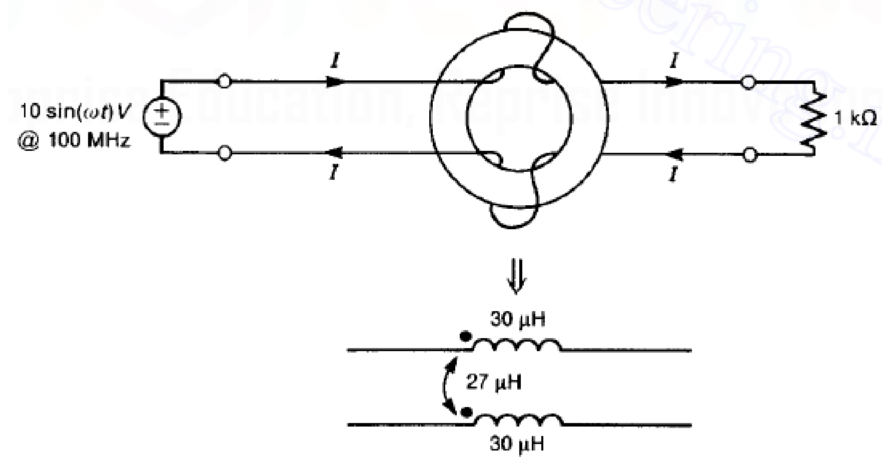


Figure 10: Application of a CMC (top), equivalent circuit (bottom)

Electrical models of CMC: Low frequency lossless

Worked example 3:
What is the voltage across the 1kΩ resistor?

Answer 3:
Fluxes are opposing and therefore in DM configuration. Use the circuit model in Figure 7 (middle) and include the resistor. Refer to Figure 10 (bottom).

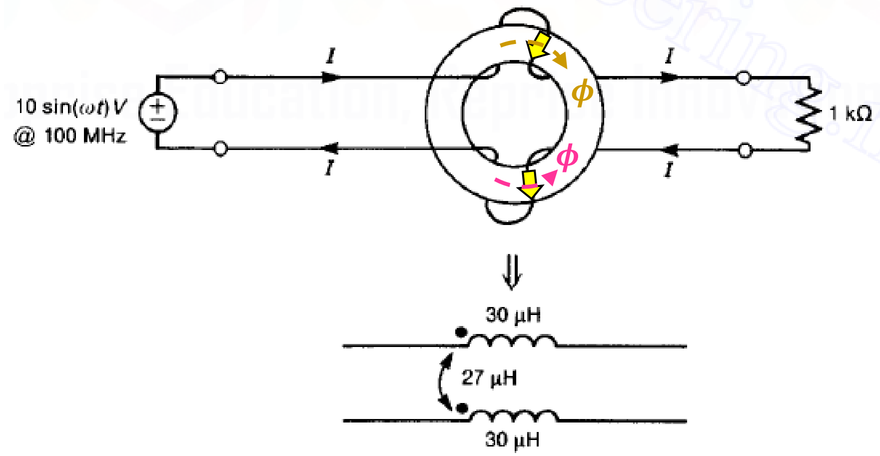


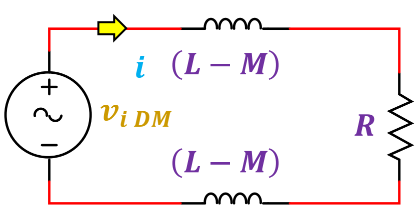
Figure 10: Application of a CMC (top), equivalent circuit (bottom)

Modify equation (9d) to yield

$$v_{i\,DM} = \{2s(L-M)+R\}i \ldots (10a)$$

The voltage across the resistor is given by

$$v_R = iR = \frac{v_{i\,DM}R}{\{2s(L-M)+R\}} = \frac{v_{i\,DM}R}{\{2j\omega(L-M)+R\}} \ldots (10b)$$



The magnitude is given by [$L-M$ = 30μH-27μH =3μH]

$$v_R = iR = \frac{v_{i\,DM}R}{\sqrt{4\omega^2(L-M)^2+R^2}} \rightarrow 2.56V \ldots (10c)$$

Electrical models of CMC:
Parasitic and lossy elements

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Various lumped element circuit models of a lossy high frequency CMC exist, which one do I choose?

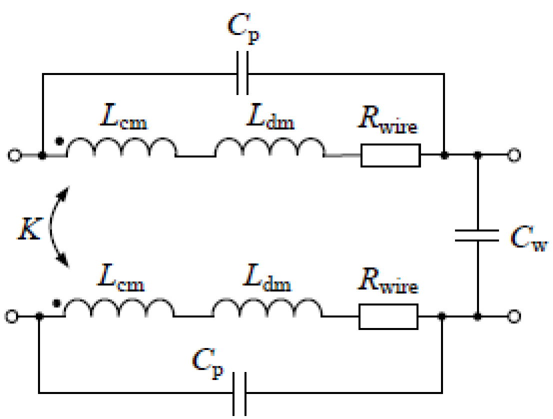

Figure 11a: CM model [1]

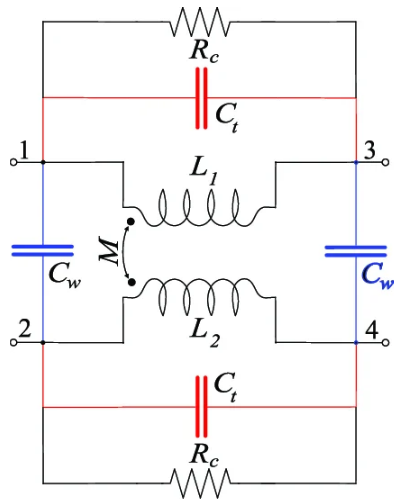

Figure 11b: CM model [2]

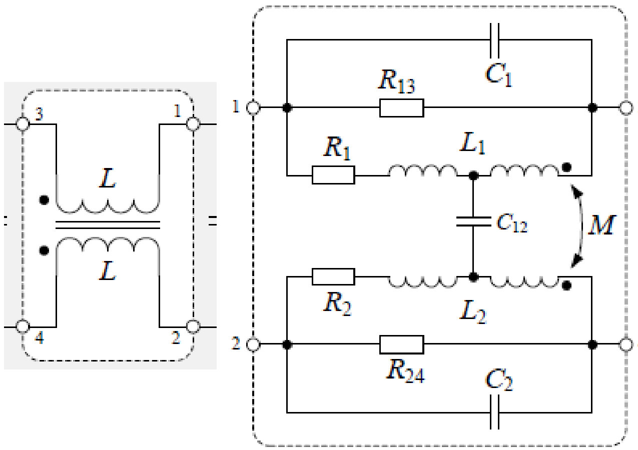

Figure 11c: CM model [3]

In-fact they are essentially the same and yield the same salient features of the impedance curves.

Parasitic self capacitance of windings (intra-winding) C_t, C_p, C_1, C_2, capacitance between windings (inter-winding) C_w, C_{12}, individual loss parameters R_{wire}, R_1, R_2, R_{13}, R_{24}, consolidated losses R_c

[1]: T. Kut, A. Lucken, S. Dickmann, and D. Schulz, "Common mode chokes and optimisation aspects", Advances in Radio Science, Open Access Proceedings, 12, 143-148, 2014.

[2]: C. Dominguez-Palacios, J. Bernal, "Characterisation of Common Mode Chokes at High Frequencies With Simple Measurements", IEEE Transactions on Power Electronics, Vol. 33, N0.5 May 2018.

[3]: K. Kostov and J. Kyyra, "Common-Mode Choke Coils Characterization", Proceedings of the 13th European Conference on Power Electronics and Applications (EPE 2009), Barcelona Spain, 8-10 September 2009.

Electrical models of CMC:
Parasitic and lossy elements

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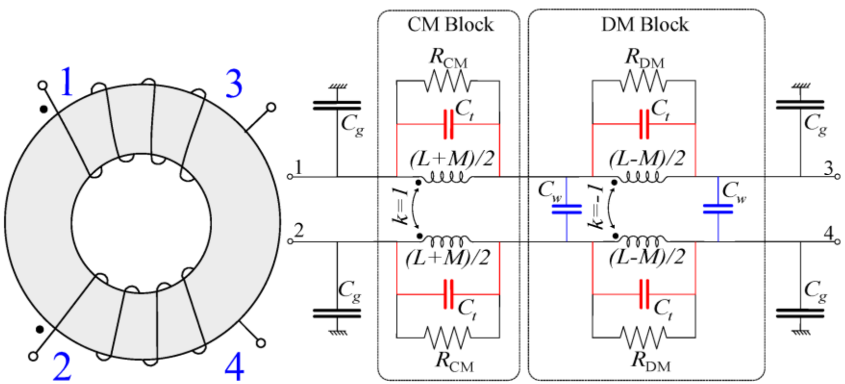
Model 4 utilises the same circuit configuration for CM and DM.



(**a**) Common mode choke. (**b**) Equivalent circuit of the CMC with CM and DM blocks.

Figure 11d: CM model [4]

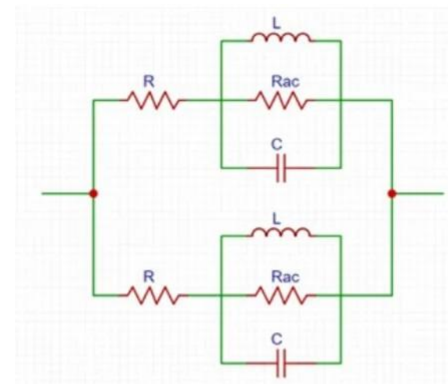


Figure 11e: CM model [5]

In this work Model 5 is adopted.

Note, Model 5 separates the DC and AC losses. The impedance curves usually do not show near zero frequency but is provided in the datasheet. The DC term can be omitted if it is much less than the impedance at the frequencies of interest.

[4]: P. Gonzalez-Vizuete, C. Dominguez-Palacios et al, “Simple setup for measuring the response to differential mode noise of common mode chokes”, Electronics, 25 February 2020.
[5]: A. Alamin, “Common Mode Chokes Basics and Applications”, ABRACON, LLC, 29 June 2022.

Impedance curves: Parameter extraction

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How are impedance curves derived?

CMC coils connected in parallel

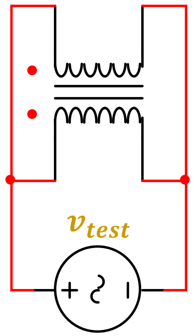

Figure 12a: Test setup for measuring the CM impedance curve

CMC coils connected in series

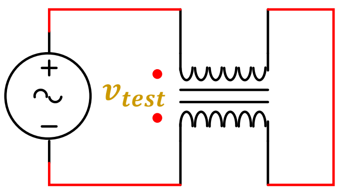

Figure 12b: Test setup for measuring the DM impedance curve

Typical Impedance Characteristics:

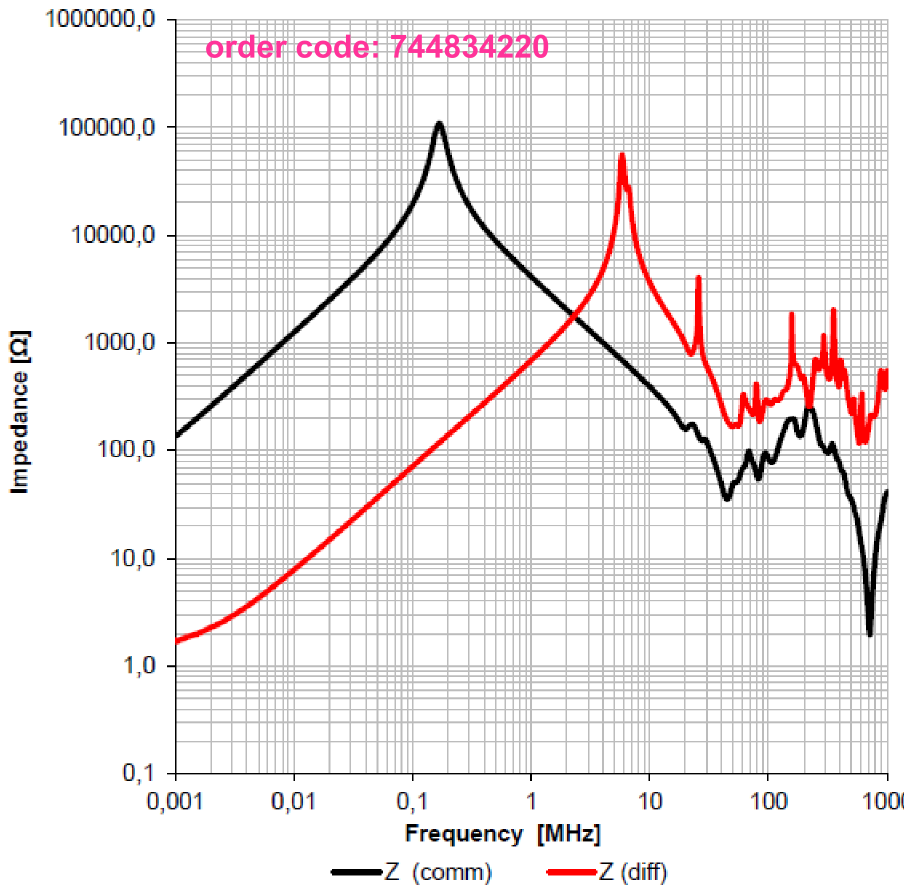

Figure 12c: Impedance curves for WE order code: 744834220

Impedance curves: Parameter extraction

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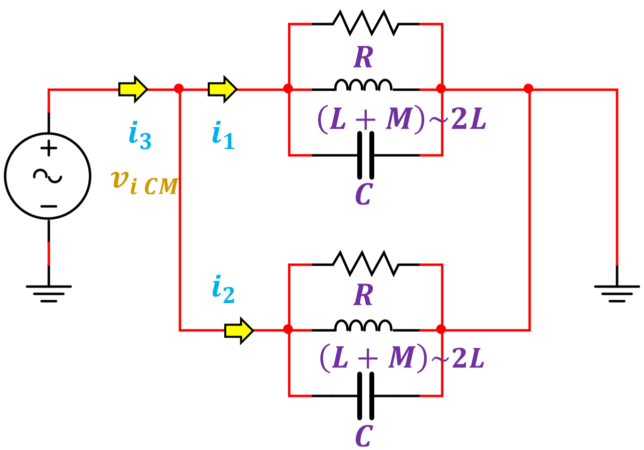
Common mode impedance

Two windings.



Single winding equivalent circuit.

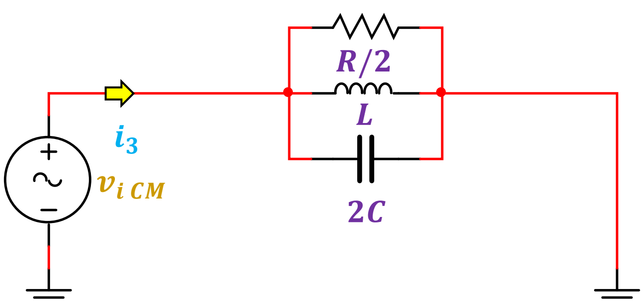


Figure 13: Common mode configurations of a CMC, two windings (top), single winding equivalent circuit (bottom)

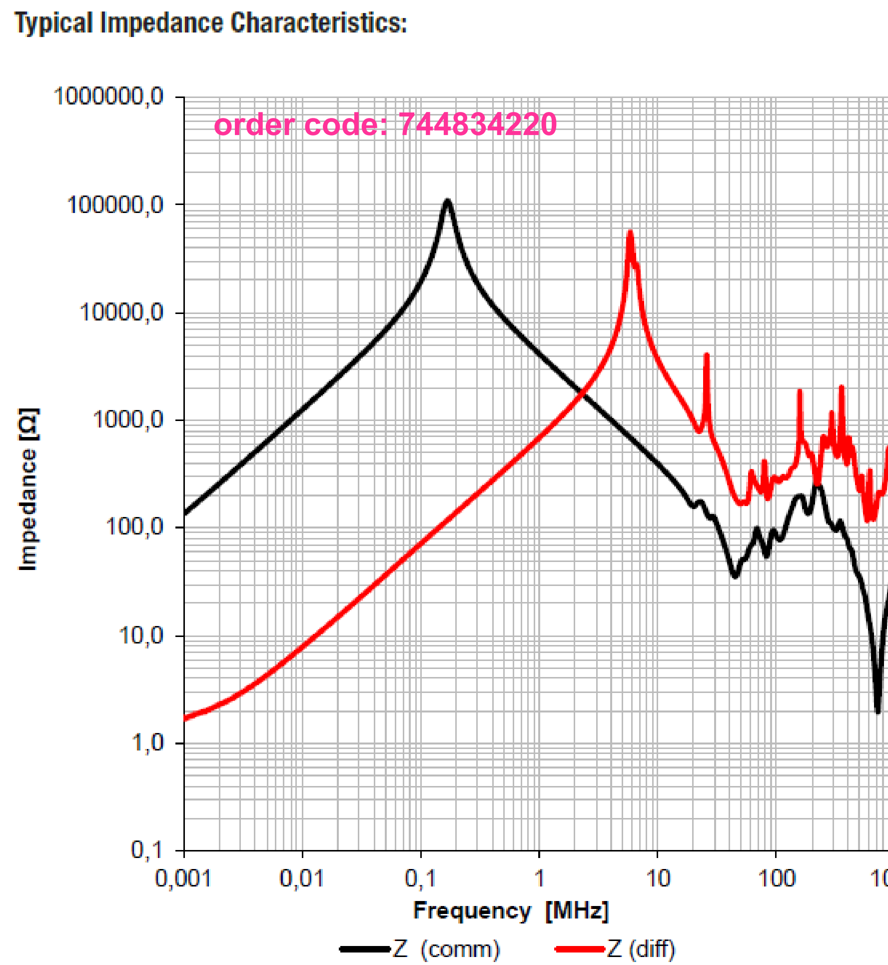


Figure 12c: Impedance curves for WE order code: 744834220

Impedance curves: Parameter extraction

Common mode impedance

From the datasheet the inductance is given as L_e = 20mH. The resonant frequency is found by inspection of the datasheet [Figure 12c] and the effective capacitance can be found using (11).

[f_r = 185kHz, C_e = 37pF, C = 18.5pF]

$$f_r = \frac{1}{2\pi\sqrt{L_e C_e}} \rightarrow C_e = \frac{1}{L_e(2\pi f_r)^2} \ldots (11)$$

The maximum impedance is found by inspection of the datasheet. [$R/2$ = 105kΩ, R = 210kΩ]

Electrical Properties:

Properties		Test conditions	Value	Unit	Tol.
Number of windings	N		2		
Inductance	L	10 kHz/ 0.1 mA	20	mH	±30%
Rated Current	I_R	@70 °C	2	A	max.
DC Resistance	R_{DC}	@ 20 °C	230	mΩ	max.
Rated Voltage	V_R	50 Hz	250	V (AC)	max.
Insulation Test Voltage	V_T	50 Hz/ 5 mA/ 2 sec.	1500	V (AC)	

Figure 14a: WE order code: 744834220 datasheet

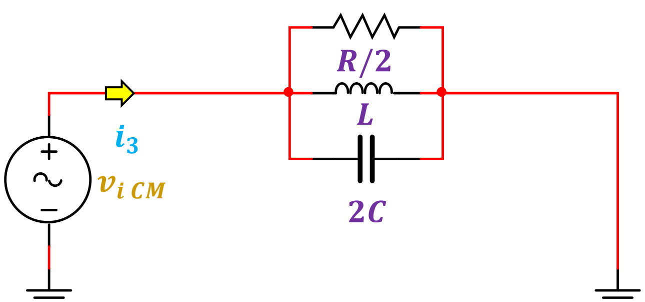


Figure 14b: CM single winding equivalent circuit ($k = 1$)

Impedance curves: Parameter extraction

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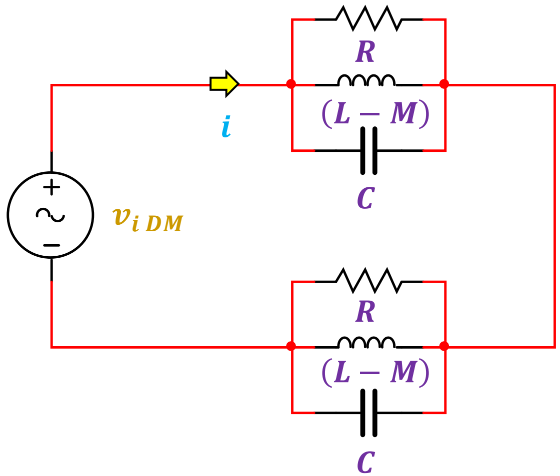
Differential mode impedance

Two windings.



Single winding equivalent circuit.

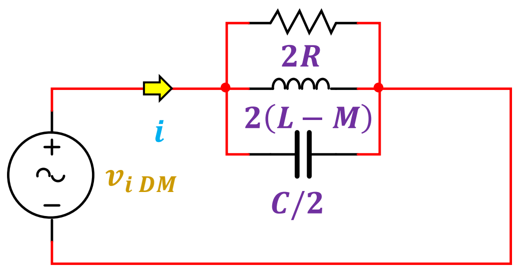


Figure 15: Differential mode configurations of a CMC, two windings (top), single winding equivalent circuit (bottom)

Typical Impedance Characteristics:

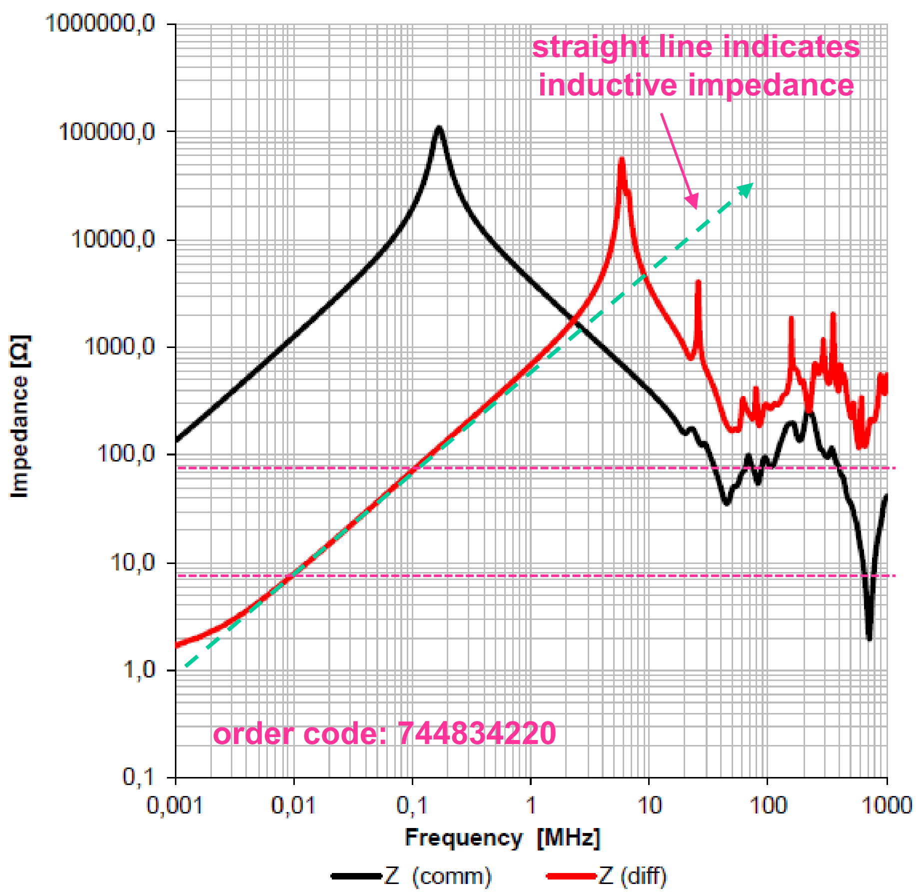


Figure 12c: Impedance curves for WE order code: 744834220

Impedance curves: Parameter extraction

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Differential mode impedance

The maximum impedance is found by inspection of the datasheet. [$2R$ = 58kΩ, R = 29kΩ]

Can deduce L_{DM} from the graph as follows

$$z_{DM} = 2s(L-M) = 2sL(1-k)$$
$$= sL_{DM} \rightarrow L_{DM} = \frac{z_{DM}}{2\pi f} \ldots (12)$$

In the linear region…
z_{DM} = 70Ω @ 100kHz, L_{DM} = 111.4μH,
$L-M$ = 55.7μH. → k = 0.997215

[f_r = 5.85MHz, C_e = 6.64pF, C = 13.3pF]

$$f_r = \frac{1}{2\pi\sqrt{L_e C_e}} \rightarrow C_e = \frac{1}{L_e(2\pi f_r)^2} \ldots (11)$$

Typical Impedance Characteristics:

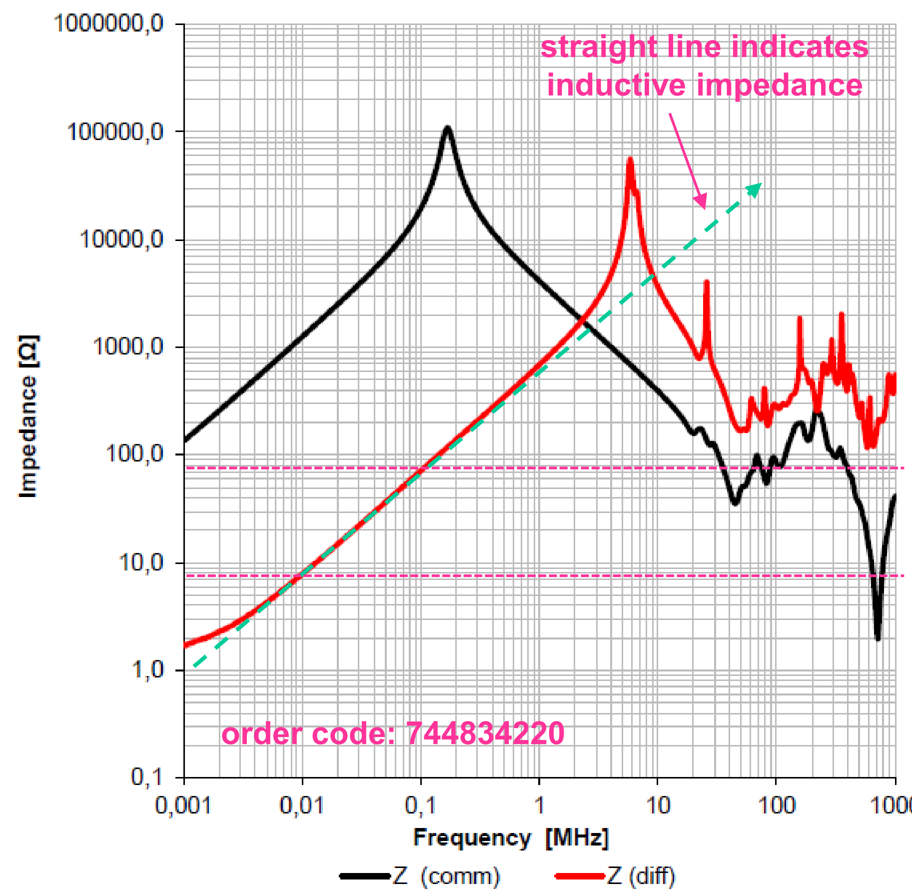


Figure 12c: Impedance curves for WE order code: 744834220

Impedance curves: Parameter extraction

Modelled frequency responses are in close agreement with the datasheet (first dominate peaks only).

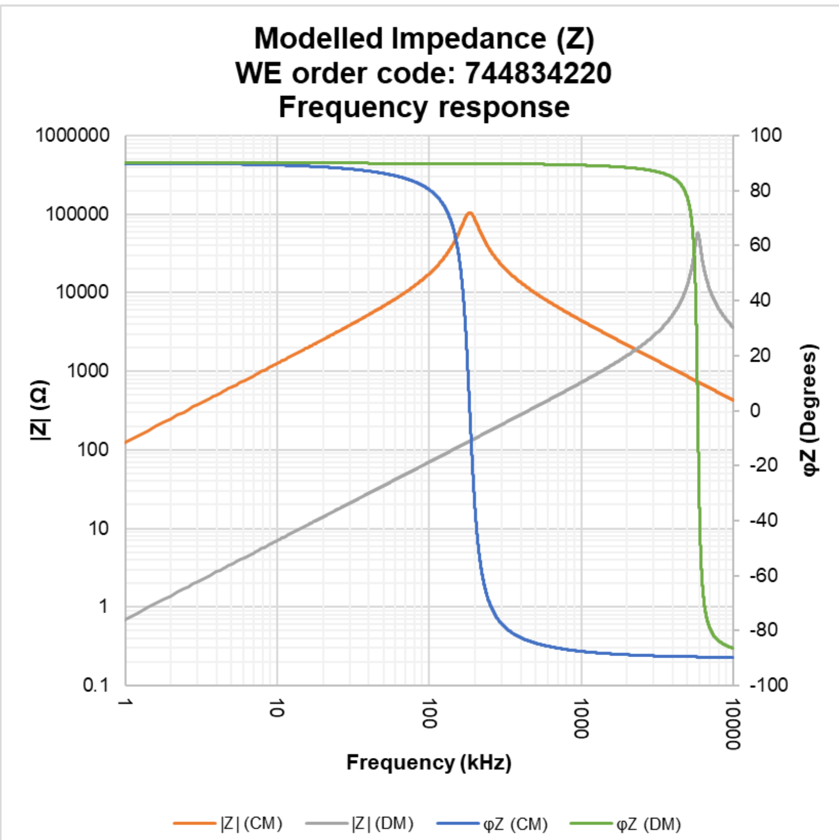


Figure 16: Modelled impedance frequency responses of 744834220

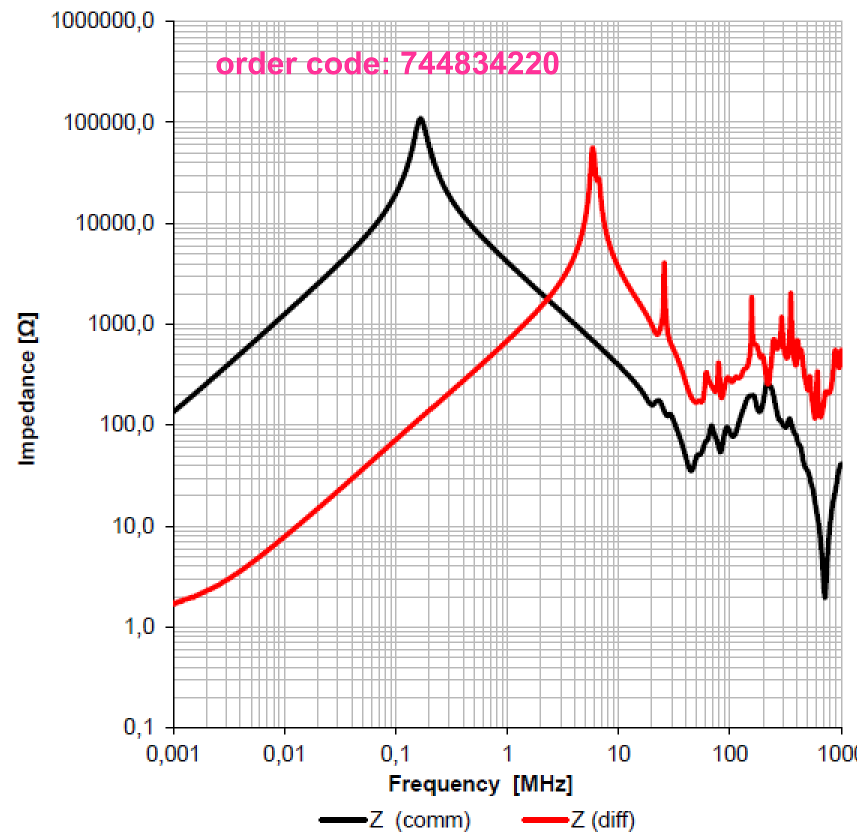
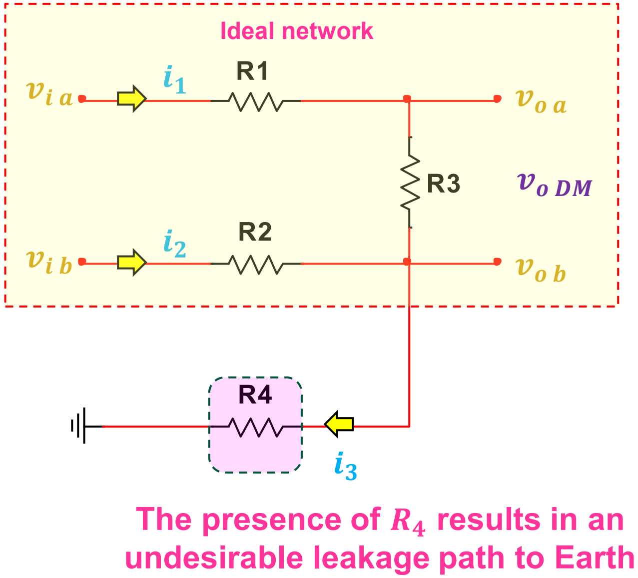


Figure 12c: Impedance curves for WE order code: 744834220

Resistive network with CM leakage: Circuit

Practical electronic circuits exhibit numerous Earth leakage paths. The art is to identify and mitigate all of them.



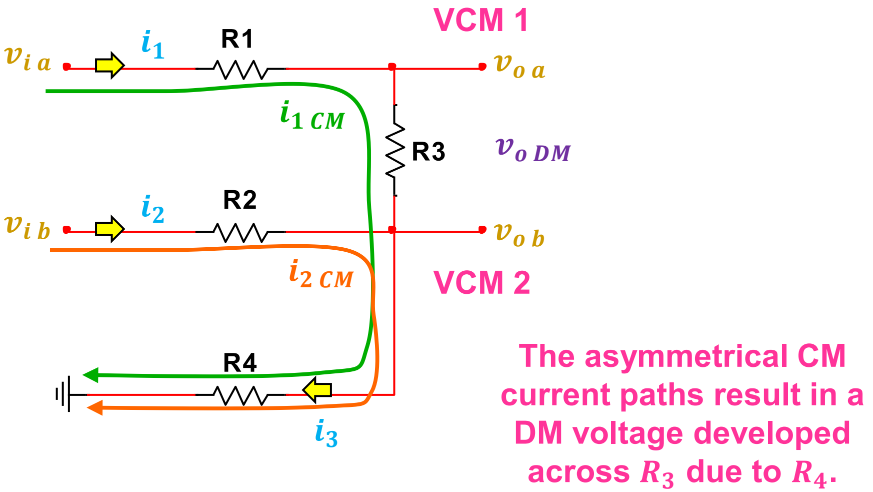


Figure 17: Practical resistive network with Earth return (left), CM current paths shown (right)

Resistive network with CM leakage: Circuit analysis

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The voltage across R_3 is given

$$v_{o\ DM} = \frac{v_{i\ CM} R_3}{\left\{R_4 + (R_1 + R_3)\left(1 + \frac{R_4}{R_2}\right)\right\}} \ldots (13a)$$

Case: R_4 vanishes, $v_{o\ DM} = 0$ as desired.

Therefore, the injection of a CM voltage yields a DM voltage and due to R_4.

Rearranging yields

$$v_{o\ DM} = \frac{v_{i\ CM} R_3}{\left\{\frac{R_4}{R_3} + \left(\frac{R_1}{R_3} + 1\right)\left(1 + \frac{R_4}{R_2}\right)\right\}} \ldots (13b)$$

Case: $R_1, R_2, R_4 \ll R_3$ then

$$v_{o\ DM} = \frac{v_{i\ CM}}{\left(1 + \frac{R_4}{R_2}\right)} = \frac{v_{i\ CM} R_2}{(R_2 + R_4)} \ldots (13c)$$

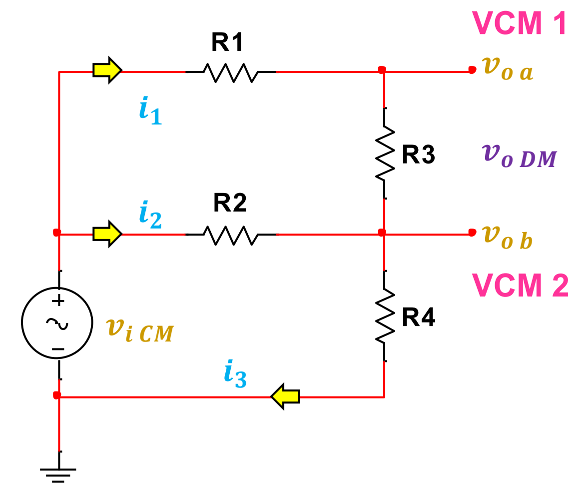

Figure 18: Resistive network

→ The impact depends on the ratio $\frac{R_4}{R_2}$.

Case: $\frac{R_4}{R_2}$ >>1, lower output due to CM injection,

Case: $\frac{R_4}{R_2}$ <<1, higher output due to CM injection.

Resistive network with CM leakage: Circuit analysis

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The voltage across R_3 is given

$$v_{o\,DM} = \frac{v_{i\,CM} R_3}{s2L\left\{1 + \frac{R_3}{2R}\right\} + \frac{R_3}{2} + \{R + 2R_4\}\left\{1 + \frac{R_3}{2R}\right\}} \text{ ... (13d)}$$

$$f_b = \frac{\frac{R_3}{2} + (R + 2R_4)\left(1 + \frac{R_3}{2R}\right)}{4\pi L\left(1 + \frac{R_3}{2R}\right)} \text{ ... (13e)}$$

Case: R_4 vanishes, $v_{o\,DM} = 0$ as desired.

Case: $R_1 = R_2 = R, R_4 \ll R_3$ then

$$v_{o\,DM} = \frac{v_{i\,CM} R}{\{sL + R + R_4\}} = \frac{v_{i\,CM} R}{(R + R_4)\left\{\left(\frac{sL}{R + R_4}\right) + 1\right\}} \text{ ... (13f)}$$

$$f_b = \frac{(R + R_4)}{2\pi L} \text{ ... (13g)}$$

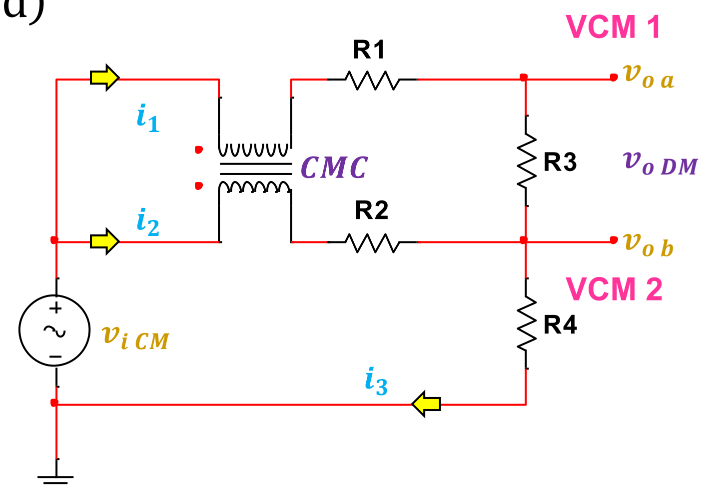

Figure 19: Resistive network with CMC compensation

→ **The introduction of a CMC changes the circuit to a first order low pass filter. Only frequencies above the break frequency are attenuated.**

Resistive network with CM leakage: Circuit analysis

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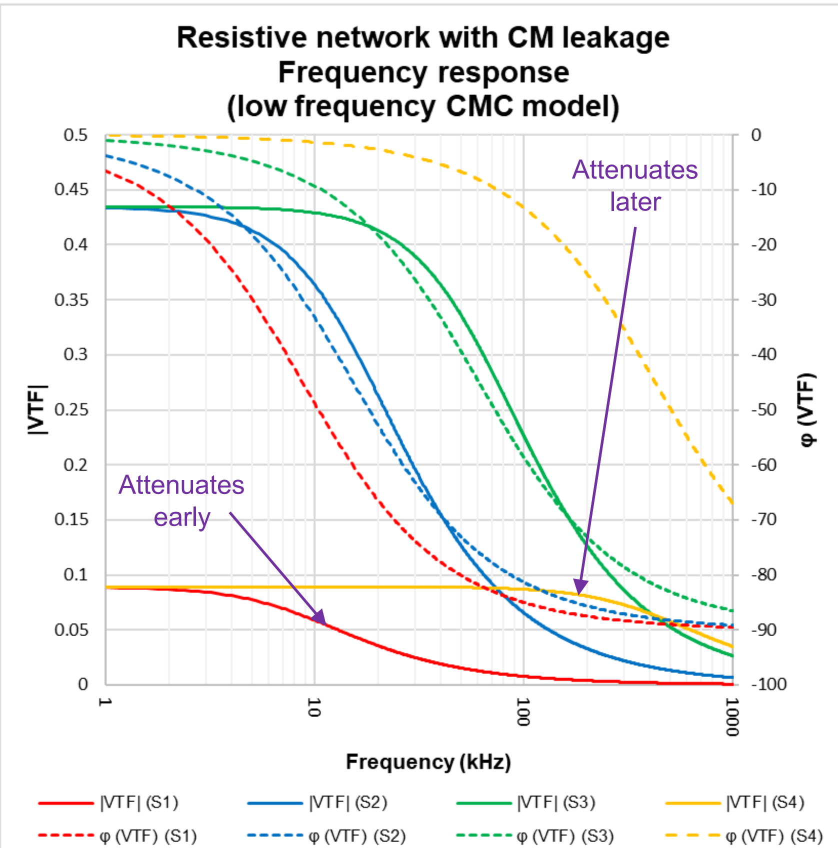
	S1	S2	S3	S4	R3	10
R1=R2=R	0.1	1	10	100	R4	1
fb (kHz)	8.75	15.25	61.01	424.8	L1=L2=L	20

All resistors (kΩ), inductor in mH.



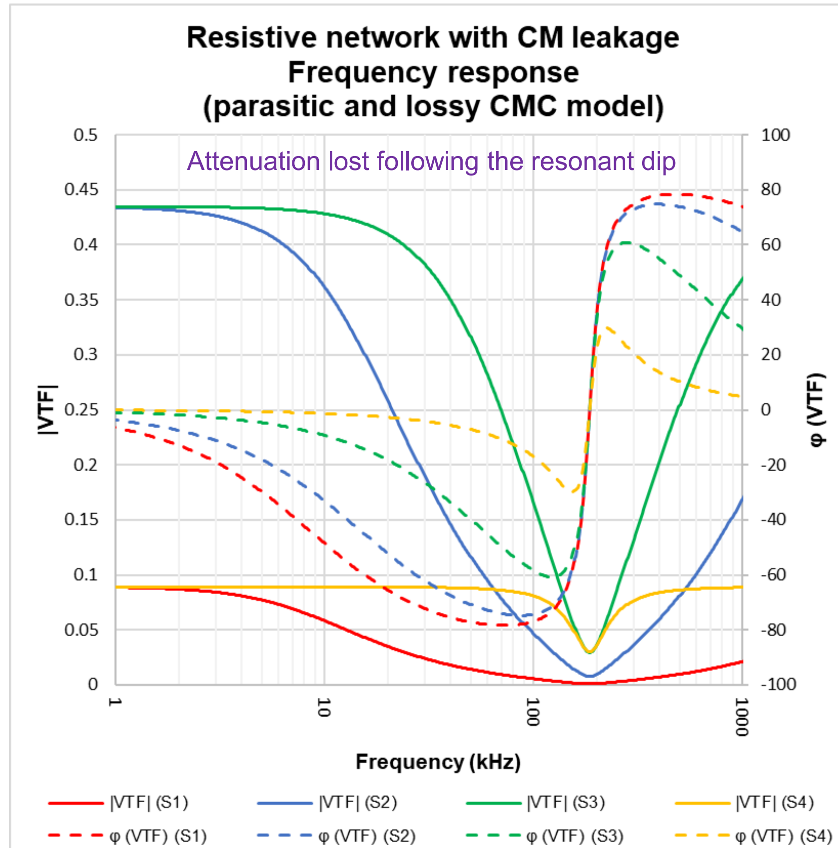
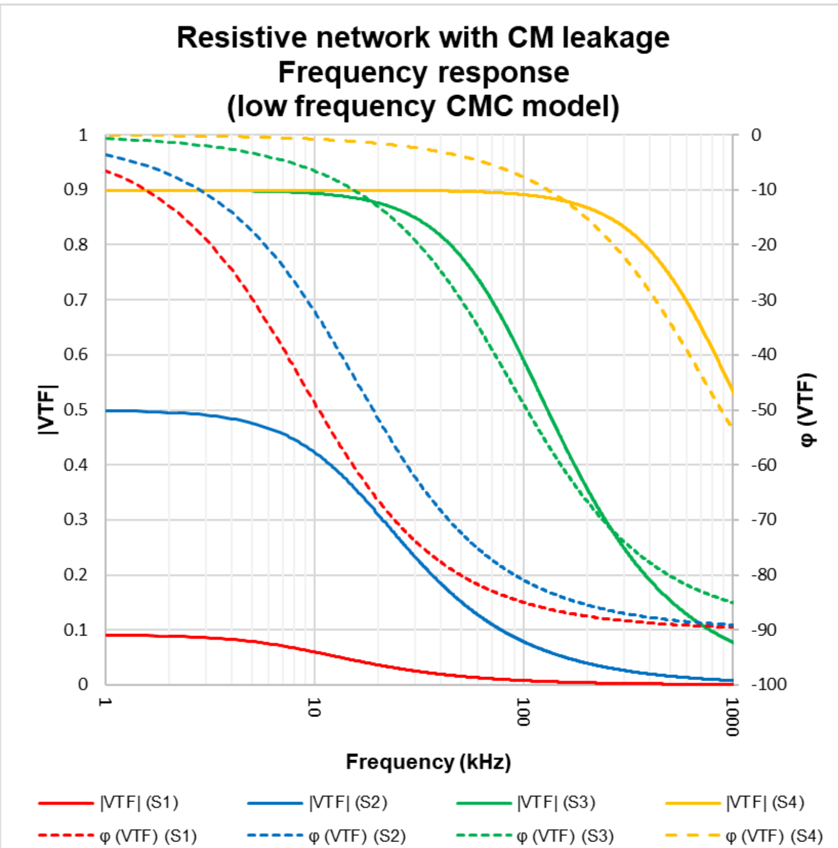


Figure 20: Frequency response, low frequency CMC model (left), parasitic and lossy CMC model (right)

Resistive network with CM leakage: Circuit analysis

	S1	S2	S3	S4	R3	1000
R1=R2=R	0.1	1	10	100	R4	1
fb (kHz)	8.75	15.91	86.76	737.4	L1=L2=L	20

All resistors (kΩ), inductor in mH.



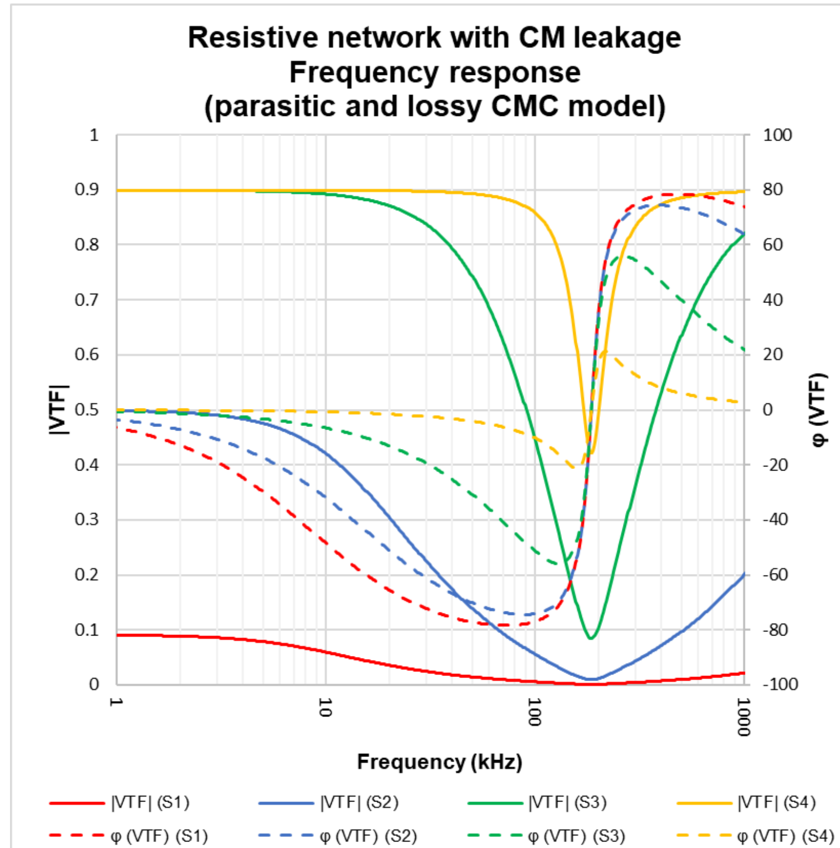


Figure 21: Frequency response, low frequency CMC model (left), parasitic and lossy CMC model (right)

Resistive network with CM leakage: Measurements

Experiment - test setup

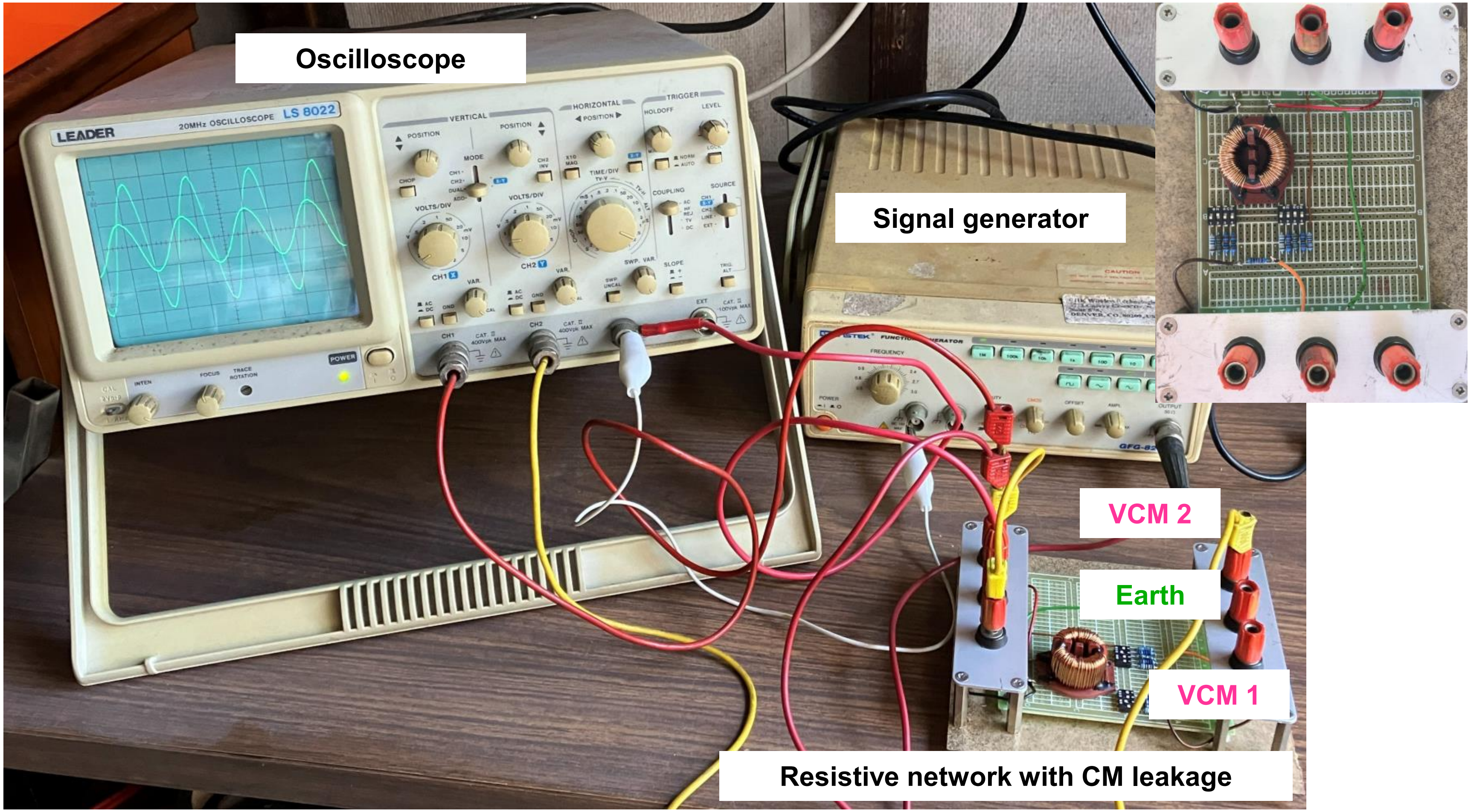


Figure 22: Experiment - test setup

Resistive network with CM leakage: Results

Experiment - results

The oscilloscope can only measure common-mode voltages. The differential voltage is calculated using (14).

$$v_{DM} = v_{CM1} - v_{CM2} \ldots (14)$$

Scenario S2 M

Frequency			Input voltage (VCM)		
Div H	Scale (µs)	Freq. (kHz)	Div V	Scale (V/Div.)	Voltage
3.8	200	1.316	5.6	2	11.2
2.7	200	1.852	5.7	2	11.4
4.8	100	2.083	5.55	2	11.1
3.2	100	3.125	5.3	2	10.6
3.8	50	5.263	5.2	2	10.4
9	10	11.111	2.4	5	12
6.6	10	15.152	5.5	2	11
3.18	10	31.447	5.45	2	10.9
4.4	2	113.636	2.3	5	11.5
7.3	1	136.986	5.45	2	10.9
3	1	333.333	5.35	2	10.7
6.6	0.2	757.576	5.8	2	11.6

Output voltage (VCM 1)			Output voltage (VCM 2)			Output voltage (VDM)	
Div V	Scale (V/Div.)	Voltage 1	Div V	Scale (V/Div.)	Voltage 2	VDM	|VTF| (S2 Meas.)
5.35	2	10.7	5.9	1	5.9	4.8	0.429
5.3	2	10.6	5.8	1	5.8	4.8	0.421
5.25	2	10.5	5.65	1	5.65	4.85	0.437
5	2	10	2.75	2	5.5	4.5	0.425
4.7	2	9.4	5	1	5	4.4	0.423
1.8	5	9	2.4	2	4.8	4.2	0.350
3.55	2	7.1	2	2	4	3.1	0.282
4.1	1	4.1	4.1	0.5	2.05	2.05	0.188
3	0.2	0.6	1.7	0.2	0.34	0.26	0.023
3	0.1	0.3	1.7	0.1	0.17	0.13	0.012
3	0.5	1.5	1.6	0.5	0.8	0.7	0.065
4	1	4	2.25	1	2.25	1.75	0.151

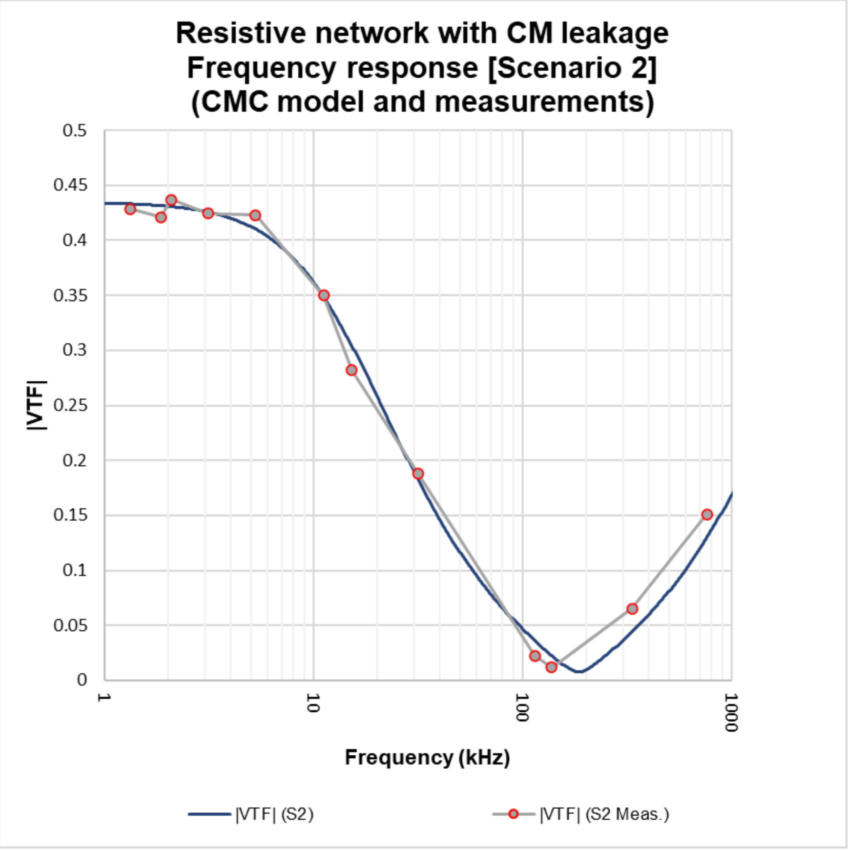


Figure 23: Frequency response, measurements (left), parasitic and lossy CMC model versus measurements (right)

Review: Insertion Loss (IL)

Consider a network with an attenuator…

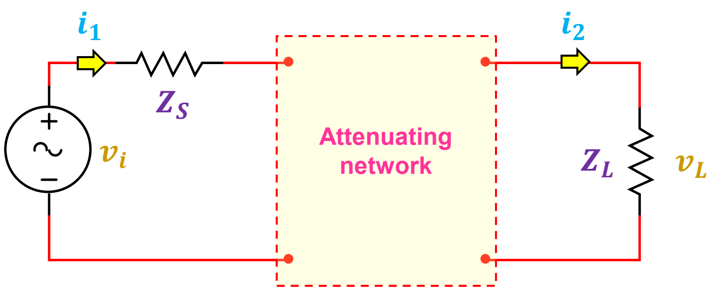


Figure 24: General arrangement of attenuator

Insertion loss is defined as the ratio of the output power without the attenuator $P_{o\,woA}$ to the output power with the attenuator $P_{o\,wA}$ and given by

$$IL = 10log\left(\frac{P_{o\,woA}}{P_{o\,wA}}\right) \ldots (15)$$

Assuming the source and load impedances are resistive, $P_{o\,woA}$ is given by

$$P_{o\,woA} = R_L {i_2}^2 = R_L\left(\frac{v_i}{R_S + R_L}\right)^2 \ldots (16)$$

Review: Insertion Loss (IL)

Consider a network with a CMC…

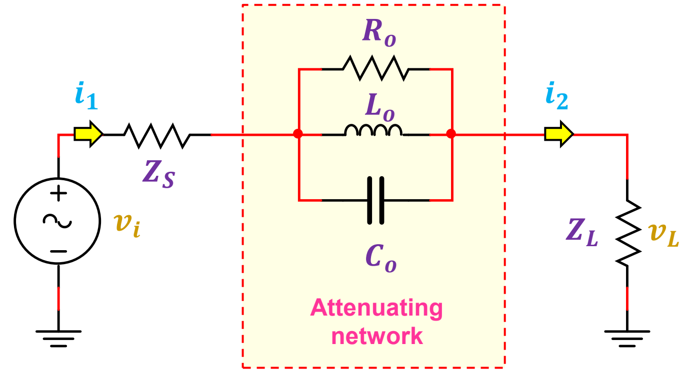


Figure 25: CMC attenuator

The impedance of the CMC is given by

$$Z_{CMC} = \frac{sL_oR_o}{s^2L_oC_oR_o + sL_o + R_o} = \frac{j\omega L_oR_o}{R_o(1-\omega^2L_oC_o) + j\omega L_o} \quad \dots(17)$$

Assuming the source and load impedances are resistive, i_2 and $P_{o\,wA}$ are given by

$$i_2 = \frac{v_i\{R_o(1-\omega^2L_oC_o) + j\omega L_o\}}{R_o(1-\omega^2L_oC_o)(R_S+R_L) + j\omega L_o(R_o+R_S+R_L)} \quad \dots(18)$$

$$P_{o\,wA} = |i_2|^2R_L = \frac{R_Lv_i{}^2\{R_o{}^2(1-\omega^2L_oC_o)^2 + (\omega L_o)^2\}}{R_o{}^2(1-\omega^2L_oC_o)^2(R_S+R_L)^2 + (\omega L_o)^2(R_o+R_S+R_L)^2} \quad \dots(19)$$

Review: Insertion Loss (IL)

The maximum IL is given by…

$$IL_{max.} = 20log\left(\frac{R_{o\ max.} + R_S + R_L}{R_S + R_L}\right) \dots (20)$$

Test setup

Practical measurements are done using a Vector Network Analyser (VNA).

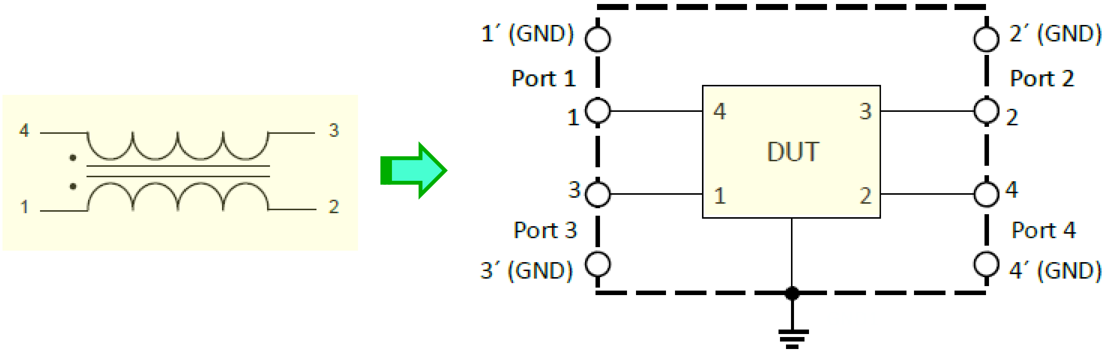


Figure 26: Test setup for measurement of 4-port S-parameters [1]

[1]: IEC International Standard, "Methods of measurements of the suppression characteristics of passive EMC filtering devices", CISPR 17:2011.

Review: Insertion Loss (IL)

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Test setup

Assuming $|i| = |i_1| = |i_2|$

Common-mode connections

$$v_a = v_b = v_{CM} = i\{(Z_S + Z_L) + s(L + M)\} \ldots (21a)$$

and

$$i_{CM} = 2i \ldots (21b)$$

Now substitute (21b) into (21a) yields

$$v_{CM} = i_{CM}\{(Z_S + Z_L)/2 + s(L + M)/2\} \ldots (21c)$$

Differential-mode connections

$$v_a = i\{(Z_S + Z_L) + s(L - M)\} \ldots (21d)$$

$$v_b = i\{-(Z_S + Z_L) - s(L - M)\} \ldots (21e)$$

(21d)-(21e) yields

$$v_a - v_b = v_{DM} = i\{2(Z_S + Z_L) + 2s(L - M)\} \ldots (21f)$$

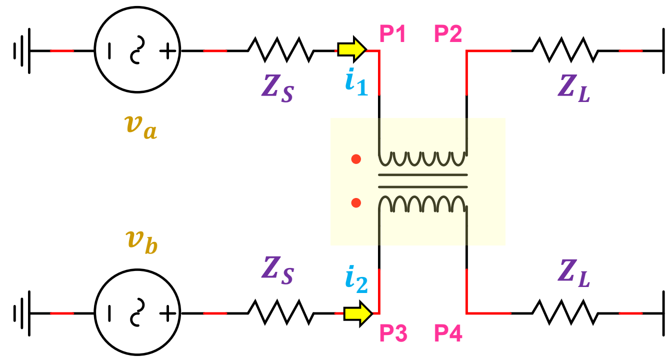

Figure 27a: VNA connections (CM)

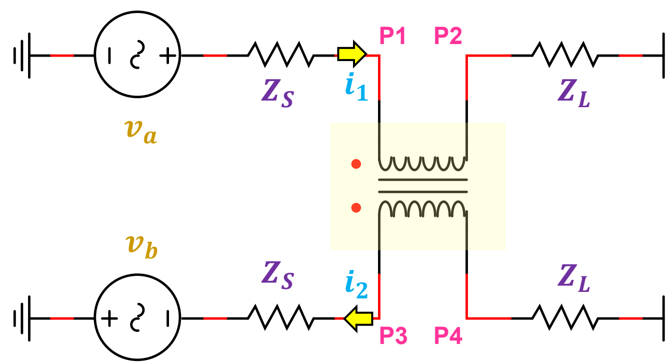

Figure 27b: VNA connections (DM)

For Z_S = Z_L = 50Ω: $Z_{S\,CM}$ = $Z_{L\,CM}$ = 25Ω and ; $Z_{S\,DM}$ = $Z_{L\,DM}$ = 100Ω

Review: Insertion Loss (IL)

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Modelled frequency responses.

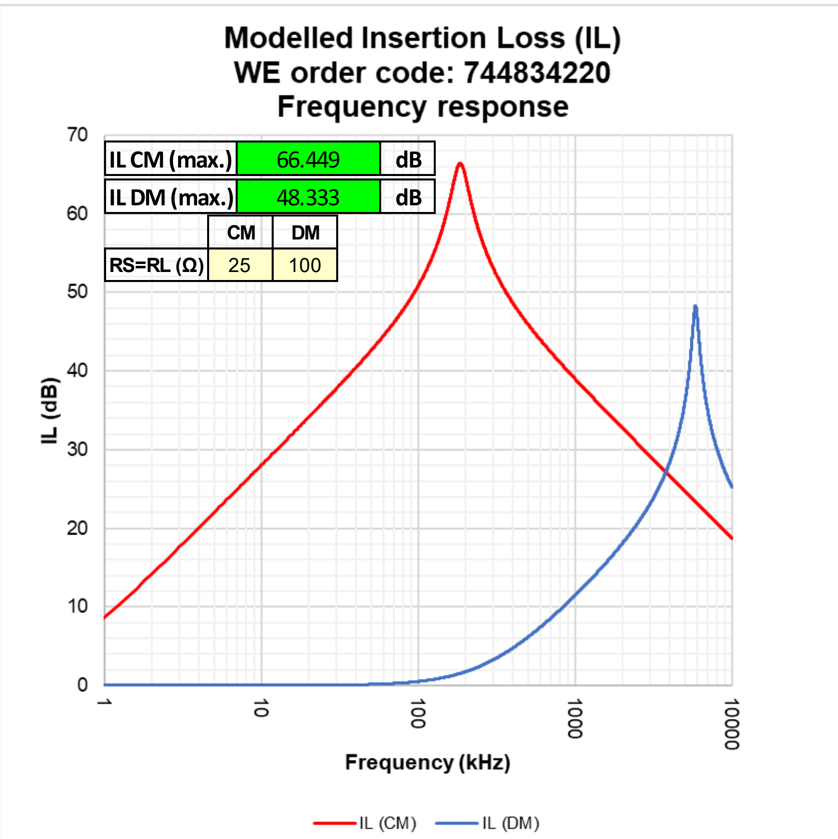

Figure 28: Modelled impedance frequency responses of 744834220

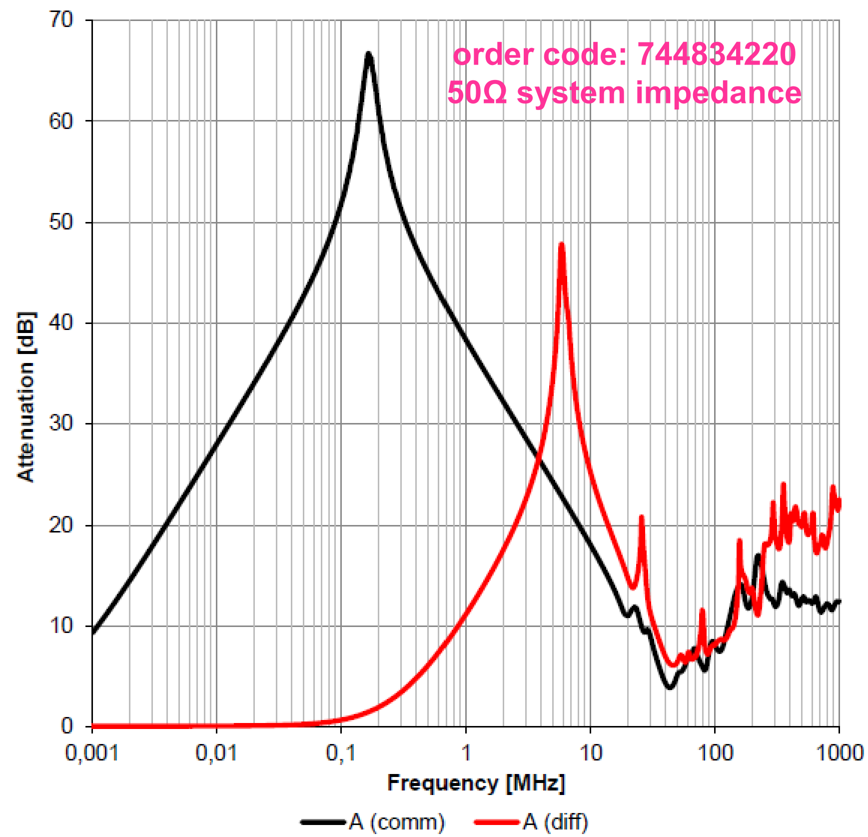

Figure 29: Insertion Loss curves for WE order code: 744834220

Worked example 4:

Find $R_{o\ max.}$ given $IL_{max.\ CM}$ = 66.5dB and $IL_{max.\ DM}$ = 48.33dB for order code: 744834220.

Answer 4:

Rearrange (20) yields (20a).

$$R_{o\ max.} = (R_S + R_L)\left\{10^{\left(\frac{IL_{max.}}{20}\right)} - 1\right\} \ldots (20a)$$

Substitute $R_{S\ CM}$ = $R_{L\ CM}$ = 25Ω.

$$R_{o\ max.} = 50\left\{10^{\left(\frac{66.5}{20}\right)} - 1\right\} = 105.6\text{k}\Omega$$

Previously found from the datasheet that $R/2$ = 105kΩ.

Substitute $R_{S\ DM}$ = $R_{L\ DM}$ = 100Ω.

$$R_{o\ max.} = 200\left\{10^{\left(\frac{48.33}{20}\right)} - 1\right\} = 51.98\text{k}\Omega$$

Previously found from the datasheet that $2R$ = 58kΩ.

Line filter incorporating a CM:
Circuit analysis

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A typical line side filter incorporating a CMC is shown.

How is this circuit analysed?

Two noise sources: (a) Common-mode noise; and (b) Differential-mode noise.
Best to first decompose the circuit into CM and DM equivalent circuits to reflect the noise types.

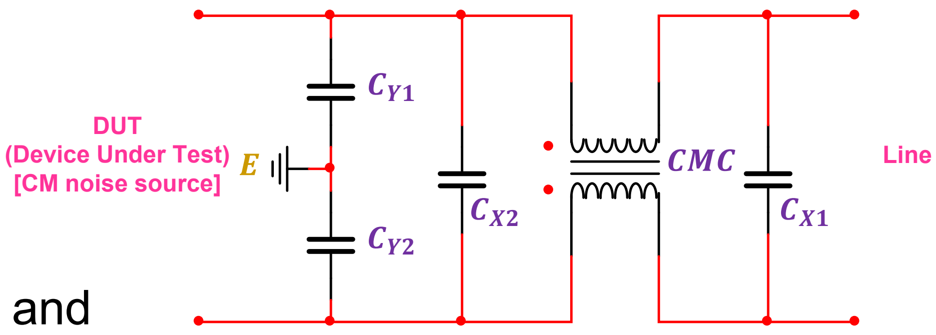

Figure 30: Typical line filter

Use appropriate source and load resistances with voltage sources at the DUT to determine the attenuation (IL).

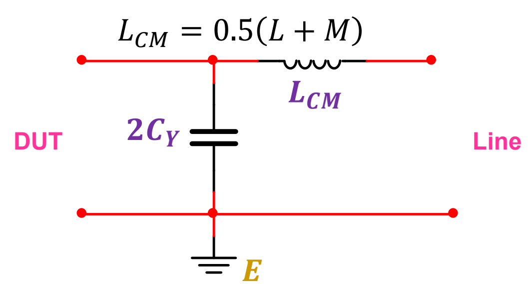

Figure 31: Typical line filter (CM equivalent circuit)

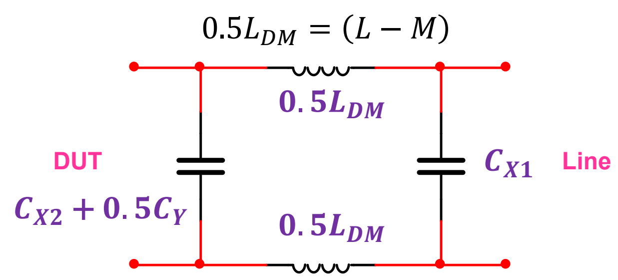

Figure 32: Typical line filter (DM equivalent circuit)

Line filter incorporating a CM: Circuit analysis

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The modelled CM circuit as follows…

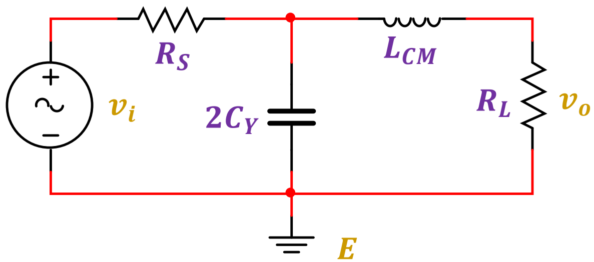

Figure 33: CM filter implementation

Increasing the "C_Y" capacitor improves the high frequency attenuation.

Attenuation increases with increasing R_S.

$$f_{min\ CM} = \left.\frac{1}{2\pi\sqrt{2L_{CM}C_Y}}\right|_{R_L=0} \quad \ldots (22)$$

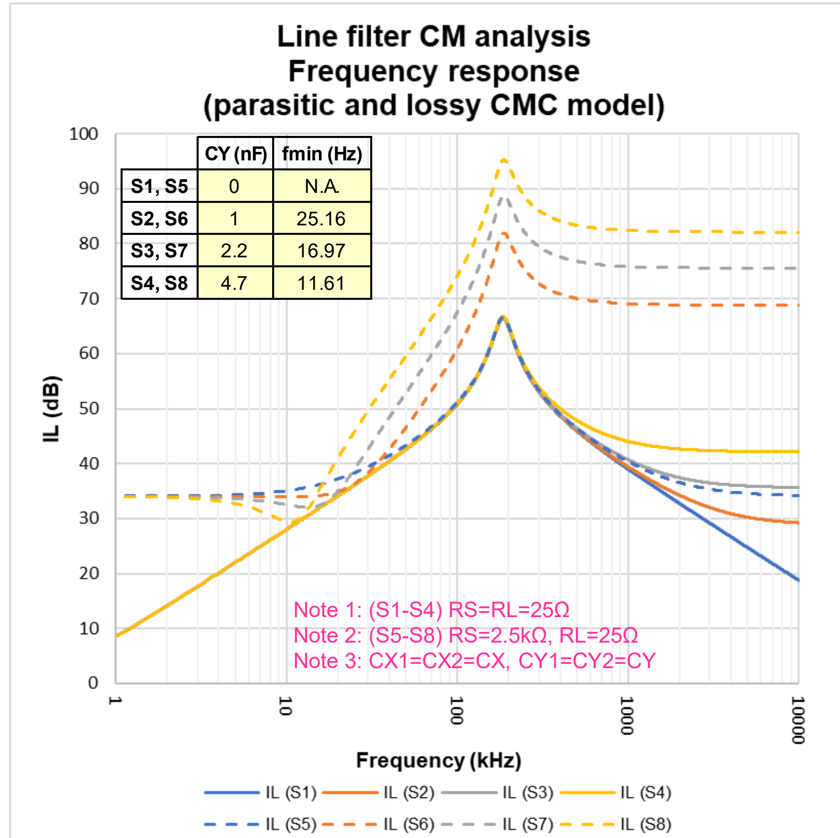

Figure 34: Modelled line filter (CM equivalent circuit)

Line filter incorporating a CM:
Circuit analysis

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The modelled DM circuit as follows…

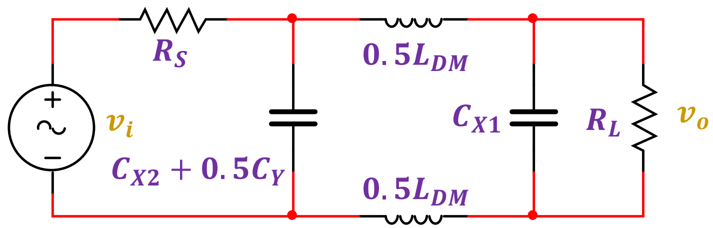

Figure 35: DM filter implementation

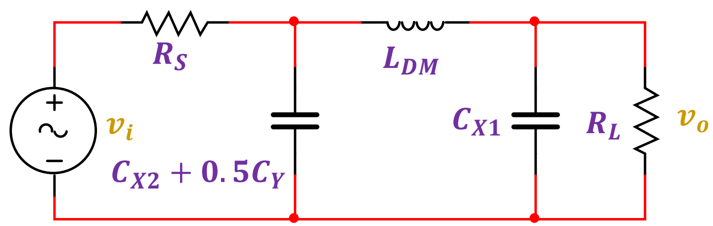

Figure 36: DM filter implementation (single sided)

Increasing the "C_X" capacitor improves the high frequency attenuation.

Attenuation increases with increasing R_S.

$$f_{min\ DM}=\left.\frac{1}{2\pi\sqrt{L_{DM}(C_{X2}+0.5C_Y)}}\right|_{R_L=0}\quad \ldots(23)$$

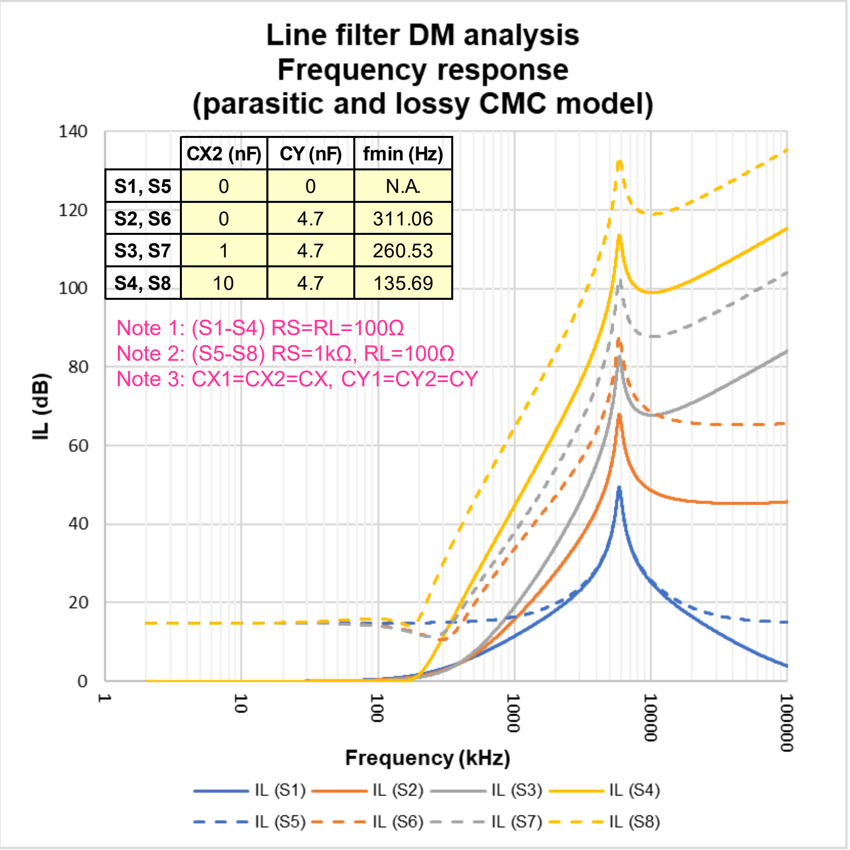

Figure 37: Modelled line filter (DM equivalent circuit)

Line filter incorporating a CM:
Circuit analysis

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The modelled DM circuit as follows…

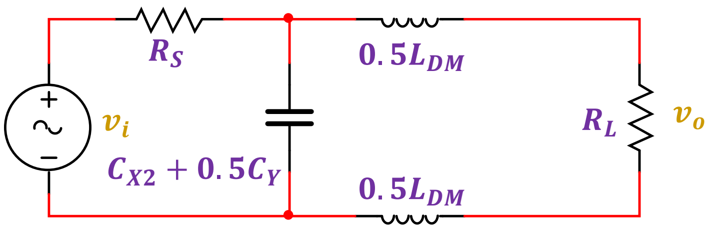


Figure 38: DM filter implementation

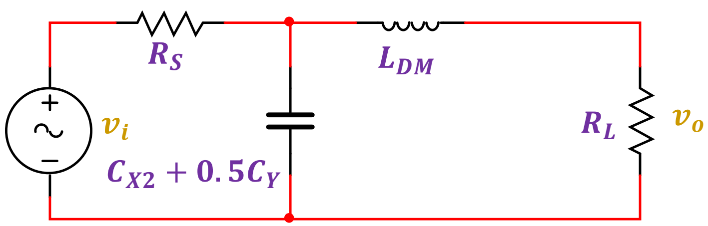


Figure 39: DM filter implementation (single sided)

Removing the "C_{X1}" capacitor flattens the attenuation following the resonance of the CMC.

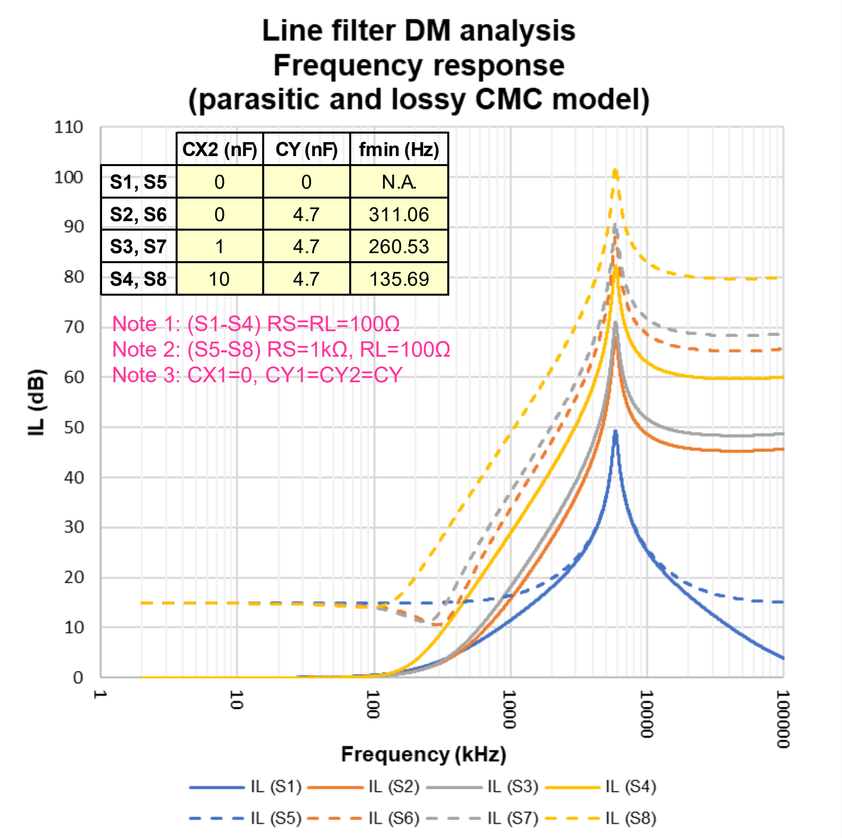
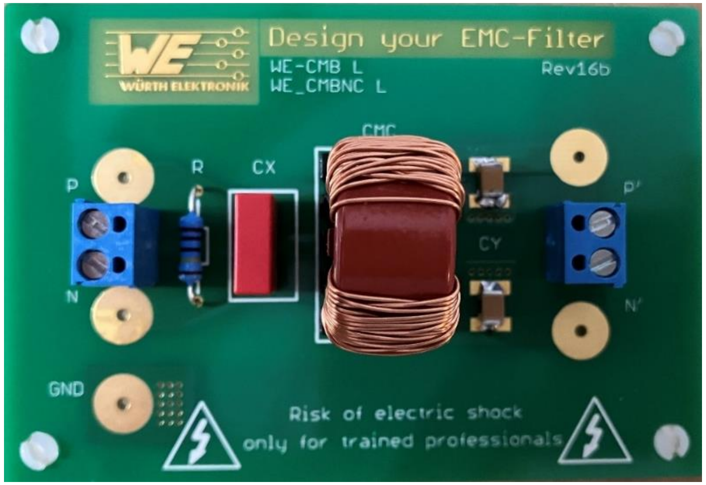


Figure 40: Modelled line filter (DM equivalent circuit)

Line filter incorporating a CM: Circuit

Implemented line filter as follows…



Designator	Value	WE P/N
CX*	10nF	890 324 023 006
CY	1nF	885 352 211 003 1
CMC	20mH	744 824 220**

Note*: CX=CX2
Note**: similar to 744 834 220

Figure 41: Implemented Line filter

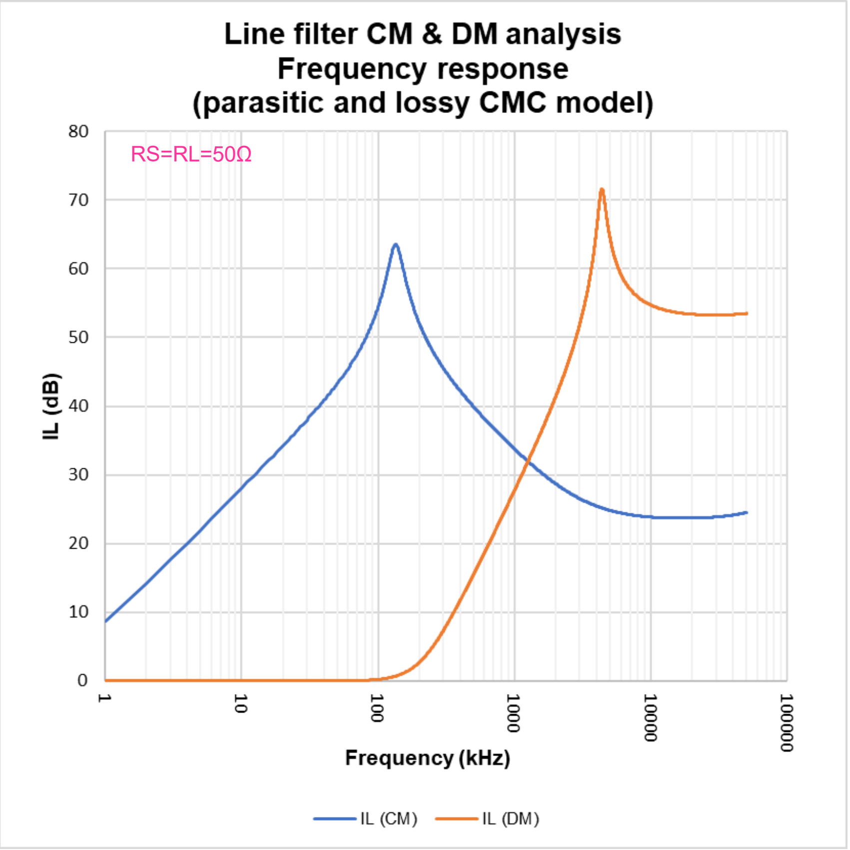


Figure 42: Implemented Line filter response

Line filter incorporating a CM: Measurements

Experiment - test setup

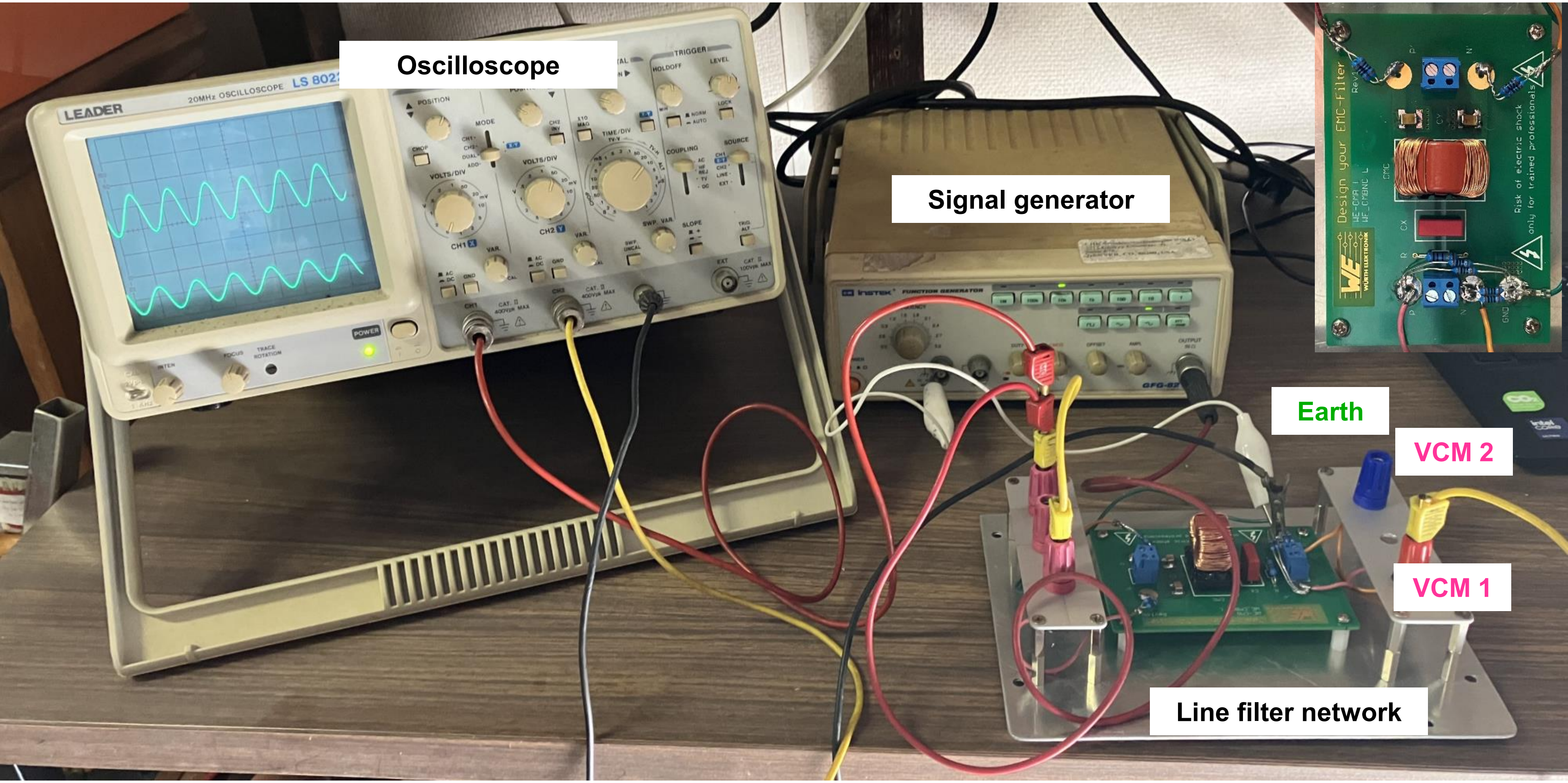


Figure 43: Experiment - test setup

Line filter incorporating a CM: Results

Experiment - results

The common mode voltage is calculated using (24).

$$v_{CM} = \frac{(v_{CM1} + v_{CM2})}{2} \ldots (24)$$

Frequency			Input voltage (VCM)		
Div H	Scale (µs)	Freq. (kHz)	Div V	Scale (V/Div.)	Voltage
9.6	500	0.208	2.5	0.5	1.250
4.6	500	0.435	3	2	6.000
7.8	100	1.282	3.9	0.05	0.195
4.6	100	2.174	4	0.05	0.200
6.3	50	3.175	4.1	0.05	0.205
4.2	50	4.762	4.2	0.05	0.210
7.8	10	12.821	4.3	0.05	0.215
6.3	5	31.746	3.9	0.2	0.780
4.6	2	108.696	4.1	2	8.200
5.8	1	172.414	3.8	2	7.600
3.75	1	266.667	3.6	2	7.200
4.5	0.2	1111.111	3.15	2	6.300
2.9	0.1	3448.276	3.4	1	3.400

Output voltage (VCM 1 = VCM 2)			Output		
Div V	Scale (V/Div.)	VCM	VCM	|VTF| (Meas.)	IL (Meas.)
2.5	0.2	0.500	0.500	0.40000	1.93820
4.2	0.1	0.420	0.420	0.07000	17.07744
3	0.01	0.030	0.030	0.15385	10.23767
2.1	0.01	0.021	0.021	0.10500	13.55561
1.5	0.01	0.015	0.015	0.07317	16.69265
1.1	0.01	0.011	0.011	0.05238	19.59593
0.45	0.01	0.005	0.005	0.02093	27.56392
1.5	0.005	0.008	0.008	0.00962	34.32007
0.6	0.01	0.006	0.006	0.00073	56.69265
2	0.01	0.020	0.020	0.00263	45.57507
0.9	0.05	0.045	0.045	0.00625	38.06180
1.3	0.05	0.065	0.065	0.01032	33.70794
2	0.05	0.100	0.100	0.02941	24.60898

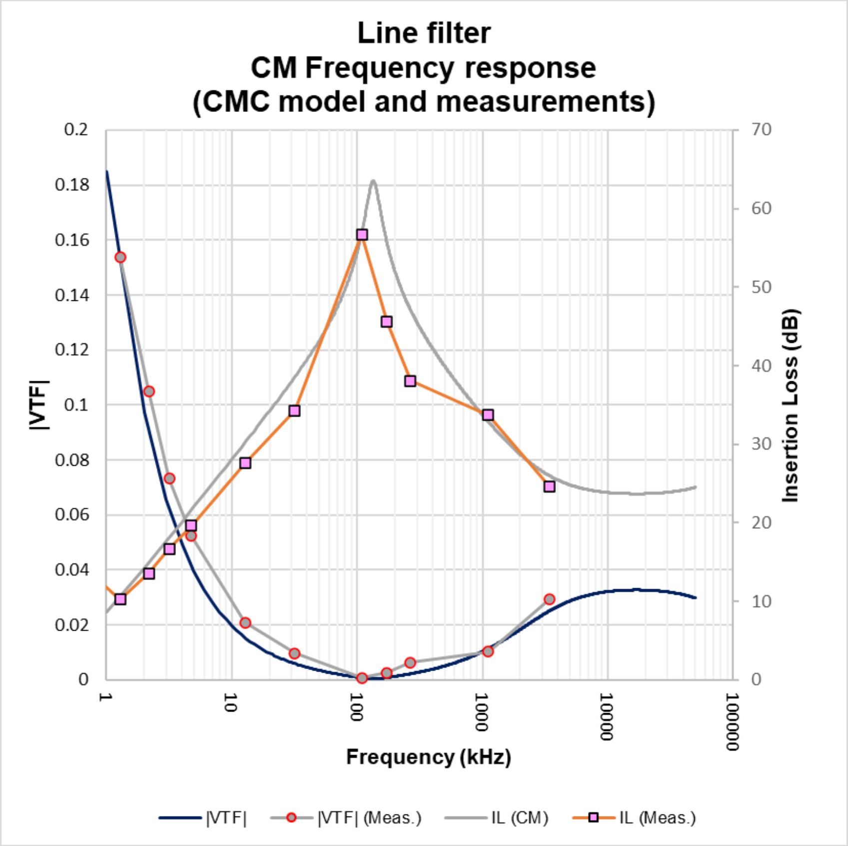


Figure 44: Frequency response, measurements (left), parasitic and lossy CMC model versus measurements (right)

Line filter incorporating a CM:
Measurements - Earth wire

Experiment with Earth wire - test setup

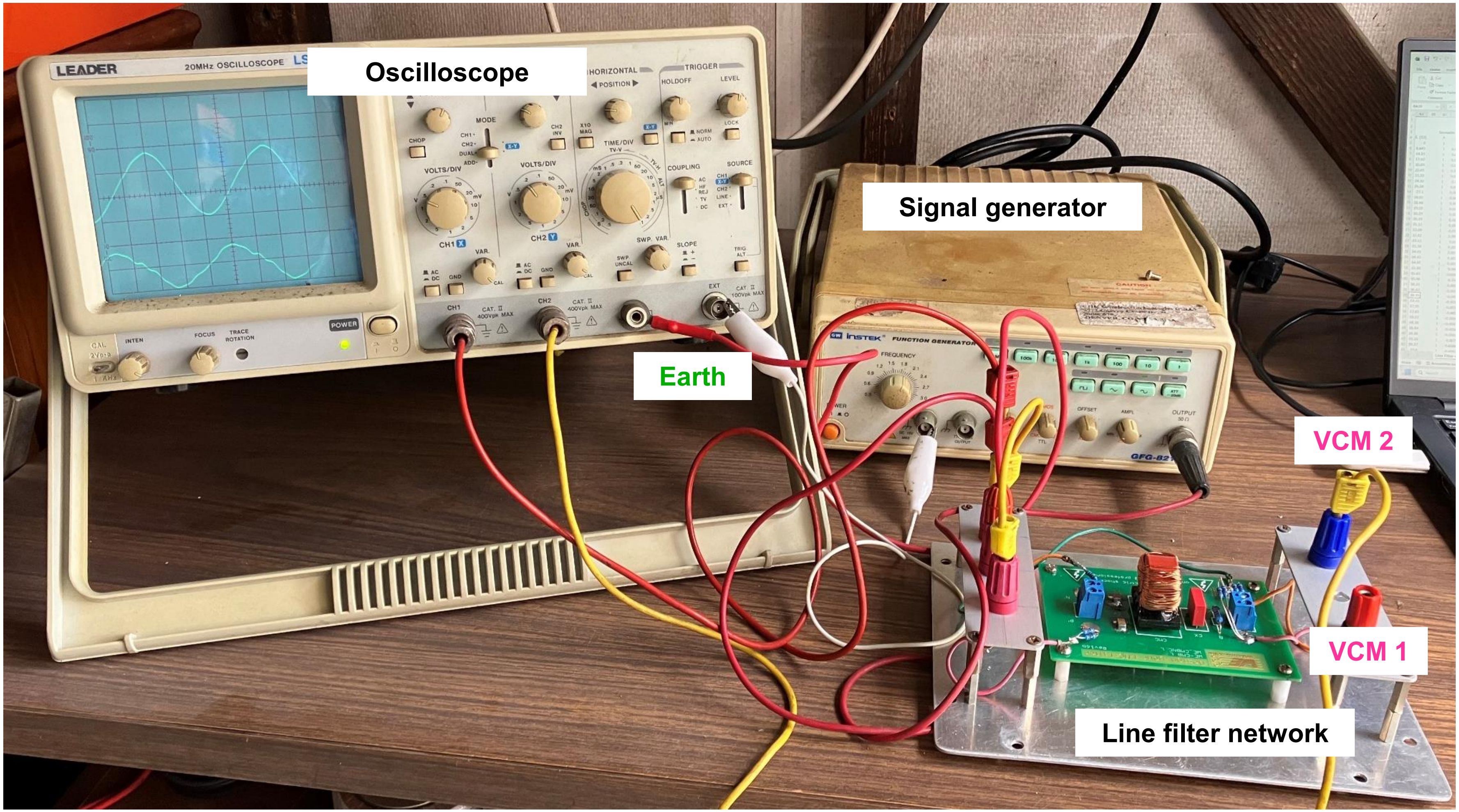


Figure 45: Experiment - test setup

Line filter incorporating a CM: Results - Earth wire

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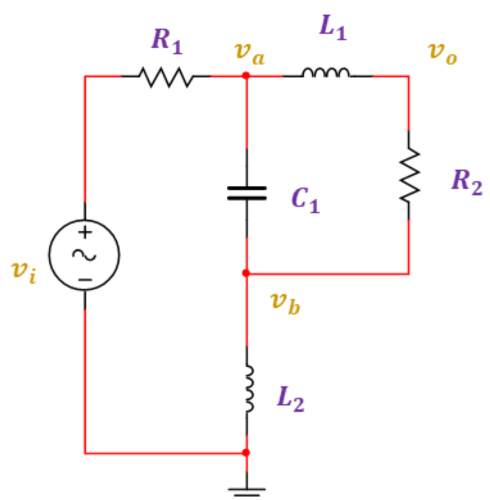
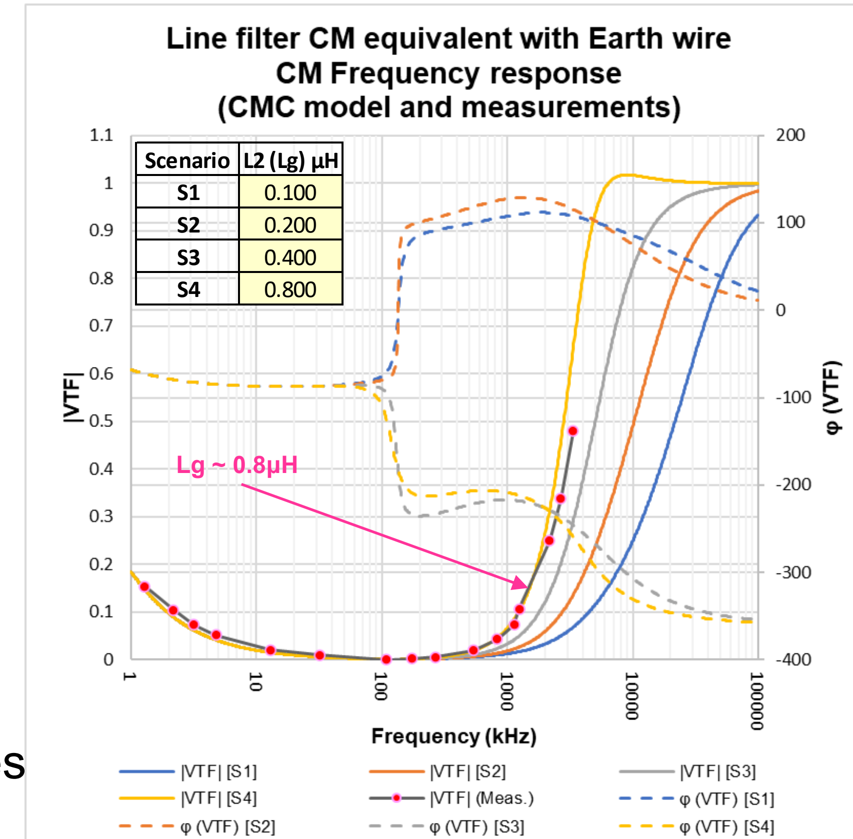
Experiment with Earth wire - results

Intentionally introduced a long Earth return path.

Equivalent CM circuit is shown.





The introduction of the Earth wire destroys the intended attenuation at higher frequencies and instead realizes a high pass filter.

Figure 46: CM equivalent circuit with Earth wire (left), parasitic and lossy CMC model versus measurements (right)

Concluding remarks:

Summary

- Introduced the working principle of the CMC.
- Highlighted two electrical equivalents to CM and DM signals.
- Introduced a: (i) low frequency CMC model; and (ii) parasitic and lossy CMC model.
- Showed how to extract model parameters from CM and DM impedance curves.
- The Voltage Transfer Function (VTF) for a resistive attenuator with Earth leakage is derived and shows how a CM voltage can convert to a DM voltage.
- Plotted the VTF and phase for various parameter values. Frequencies below the break frequencies are not attenuated. The resonance of the CMC due to parasitic capacitances impacts performance of the CMC and the overall circuit; acts as a band-stop filter.
- Any EMC circuit should first be analysed with the low frequency model of the CMC to identify break frequencies.
- Modelled the Insertion Loss.
- Used the CM and DM equivalent circuits to analyse the attenuation (IL) of a line filter incorporating a CMC.
- Showed how circuit parameters affect the attenuation frequency response of a line filter and the impact of an inductive Earth return path.

About the author: Biography

Overview

Over 35 years experience in engineering. Trained as a design engineer, and later held senior management positions within engineering organisations, where he improved the engineering and sales capabilities. Pioneered Australia's first, Class A Power Quality Analyser.

Consulting Engineer - electronic design & Power Quality

Design in electronics and EMC. Over 15 years experience in Power Quality. Has conducted many Power Quality investigations and provided recommendations for mitigation. Provides training in Engineering and Power Quality.

Interests

Electrical / electronic circuits and systems; data acquisition; photonics; EMC; and electromagnetics.

Education

- Bachelor of Engineering in electrical engineering with Honours (UNSW 1995)
- Bachelor of Science in physics (UNSW 1995)
- Doctor of Philosophy (USYD 2003) [photonics].