Explanation of Electromagnetic Interference (EMI) in Switching Power Supply

Speakers

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Power ^e Lab

The Power Electronics Lab., Hong Kong University

A brief introduction to the Power ^e Lab

Our Mission : To advance switching power converter technologies

- **To develop excellence in power electronics technologies**
- **To apply the technologies to products and foster cooperation with industries**

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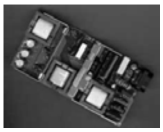
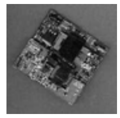
Email : mhp@eee.hku.hk **Web site :** *www.eee.hku.hk/power_electronics_lab/*

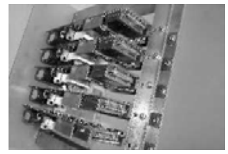
Our work in the **Power ^e^Lab**



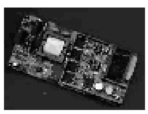
High Power 120W
AC/DCadapter Platform



Half brick DCDC
Converter Platform

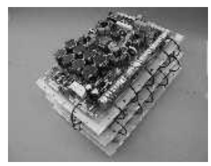


High current Converter
Platform 1V5 200A



ACDC Converter
Platform 1V5 40A

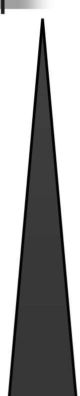
Battery charger
Platform 12V 65W



4.5kVA Power Amplifier

More in the Power ^e^Lab website

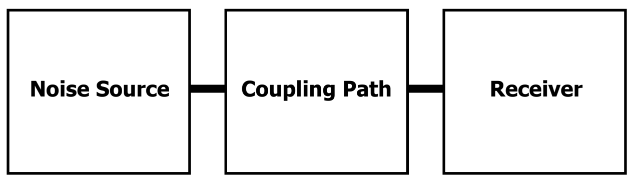
What you are going to learn today. . . .



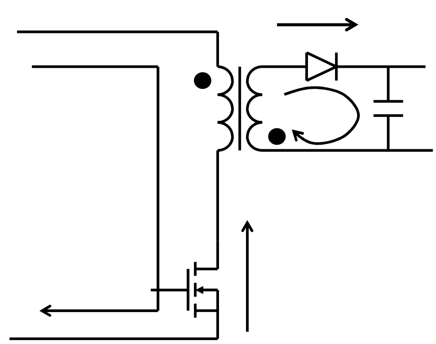
- Easy – EMI Basics. What and how people test your product.
- Not so easy – General attitude of an EMI engineer.
- Difficult – How EMI is produced.
- More difficult – How EMI comes and goes.

Basic Blocks

- Every EMI issue has the following 3 basic blocks



Noise Sources



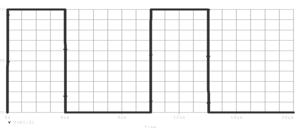
- Switching voltage and current waveforms in a switching power supply

Waveform produces frequency spectrum

- Rectangular

10kHz 500MHz

100



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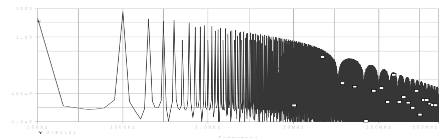
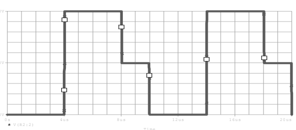


- Forward

100



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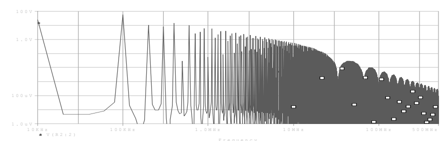
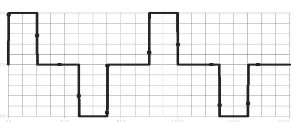
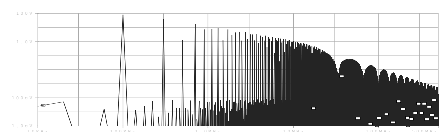


- Bridge

100



-100

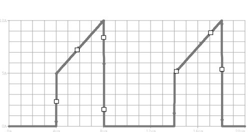


Waveform produces frequency spectrum

10kHz 500MHz

- Continuous Flyback

10



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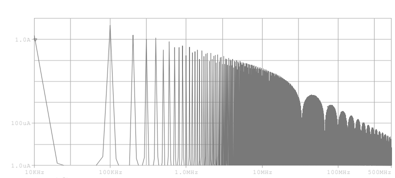
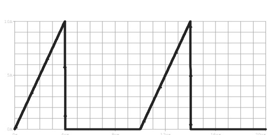


- Discontinuous Flyback

10



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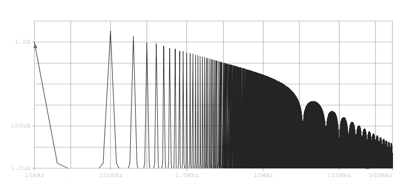


Prepared by Franki Poon & Bryan Pong

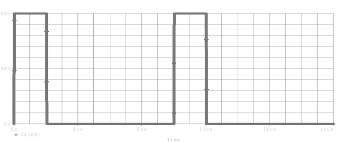
Effect of duty cycle

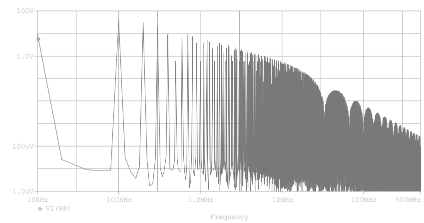
- Duty cycle = 0.2

10kHz 500MHz

100

0

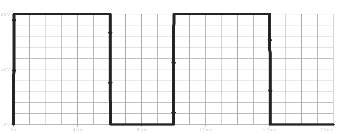


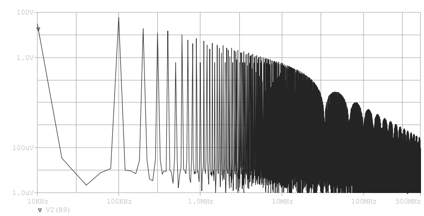


- Duty cycle = 0.6

100

0





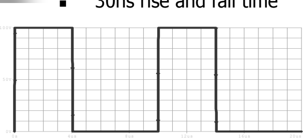
Effect of waveform slope (dv/dt)

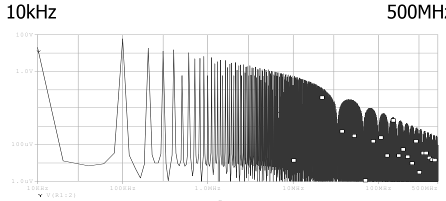
- 30ns rise and fall time

10kHz 500MHz

100

0

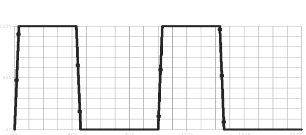


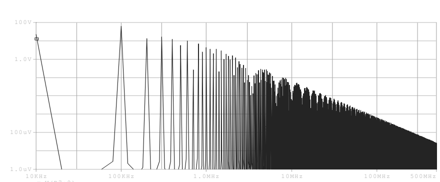


- 300ns rise and fall time

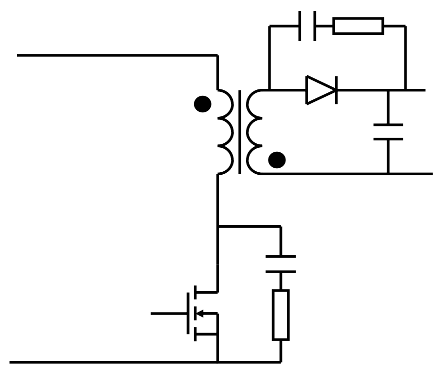
100

0





Snubber circuit reduces dv/dt

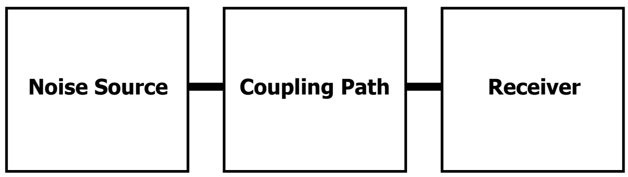


Notes on Noise Sources

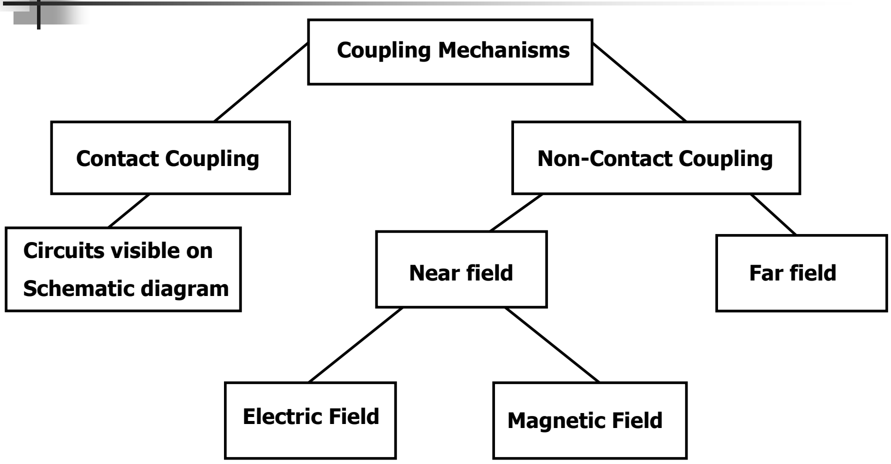
- Voltage and current waveforms
- Noise sources in switching power supply has little effect beyond 200MHz
- Waveshape affect base band frequencies
- Rising and falling edges affect high frequency spectrum
- Duty cycle has little effect on the spectrum

Basic Blocks

- Every EMI issue has the following 3 basic blocks



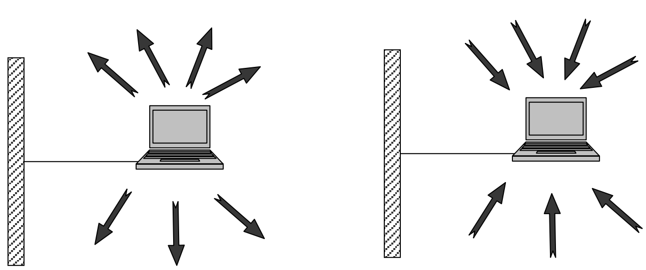
Coupling Paths



Receiver

- Standard test equipment set up
  - Conducted Measurement set up
  - Radiated Measurement set up

EMI standards



Electromagnetic Emission (Our Interest)

Electromagnetic Immunity

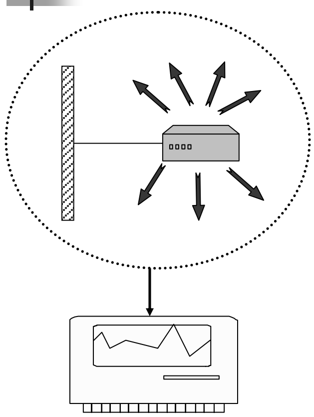
Emission standards

Reference	Description (Emission Standard)
CISPR13 /EN55013	Limits and methods of measurement of radio interference characteristics of sound and TV broadcast receivers and associated equipment.
CISPR14 /EN55014	Limits and methods of measurement of radio interference characteristics of electric motor operated and thermal appliances for household and similar purposes, electric tools and similar electrical apparatus. (Latest revision cover all electrical household appliances)
CISPR15 /EN55015	Limits and methods of measurement of radio interference characteristics of electrical lighting and similar equipment.
CISPR22 /EN55022	**Limits and methods of measurement of radio interference characteristics of information technology equipment**.
IEC61000-3-2 /EN61000-3-2	Limits for harmonic current emission (<= 16A per phase)
IEC61000-3-3 /EN61000-3-3	Limitation of voltage fluctuations and flicker in low voltage supply system (<=16A per phase)
EN50081-1	Generic residential emission standards
EN50081-2	Generic industrial emission standards
FCC 15B	USA National EMI Standard

Immunity standards

Reference	Description(Immunity Standards)
CISPR20 /EN55020	Limits and methods of measurement of immunity characteristics of sound and TV broadcast receivers and associated equipment.
IEC61000-4-2 /EN61000-4-2	Electrostatic discharge immunity test
IEC61000-4-3 /EN61000-4-3	Radiated radio frequency electromagnetic field immunity test
IEC61000-4-4 /EN61000-4-4	Electrical fast transient immunity test
IEC61000-4-5 /EN61000-4-5	Surge immunity test
IEC61000-4-6 /EN61000-4-6	Immunity to conducted disturbances induced by radio frequency fields above 9kHz.
IEC61000-4-11 /EN61000-4-11	Voltage dips, short interruptions and voltage variations immunity test.
EN50082-1	Generic residential immunity standard
EN50082-2	Generic industrial immunity standard

Measurement – use what type of equipment ?



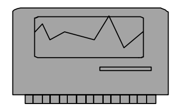
Spectrum Analyzer

⓪ Cheap

① One is enough – 10kHz –1GHz

② Less accurate

EMI Receiver



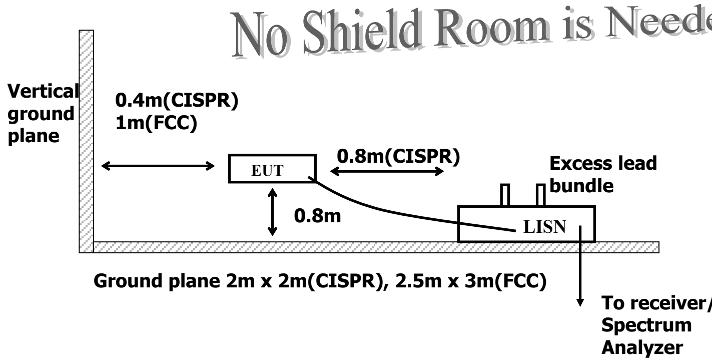
⓪ Expensive

① Two are needed – 10kHz to 30MHz, 30MHz to 1GHz

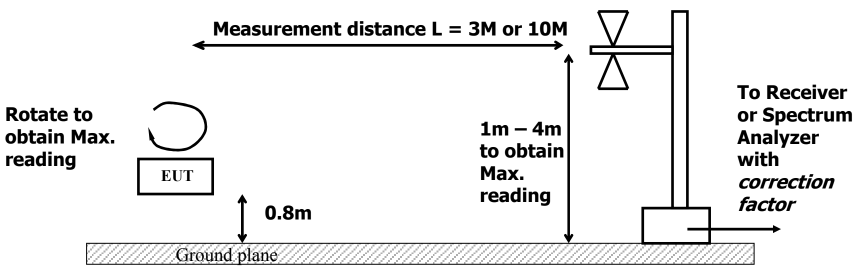
② More accurate

Measurement Set Up – Conducted (< 30MHz)

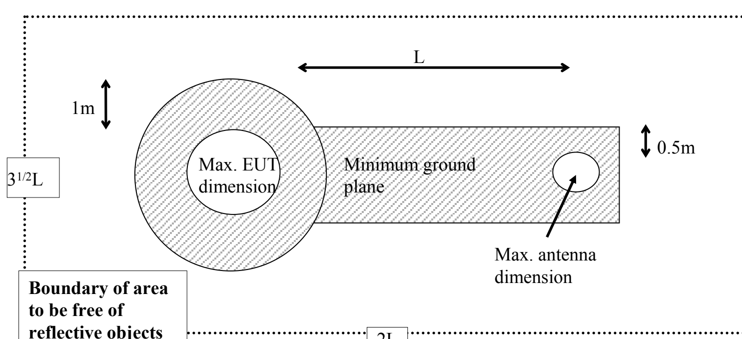
No Shield Room is Needed !!



Measurement Set Up – Radiated EMI(> 30MHz)



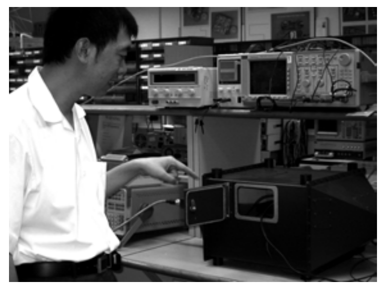
Radiated Set Up – Open site Grounding



Anechoic chamber is Needed in practice!!

Radiated Set Up - diagnosis

- Anechoic chamber filled with ferrite absorbers to absorb EM reflections
- Small TEM cell provides convenient way to diagnose EMI problem



Measurement – Limit level

	0.15MHz – 0.5MHz	0.5MHz – 5MHz	5MHz – 30MHz
	CISPR22 conducted emission limit		
Average limit (B)	56 dBuV – 46 dBuV **630 uV - 200 uV**	46 dBuV **200 uV**	50 dBuV **316 uV**
Quasi peak limit (B)	66 dBuV – 56 dBuV **2000 uV – 630 uV**	56 dBuV **630 uV**	60 dBuV **1000 uV**

Can you make an amplifier which receives signal from 150kHz to 1GHz at 200uV signal level ??

	30MHz – 230MHz	230MHz – 1G
CISPR22 radiated emission limit		
Quasi peak limit(10m class A)	40dBuV/m **100 uV/m**	47dBuV/m **223 uV/m**
Quasi peak limit(10m class B)	30dBuV/m **31uV/m**	37dBuV/m **70 uV/m**

Measurement – about error

According to "EMC for product Designers" - Tim Williams

RF measuring receiver -	*+/- 2.5dB (worse for spectrum analyzer)*
Impedance mismatch	*+/- 1dB*
Antenna	*+/- 4dB*
Antenna cable	*+/- 2.5dB*
Anechoic chamber	*+/-3dB*
Test engineer	*+/- 4dB*

Total = **17 dB !**

Measurement – short summary

- Spectrum Analyzer is cheaper for in house pre-compliance test.
- Conducted measurement is rather simple.
- Radiated measurement is difficult.
- Different test Laboratory will give you different results.

Most Important Concept - LOG

- Equipment reading are in LOG scale, it lies in our mind that

$$Reading = 20Log(\frac{Measured}{10^{-6}})dBuV$$

Can you imagine what a number will become when it is divided by 10^{-6}, then take **LOG**, and finally multiplied by 20 ??

Most Important Concept - LOG & Sum

500uV = 54 dBuV

1000uV = 60 dBuV

2000uV = 66 dBuV

500 uV + 1000 uV + 2000 uV = 3500 uV = 71 dBuV

Generic human intuitive comparison

Compare linear result 3500 / 500 = 7 times

Compare LOG result 71/54 = 1.3 times

What does 1.3 times tell us ?

Most Important Concept - LOG & Subtract

3500uV = 71 dBuV

2000uV = 66 dBuV

1000uV = 60 dBuV

3500 uV - 2000 uV - 1000 uV = 500 uV = 54 dBuV

Generic human intuitive comparison tells us

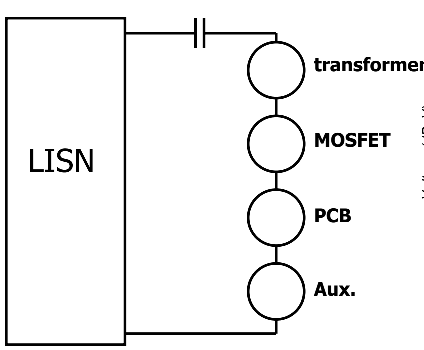
Compare linear result 500 / 3500 = 0.143 times

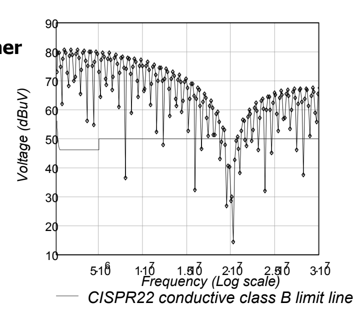
Compare LOG result 54/71 = 0.76 times

What does 0.76 times tell us ?

LOG Reading – an example

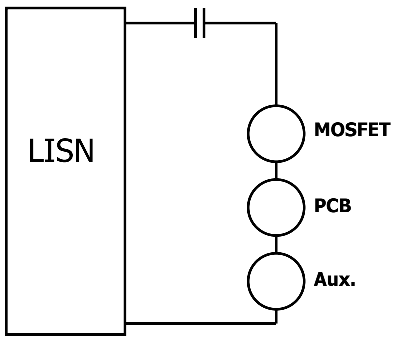
Assume that noise is produced by four contributors

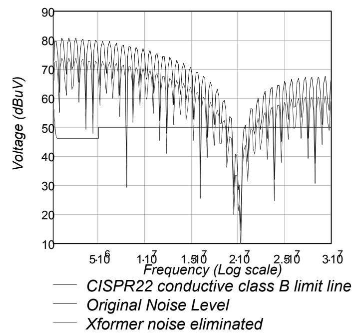




Example – eliminate effect of the transformer

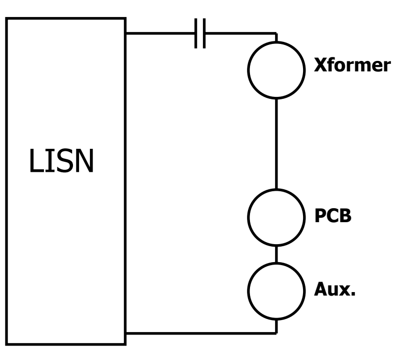
Conclusion – Little effect

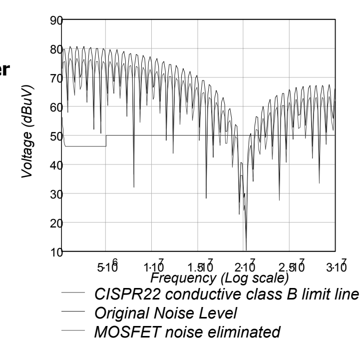




Example – eliminate effect of the *MOSFET*

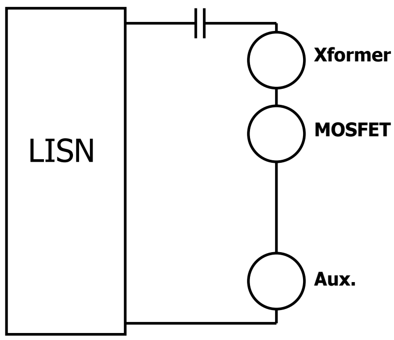
Conclusion – Very Little effect

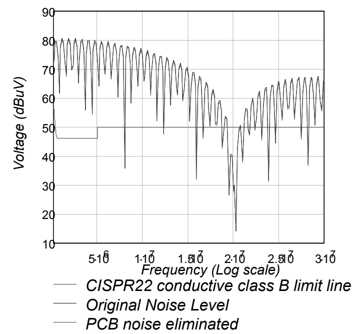




Example – eliminate effect of the PCB

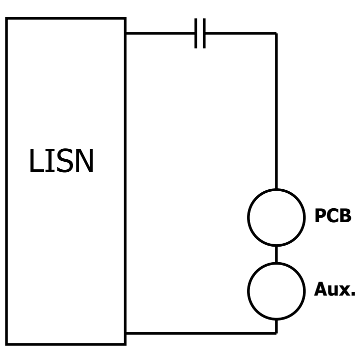
Conclusion – No effect

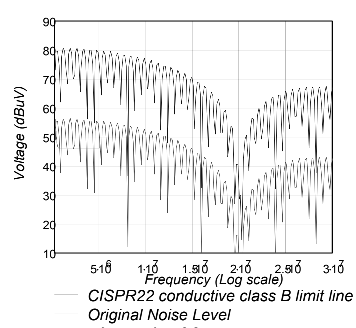




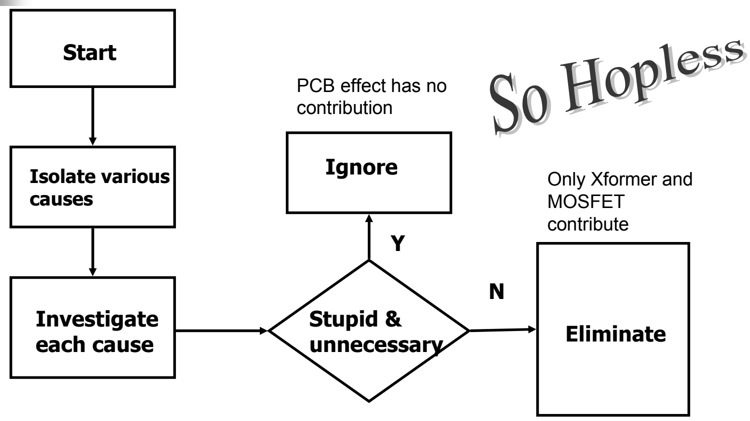
Example – eliminate the little and the very little

Conclusion – Hopeless, still exceeds the limit

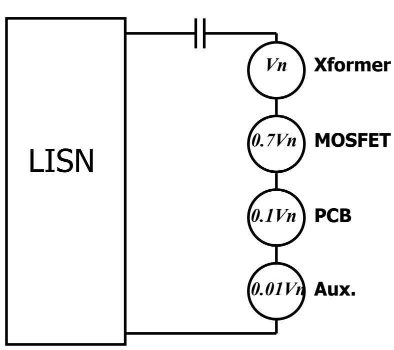


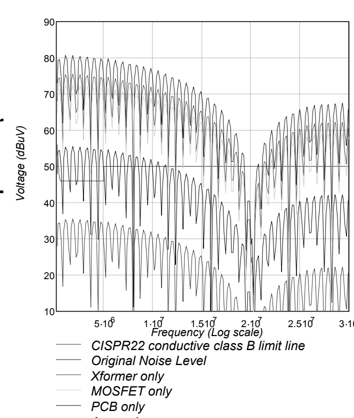


Example – already in a professional way ?

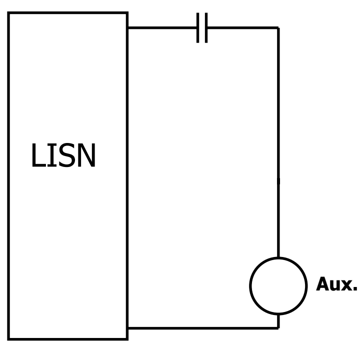


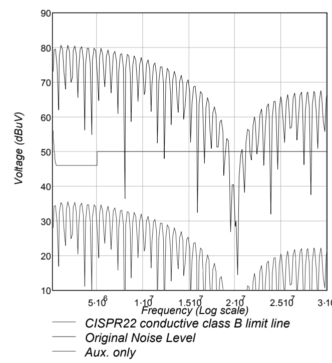
Wait a minute……….





We're wrong twice – eliminate the No Effect





Wrong three times ?

~~So PCB is important~~

Xformer
⇩
MOSFET
⇩
PCB
⇩
Bingo !
⇩
PCB is important

PCB
⇩
MOSFET
⇩
Xformer
⇩
Bingo !
⇩
Xformer is important

Wrong Concepts

- There is a dominant noise mechanism or path – *Wrong!*
- Some other noise mechanism can be ignored as it shows no effect – *Wrong!*
- Yesterday EMI solution did not work in today's problem – *Wrong!*

Right Concept

- "You will not see a result until you have eliminated the **LAST** problem"

Peter Bardos

Remember

- Two equal noise level add together only make a 6 dB difference

$$Reading = 20Log(\frac{Measured + Measured}{10^{-6}})dBuV$$

$$\downarrow$$

$$Reading = (20Log(\frac{Measured}{10^{-6}}) + 20Log(2))dBuV$$

$$\downarrow$$

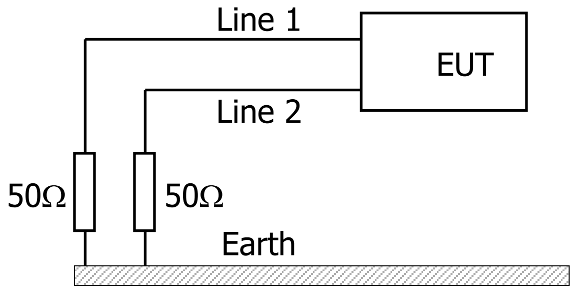
$$Reading = (20Log(\frac{Measured}{10^{-6}}) + 6)dBuV$$

Take a break

Any Short Question ?

Picking up the noise - LISN

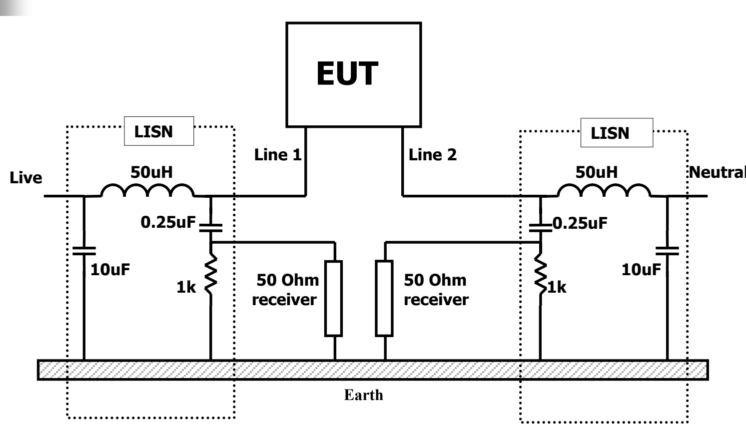
Line Impedance Stabilization Network – ac Only



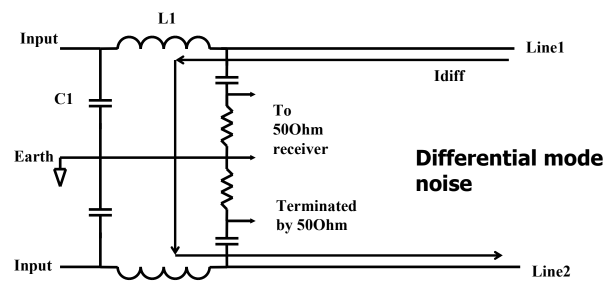
Simple Mission –

50 Ω to Earth

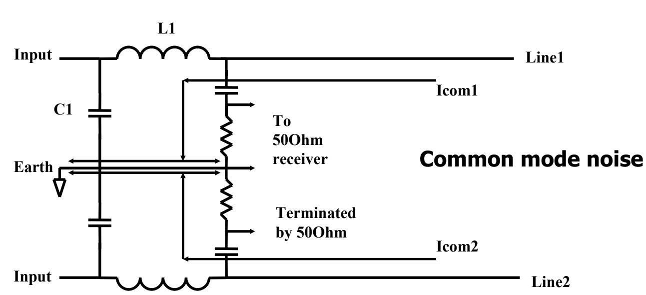
LISN – a little bit more detail



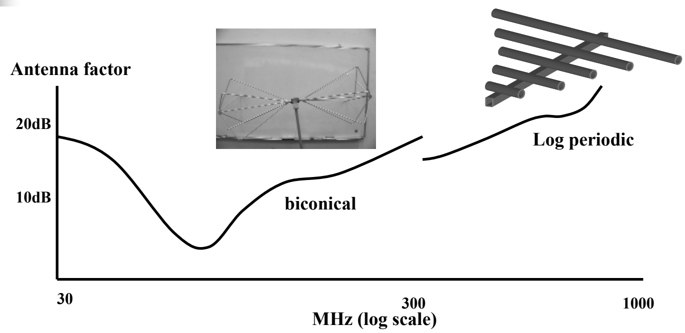
LISN – detects line to line noise



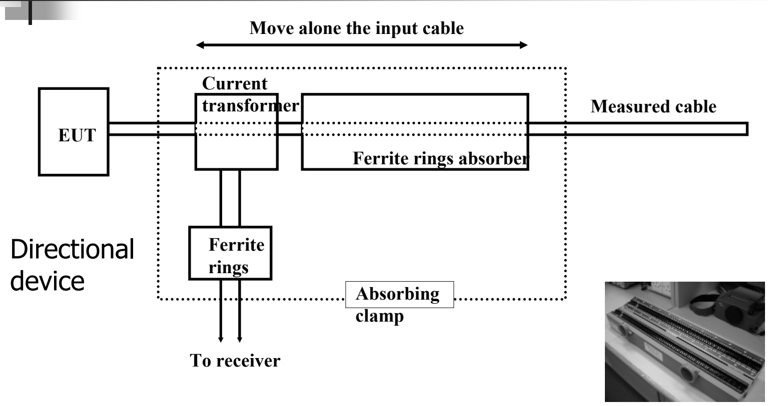
LISN – detects line to earth noise



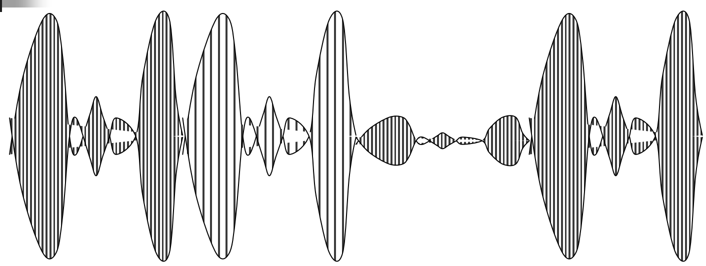
Picking up the noise in space - Antenna



Predicting noise to space- Absorption clamp



Nature of EM Noise



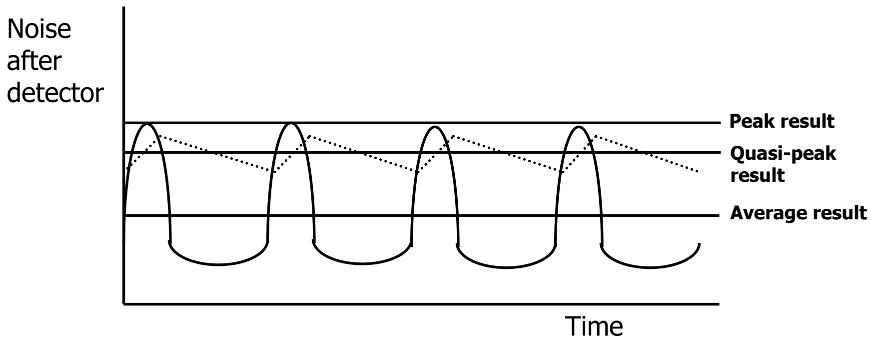
- Time varying
- Amplitude varying
- Frequency varying

It changed – After we have measured it !

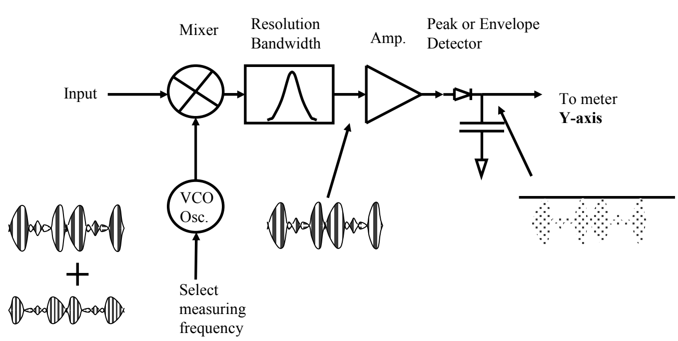
Nature of EM noise– Worse, normal and good

- Peak measurement – the worse, measure the peak noise within a period of time.
- Average measurement – the good, measure the averaged noise within a period of time
- Quasi-peak measurement – the normal, between peak and average measurements.

Peak, Quasi-peak, average

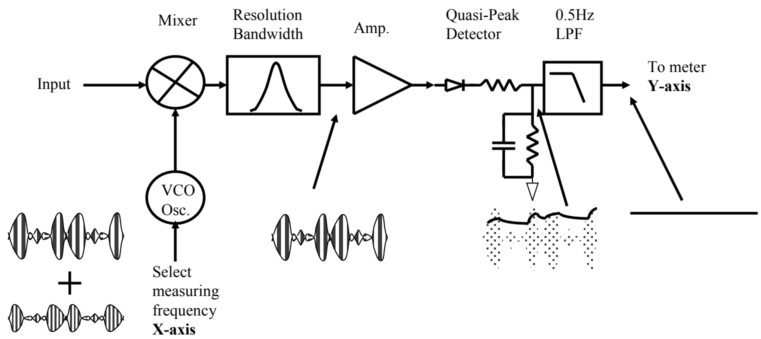


Peak detector – simplified



Simplified Peak EMI receiver

Quasi-peak detector – simplified



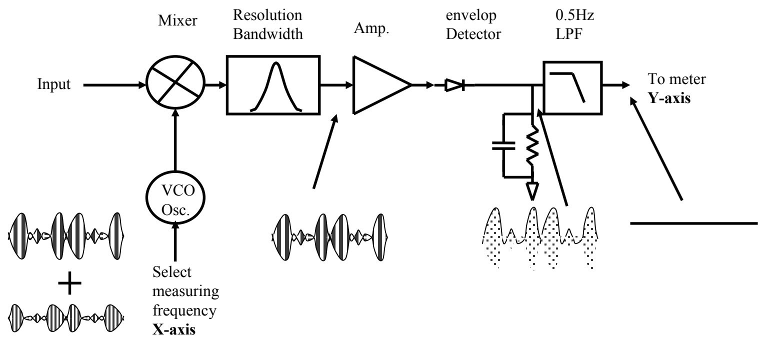
Quasi-Peak EMI receiver

Quasi-peak constant

QP-detector	10 - 150kHz	0.15 – 30MHz	30 – 300MHz	0.3 – 1GHz
6dB bandwidth	0.2kHz	9kHz	120kHz	120kHz
Charge time	45mS	1mS	1mS	1mS
Discharge time	500mS	160mS	550mS	550mS

What happens if the noise occurrence time is less than the charge time ?

Average detector – simplified

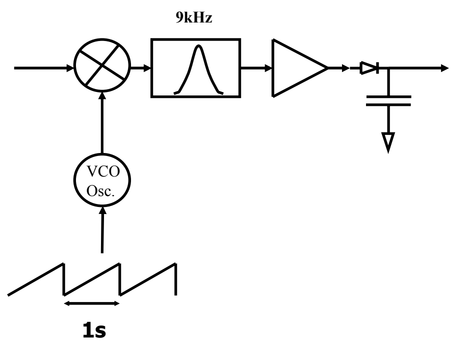


Peak constant ?

QP-detector	*10 - 150kHz*	*0.15 – 30MHz*	*30 – 300MHz*	*0.3 – 1GHz*
6dB bandwidth	*0.2kHz*	*9kHz*	*120kHz*	*120kHz*
Charge time	*?*	*?*	*?*	*?*
Discharge time	*?*	*?*	*?*	*?*

Don't forget every detector has a charging time constant.

Detector – how long does a signal exist



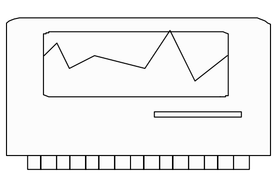
Period for detection at a certain frequency

$$T_{charge} = \frac{BW}{f_{stop} - f_{initial}} T_{sweep}$$

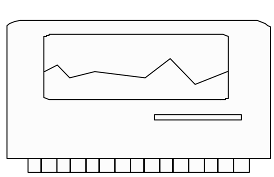
For conducted EMI range and sweep is 1s

$$T_{charge} = 0.3ms$$

Detector – fast and slow sweep



Sweep time = 10 s



Sweep time = 1 s

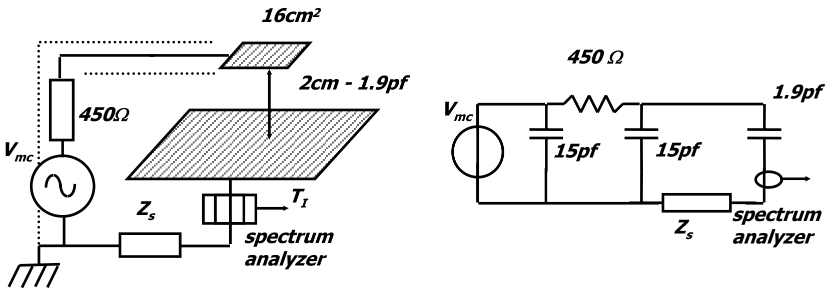
Short summary

- LISN, spectrum, receiver, antenna, absorption clamp are introduced.
- Peak detector is used for screen display as it gives fastest response.
- Quasi-peak and average are used in most standards.
- You can cheat the detector or display screen if the noise pop out faster than the charge time.
- Don't be cheated by the screen if sweep time is too fast.

Any Short Question?

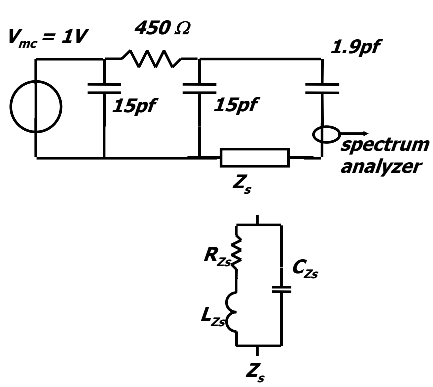
From easy to not so easy

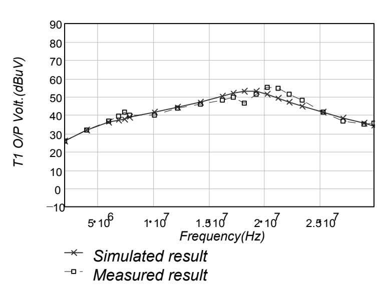
Invisible coupling – capacitive



Does a capacitive object work like a capacitor in a circuit ?

Capacitor is capacitor



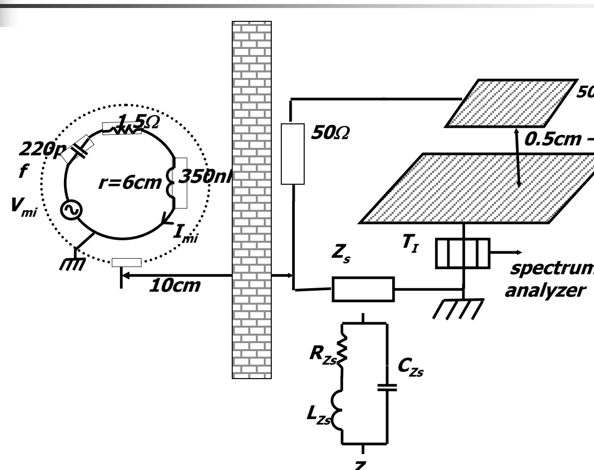


Mutual Capacitive Coupling

Capacitor of course is capacitor

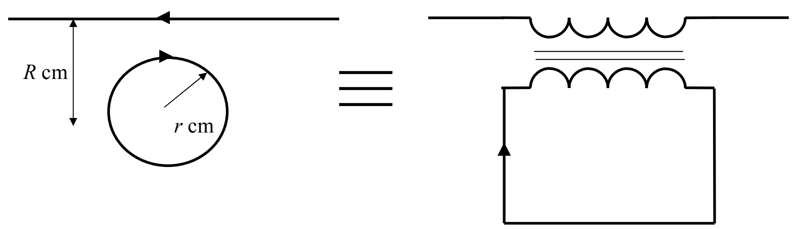
- The above experiment actually does not intend to prove a two plate structure is a capacitor.
- It proves two separate physical objects can have effect very much like a simple capacitor coupled together and can give accurate result even the two separate objects connected to a more complicated circuit.
- Don't forget a power supply is a complicated circuit, with a lot of separate parts and traces.

Invisible coupling – inductive



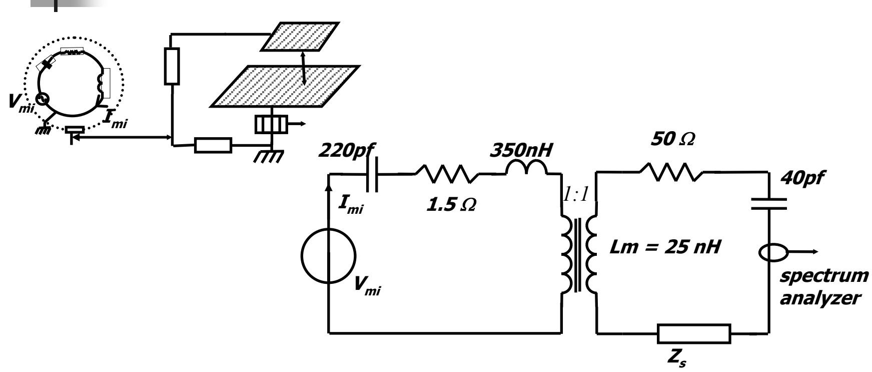
Do I pick up something here ?

Mutual inductive coupling – transformer

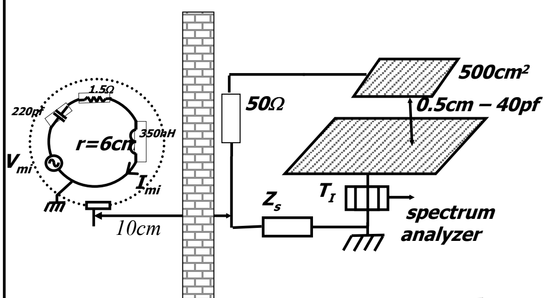


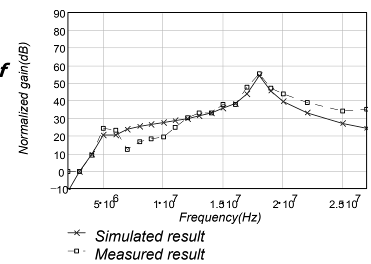
$$Lm = Z_{M\_line\_loop} = u_0 \left[\frac{R}{100} - \sqrt{\left(\frac{R}{100}\right)^2 - \left(\frac{r}{100}\right)^2} \right]$$

Inductive coupling – equivalent model



Mutual inductive coupling = transformer ?





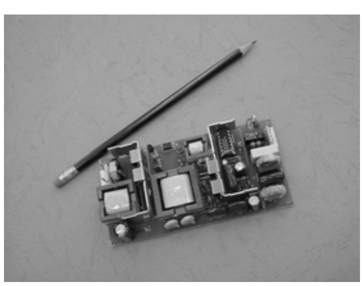
Mutual Inductive Coupling

(f)

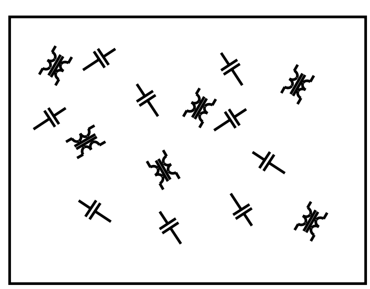
Yes, it does.

As an EMI engineer

You don't see this



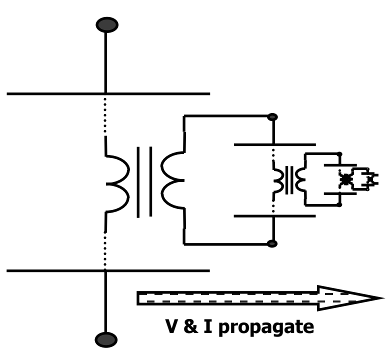
You see this



Reminder

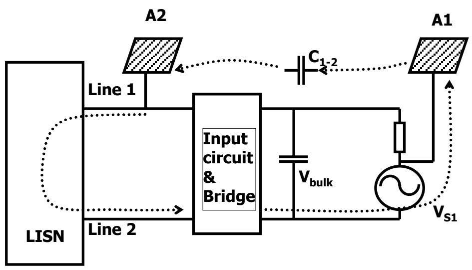
- Any two nodes, two objects, two components, two traces … etc, has an invisible capacitance and capacitive coupling effect
- Any two segments, two loops, two traces, two paths …etc, produce an invisible transformer and have inductive coupling effect.
- Is there any combination of capacitive-inductive effect?

Capacitive-Inductive effect



Simple idea of Electro-Magnetic wave propagation.

Capacitive coupling – trace to trace



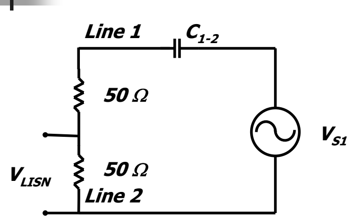
Say

C_{1-2} = 0.1pf

V_{S1} = 300V

C_{bulk} is blocked by Input circuit & Bridge

Capacitive coupling – trace to trace



$$V_{LISN} = \left| \frac{50}{50 + 50 + \frac{1}{2\pi f j C_{1-2}}} \right| \times 300$$

As

C_{1-2} = 0.1pf

V_{S1} = 300V

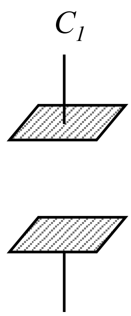
At 150kHz

V_{LISN} = 1400uV

EN55022 B limit at 150kHz is 630uV

Already exceeds limit just because of 0.1pf

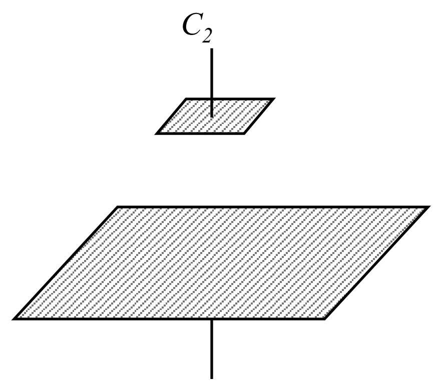
Capacitive coupling



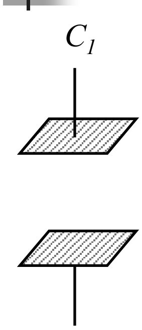
$C_1 = C_2$?

$C_1 > C_2$?

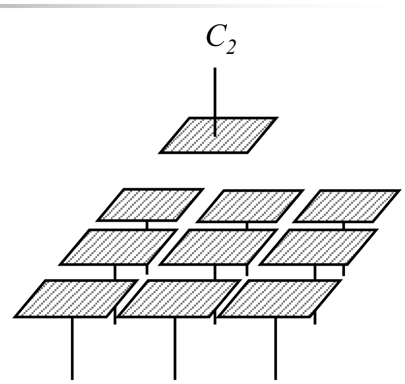
$C_1 < C_2$?



Capacitive coupling – which is bigger

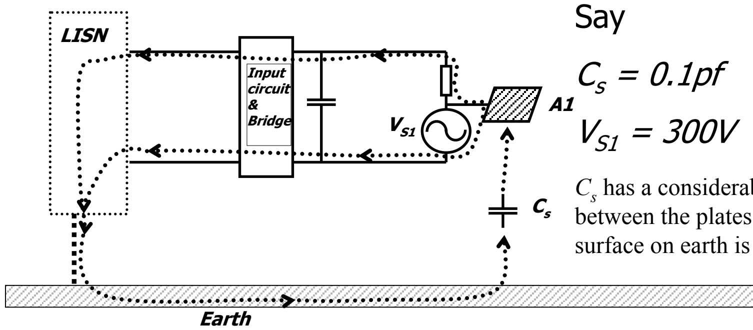


$C_1 << C_2$



Imagine C_2 approximate as the sum of all the capacitors

Capacitive coupling – trace to ground



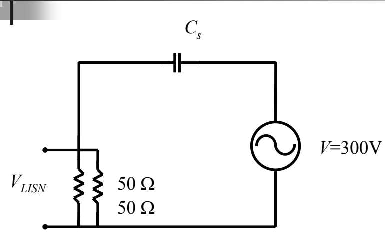
Say

C_s = 0.1pf

V_{S1} = 300V

C_s has a considerable length between the plates but the surface on earth is very large

Capacitive coupling – trace to ground



$$V_{LISN} = \left| \frac{50/2}{50/2 + \frac{1}{2\pi f j C_s}} \right| \times 300$$

Assume

C_s = 0.1pf

V_{S1} = 300V

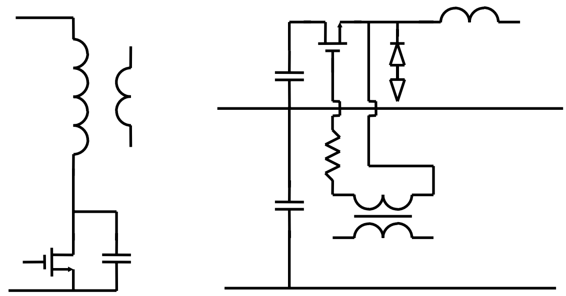
At 150kHz

V_{LISN} = 700uV

EN55022 B limit at 150kHz is 630uV

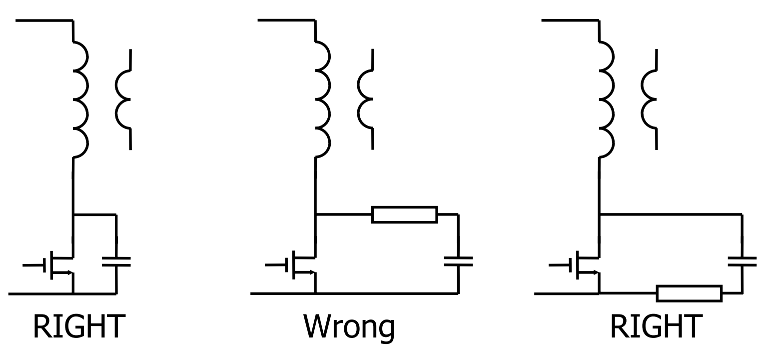
Exceed limit again !

HVHF circuits

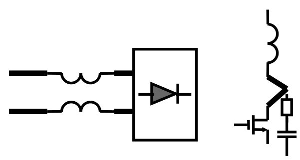


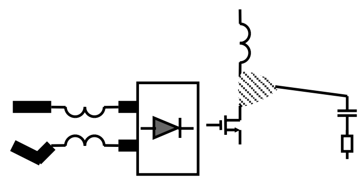
High
Voltage
High
Frequency

HVHF circuits – reduce to a size As Small As Possible ASAP



Capacitive coupling – PCB trace rule

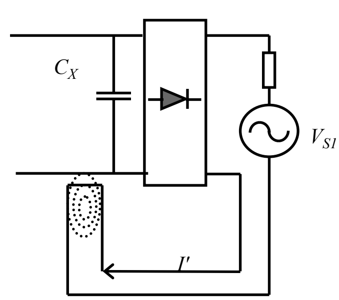


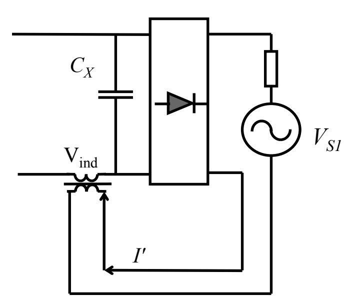


Good – small trace area, symmetrical, good separation

Bad – large trace area, asymmetrical, not enough separation and long connection wire.

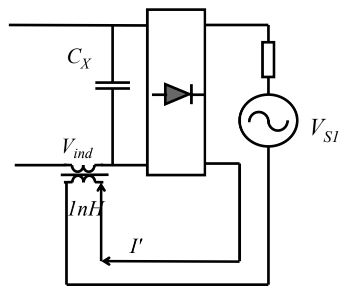
Inductive coupling – trace to trace





Although the loop has low voltage, it generates other kind of noise.

Inductive coupling – trace to trace induction



Say

L_m = 1nH

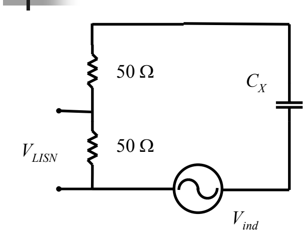
I' = 1A @ 150kHz

$V_{ind} = I' \, 2 \pi f L_m$

V_{ind} = 940 uV

C_x gives a low impedance path for the induced current to flow

Inductive coupling – trace to trace result



$$V_{LISN} = \left| \frac{50}{50 + 50 + \frac{1}{2\pi f j C_X}} \right| \times 940uV$$

Say

C_X = 0.1uF

At 150kHz

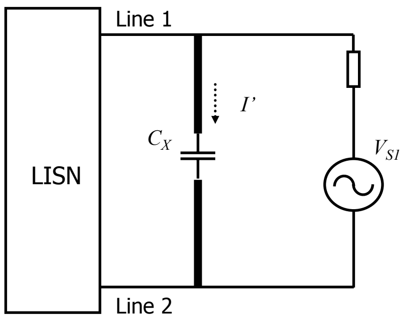
V_{LISN} = 460uV

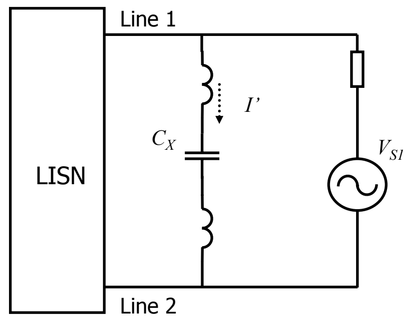
EN55022 B limit at 150kHz is 630uV

Very close to limit!

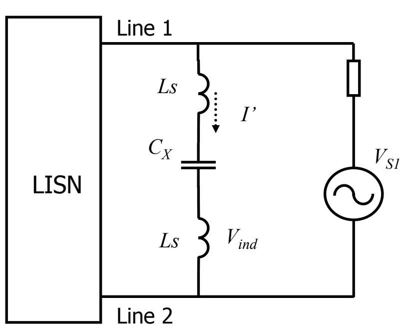
Inductive coupling – the trace itself

- **Self inductance**





Inductive coupling – trace induced voltage



Let say

$L_m = 10nH$

$I' = 1A$ @ $150kHz$

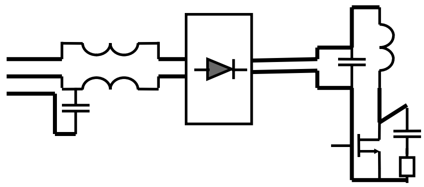
$V_{ind} = I' 2 \pi f Ls$

$V_{ind} = 9400\ uV$

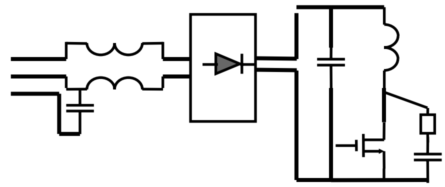
EN55022 B limit at 150kHz is 630uV

Is it horrible ?

Inductive coupling – PCB trace rule



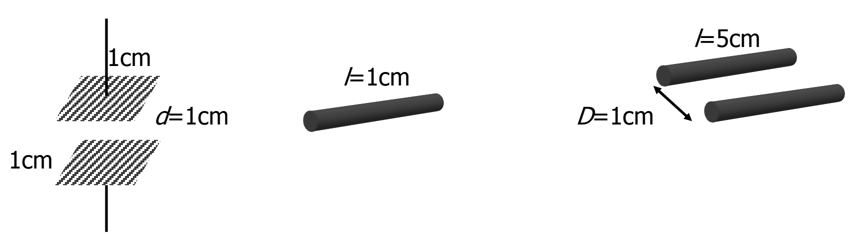
Good – small loop area, good separation between loops, node terminated at capacitor terminals



Bad – large loop area, short separation between loops, nodes are not terminated at capacitor terminals

Typical capacitor and inductor parameter values

$C = 0.085A/d$ pf $L = 0.002l(\ln(2l/r)-0.75)$ uH $Lm = 0.002l(\ln(2l/D)-1+D/l)$ uH



C = 0.0885pf **L_{awg18} =5.8nH** **Lm_{awg18} =15nH**

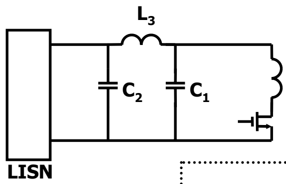
Short conclusion

- Very small capacitor may cause serious capacitive coupling effect
- Very small inductor may cause serious inductive coupling effect, either mutual or self inductive coupling.
- Very small pieces of object may cause devastating magnitude of capacitance or inductance.

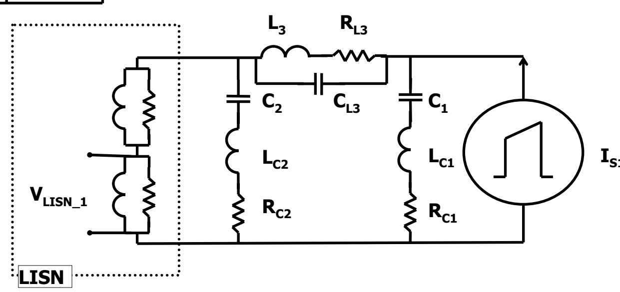
Any Short Question?

From not so easy to difficult

An obvious noise source – input ripple current

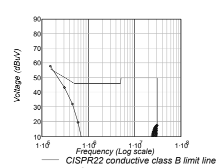


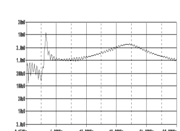
Well known equivalence



Input ripple current – simulation

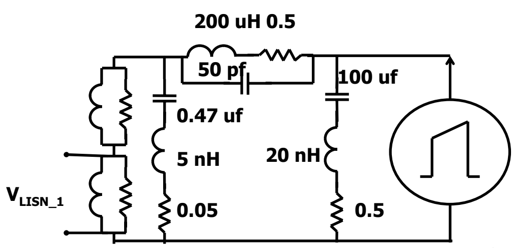
- Don't be scared by complicated circuit.
- You don't need to calculate for the answer.
- You ONLY need to simulate it's result. SPICE, Math software. . . etc may help

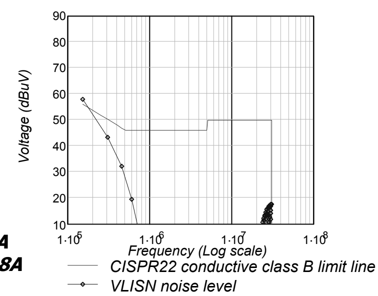




(g)

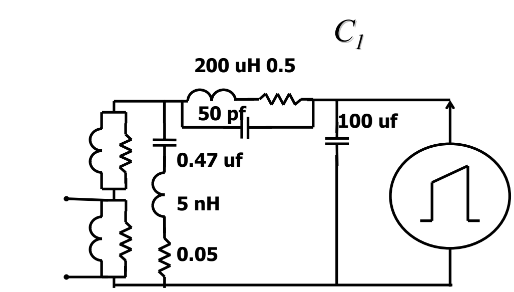
Input ripple current – typical result

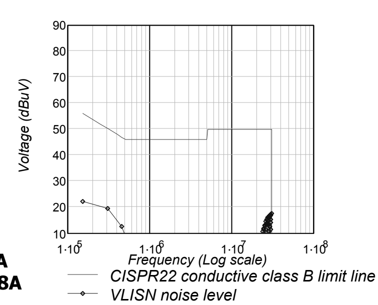




I_{S1_ini} = 0.5A
I_{S1_peak} = 0.8A
t_r=50 ns
t_f=50 ns
t_{on} = 2 us
T = 6.6 us

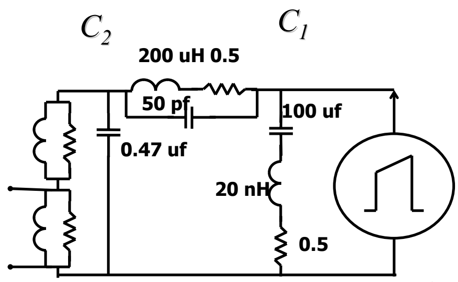
Input ripple current – ideal C_1



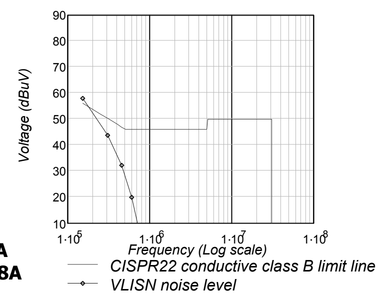


I_{S1_ini} = 0.5A
I_{S1_peak} = 0.8A
tr=50 ns
tf=50 ns

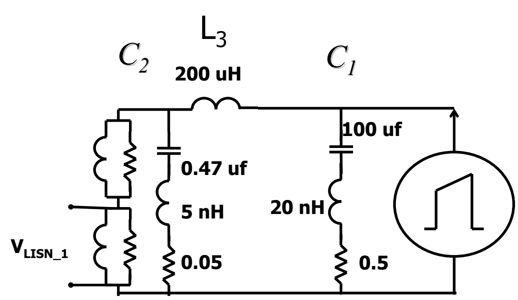
Input ripple current –ideal C_2



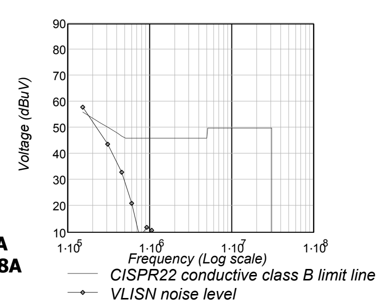
I_{S1_ini} = 0.5A
I_{S1_peak} = 0.8A
tr=50 ns
tf=50 ns



Input ripple current – ideal L_3

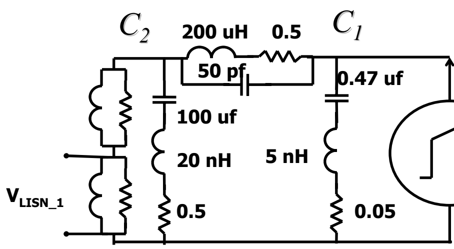


I_{S1_ini} = 0.5A
I_{S1_peak} = 0.8A
tr=50 ns
tf=50 ns



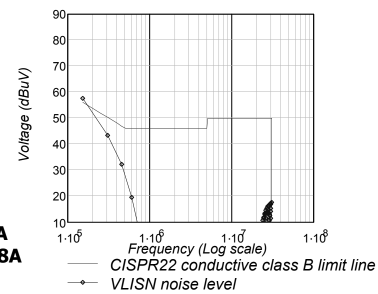
Input ripple current – swap C_1, C_2

L_3 less rms current

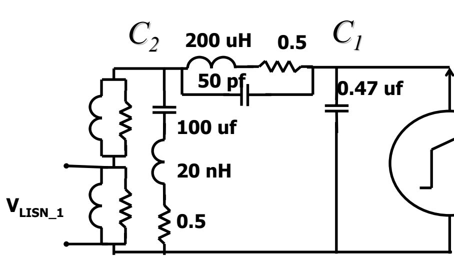


I_{S1_ini} = 0.5A
I_{S1_peak} = 0.8A
tr=50 ns
tf=50 ns

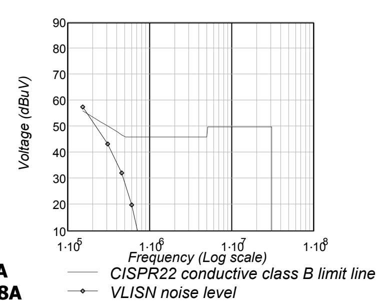
Not much difference



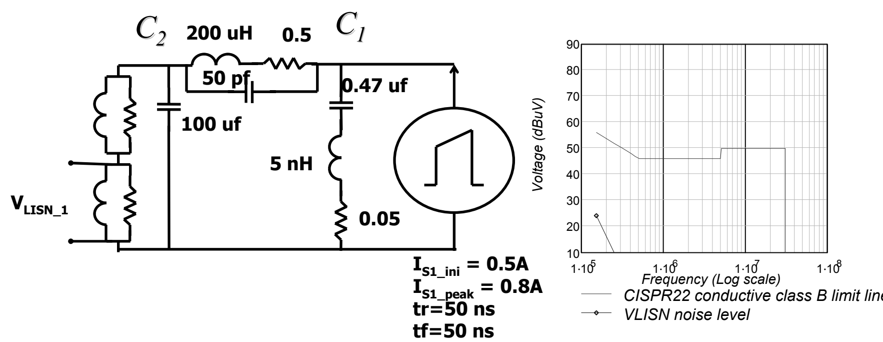
Input ripple current – ideal C_1 again



I_{S1_ini} = 0.5A
I_{S1_peak} = 0.8A
tr=50 ns
tf=50 ns



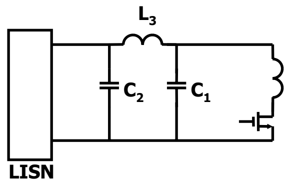
Input ripple current – ideal C_2 again



Input ripple current – short summary

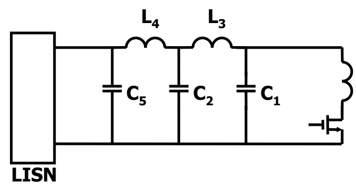
- Realistic equivalent circuit has difference with ideal elements.
- Equivalent series resistance of a capacitor contribute to low frequency EMI.
- Equivalent series inductance of a capacitor contribute to high frequency EMI.
- Perfect the components with largest value is very effective. E.g. 100 uf

Input ripple current – two stage design

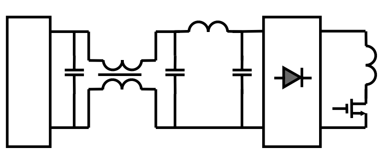


Add one more stage ?

Wait a minute !

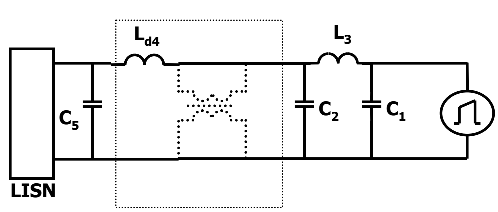


Input ripple current – make use of leakage

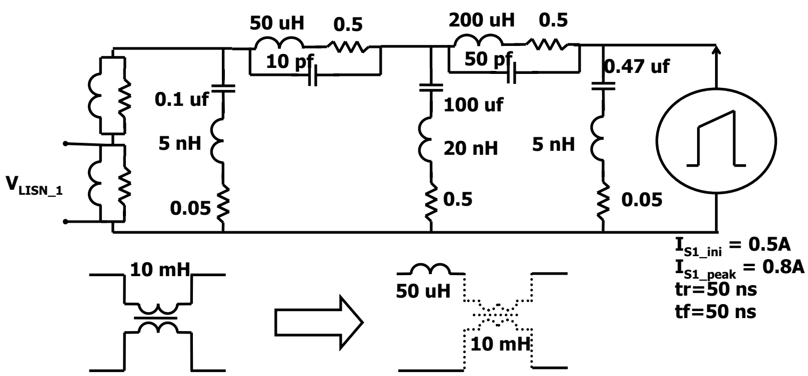


There is a Common Mode Choke (CMC) anyway.

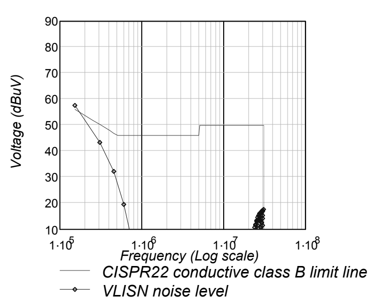
Make use of it's leakage inductance !



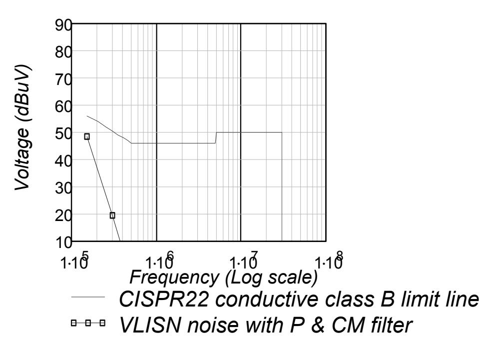
Input ripple current – two stage equivalence



Input ripple current – two stage result

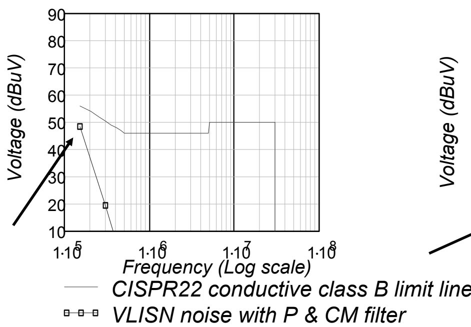


Single Stage Filter

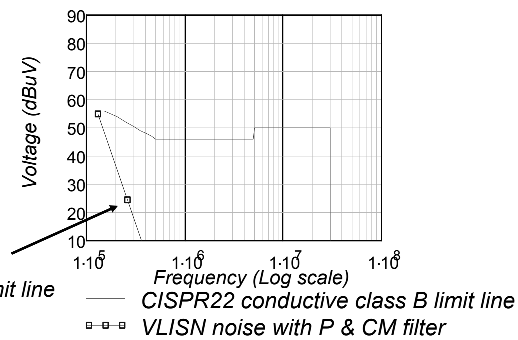


Two Stage Filter

Input ripple current – common trick

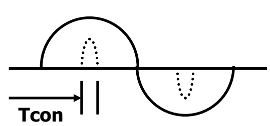


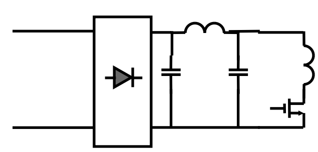
fs = 150kHz, 8 dB margin

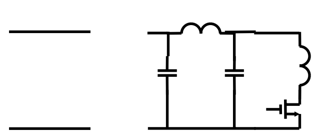


fs = 130kHz, 30 dB margin

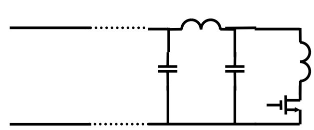
Input ripple current – Disappears





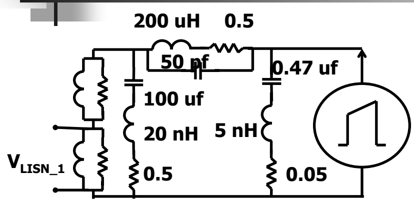


Beyond conduction time t ≠ Tcon

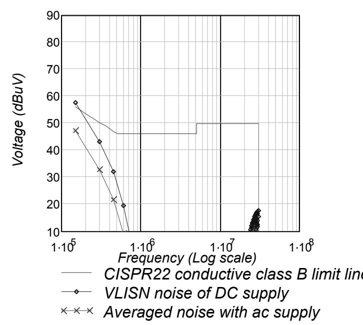


During conduction time t=Tcon

Input ripple current – average result



Assuming conduction time Tcon = 3 ms



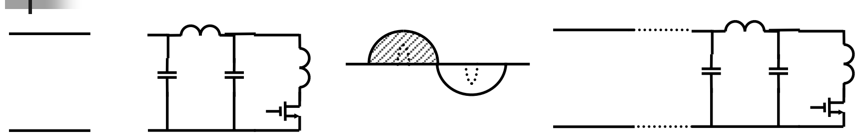
Voltage picked up at LISN with P filter

$$V_{LISN\_peak} = V_{LISN\_dc}$$

$$V_{LISN\_quasi-peak} = V_{LISN\_dc}$$

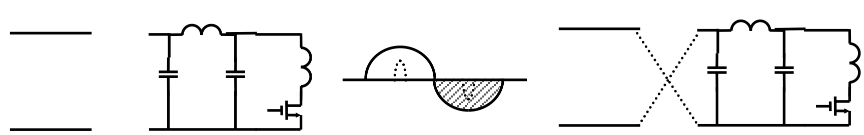
$$V_{LISN\_average} = V_{LISN\_dc} \frac{2Tcon}{T_{line}}$$

At different time – different equivalent circuit



Beyond conduction time 0<t<π and t ≠ Tcon

During conduction time 0<t<π and t=Tcon

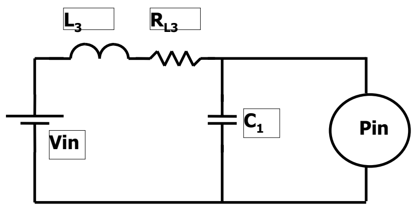


Beyond conduction time π<t<2π and t ≠ Tcon

During conduction time π<t<2π and t=Tcon

Apply to all analysis !!

Input ripple current – stability



As input of converter is a power source Pin.

Approximate the differential Eqn.

$$\frac{d^2 v_{C1}}{dt^2} + \left[\frac{R_{L3}}{L_3} - \frac{Pin}{{v_{C1}}^2 C_1}\right]\frac{dv_{C1}}{dt} + \frac{v_{C1}}{L_3 C_1} = \frac{Vin}{L_3 C_1}$$

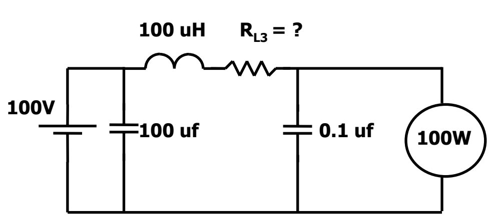
- big C_1 is good
- big R_{L3} is good
- small Vin is bad
- large L_3 is bad

Keep first order coefficient > 0

$$\frac{R_{L3}}{L_3} > \frac{Pin}{{v_{C1}}^2 C_1}$$

Input filter – stability issue

V_{in} = v_{C1} approximately



$$\frac{R_{L3}}{L_3} > \frac{Pin}{{v_{C1}}^2 C_1}$$

RL3 > 10Ω ! !

Usually winding resistance RL3 = 0.2 Ω

Every converter should oscillate ! ! But . . .

Input filter – why usually stable ?

- Because skin effect increases the winding resistance – WRONG
- Because proximity effect increases the winding resistance – WRONG
- Because parasitic capacitor inhibits the oscillation – WRONG
- Because the inductor is no longer an inductor – Meaningless

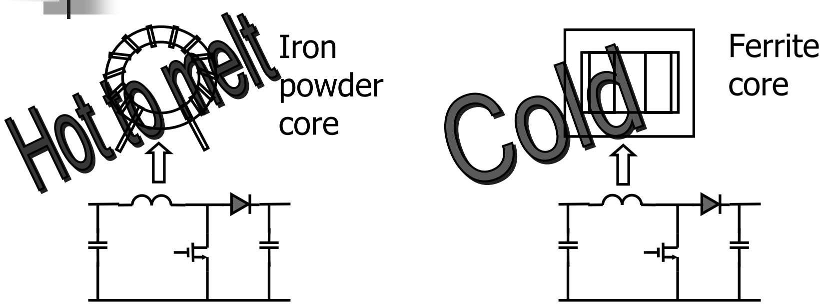
Input filter – what ac inductor is

Inductance — **Resistor reflecting core losses** — **Resistor reflecting skin / proximity losses** — **Resistor reflecting dc winding losses**

Frequency dependent — **Frequency dependent** — **Depend on Frequency & winding structure** — **Wire size dependent**

DOMINANT !

Input filter – core losses issue



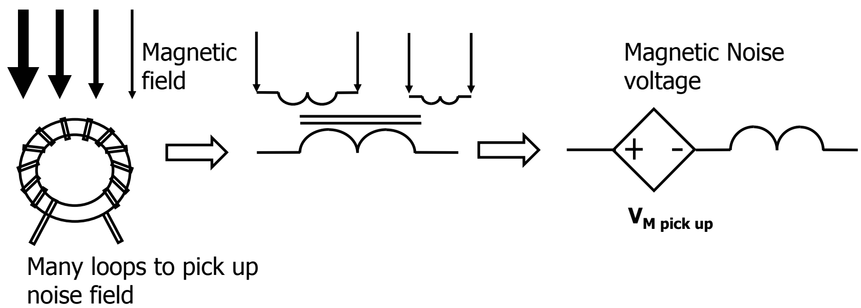
Every engineer know core losses is significant, don't ignore the ac resistor reflecting core losses.

Input filter – why usually stable ? again

- Because core losses of the filtering inductor provide extra resistance – RIGHT.
- Because the higher the inductance, the higher the core losses resistance – RIGHT.
- Because the capacitor C_1 is usually bigger than the example – RIGHT.
- Because the oscillating frequency may fall out of regulating region of the converter, and becomes a circuit with positive resistance – MAY BE.

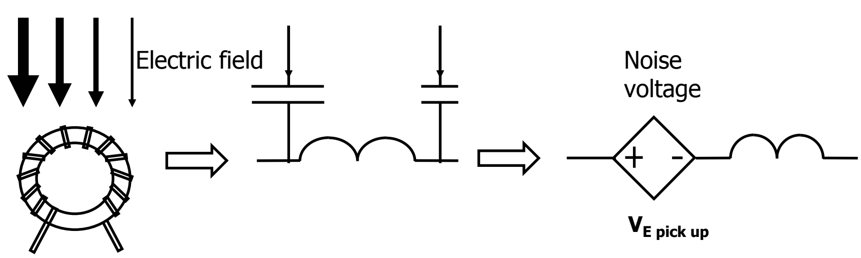
Input filter = Input magnetic receiver

- Recall the idea of inductive coupling and mix it with the filter.



Input filter = Input electric receiver

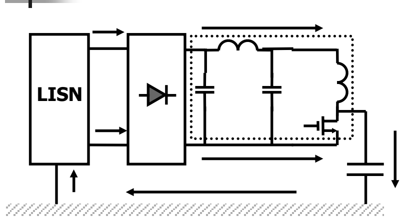
- Recall the idea of capacitive coupling and mix it with the filter.



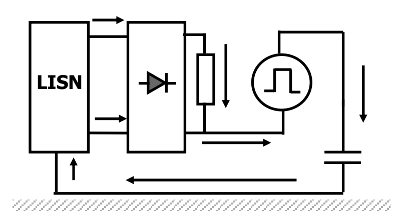
Input filter – summary

- Leakage inductance can be made used for ripple current filtering.
- Choose low ESR for big capacitor.
- Conduction angle or boost PFC yield lower average value than seen on screen.
- Input filtering circuit is also a receiver circuit.
- Core losses resistor is introduced

Invisible path – drain to earth capacitor

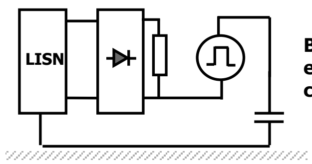


Simplified circuit showing drain to earth capacitor causing invisible current flow

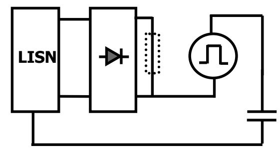


Equivalent circuit using equivalent input resistance and equivalent voltage source

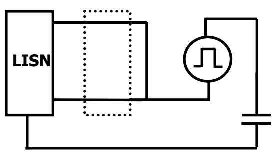
Drain to earth capacitor – equivalent model



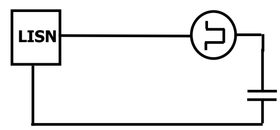
Basic equivalent circuit



Input capacitor is large

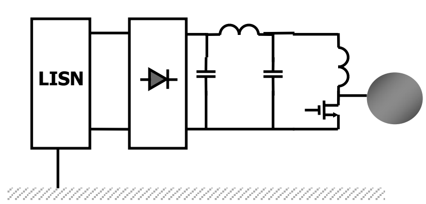


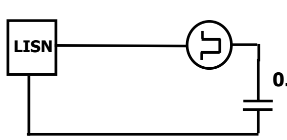
Conduction period only



Input lines are paralleled

Drain to earth capacitor – how large?





Let the total surface area attach to the drain is equal to a sphere with 1cm² surface area.

Equivalent radius *r*

r = 0.28cm

As the self capacitance of a sphere of *r cm*

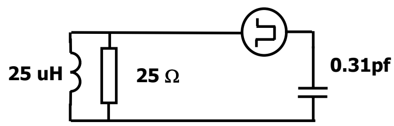
$C_{sphere} = 4\pi 0.0885r$ *pf*

The equivalent drain self capacitance is

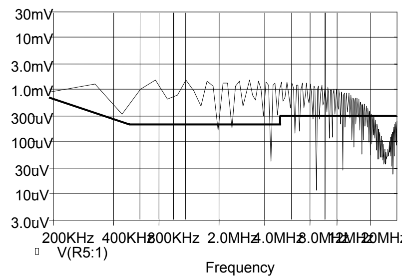
$C_{drain} = 0.31$ *pf*

Drain to earth capacitor – simulation

Vpeak =400 V
Tr = 50 ns
Tf = 50 ns
Pw = 2 us
Per = 6.6 us

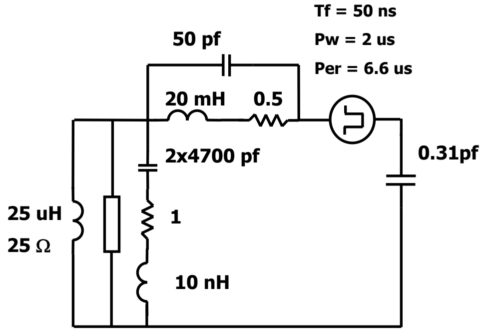


Fails just because of 0.31 pf !

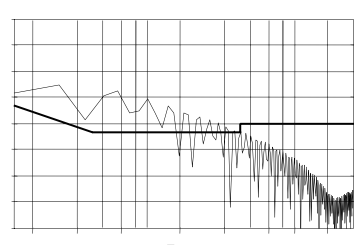


Filtering – doesn't work ?

Vpeak =400 V
Tr = 50 ns
Tf = 50 ns
Pw = 2 us
Per = 6.6 us

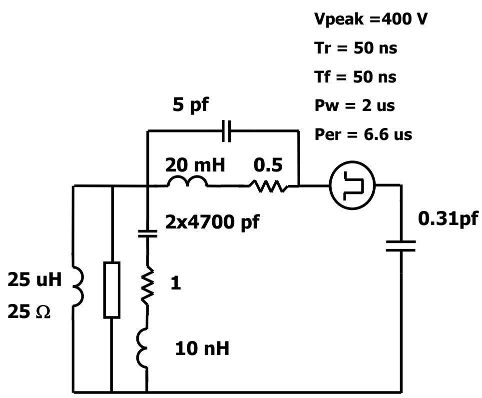


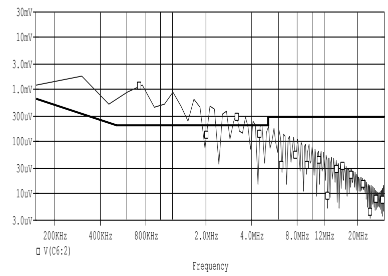
What's wrong? It must be the CMC stray capacitor.



Filtering – parasitics not crucial

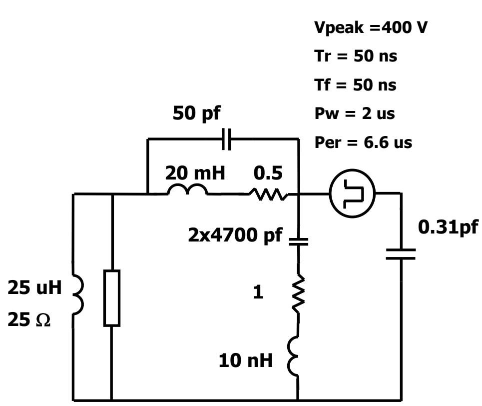
What's wrong? Beware of the LISN impedance

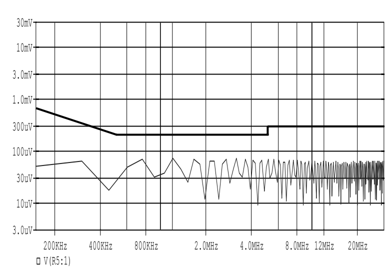




Filtering – right filter design

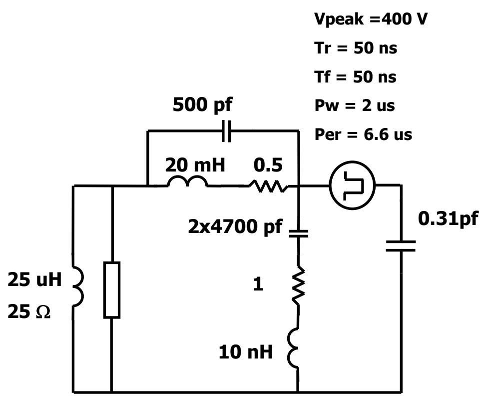
DONE !

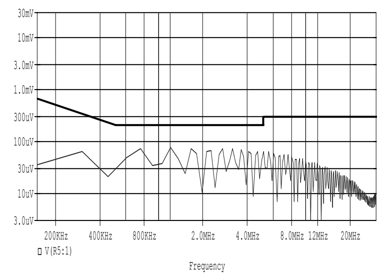




Filtering – wrong filter design again

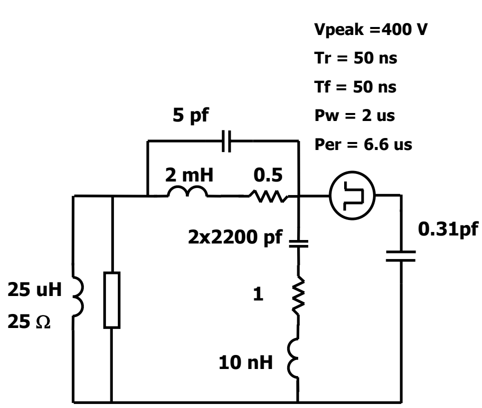
Don't always blame the parasitic elements

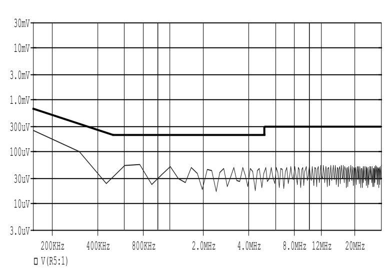




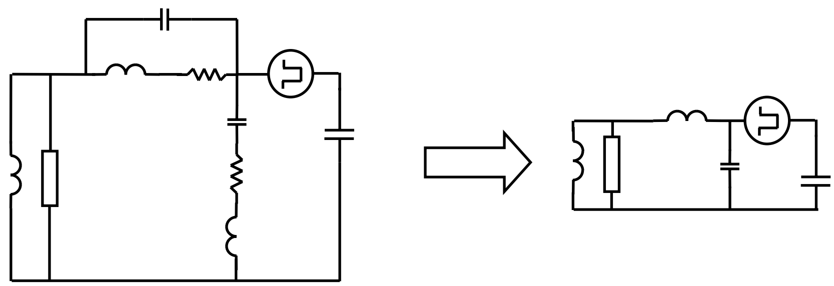
Filtering – how small it can be ?

A very small filter can filter out the noise !!

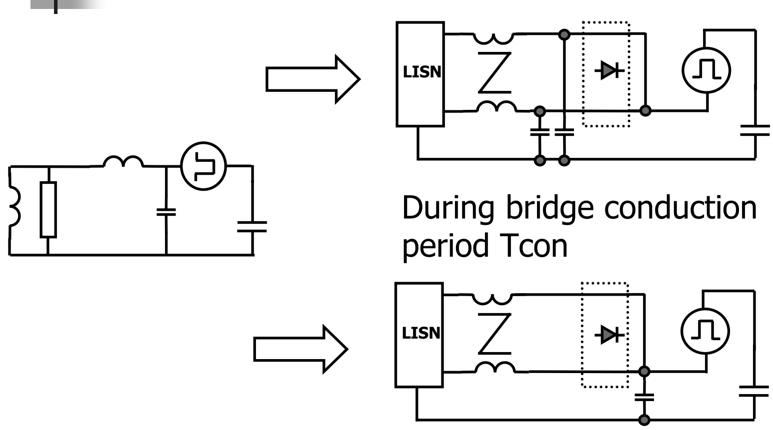




Filtering – simplified view

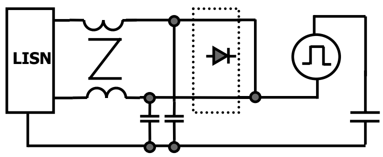


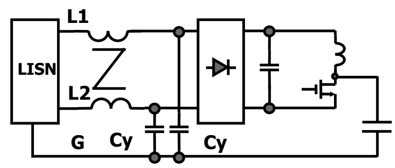
Filtering – get back to the real circuit



During bridge conduction period Tcon

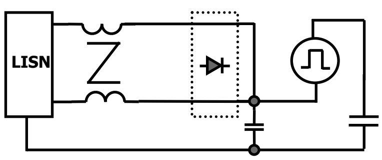
Filtering – get back to the real circuit

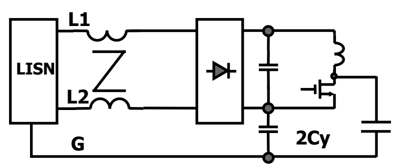




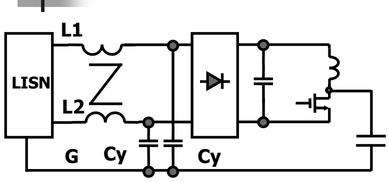
During bridge conduction period Tcon

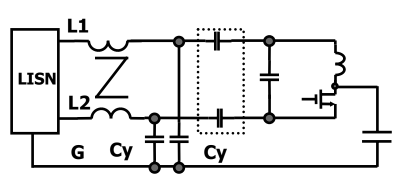
Practical Look





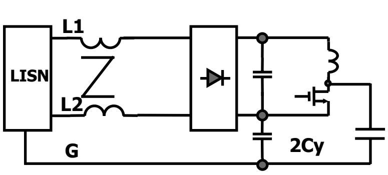
Filtering – are the two practical circuit equivalent ?

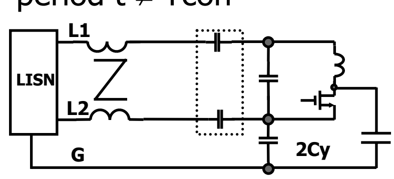




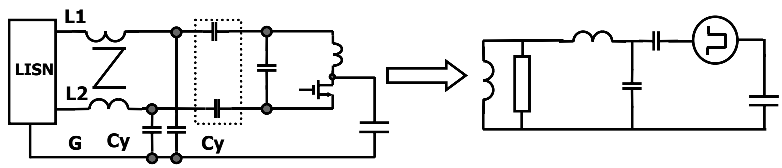
Practical Look

During bridge non-conduction period t ≠ Tcon

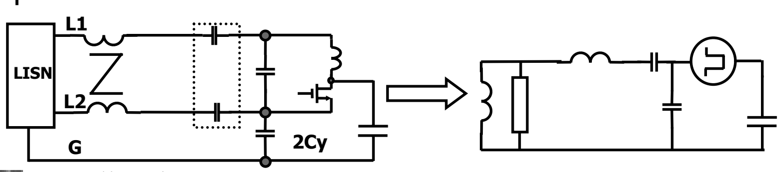




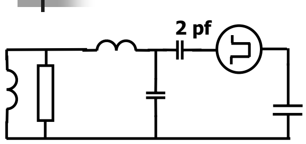
Two different filters – go to their equivalence



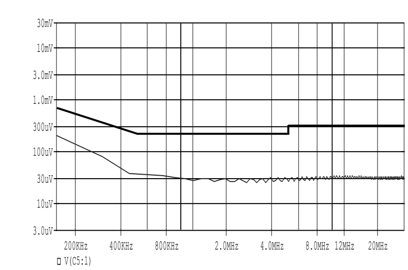
During bridge non-conduction period t ≠ Tcon

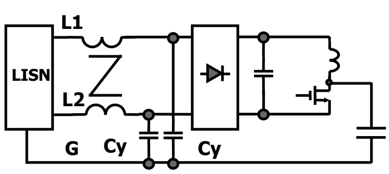


Two different filter – Cy on the left hand side

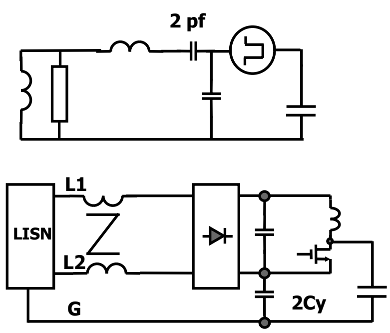


Not bad during non-conduction period



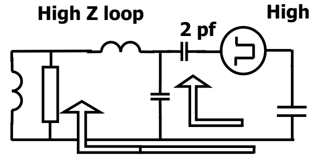


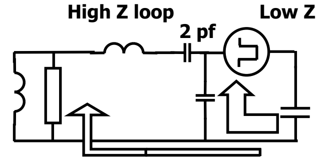
Two different filter – Cy on the right hand side

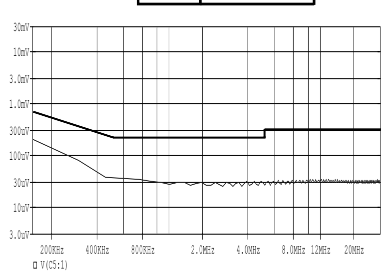


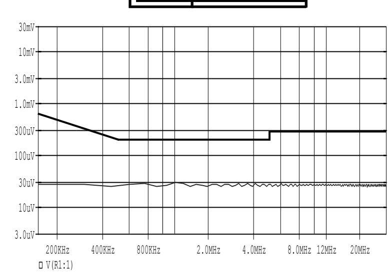
Better during non-conduction period

Two different filters – left and right

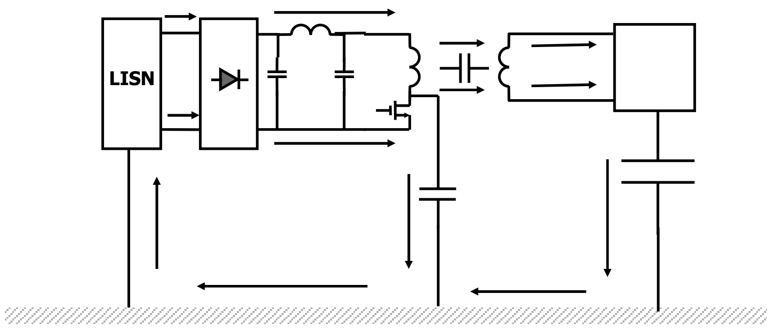




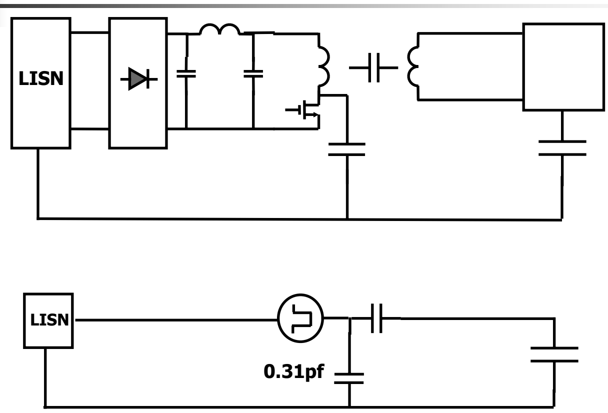




Invisible path – Secondary to earth capacitor

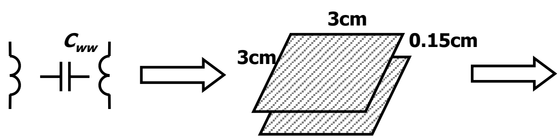


Sec. to earth capacitor – circuit model



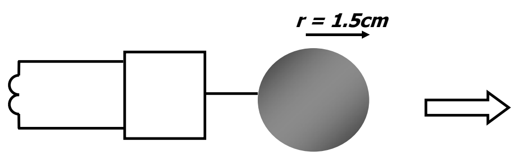
Power[e]Lab HKU

Sec. to earth capacitor – how big ?



C = 0.085A/d pf

C_{ww} *= 53 pf*



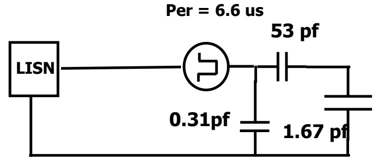
C_{sphere} = 4 π0.0885r pf

C_{sE} *= 1.67 pf*

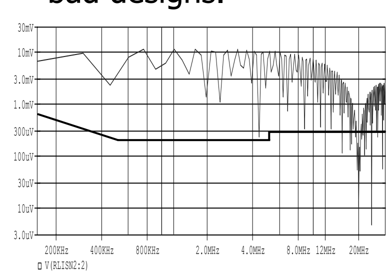
Power[e]Lab HKU

Sec. to earth capacitor – rare noise

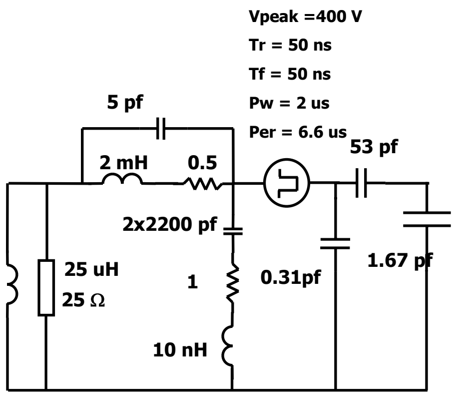
Vpeak =400 V
Tr = 50 ns
Tf = 50 ns
Pw = 2 us
Per = 6.6 us



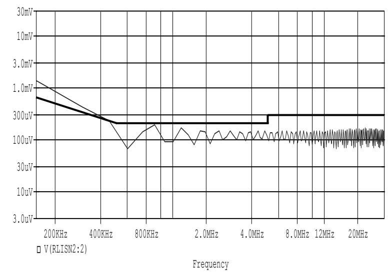
Greatly exceeds limit – usually come across in bad designs.



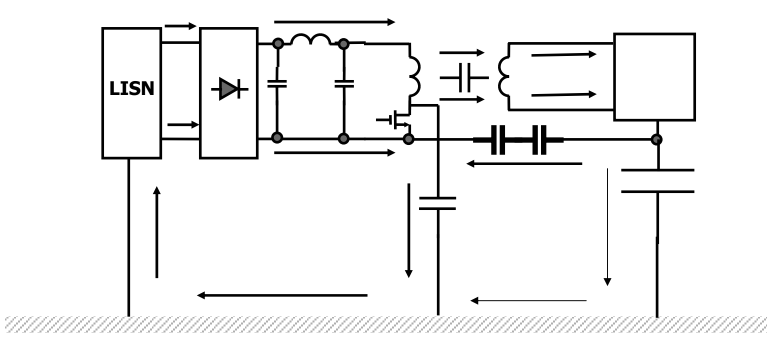
Sec. to earth capacitor – with filter



Still exceeds limit even after filter is added.

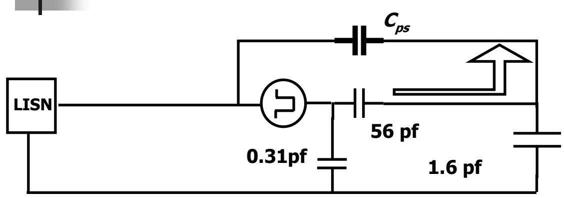


Sec. to earth capacitor – Pri. To Sec. Capacitor

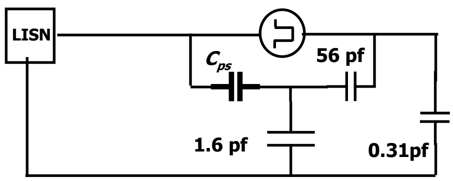


The primary to secondary capacitor can by pass the noise current generated from the primary side.

Pri. To Sec. Capacitor – circuit model

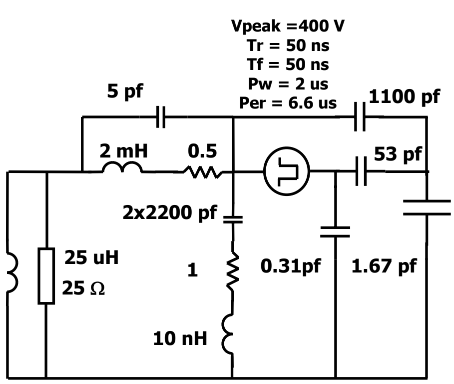


Provide a low impedance path to shunt or by pass the current flowing to earth

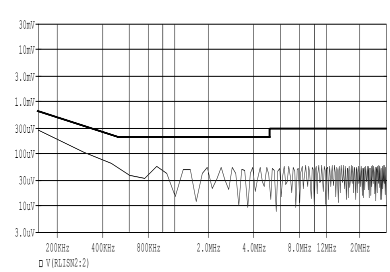


Or you can interpreter *Cps* as dividing down the noise voltage

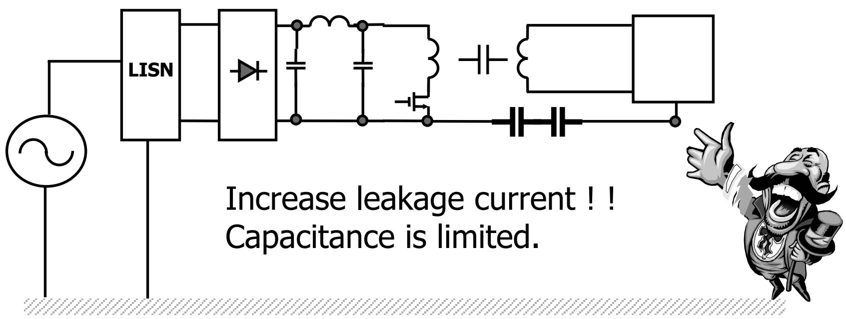
Pri. To Sec. Capacitor – save power



Much better solution as no extra power losses is produced.

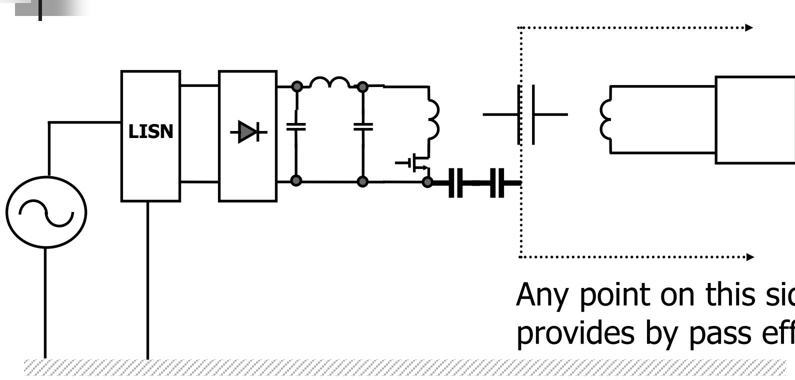


Pri. To Sec. Capacitor – drawback



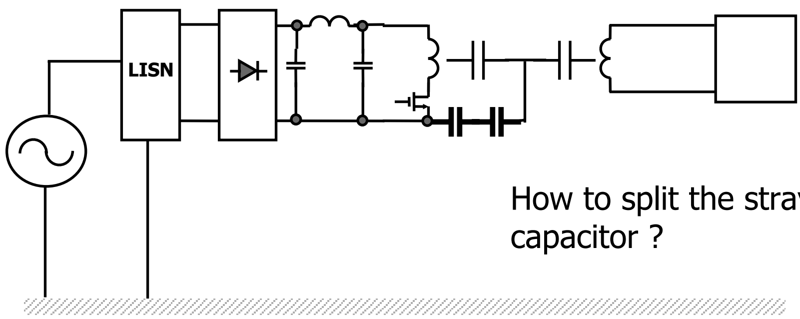
Increase leakage current ! !
Capacitance is limited.

Sec. to earth capacitor – by pass elsewhere



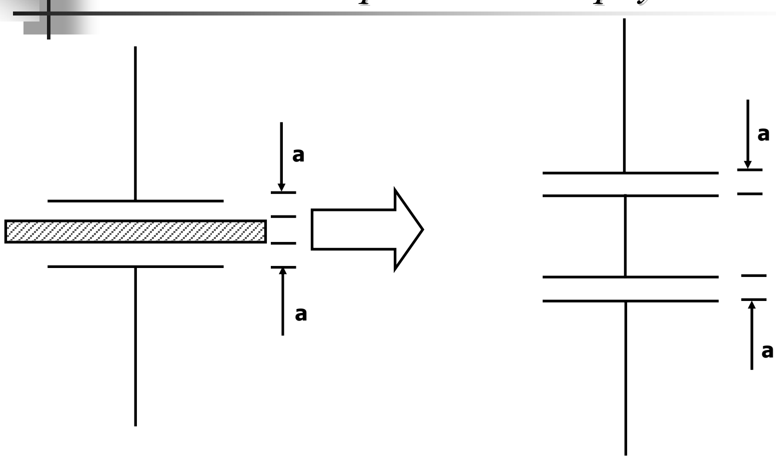
Any point on this side
provides by pass effect

Sec. to earth capacitor – by pass inside ?

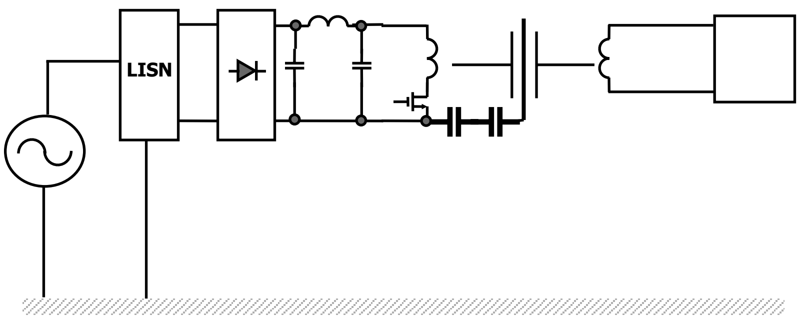


How to split the stray capacitor ?

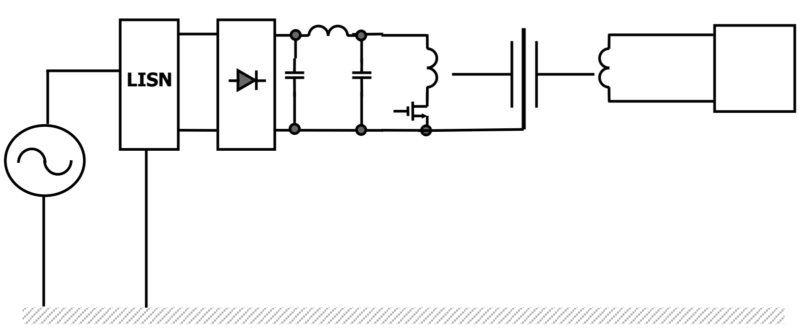
Sec. to earth capacitor – F.5 physics



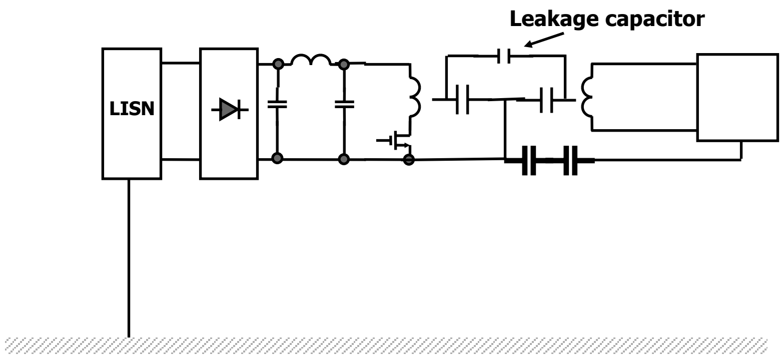
Sec. to earth capacitor – add one more plate



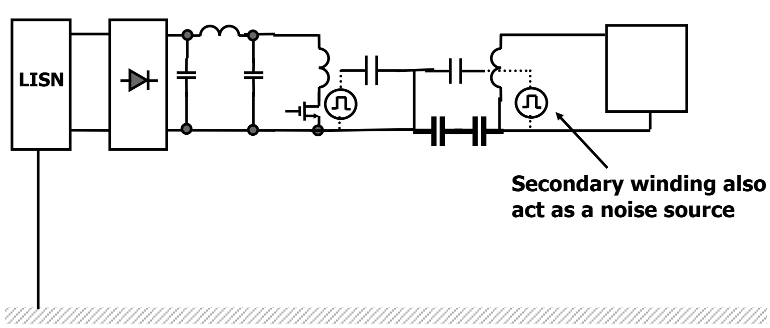
Sec. to earth capacitor – better way to by pass



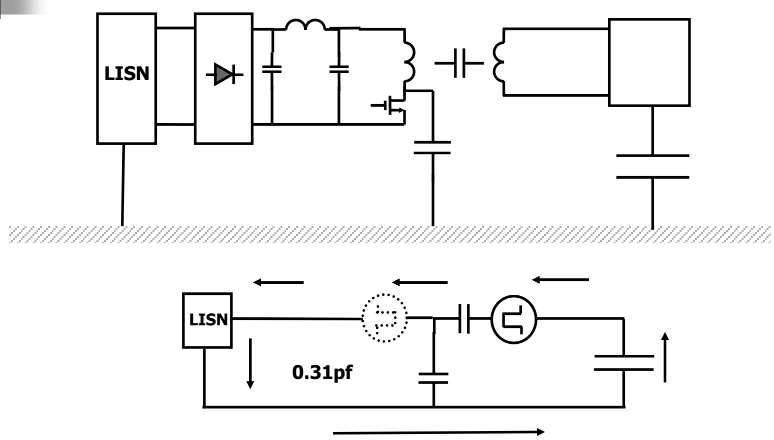
Sec. to earth capacitor – use both methods



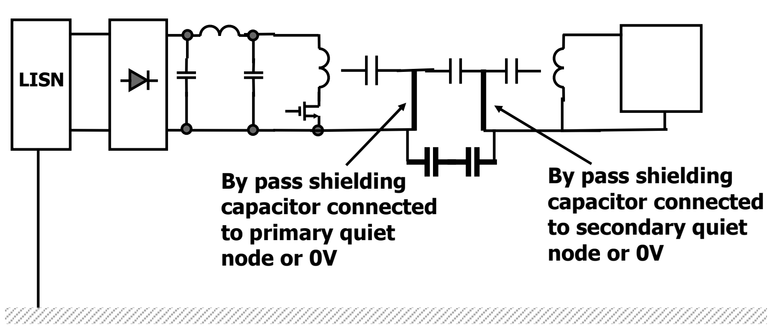
Sec. to earth capacitor – another noise source



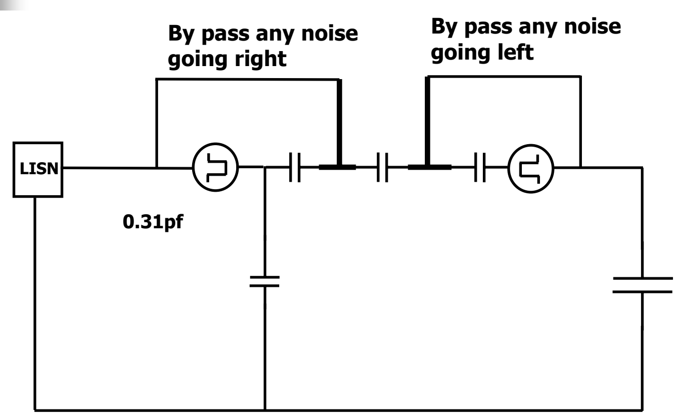
Sec. to earth capacitor – noise source on Sec. side



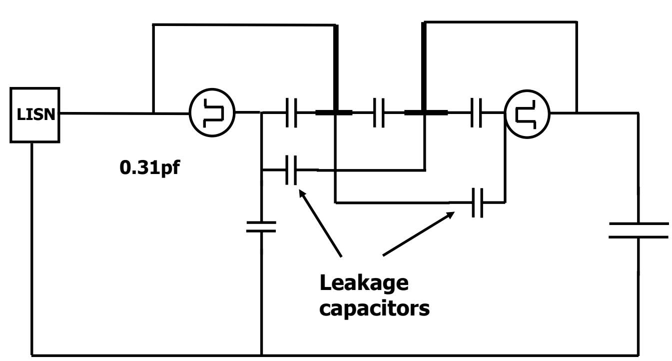
Sec. to earth capacitor – final solution



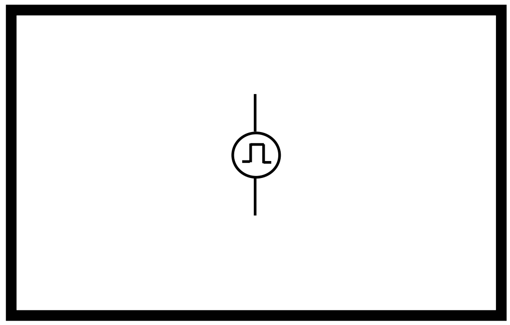
By pass or simply short circuit



Don't forget the leakage capacitors

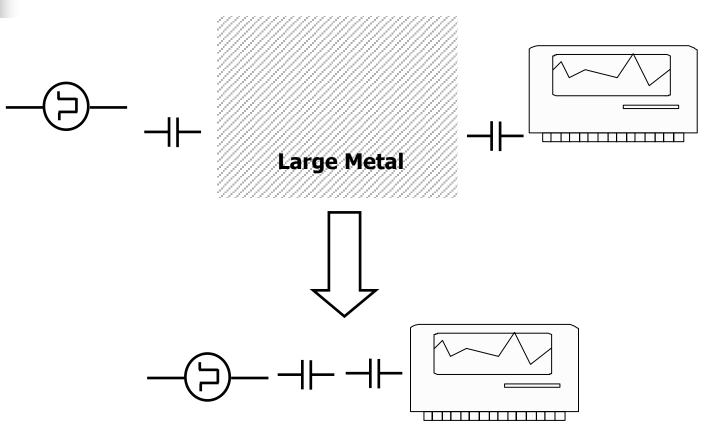


Shielding, by pass or short circuit ?

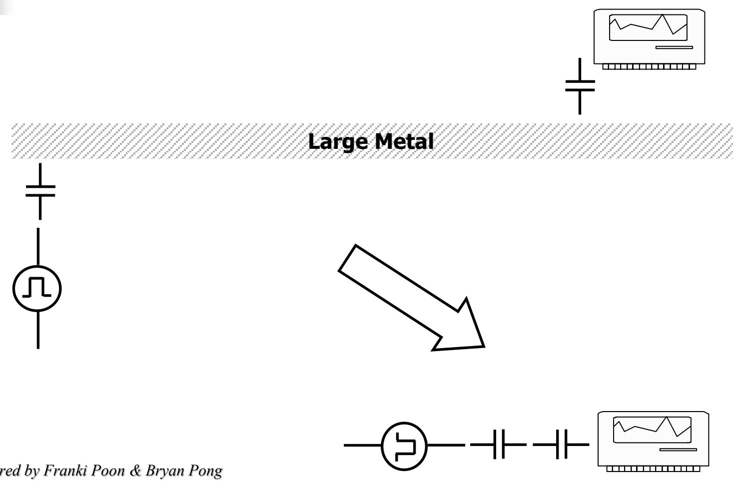


Does it "shield" all the noise going out ?

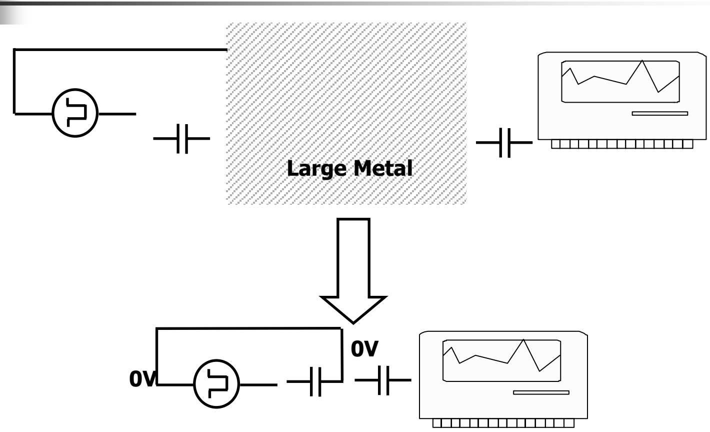
Revision again - 1



Revision again - 2

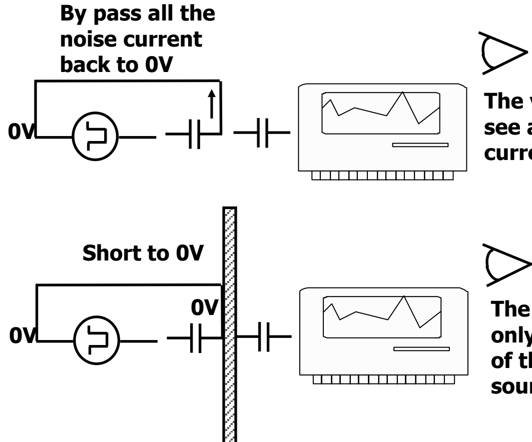


Don't float the metal plate



By pass and short circuit

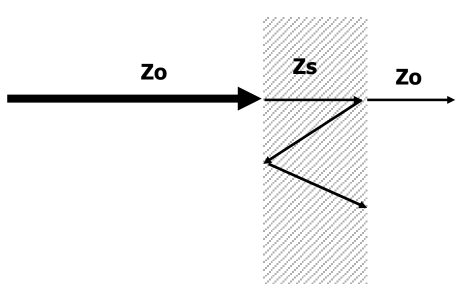
By pass all the noise current back to 0V



The victim would see any noise current flow in

The victim would only see the 0V of the noise source

Wait a minute



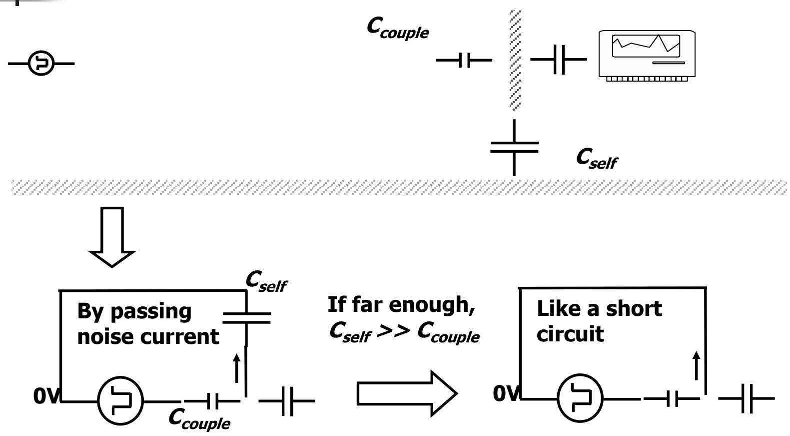
Shielding -

Usually come across characteristic impedance, attenuation, reflection losses

The Truth is -

Plane wave propagation, or noise source is located at a far distance from the shield.

Still use by pass and short circuit concept

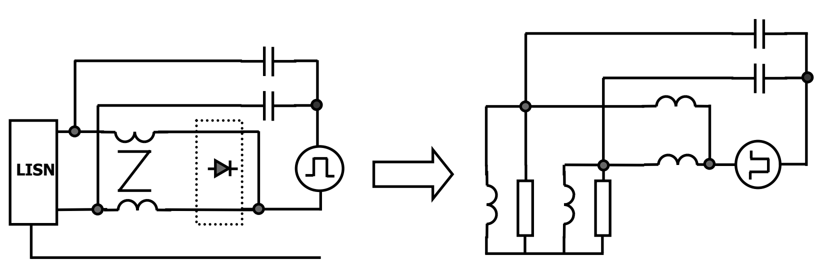


Short summary

- Lump element circuit is possible to simulate EMI behavior.
- Parasitic elements is not enough to explain all cases. (More concept will be introduced.)
- So call electric field shielding must be terminated one end to a quiet node or 0V of the noise source. NO FLOATING !
- So call electric field shielding is a kind of by pass, shunt or short circuit equivalent in a lump element model.

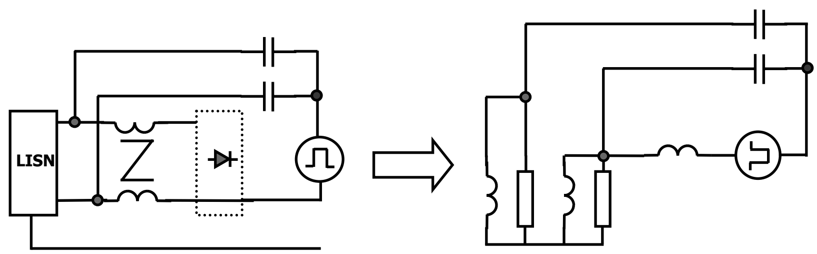
Any short question ?

Input terminal – conduction period



During bridge conduction period t = Tcon

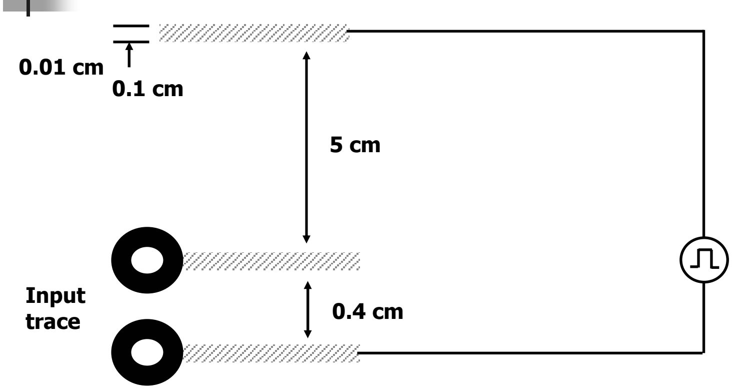
Input terminal – non-conduction period



During bridge non-conduction period t ≠ Tcon

Even worse

Input terminal – coupling capacitor



Input terminal – coupling capacitor value

$$C_{trace\_trace} = \frac{0.0885\pi(\varepsilon_r + 1)l^2}{2\ln(\frac{\pi S}{W + t})}10^{-14}$$

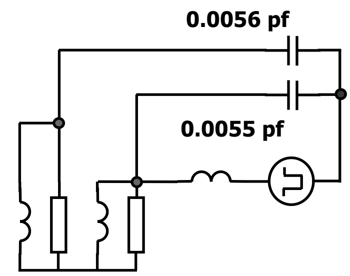
S1 = 5 cm

S2 = 5.4 cm

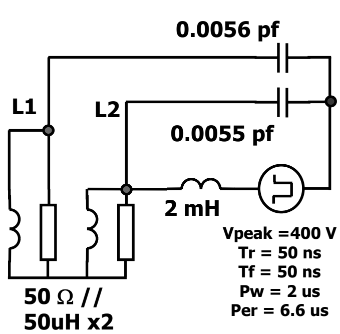
W = 0.1 cm

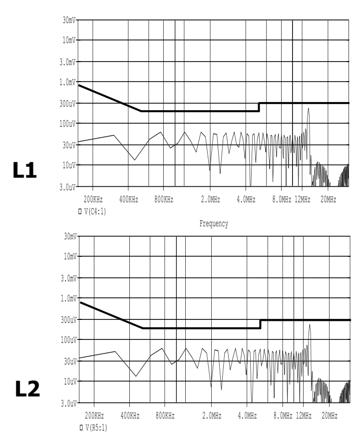
t = 0.01 cm

εr = 4

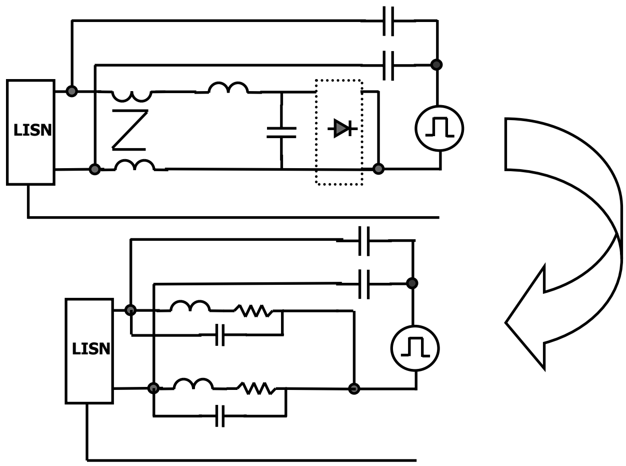


Input terminal – simulation

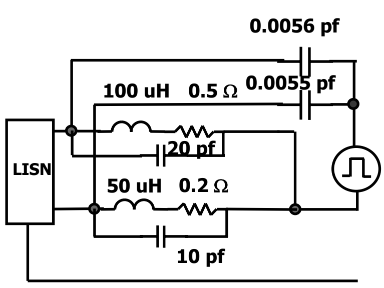




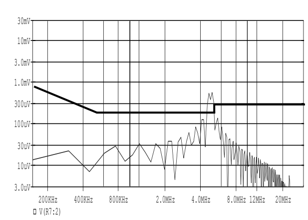
Input terminal – imbalance impedance



Input imbalance impedance – simulation

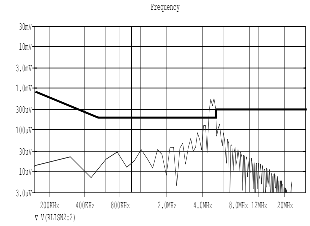


L1

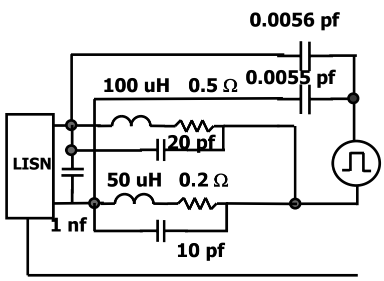


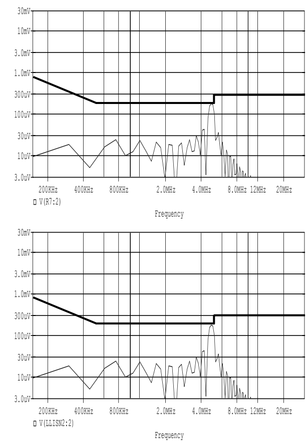
Limit Exceeded !!

L2



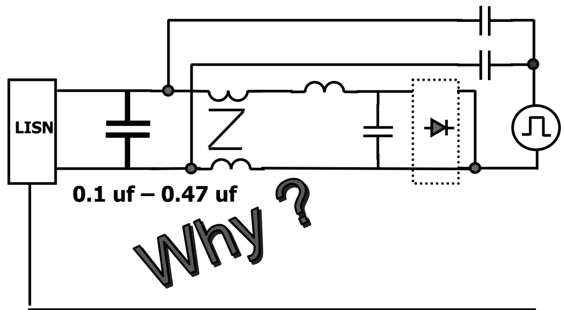
Input imbalance impedance – solution



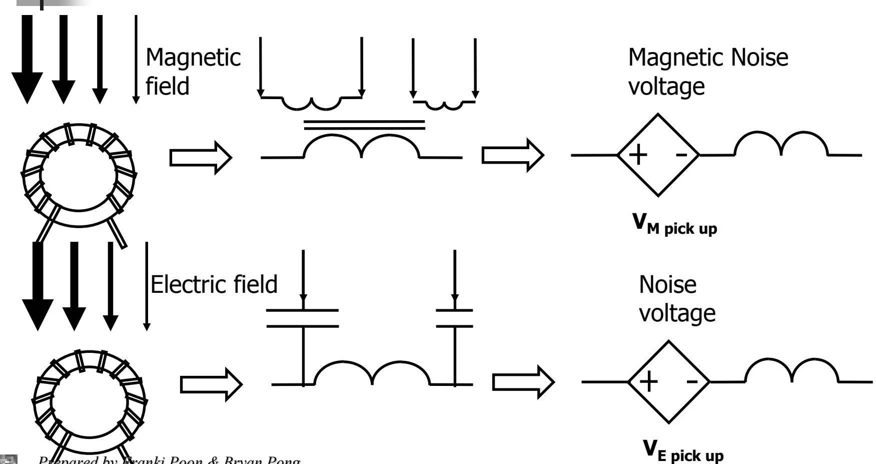


Pass in simulation ?

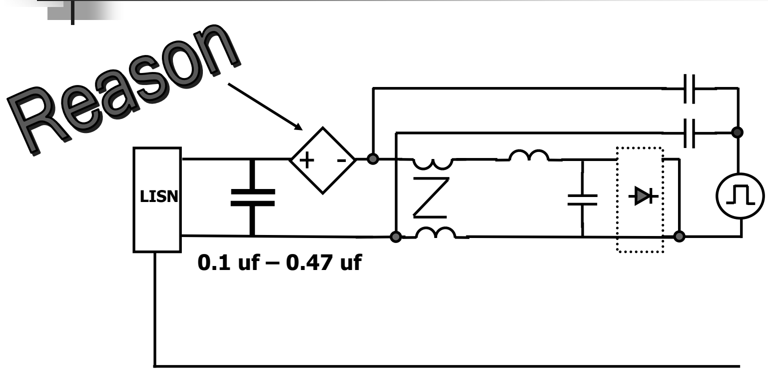
Input imbalance impedance solution – Real?



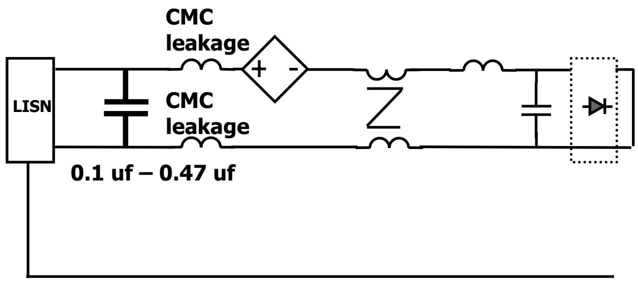
Don’t forget



Input imbalance impedance solution – hence

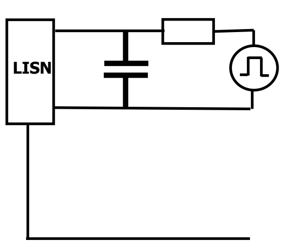


Input imbalance impedance – bad CMC

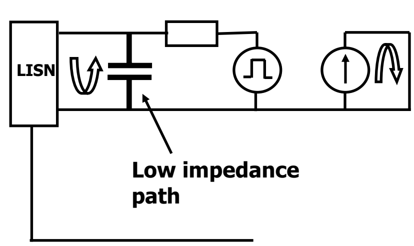


A filter is formed by the leakage inductance of the CMC to provide extra attenuation on the noise picked up by CMC

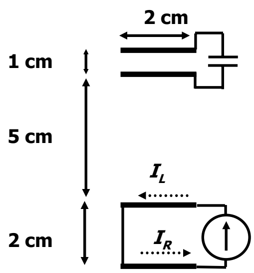
Input again – is everything fine?

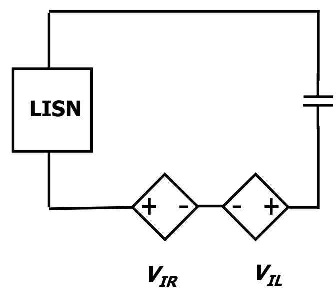


The large input X-capacitor provides a final low impedance loop with the LISN. Magnetic couple will contribute to noise pick up by the LISN

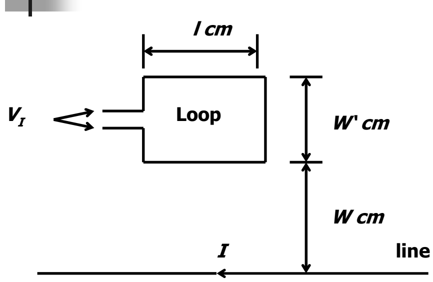


Input again – mutual inductance





Approximated line to loop mutual inductance



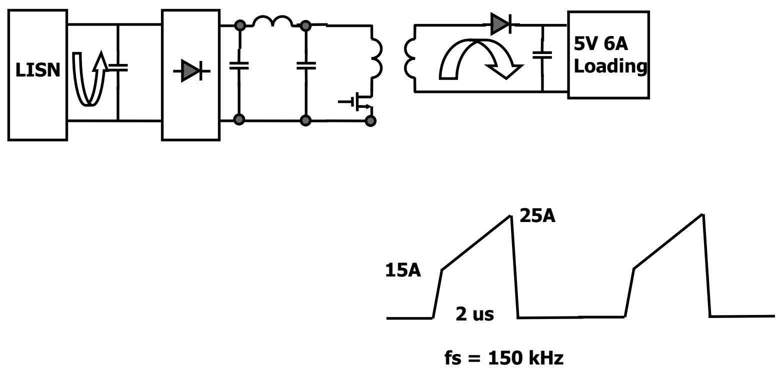
$$L_{line\_loop} = 0.002l(\ln(\frac{W+W'}{W})uH$$

W′ = 1 cm
W = 5 cm
L = 2 cm
L_{line_loop} = 0.73 nH

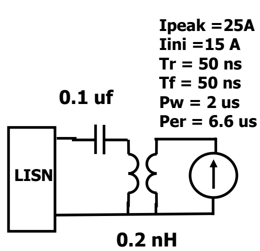
W′ = 1 cm
W = 7 cm
L = 2 cm
L_{line_loop} = 0.53 nH

$L_{line\_loop\_Eqv.}$ = 0.2 nH

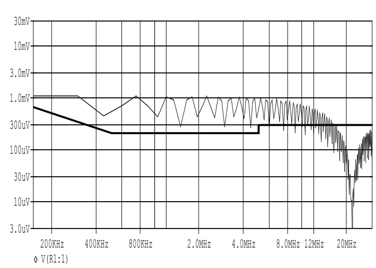
Input loop noise – example



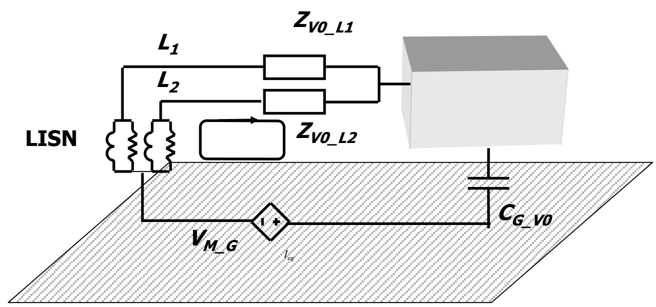
Input loop noise – magnetic induction



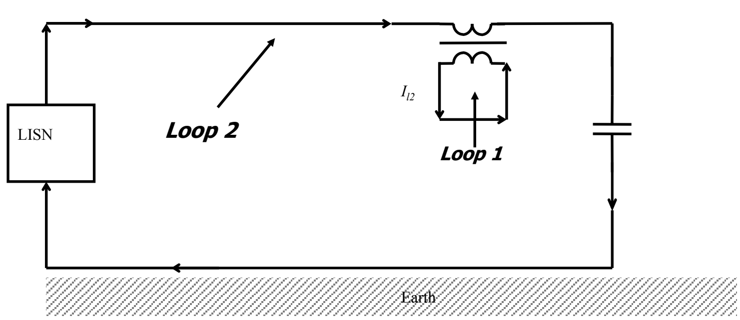
Exceed limit because of small input loop.



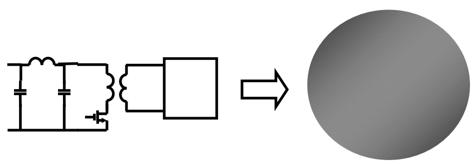
Other noise loop ?



Converter to earth Loop



Converter to earth Loop – capacitor



Let the total surface area of the whole converter is equal to a sphere with equivalent radius r

r = 5cm

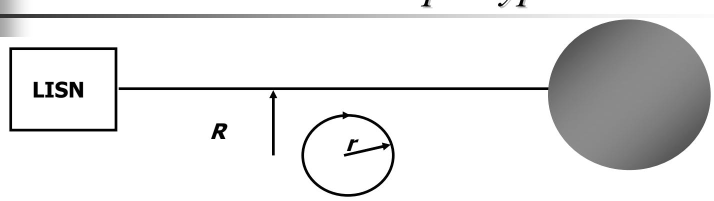
As the self capacitance of a sphere of *r cm*

$C_{sphere} = 4\pi 0.0885r$ *pf*

The equivalent drain self capacitance is

$C_{drain} = 5.5$ *pf*

Converter to earth Loop – typical value



r = 1 cm

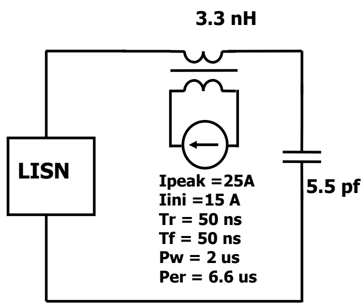
R = 2 cm

$$M_{line\_loop} = u_0\left[\frac{R}{100} - \sqrt{(\frac{R}{100})^2 - (\frac{r}{100})^2}\right]$$

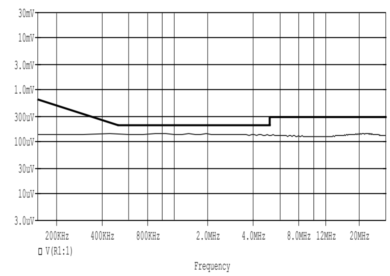
The mutual inductance is

$Z_{line\_circle} = 3.3$ *nH*

Converter to earth Loop – raw noise

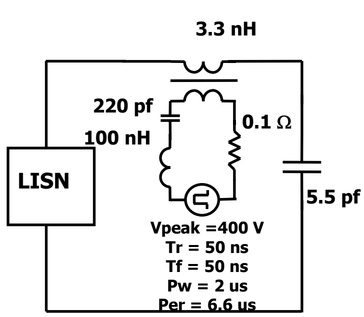


25A still can't fail it!

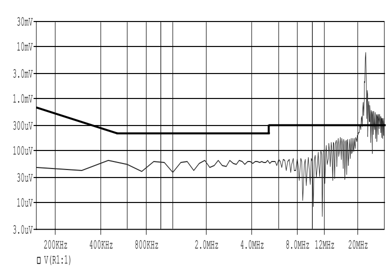


Be careful, really close !

Converter to earth Loop – resonate loop

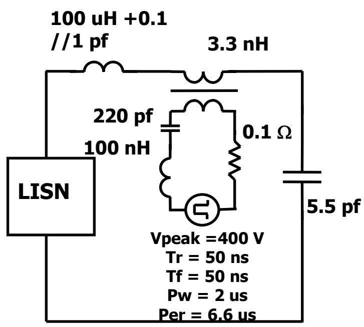


300 uA fail it by 30 dB !!



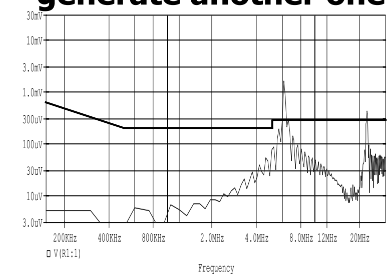
Fail, much worse than the 25A case !

Resonate loop – CMC choke



Inductor only drift the resonate point.

Kill the original resonant circuit but generate another one



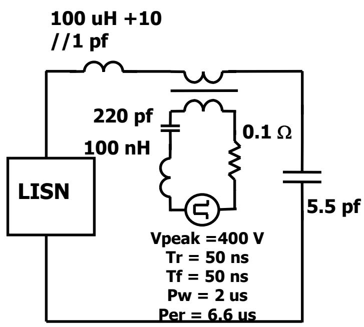
Resonate loop – RESISTOR

Inductance	Resistor reflecting core losses	Resistor reflecting skin / proximity losses	Resistor reflecting dc winding losses

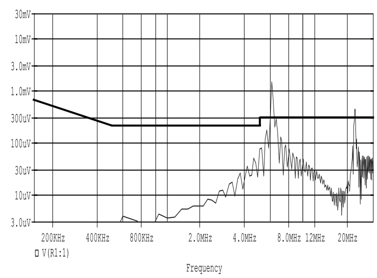
Frequency dependence	Frequency dependence	Frequency dependence & winding structure	Wire size dependence

Remember this ?

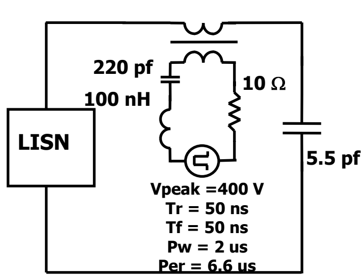
Resonate loop – increase resistance



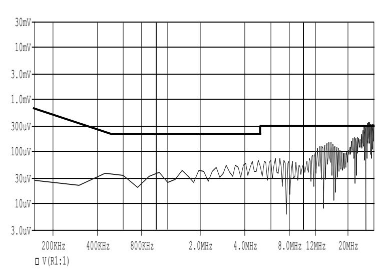
Unfortunately, not much better.



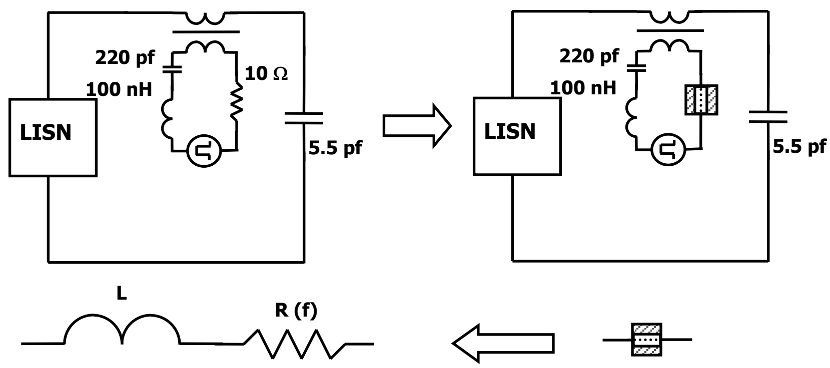
Increasing resistance – at the right place



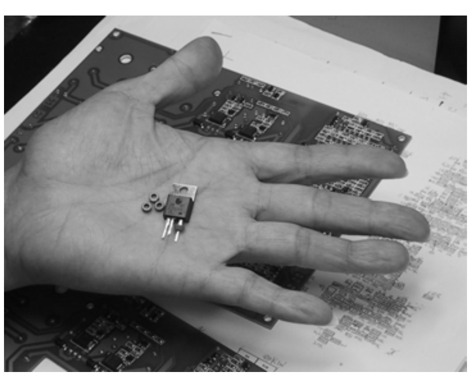
Much better, but how ?

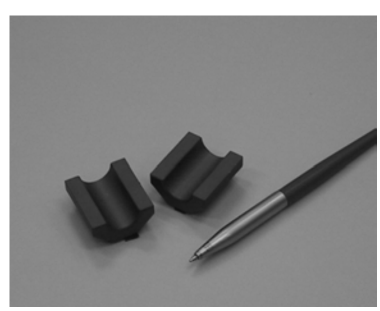


Increasing resistance – lossy ferrite

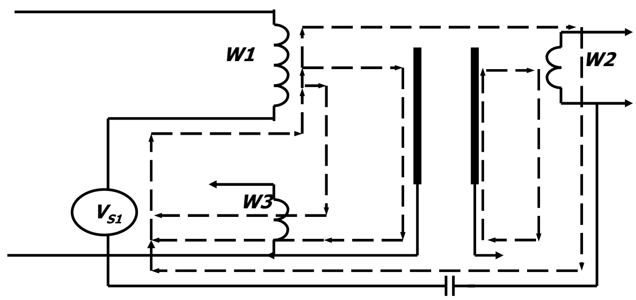


Ferrite beads





Invisible loop – inside xformer



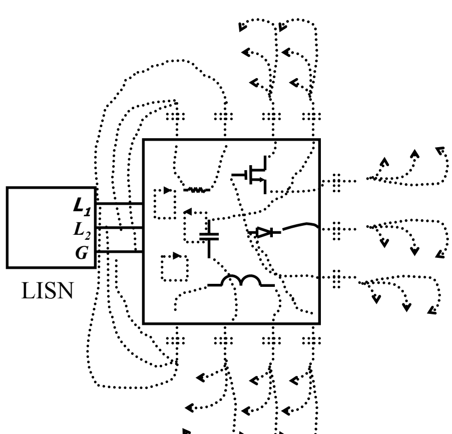
Xformer is tightly packed and has large stray capacitor to introduce many loops inside.

Short summary

- Capacitive coupling to input terminal causes EMI.
- Solutions for capacitive coupling lead to more magnetic coupling effect.
- The whole converter to earth has a large capacitor.
- Magnetic coupling causes EMI due to the loop form by the converter to earth capacitor.
- Resonance causes unexpected EMI level.
- Damping,not inductor, is the solution for resonance.

Any short question ?

How does EMI come out?



Contacted -

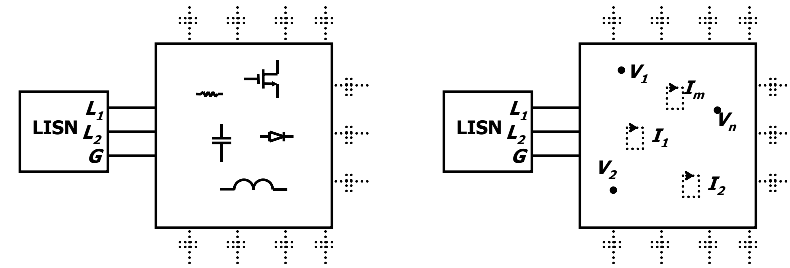
can be understood

through circuit diagram

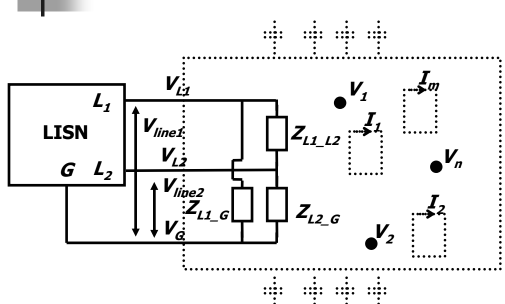
Non-Contacted -

Mutual invisible capacitor & Mutual invisible inductor

V & I Only



Only LISN terminals voltage are concerned

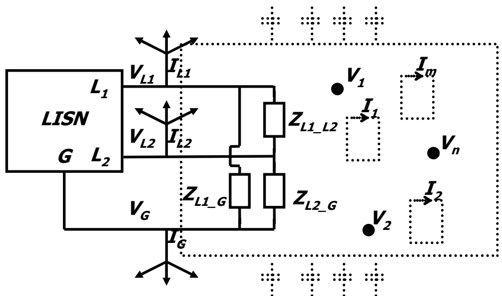


- No matter how complicated a circuit, EMI are voltage measurements, V_{Line1} and V_{Line2}, across LISN terminals.

- V_{line1} = VL1-VG
- V_{Line2} = VL2 – VG

- Is there a simple way to look at it?

Circuit theory – voltage node

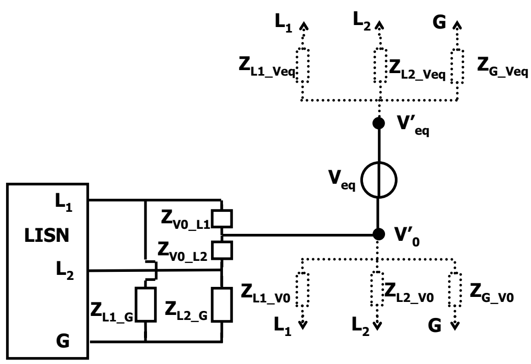


$$I_{L1} = \sum_{i=1}^{n} \frac{V_i - V_{L1}}{Z_{L1\_i}}$$

$$I_{L2} = \sum_{i=1}^{n} \frac{V_i - V_{L2}}{Z_{L2\_i}}$$

$$I_G = \sum_{i=1}^{n} \frac{V_i - V_G}{Z_{G\_i}}$$

Equivalent voltage source



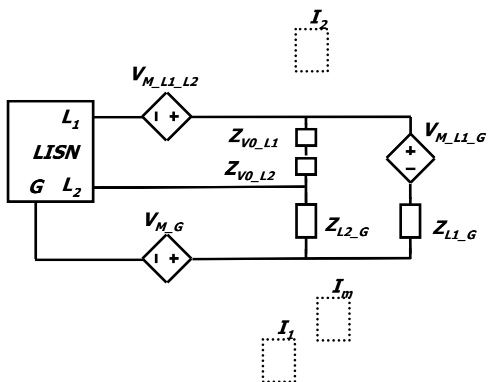
$$I_{L1} = \frac{V'_{eq} - V_{L1}}{Z_{L1\_Veq}} + \frac{V'_0 - V_{L1}}{Z_{L1\_V0}}$$

$$I_{L2} = \frac{V'_{eq} - V_{L2}}{Z_{L2\_Veq}} + \frac{V'_0 - V_{L2}}{Z_{L2\_V0}}$$

$$I_G = \frac{V'_{eq} - V_G}{Z_{G\_Veq}} + \frac{V'_0 - V_G}{Z_{G\_V0}}$$

One voltage source and six mutual impedances

Simple circuit theory – current node

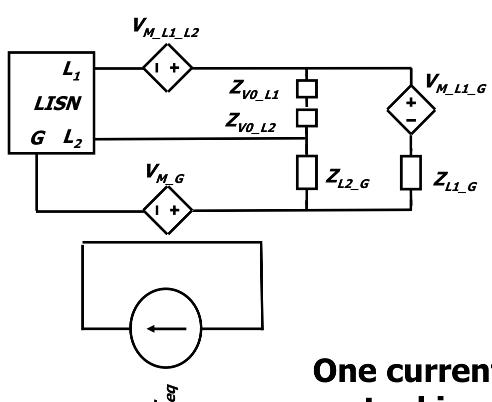


$$V_{M\_L1\_L2} = \sum_{i=1}^{m} I_i Z_{M\_L1\_L2\_i}$$

$$V_{M\_L1\_G} = \sum_{i=1}^{m} I_i Z_{M\_L1\_G\_i}$$

$$V_{M\_G} = \sum_{i=1}^{m} I_i Z_{M\_G\_i}$$

Equivalent current source



$$V_{M\_L1\_L2} = I_{eq} Z_{M\_L1\_L2\_Ieq}$$

$$V_{M\_G} = I_{eq} Z_{M\_G\_Ieq}$$

$$V_{M\_L1\_G} = I_{eq} Z_{M\_L1\_G\_Ieq}$$

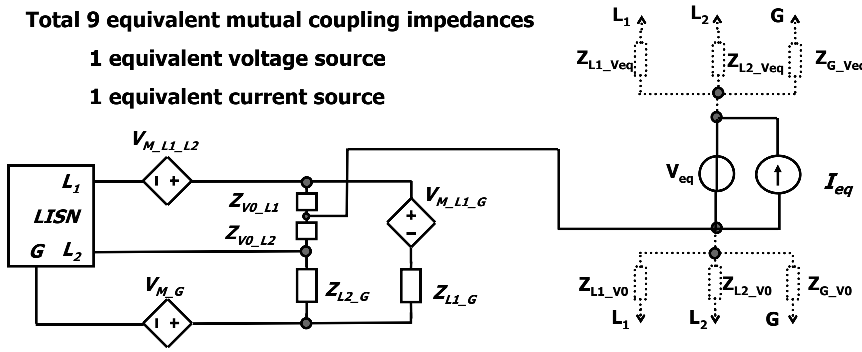
One current source and three mutual impedance

Minimum Coupling Model

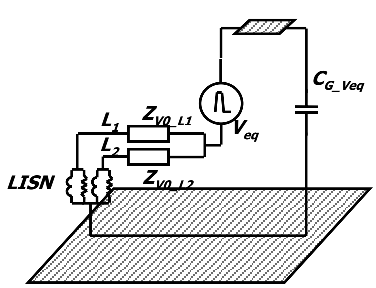
Total 9 equivalent mutual coupling impedances

1 equivalent voltage source

1 equivalent current source



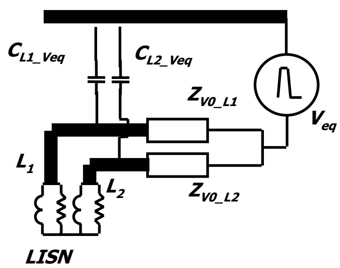
Physical meaning – C_{G_Veq}



C_{G_Veq} –

Hot switching node to earth equivalent capacitor

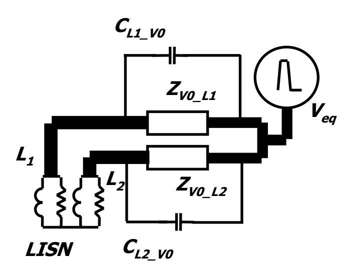
Physical meaning – C_{L1_Veq} & C_{L2_Veq}



C_{L1_Veq} & C_{L2_Veq} –

Hot switching node to input traces represented by equivalent capacitors

Physical meaning – C_{L1_V0} & C_{L2_V0}

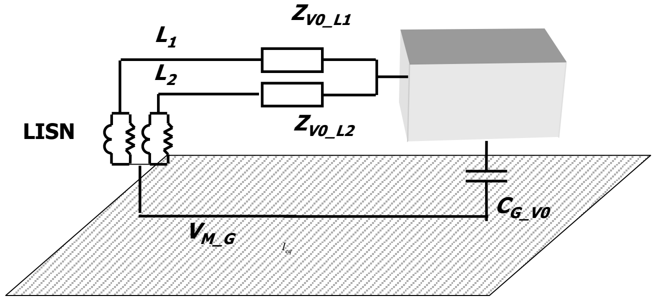


C_{L1_V0} & C_{L2_V0} –

0V node to input traces have equivalent capacitors

Absorbed in the input impedance.

Physical meaning – C_{G_V0}

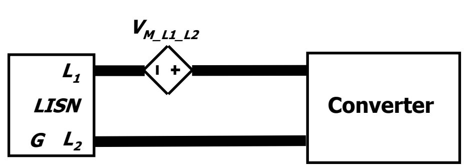


C_{G_V0} –

Converter to earth equivalent capacitor

Physical meaning – $Z_{M\_L1\_L2\_Ieq}$

$$V_{M\_L1\_L2} = I_{eq} Z_{L1\_L2\_Ieq}$$

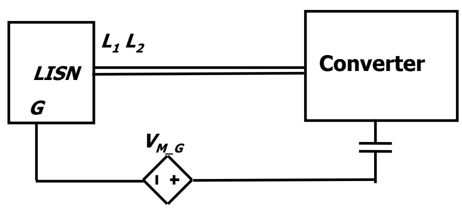


$Z_{M\_L1\_L2\_Ieq}$ –

Input lines loop mutual inductive impedance

Physical meaning – $Z_{M\_G\_Ieq}$

$$V_{M\_G} = \sum_{i=1}^{m} I_i Z_{M\_G\_i}$$

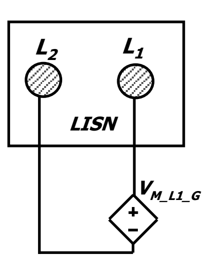


$Z_{M\_G\_Ieq}$ –

Earth to converter loop mutual inductive impedance

Physical meaning – $Z_{M\_L1\_G\_Ieq}$

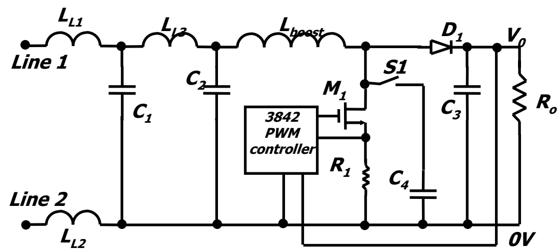
$$V_{M\_L1\_G} = I_{eq} Z_{M\_L1\_G\_Ieq}$$



$Z_{M\_L1\_G\_Ieq}$ –

Cross section of Line 1, line 2 and earth loop mutual inductive impedance

Overall simulation



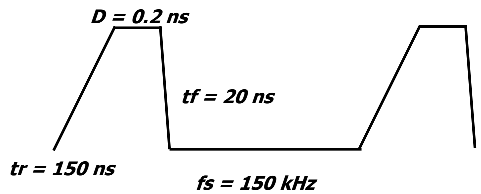
Vp = 400V

tr = 150 ns

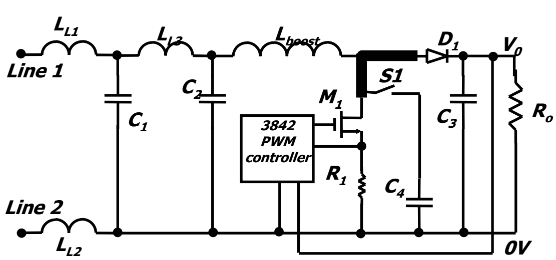
tf = 20 ns

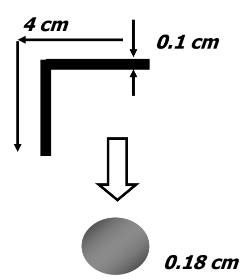
D = 0.2

Fs = 150 kHz



Realistic parameter - C_{G_Veq}

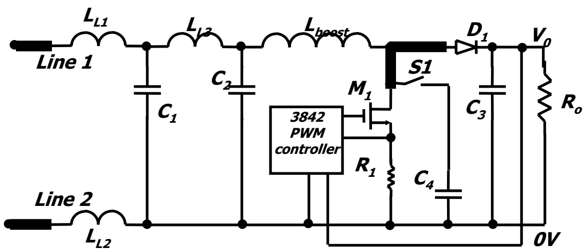


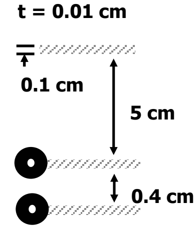


$$C_{sphere} = \frac{4\pi 0.085}{\frac{1}{r}} pf$$

C_{G_Veq} = 0.2 pf

Realistic parameter - C_{L1_Veq} & C_{L2_Veq}





$$C_{trace\_trace} = \frac{0.0885\pi(\varepsilon_r + 1)l^2}{2\ln(\frac{\pi S}{W+t})}10^{-14}$$

S1 = 5 cm

S2 = 5.4 cm

W = 0.1 cm

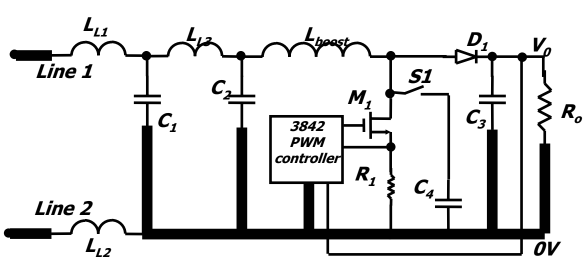
t = 0.01 cm

$\varepsilon r = 4$

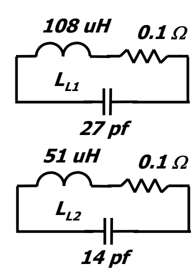
$C_{L1\_Veq} = 0.0056$ pf

$C_{L2\_Veq} = 0.0055$ pf

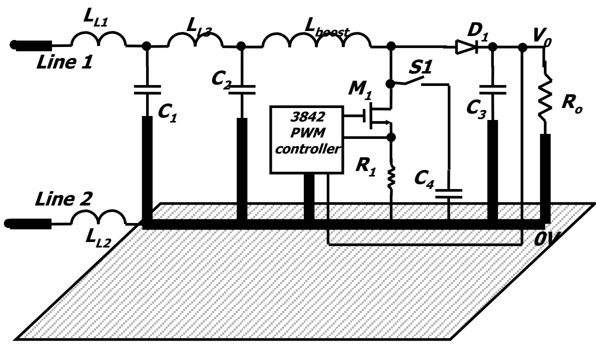
Realistic parameter - C_{L1_V0} & C_{L2_V0}



Absorbed in input impedance.



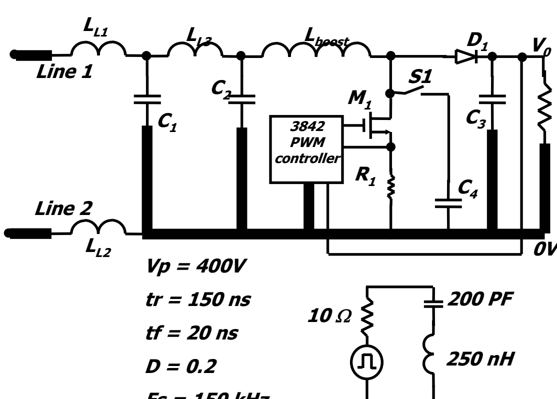
Realistic parameter - C_{G_V0}

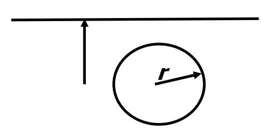


Measured as

C_{G_V0} = 6 pf

Realistic parameter - $Z_{M\_G\_Ieq}$





$$M_{line\_loop} = u_0\left[\frac{R}{100} - \sqrt{(\frac{R}{100})^2 - (\frac{r}{100})^2}\right]$$

r = 2 cm

R = 1.9 cm

The mutual inductance is

$Z_{M\_G\_Ieq}$ =17 nH

Realistic parameter - $Z_{M\_L1\_G\_Ieq}$, $Z_{M\_L2\_G\_Ieq}$

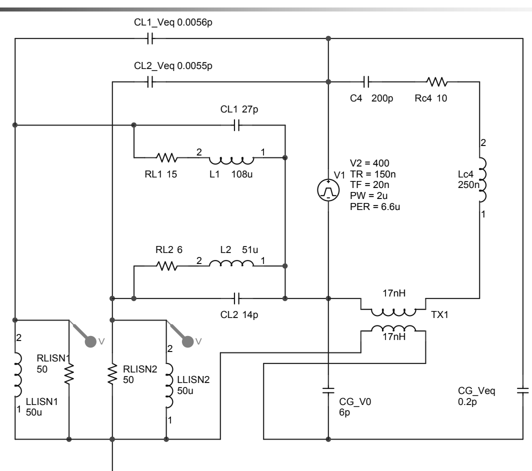
As the input loops are small and having quite a high input impedance, hence for simplicity,

Just set

$Z_{M\_L1\_G\_Ieq} = 0$

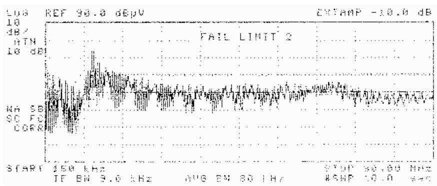
$Z_{M\_L2\_G\_Ieq} = 0$

PSPICE Simulation

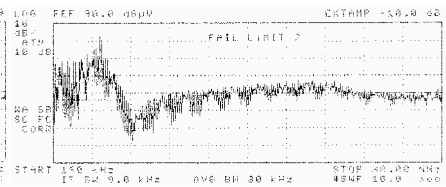


(b)

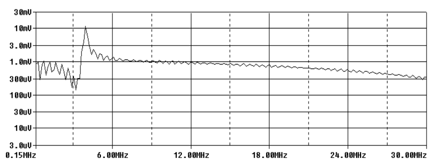
Simulation & Measured Results – S1 open



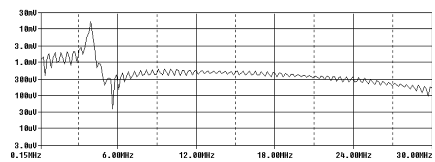
Line 1 measured result S1 open



Line 2 measured result S1 open

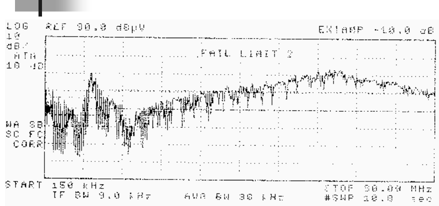


Line 1 simulated result S1 open

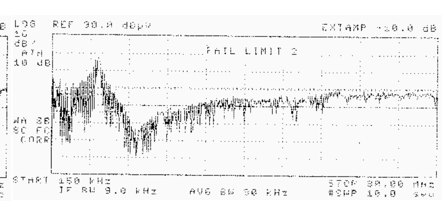


Line 2 simulated result S1 open

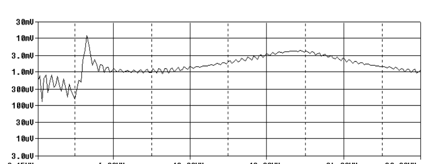
Simulation & Measured Results – S1 closed



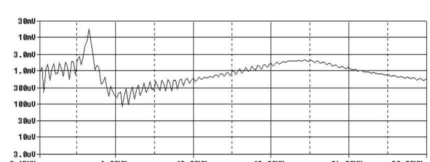
Line 1 measured result S1 close



Line 2 measured result S1 close



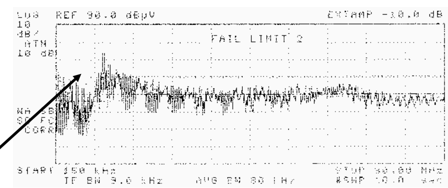
Line 1 simulated result S1 close



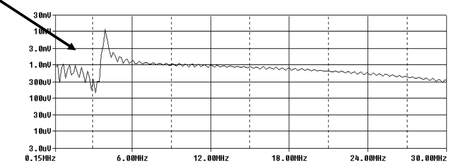
Line 2 simulated result S1 close

S1 open – Capacitive coupling only

Resonate behavior between the input equivalent impedances



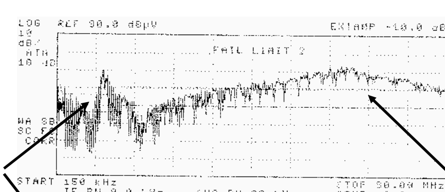
Line 1 measured result S1 open



Line 1 measured result S1 open

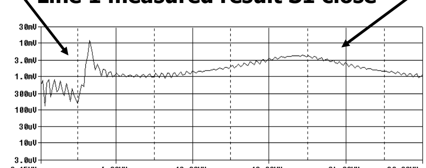
S1 close – Capacitive & inductive coupling

Resonate behaviors between the input equivalent impedance



Line 1 measured result S1 close

Resonate behaviors of the source loop and mutual inductive coupling



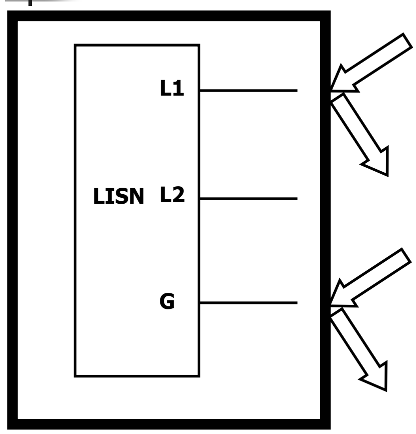
Line 1 measured result S1 close

Minimum Coupling Model

- A minimum of *six* capacitive mutual coupling impedance is concluded.
- A minimum of *three* inductive mutual coupling impedance is concluded.
- Complicated EMI waveform can be simulated by simple lump element circuit.
- It is a minimum model, not maximum !
- Good for diagnosis purpose.

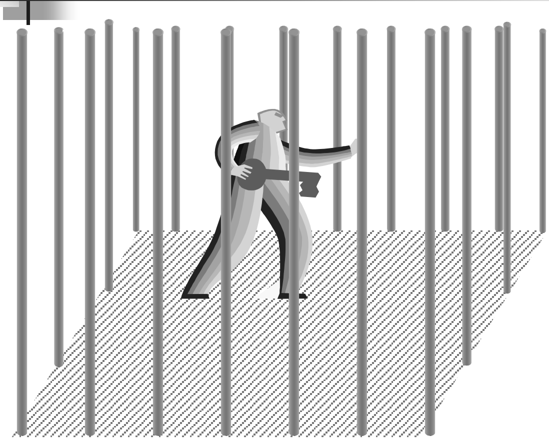
Any short question ?

Shielding – Purpose



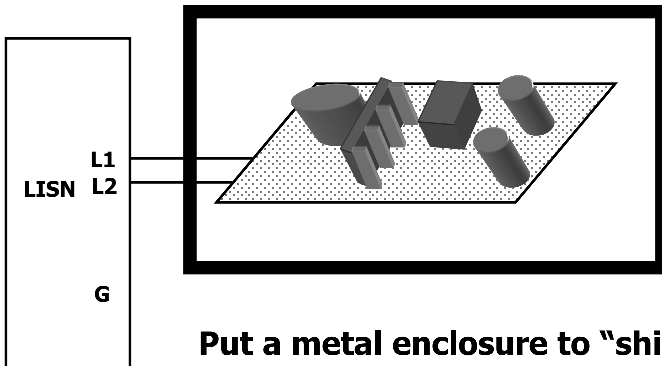
Don't let any current flow into the LISN

Shield or being shielded



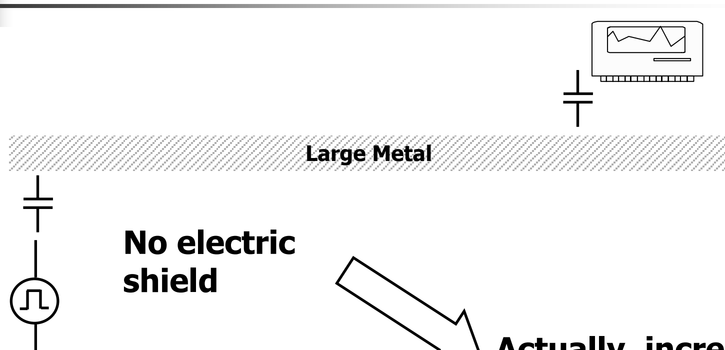
I lock up the whole world. Ha, ha . . .

Shielding – wrong idea 1



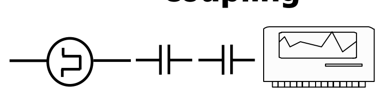
Put a metal enclosure to "shield" noise from going out - Wrong

Shielding – total recall 1

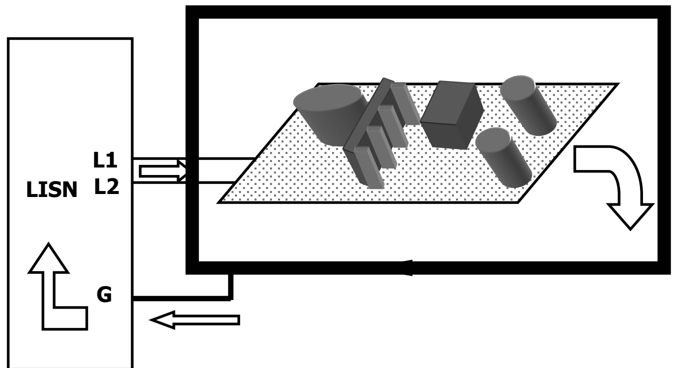


No electric shield

Actually, increase coupling

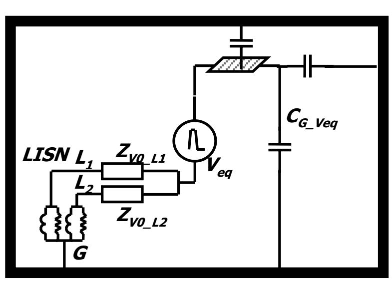


Shielding – wrong idea 1



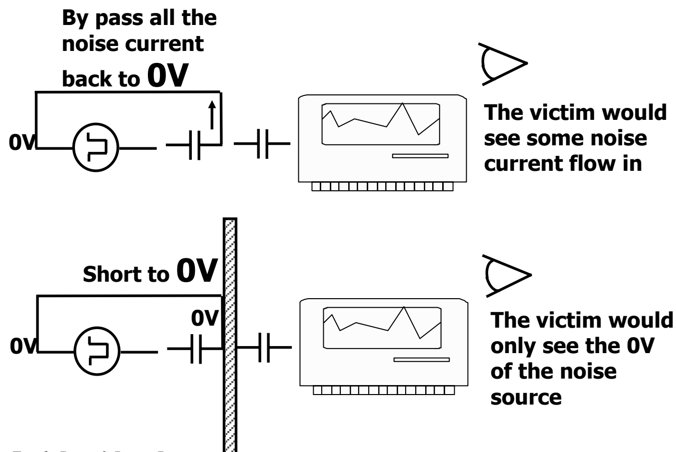
Put a earthed enclosure to "shield" noise from going out - Wrong

Shielding – total recall 2

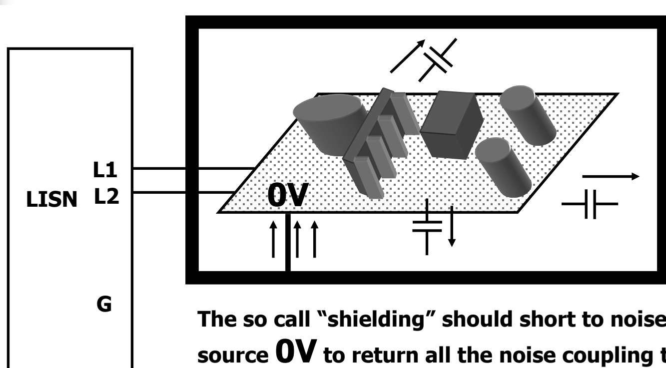


An earthed enclosure actually increases the equivalent hot node to earth capacitance C_{G_Veq} and increases noise.

Shielding is all about by passing or short circuit

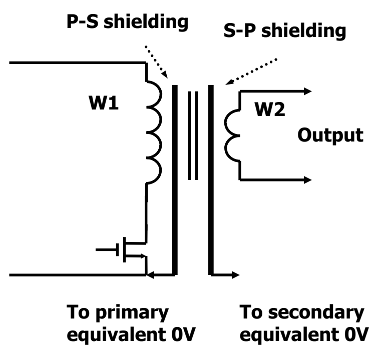


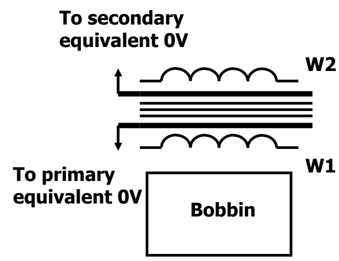
0V is the point



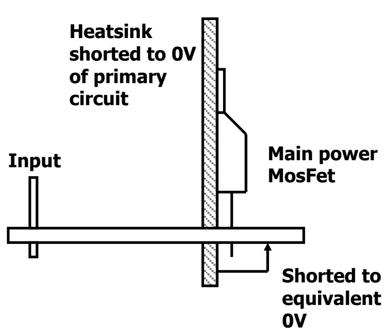
The so call "shielding" should short to noise source **0V** to return all the noise coupling to outside.

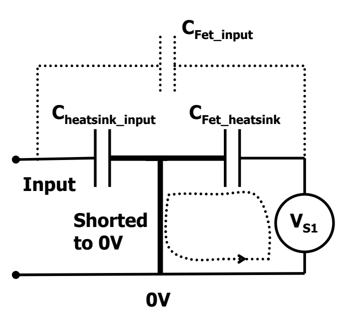
0V is the point - Xformer



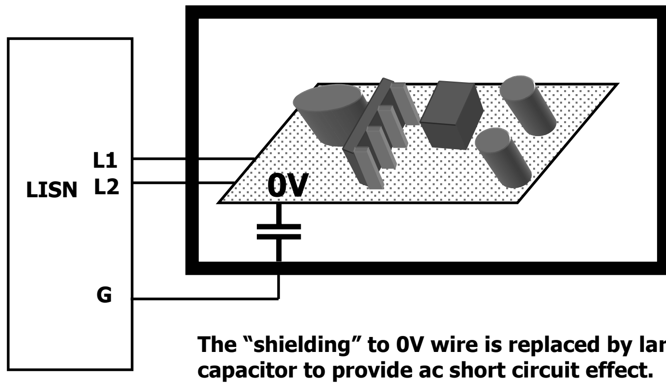


0V is the point - MOSFET



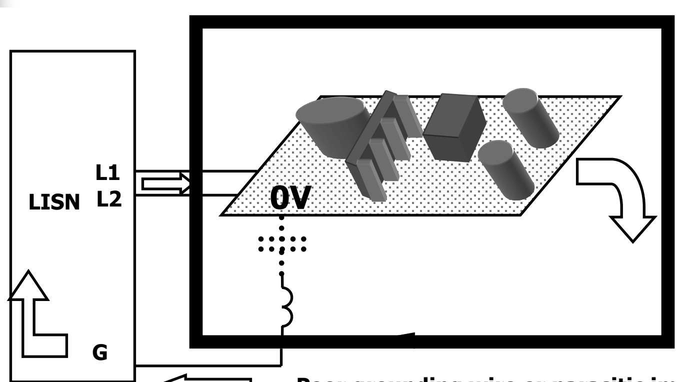


Grounded Case ?



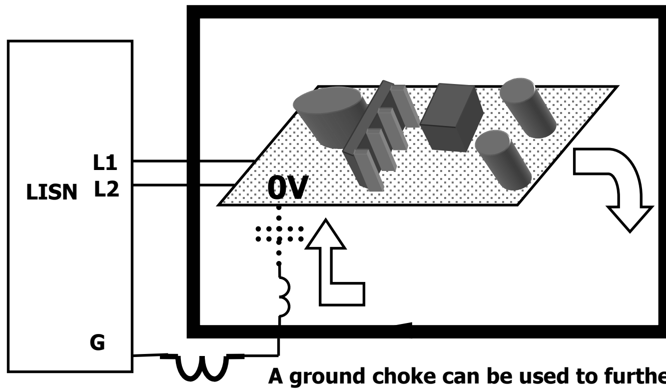
The "shielding" to 0V wire is replaced by large capacitor to provide ac short circuit effect. Then the case can be shorted to earth for safety purpose.

Grounding wire



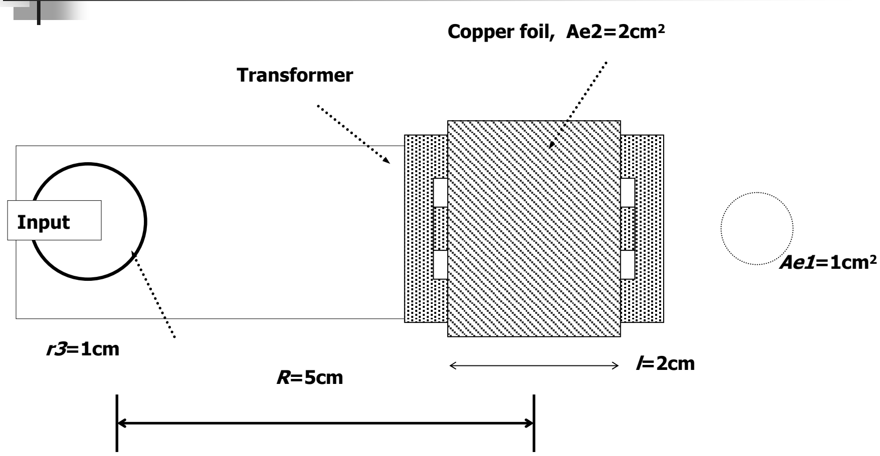
Poor grounding wire or parasitic impedance of the grounding capacitor force the coupling current flow back to G terminal of LISN.

Grounding choke

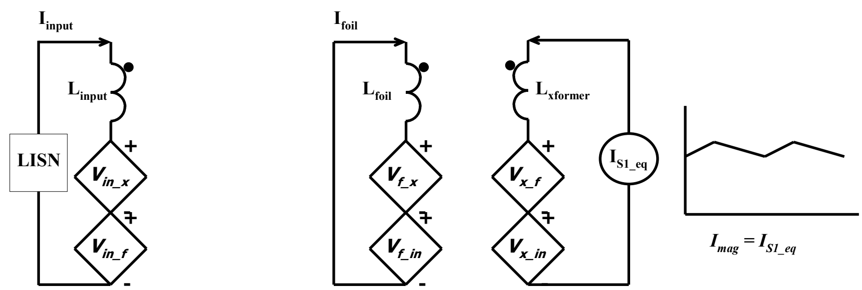


A ground choke can be used to further increase the impedance of the ground path to avoid noise current flowing in.

Magnetic shielding ?

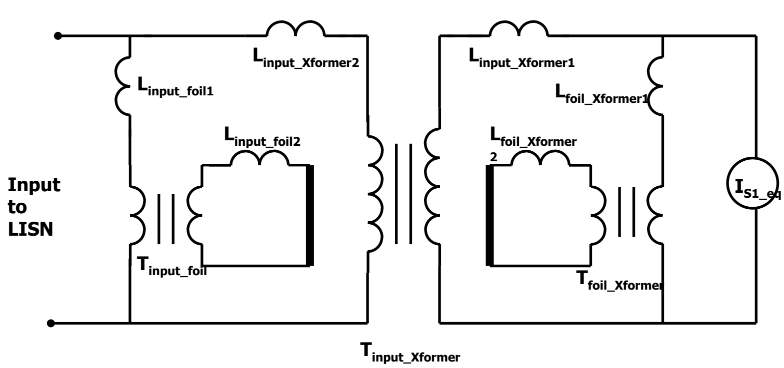


Flux band - modeling



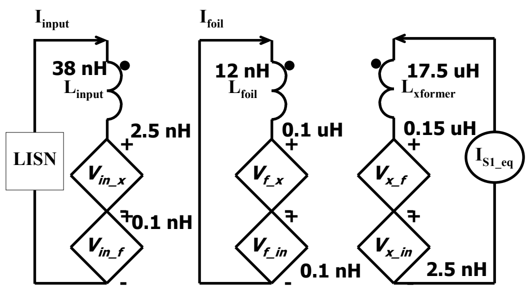
$I_{mag} = I_{S1\_eq}$

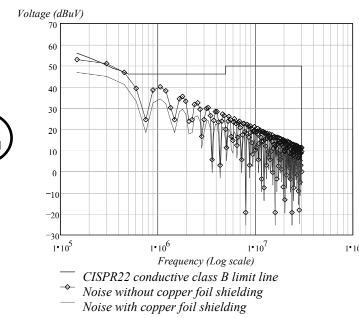
3 Xformers



Simulation

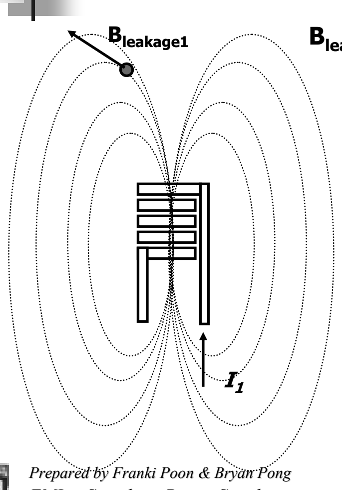
Only 6 dB reduction !



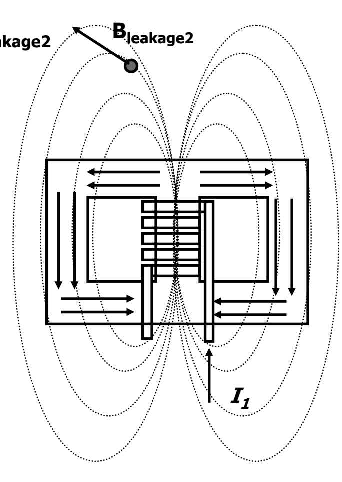


Inductive couple noise coupled from main tranformer

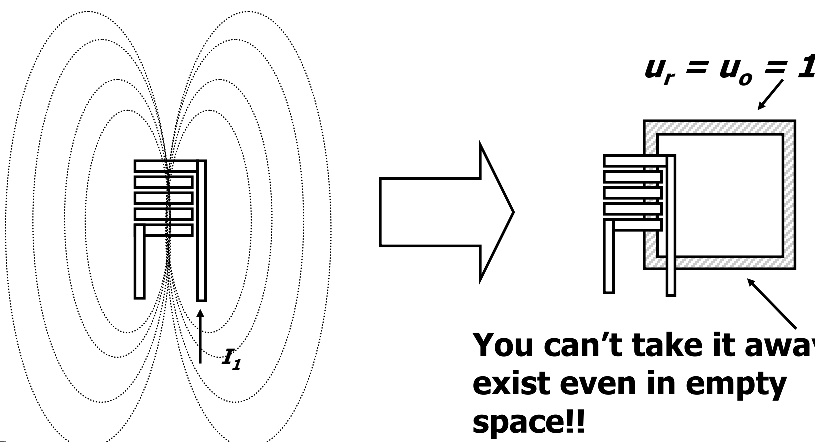
Flux concept – Believe it or Not?



$B_{leakage1} \cong B_{leakage2}$

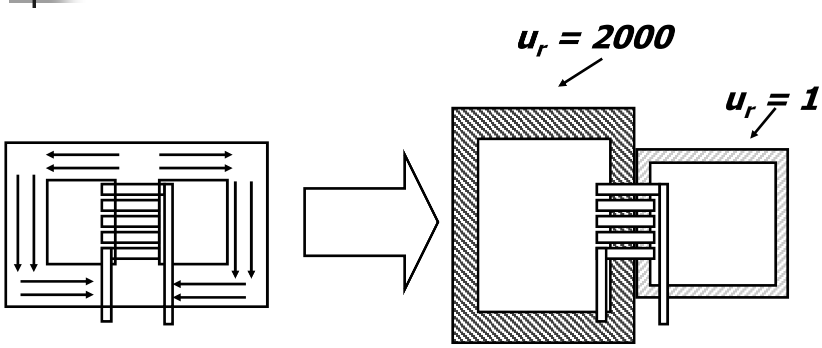


Flux concept – air core is core

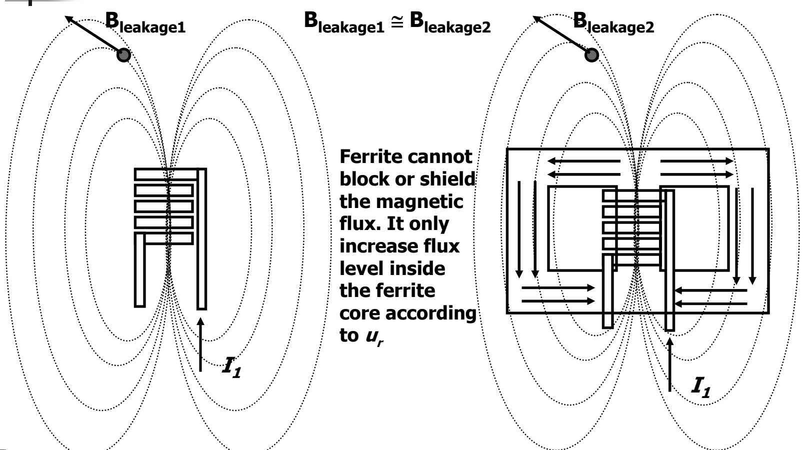


You can't take it away ! It exist even in empty space!!

Flux concept – air core and ferrite core

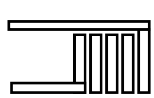


Flux concept – as a result



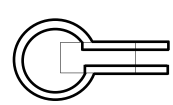
Ferrite cannot block or shield the magnetic flux. It only increase flux level inside the ferrite core according to u_r

Flux concept – general coupling



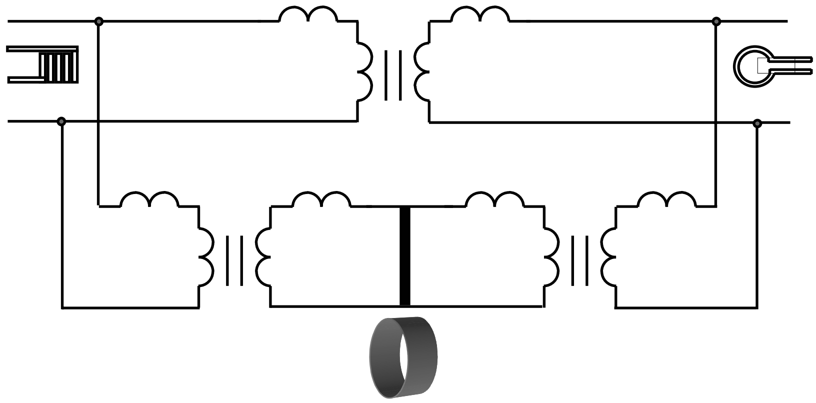
Noise Source

Short Ring

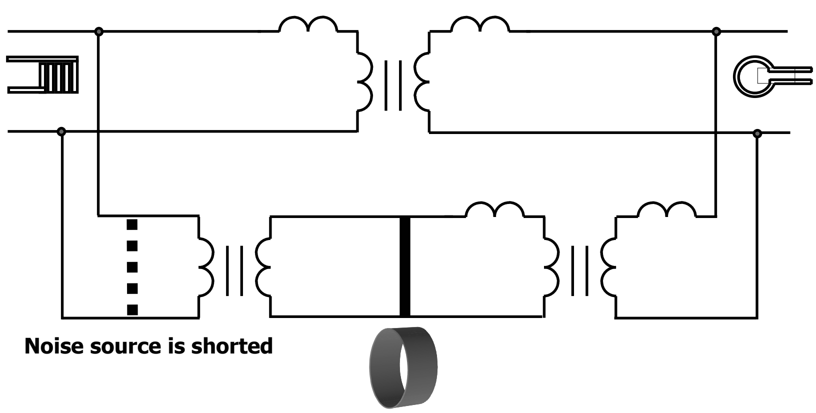


Pick up

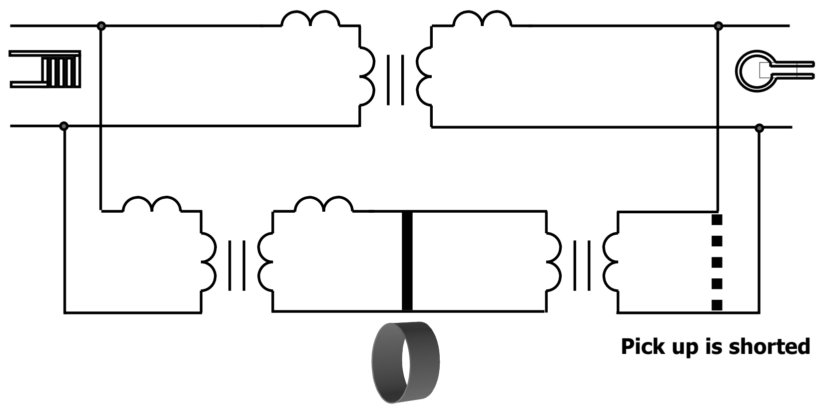
General coupling - Xformer model



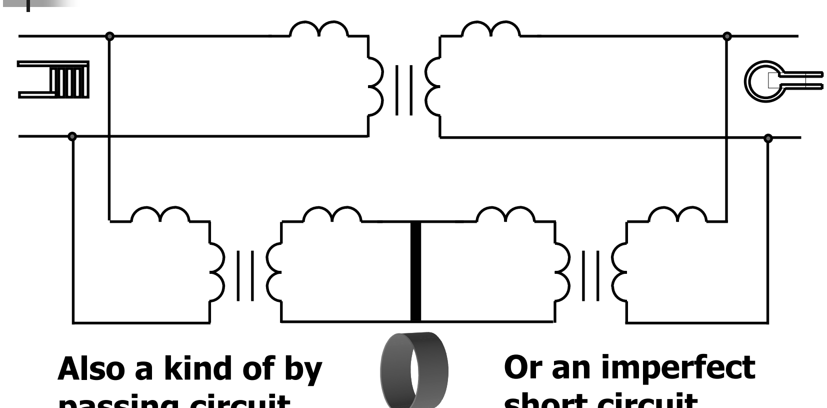
General coupling - close to noise source



General coupling - close to pick up



General coupling - somewhere in between



Also a kind of by passing circuit

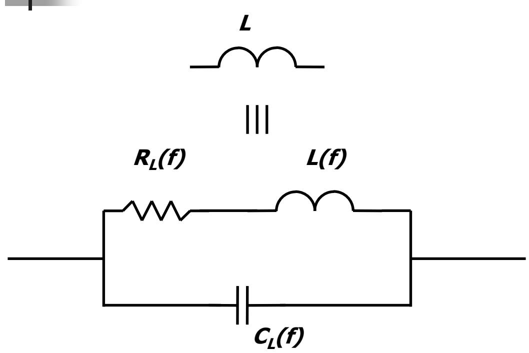
Or an imperfect short circuit

Short Summary

- By pass or short circuit is a basic concept for electric or magnetic "shielding".
- Easier to by pass capacitive coupling effect.
- Surrounding the noise source with ground or earth is **not** a general "shielding" concept.

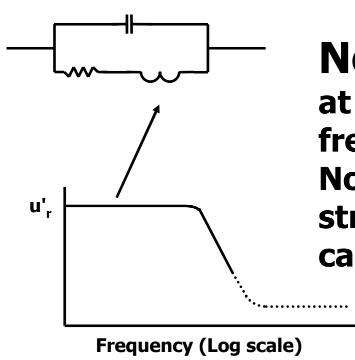
Any short question ?

Inductor Model – not only parasitics

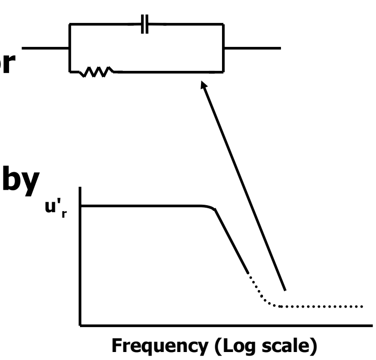


Things change with operating frequency

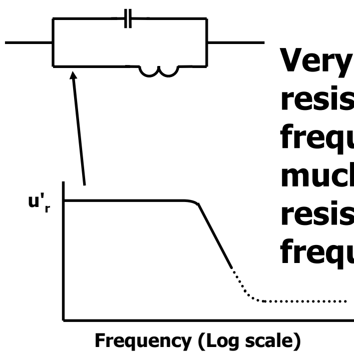
Inductor Model – permeability $u_r(f)$



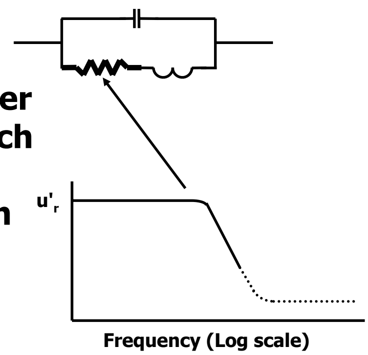
No inductor at higher frequency. Not caused by stray capacitor



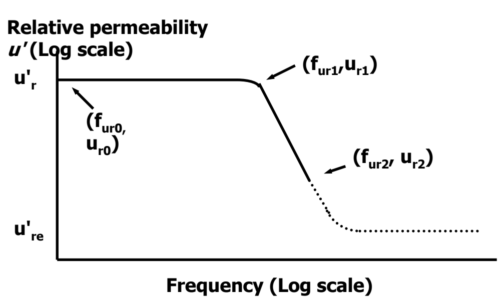
Inductor Model – losses



Very small resistor at lower frequency. Much much bigger resistor at high frequency.



Permeability – interpolation



From data sheet

Interpolate the permeability against frequency with the following relation

$$u_i(f) = \left| \frac{u_{re}\left(jf^{m} - f_{ur1}{}^{m} \frac{u_{r0}}{u_{re}}\right)}{jf^{m} - f_{ur1}{}^{m}} \right|$$

Where m should satisfy the following relation

$$u_{r2} - \left| \frac{u_{re}\left(jf_{ur2}{}^{m} - f_{ur1}{}^{m} \frac{u_{r0}}{u_{re}}\right)}{jf_{ur2}{}^{m} - f_{ur1}{}^{m}} \right| = 0$$

Permeability interpolation – an example

H5C2 TDK data is sampled from data sheet as

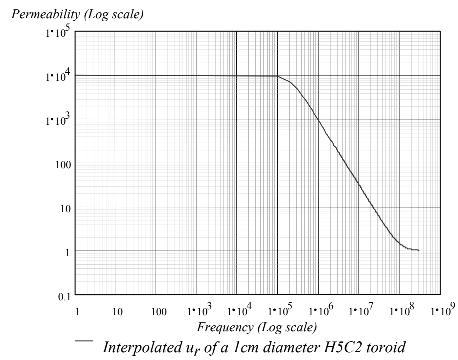
u_{r0} = 10^4,

u_{r1} = 0.7x10^4, ***f_{ur1} = 0.2x10^6,***

u_{r2} = 2200, ***f_{ur2} = 0.55x10^6***

Hence m can be calculated as

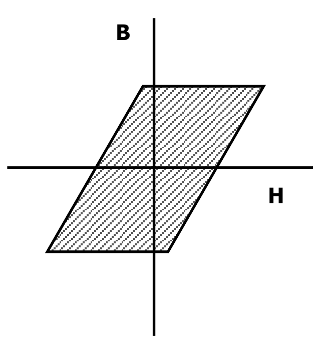
m = 1.47



Interpolated permeability

Power^e^Lab HKU

We start with losses



Hysteresis losses -

Losses ∝Area of B/H loop

Losses ∝B^2

Or

$$W_h = k_h V_{vol} B^2 f_s$$

Hysteresis losses series resistor

As

$$W_h = k_h Vol_s B_{rms}^{\ 2} f$$

Approximate flux level is dominated by injecting current, or

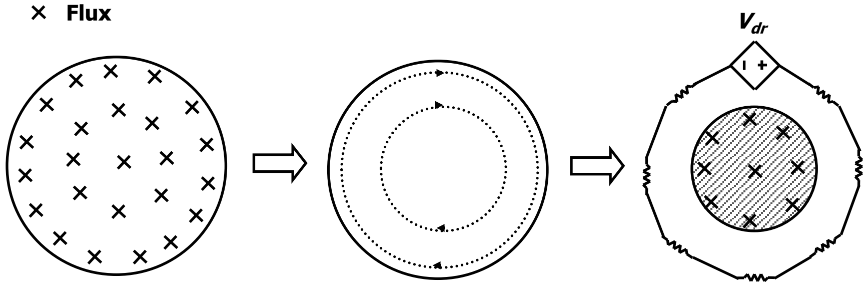
$$B = u_o u_r \frac{N}{l_{eq}} I$$

Hence

$$W_h = k_h \frac{u_o u_r N^2 Vol_s}{l_{eq\_s}^{\ 2}} f I_{rms}^{\ 2} \qquad W_h = R_h I_{rms}^{\ 2}$$

Eddy current losses

× **Flux**

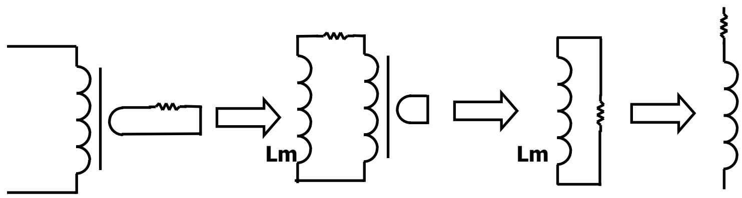


Flux penetrate the ferrite core

Induced current flowing round the core

Equivalent voltage source and distributed resistor

Eddy current losses – physical meaning



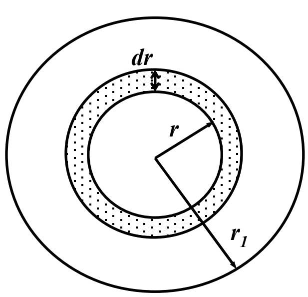
Equivalent Xformer model

Transfer resistor to primary side

Simplified version

From parallel to series configuration

Eddy current series resistor



Cross section of a toroid

The equivalent voltage generated at the ferrite ring *dr*

$$V_{dr} = \frac{d\phi_{Ae}}{dt}\frac{r^2}{r_1^2}$$

Or

$$V_{dr} = Ae_s \frac{dB}{dt}\frac{r^2}{r_1^2}$$

For sine wave excitation, the rms equivalent voltage is

$$V_{dr\_rms} = Ae_s \omega B_{rms} \frac{r^2}{r_1^2}$$

Finding eddy current series resistor

The equivalent resistance of the ring can be described as

$$R_{dr} = \frac{2\pi r}{k_R l_{es} \times dr}$$

l_{es} = effective length of the magnetic circuit

The overall losses is the summation of each ring, hence

$$W_e = \int_0^{r1} \frac{k_R \left(Ae_s \omega B_{rms} \frac{r^2}{r_1^2} \right)^2 l_{es}}{2\pi r} dr$$

Eddy current series resistor is

Overall eddy current losses becomes

$$W_e = k_e Vol_s Ae_s B_{rms}^{\ 2} f^2$$

Approximate flux level is dominated by injecting current, or

$$B = u_o u_r \frac{N}{l_{eq}} I$$

hence

$$W_e = k_e \frac{u_o u_r N^2 Vol_s Ae_s}{l_{eq\_s}^{\ 2}} f^2 I_{rms}^{\ 2} \qquad W_e = R_e I_{rms}^{\ 2}$$

Ferrite losses – explained as resistor

Total losses becomes

$$W_t = (R_h + R_e) I_{rms}{}^2$$

and

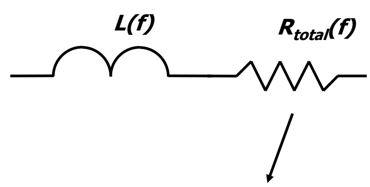
$$R_h(f) = k_h \frac{u_o u_r N^2 Vol_s}{l_{eq\_s}{}^2} f \qquad R_e(f) = k_e \frac{u_o u_r N^2 Vol_s Ae_s}{l_{eq\_s}{}^2} f^2$$

Ferrite losses provide the coefficients

$$k_e = \frac{W_{core2} f_1 B_{p1}{}^2 - W_{core1} f_2 B_2{}^2}{f_1 f_2{}^2 B_{p1}{}^2 B_{p2}{}^2 Ae_s Vol_s - f_1{}^2 f_2 B_{p1}{}^2 B_{p2}{}^2 Ae_s Vol_s}$$

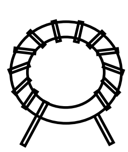
$$k_h = \frac{W_{core1} f_2{}^2 B_{p2}{}^2 - W_{core2} f_1{}^2 B_1{}^2}{f_1 f_2{}^2 B_{p1}{}^2 B_{p2}{}^2 Vol_s - f_1{}^2 f_2 B_{p1}{}^2 B_{p2}{}^2 Vol_s}$$

Ferrite losses- some approximated idea



$\propto N^2$ and $\propto f^2$

Ferrite losses resistor



N=10T

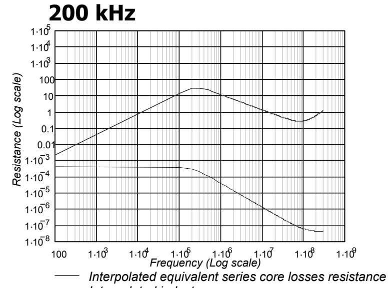
H5C2 10mm toroid

A_e = 0.07 cm²

L_e = 2.2 cm

Series resistor can be much higher than winding resistance.

Inductance fall at around 200 kHz



Series core loss resistance

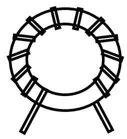
Frequency dependent – any difference ?

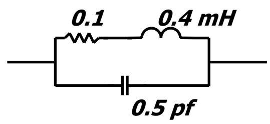
N=10T

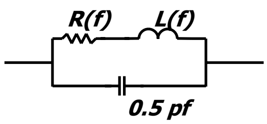
10mm toroid

A_e = 0.07 cm^2

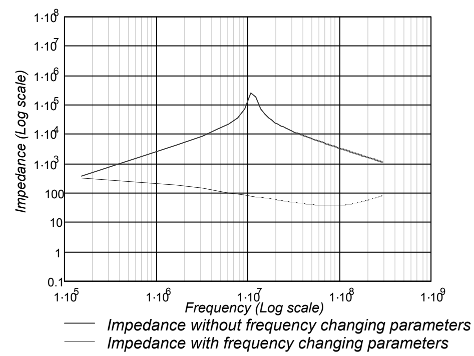
L_e = 2.2 cm





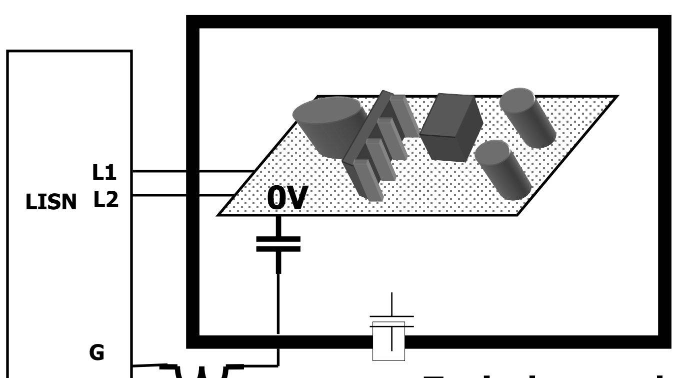


1,000 times difference between fixed and frequency varying parasitic



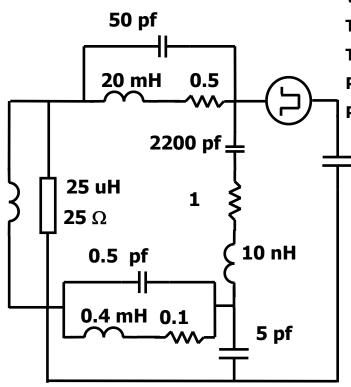
Inductor's impedance

Frequency dependent – is EMI different ?



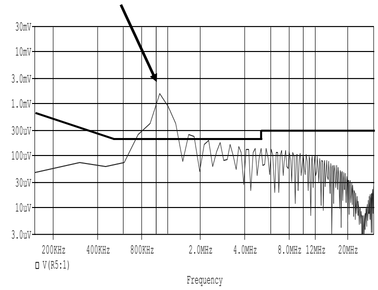
Typical example

EMI is different – typical example

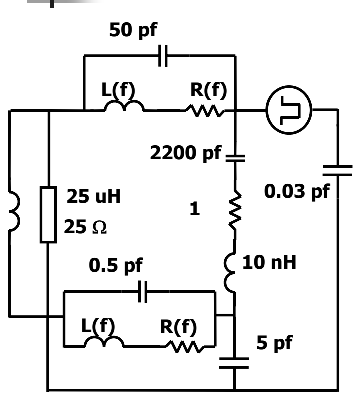


Vpeak =400 V
Tr = 50 ns
Tf = 50 ns
Pw = 2 us
Per = 6.6 us

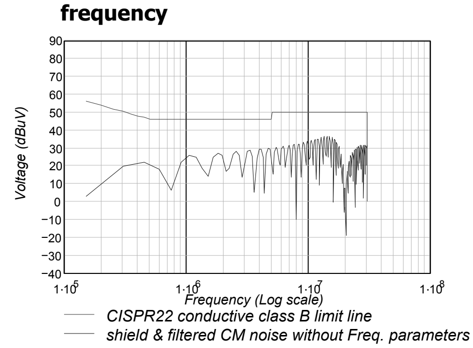
Resonate occurs due to L and C. But you seldom see resonance after adding ground choke.



EMI is different – changing L and C

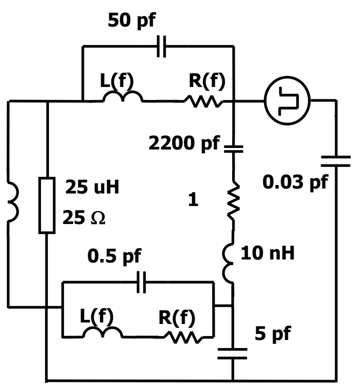


The inductor change it's value at where it should resonate. Damping resistor increase at resonate frequency



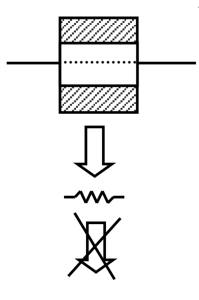
CM noise with Freq. dependent filter

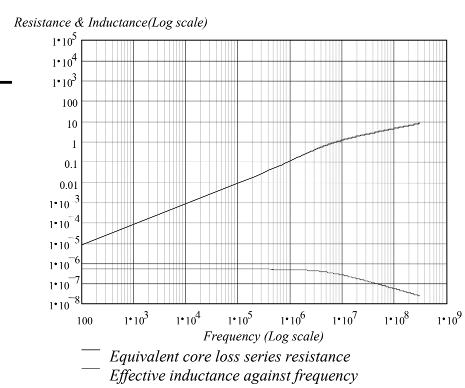
Changing L and C – no more simple prediction



- ~~Filter design~~
  - ~~Step 1 – determinate the resonate~~
  - ~~Step 2 – choose the order~~
  - ~~Step 3 – choose damping factor~~
  - ~~Step 4 – . . . .~~

Example 2 – ferrite bead

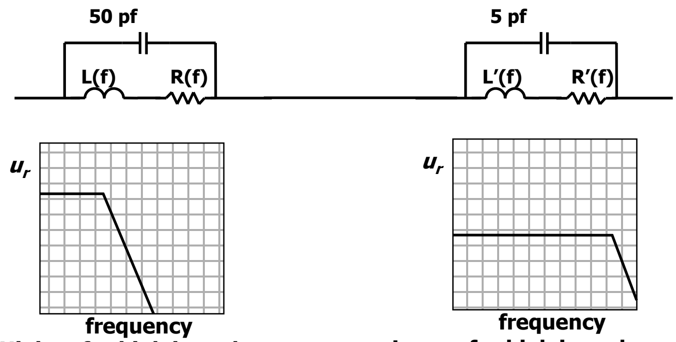




Core loss series resistance & Inductance against frequency

A small ferrite bead gives almost 10 Ω at 100 MHz, while keeping 0.01 Ω only at 100 kHz.

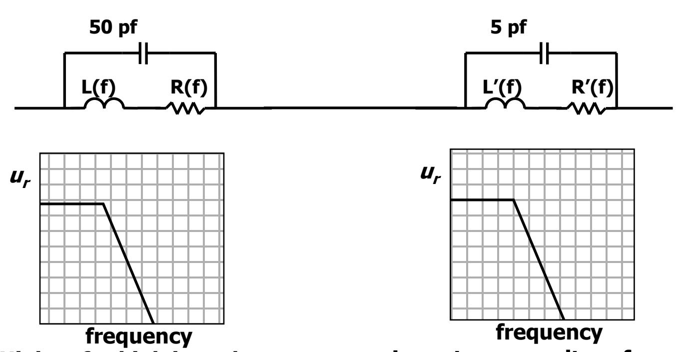
Example 3 – series CMC



High u_r for high impedance at low frequency

Low u_r for high impedance at high frequency

Series CMC – cheap alternative



High u_r for high impedance at low frequency

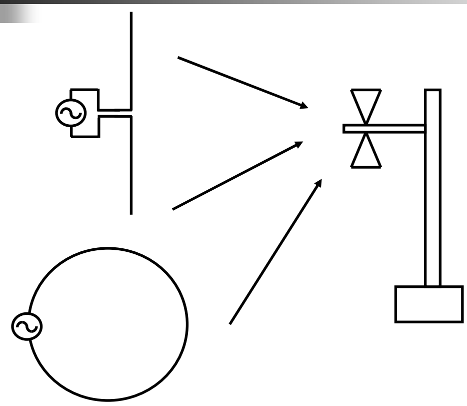
Low stray capacitpor for medium impedance at high frequency

Short Summary

- Permeability of a high permeability ferrite usually start to roll off at around 200kHz.
- So it usually give maximum impedance at that frequency
- Resistive Losses can be very high depending on N^2 and f^2.
- The equivalent loss resistor pay a great role in filtering design to provide damping effect.
- Magnetic material do not work on the way I approximate. It is more complicated and highly non-linear.

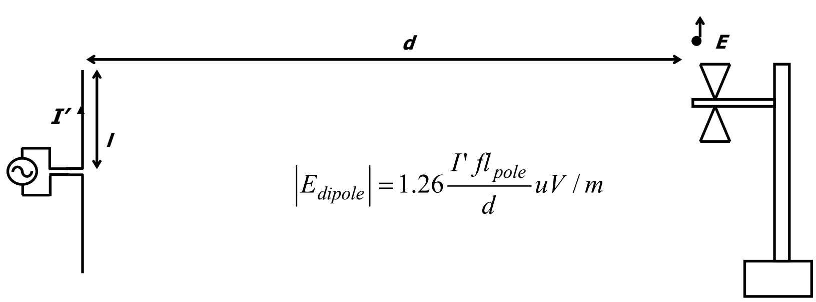
Any short question ?

Radiated emission



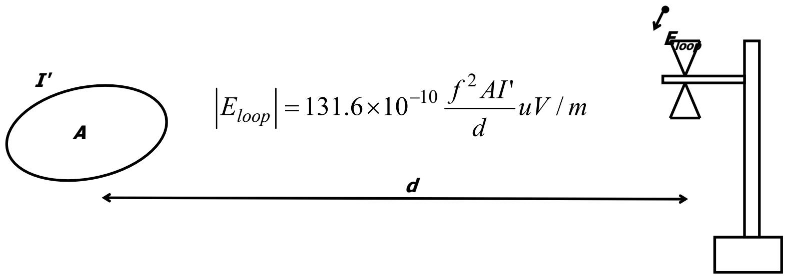
Radiated emission is transmitted and received by an antenna.

Antenna theory 1



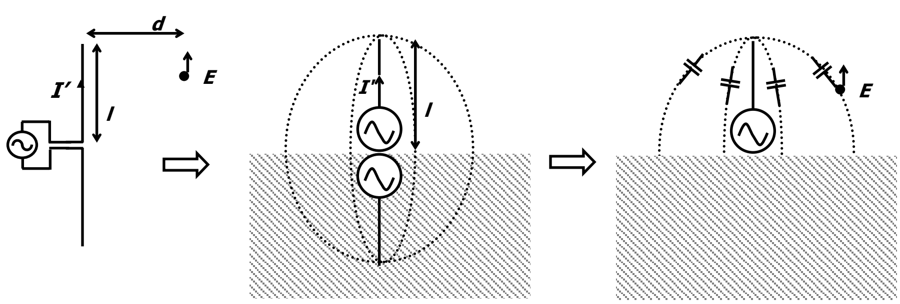
$$\left|E_{dipole}\right| = 1.26\frac{I' f l_{pole}}{d} uV/m$$

Antenna theory 2



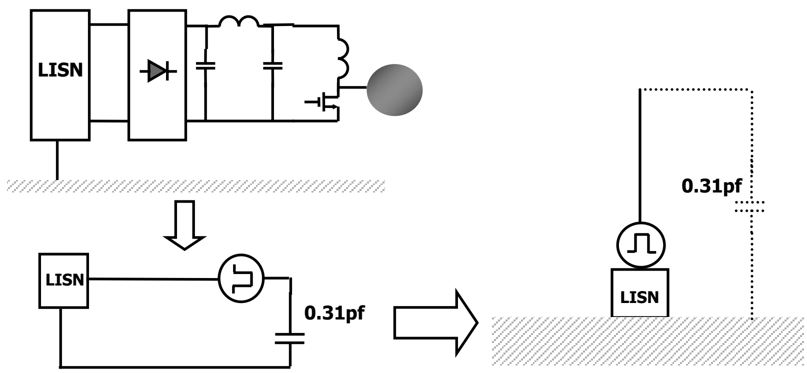
$$\left|E_{loop}\right| = 131.6\times10^{-10}\frac{f^{2}AI'}{d}uV/m$$

Dipole – capacitive like antenna

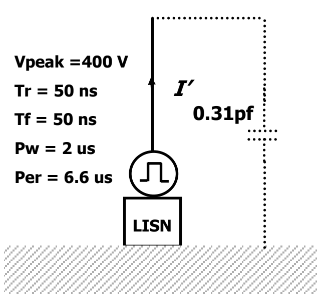


$$\left|E_{dipole}\right| = 1.26\frac{I' f l_{pole}}{d}uV/m$$

Dipole – cable and converter

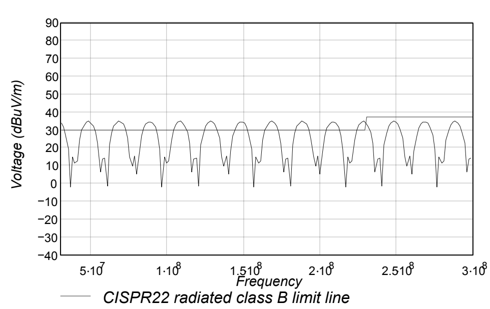


Cable and converter – 10m simulation



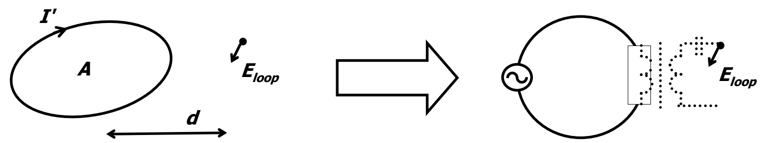
$$\left|E_{dipole}\right| = 1.26\frac{I' f l_{pole}}{d} uV/m$$

Limit Exceeded !!



10m radiated noise generated by cable

Loop – inductive like antenna

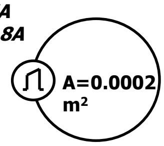


$$\left|E_{loop}\right| = 131.6 \times 10^{-10} \frac{f^2 A I'}{d} uV/m$$

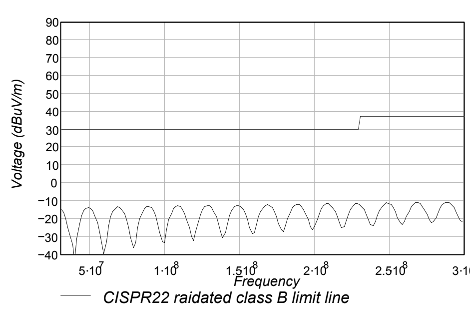
Loop antenna – current source excitation

Very very little noise is generated

I_{S1_ini} = 0.5A
I_{S1_peak} = 0.8A
t_r=50 ns
t_f=50 ns
t_{on} = 2 us
T = 6.6 us



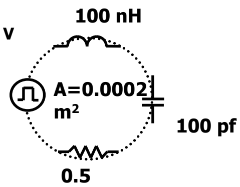
$$\left|E_{loop}\right| = 131.6 \times 10^{-10} \frac{f^2 A I'}{d} uV/m$$



10m radiated noise by loop antenna

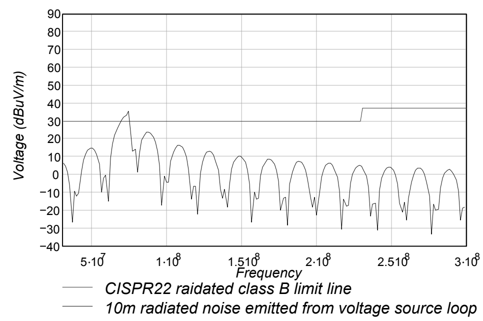
Loop antenna – voltage source excitation

Vpeak =400 V
Tr = 50 ns
Tf = 50 ns
Pw = 2 us
Per = 6.6 us



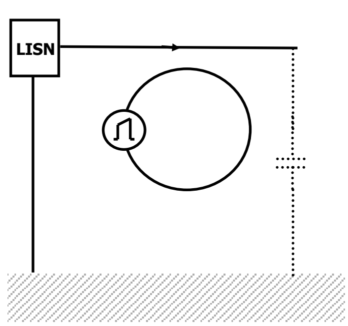
$$\left|E_{loop}\right| = 131.6\times10^{-10}\,\frac{f^2 AI'}{d}\,uV/m$$

Limited excessive emission due to resonance of the loop



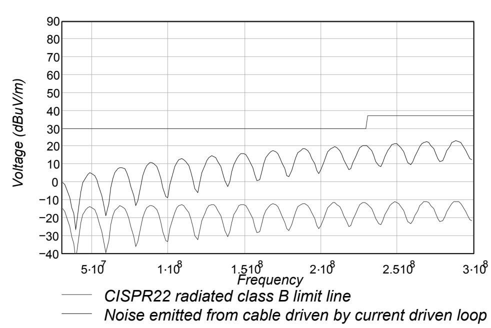
10m radiated noise by loop antenna

Dipole antenna – an amplifier



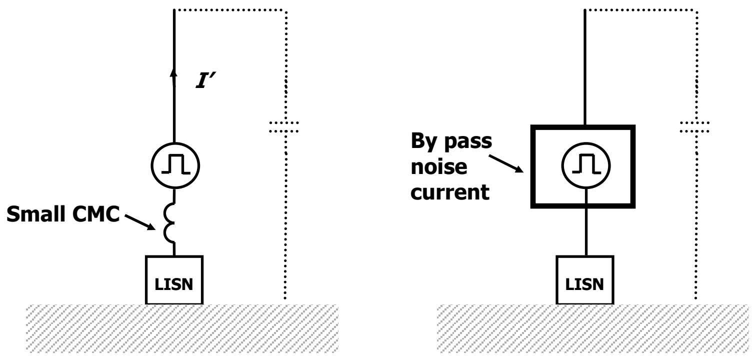
Converter cable will pick up the noise current by mutual inductive couple.

Converter cable will amplify the loop noise and becomes the dominant emission antenna

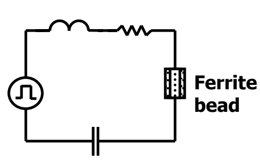


Cable radiated noise by inductive couple

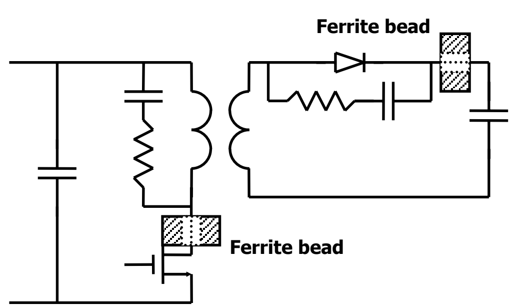
Cable and converter – suppression



Loop antenna – suppression



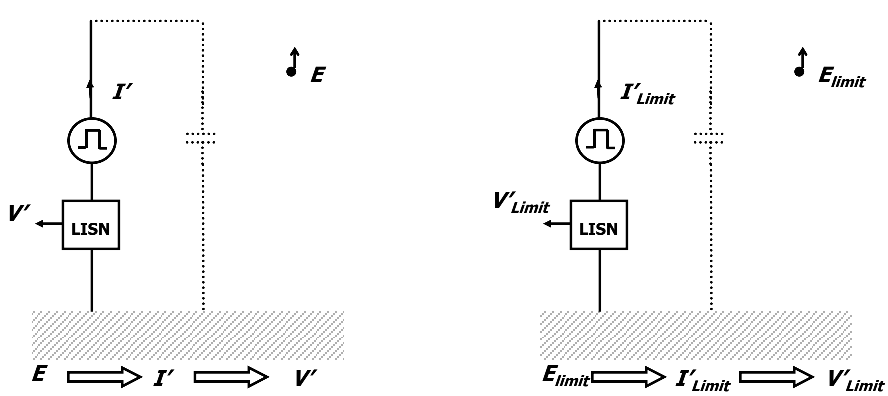
Add ferrite bead at the current loop



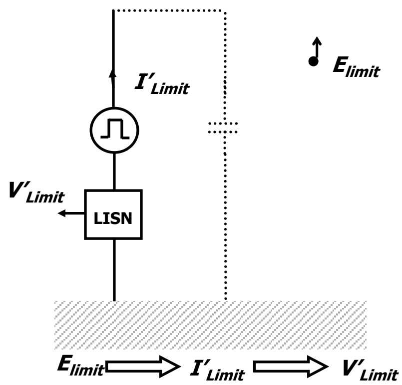
Short summary

- Cables generally emit more noise than loop
- A loop can emit substantial noise at resonate condition.
- A cable acts as an amplifier & picks up noise from a loop close by and emits at a much greater level.
- Impedance with small stray capacitance and high resistance can reduce radiated noise.

Misc. – Predicting radiated EMI



Misc. – Predicting radiated EMI



As E field is generated by a dipole

$$\left|E_{dipole}\right| = 1.26\frac{I' fl_{pole}}{d} uV/m$$

The corresponding current limit flowing in the input cable is

$$I_{Limit} = \frac{E_{Limit}\, d}{1.26\, fl_{cable}} 10^6$$

The corresponding voltage limit measured at the LISN

$$V_{Limit} = \frac{E_{Limit}\, dZ_{LISN\_cm}}{1.26\, fl_{cable}} 10^6$$

Power^e^Lab HKU

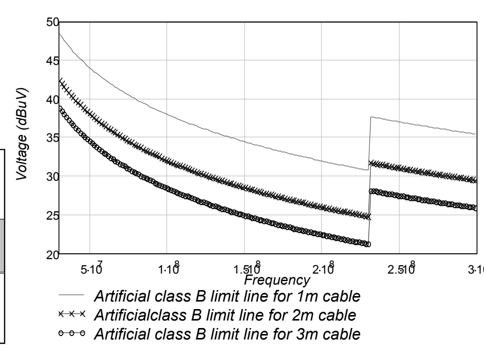
Misc. – Predicting radiated EMI

Assuming input and output cable are the same and the receiving antenna is 10m away

$$V_{LISN\_RF\_Limit} = \frac{250 E_{Limit}}{1.26\, fl_{cable}} 10^6$$

	30MHz – 230MHz	230MHz –1G
CISPR22 radiated emission limit		
Quasi peak limit(10m class B)	*30dBuV /m*	*37dBuV /m*

Artificial Limit line of CISPR22 measured at LISN

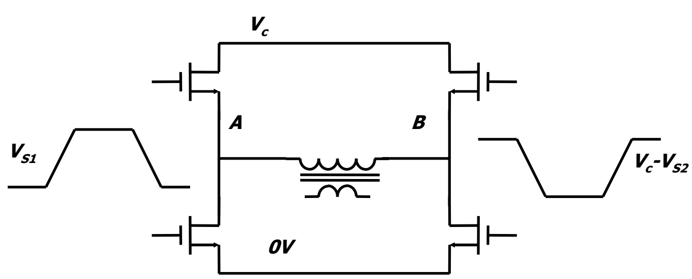


Artificial radiated class B limit line

Prepared by Franki Poon & Bryan Pong
EMI in Switching Power Supply www.eee.hku.hk/power_electronics_lab/ 292

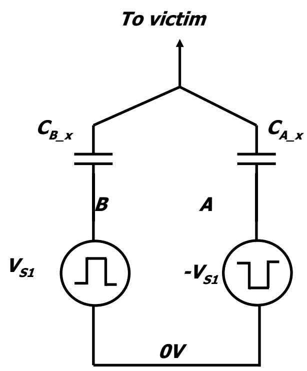
Any short question ?

MISC - Cancellation



A full-bridge configuration has an inherent cancellation of voltage swing. The left leg will having an equal but opposite swing compared with the right leg.

MISC – capacitive coupling cancellation



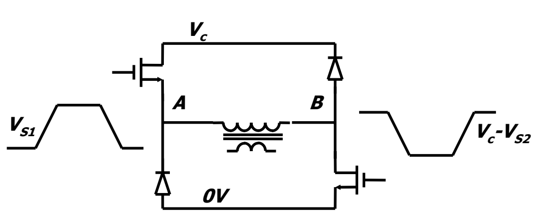
If

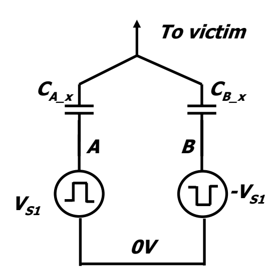
$$C_{B\_x} = C_{A\_x}$$

Then,

$$V_{victim} = 0$$

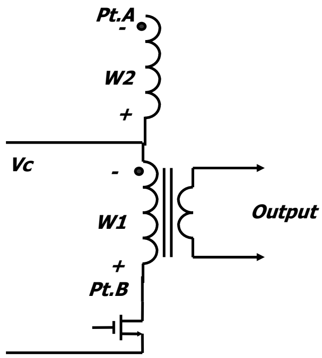
MISC – capacitive coupling cancellation



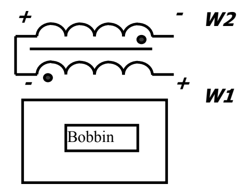


A two wheeler forward or flyback configuration has an inherent cancellation of voltage swing. The left leg has an equal but opposite swing compared with the right leg.

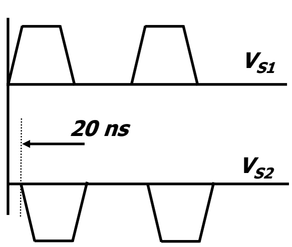
MISC – capacitive coupling cancellation



A general method for voltage cancellation can make use of an anti phase winding to complete the task.



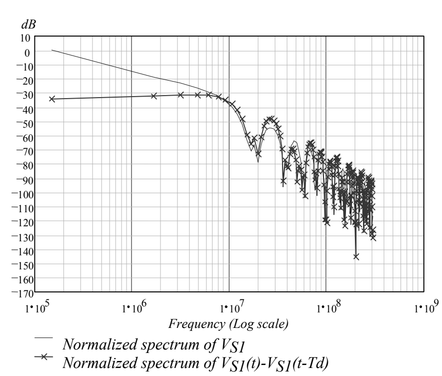
MISC – capacitive coupling cancellation



$V_{S2}(t) = V_{S1}(t+20\ ns)$

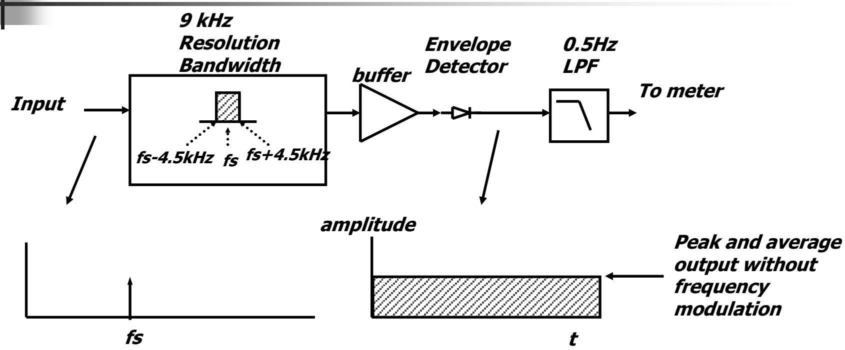
Be careful with time delay !

A 20 ns delay will eliminate the cancellation effect at 10 MHz



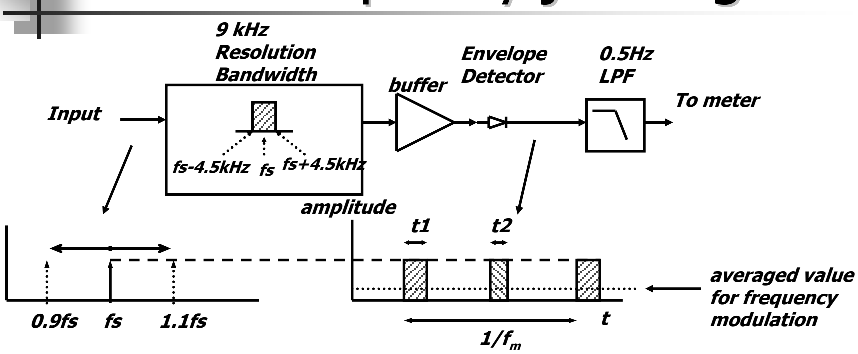
Normalized noise source spectrum

Misc - Frequency jittering



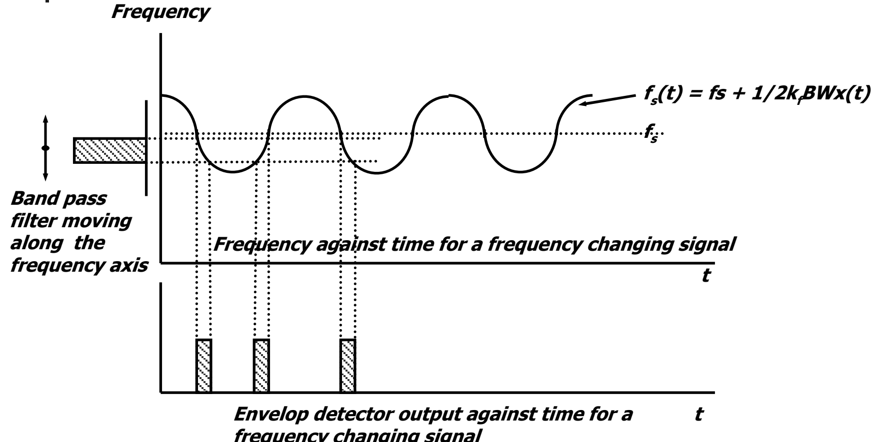
A single frequency injection into to a receiver make the detector produce a dc voltage output with ripple where the peak, quasi-peak and average are the same

Misc - Frequency jittering



A changing frequency injection into the receiver make the detector produce a pulsing output voltage where the average value will have much lower value.

Misc - Frequency jittering



Misc - Frequency jittering

Don(fBW) = normalized average value at the detector output

$$D_{on}(f_{BW}) = \int_{f-\frac{BW}{2}}^{f+\frac{BW}{2}} Pdf(f)df$$

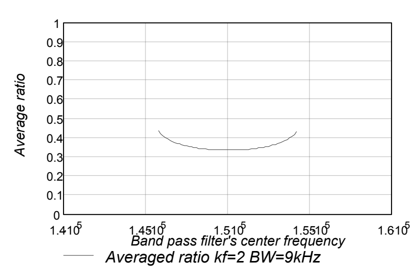
The frequency jitter in a way

$$f = fs + 1/2k_f BW\sin(2\pi f_m t)$$

The probability density function of the operating frequency is

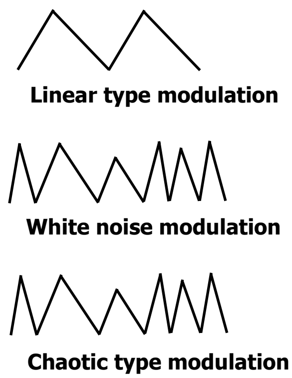
$$Pdf(f) = \frac{1}{\sqrt{1-\frac{2\pi(f-f_s)^2}{k_f BW}}}$$

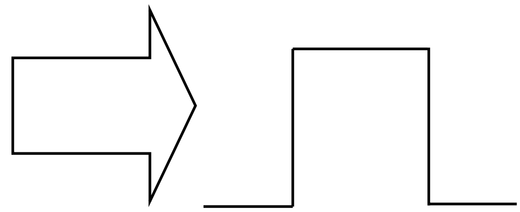
The average value under a sine wave modulation will have a factor shown below



Average ratio

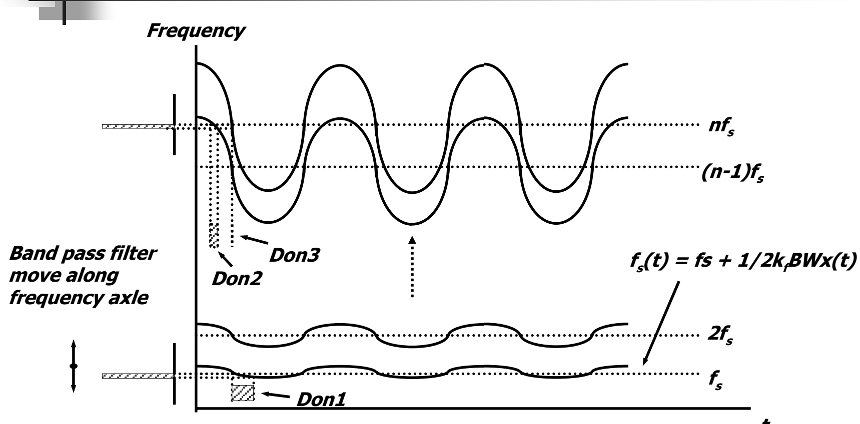
Misc - Frequency jittering





Yield flat frequency distribution

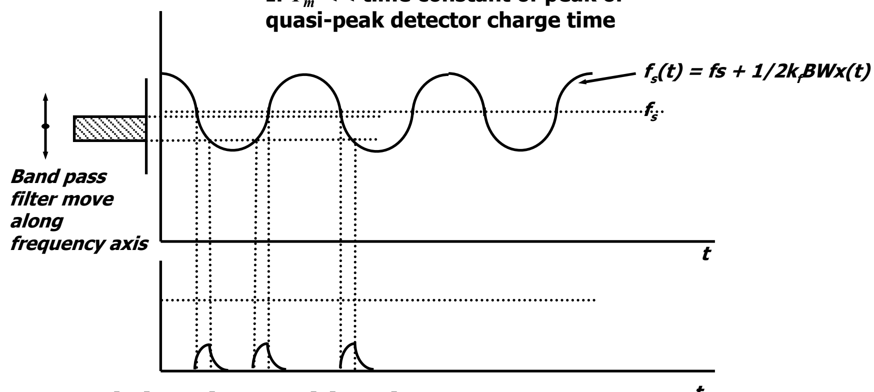
Misc - Frequency jittering



Frequency will overlap at high frequency range.

Misc - Frequency jittering

If T_m << time constant of peak or quasi-peak detector charge time

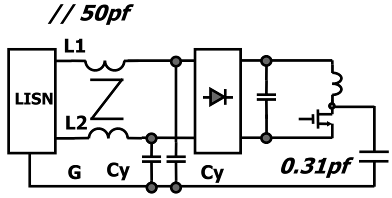


Don't be cheated by the spectrum screen !

Input cable

Refresh

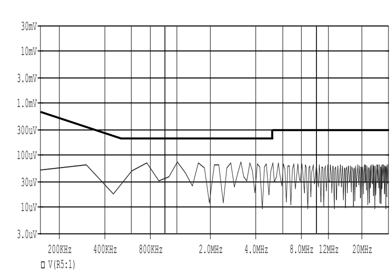
CMC = 20 mH +0.5 Ω // 50pf



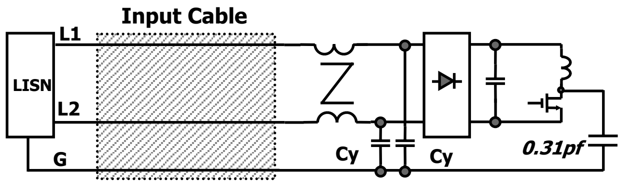
Cy = 2200 pf

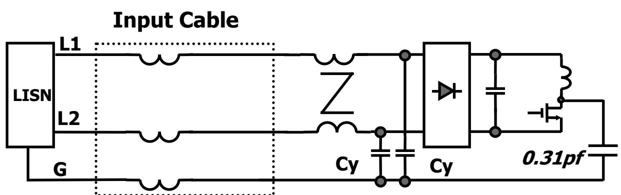
No input cable parameter is considered.

No problem !



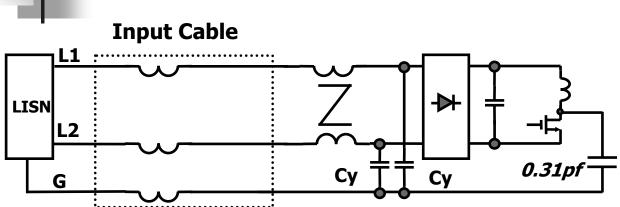
Input cable





Consider the inductance of each wire

Input cable



Consider the inductance of the each wire

$$L = 0.002l(\ln(\frac{4l}{d} - 0.75))uH$$

For a 1m cable

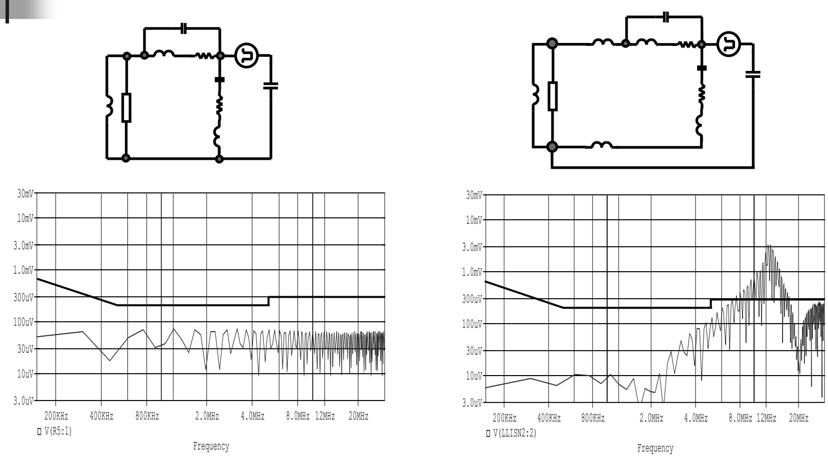
l = 100 cm

d = 0.1 cm

hence

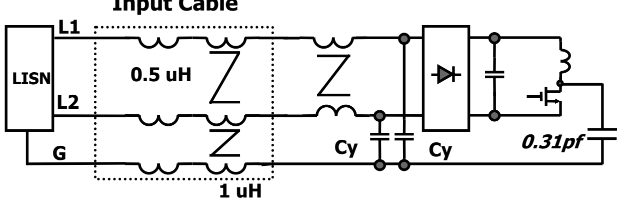
L = 1.5 uH

Input cable – cable inductance



Input cable – mutual & self inductance

Input Cable



Consider the mutual and self inductance of the input cable

$$L_{12} = 0.002l(\ln(\frac{2l}{W}) - 1 + \frac{W}{l})uH$$

For a 1m cable

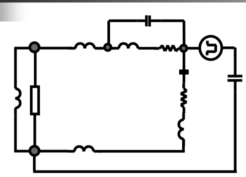
l = 100 cm

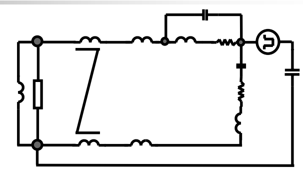
W = 0.4 cm

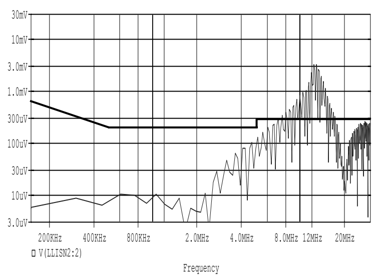
hence

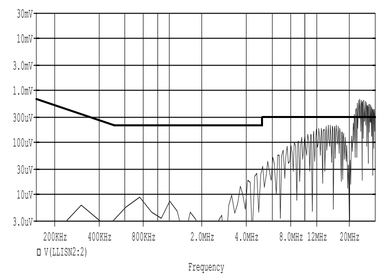
L_{12} = 1 uH

Input cable – mutual & self inductance

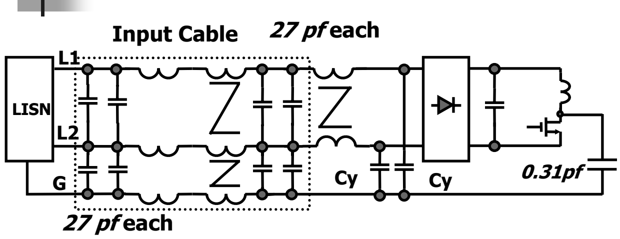








Input cable – inductance & capacitor



Consider the mutual capacitor, mutual and self inductance of the input cable

$$C = \frac{0.0885 l \pi \varepsilon_r}{\ln(2\frac{W}{d})} pF$$

For a 1m cable

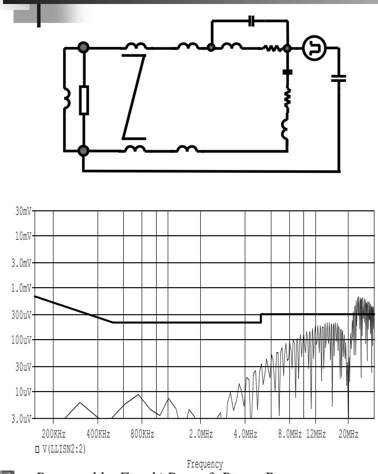
l = 100 cm

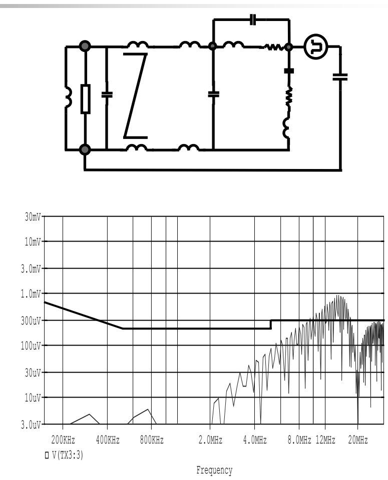
W = 0.4 cm

hence

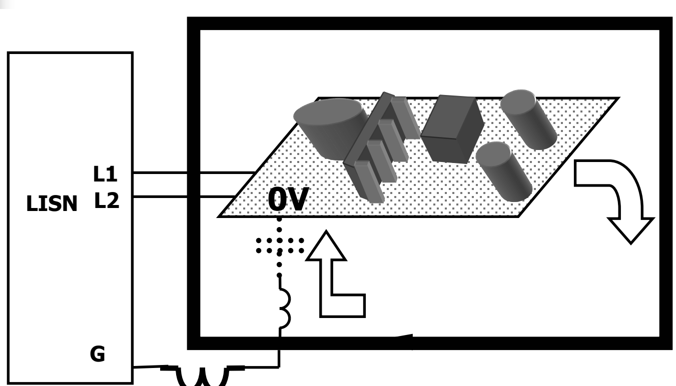
C = 54 pf

Input cable – inductance & capacitance





Input cable – inductance & capacitance

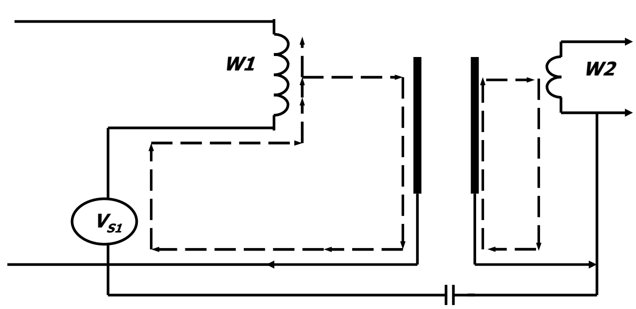


Solution

Short Summary

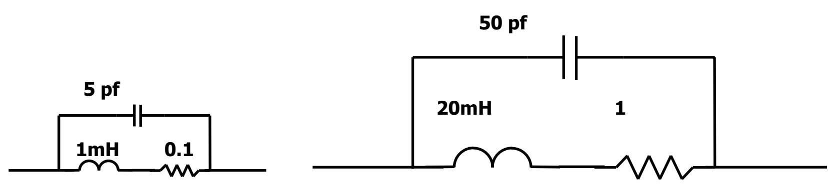
- An anti-phase noise source is a possible solution to eliminate noise.
- Frequency jittering or modulation can reduce average reading.
- Input cable construction contributes to noise distribution pick up by the LISN.

Good or Bad ?



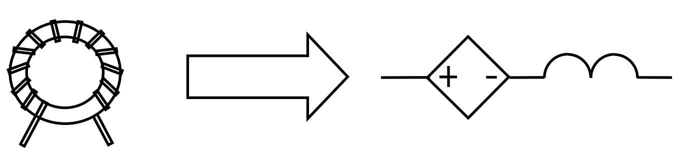
Faraday shield produces more invisible loops

Good or Bad ?



Increase number of turns will increase stray capacitance

Good or Bad ?



Add choke or CMC will pick up more noise

Conclusion ?

All Good things can cause

BAD EFECTS

Question ?

Can BAD things cause

GOOD EFECT ?

Simple logic

Statement 1 - All my correct solution doesn't work

Statement 2 - If there exist a solution

Logic derivation - The solution must be incorrect !

Sometimes we have to

Think in a wrong way

Overall Summary

- EMI behavior is, at least, a summation of all of the above discussions.
- It is never an easy task to predict EMI result.
- Better understanding help prevention and diagnosis.

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Bye bye, I miss you all