科环2012

哈爾濱工業大學
深圳研究生院

电磁兼容原理与应用整改

EMC & its Deisgn

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内 容

一. 开关电源干扰形成机理

二. 无源EMI滤波器设计

三. 新型EMI抑制技术

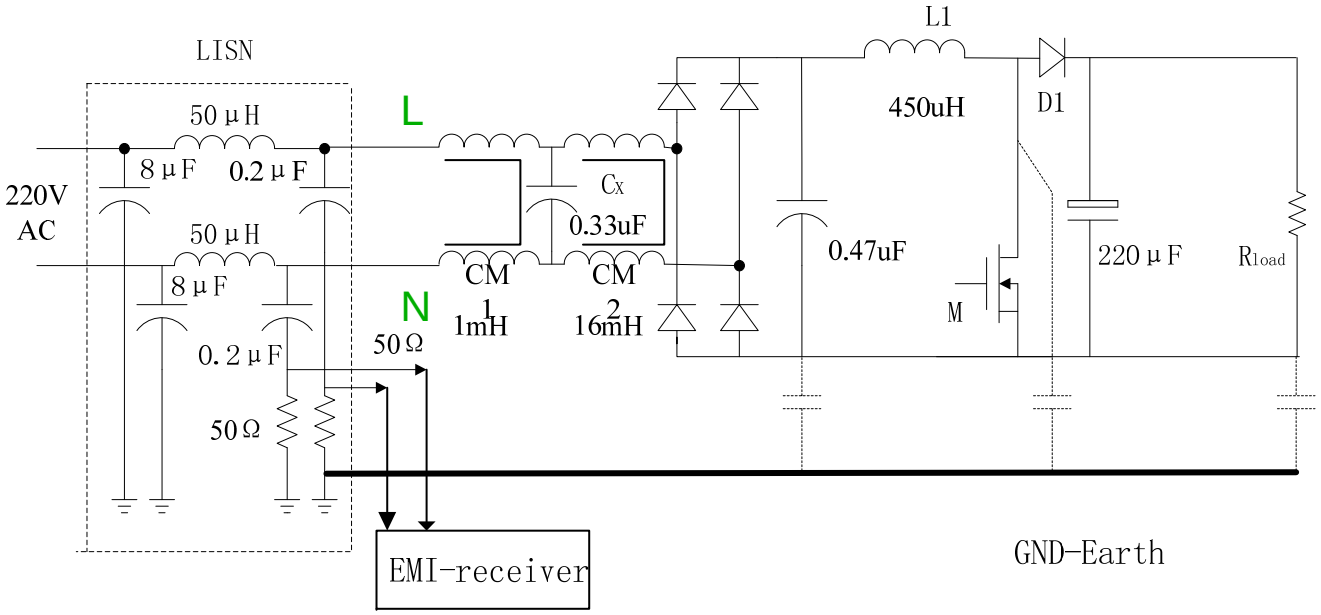
四. 滤波器的特殊问题

一：电力电子装置的传导电磁干扰发射(150kHz-30MHz)

1.1 电力电子装置传导干扰发射基本原理

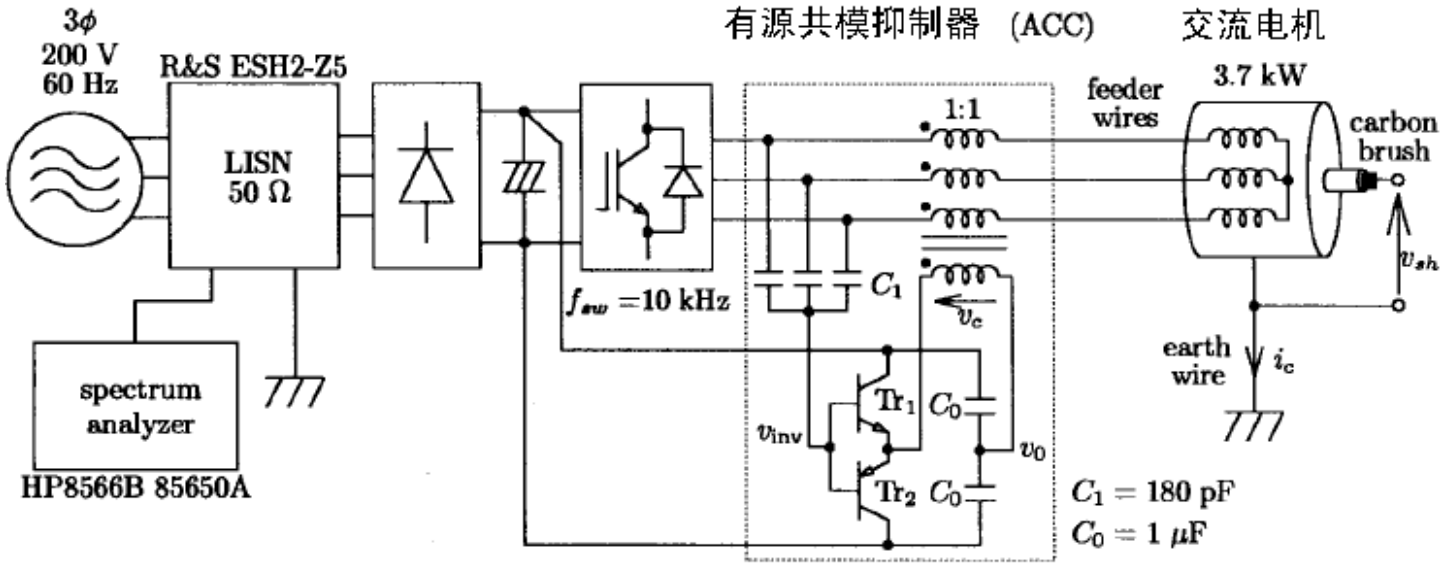
1.1.1：测试布局和检测量

单相：L，N line



EMI接收机测量上述线上的射频干扰量值，均要小于限值

三相：L1，L2，L3，Earth



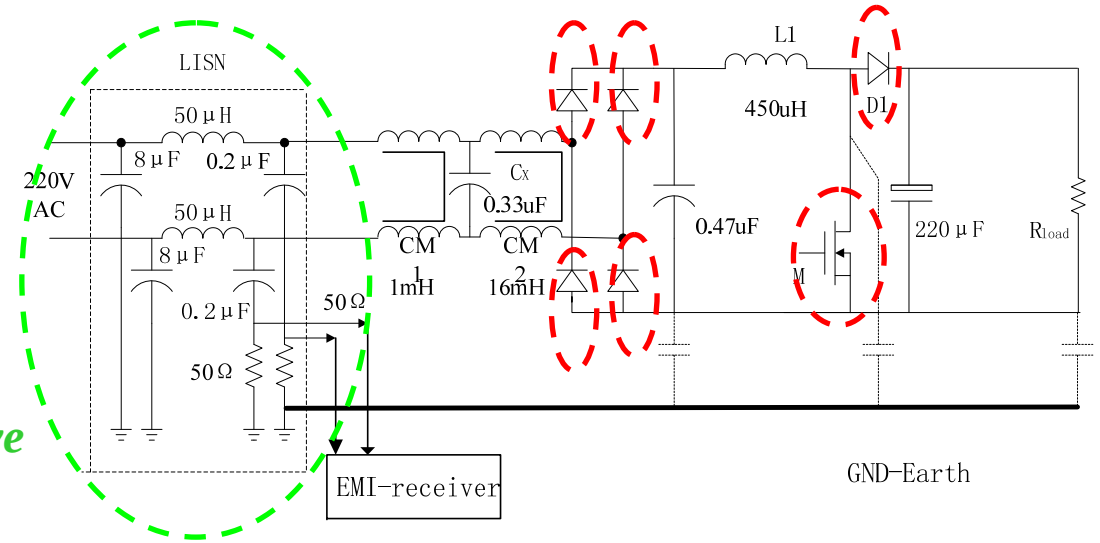
EMI接收机测量上述线上的射频干扰量值，均要小于限值

1.1.2 电力电子装置电磁干扰的产生源头和传播机理

Three factors of EMI! ***EMI source, coupling paths, sensitive objective***

电磁干扰产生的源头

EMI source



Sensitive objective

There are lots of different opinions. Mosfet, Diode, transformer, AC loop etc

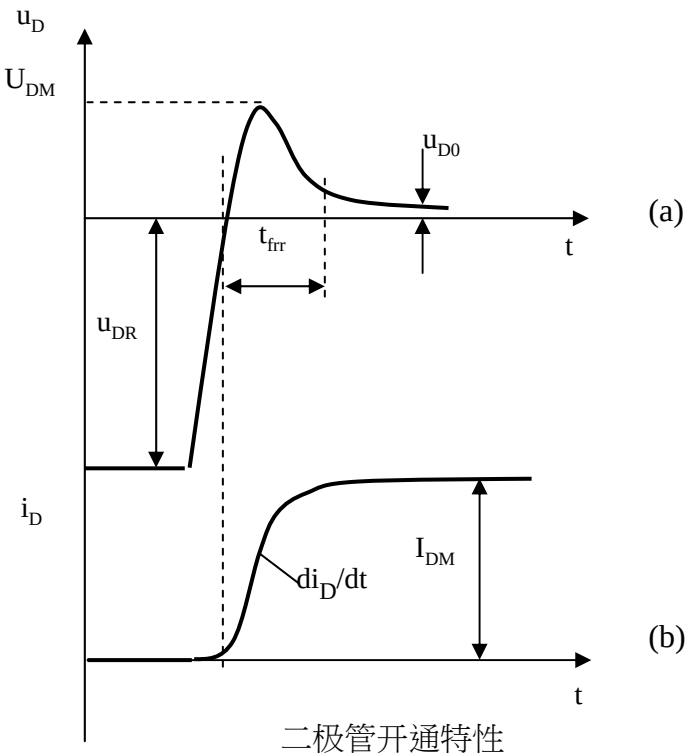
Strictly speaking,

Only Nonlinear switching devices are true EMI sources for EMI emission!

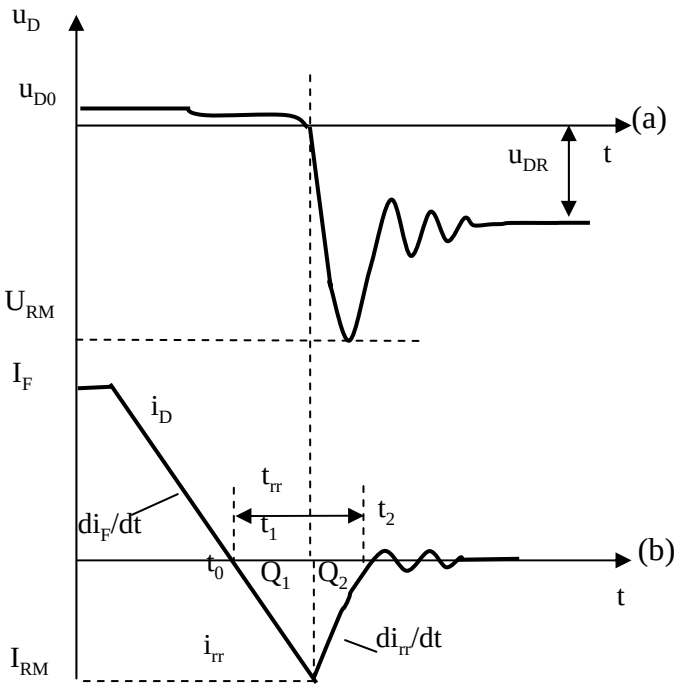
Others are coupling paths!

Only for Radiation emission or simply analysis, others transformer and AC loop can be treated as EMI source!

A: Diode turn-on and turn-off

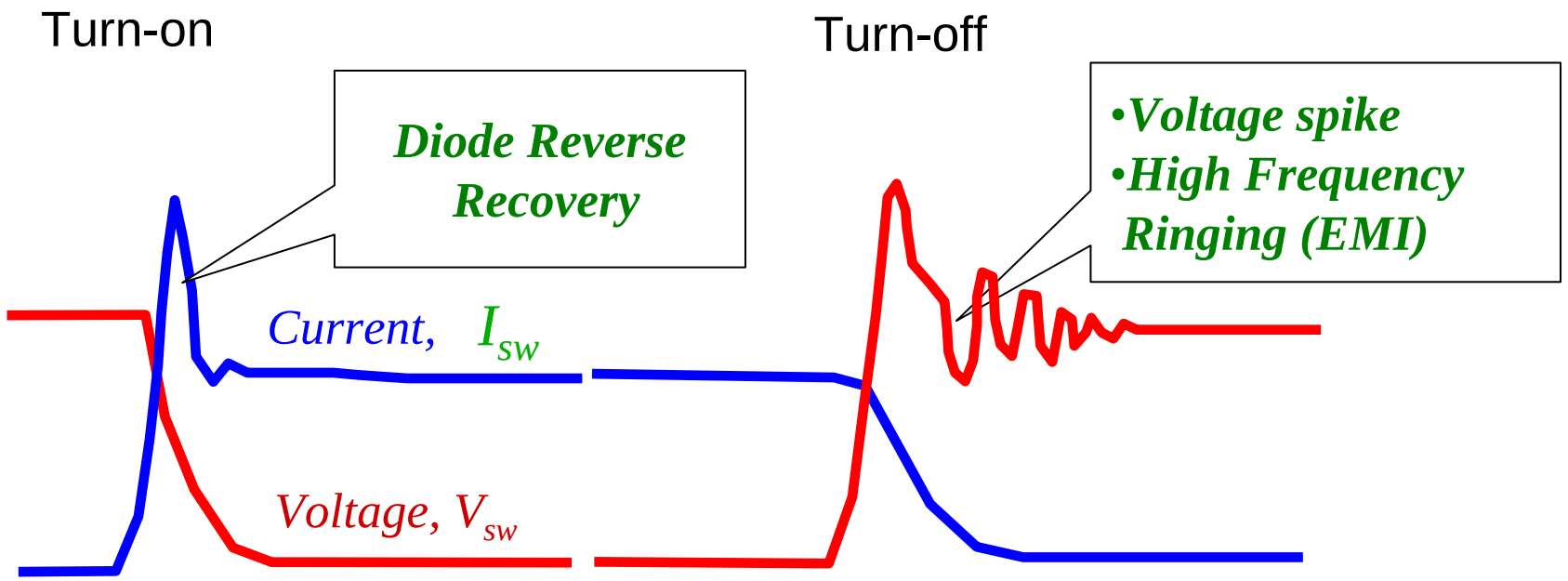


二极管开通特性



二极管的反向恢复过程（硬恢复）

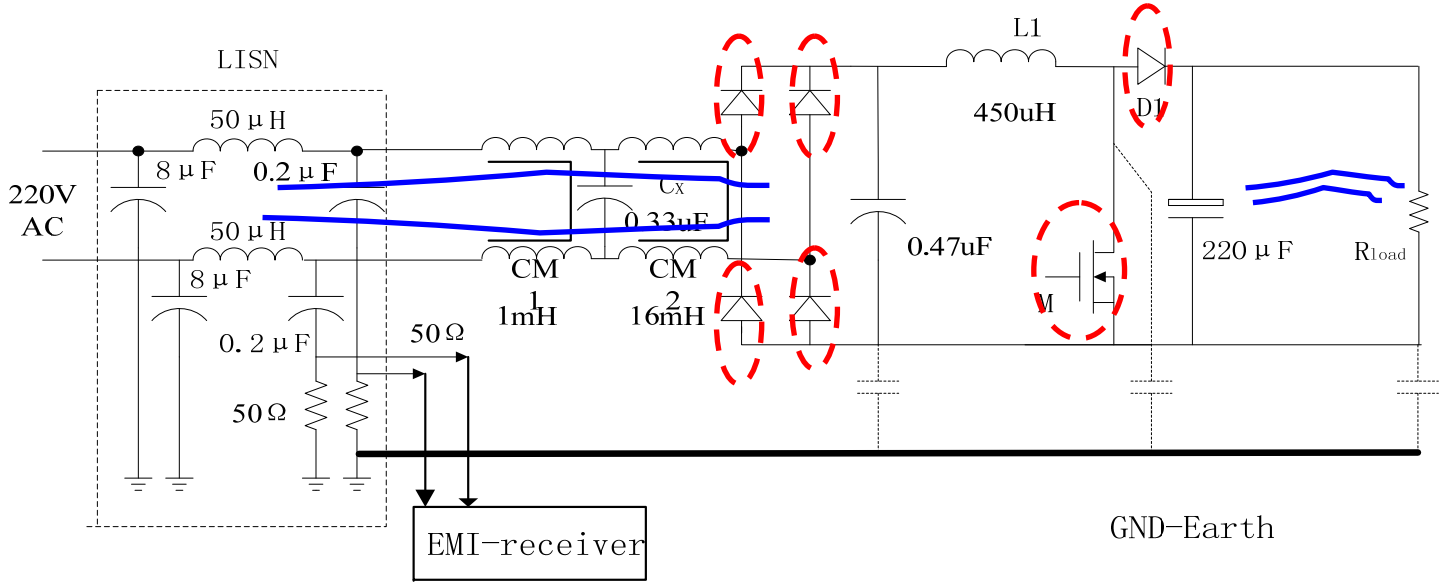
B: Transistor turn-on and turn-off



How about coupling paths! The difficult factors!

Basic EMI coupling mechanism

A: Along metal Lead



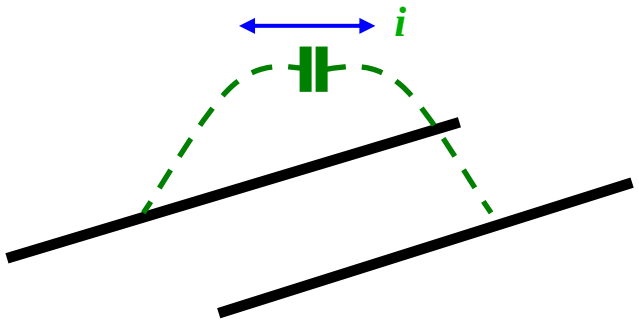
Basic EMI coupling mechanism

B: space Induct effect

B1: Capacitive coupling effect:

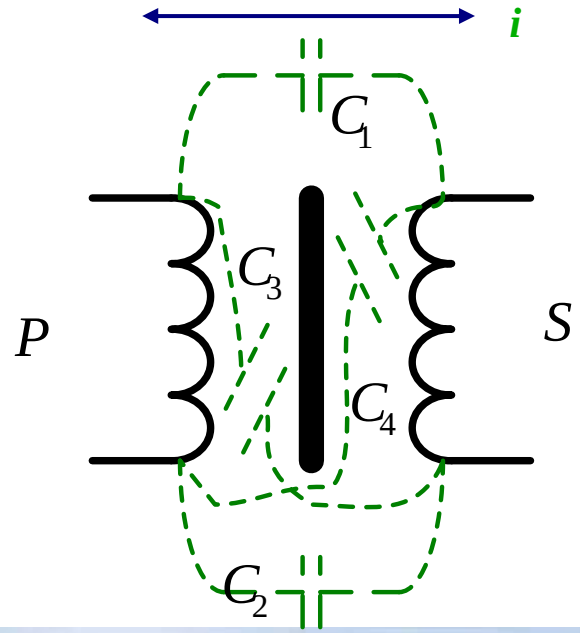
There is a coupling capacitor between every-two conductors!

Trace



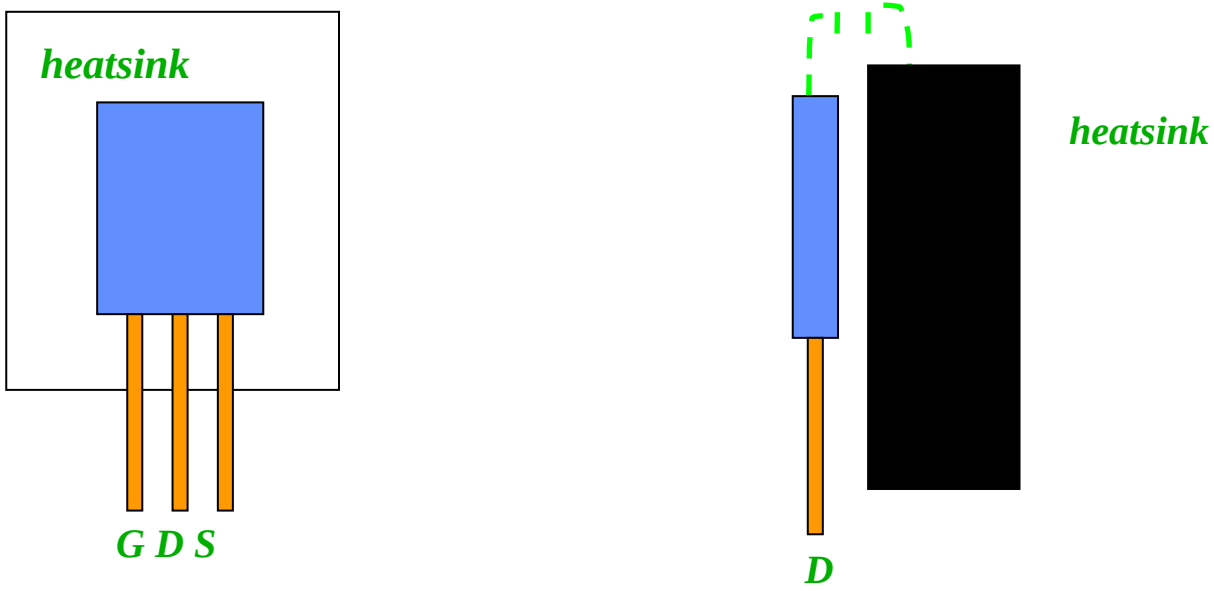
$$C_{12} = k\frac{S_1 S_2}{D}$$

Transformer

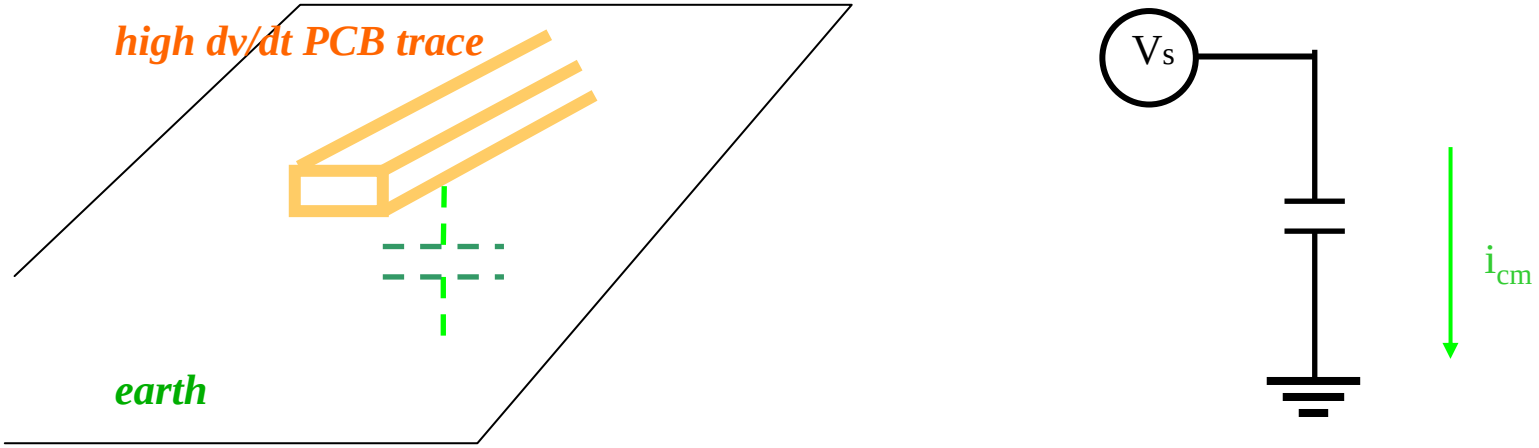


B1: Capacitive coupling effect:

Capacitor between drain to heatsink



Capacitor between high dv/dt trace or metal to earth

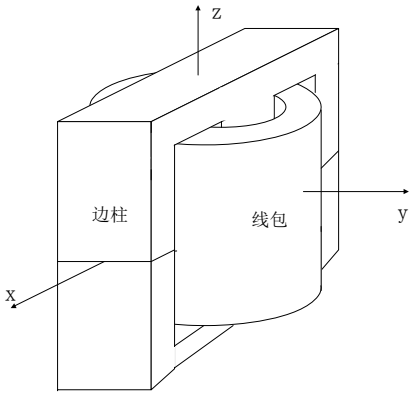


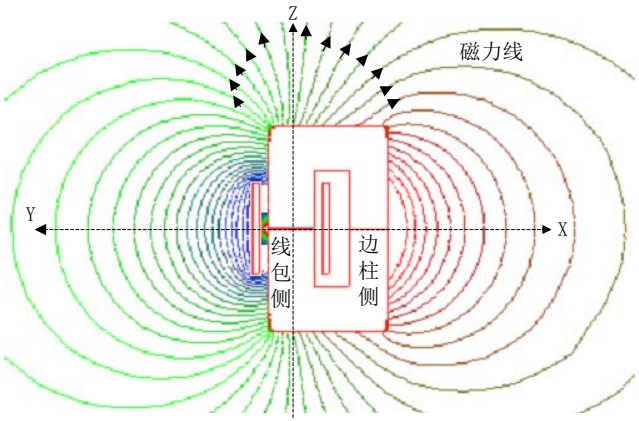
B2: Inductive coupling effect:

There is a coupling inductor between every-two loops!

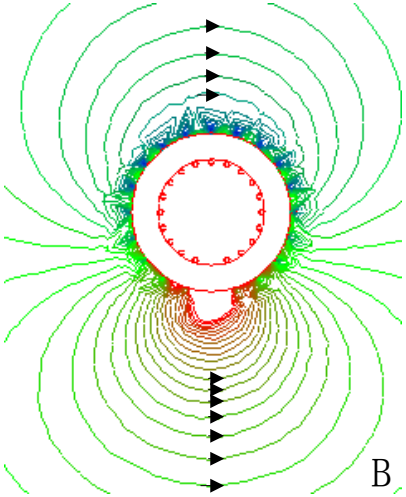
Typical magnetic loops:

Inductor1: Transformer:

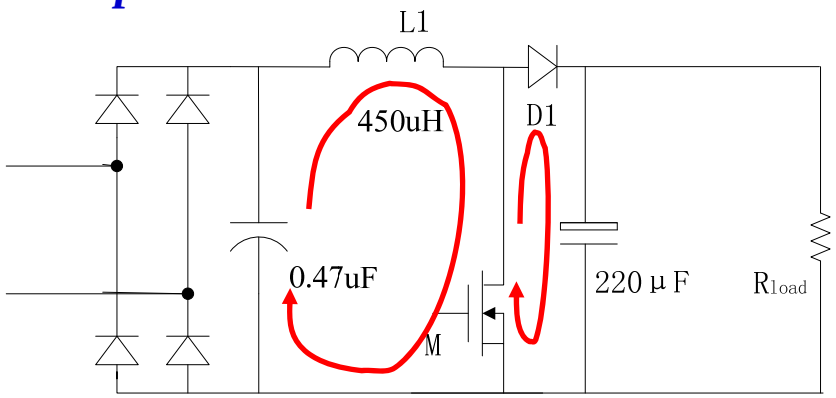


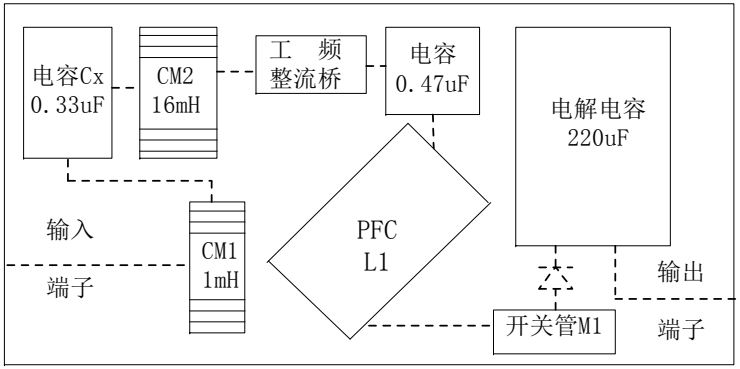


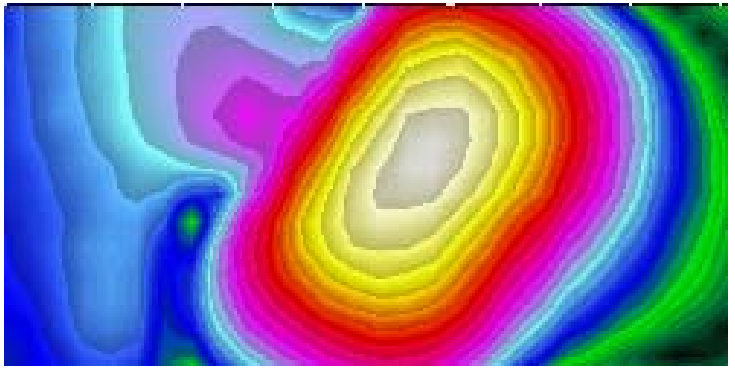
Inductor2:



High frequency AC loops





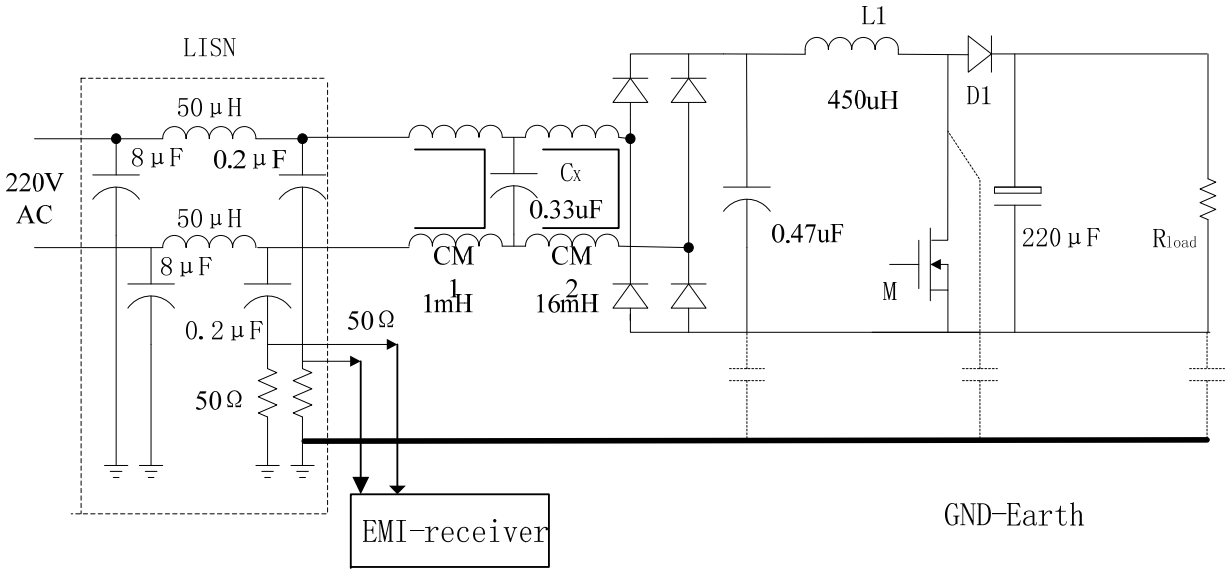


Inductive coupling: ***produce EMI directly some time ➔sensitive circuit***
complicit EMI coupling paths.➔ influence EMI filter performance.

1.1.3 电力电子装置电磁干扰的共模/差模分析

Why?

Example: Single phase



Emission on L line: V_L

Emission on L line: V_N

$$V_{CM} = (V_L + V_N)/2$$
$$V_{DM} = (V_L - V_N)$$

Vcm & Vdm

$$V_L = V_{CM} + V_{DM}/2$$
$$V_N = V_{CM} - V_{DM}/2$$

So, V_L &V_N V_{cm} & V_{dm} are same!

Why? 因为差模回路和共模回路有不同的特点和性质，分开考虑，便于把握EMI形成、传播和抑制。

差模回路：voltage or current between L&N or among L1、L2、L3

Equivalent internal impedance is small! Paths is clear!

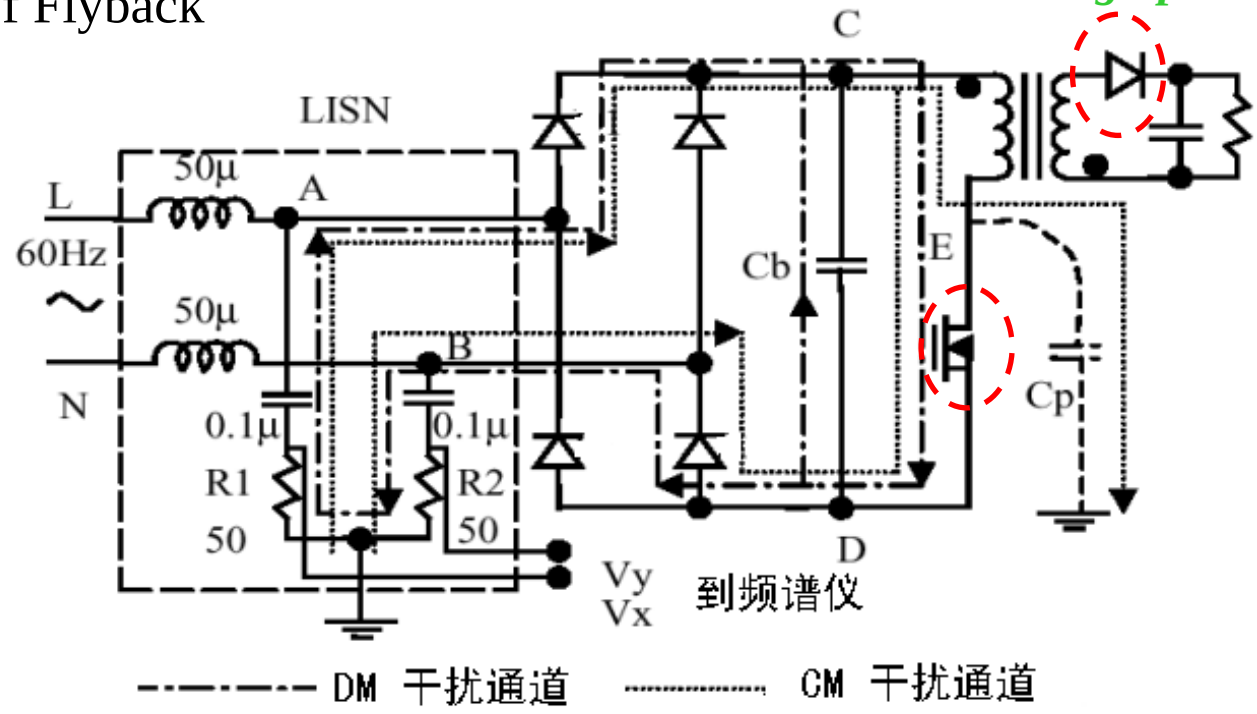
Through lines-load

共模回路：voltage or current between lines and Earth

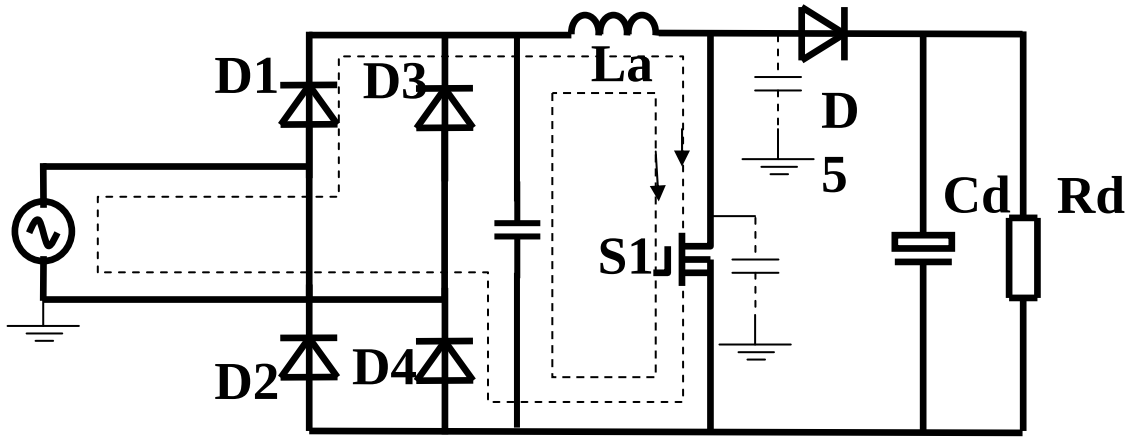
Equivalent internal impedance is large! Paths is unclear in most case!

Through parasitic capacitor

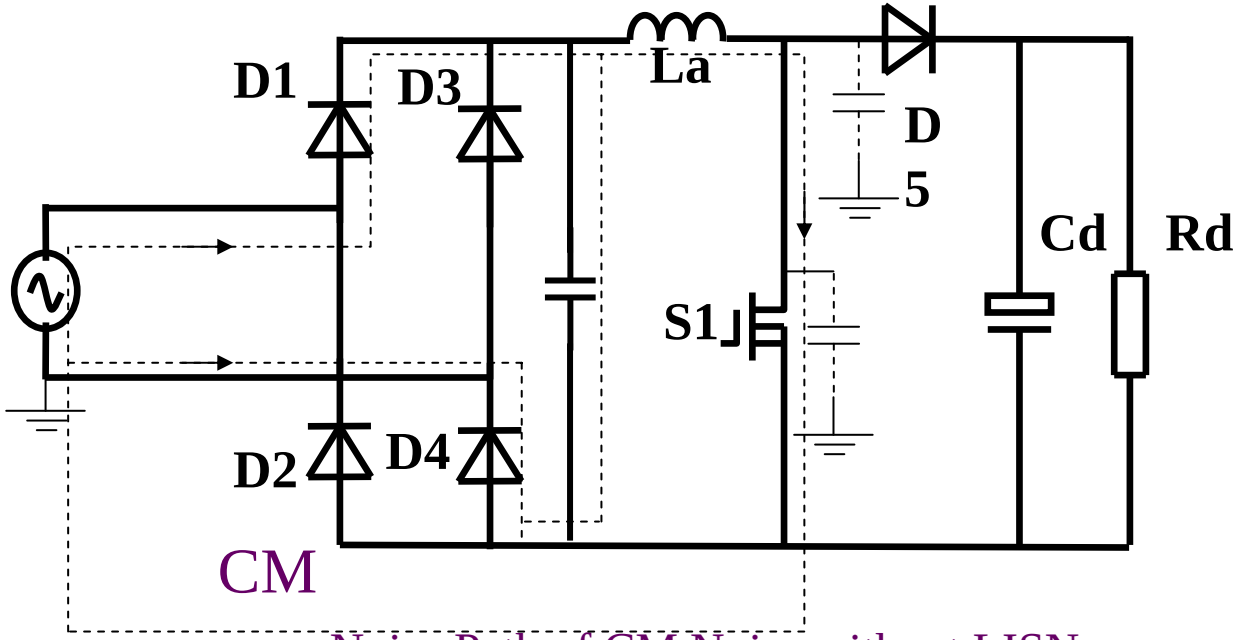
Example1 of Flyback



Example2 of a Boost PFC

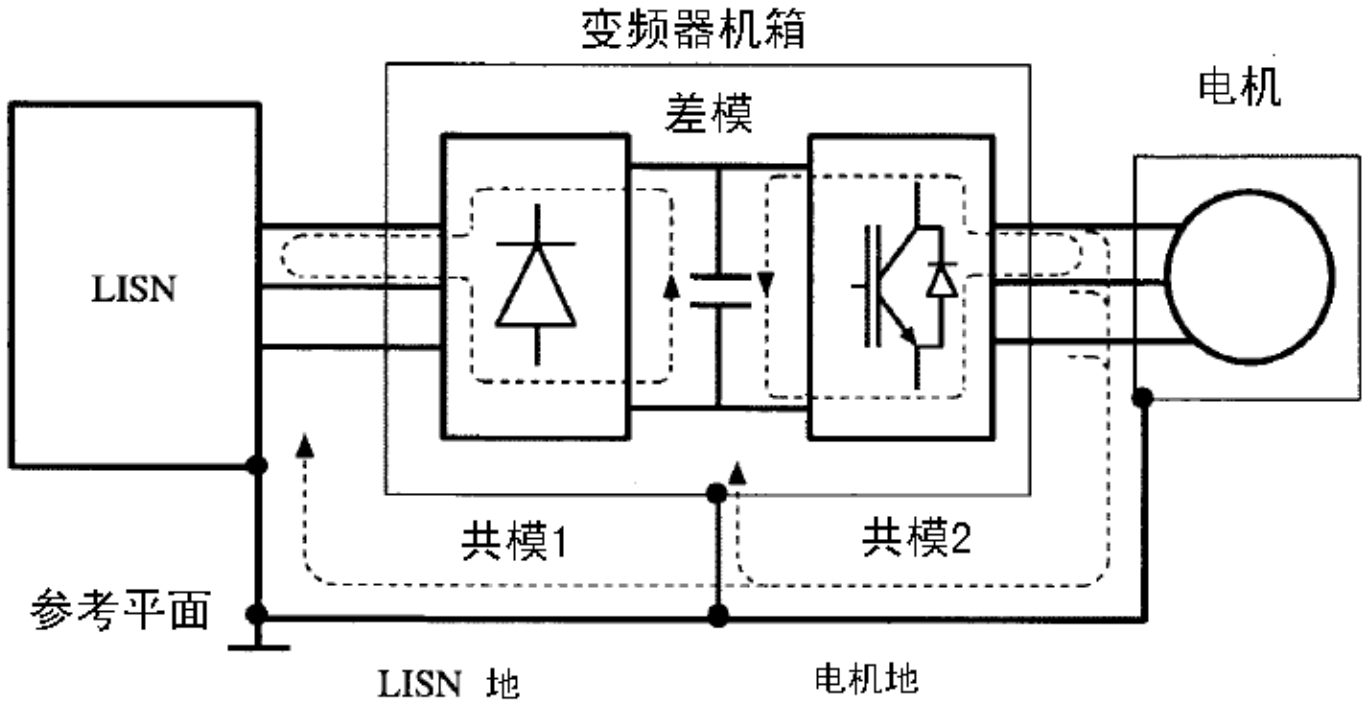


Noise Path of DM Noise without LISN



Noise Path of CM Noise without LISN

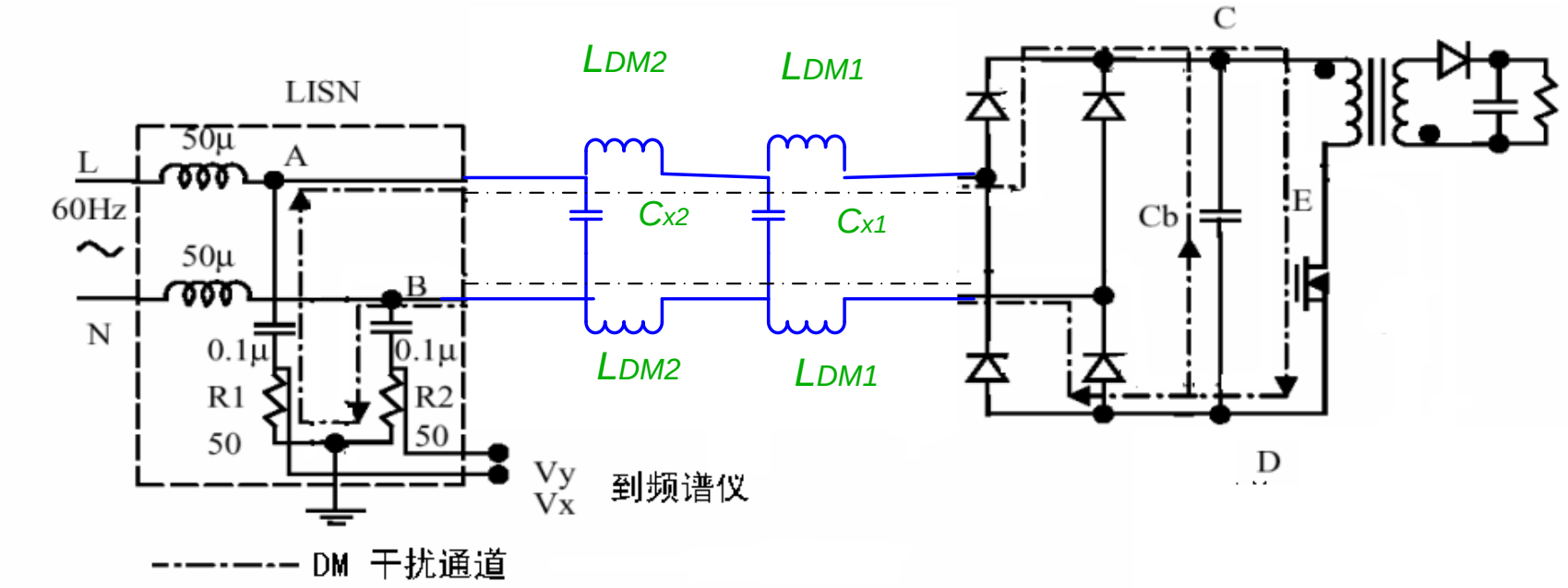
Example3 of a INVERTR



Useness of DM/CM Analysis：

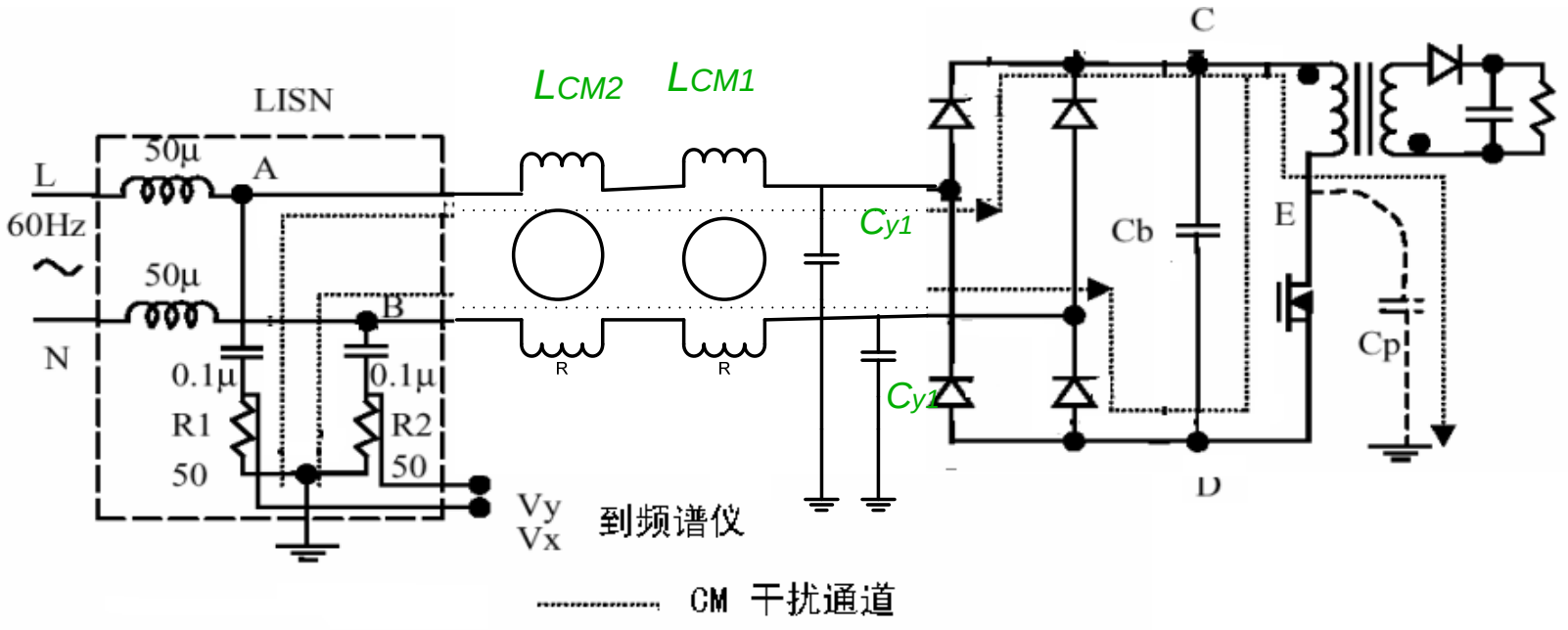
It is very useful for EMI filter design and EMI debug!

DM EMI filter to control DM emission! It has no influence on CM EMI.



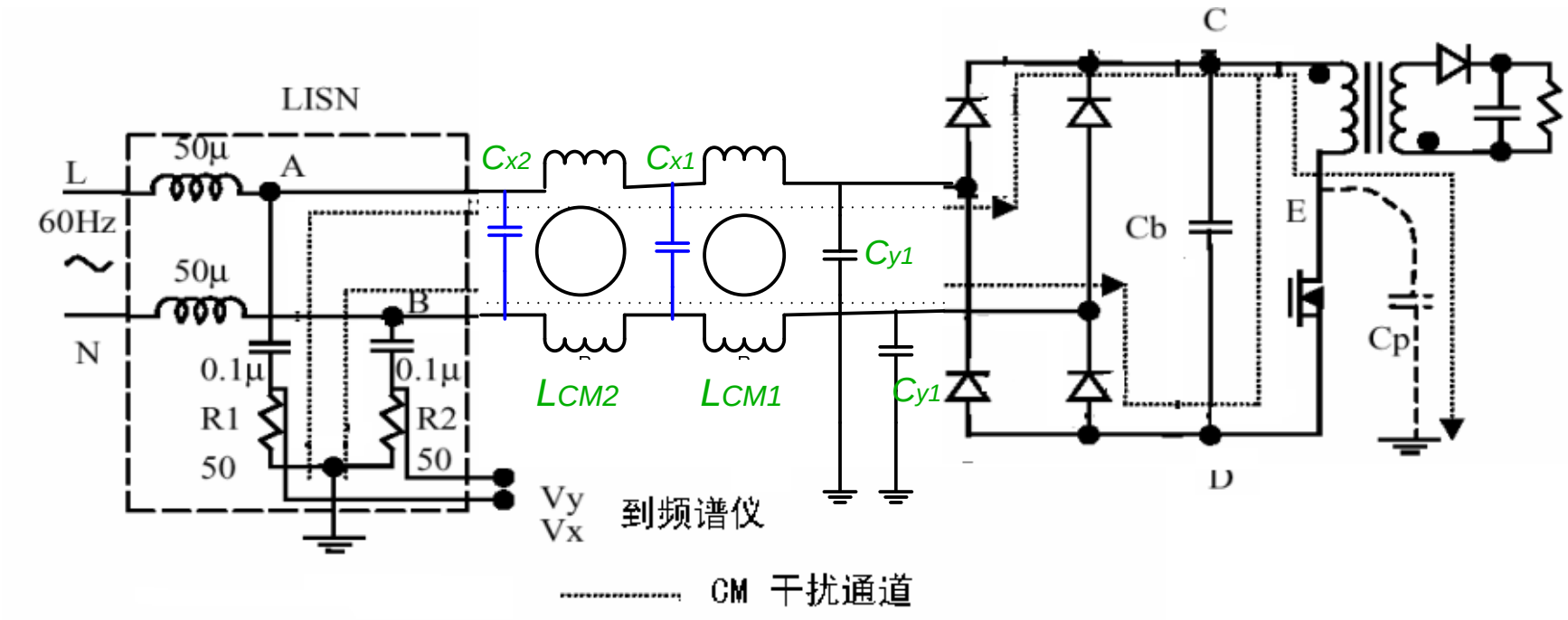
Generally, Cx is large several uF, Ldm is small!

CM EMI filter to control CM emission! It has no influence on DM EMI.



An actual EMI filter to control EMI emission!

CM filter+DM filter

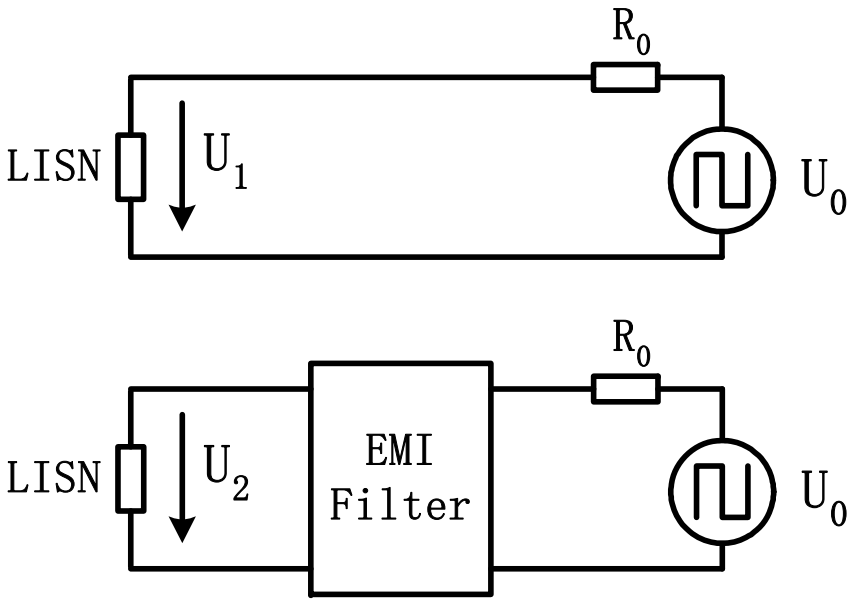


The leakage inductance of CM choke can be used as L_{DM}

二 电力电子装置EMI滤波器抑制技术

2. 1 EMI滤波器的设计和使用

Insertion Loss Definition



U_0: Noise Source

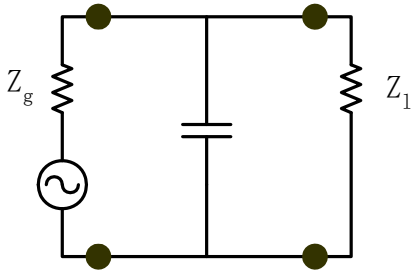
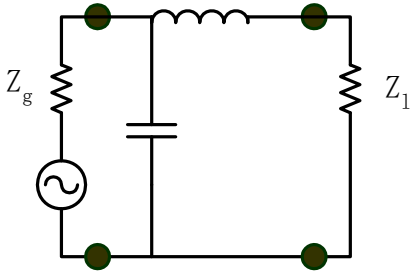
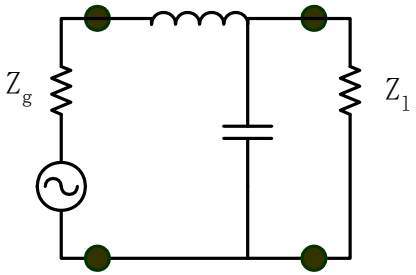
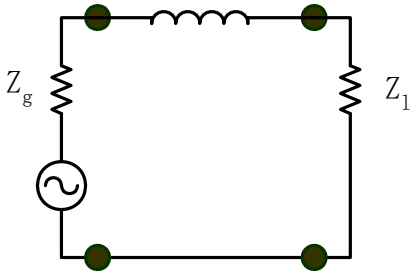
R_0: Noise Source Impedance

U_1: Voltage on LISN when without Filter

U_2: Voltage on LISN when with Filter

$$IL = 20Log(\frac{U_1}{U_2})$$

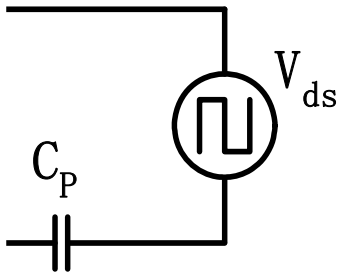
A: How to select the best EMI filter topology?

Z_g \ Z_l	High	Low
High		
Low		

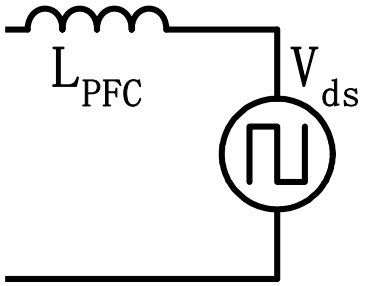
Z_g: Noise Impedance Z_1: LISN Impedance

If one stage is not enough, several stages filter can be used!

Power supply EMI can be separated into equivalent CM/DM EMI source model.

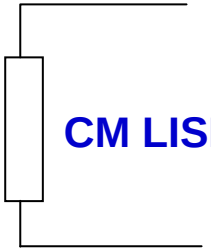


CM source

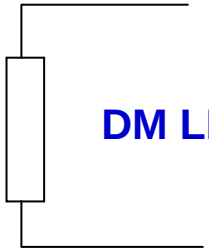


DM source

Generally—internal DM source impedance is small!
internal CM source impedance are large!



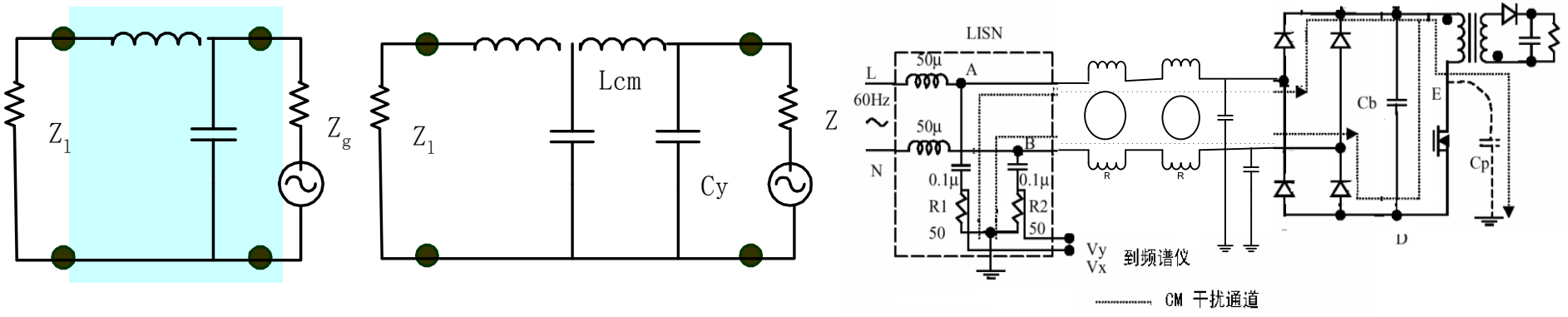
CM LISN=25 ohm



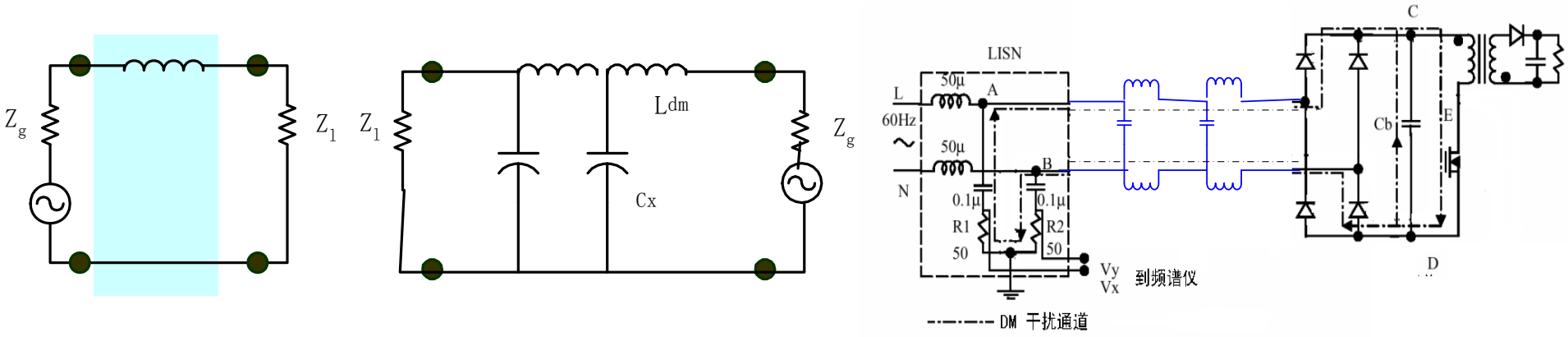
DM LISN=100 ohm

Generally—Both LISN DM impedance and CM impedance are small!

So, better CM filter topology

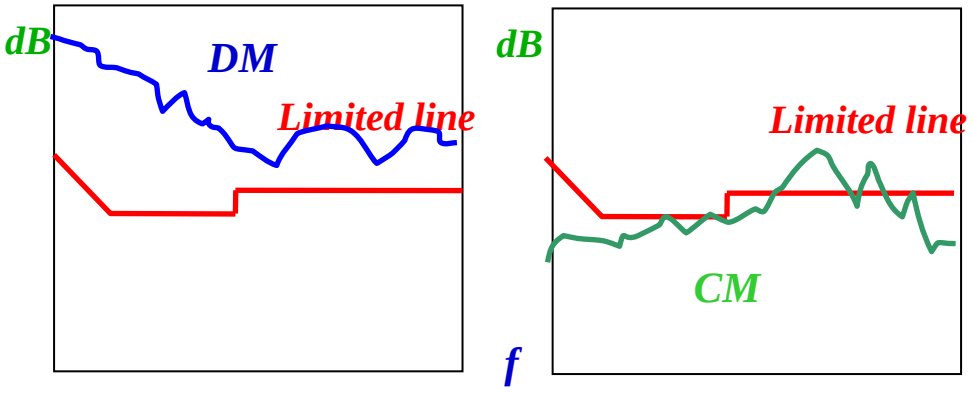


So, better DM filter topology

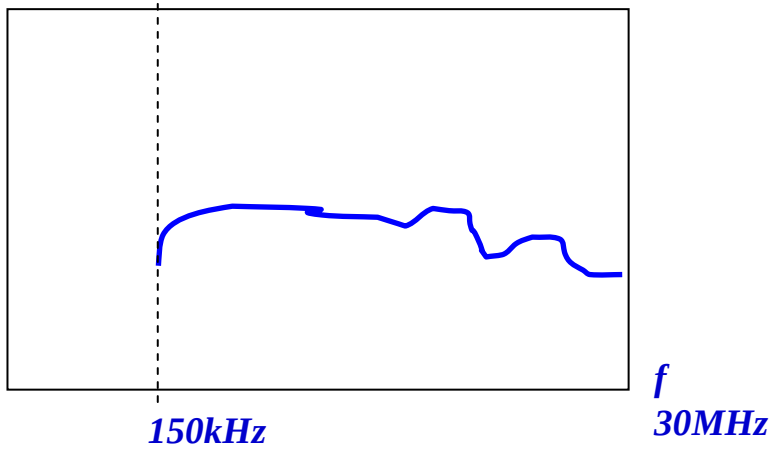


B: How to decide inductance, capacitance value of EMI filter topology?

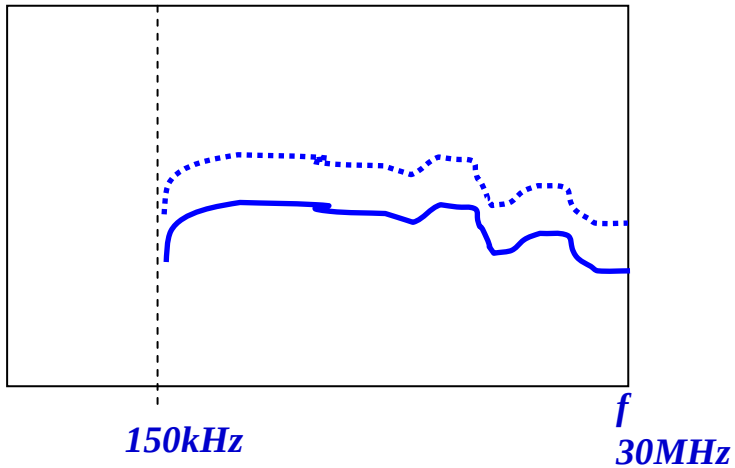
Step1: Separate CM/DM emission using test or simulation results!



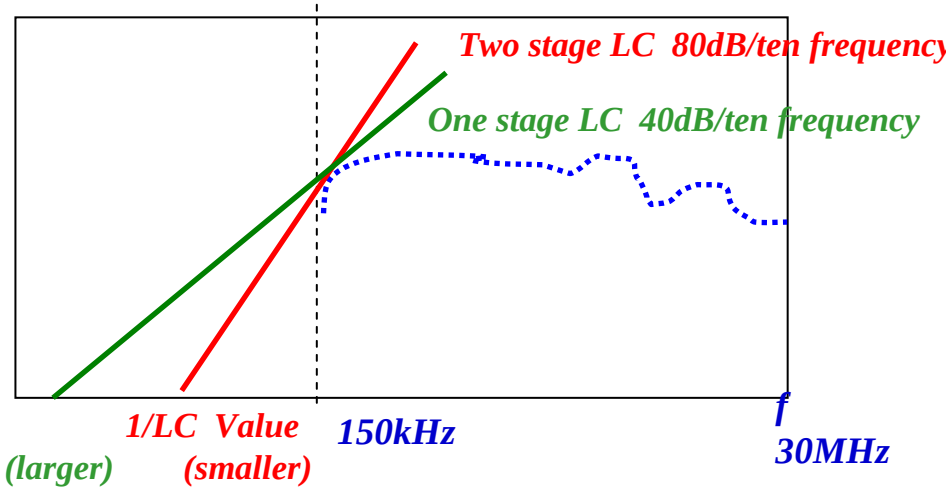
Step2: Using CM/DM emission decrease limited line, the IL needed of filter are gotten.



Step3: adding 10 dB margin for both CM/DM IL needed



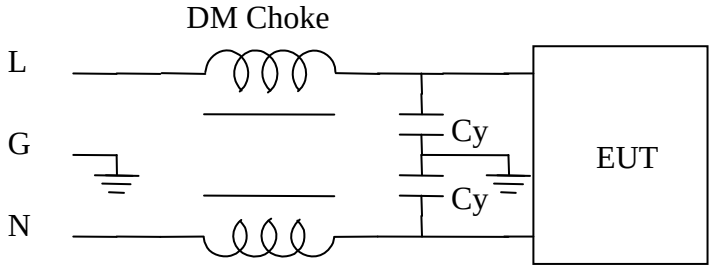
Step4: According LC number, draw N*40dB line which is tangential to dot IL line.



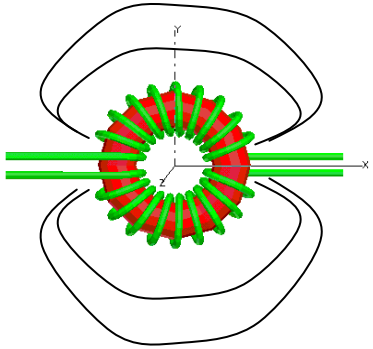
Step5: LC value, consider other factor, we can decide L and C.

For CM, the max Cy value is limited by leakage current, so Lcm=f0/Cy.

Lcm is called CM choke too.

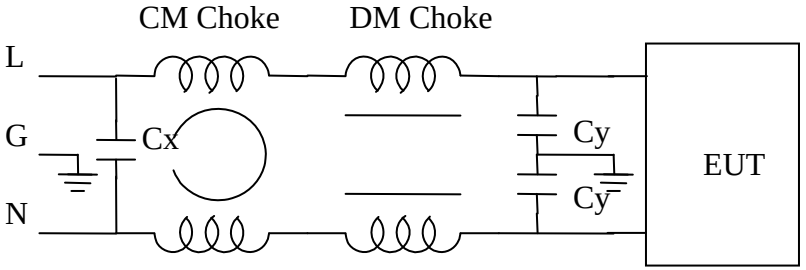


For DM, for Cx can be easy large enough, Ldm is select small. In most case Ldm can be replaced by the leakage inductor od CM choke.



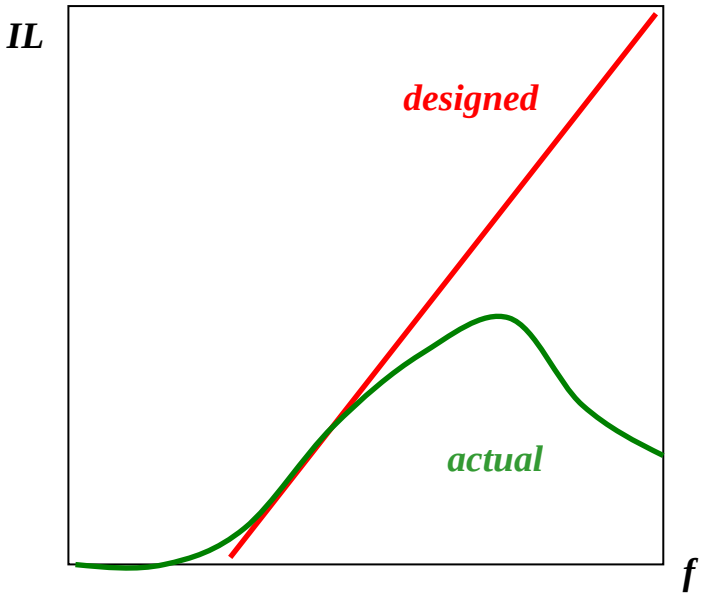
leakage inductor

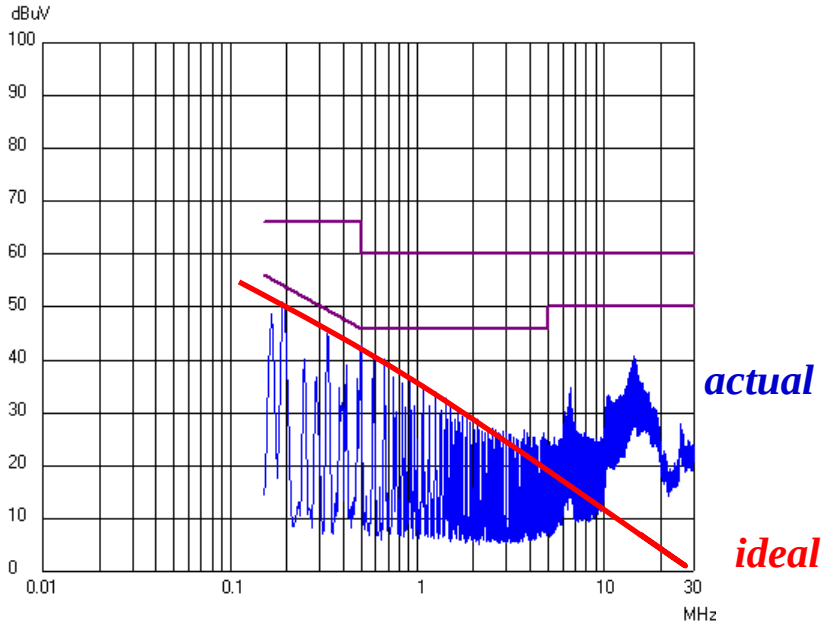
Step6: finish design and test.

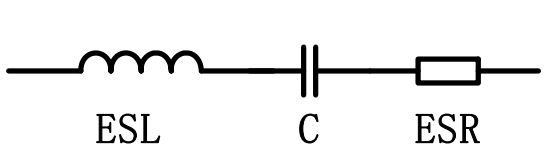


C: Actual problem during EMI filter use

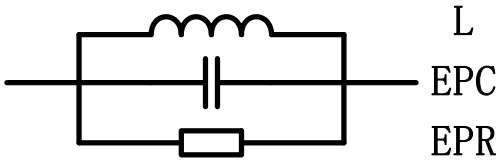
1: HF IL are lower than expected.







Capacitor Model



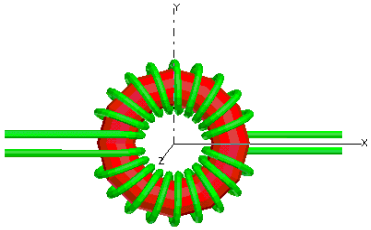
Inductor Model

What to do?

Decrease parasitic as possible!

1: Using good HF capacitor or inductor! Small parasitic parameter!

对于电感：



铁氧体：易饱和、导磁率高，常用作共模扼流圈的磁芯

锰锌：μr = 500 ~ 10000 for lower frequency CM choke

镍锌：μr = 10 ~ 100 fit for HF CM choke

采用少匝，交错绕制等办法减小线圈的EPC!

非晶，纳米晶磁芯

特点：类似于锰锌铁氧体、高u, 高Bs，LF

用途：电感、变压器，LF CM choke

安泰

铁基非晶

饱和磁感应强度Bs	1.25 T	饱和磁致伸缩系数	2×10^{-6}
居里温度Tc	560 °C	密度d	7.2 g/cm^3
晶化温度Tx	510 °C	电阻率	130muOhm-cm
硬度Hv	880kg/mm^2	热膨胀系数	

产品牌号	R-N-L	R-N-M
初始导磁率	$>3\times10^4$	$>8\times10^4$
最大导磁率	$>5\times10^4$	$>45\times10^4$

铁基纳米晶

饱和磁感应强度Bs	1.25 T	饱和磁致伸缩系数	2×10^{-6}
居里温度Tc	560 °C	密度d	7.2 g/cm^3

产品牌号	R-N-L	R-N-M	R-N-H
初始导磁率	$>3\times10^4$	$>8\times10^4$	$>1\times10^4$
最大导磁率	$>5\times10^4$	$>45\times10^4$	$>50\times10^4$

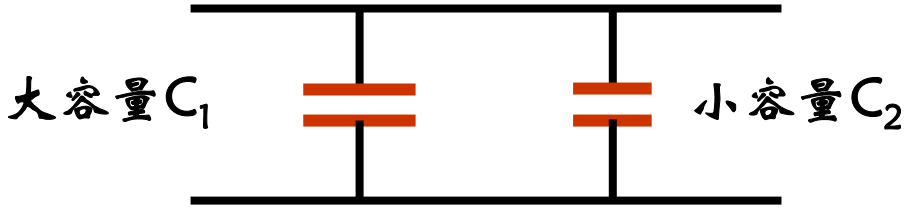
钴基非晶

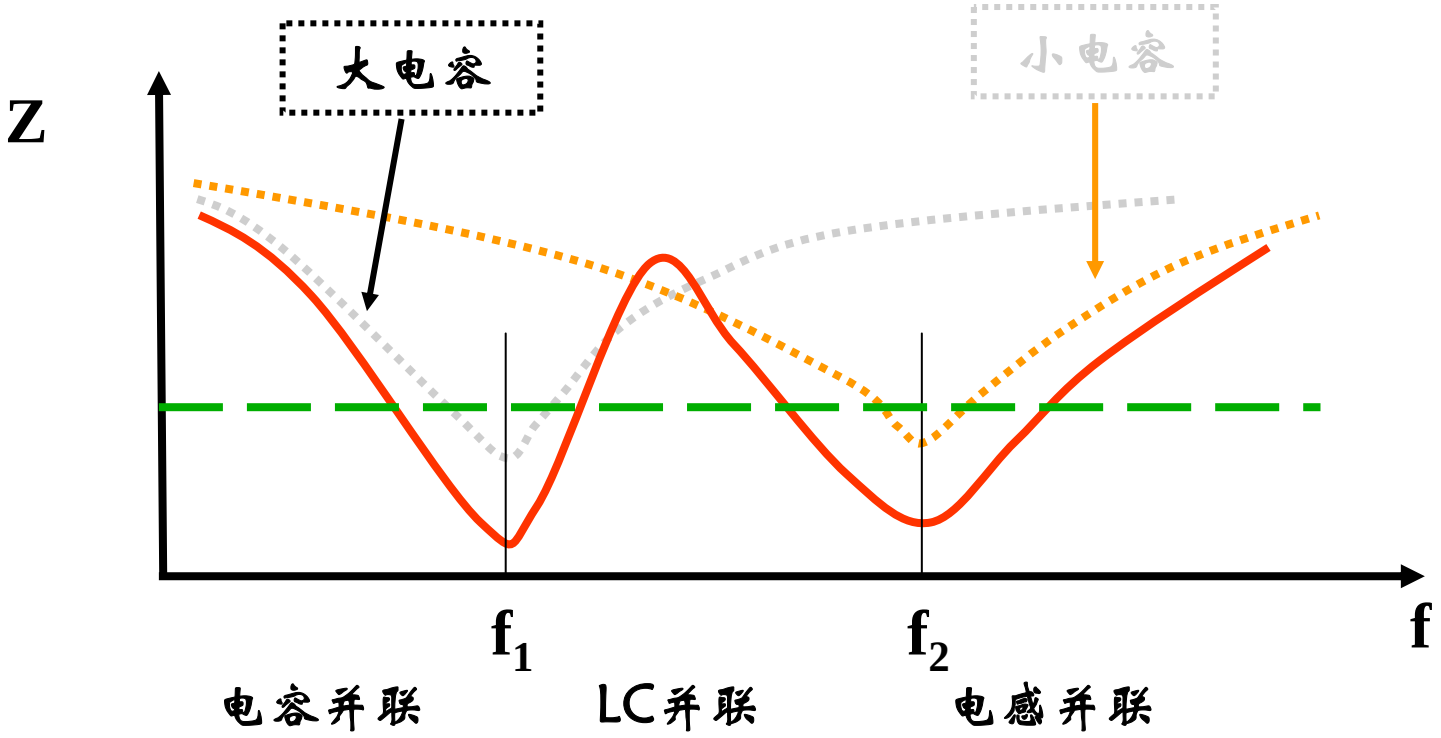
产品牌号	R-N-L	R-N-M
初始导磁率	$>3\times10^4$	$>8\times10^4$
最大导磁率	$>5\times10^4$	$>45\times10^4$

饱和磁感应强度Bs	1.25 T	饱和磁致伸缩系数	2×10^{-6}
居里温度Tc	560 °C	密度d	7.2 g/cm^3
晶化温度Tx	510 °C	电阻率	130muOhm-cm
硬度Hv	880kg/mm^2	热膨胀系数	

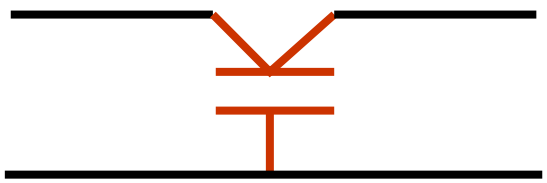
对于电容：

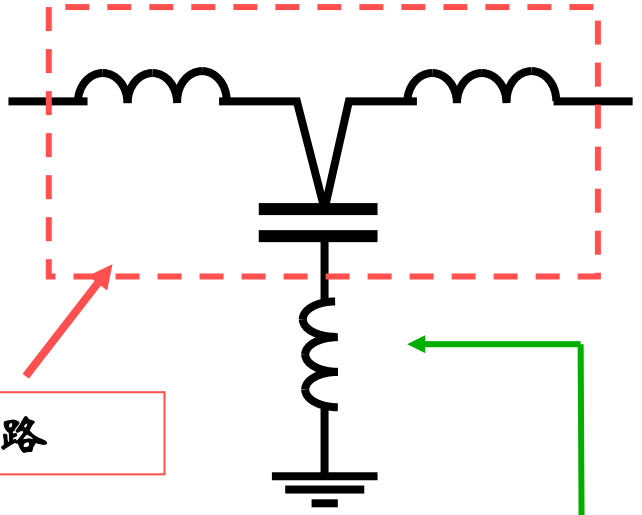
1：采用高频性能好的小电容。

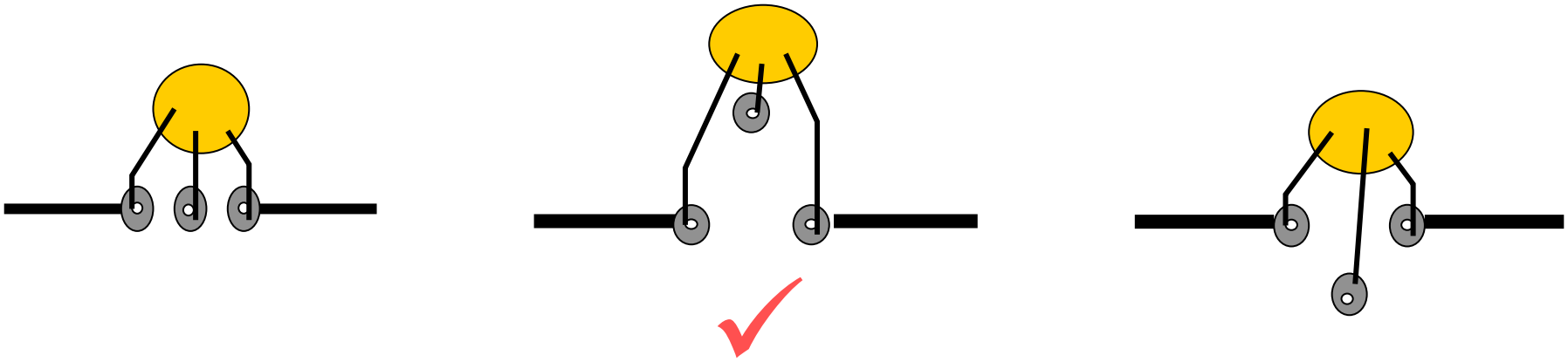




使用三端电容器

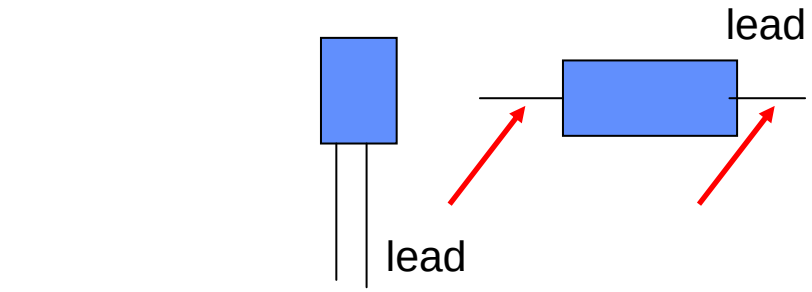


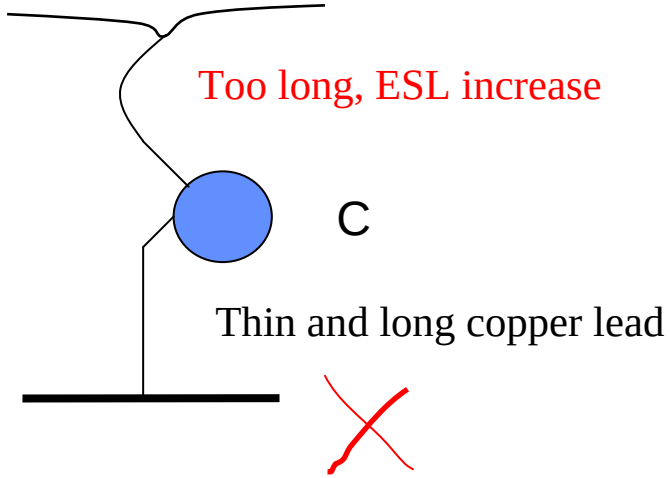


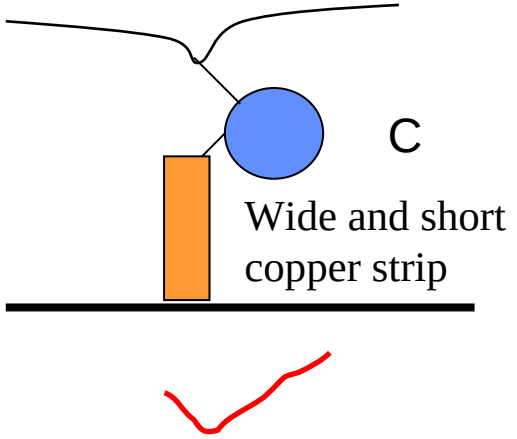


一些新型结构电容，x2y,

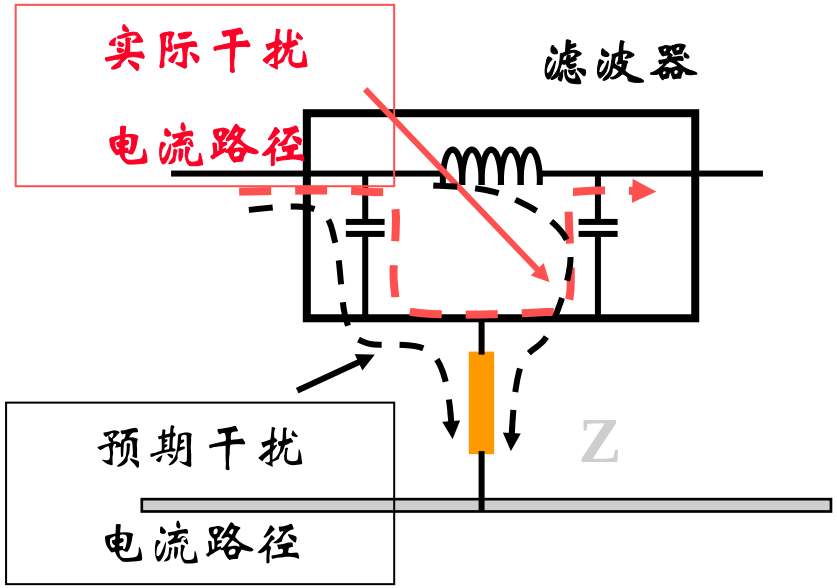
2: Decrease lead length of capacitor as shorter as possible. ESL!

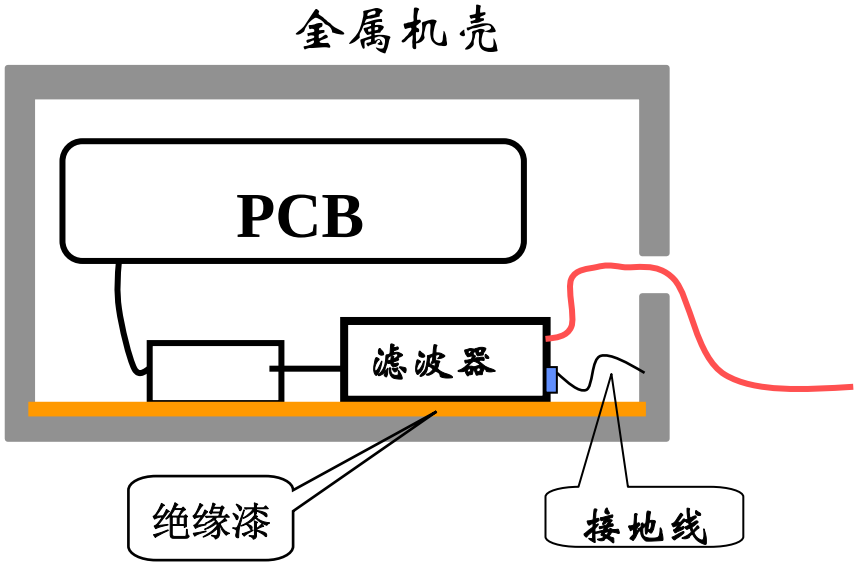




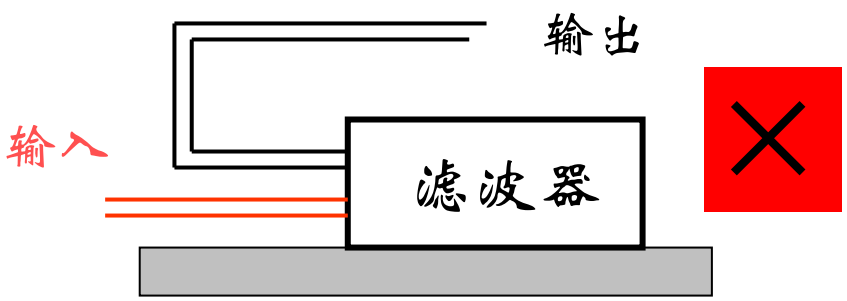


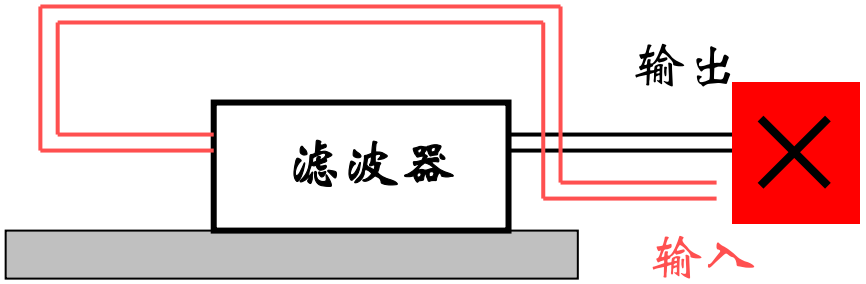
3: Carefully installment!



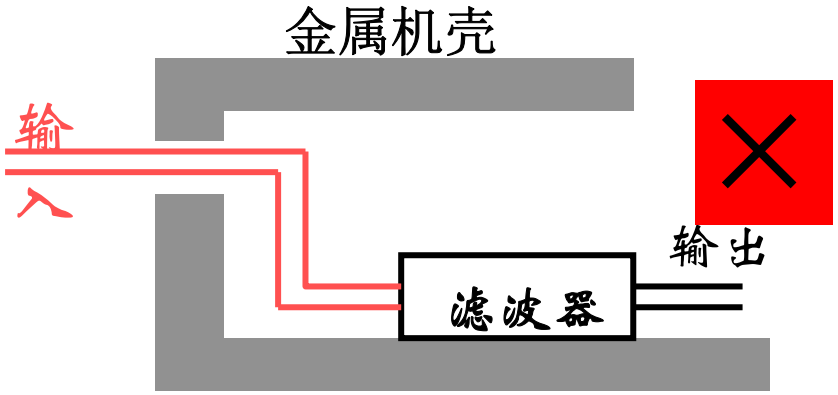


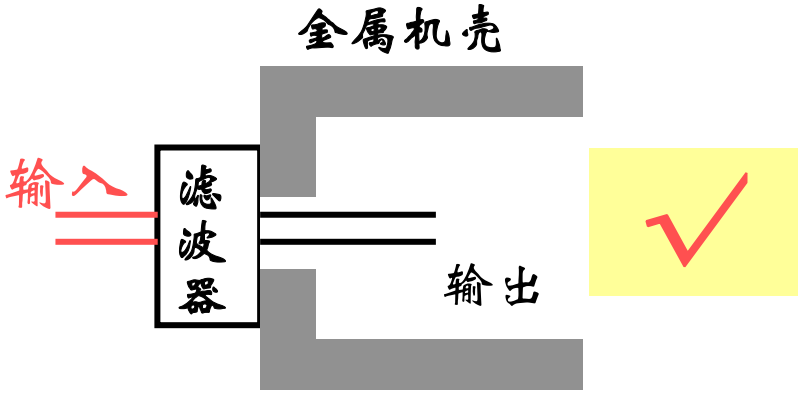
滤波器的输入输出引线应拉开距离，严禁并行走线和交叉走线。





滤波器的输入、输出引线之间尽可能实现屏蔽隔离。

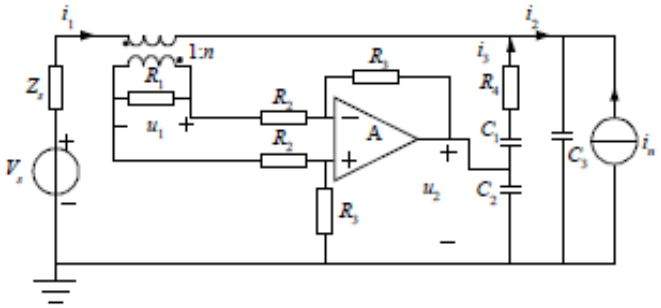


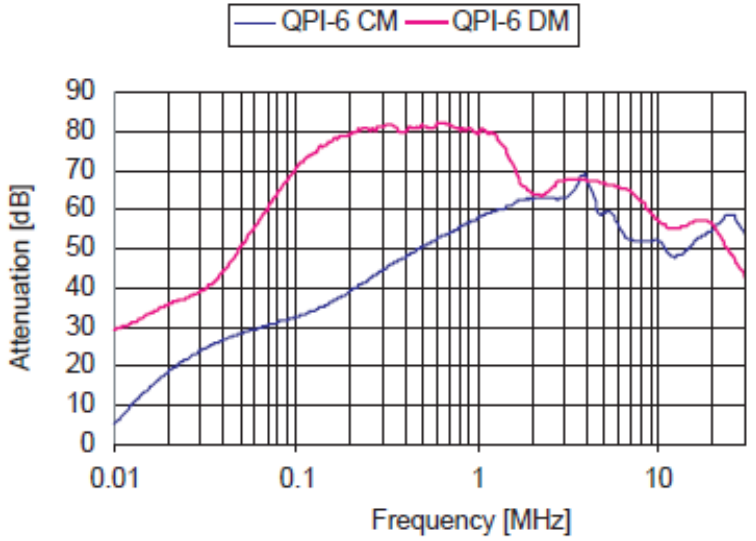


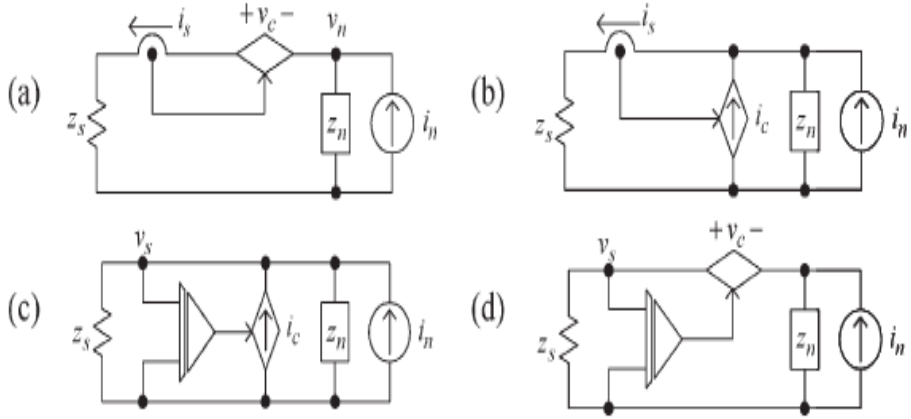
有源滤波器，可在150kHz-几MHz有效

Active EMI filter for DC/DC

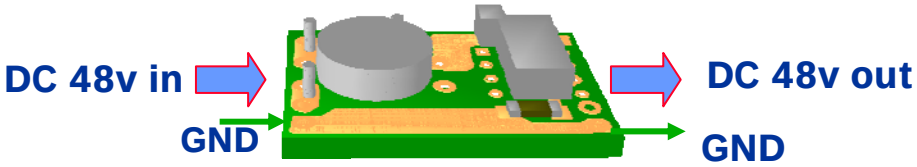
Picor Com



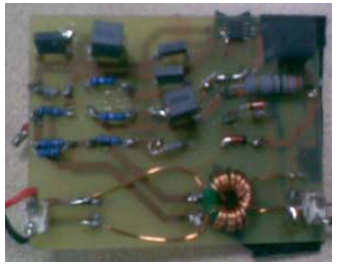




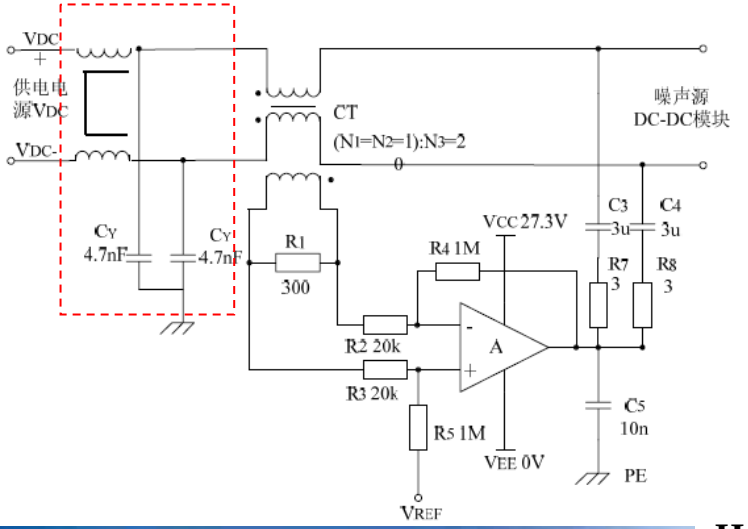
ALL active EMI filter topology

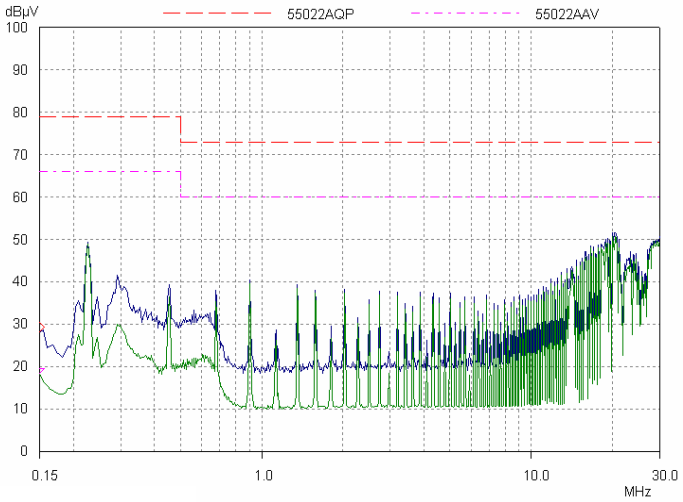


Delta/ Xjtu/



Emerison/ Hit

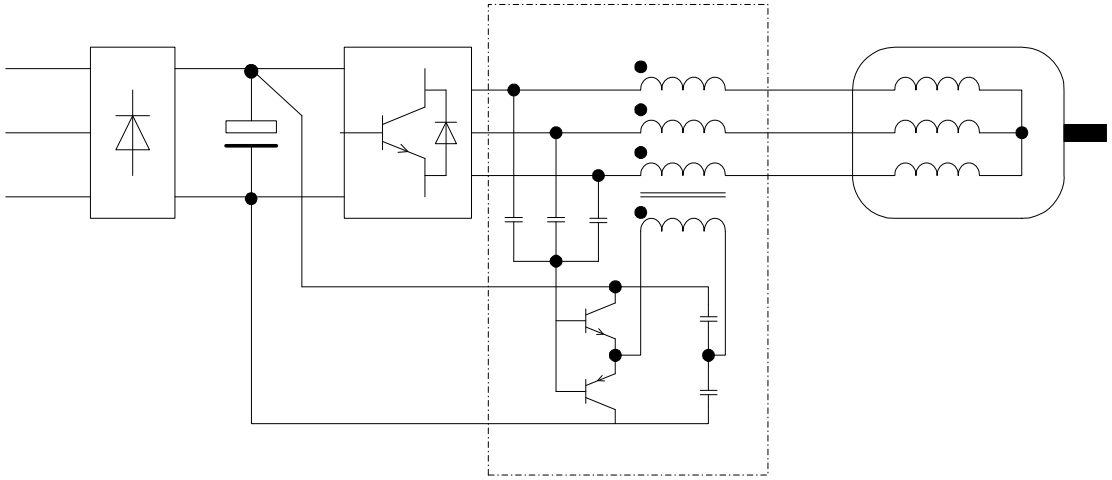


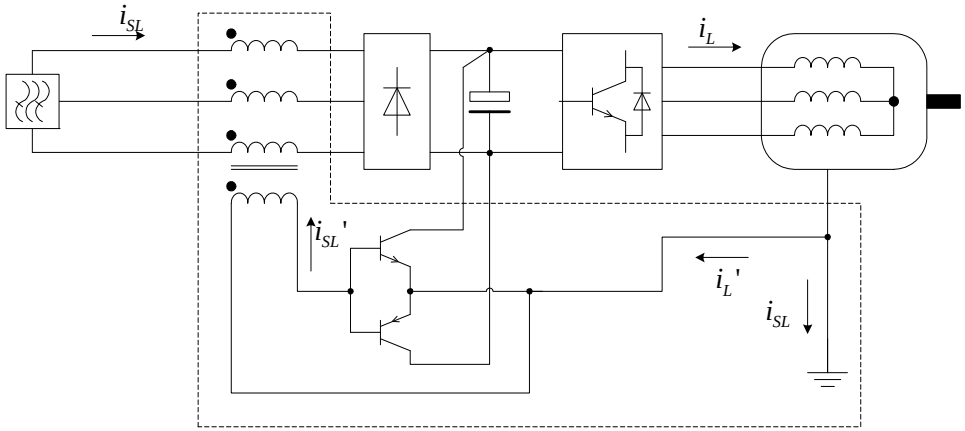


Hybird EMI filter

也用于逆变电源

Active Common Mode Noise Canceller

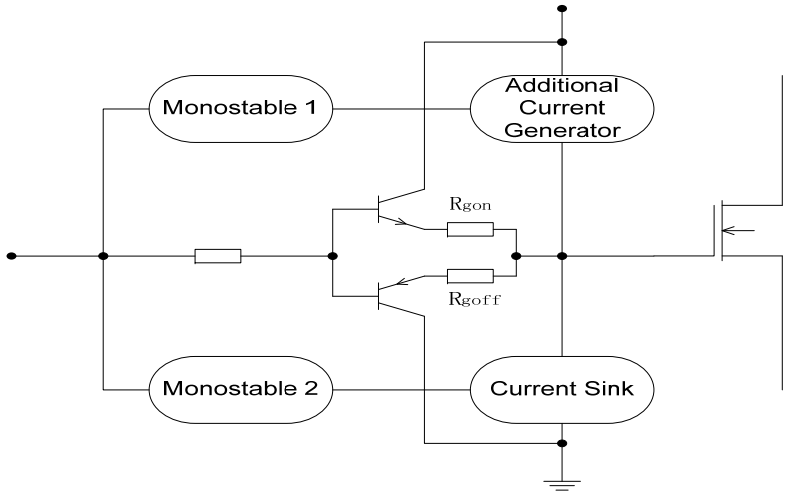


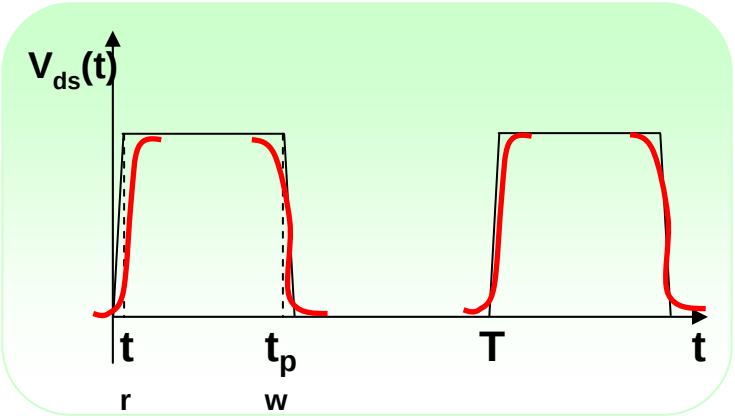


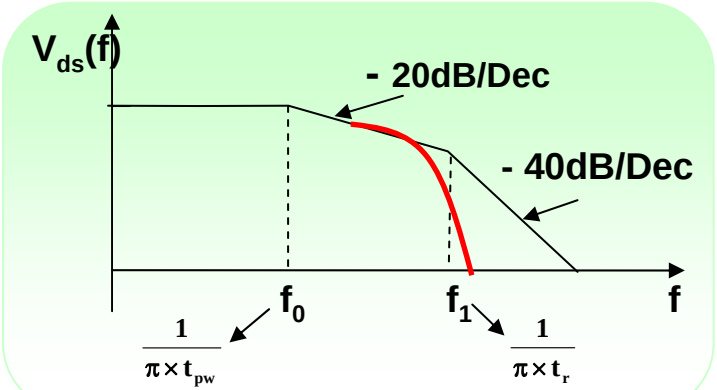
Active EMI Filter

三：根据电源拓扑、结构、控制等多种方面，采用新型抑制方法

B1:改善门极驱动





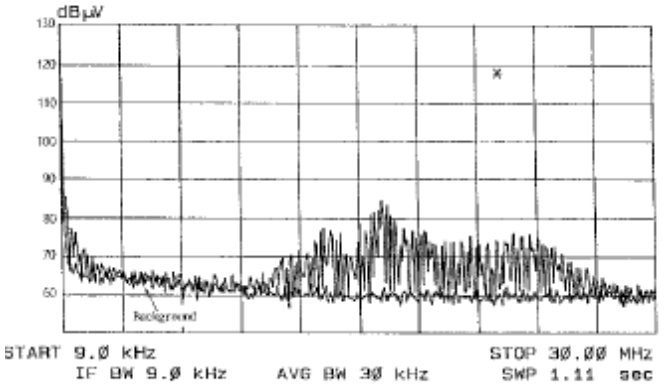


适当的驱动可使功率损耗和高频频谱得到平衡

已商业化。

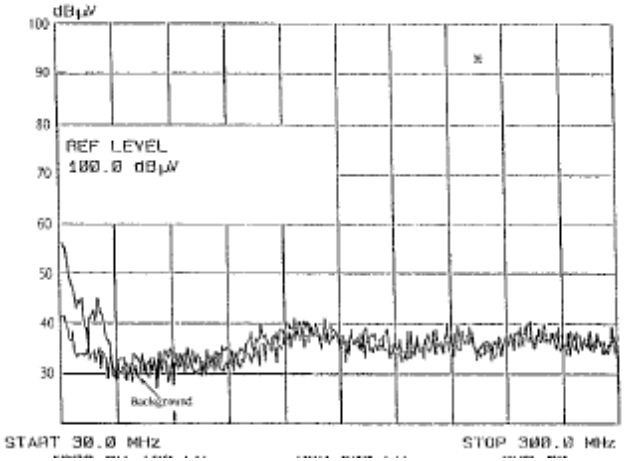
B2：合适的软开关技术

City University of Hong Kong



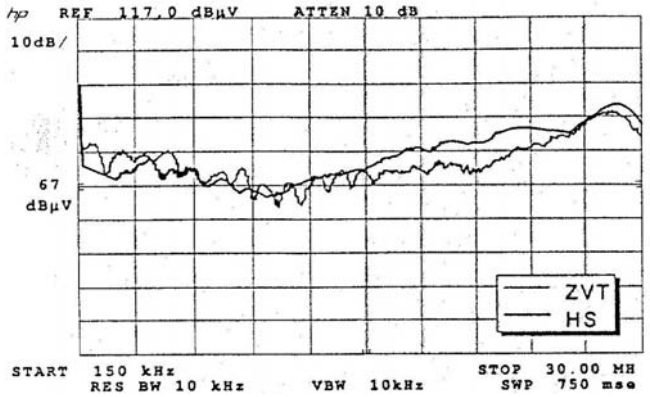
传导发射

BUCK/BOOST/FLYBACK

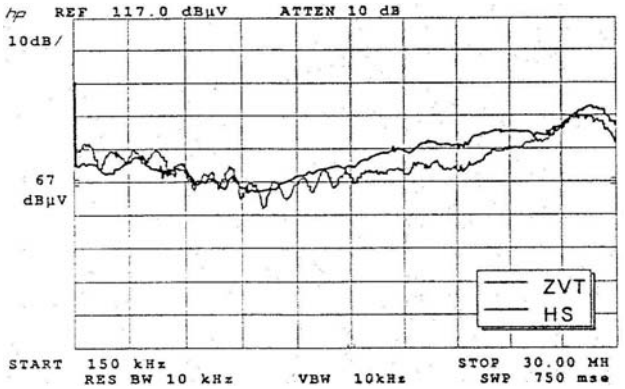


辐射发射

CPES Hard-switching vs. soft-switching of a inverter



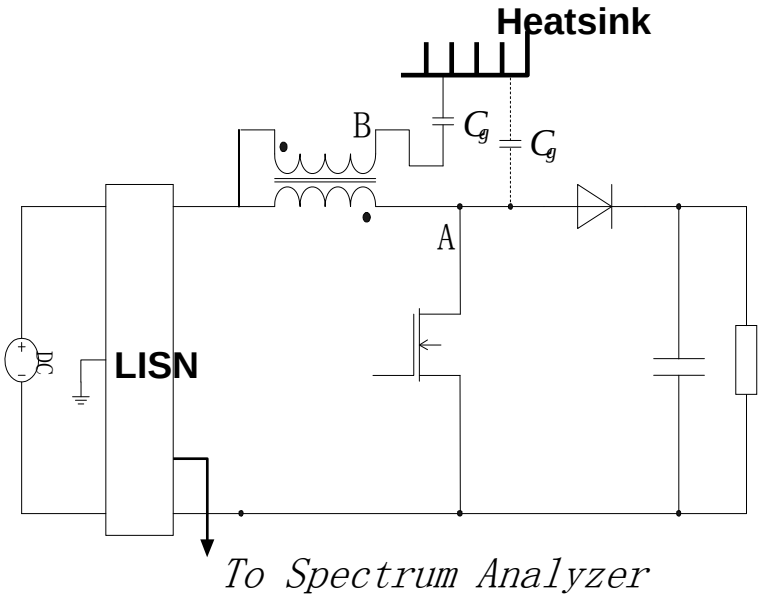
L 线传导发射

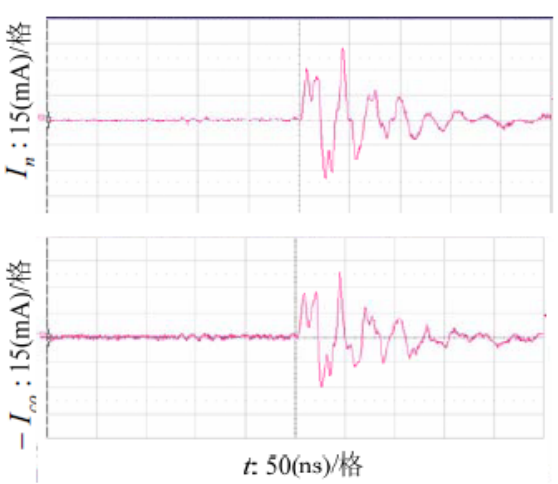


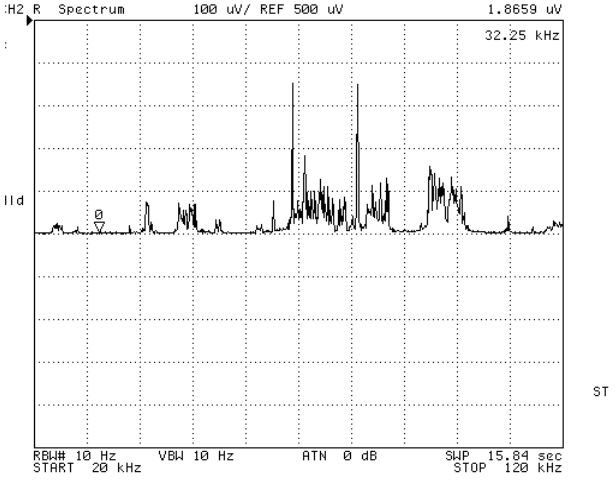
N 线传导发射

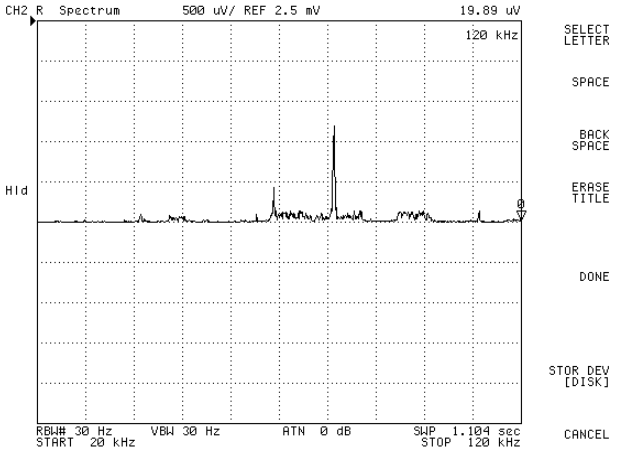
B3：反向补偿技术

Feedback Coil in the Boost Inductor

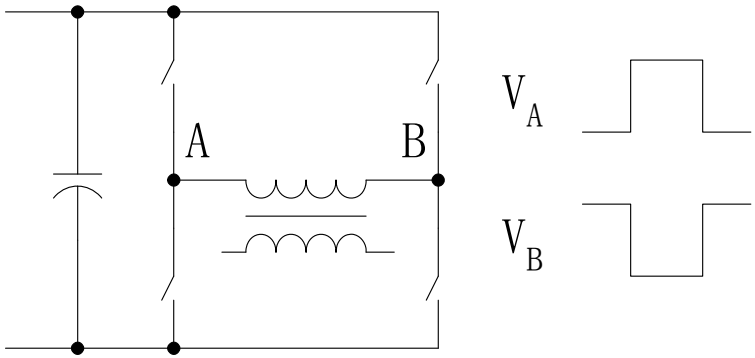








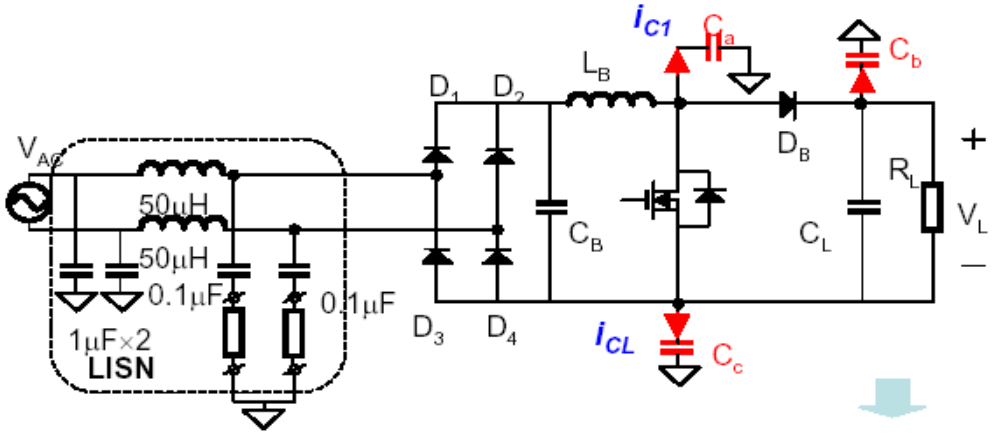
B4：对称平衡结构➔抑制共模发射的有效办法

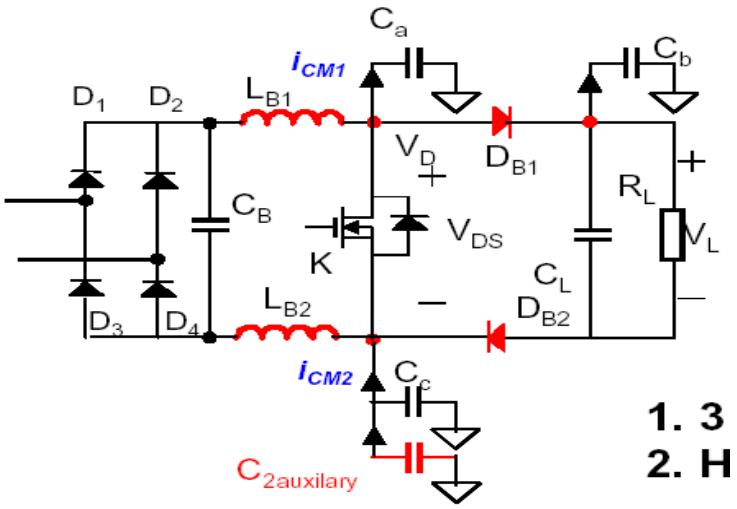


ZERO CM EMISSION!

FBSP bad CM emission!!

Symmetric trigger



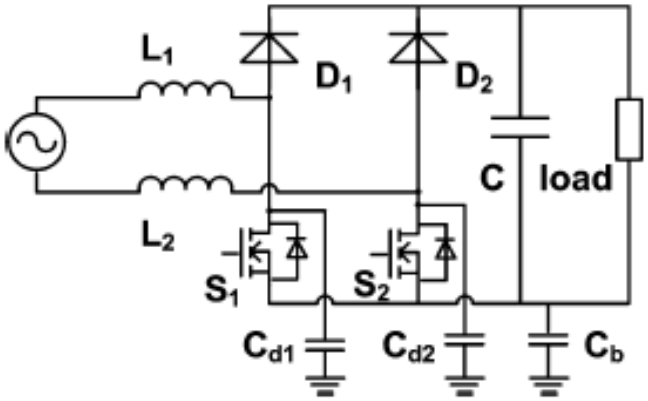


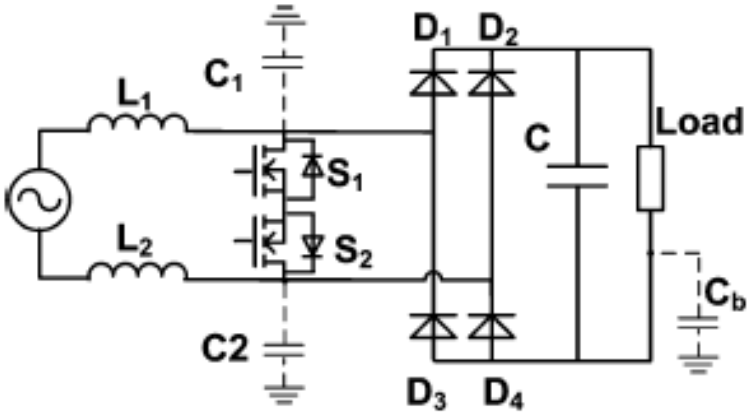
Symmetric structure

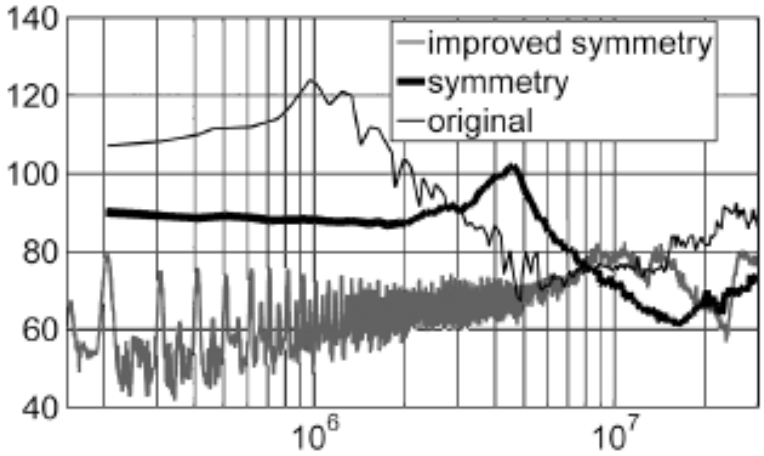
These principle has early been proposed in 90's and it can be used in any topology.

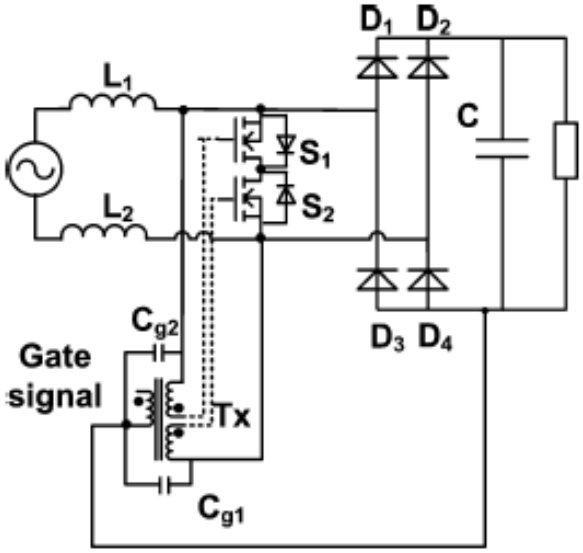
Low effectiveness, high cost!

Dual Boost：CM Emission is large.



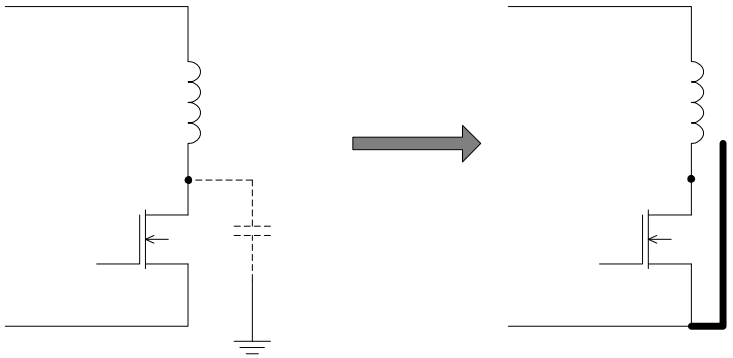


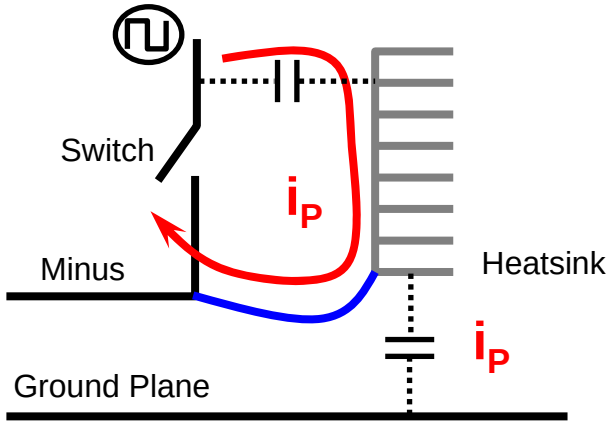




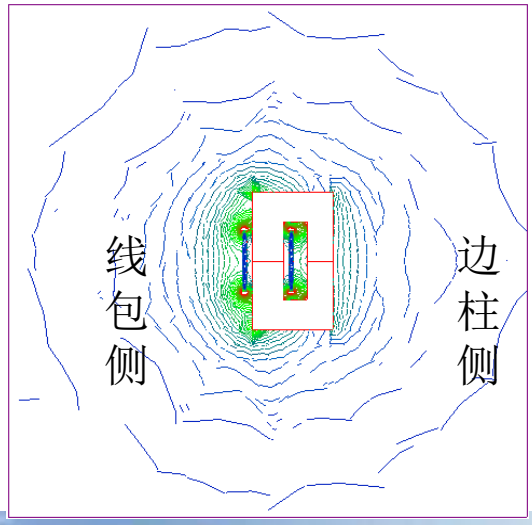
B5：巧用屏蔽

1. Heatsink Connected to the Minus bus

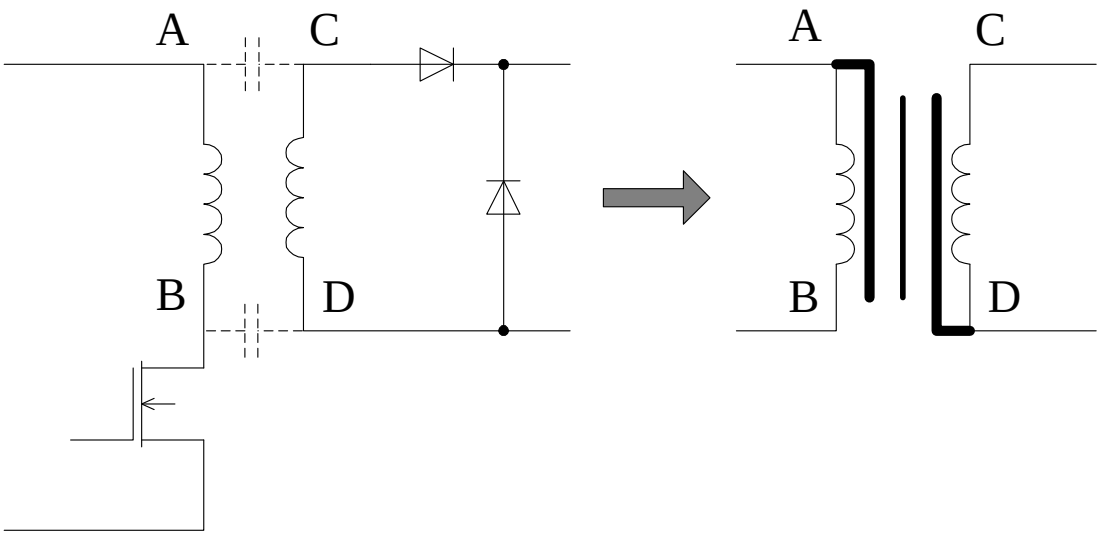




2 . Copper Foil around X'FORM



3: Shielding primary and secondary of transformer



Delta com：USA patent 20070171585
Method for suppressing common mode noise

B6：频率调制技术

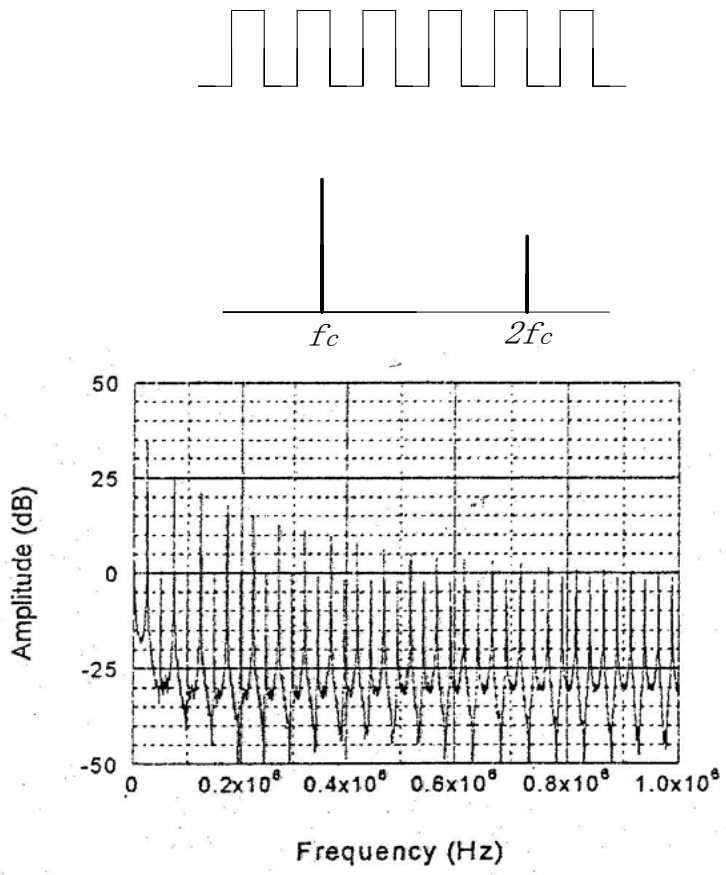


Fig 1a. Constant 25kHz PWM

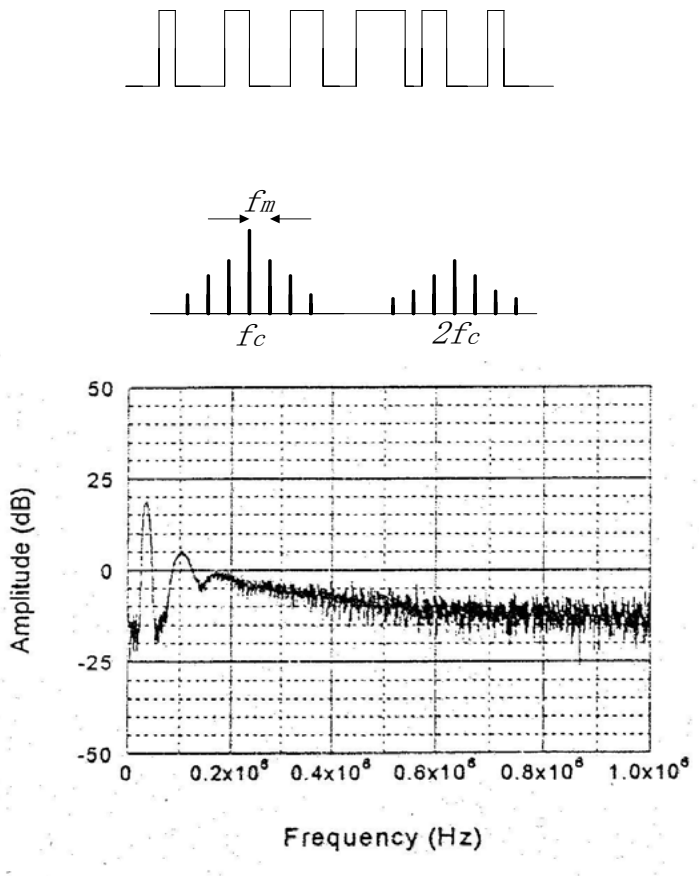


Fig 1c. Δf=20kHz (frequency varied from 25kHz to 45kHz), n=256.

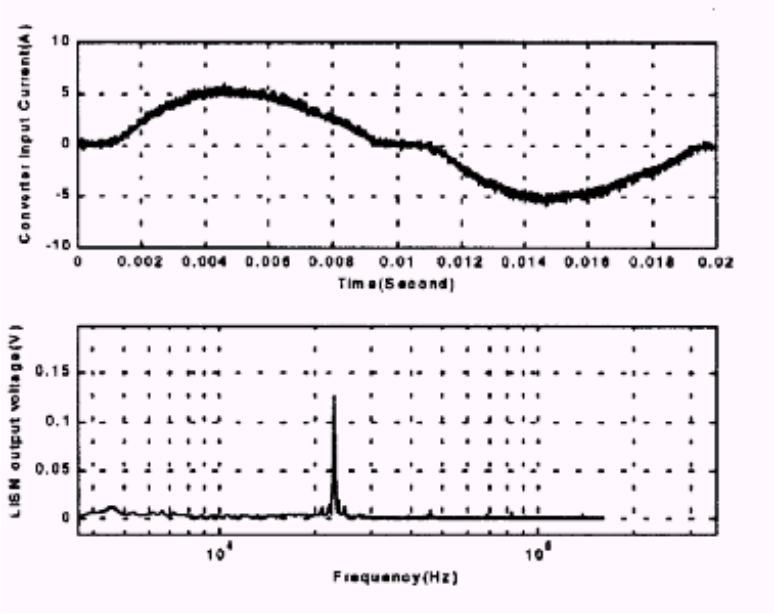
Switching frequency modulation

__ proposed by F. Lin et al , IEEE PESC'93

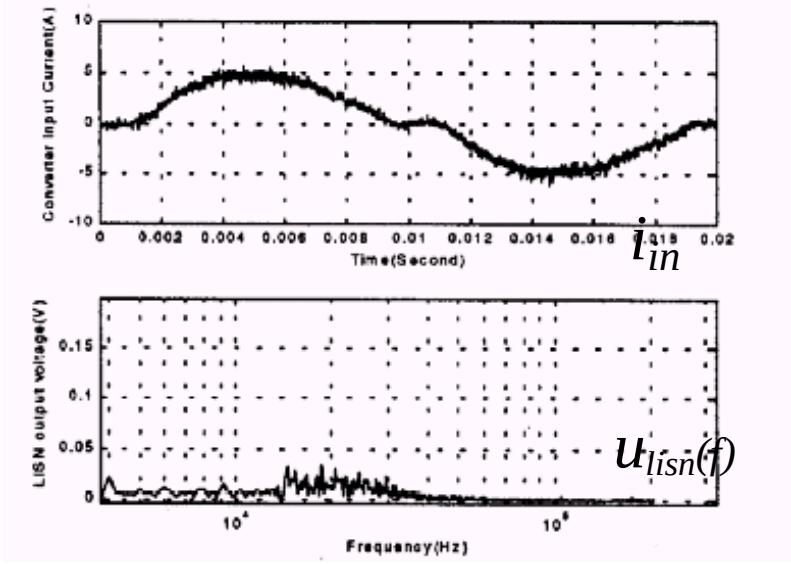
- ***Random modulation***
  _____ *proposed by D.A. Stone et al, IEEE APEC'96*

- ***Sigma - Delta modulation***
  _____ *proposed by J. Paramesh et al, IEEE APEC'99*

- ***Comparison : PWM & RPWM*** [43]



PWM, f = 25 kHz

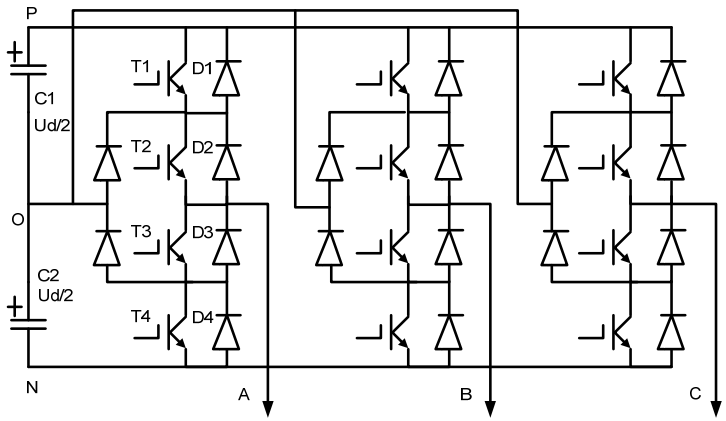


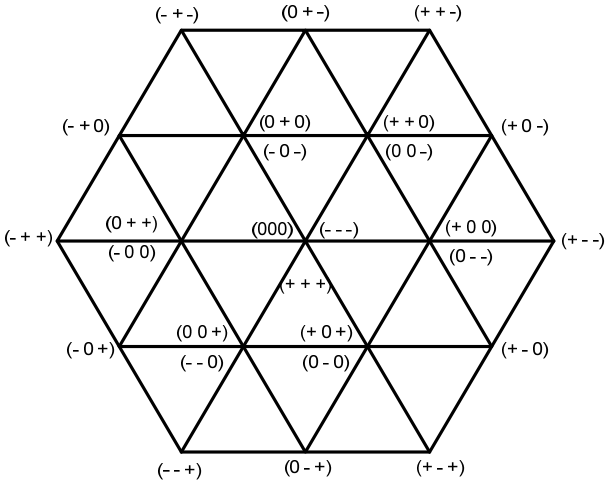
RPWM, 15 kHz< f <30 kHz

已商业化!

抖频幅度要大于10kHz. 输出直流有调制纹波!

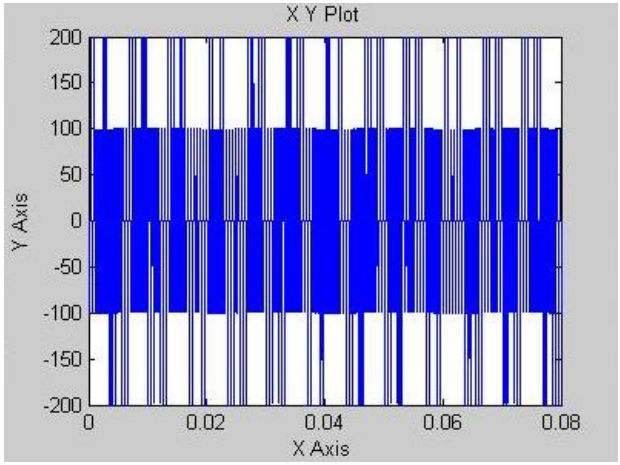
B7：合理触发控制

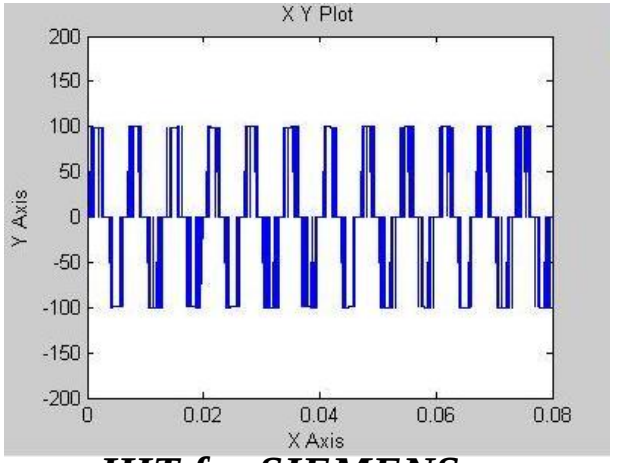




三电平逆变器共存在27状态，存在Ua+Ub+Uc小的SVPWM策略

CM Voltage 可从Ubus/3 降到 Ubus/6 ！



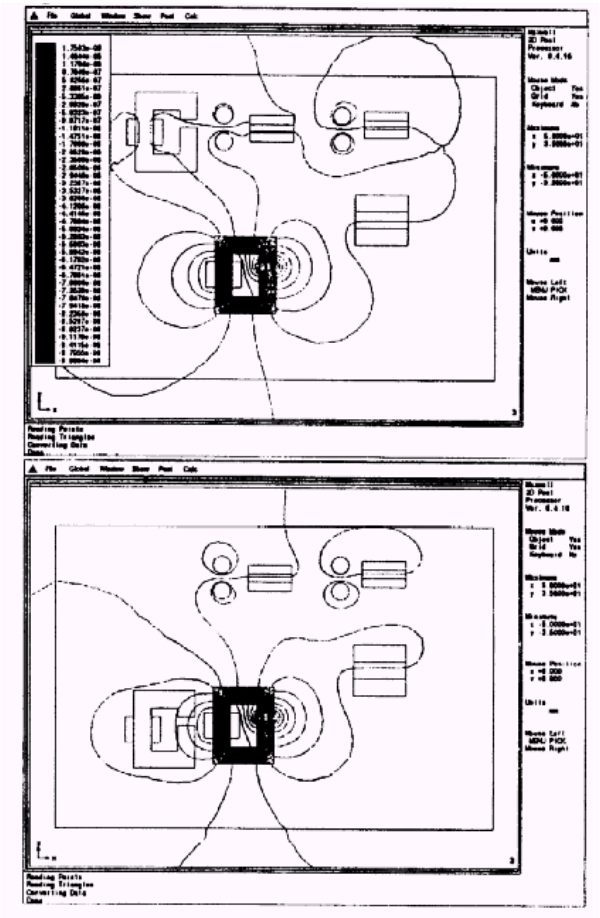


HIT for SIEMENS

B8：PCB精心设计

减小dv/dt导体面积，减小di/dt回路面积！
敏感电路远离高dv/dt、di/dt点！

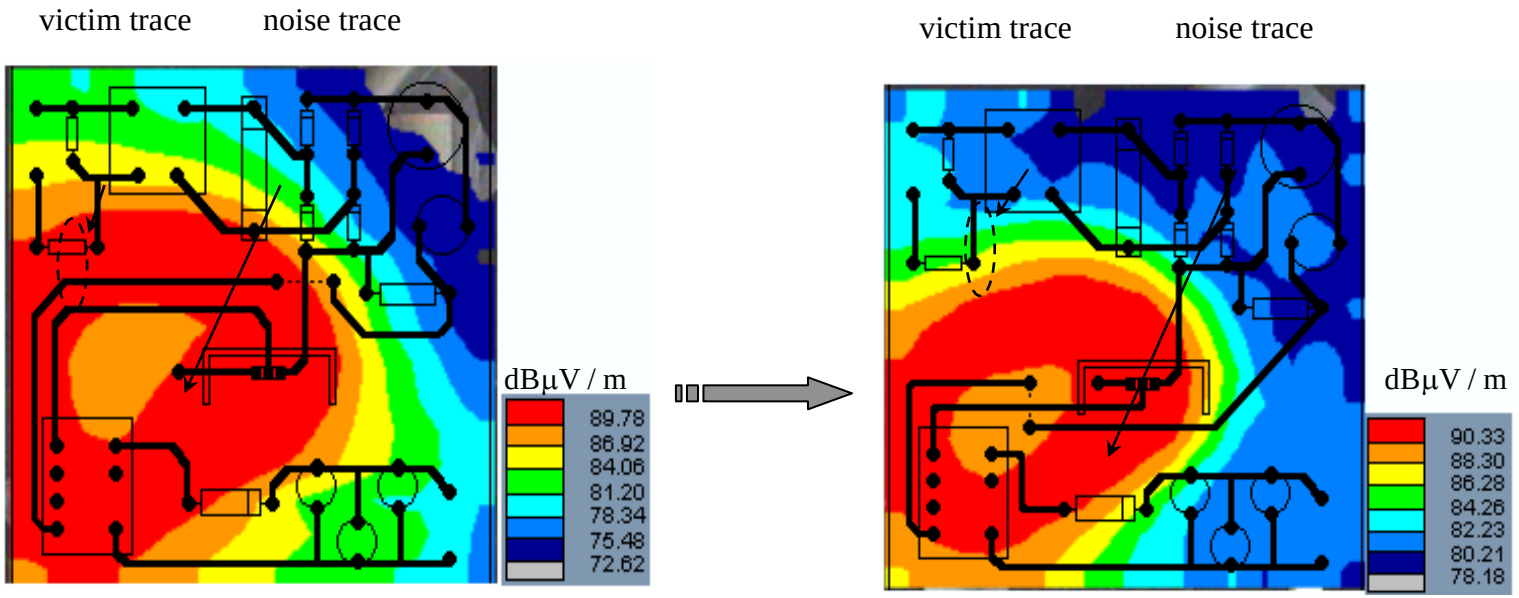
MAXWELL Software Assistant Method



(a) Flux plot of quasi-resonant boost converter with basic layout

(b) Flux plot of quasi-resonant converter with changed good layout

Routing Traces by Electrical Field Emission scan

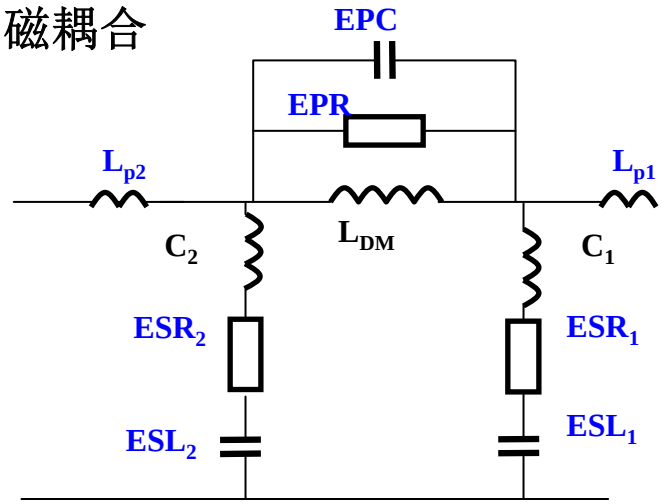


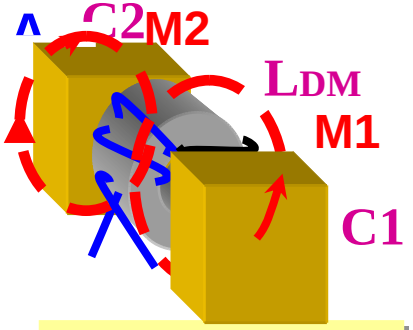
___ proposed by X. Wu Zhejiang Univ, IEEE APEC'99

- The victim trace in weaker emission area is likely to pick up less noise;
- PCB designers can arrange critical trace in suitable position to receive less interference according to emission map.

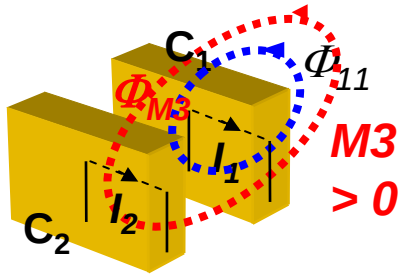
四：EMI滤波器的特殊问题

磁耦合



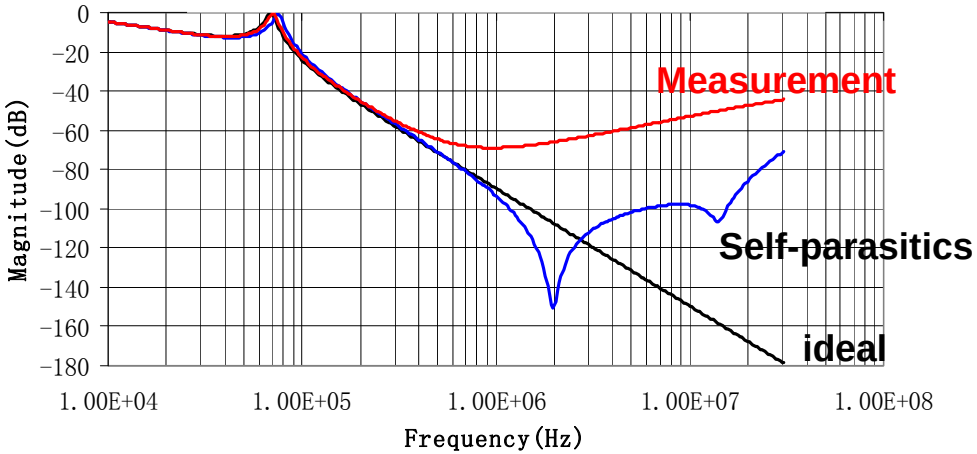


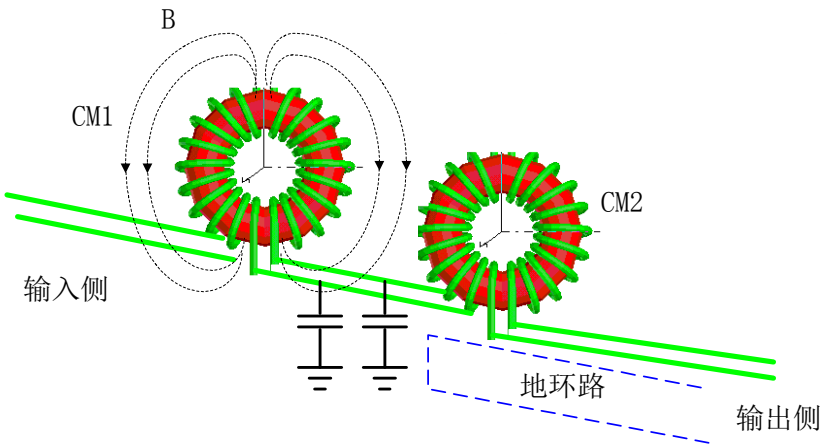
M1,2 : -89.3nH



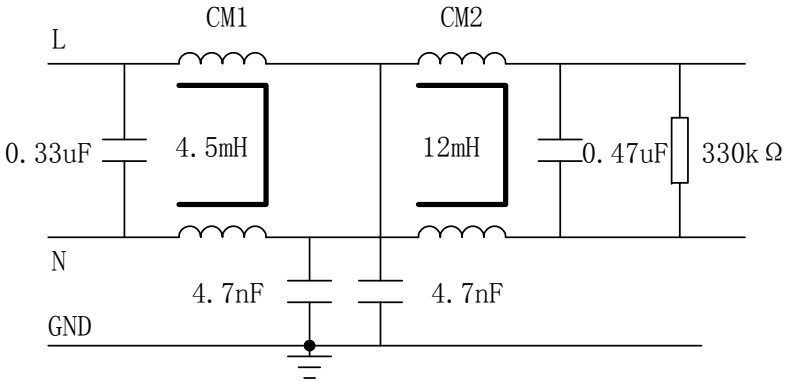
Parallel

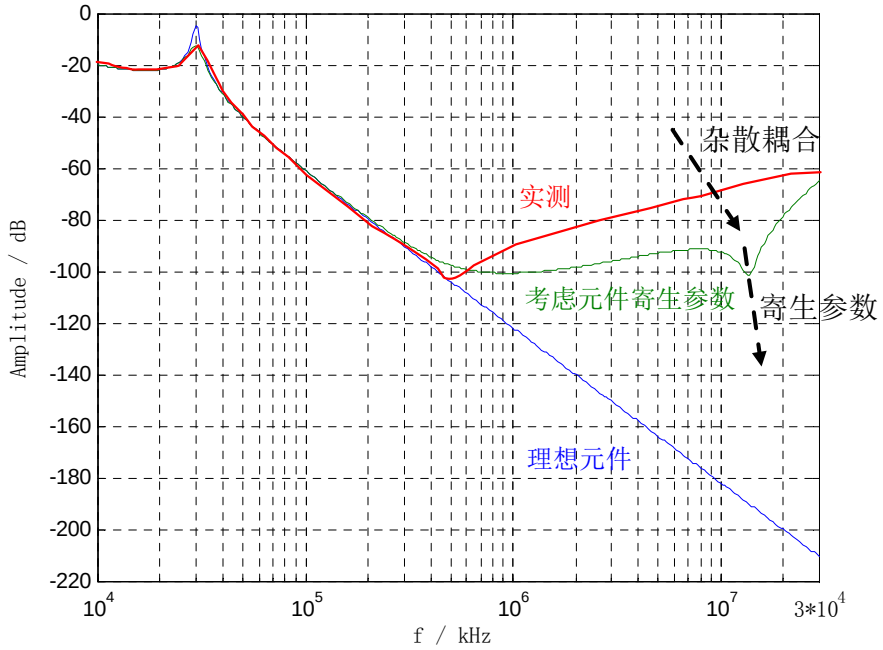
Insertion Voltage Gain



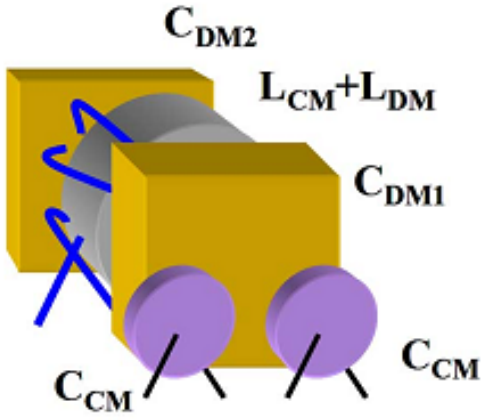

B
CM1
CM2
输入侧
地环路
输出侧

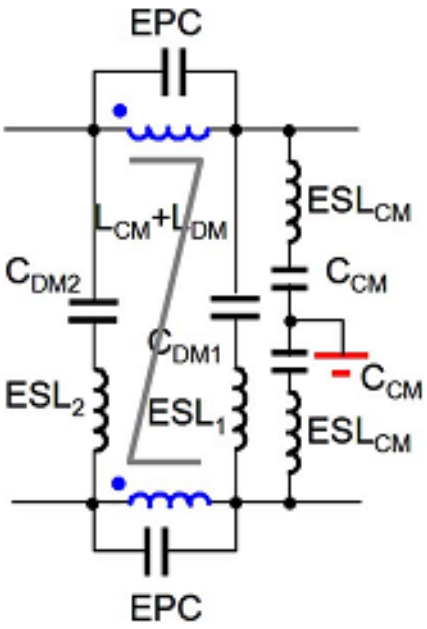
电耦合

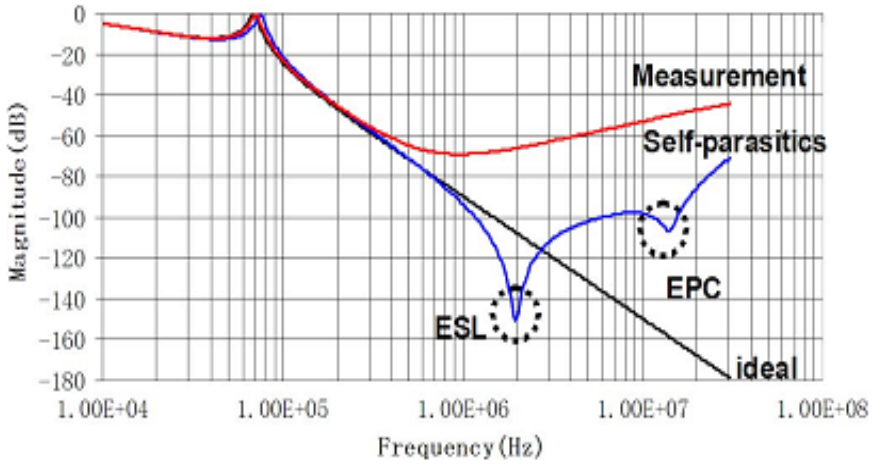

L
CM1
CM2
0.33uF
4.5mH
12mH
0.47uF
330kΩ
N
4.7nF
4.7nF
GND

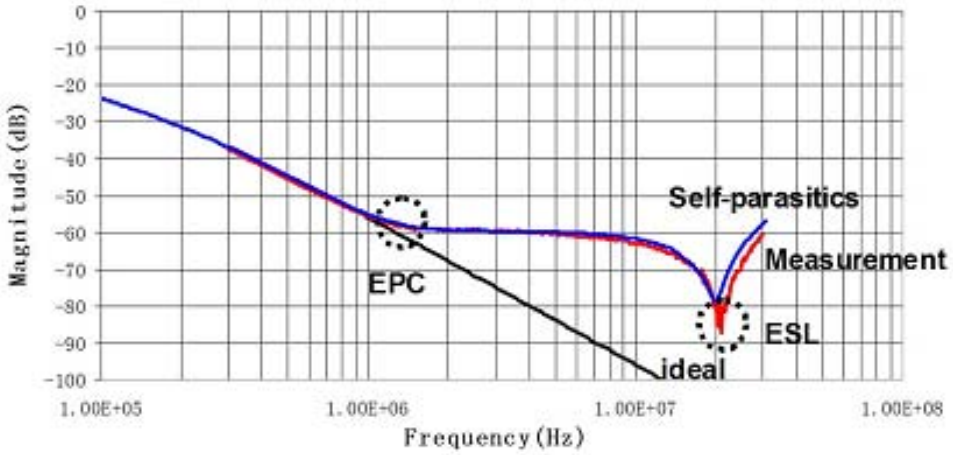

0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
Amplitude / dB
10^4
10^5
10^6
10^7
3*10^4
f / kHz
杂散耦合
实测
考虑元件寄生参数
寄生参数
理想元件

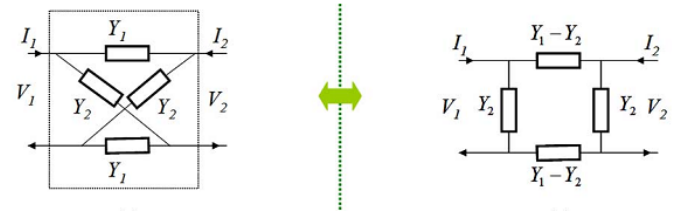
寄生参数/耦合的抑制

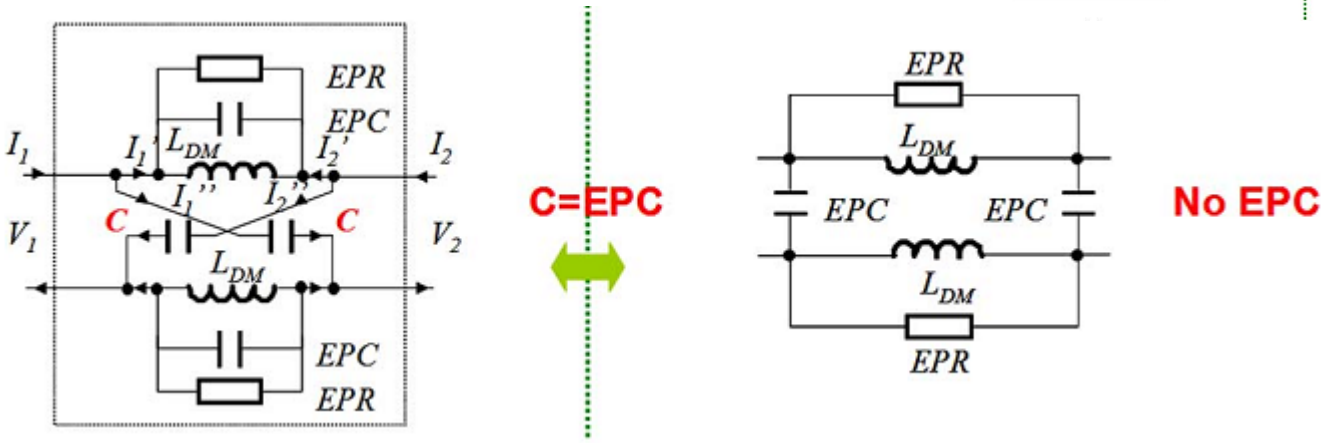

C_{DM2}
$L_{CM}+L_{DM}$
C_{DM1}
C_{CM}
C_{CM}

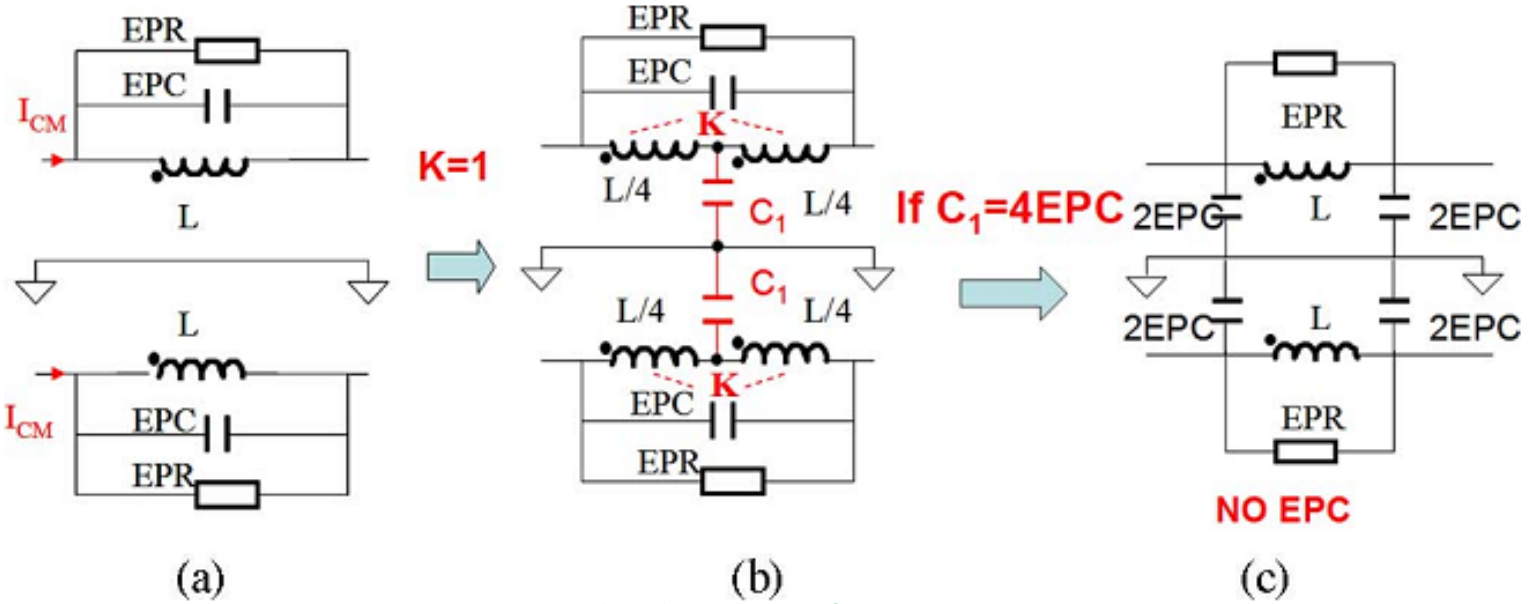

EPC
$L_{CM}+L_{DM}$
ESL_{CM}
C_{DM2}
C_{CM}
C_{DM1}
C_{CM}
ESL_2
ESL_1
ESL_{CM}
EPC


Magnitude (dB)
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
Measurement
Self-parasitics
EPC
ESL
ideal
1.00E+04
1.00E+05
1.00E+06
1.00E+07
1.00E+08
Frequency (Hz)

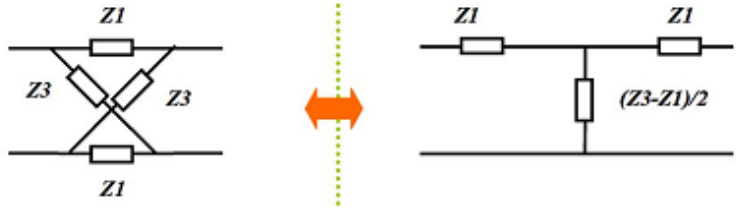

Magnitude (dB)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
Self-parasitics
Measurement
EPC
ESL
ideal
1.00E+05
1.00E+06
1.00E+07
1.00E+08
Frequency (Hz)

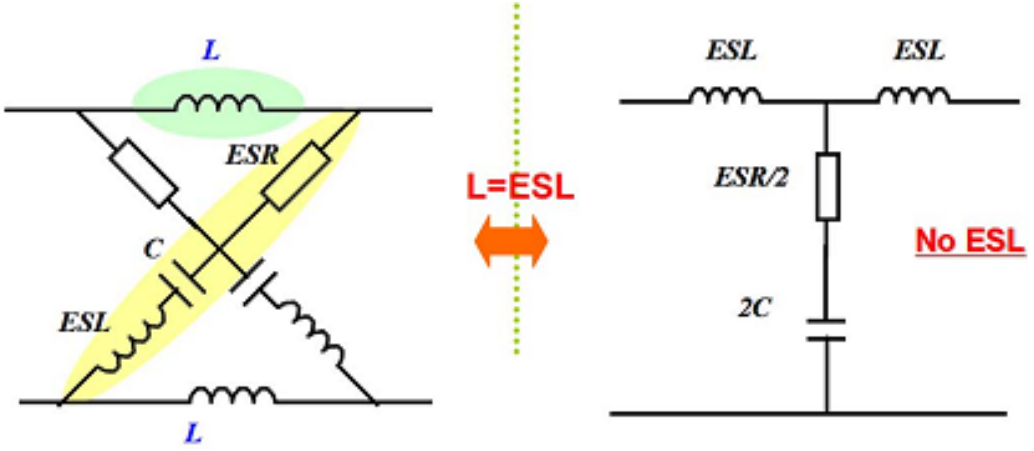

I_1
Y_1
I_2
V_1
Y_2
Y_2
V_2
Y_1
Y_1-Y_2
I_1
I_2
V_1
Y_2
Y_2
V_2
Y_1-Y_2

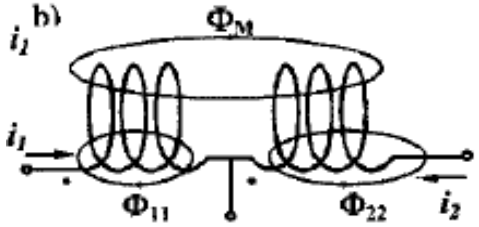

EPR
EPC
I_1
I_1'
L_{DM}
I_2'
I_2
I_1''
I_2''
C
C
V_1
V_2
L_{DM}
EPC
EPR
C=EPC
EPR
L_{DM}
EPC
EPC
L_{DM}
EPR
No EPC

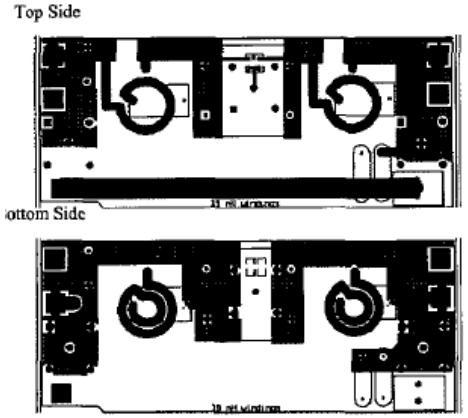

EPR
EPC
I_{CM}
L
L
I_{CM}
EPC
EPR
K=1
EPR
EPC
K
L/4
C_1
L/4
C_1
L/4
L/4
K
EPC
EPR
If C_1=4EPC
EPR
2EPC
L
2EPC
2EPC
L
2EPC
EPR
NO EPC
(a)
(b)
(c)

电感EPC的抑制

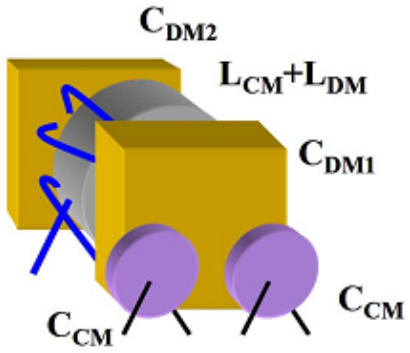

Z1
Z3
Z3
Z1
Z1
Z1
(Z3-Z1)/2

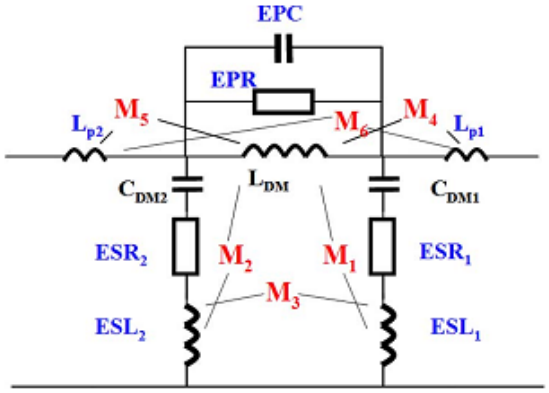

L
ESR
C
ESL
L
L=ESL
ESL
ESL
ESR/2
No ESL
2C

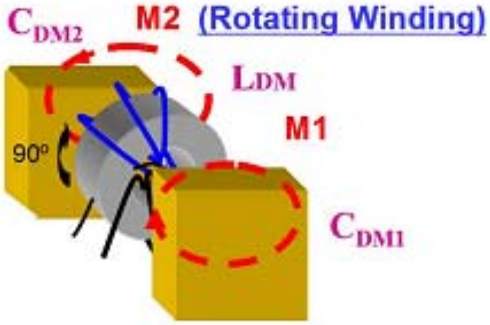

b)
i_1
Φ_M
i_1
Φ_{11}
Φ_{22}
i_2

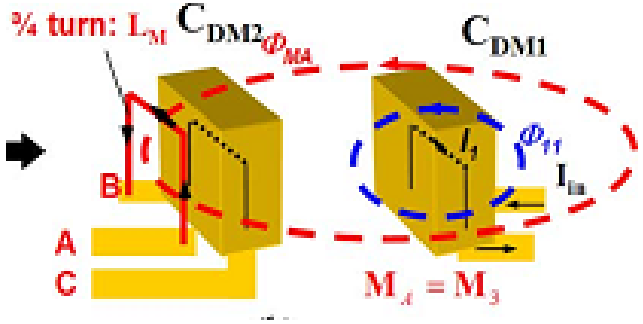

Top Side
ottom Side

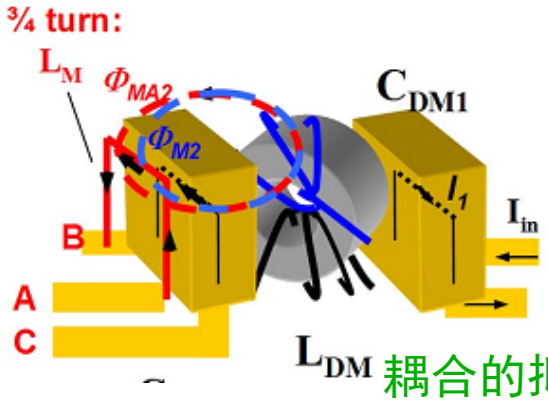
电容ESL抑制

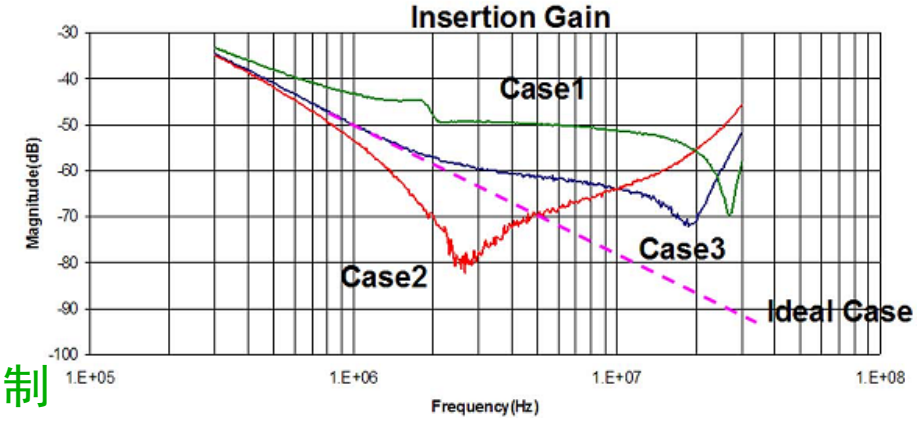

C_{DM2}
$L_{CM}+L_{DM}$
C_{DM1}
C_{CM}
C_{CM}


EPC
EPR
L_{p2}
M_5
M_6
M_4
L_{p1}
C_{DM2}
L_{DM}
C_{DM1}
ESR_2
M_2
M_1
ESR_1
M_3
ESL_2
ESL_1


C_{DM2}
M2 (Rotating Winding)
L_{DM}
M1
90°
C_{DM1}


¾ turn: L_M
C_{DM2}
Φ_{MA}
C_{DM1}
Φ_{11}
I_{in}
B
A
C
$M_A = M_3$


¾ turn:
L_M
Φ_{MA2}
C_{DM1}
Φ_{M2}
I_1
I_{in}
B
A
C
L_{DM}


Insertion Gain
Case1
Case2
Case3
Ideal Case
Magnitude(dB)
-30
-40
-50
-60
-70
-80
-90
-100
1.E+05
1.E+06
1.E+07
1.E+08
Frequency(Hz)

耦合的抑制

Any questions?

Thanks for your attention!

谢谢大家！