



# 适用于电场耦合式无线电能传输系统的 耦合器模型与高阶补偿网络理论

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02

**容性耦合器模型**

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生活离不开电

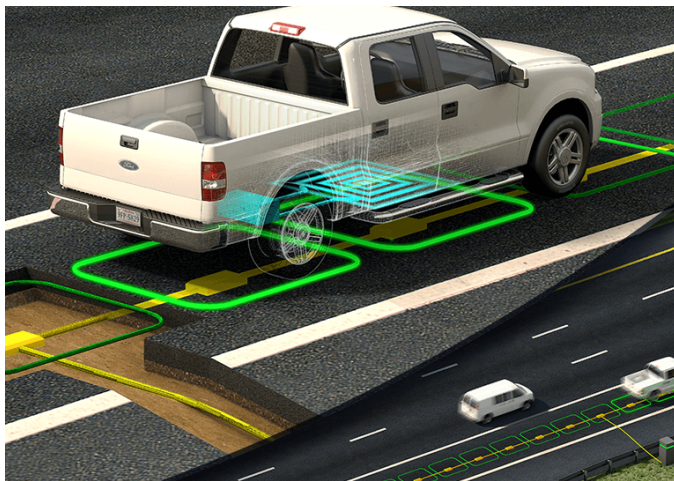
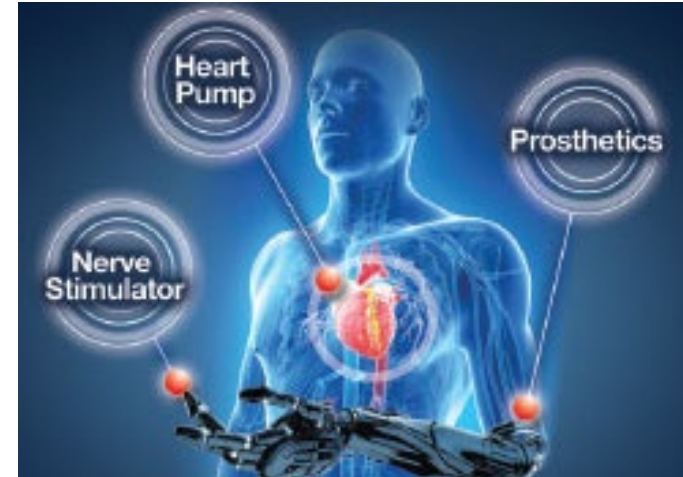
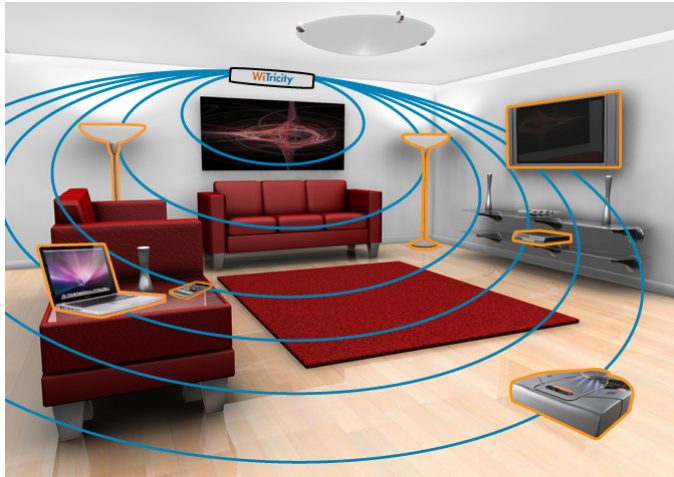


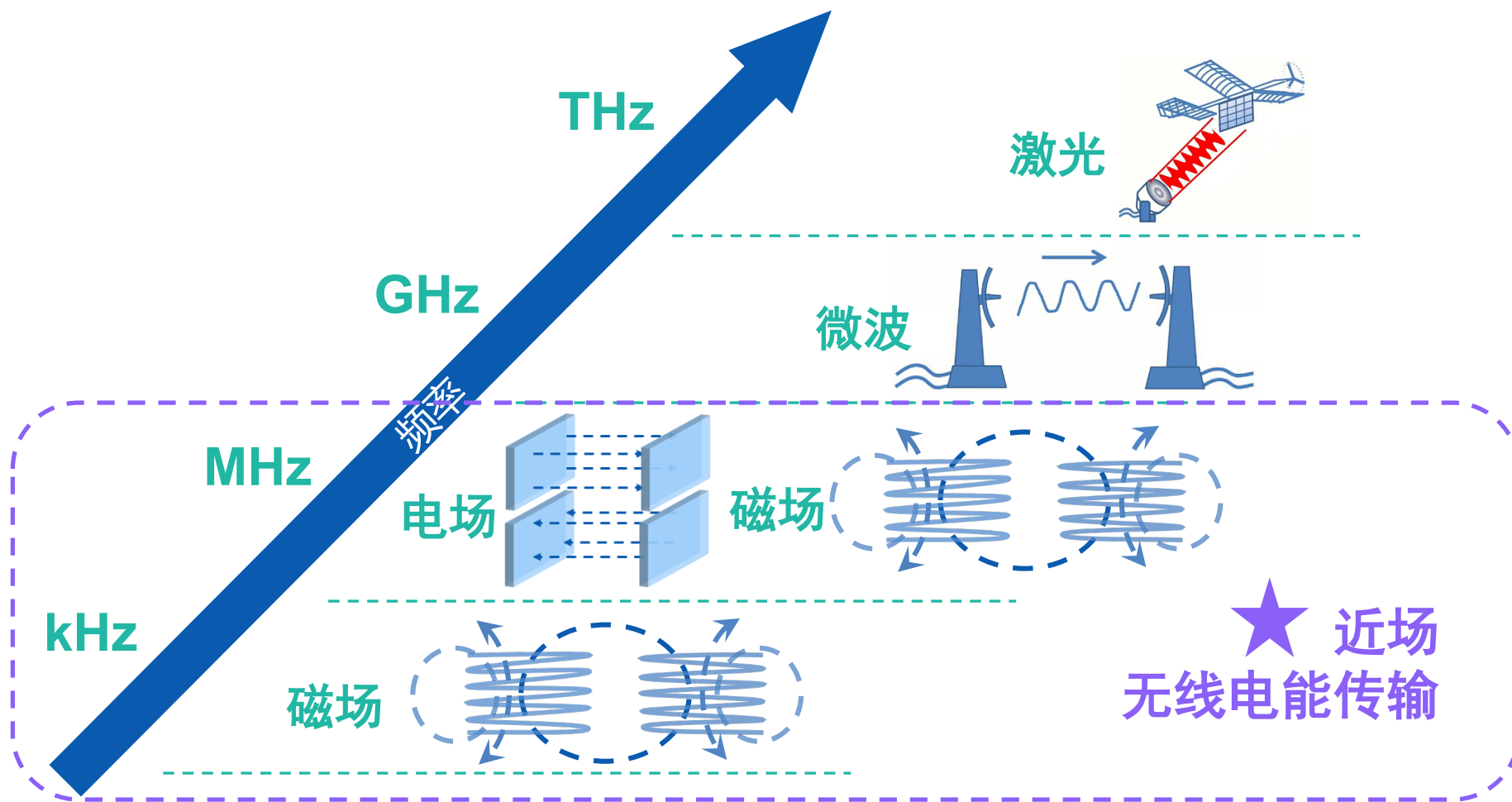
们用电的方式弄得很便捷可以



改变我们的生活

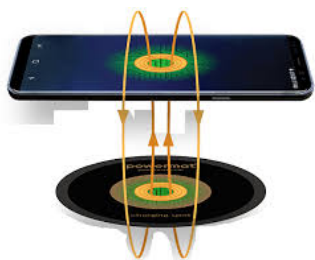
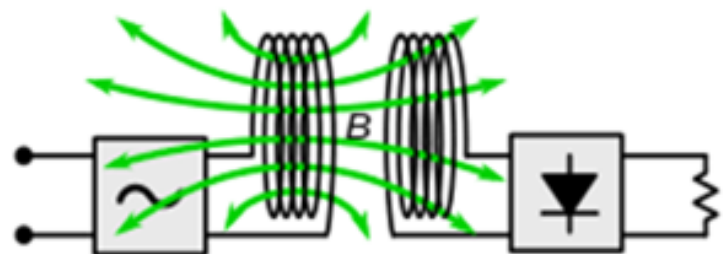






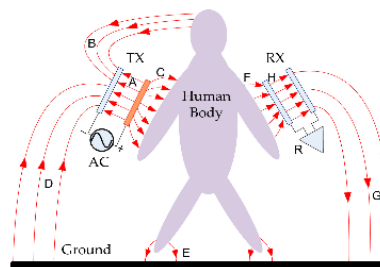
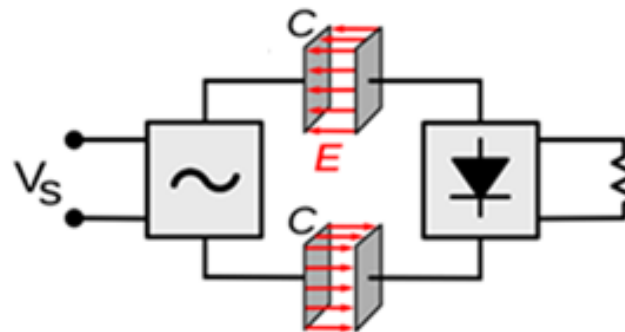
## 近场无线电能传输

### 磁场耦合无线电能传输 (IPT)



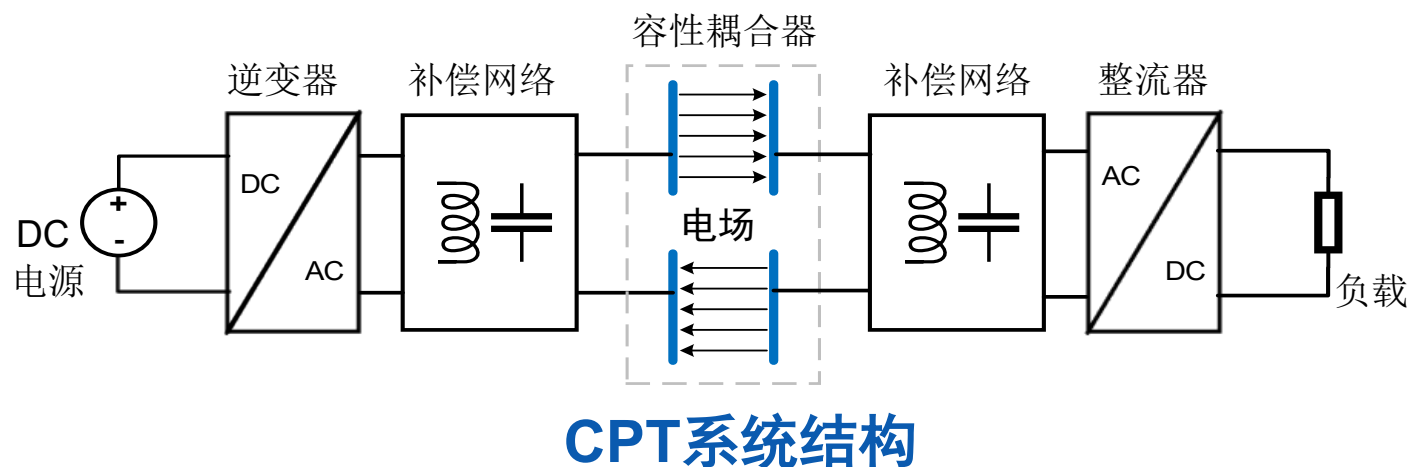
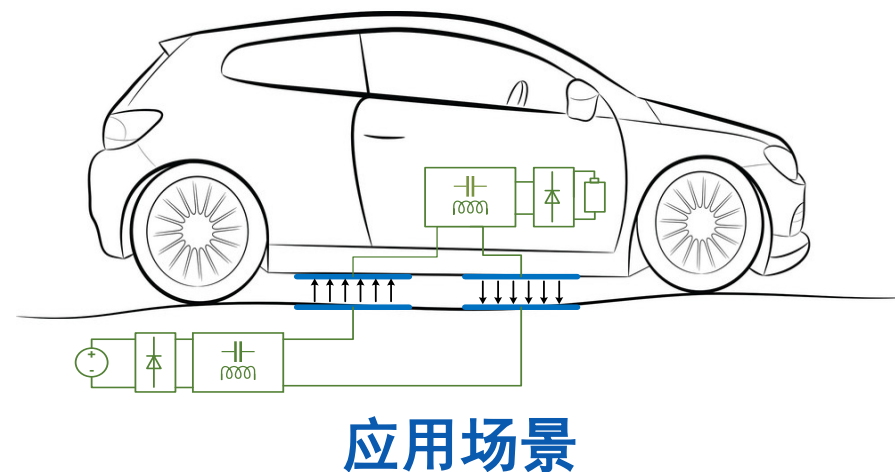
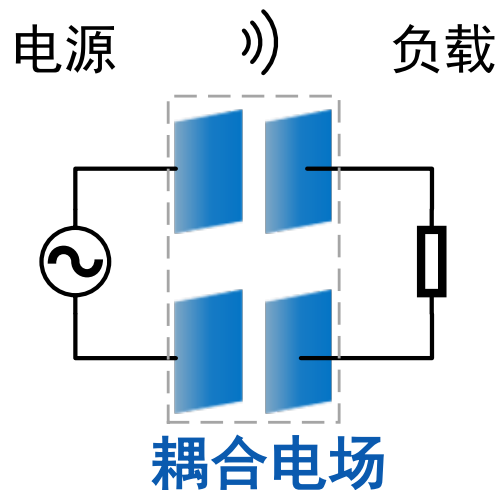
- 工作频率高 (kHz-MHz)
- 对周围金属物体敏感

### 电场耦合无线电能传输 (CPT)



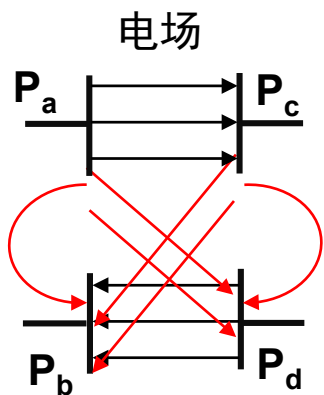
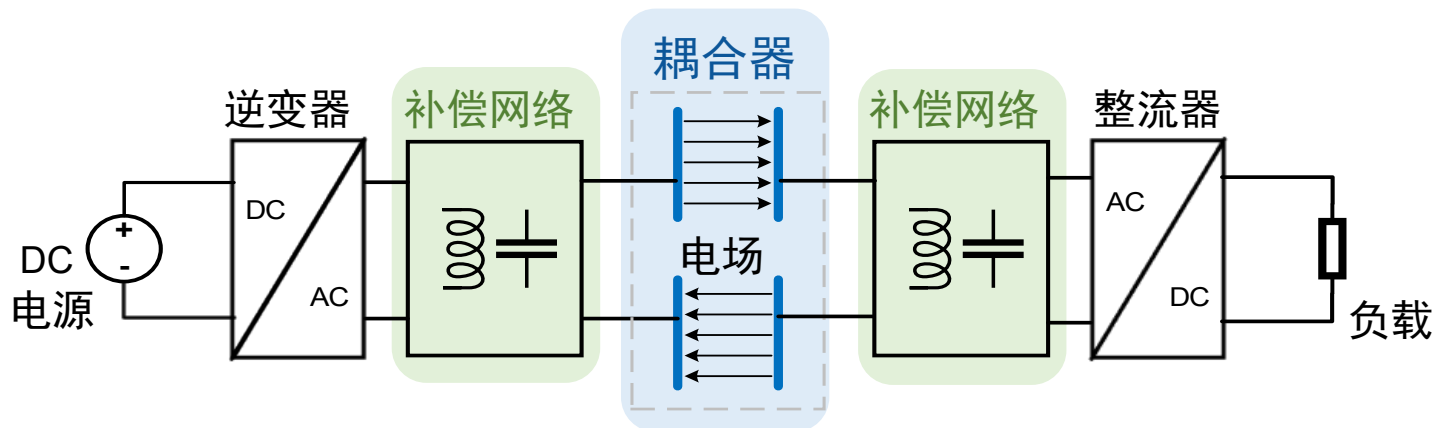
- 工作频率高(MHz)
- 无涡流损耗

# 电场耦合式无线电能传输 (CPT)

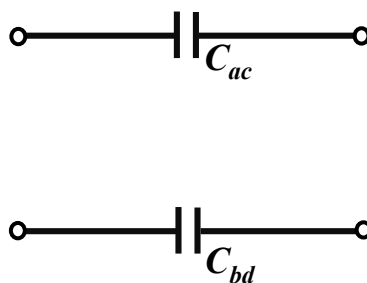




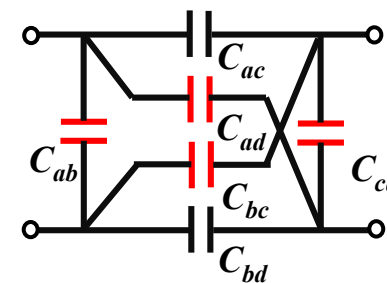
## CPT研究现状—耦合器模型



物理模型

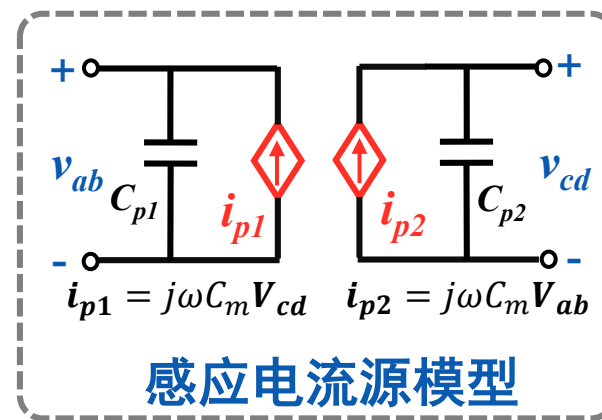
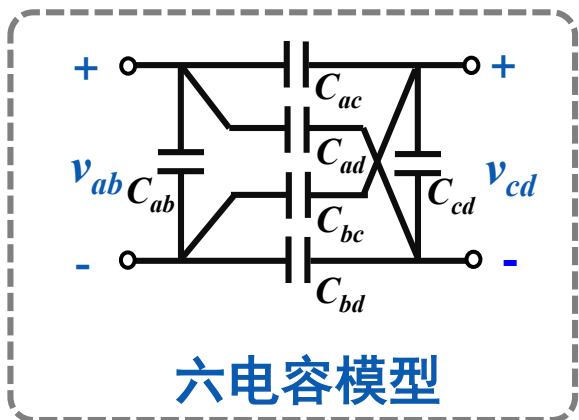


两个分立电容模型



六电容模型

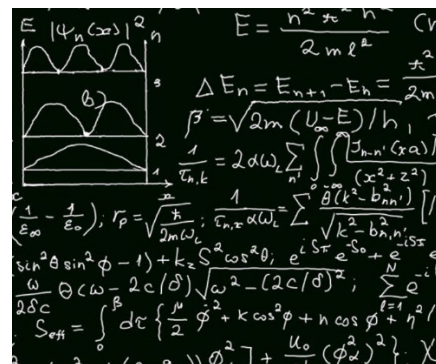
## CPT研究现状—耦合器模型



$$\left\{ \begin{aligned} C_{p1} &= C_{ab} + \frac{(C_{ac} + C_{ad})(C_{bc} + C_{bd})}{C_{ac} + C_{ad} + C_{bc} + C_{bd}} \\ C_{p2} &= C_{cd} + \frac{(C_{ac} + C_{bc})(C_{ad} + C_{bd})}{C_{ac} + C_{ad} + C_{bc} + C_{bd}} \\ C_{pm} &= \frac{C_{bd}C_{ac} - C_{ad}C_{bc}}{C_{ac} + C_{ad} + C_{bc} + C_{bd}} \\ k &= \frac{C_{pm}}{\sqrt{C_{p1}C_{p2}}} \end{aligned} \right.$$



$C_{p1}, C_{p2}$   
与耦合状态有关

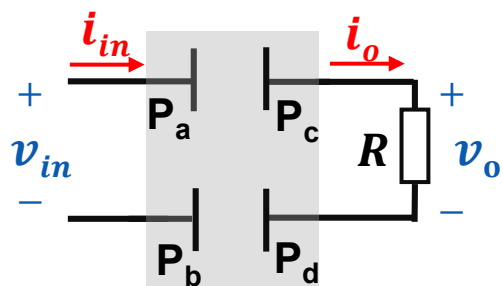


[1]. H. Zhang, F. Lu, H. Hofmann, W. Liu and C. C. Mi, "A Four-Plate Compact Capacitive Coupler Design and LCL-Compensated Topology for Capacitive Power Transfer in Electric Vehicle Charging Application," in *IEEE Transactions on Power Electronics*, vol. 31, no. 12, pp. 8541-8551, Dec. 2016.

## CPT研究现状—补偿网络



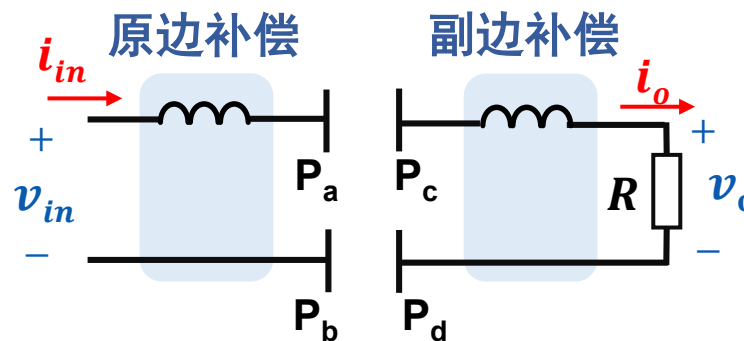
为什么需要补偿网络?



耦合电容容值过小

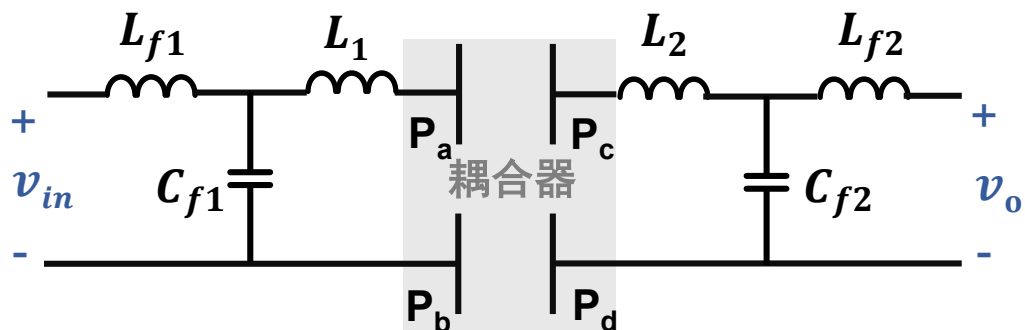
输出电压/功率低

添加补偿网络

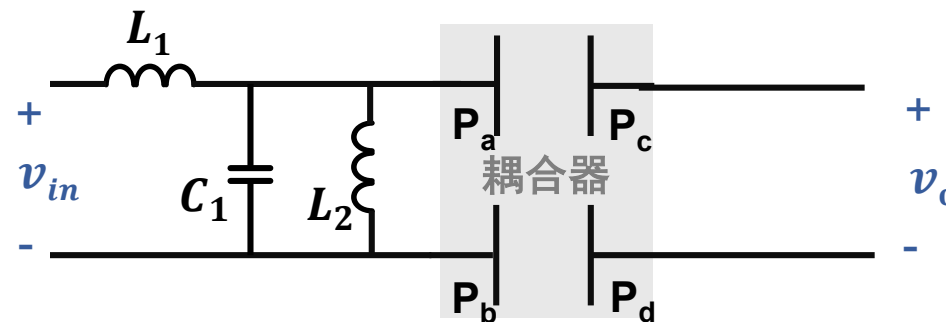


输出功率提高

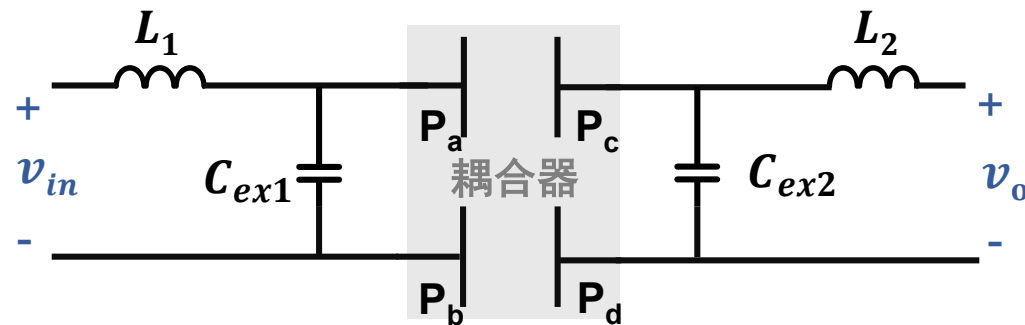
## CPT研究现状—补偿网络



双边LCL补偿网络[1]



F型补偿网络[3]



双边LC补偿网络[2]



按照个案进行分析  
缺乏统一的分析方法

[2]. F. Lu, H. Zhang, H. Hofmann and C. C. Mi, "A Double-Sided LC-Compensation Circuit for Loosely Coupled Capacitive Power Transfer," in IEEE Transactions on Power Electronics, vol. 33, no. 2, pp. 1633-1643, Feb. 2018.  
 [3]. Y. Su, Y. Zhao, A. P. Hu, Z. Wang, C. Tang and Y. Sun, "An F-Type Compensated Capacitive Power Transfer System Allowing for Sudden Change of Pickup," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 7, no. 2, pp. 1084-1093, June 2019.

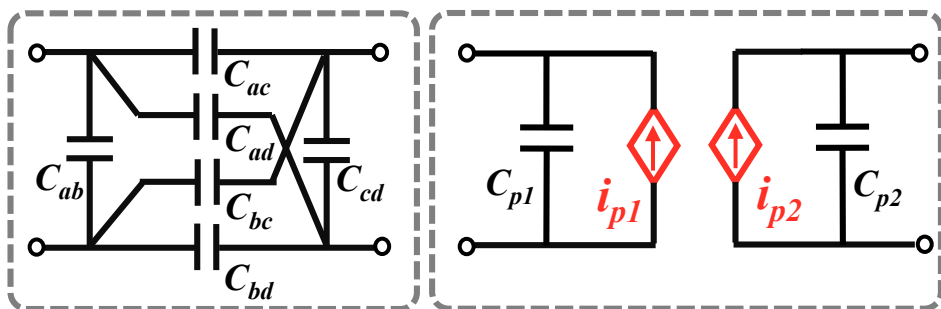
## 研究目标

### 耦合器模型

物理结构



电路模型



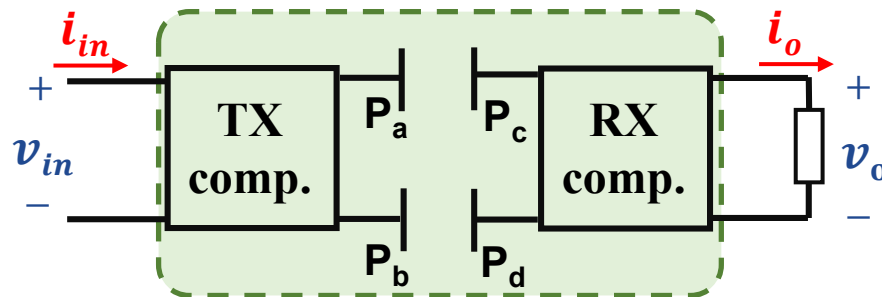
➤ 复杂

➤ 变耦合

新模型

### 补偿网络

补偿

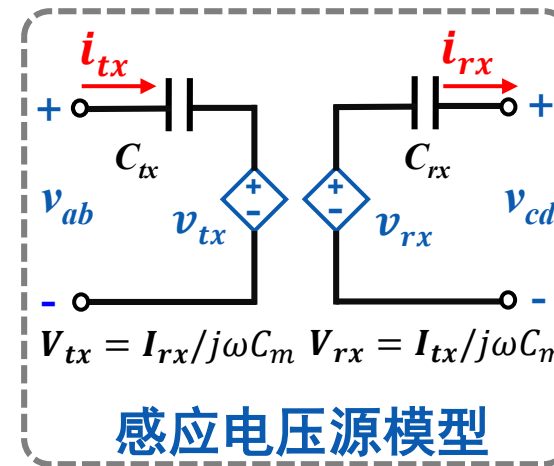
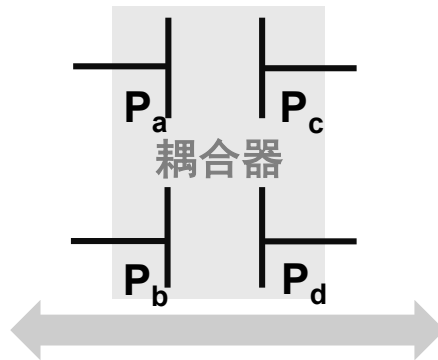
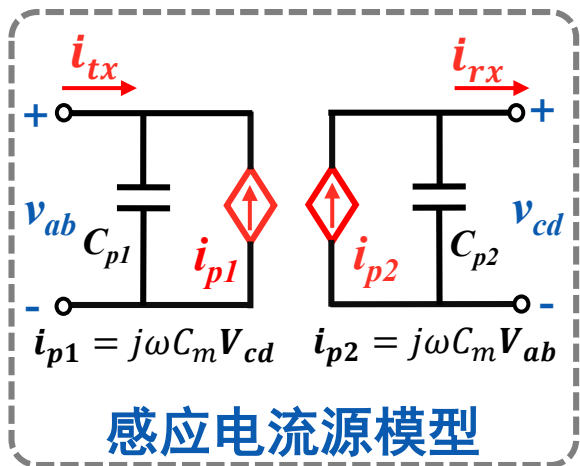


➤ 按照个案进行分析

➤ 分析方法复杂

统一的补偿网络分析方法

## 感应电压源模型



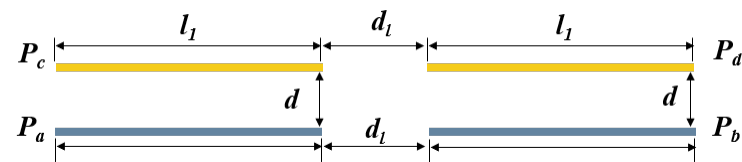
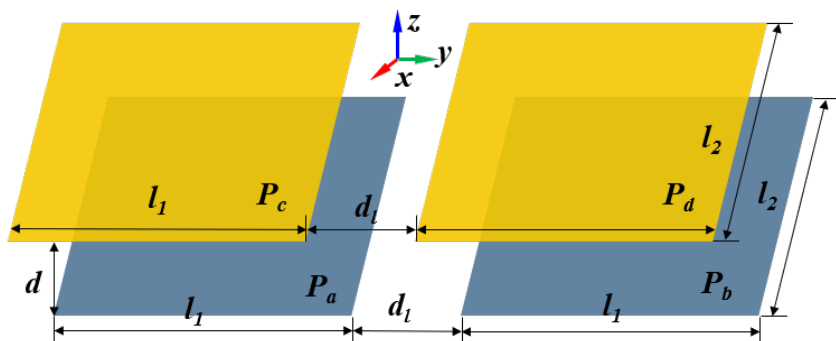
$C_{p1}, C_{p2}$   
与耦合状态有关

$$\begin{cases} C_{tx} = \frac{C_{p1}C_{p2} - C_{pm}C_{pm}}{C_{p2}} \\ C_{rx} = \frac{C_{p1}C_{p2} - C_{pm}C_{pm}}{C_{p1}} \\ C_m = \frac{C_{p1}C_{p2} - C_{pm}C_{pm}}{C_{pm}} \\ k = \frac{\sqrt{C_{tx}C_{rx}}}{C_m} \end{cases}$$

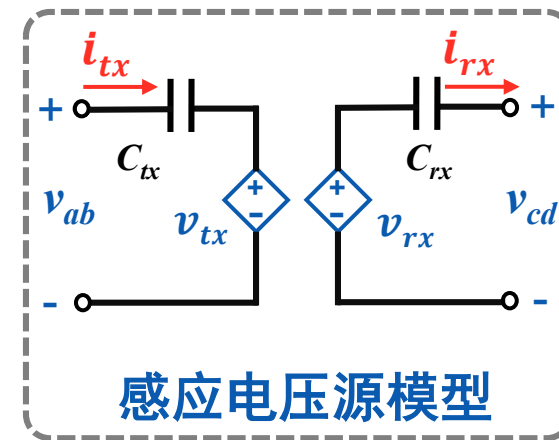
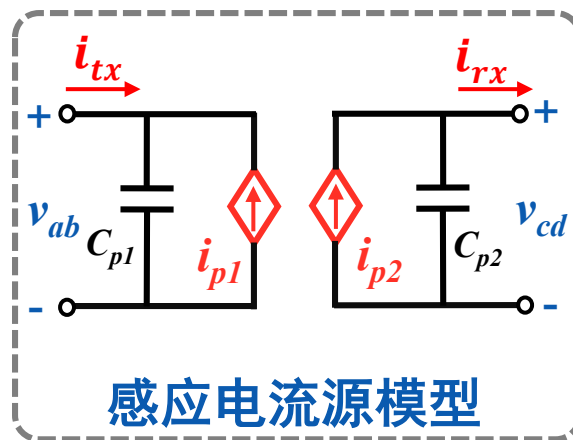
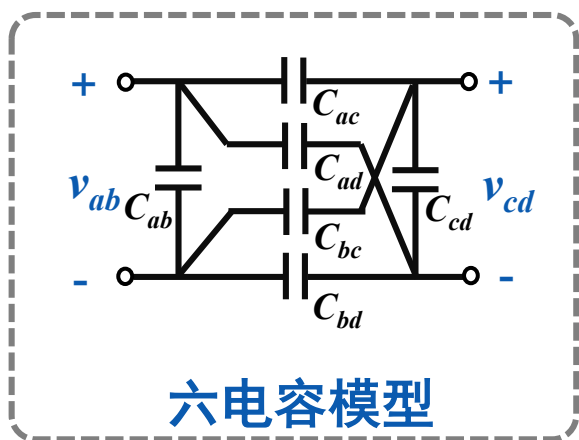


$C_{tx}, C_{rx}$   
与耦合状态无关

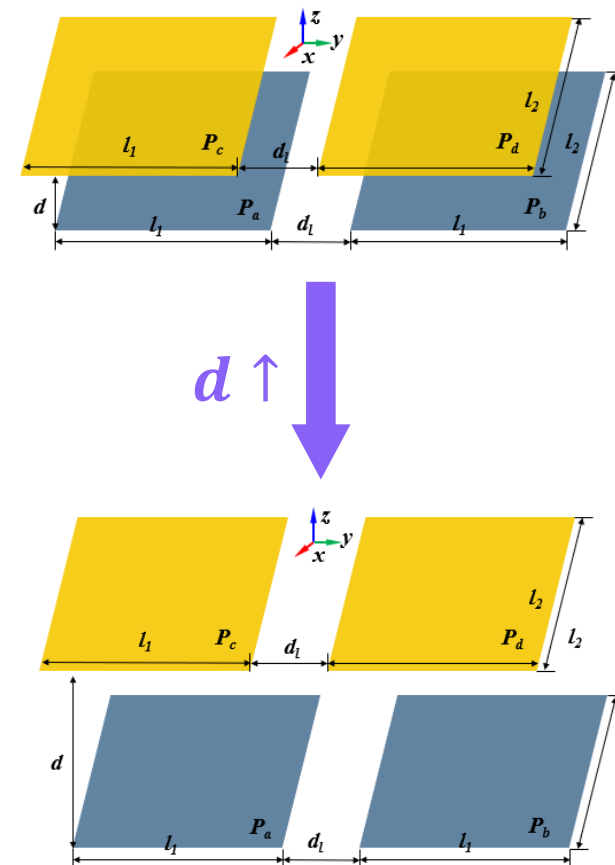
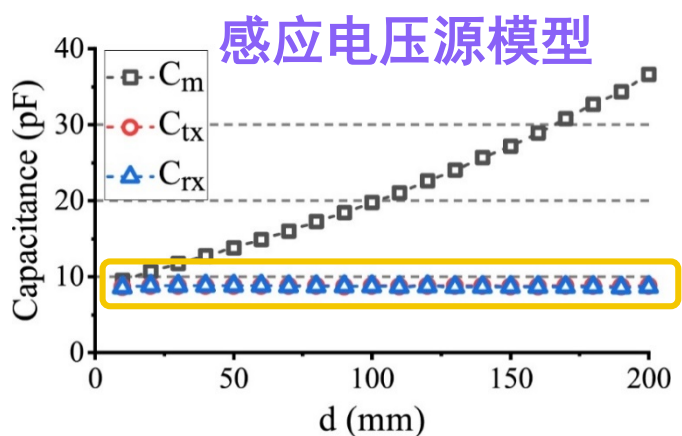
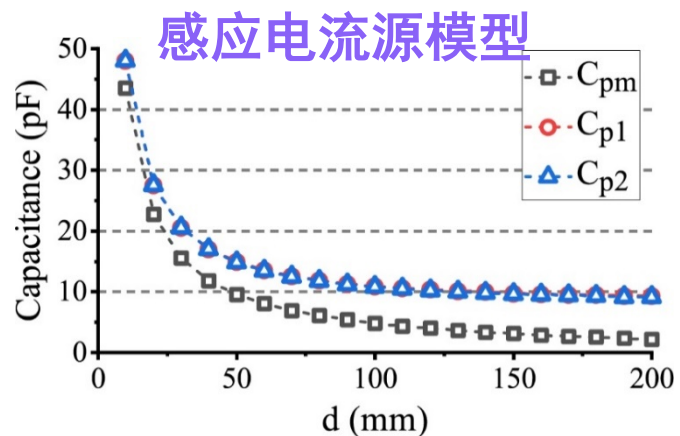
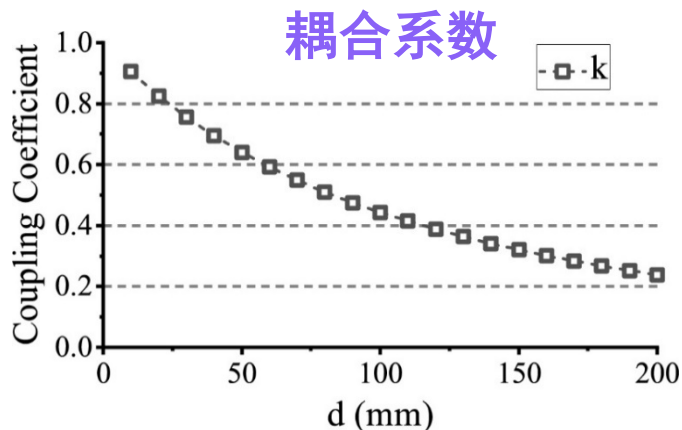
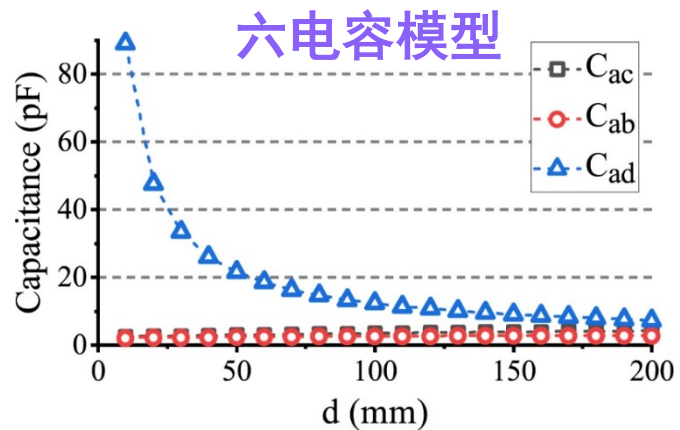
## Maxwell仿真验证



$$l_1 \times l_2 = 300\text{mm} \times 300\text{mm}; d_l = 180\text{mm}$$



## Maxwell仿真验证

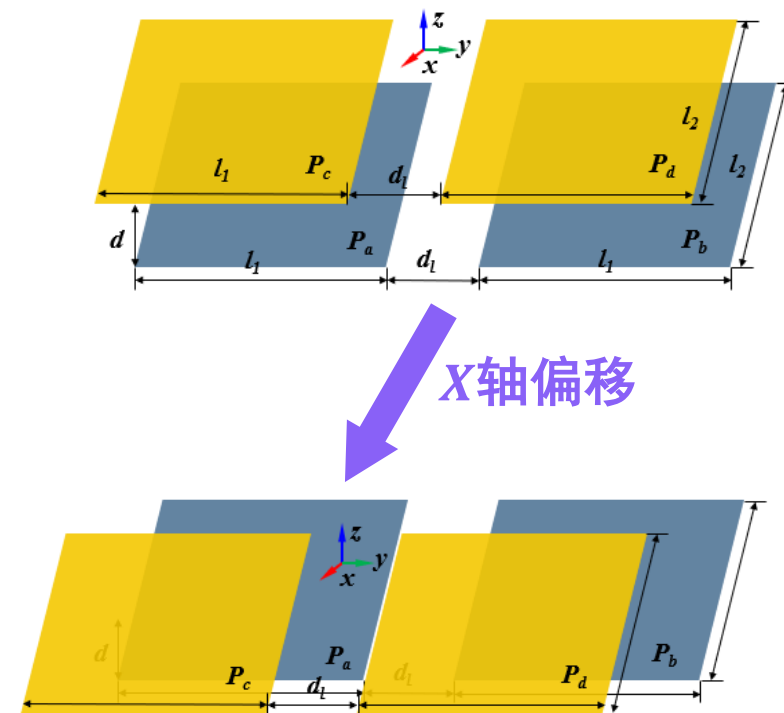
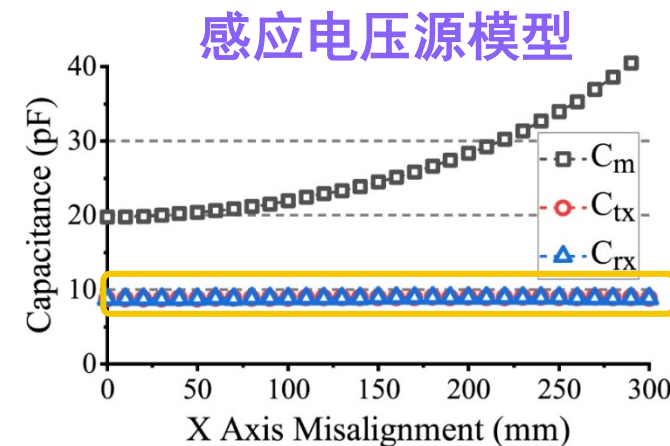
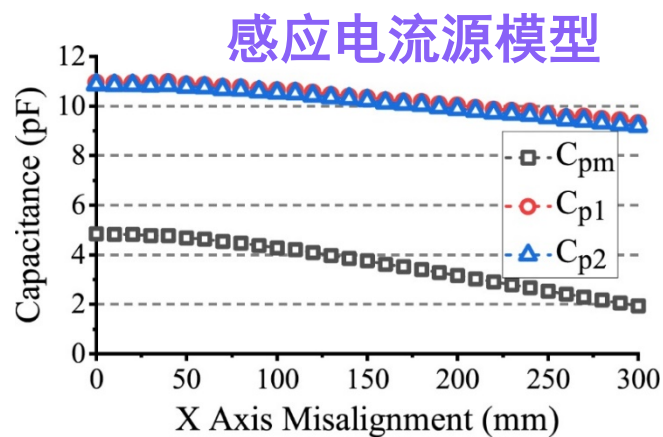
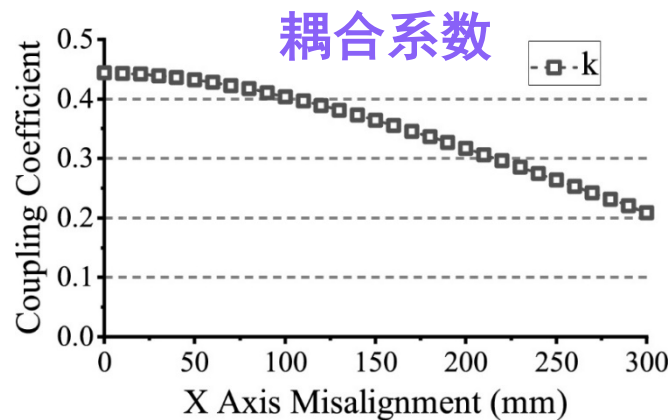
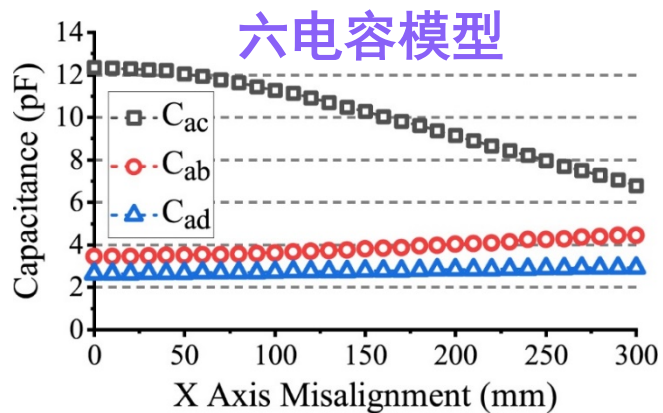


与耦合无关

容性耦合器参数随着距离 $d$ 的变化情况



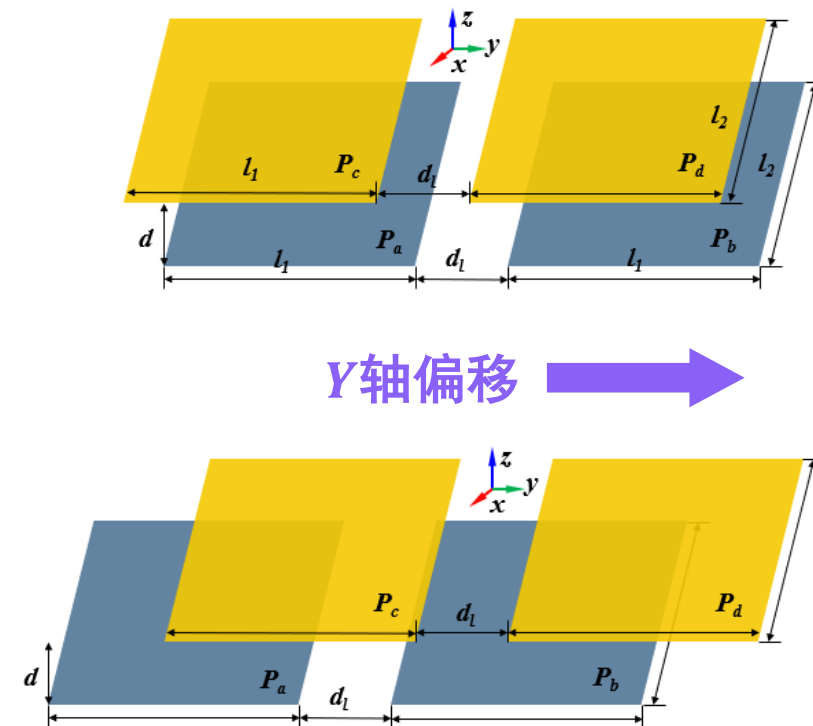
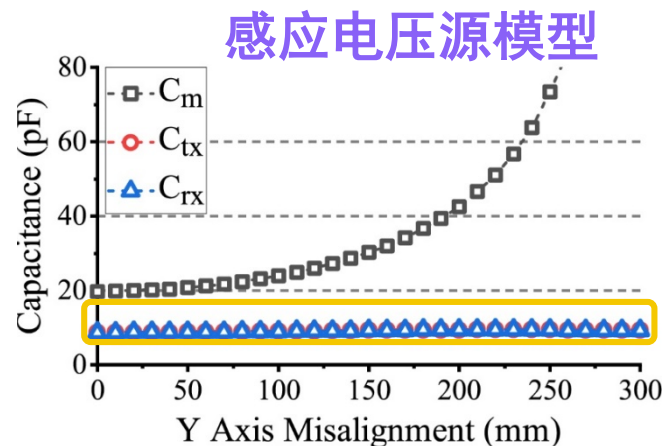
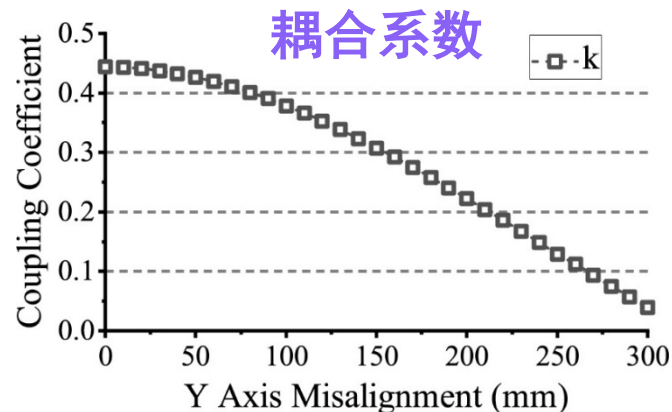
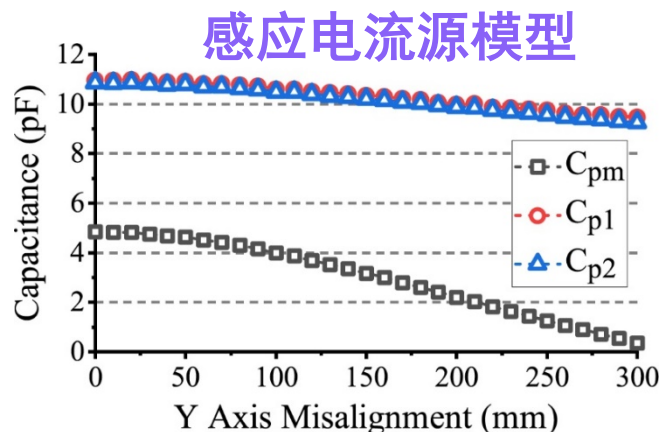
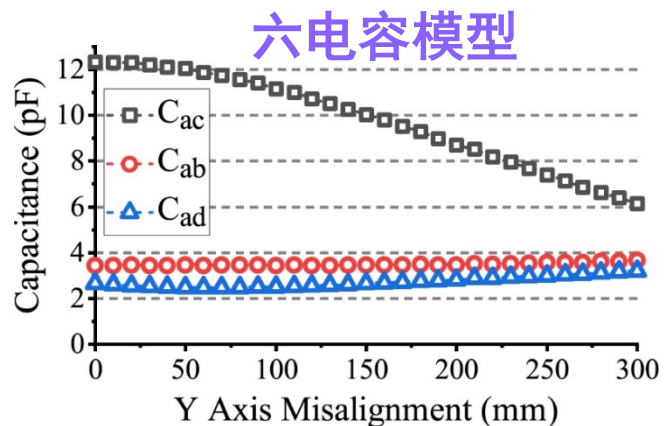
## Maxwell仿真验证



😊  
与耦合  
无关

容性耦合器参数随着接收端极板沿X轴偏移的变化情况

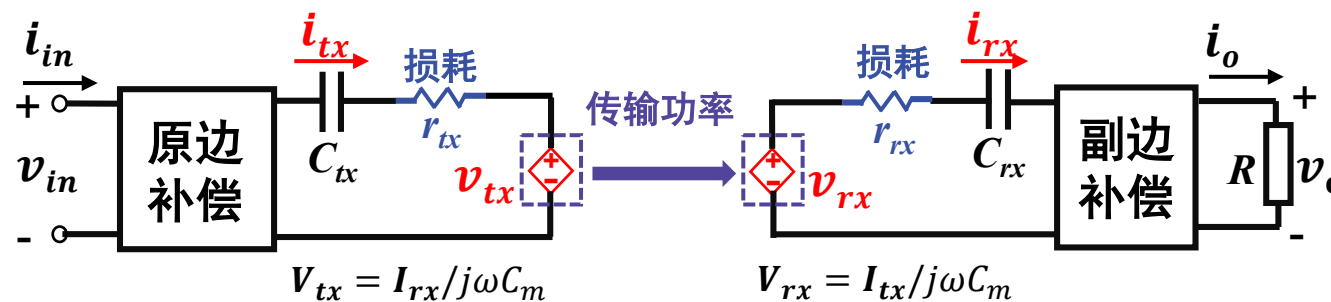
## Maxwell仿真验证



😊  
与耦合  
无关

容性耦合器参数随着接收端极板沿Y轴偏移的变化情况

## 系统能量传输特性 – 最优效率分析



### 系统传输功率

$$P_t = \text{real}[V_{tx} I_{tx}^*] = \frac{I_{tx} I_{rx} \sin\theta}{\omega C_m}$$

$\theta$ :  $I_{tx}$  与  $I_{rx}$  的相位差

### 损耗分析

$$P_{\text{loss}} \geq I_{tx}^2 r_{tx} + I_{rx}^2 r_{rx} \geq 2 I_{tx} I_{rx} \sqrt{r_{tx} r_{rx}} = P_{\text{min}}$$

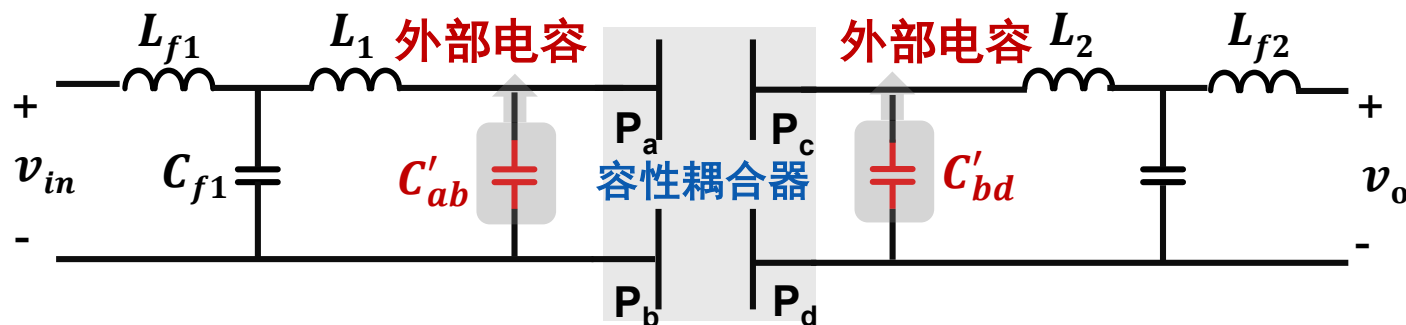
$$Q_{tx} = \frac{1}{\omega C_{tx} r_{tx}}; Q_{rx} = \frac{1}{\omega C_{rx} r_{rx}}$$

$$P_{\text{min}} = 2\omega C_m P_t \sqrt{\frac{1}{\omega^2 Q_{tx} Q_{rx} C_{tx} C_{rx}}} = \frac{2P_t}{k\sqrt{Q_{tx} Q_{rx}}}$$

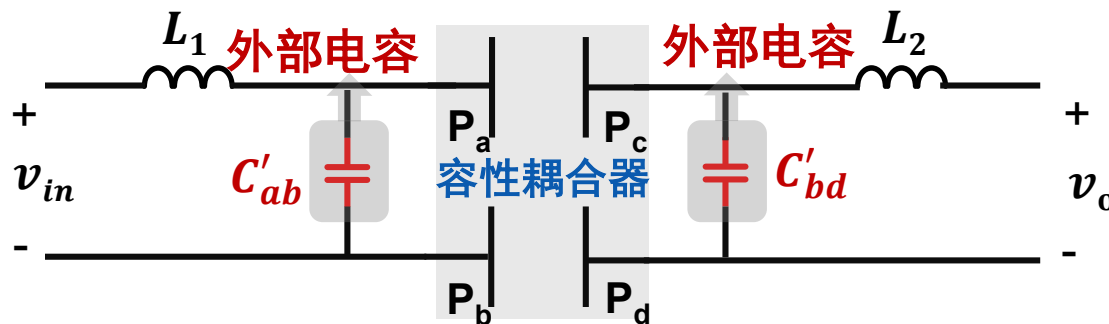
### 最优效率

$$\eta \leq \eta_{\text{max}} = \frac{P_t}{P_t + P_{\text{min}}} = \frac{1}{1 + 2/(k\sqrt{Q_{tx} Q_{rx}})}$$

## 系统能量传输特性 – 外部电容



双边LCLC补偿网络CPT系统[4]



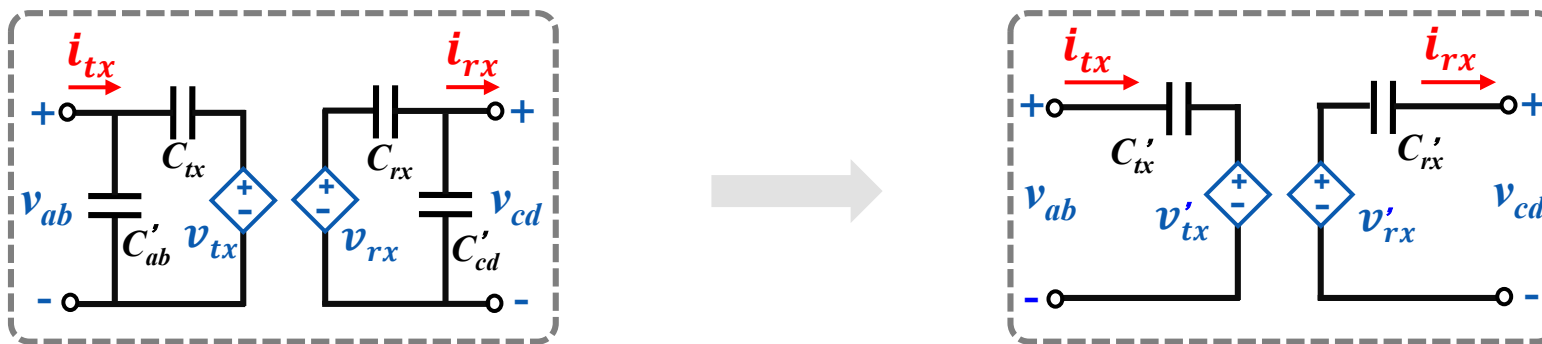
双边LC补偿网络CPT系统[2]



外部并联电容对系统的影响

[4] F. Lu, H. Zhang, H. Hofmann and C. Mi, "A Double-Sided LCLC-Compensated Capacitive Power Transfer System for Electric Vehicle Charging," in *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6011-6014, Nov. 2015.

## 系统能量传输特性 – 外部电容



### KCL and KVL

$$\begin{cases} I_{tx} = I_{C'_{ab}} + I_{C_{tx}} = \left( V_{ab} - \frac{I_{C_{rx}}}{j\omega C_m} \right) j\omega C_{tx} + j\omega C'_{ab} V_{ab} \\ I_{rx} = I_{C'_{cd}} + I_{C_{rx}} = \left( V_{cd} - \frac{I_{C_{tx}}}{j\omega C_m} \right) j\omega C_{rx} + j\omega C'_{cd} V_{cd} \\ V_{ab} = \frac{I_{C_{tx}}}{j\omega C_{tx}} + \frac{I_{C_{rx}}}{j\omega C_m} \\ V_{cd} = \frac{I_{C_{rx}}}{j\omega C_{rx}} + \frac{I_{C_{tx}}}{j\omega C_m} \\ k = \frac{\sqrt{C_{tx} C_{rx}}}{C_m} \end{cases}$$

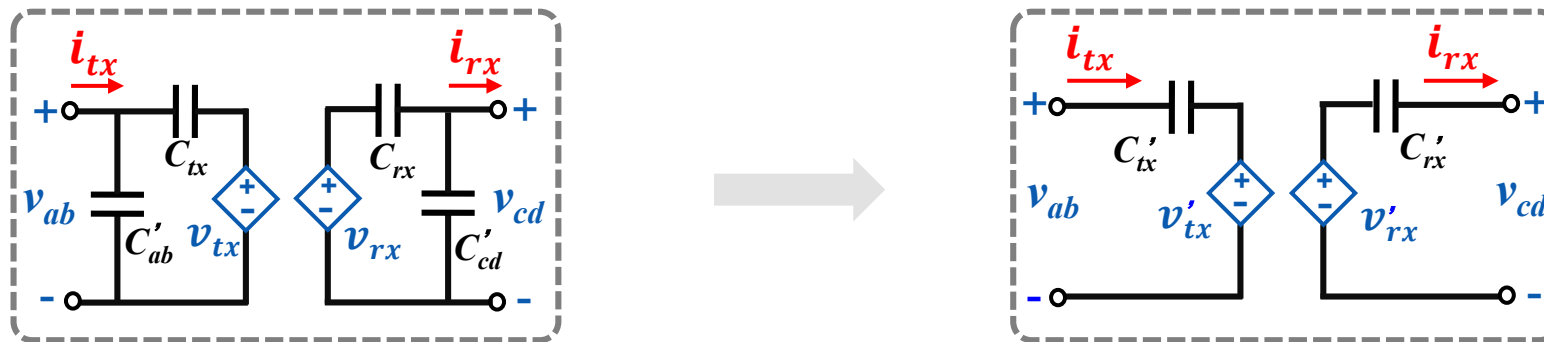
$$\begin{cases} C'_{tx} = C'_{ab} + \frac{(C'_{cd} + C_{rx})C_{tx}}{C_{rx} + C'_{cd}(1 - k^2)} \\ C'_{rx} = C'_{cd} + \frac{(C'_{ab} + C_{tx})C_{rx}}{C_{tx} + C'_{ab}(1 - k^2)} \\ C'_m = \frac{C_m(C'_{ab} + C_{tx})(C'_{cd} + C_{rx})}{C_{tx}C_{rx}} - \frac{C'_{ab}C'_{cd}}{C_m} \end{cases}$$

$$C'_{tx} = C'_{ab} + \frac{(C'_{cd} + C_{rx})C_{tx}}{C_{rx} + C'_{cd}(1 - k^2)} \geq C'_{ab} + C_{rx}$$



减小补偿电感感值

## 系统能量传输特性 – 外部电容



$$\begin{aligned} \left(\frac{k'}{k}\right)^2 &= \left(\frac{\sqrt{C'_{tx}C'_{rx}/C'_m}}{\sqrt{C_{tx}C_{rx}/C_m}}\right)^2 \\ &= \frac{C_m^4 C_{tx} C_{rx}}{(C_m^2 C_{rx} + C_m^2 C'_{cd}(1-k^2))(C_m^2 C_{tx} + C_m^2 C'_{ab}(1-k^2))} \\ &= \frac{\alpha \times \gamma}{(\alpha + \beta)(\gamma + \delta)} \end{aligned}$$

where  $\alpha = C_m^2 C_{rx}$ ;  $\beta = C_m^2 C'_{cd}(1 - k^2)$ ;  $\gamma = C_m^2 C_{tx}$ ;  $\delta = C_m^2 C'_{ab}(1 - k^2)$

$\alpha, \beta, \gamma, \delta > 0$

$k'/k < 1$

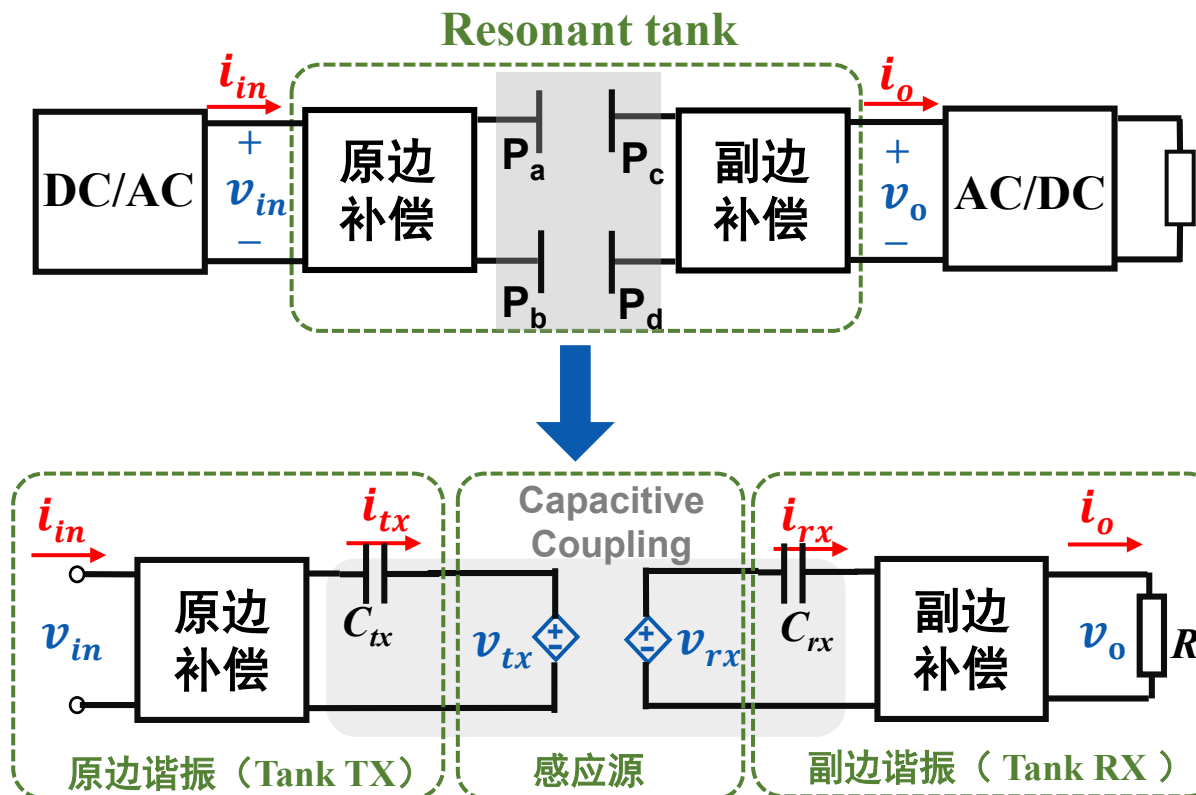


降低耦合系数（可能降低系统效率）

$$\eta \leq \frac{1}{1 + 2/(k\sqrt{Q_{tx}Q_{rx}})}$$

**目标**

提出适用于CPT系统的高阶补偿网络分解与合成方法



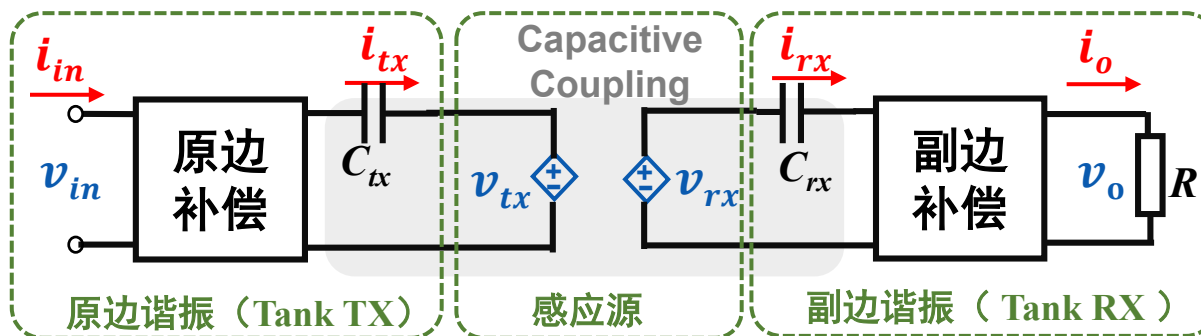
$$V_{tx} = I_{rx} / j\omega C_m \quad V_{rx} = I_{tx} / j\omega C_m$$

**基于感应电压源模型的CPT系统分解**

## 系统设计目标:

增加系统的可控性  $\longrightarrow$  耦合无关性谐振  
 负载无关性输出

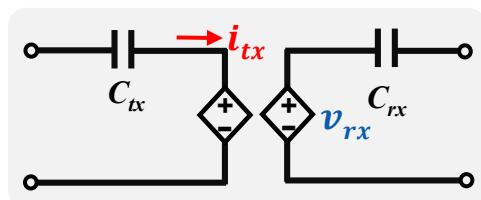
减小电压电流应力  $\longrightarrow$  反射阻抗纯阻性  
 提高系统效率



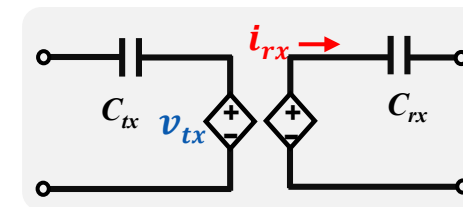
$$G_{coupler,iv} = \frac{v_{rx}}{i_{tx}} = \frac{1}{j\omega C_m}$$

$$V_{tx} = I_{rx}/j\omega C_m \quad V_{rx} = I_{tx}/j\omega C_m$$

$$G_{coupler,vi} = \frac{i_{rx}}{v_{tx}} = j\omega C_m$$



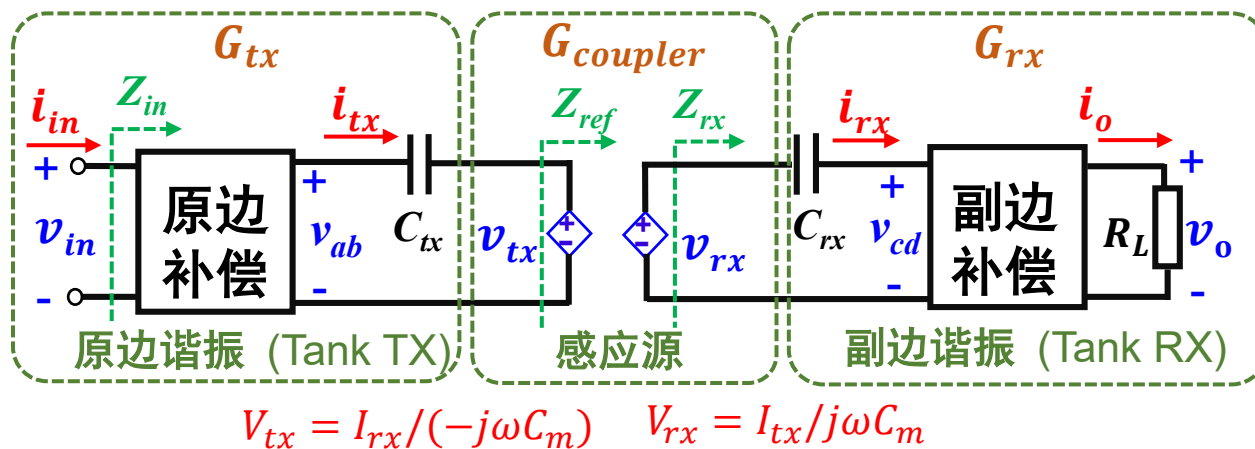
感应电压源模型具有  
实现耦合无关性谐振的能力



[5]. J. Hou, Q. Chen, Z. Zhang, S. Wong and C. K. Tse, "Analysis of Output Current Characteristics for Higher Order Primary Compensation in Inductive Power Transfer Systems," in *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 6807-6821, Aug. 2018.

[6]. J. Lu, G. Zhu, D. Lin, S. Wong and J. Jiang, "Load-Independent Voltage and Current Transfer Characteristics of High-Order Resonant Network in IPT System," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 1, pp. 422-436, March 2019.





**负载无关性输出**

$$G_{sys} = G_{tx} * G_{coupler} * G_{rx}$$



原边/副边谐振必须  
实现负载无关性输出

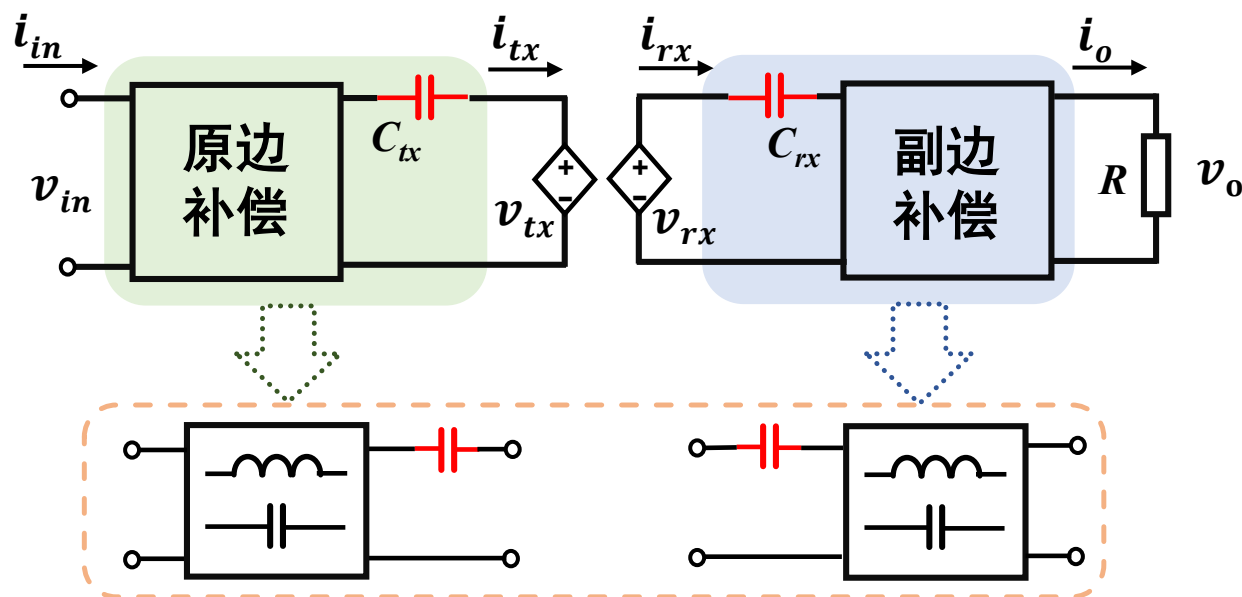
**反射阻抗纯阻性**

$$Z_{ref} = \frac{k^2}{\omega^2 C_{tx} C_{rx}} \times \frac{1}{Z_{rx}}$$



原边/副边谐振必须  
实现反射阻抗纯阻性

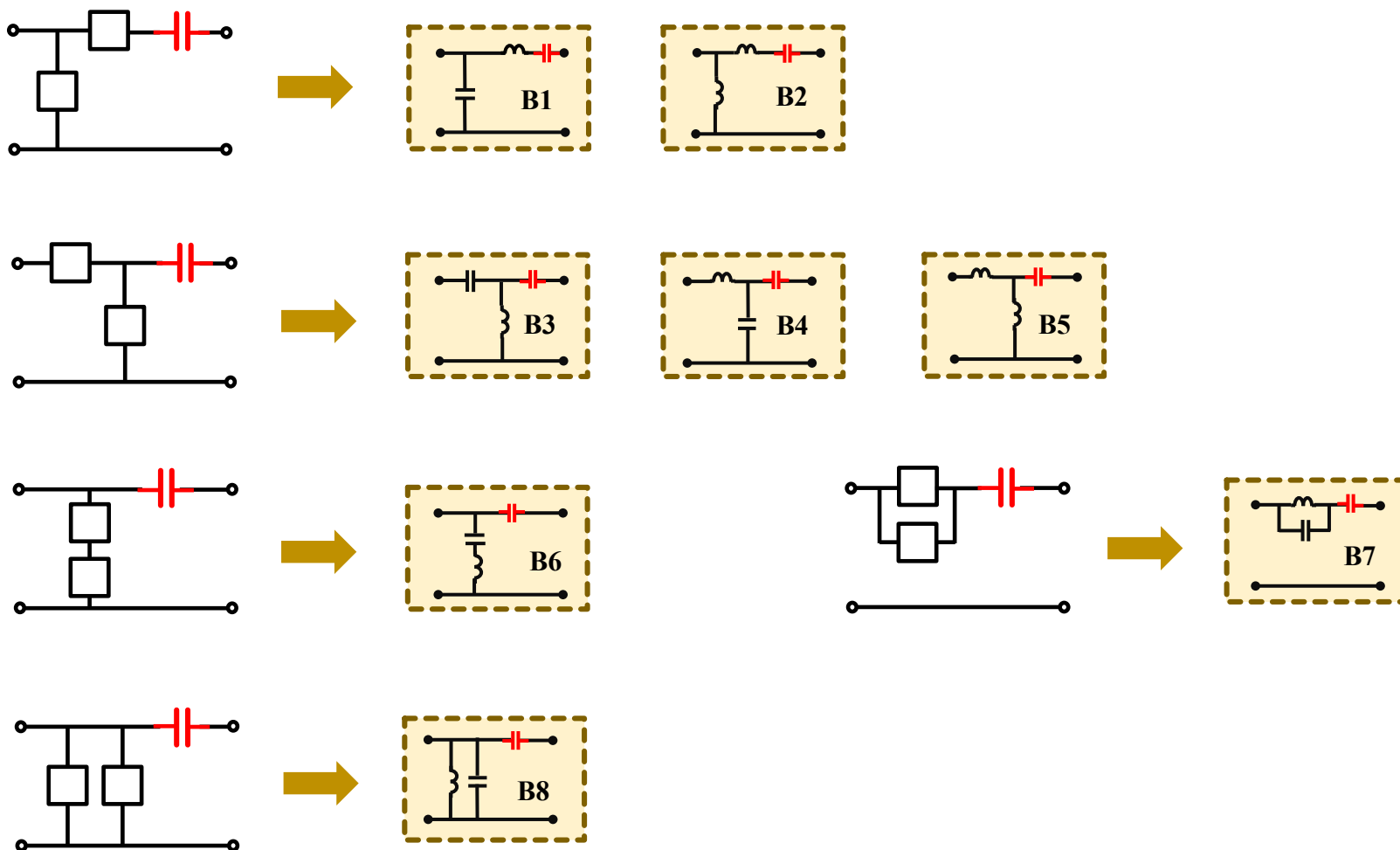
## 二阶候选网络



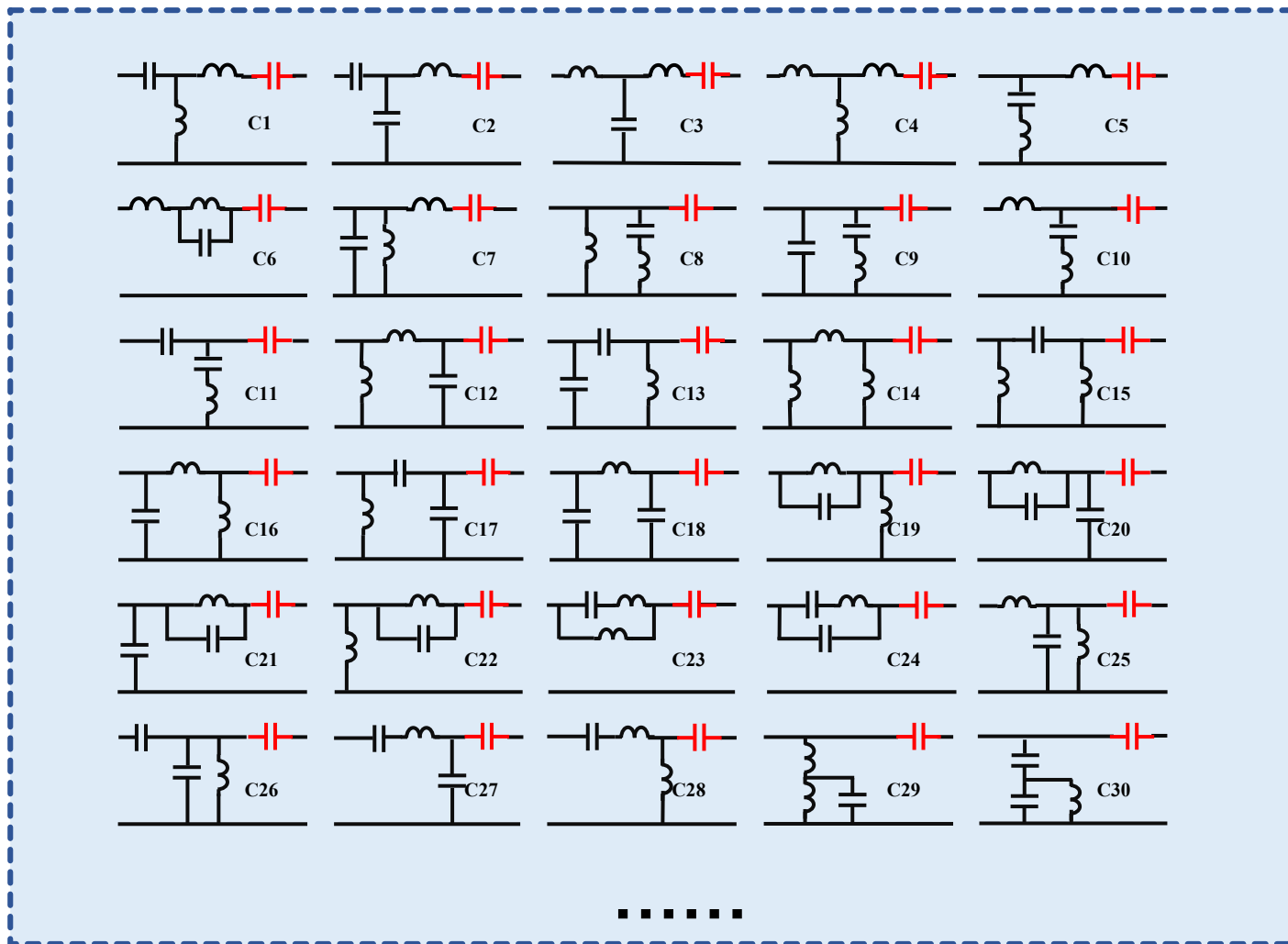
CPT系统原边谐振模块和副边谐振模块



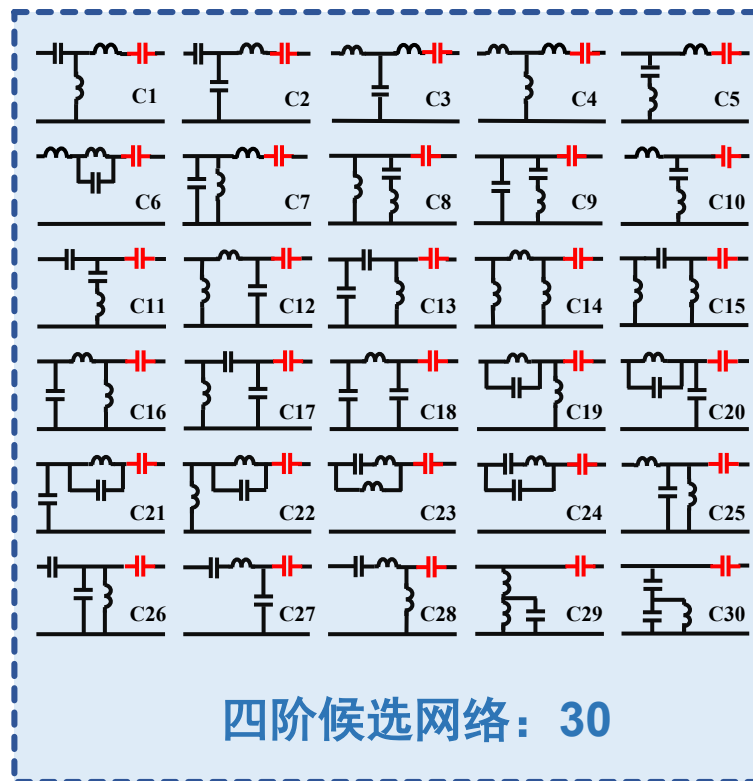
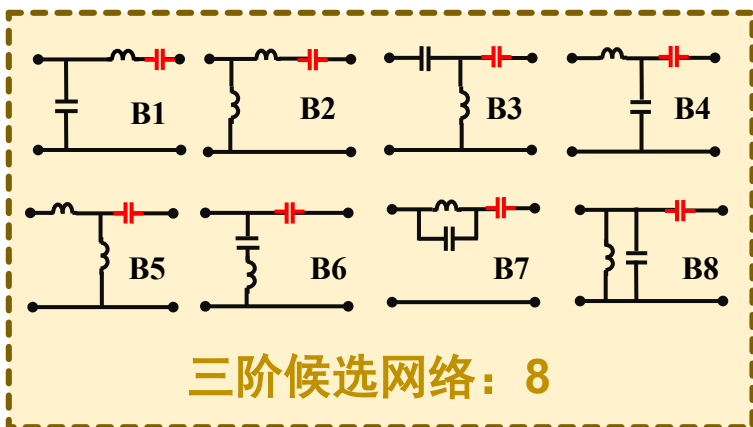
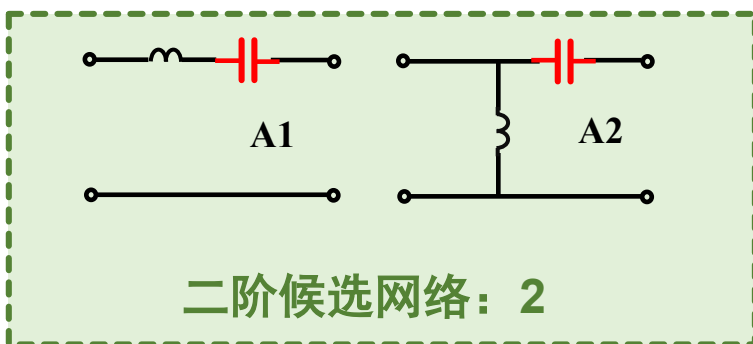
### 三阶候选网络



## 高阶候选网络

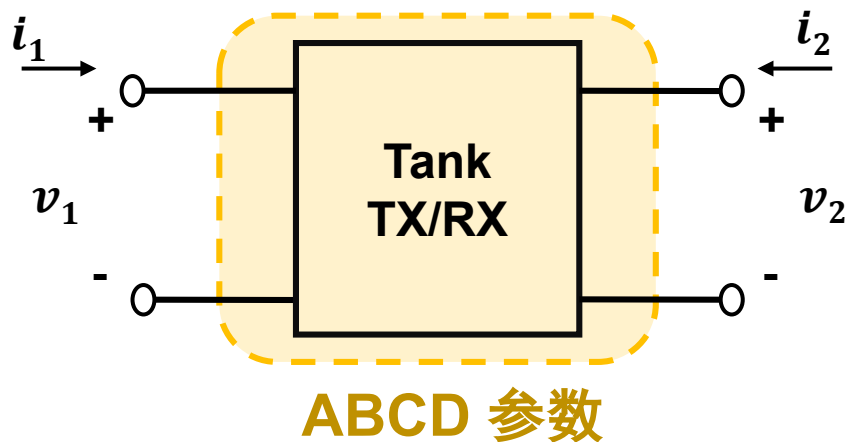


# 候选网络



.....

## ABCD参数



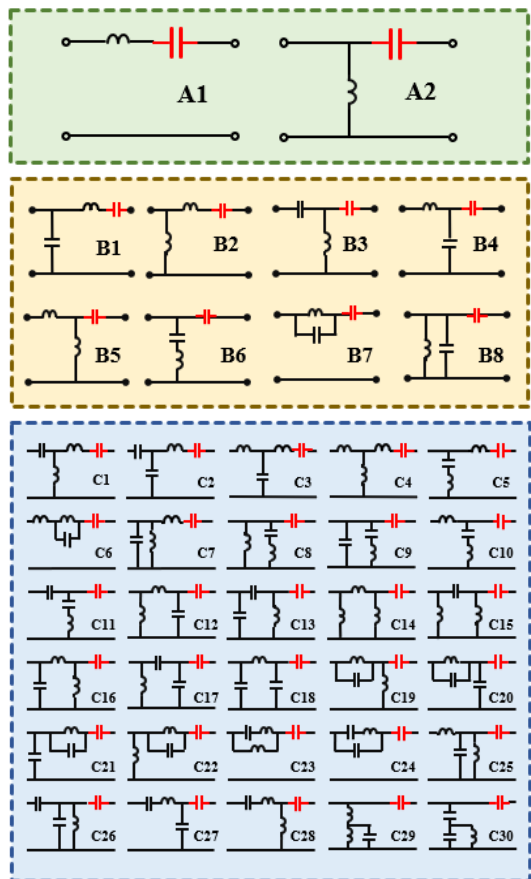
$$\begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix}$$

$$A = \left. \frac{V_2}{V_1} \right|_{I_1=0}; \quad B = \left. \frac{V_2}{I_1} \right|_{V_1=0}$$

$$C = \left. -\frac{I_2}{V_1} \right|_{I_1=0}; \quad D = \left. -\frac{I_2}{I_1} \right|_{V_1=0}$$

	负载无关性输出	反射阻抗纯阻性
V2V	$B = 0$	$C = 0$
I2V	$A = 0$	$D = 0$
V2I	$D = 0$	$A = 0$
I2I	$C = 0$	$B = 0$

	传递函数	阻抗转换
V2V	$G_{vv} = A$	$D/A \times R_L$
I2V	$G_{iv} = B$	$B/C \times 1/R_L$
V2I	$G_{vi} = C$	$B/C \times 1/R_L$
I2I	$G_{ii} = D$	$D/A \times R_L$

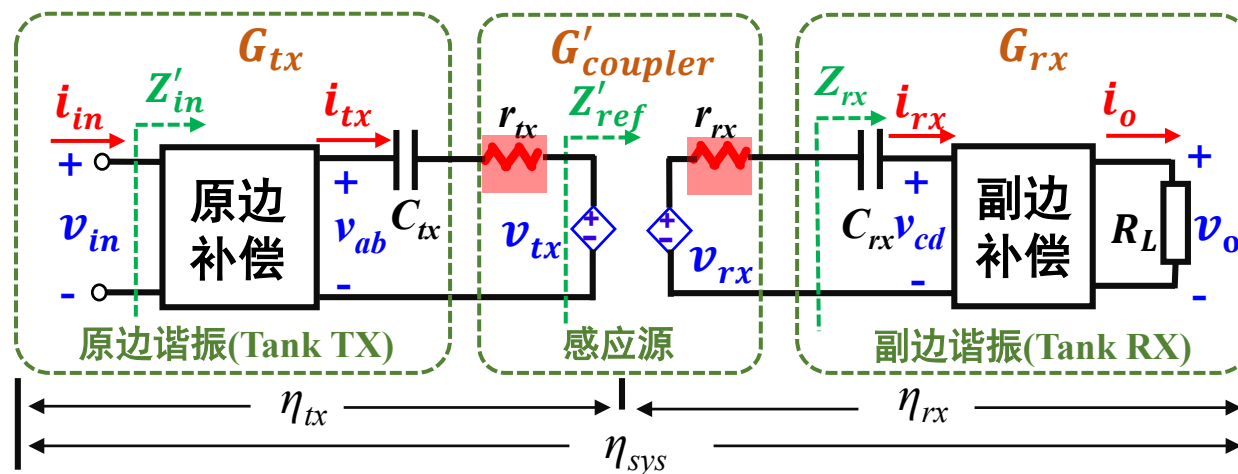


**ABCD**  
参数

	负载无关性输出	反射阻抗纯阻性
V-2-V	A1,B1,B2,B3,B4,B5,B7,C1,C2,C3,C4,C5,C6,C7,C10,C11,C12,C13,C14,C15,C16,C18,C19,C20,C21,C22,C23,C24,C25,C26,C27,C28	A1,B8,C6,C7,C16,C23,C24,C25
V-2-I	B3,B4,C1,C3,C10,C11,C12,C13,C15,C18,C19,C20,C25,C26,C27,C28	B3,C1,C3,C11,C18,C19,C26,C28
I-2-I	A1,B7,B8,C6,C7,C8,C9,C12,C13,C15,C16,C17,C18,C23,C24,C25,C26,C29,C30	A1,B8,C6,C7,C16,C23,C24,C25
I-2-V	A2,B1,B2,B3,B5,B6,B8,C1,C2,C3,C4,C5,C7,C8,C9,C10,C11,C12,C13,C14,C15,C16,C18,C19,C21,C22,C25,C26,C28,C29,C30	B3,C1,C3,C11,C18,C19,C26,C28



## 等效串联电阻的影响



### 效率

$$\eta_{tx} = \frac{Z'_{ref}}{Z'_{ref} + r_{tx}}$$

$$\eta_{rx} = \frac{Z_{rx}}{Z_{rx} + r_{rx}}$$

$$\eta_{sys} = \eta_{tx} \eta_{rx}$$

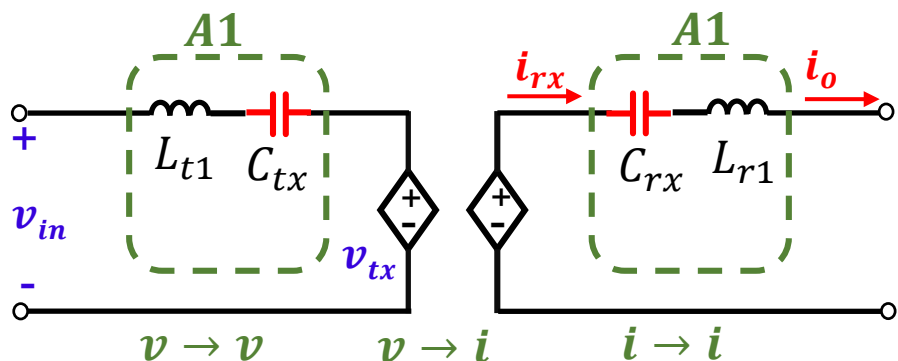
### 传递函数

$$G'_{coupler,iv} = \frac{v_{rx}}{i_{tx}} \frac{Z_{rx}}{Z_{rx} + r_{rx}} = G_{coupler,iv} \times \eta_{rx}$$

$$G'_{coupler,vi} = \frac{i_{rx}}{v_{tx}} \frac{Z_{tx}}{Z_{tx} + r_{tx}} = G_{coupler,vi} \times \eta_{tx}$$



## 案例1—串联串联补偿

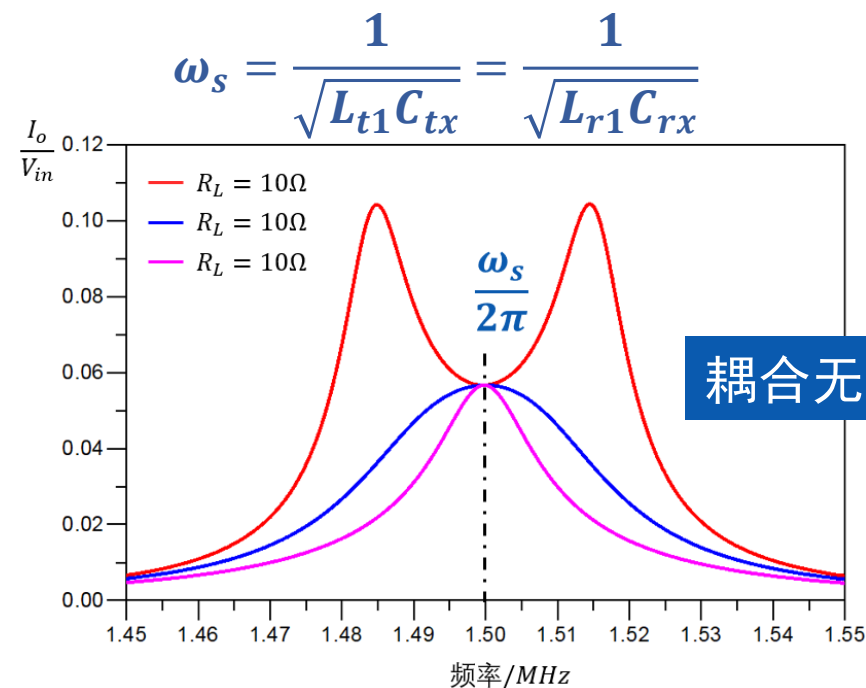


$$\begin{bmatrix} V_o \\ I_o \end{bmatrix} = \begin{bmatrix} A_{tx} & B_{tx} \\ C_{tx} & D_{tx} \end{bmatrix} \begin{bmatrix} 0 & \frac{1}{j\omega C_m} \\ -j\omega C_m & 0 \end{bmatrix} \begin{bmatrix} A_{rx} & B_{rx} \\ C_{rx} & D_{rx} \end{bmatrix} \begin{bmatrix} V_o \\ I_o \end{bmatrix}$$

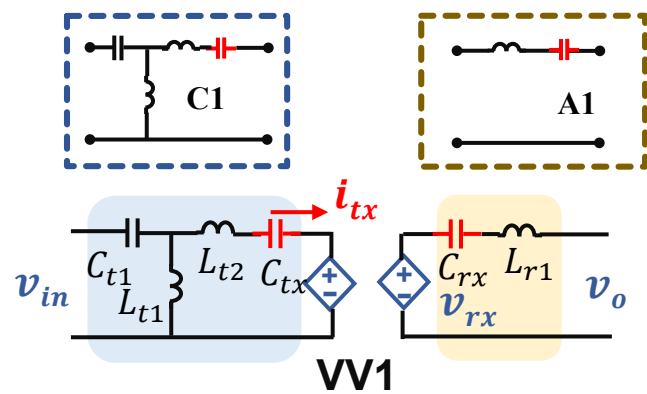
$$B_{tx} = 0, C_{tx} = 0$$

$$B_{rx} = 0, C_{rx} = 0$$

$$\begin{bmatrix} V_o \\ I_o \end{bmatrix} = \begin{bmatrix} 1 & j\omega L_{t1} + \frac{1}{j\omega C_{tx}} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & \frac{1}{j\omega C_m} \\ -j\omega C_m & 0 \end{bmatrix} \begin{bmatrix} 1 & j\omega L_{r1} + \frac{1}{j\omega C_{rx}} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_o \\ I_o \end{bmatrix}$$

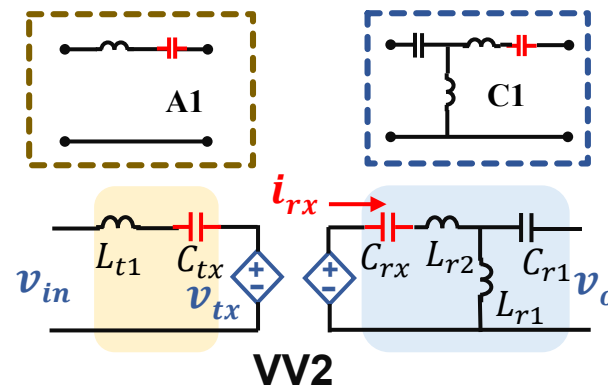


## 案例2 – V2V转换



### 谐振条件

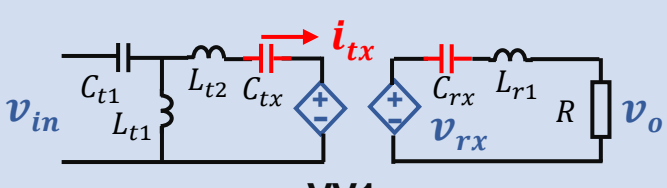
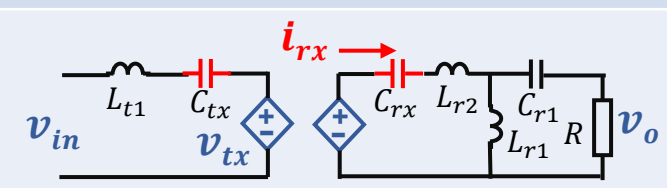
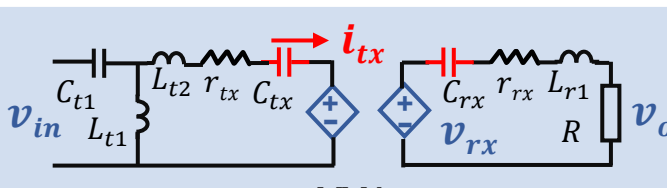
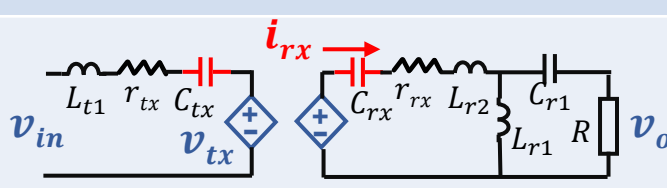
1.  $j\omega L_{t1} + \frac{1}{j\omega C_{t1}} = 0 (A_{tx} = 0, D_{tx} = 0)$
2.  $j\omega L_{t1} + j\omega L_{t2} + \frac{1}{j\omega C_{tx}} = 0 (A_{tx} = 0, D_{tx} = 0)$
3.  $j\omega L_{r1} + \frac{1}{j\omega C_{rx}} = 0 (B_{rx} = 0, C_{rx} = 0)$
4.  $m_t = \frac{C_{tx}}{C_{t1}}$



### 谐振条件

1.  $j\omega L_{t1} + \frac{1}{j\omega C_{t1}} = 0 (B_{tx} = 0, C_{tx} = 0)$
2.  $j\omega L_{r1} + j\omega L_{r2} + \frac{1}{j\omega C_{rx}} = 0 (A_{rx} = 0, D_{rx} = 0)$
3.  $j\omega L_{r1} + \frac{1}{j\omega C_{rx}} = 0 (A_{rx} = 0, D_{rx} = 0)$
4.  $m_r = \frac{C_{rx}}{C_{r1}}$

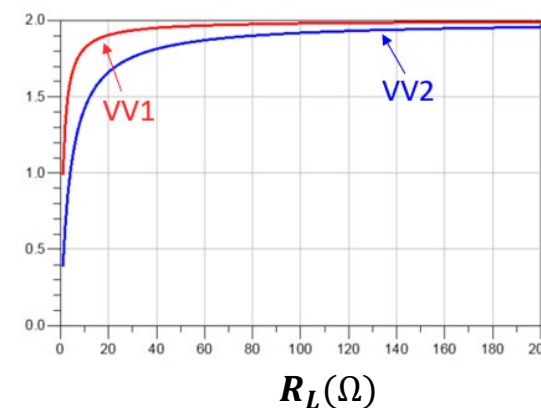
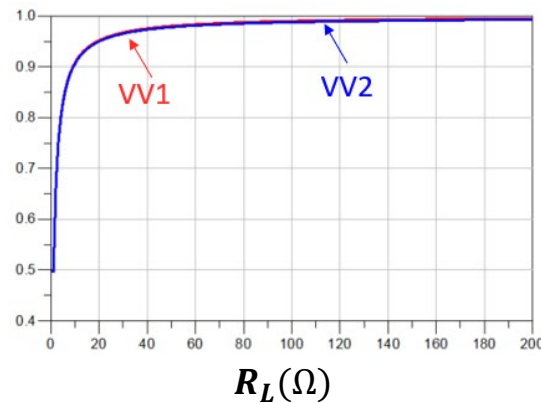
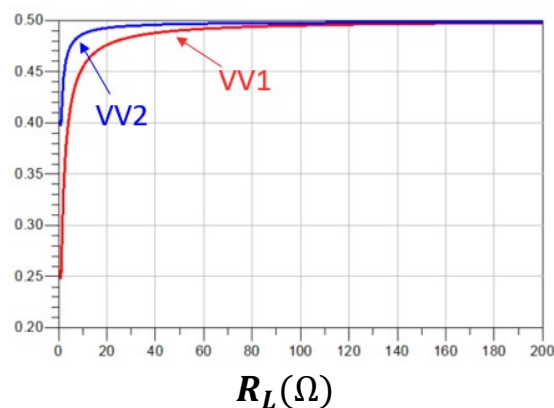
## 案例分析 – V2V转换

理想模型 (无ESR)	电压传输比	效率
 <p>VV1</p>	$G_{vv1} = \frac{k}{m_t} \sqrt{\frac{C_{rx}}{C_{tx}}}$	1
 <p>VV2</p>	$G_{vv2} = \frac{m_r}{k} \sqrt{\frac{C_{tx}}{C_{rx}}}$	1
非理想模型 (存在ESRs)	电压传输比	效率
 <p>VV1</p>	$G_{vv1} * \eta_{rx}$	$\eta_{sys\_1} = \frac{k^2 / (\omega^2 C_{tx} C_{rx})}{k^2 / (\omega^2 C_{tx} C_{rx}) + r_{tx}(R + r_{rx})} * \frac{R}{R + r_{rx}}$
 <p>VV2</p>	$G_{vv2} * \eta_{tx}$	$\eta_{sys\_2} = \frac{k^2 / (\omega^2 C_{tx} C_{rx})}{k^2 / (\omega^2 C_{tx} C_{rx}) + r_{tx}(\frac{X^2}{R} + r_{rx})} * \frac{\frac{X^2}{R}}{\frac{X^2}{R} + r_{rx}}$ <p style="text-align: center;"><math>X = k * G_{vv2} / (\omega^2 C_{tx} C_{rx})</math></p>

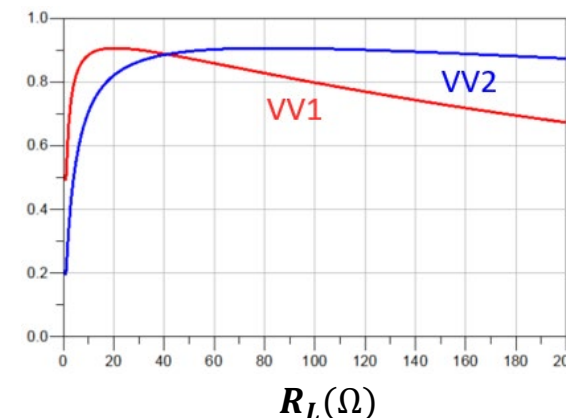
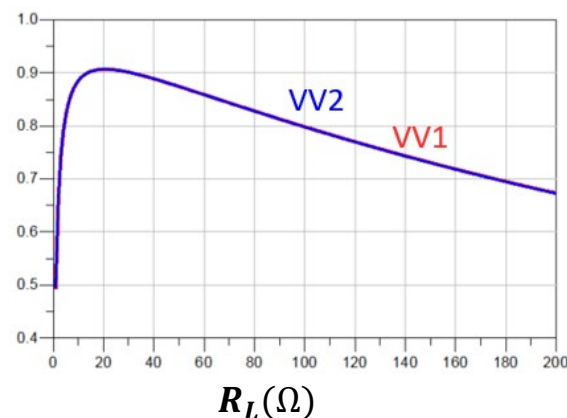
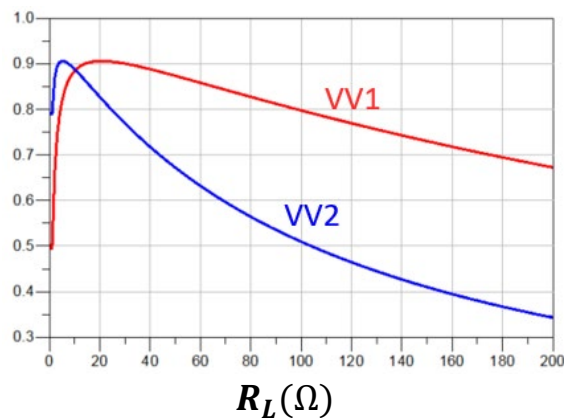
## 案例分析 – V2V转换

$f_s$	$C_{tx} & C_{rx}$	$Q_{tx} & Q_{rx}$	$k$
2MHz	300pF	300	0.068

$G_{vv}$  :



效率:

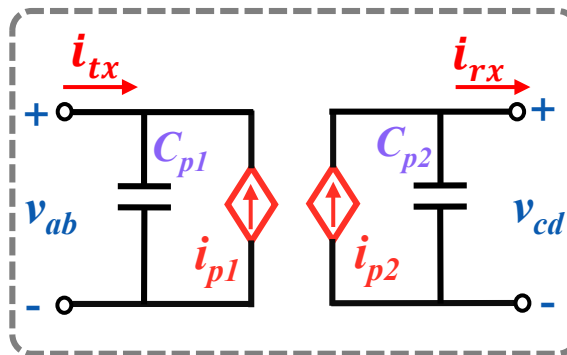


对于不同的  $G_{vv}$ , VV1和VV2补偿在输出精度和效率上的表现不同

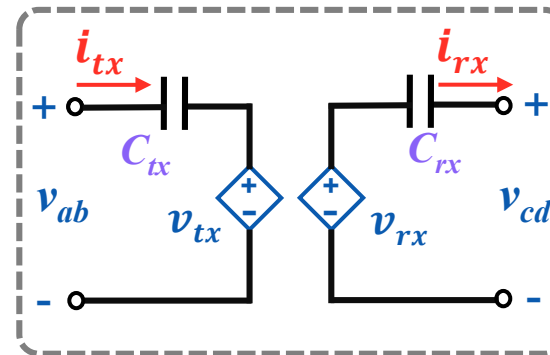
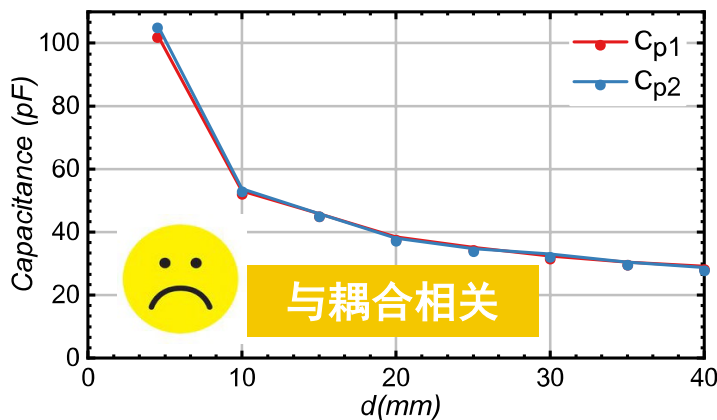
# 容性耦合器



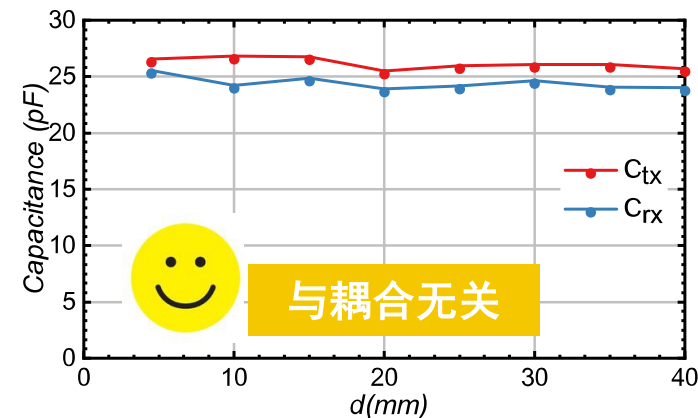
实验装置



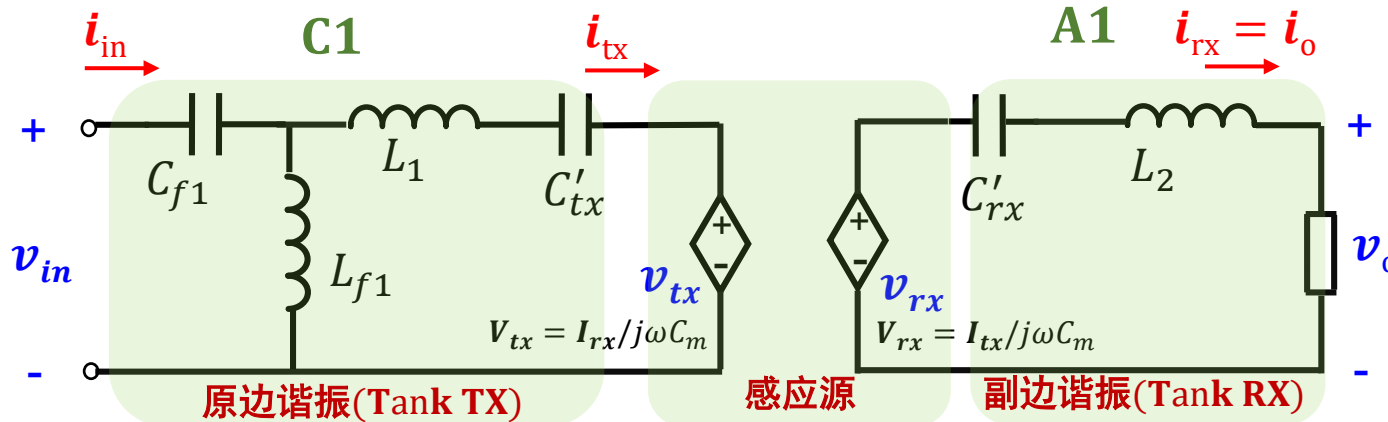
感应电流源模型



感应电压源模型



## CLL-L补偿网络—恒压输出



电压→电流转换

电流→电压转换

电压→电压转换

谐振条件

谐振条件(D=0, A=0)

$$j\omega L_{f1} \pm 1 / (j\omega C_{f1}) \pm j\omega L_1 \pm 1 / (j\omega C_{tx})$$

传递函数

$$\frac{I_{tx}}{V_{in}} = \frac{j\omega L_{f1}}{j\omega L_{f1}}$$

系统整体传递函数

转换比

$$\frac{V_{rx}}{I_{tx}} = j\omega C_m$$

$$\frac{V_{rx}}{I_{tx}} = j\omega C_m$$

谐振条件(B=0, C=0)

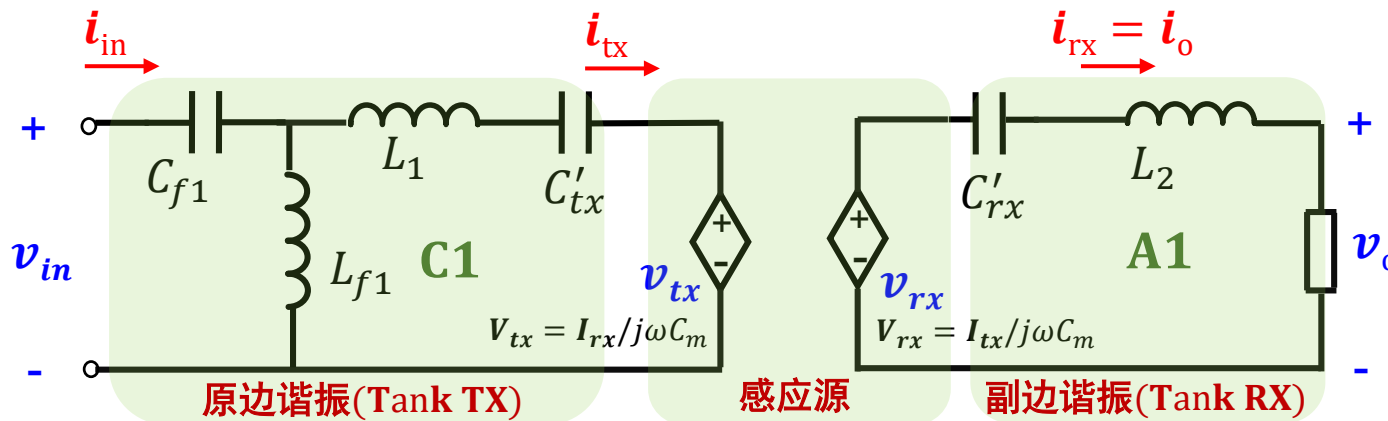
$$j\omega L_{f2} \pm 1 / (j\omega C_{rx})$$

传递函数

$$\frac{V_o}{V_{rx}} = \frac{V_o}{V_{rx}} = 1$$

$$\frac{V_o}{V_{in}} = \frac{k C_{f1}}{\sqrt{C_{tx} C_{rx}}} = \frac{C_{f1}}{C_m}$$

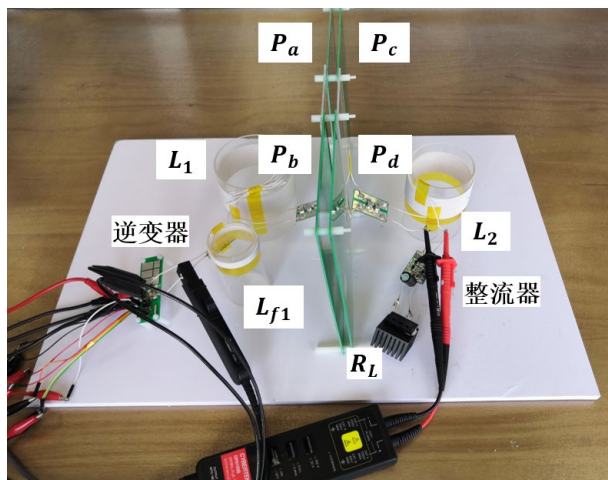
## CLL-L补偿网络—恒压输出



V2I

I2V

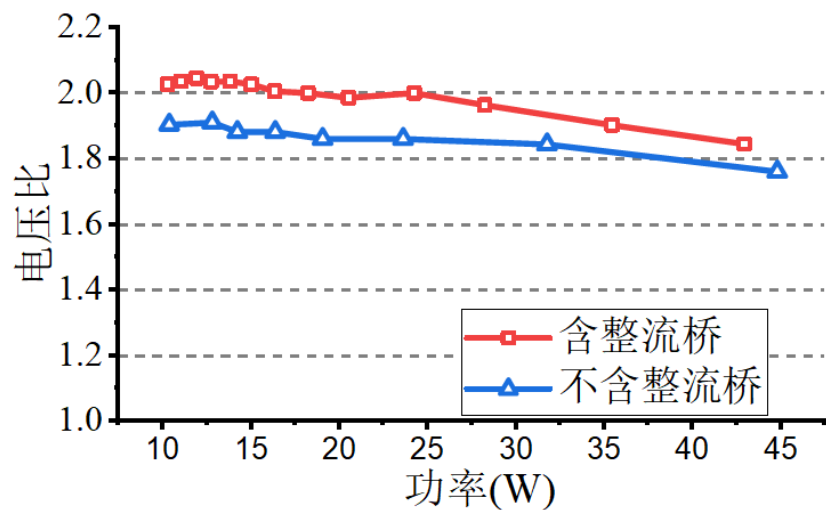
V2V



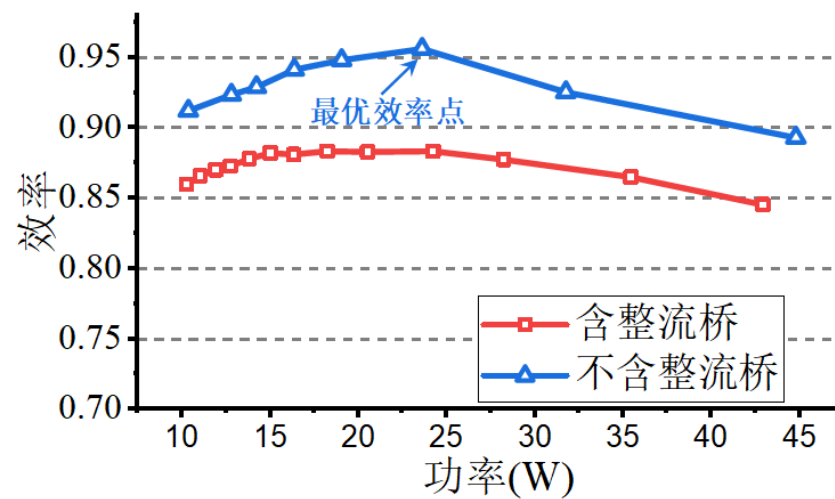
实验实物图

Parameter	Design Value	Parameter	Design value
$V_o/V_{in}$	2	$P_o$	45W
$f_s$	2 MHz	$C_{f1}$	1715.7 pF
$L_{f1}$	3.69 $\mu$ H	$L_1$	78.9 $\mu$ H
$L_2$	45.8 $\mu$ H	$Q_{L_{f1}}$	386
$Q_{L1}$	373	$Q_{L2}$	464
$l_1$	120 mm	$l_2$	200 mm
$d$	10 mm	$d_l$	70 mm
$C'_{ab}$	62.5 pF	$C'_{cd}$	125.1 pF
$C'_{tx}$	76.6 pF	$C'_{rx}$	138.3 pF
$C'_m$	857.9 pF	$k$	0.12
$Q_{tx}$	391	$Q_{rx}$	464

实验参数



不同功率下系统的电压传输比



不同功率下系统效率



## 总结

1. 建立了容性耦合器电路模型，简化了系统谐振状态的分析
2. 提出了适用于CPT系统的高阶补偿网络理论，为系统分析提供了统一的方法
3. 提出了CLL-L补偿网络，实现了恒压输出

[1] **S. Wang**, J. Liang, and M. Fu\*, "Capacitive Power Transfer Systems Based on Induced Voltage Source Model", IEEE Transactions on Power Electronics, early access.

[2] **S. Wang**, J. Liang, H. Wang, and M. Fu, "An Induced Voltage Source Model for Capacitive Power Transfer", IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, Mar. 15-19, 2020.

- 感谢各位老师百忙之中出席今天的答辩
- 感谢傅老师一直以来对我的指导和帮助
- 感谢实验室的各位同学给予我的帮助

