Part III: Compensation Design

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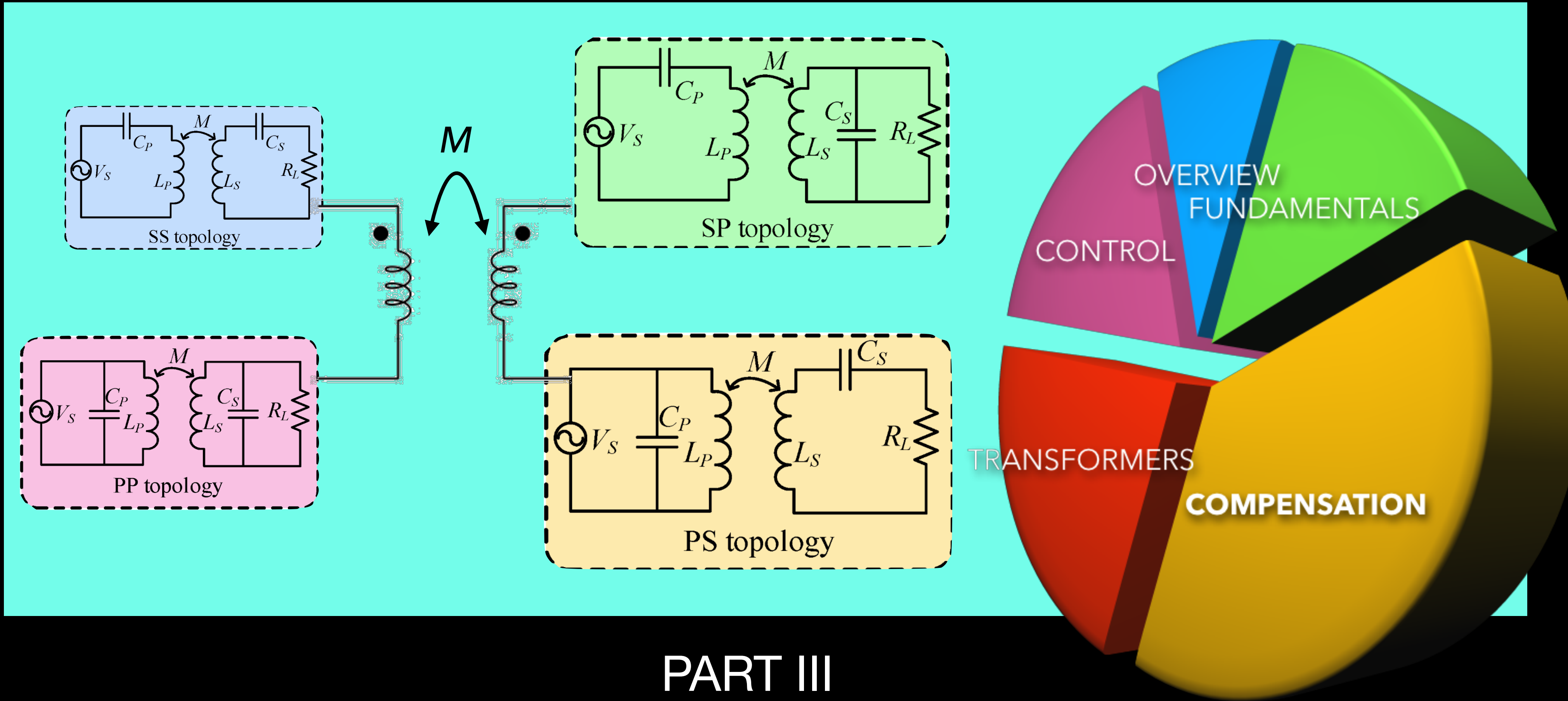
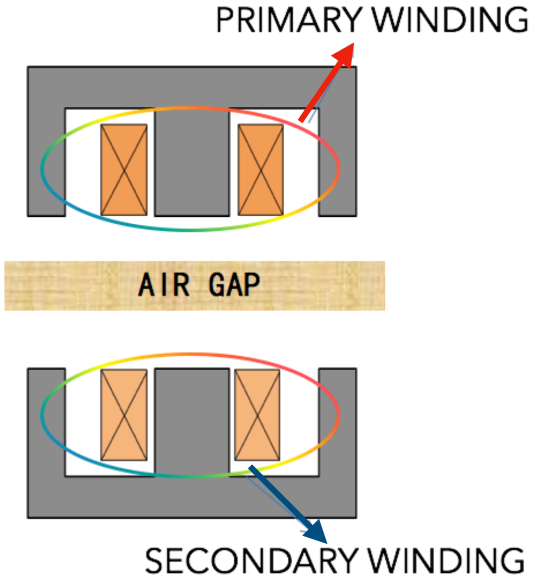
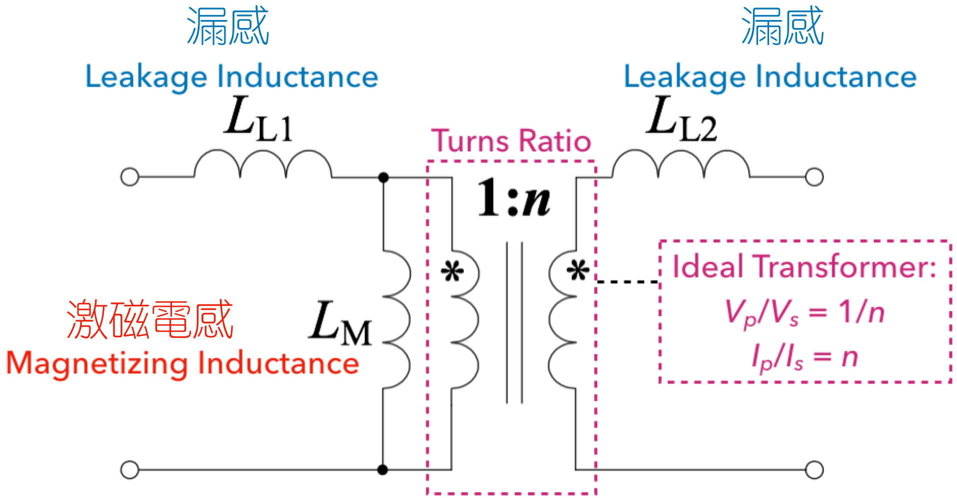


PART III

COMPENSATION DESIGN

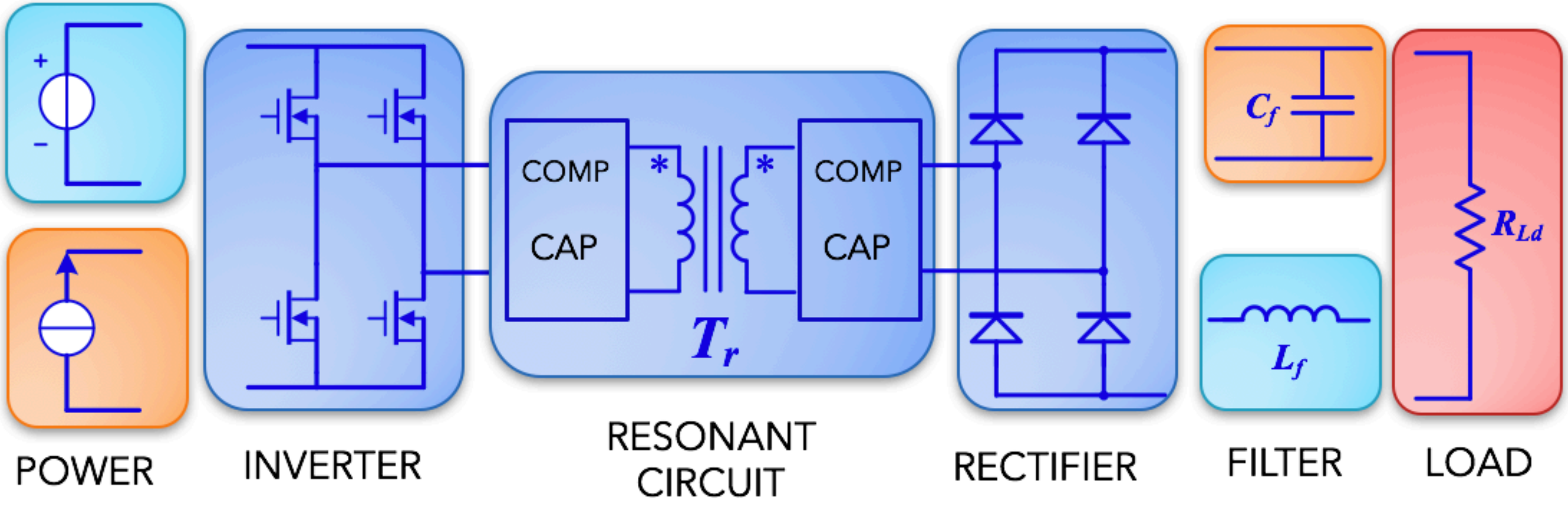
Purpose of Compensation





- Reduce INPUT volt-amp (remove reactive power)
- Reduce switches' voltage and current stresses
- Increase power transfer capacity
- Increase efficiency
- Minimize sensitivity to parameter variations

Typical Circuit



系統典型

PRIMARY SIDE

Input voltage or
current source

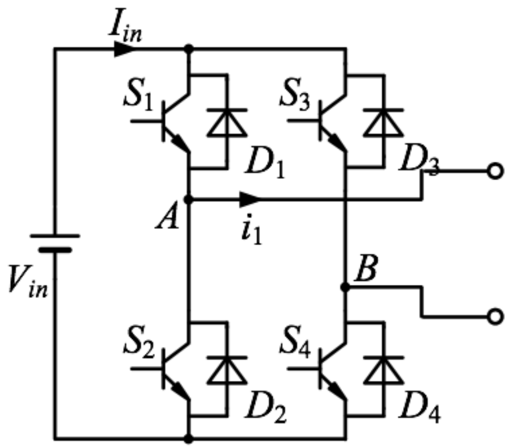
SECONDARY SIDE

C filter
LC filter

Basic Connection at Input Side

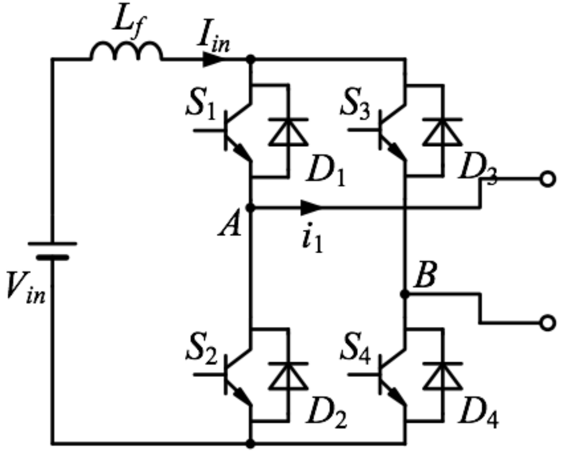
PRIMARY SIDE

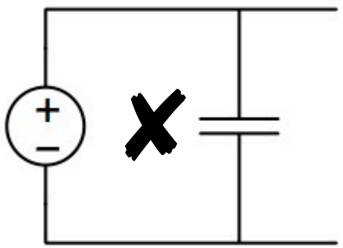
Voltage source input



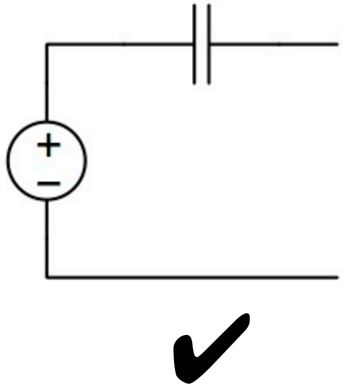
PRIMARY SIDE

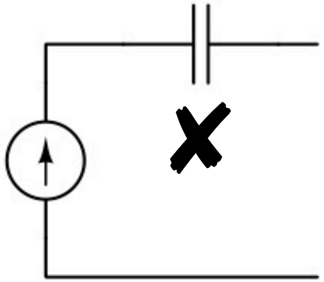
Current source input



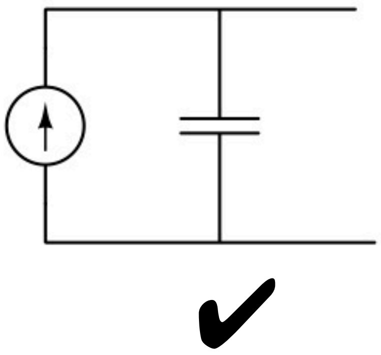


Capacitor voltage cannot change. No resonance!

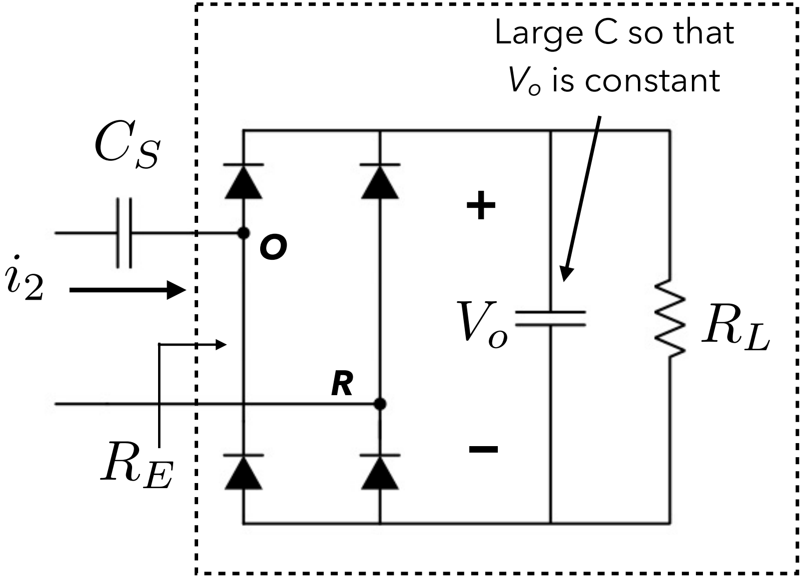


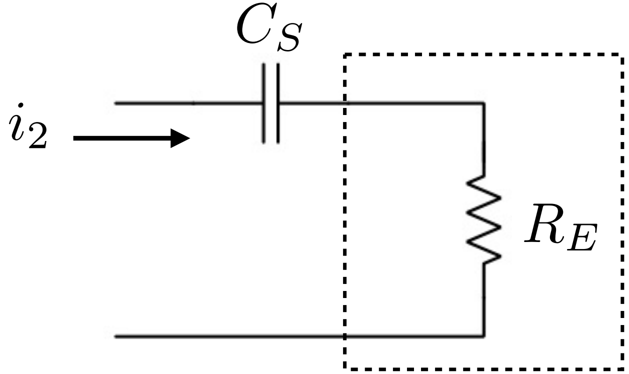


Capacitor current cannot change. No resonance!



Secondary Side Circuit

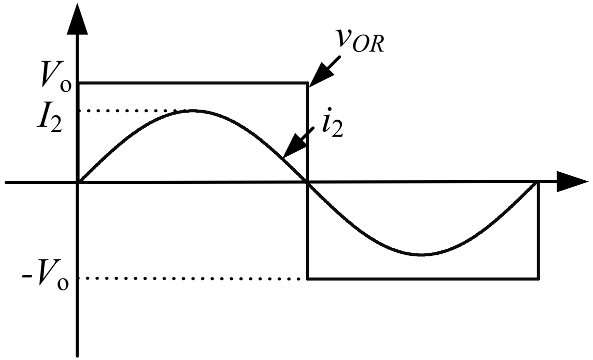




If C is a large, output voltage V_o is constant.

V_{OR} is constant.

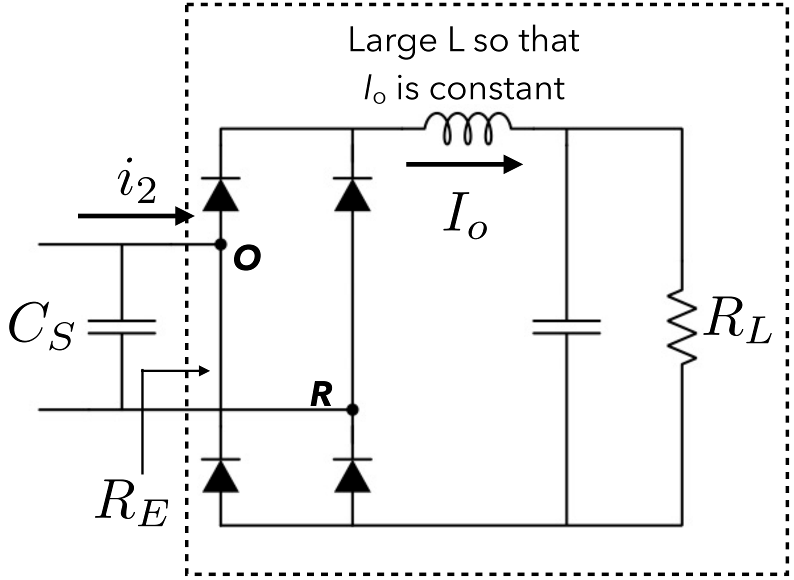
i_2 and V_{OR} are in phase.



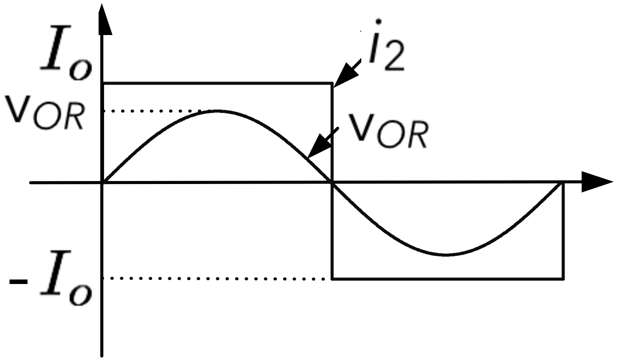
$$R_E = \frac{V_{OR}}{i_2} = \frac{\frac{4}{\pi} V_o \sin \omega t}{I_2 \sin \omega t} = \frac{\frac{4}{\pi} V_o}{\frac{\pi}{2} I} = \frac{8 V_o}{\pi^2 I} = \frac{8}{\pi^2} R_L$$

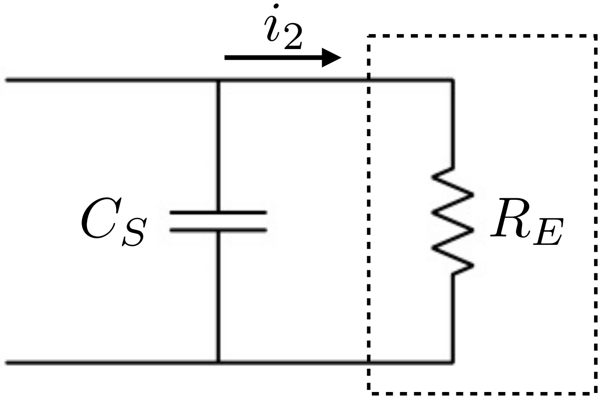
$$R_E = \frac{8}{\pi^2} R_L$$

Secondary Side Circuit



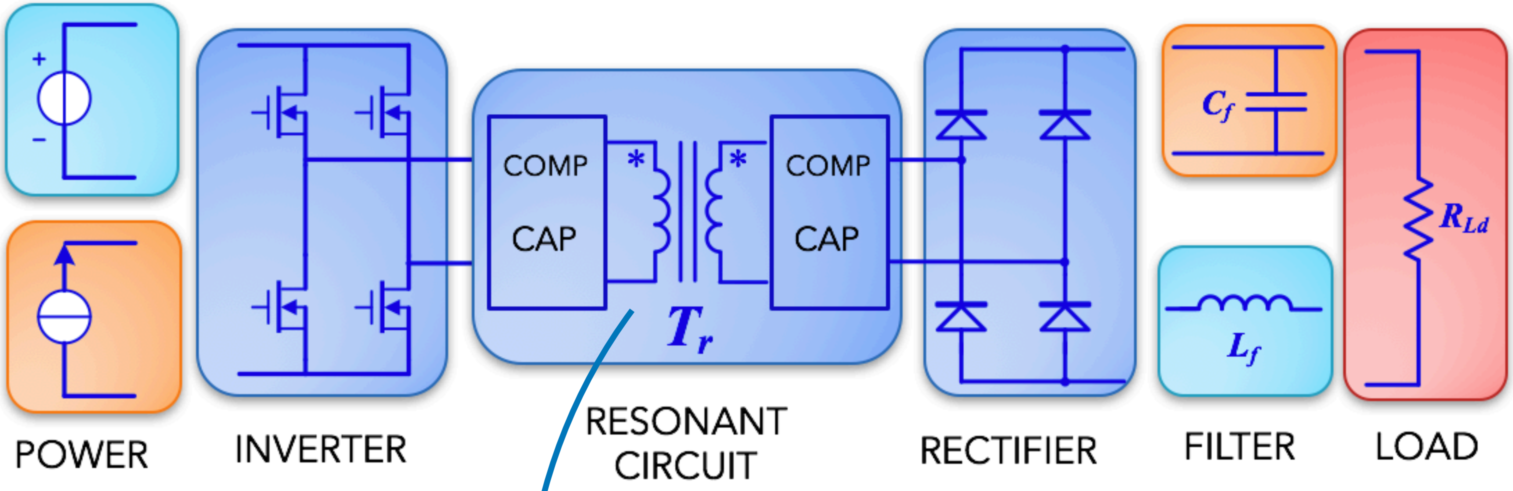
If LC is a large filter, output current I_o is constant.
Similarly, i_2 and v_{OR} are in phase.



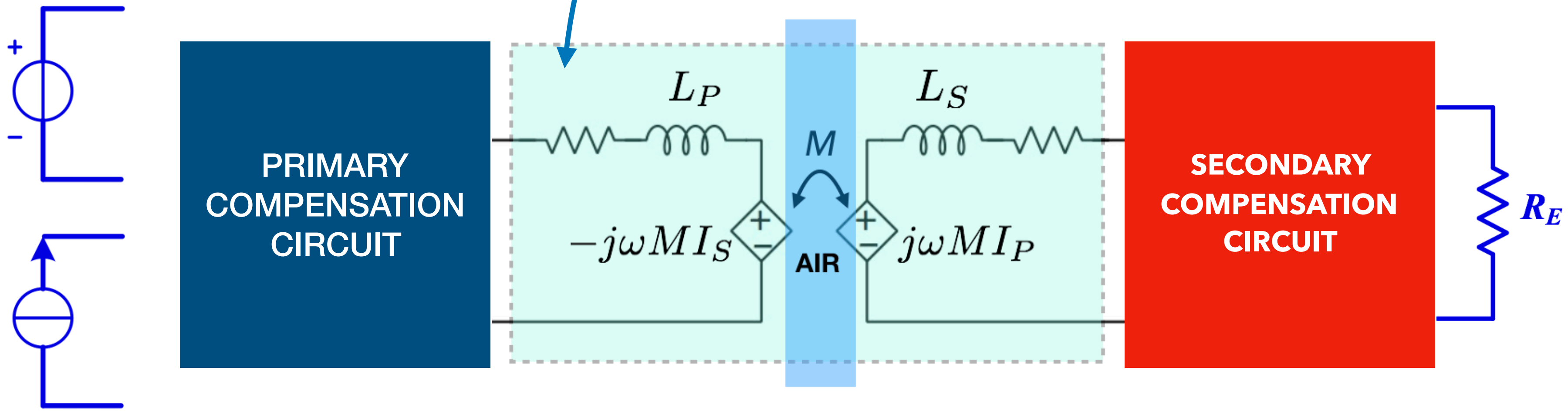


$$R_E = \frac{\pi^2}{8} R_L$$

Simplified System

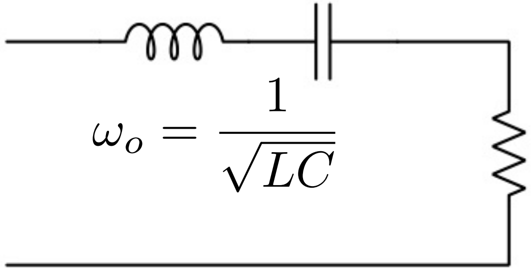


系統簡化



Resonant Compensation

Series compensation

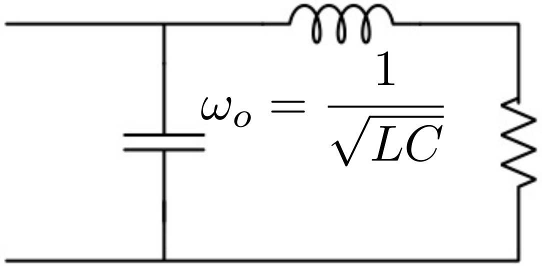


$$\omega_o = \frac{1}{\sqrt{LC}}$$

The voltage across C and L will exactly cancel each other at resonant frequency. For large Q, the individual voltages on C and L can be very large at/near the resonant frequency.

$$Q = \omega CR = \frac{\omega L}{R} \qquad Q_o = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Parallel compensation

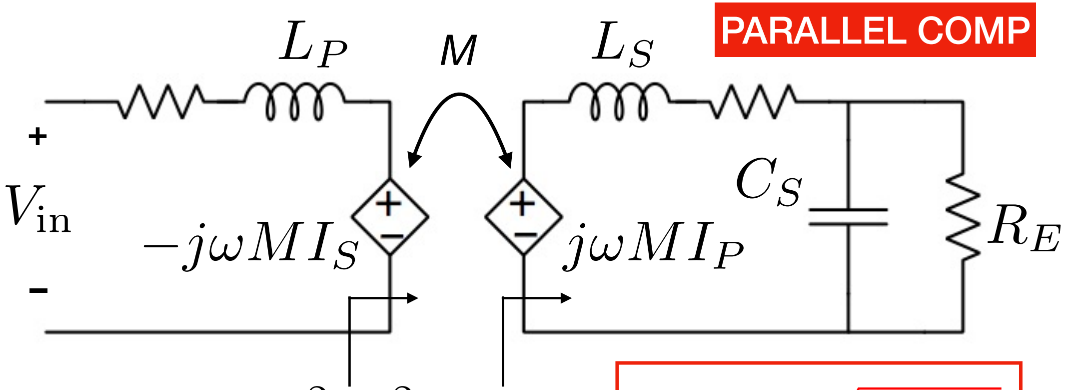


$$\omega_o = \frac{1}{\sqrt{LC}}$$

Note that this is not the exact dual of the series compensation, with the inductor in series with the load. Near the resonant frequency, the currents in C and L cancel, if Q is large. Basically, at large Q, the resistance is much smaller than the reactance of the inductance or the capacitor. So, the circuit is almost like L || C and is open-circuit at resonant frequency.

Secondary Single Cap Compensation

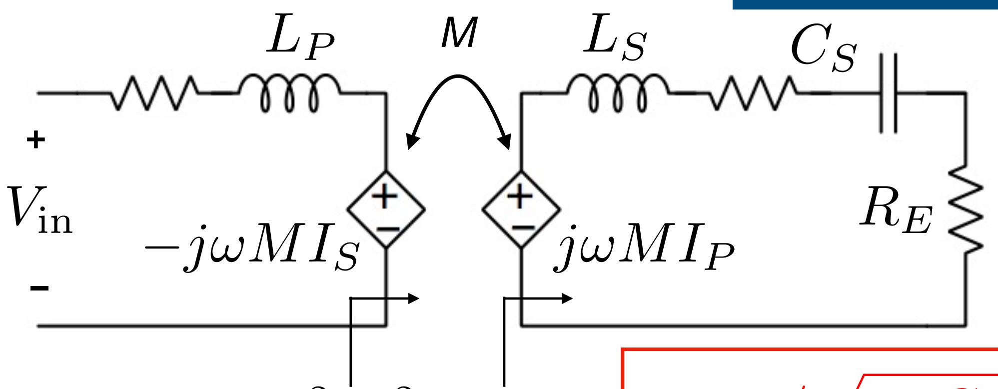
PARALLEL COMP



$$Z_r = \frac{\omega^2 M^2}{Z_S} \qquad Z_S$$

$$\boxed{\omega = 1/\sqrt{L_S C_S}}$$

SERIES COMP



$$Z_r = \frac{\omega^2 M^2}{Z_S} \qquad Z_S$$

$$\boxed{\omega = 1/\sqrt{L_S C_S}}$$

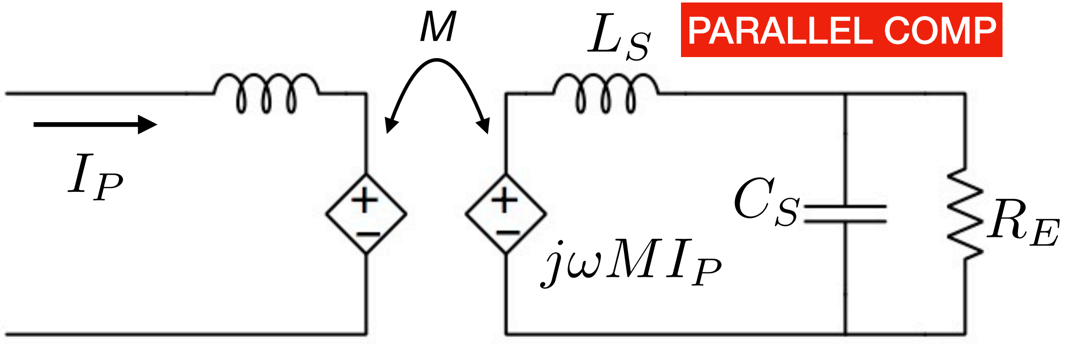
Reflected impedance at primary $Z_r = \dfrac{\omega^2 M^2}{Z_S}$

Current at primary $I_P = \dfrac{V_{\text{in}}}{j\omega L_P + Z_r}$

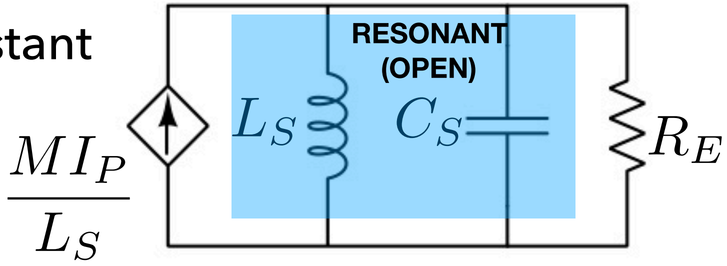
Power transferred from P to S: $P = I_P^2 \Re[Z_r]$

COMP TYPE	Real Part of Reflected Z_r	Imaginary Part of Reflected Z_r	Characteristics
SERIES	$\dfrac{\omega^2 M^2}{R_E}$	0	No reactive part
PARALLEL	$\dfrac{M^2 R_E}{L_S^2}$	$-\dfrac{\omega M^2}{L_S}$	Z_r is capacitive, and reactive part is independent of load

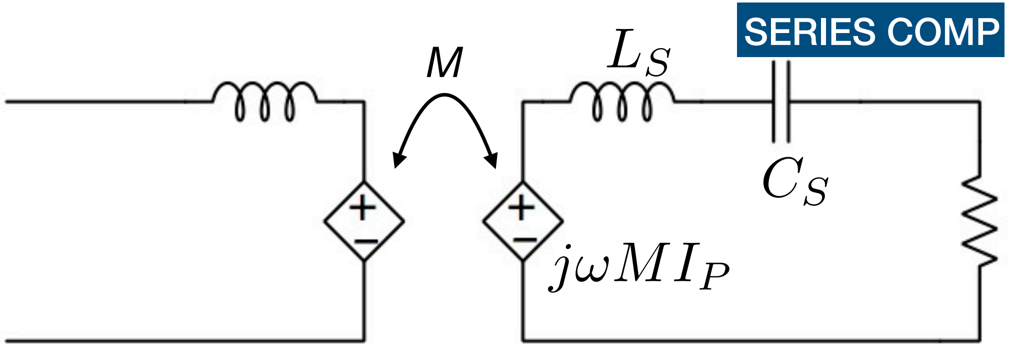
Secondary Single Cap Compensation



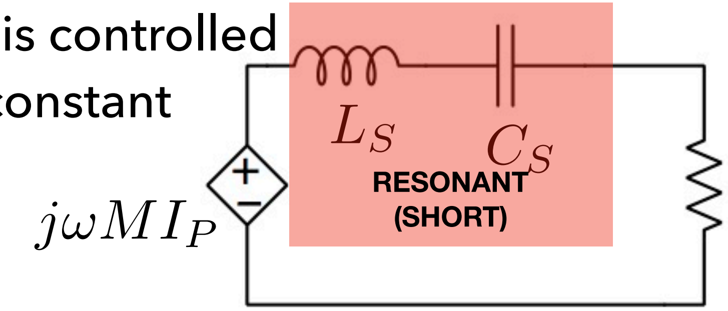
Suppose I_P is controlled to be constant



Then, the output current is exactly $M\ I_P/L_S$ independent of the load, which is excellent for charging application.



Suppose I_P is controlled to be constant

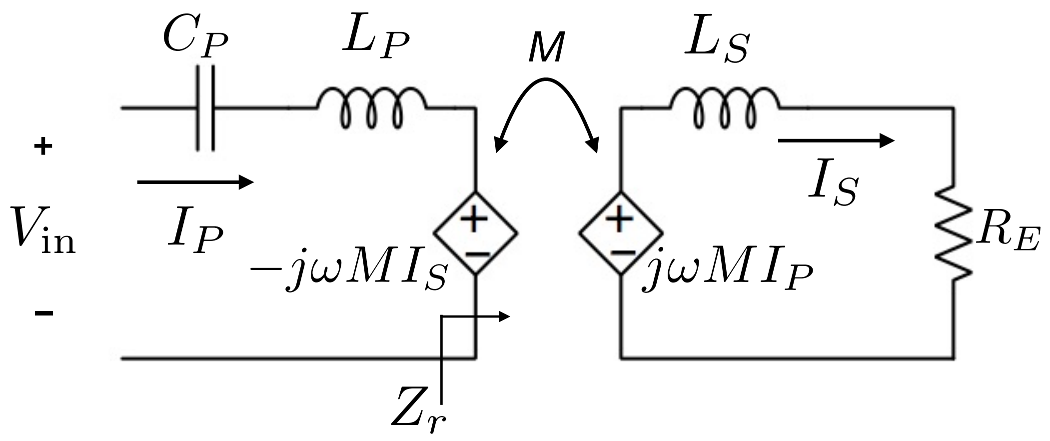


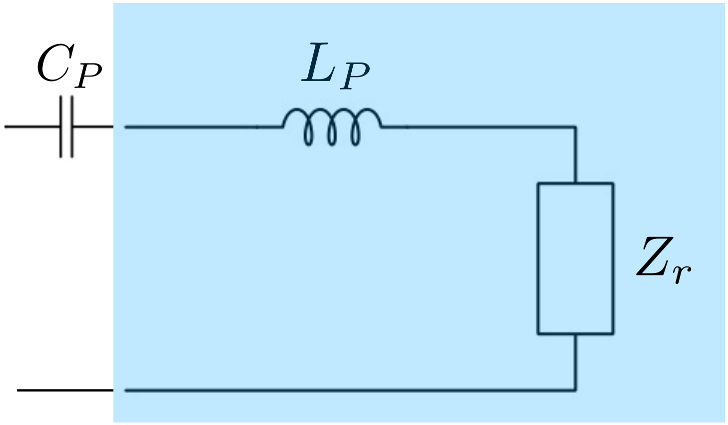
Then, the output voltage is exactly $j\omega\ M\ I_P$ independent of the load, which is excellent for regulated voltage application.

BOTH CASES HAVE MAX POWER TRANSFER CAPACITY, BUT POOR INPUT POWER FACTOR.

Primary Single Cap Compensation

SERIES COMP





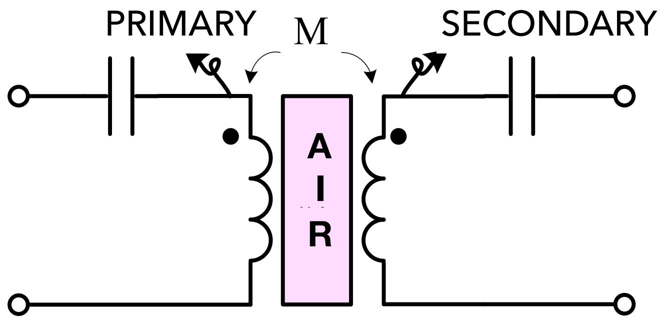
At resonance of C_P and $L_P + Im[Z_r]$, the input voltage goes directly to the ideal transformer and to the output. The input power factor can be maximized, theoretically to 1.

Basically, the reactive voltage across C_P cancels out the whole reactive voltage across the primary coil.

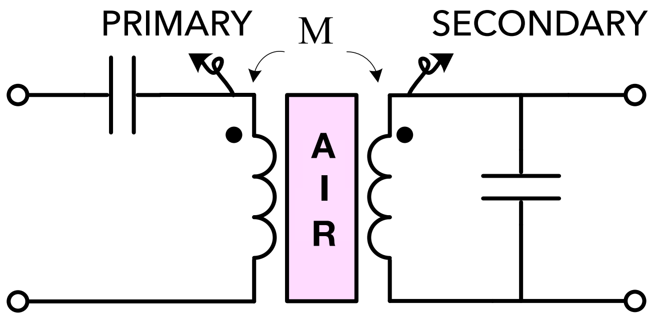
Primary compensation reduces input VOLT-AMP, i.e., improves power factor!

THUS, SINGLE CAP COMPENSATION AT EITHER PRIMARY or SECONDARY CANNOT ACHIEVE BOTH HIGH INPUT POWER FACTOR AND MAXIMUM POWER TRANSFER.

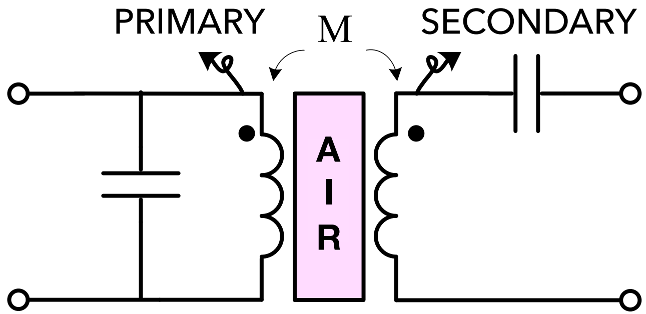
Two Capacitors Compensation



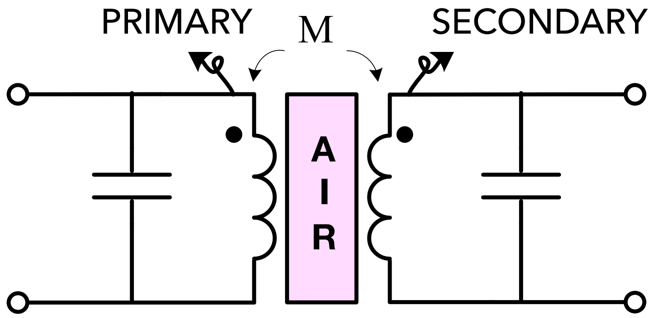
(a) S/S COMP



(b) S/P COMP



(c) P/S COMP



(d) P/P COMP

Two Capacitors Compensation

- To maximize the power transfer capacity, the secondary compensation capacitor C_S should cancel completely the self-inductance L_S (in the coupled inductor model).
- To minimize the input VOLT-AMP (maximize power factor), the primary compensation capacitor C_P should cancel out completely the primary side self-inductance and all reflected reactive part from secondary.
- **For SS, the change of k does not cause mismatch in the resonant frequenies of the two sides.**

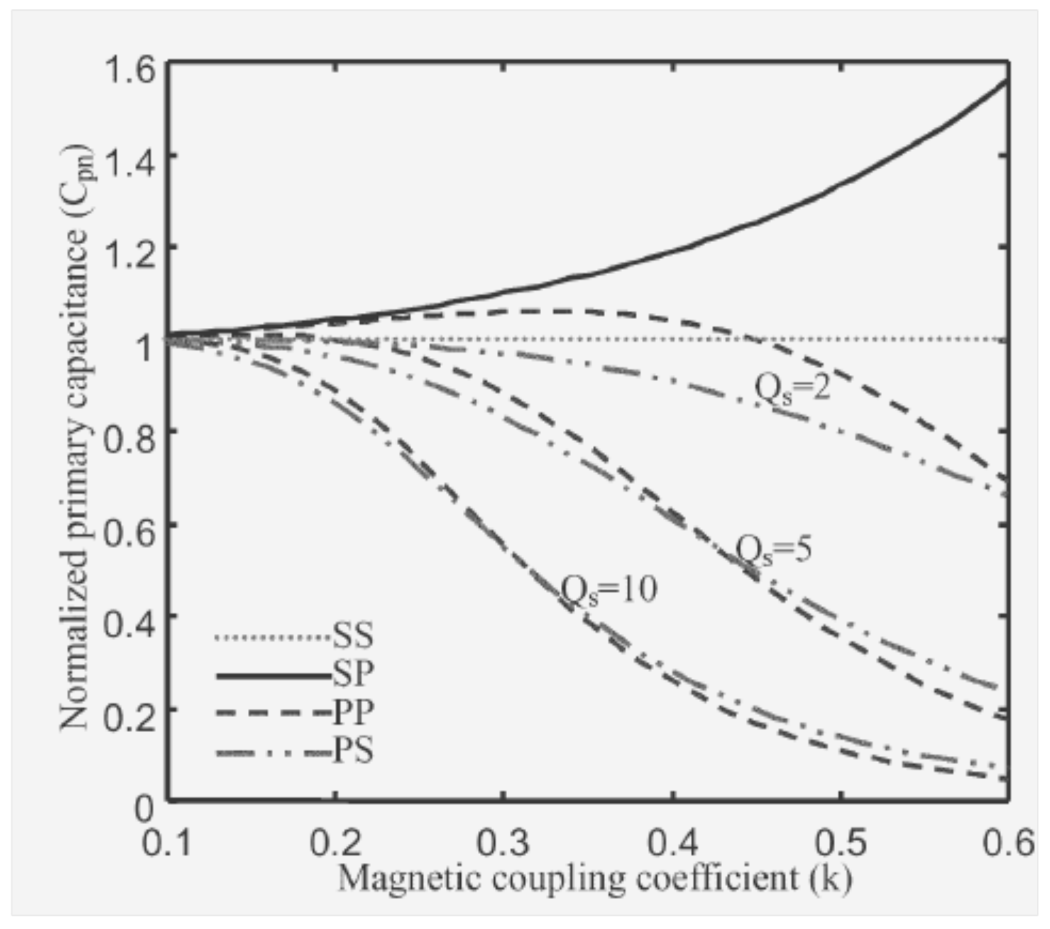
Normalized primary compensation capacitor

$$C_{pn} = \frac{C_P}{\left(\frac{C_S L_S}{L_P}\right)}$$

Topology	Primary Capacitance C_p	Normalized Primary Capacitance C_{pn}
SS	$\frac{C_s L_s}{L_p}$	1
SP	$\frac{C_s L_s^2}{L_p L_s - M^2}$	$\frac{1}{1-k^2}$
PP	$\frac{\left(L_p L_s - M^2\right) C_s L_s^2}{\frac{M^4 C_s R}{L_s} + \left(L_p L_s - M^2\right)^2}$	$\frac{1-k^2}{Q_s^2 k^4 + \left(1-k^2\right)^2}$
PS	$\frac{C_s L_s}{\frac{M^4}{L_p C_s L_s R} + L_p}$	$\frac{1}{Q_s^2 k^4 + 1}$

I_p is generally not constant, p. 11 is not applicable.
Parallel C does not cancel the self-inductance completely.
Thus, PS, PP, SP are k dependent!

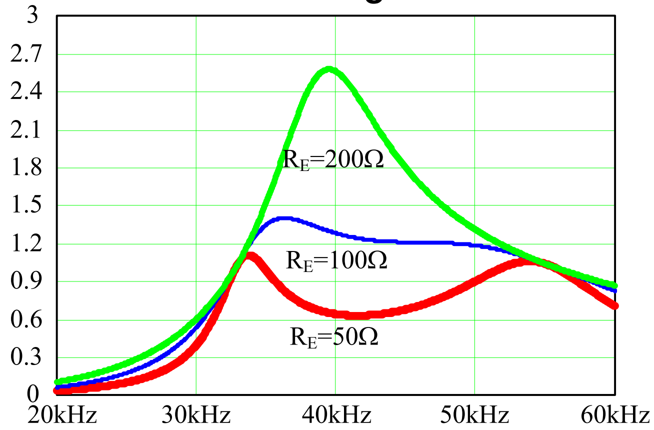
Two Capacitors Compensation



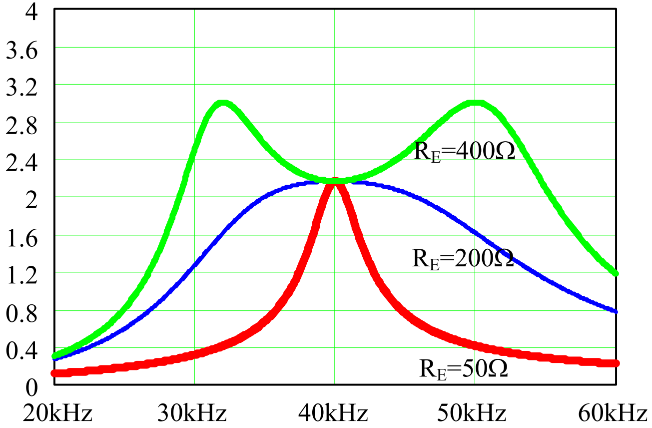
Topology	Primary Capacitance C_p	Normalized Primary Capacitance C_{pn}
SS	$\frac{C_s L_s}{L_p}$	1
SP	$\frac{C_s L_s^2}{L_p L_s - M^2}$	$\frac{1}{1-k^2}$
PP	$\frac{\left(L_p L_s - M^2\right) C_s L_s^2}{\frac{M^4 C_s R}{L_s} + \left(L_p L_s - M^2\right)^2}$	$\frac{1-k^2}{Q_s^2 k^4 + \left(1-k^2\right)^2}$
PS	$\frac{C_s L_s}{\frac{M^4}{L_p C_s L_s R} + L_p}$	$\frac{1}{Q_s^2 k^4 + 1}$

Voltage Output Curves

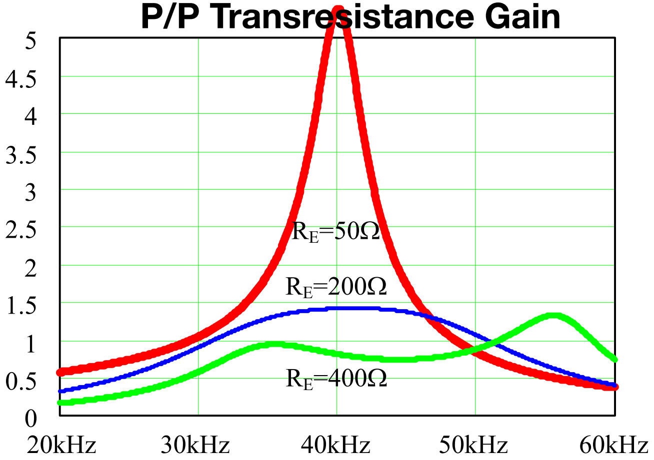
S/S Voltage Gain



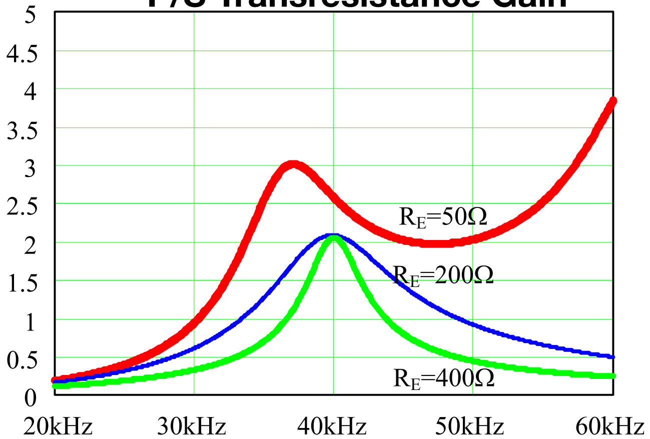
S/P Voltage Gain



P/P Transresistance Gain



P/S Transresistance Gain



Observe:

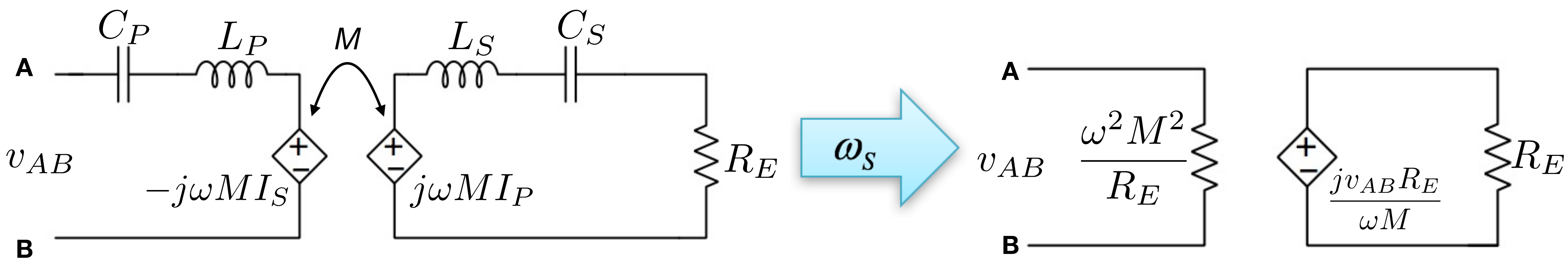
Which compensation can achieve load-independent voltage gain?

Where (what frequency) would this occur?

- S/S at two frequencies
- S/P at one frequency
- P/P approximately over some range

S/S Compensation

Compensation of self inductances (in coupled inductors model)



😀 Input is resistive. Unity power factor!

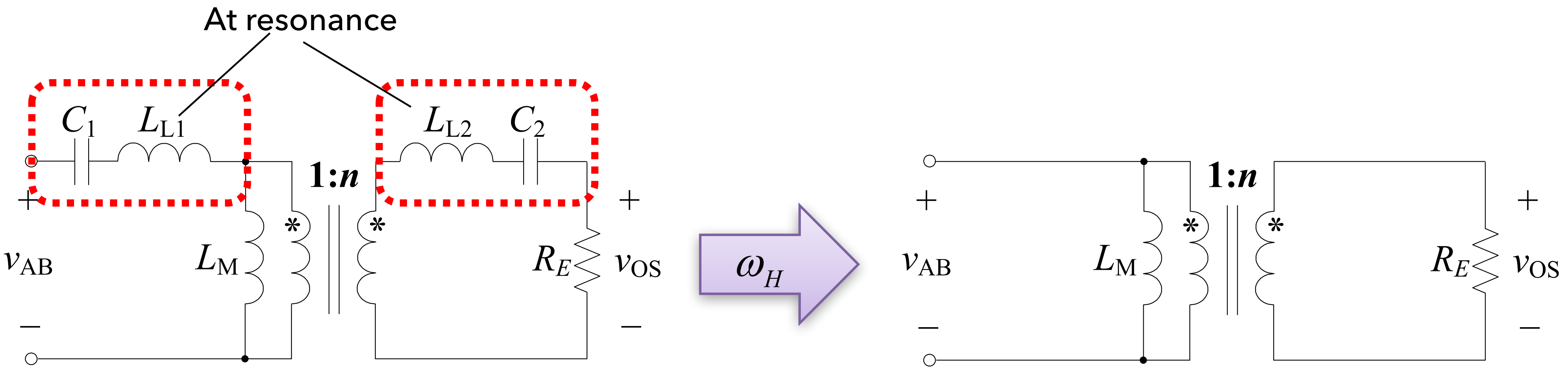
😀 Output current is constant, independent of load!

😫 Output voltage is proportional to load.

😫 Input current can be very high at light load or no load.

S/S Compensation

Compensation of leakage inductances (in transformer model)



😀 Output voltage is independent of load!

😫 Input is reactive (inductive).

😫 VA becomes relatively high at light load.
Low input power factor!

Classic Example of S/S Compensation

KAIST

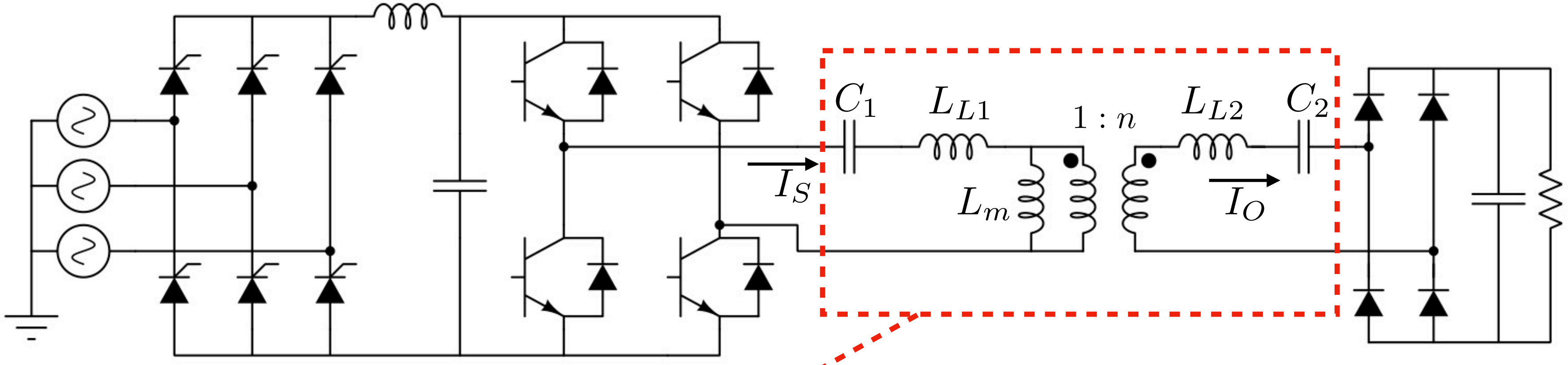
27 kW output,

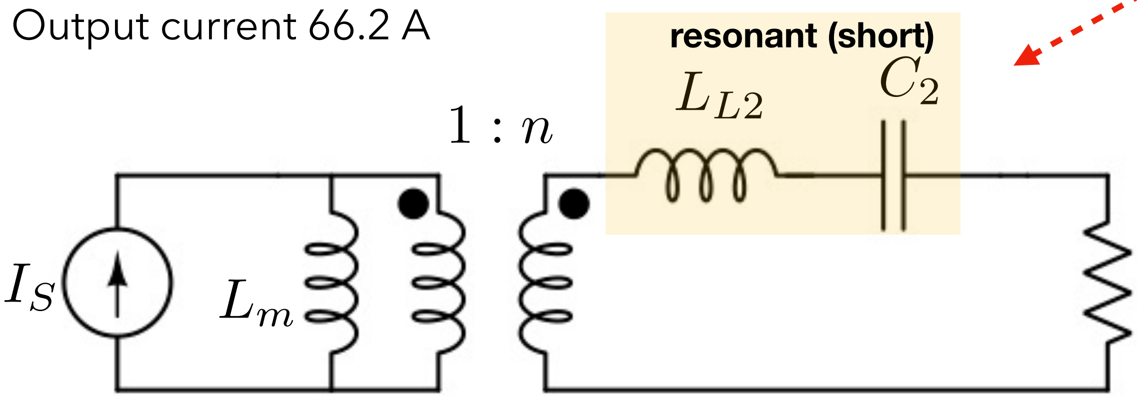
27 cm air gap,

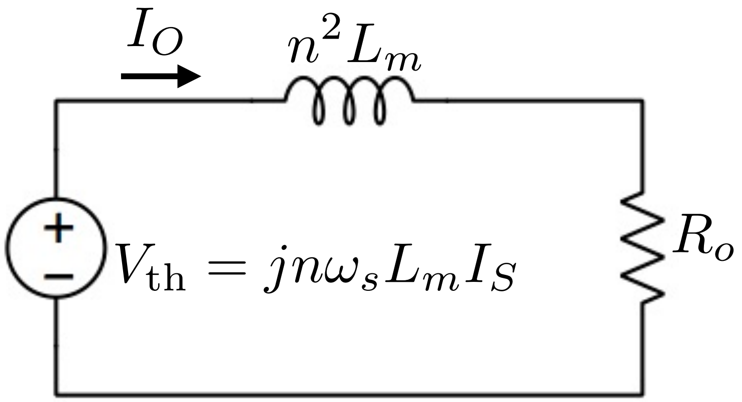
Highest efficiency 74%

Output voltage 408 V

Output current 66.2 A







IEEE TRANSACTIONS ON POWER ELECTRONICS, DECEMBER 2011

Narrow-Width Inductive Power Transfer System for Online Electrical Vehicles

J. Huh, *Student Member, IEEE*, S. W. Lee, *Student Member, IEEE*, W. Y. Lee, *Student Member, IEEE*, G. H. Cho, *Senior Member, IEEE*, and C. T. Rim, *Senior Member, IEEE*

***Abstract*—A new inductive power transfer system with a narrow rail width, a small pickup size, and a large air gap for online electric vehicles is proposed in this paper. By introducing a new core structure, the orientation of the magnetic flux alternates along with the road; hence, an inductive power transfer system with a narrow rail width of 10 cm, a large air gap of 20 cm, and a large lateral displacement about 24 cm was implemented. The resonant circuit of the inductive power transfer system, driven by a current source, was fully characterized. The experimental results showed that the maximum output power was 35 kW and that the maximum efficiency was 74% at 27 kW. The proposed system was found to be adequate for electric vehicles, allowing them to drive freely on specially implemented roads by obtaining power from the buried power supply rail.**

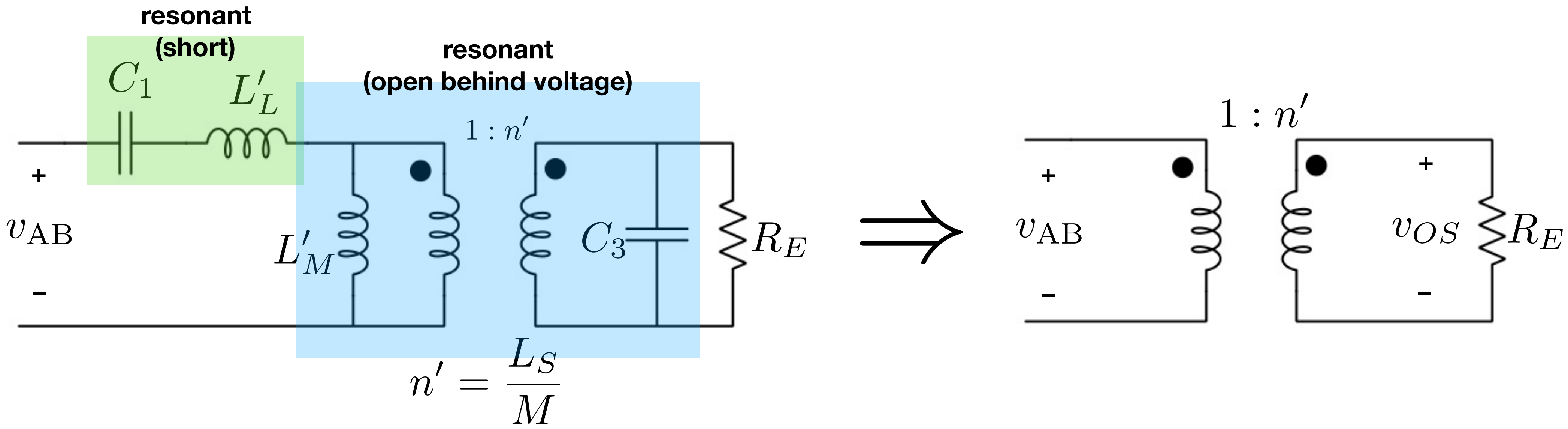
***Index Terms*—Contactless power transfer system, narrow-width rail, online electrical vehicle, wireless power transfer.**

V_o	Output voltage at the equivalent output resistance (rms).
N_1	The number of turns of two poles of a power supply rail.
N_2	The number of turns of two pickups.
n	Turn ratio N_2/N_1.
ω_i	Power supply rail angular frequency.
ω_s	Switching angular frequency.

I. Introduction

GLOBAL warming due to the emission of greenhouse gases such as CO_2 and the depletion of petroleum resources is becoming a very important issue. To address this in the transportation area, automobile manufacturers have been developing

S/P Compensation



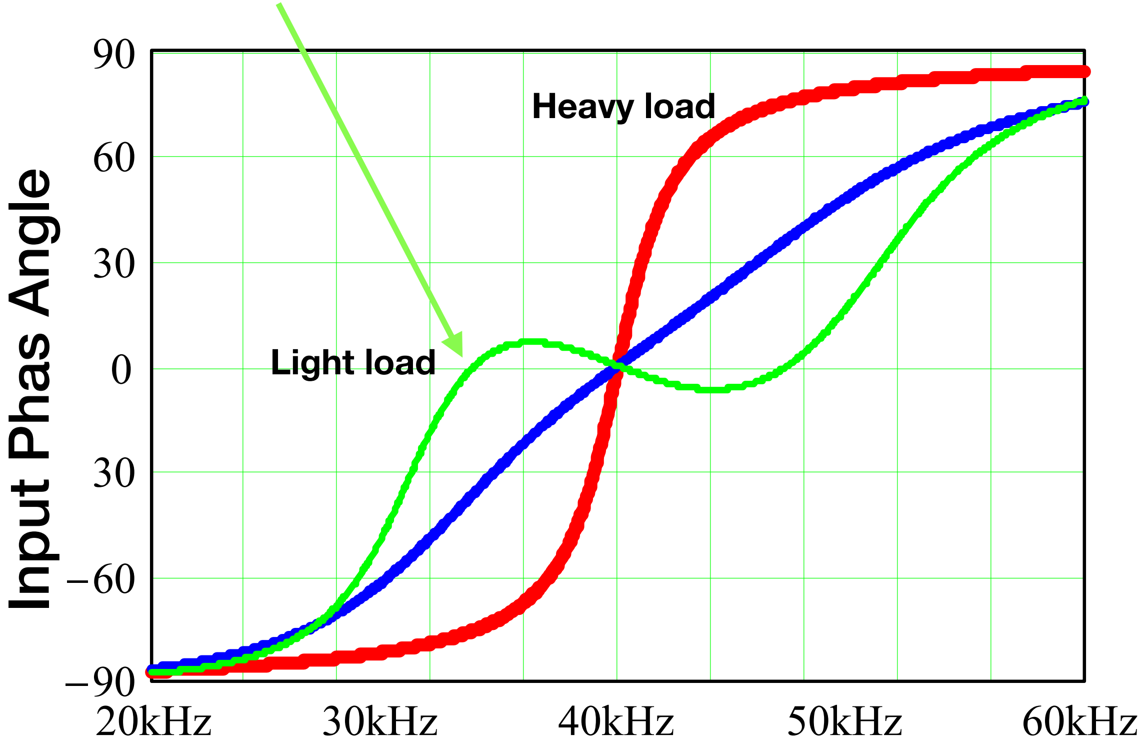
Voltage gain only affected by C1.
Input phase angle affected by C3.

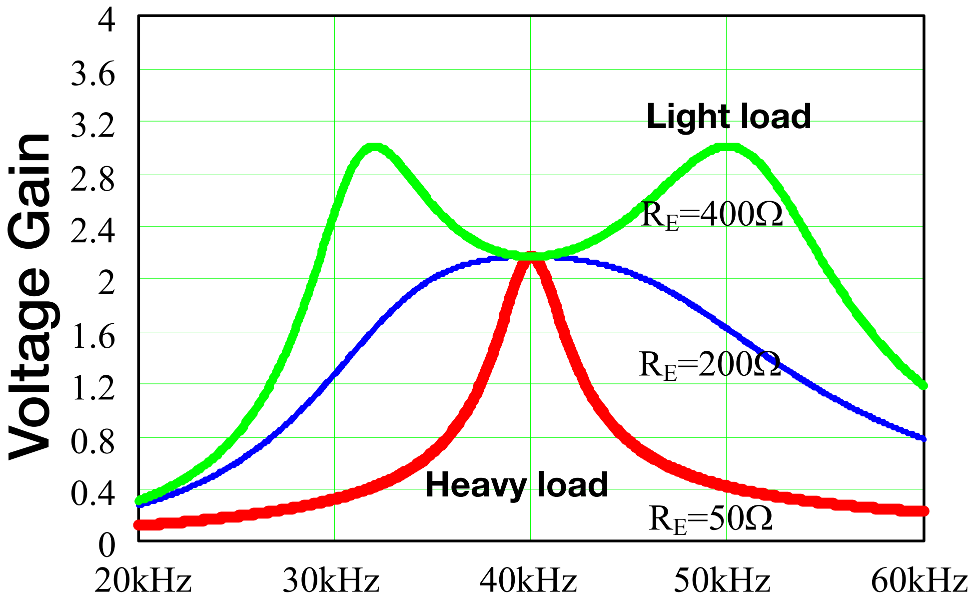
😀 **Input is resistive. Unity power factor!**
😀 **Output voltage is constant, independent of load!**

😫 Input current rushes up under shorted load.
😫 At light loads, frequency splits for input phase angle and locked phase occurs.

S/P Compensation

Locked phase possible at light load when high gain PLL is used in control



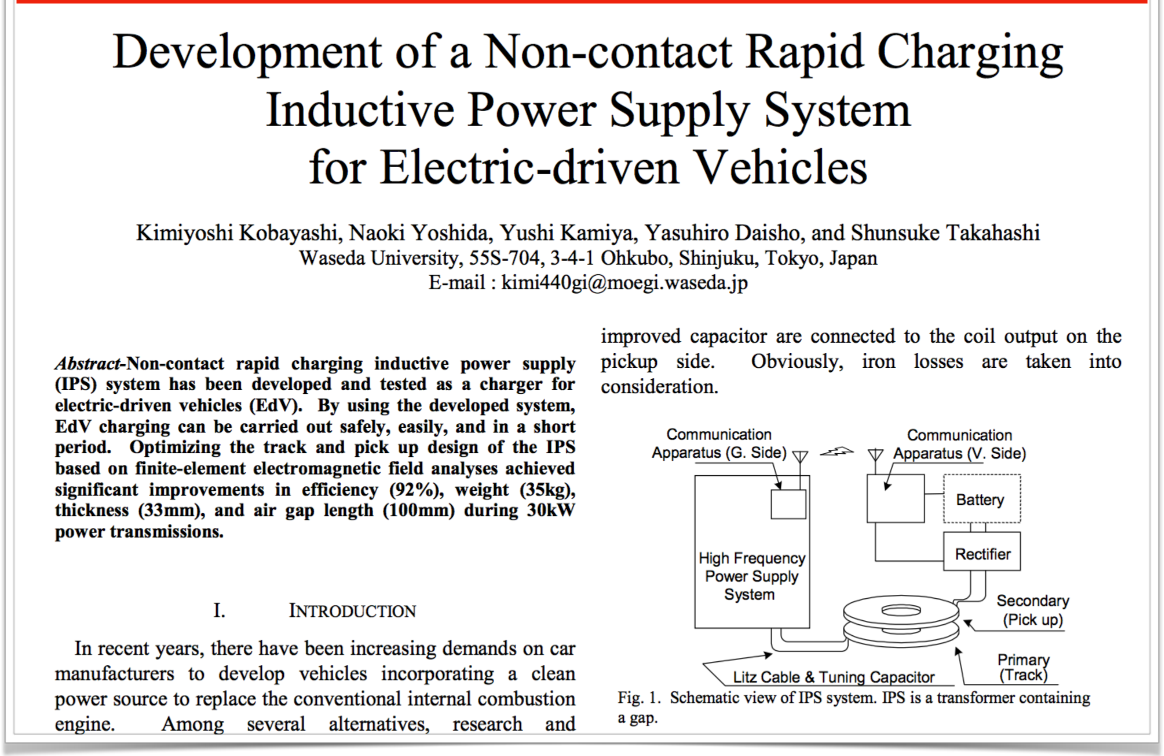


S/P Application Example

Waseda University

30 kW, 22 kHz, 10cm gap, 92% efficiency

IEEE Vehicle Power and Propulsion Conference (VPPC), 2010.



Development of a Non-contact Rapid Charging Inductive Power Supply System for Electric-driven Vehicles

Kimiyoshi Kobayashi, Naoki Yoshida, Yushi Kamiya, Yasuhiro Daisho, and Shunsuke Takahashi
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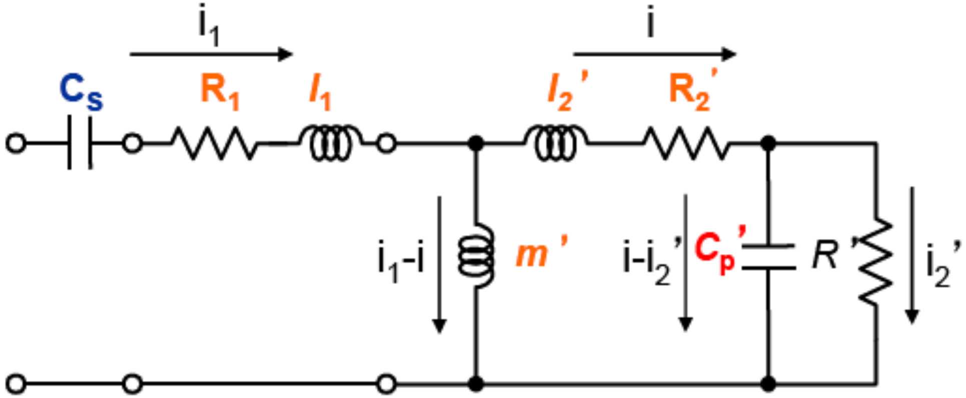
***Abstract*-Non-contact rapid charging inductive power supply (IPS) system has been developed and tested as a charger for electric-driven vehicles (EdV). By using the developed system, EdV charging can be carried out safely, easily, and in a short period. Optimizing the track and pick up design of the IPS based on finite-element electromagnetic field analyses achieved significant improvements in efficiency (92%), weight (35kg), thickness (33mm), and air gap length (100mm) during 30kW power transmissions.**

I. INTRODUCTION

In recent years, there have been increasing demands on car manufacturers to develop vehicles incorporating a clean power source to replace the conventional internal combustion engine. Among several alternatives, research and

improved capacitor are connected to the coil output on the pickup side. Obviously, iron losses are taken into consideration.

Fig. 1. Schematic view of IPS system. IPS is a transformer containing a gap.



Series compensation for resistive input (high power factor)

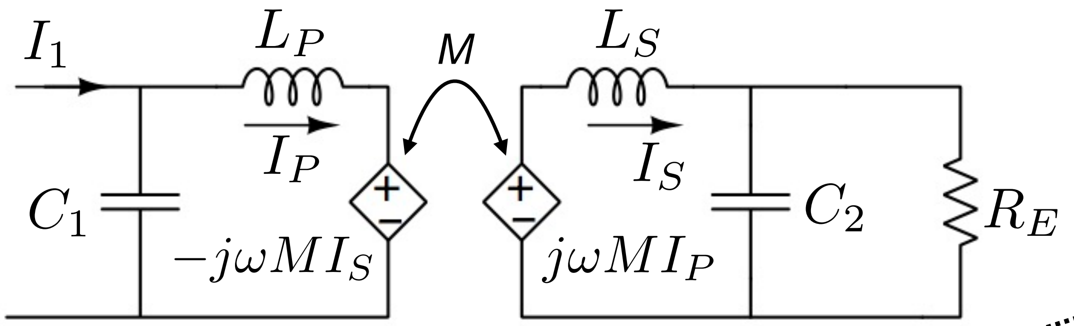
Parallel compensation for maximizing power transfer efficiency.

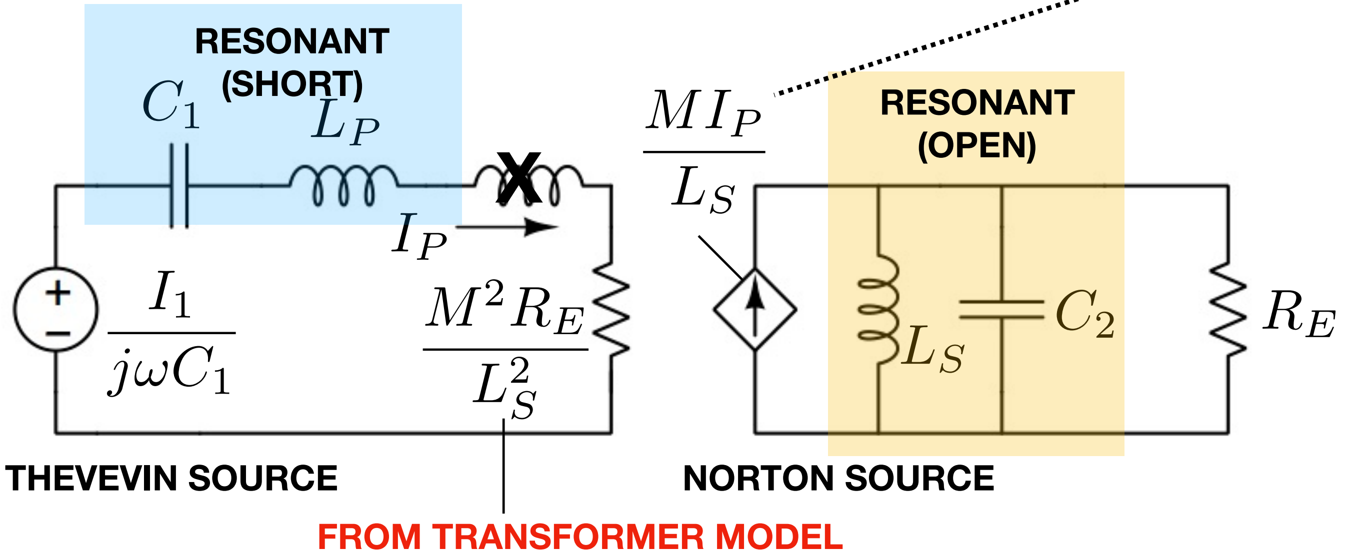
CAUTION IN READING CIRCUITS:

Don't judge the circuit by how it looks. The capacitor at the output is for resonance, NOT for output filtering!

P/P Compensation

The input should normally be a current source, such as current fed from an inverter.





$$\frac{M I_P}{L_S} = \frac{L_S I_1}{j\omega M C_1 R_E}$$

$$\Rightarrow V_O = \frac{L_S I_1}{j\omega M C_1}$$

😀 Output voltage is constant, independent of load!

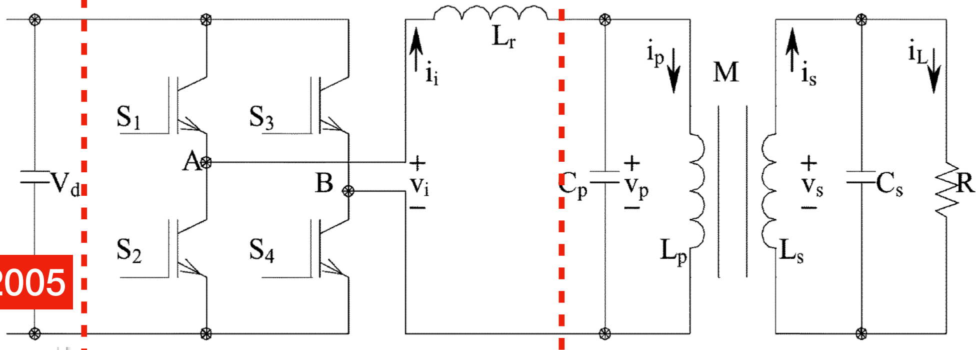
😫 Input impedance is capacitive!

P/P Application Example

University of Auckland (2005)

30 kW, 150 A, 20 kHz, 6 Ω load

k = 0.45



EQUIVALENT CURRENT SOURCE INPUT

OUTPUT VOLTAGE INDEPENDENT OF LOAD

IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, OCTOBER 2005

Design Considerations for a Contactless Electric Vehicle Battery Charger

Chwei-Sen Wang, Oskar H. Stielau, and Grant A. Covic, *Senior Member, IEEE*

***Abstract*—This paper overviews theoretical and practical design issues related to inductive power transfer systems and verifies the developed theory using a practical electric vehicle battery charger. The design focuses on the necessary approaches to ensure power transfer over the complete operating range of the system. As such, a new approach to the design of the primary resonant circuit is proposed, whereby deviations from design expectations due to phase or frequency shift are minimized. Of particular interest are systems that are neither loosely nor tightly coupled. The developed solution depends on the selected primary and secondary resonant topologies, the magnetic coupling coefficient, and the secondary quality factor.**

***Index Terms*—Battery charging, electric vehicle, electromagnetic coupling, inductive power transfer, resonance.**

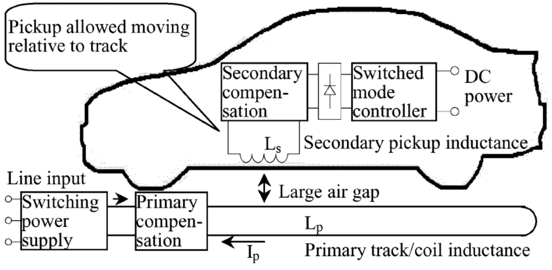
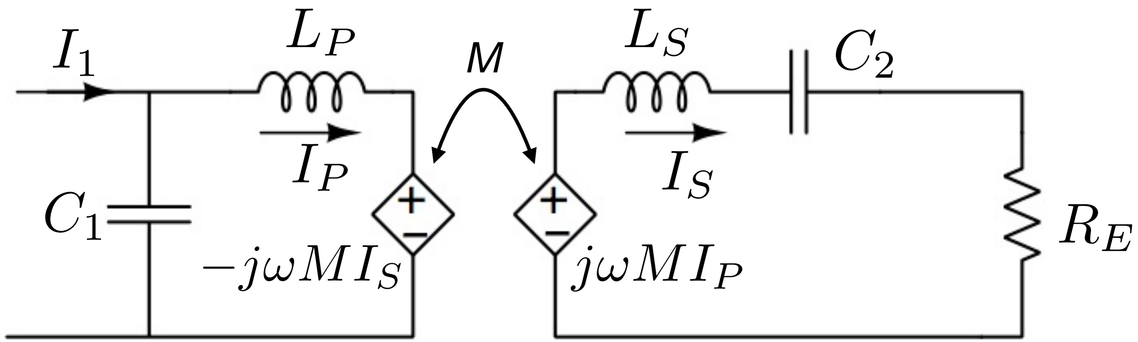


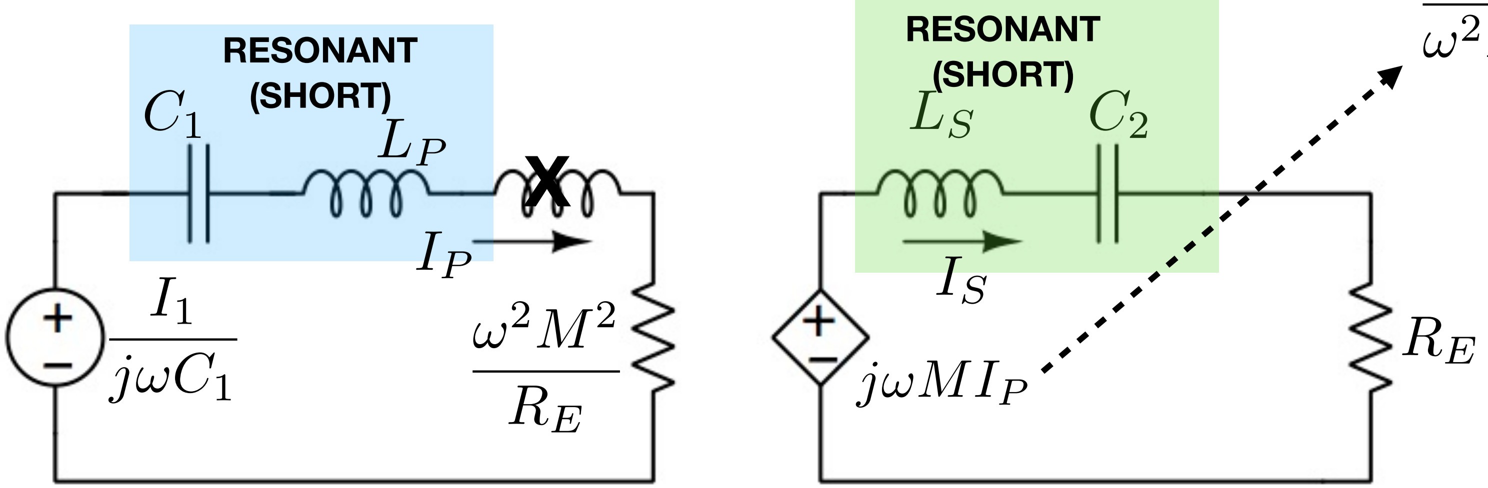
Fig. 1. Structure of inductive power transfer system.

Nominal frequency	20kHz
Rated power	30kW
Primary rated current	150A
Rated load	6Ω
Primary inductance	29.6μH
Primary capacitance	2.28μF
Mutual inductance	12.7μH
Secondary inductance	26.9μH
Secondary capacitance	2.42μF

P/S Compensation I

Again the input should normally be a current source, such as current fed from an inverter.





THEVEVIN SOURCE

$$\frac{R_E I_1}{\omega^2 M C_1} \Rightarrow I_O = \frac{I_1}{\omega^2 M C_1}$$

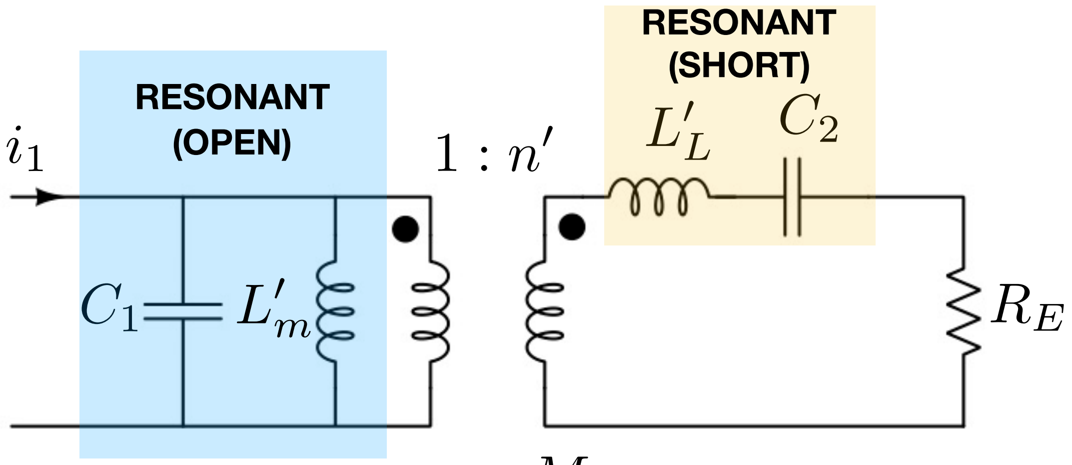
😀 Output current is constant, independent of load, if input current is fixed.

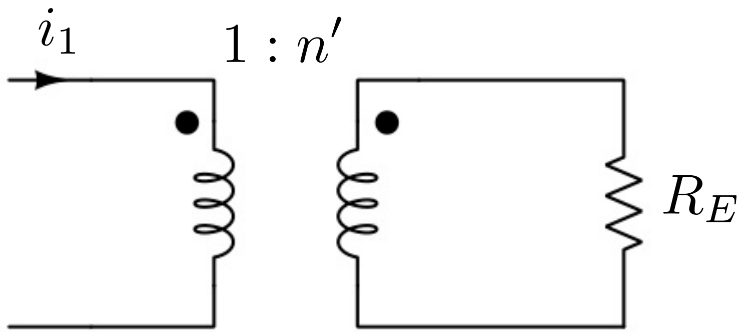
😫 Input impedance is capacitive!

P/S Compensation II

Again the input should normally be a current source, such as current fed from an inverter.

But we use the transformer leakage inductance model.





$$n' = \frac{M}{L_P}$$

$$\omega_P^2 = \frac{1}{L_P C_1} = \frac{1}{(L_S - M)C_2}$$

😀 Output current is constant, independent of load, if input current is fixed.

😀 Input impedance is resistive

Optimization Example

Hong Kong Polytechnic Univ. 2014

Design for Efficiency Optimization and Voltage Controllability of Series–Series Compensated Inductive Power Transfer Systems

Wei Zhang, *Student Member, IEEE*, Siu-Chung Wong, *Senior Member, IEEE*, Chi K. Tse, *Fellow, IEEE*, and Qianhong Chen, *Member, IEEE*

***Abstract*—Inductive power transfer (IPT) is an emerging technology that may create new possibilities for wireless power charging and transfer applications. However, the rather complex control method and low efficiency remain the key obstructing factors for general deployment. In a regularly compensated IPT circuit, high efficiency and controllability of the voltage transfer function are always conflicting requirements under varying load conditions. In this paper, the relationships among compensation parameters, circuit efficiency, voltage transfer function, and conduction angle of the input current relative to the input voltage are studied. A design and optimization method is proposed to achieve a better overall efficiency as well as good output voltage controllability. An IPT system design procedure is illustrated with design curves to achieve a desirable voltage transfer ratio, optimizing between efficiency enhancement and current rating of the switches. The analysis is supported with experimental results.**

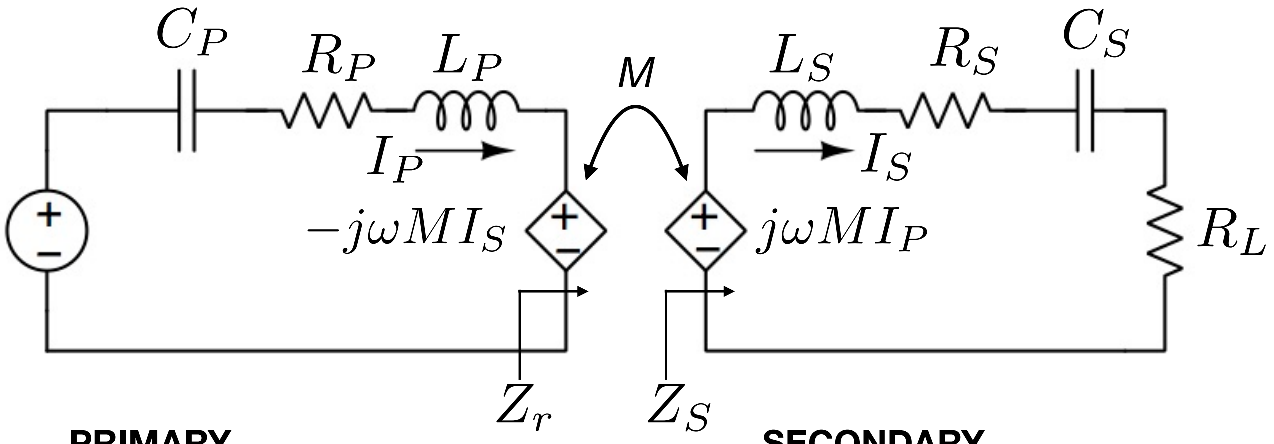
sence of mechanical contact between the power supply side and the load, the IPT system has advantages of low maintenance cost, high reliability, and the ability to operate in ultraclean or ultradirty environment. Common applications of this technology include wireless power supply to home appliances such as electric toothbrush, wireless charging of mobile phones using a charging platform [1]–[3], and in medical use such as wireless power supply to implantable devices [4], [5]. Medium- to high-power applications of this technology include continuous power transfer to people movers [6], and contactless battery charging for moving actuator [7], or electric vehicles [8]–[10].

It is common that IPT involves a large separation between the primary and secondary winding [11], [12]. Therefore, the electric characteristics of the transformers used are very differ-

S/S Compensation Optimization

Can we control the output voltage as well as maximizing efficiency?

Transformer efficiency optimization:



PRIMARY

$$\eta_P = \frac{\Re[Z_r]}{R_P + \Re[Z_r]}$$

SECONDARY

$$\eta_S = \frac{R_L}{R_L + R_S}$$

where $\Re[Z_r] = \dfrac{\omega^2 k^2 L_P L_S (R_L + R_S)}{(R_L + R_S)^2 + (\omega L - \frac{1}{\omega C_S})^2}$

$$\eta_T = \eta_P \eta_S = \frac{1 - \frac{Q_O}{Q_S}}{1 + \frac{1 + Q_O^2 \left(\frac{\omega}{\omega_S} - \frac{\omega_S}{\omega}\right)^2}{k^2 \frac{\omega}{\omega_S} Q_O \frac{\omega}{\omega_P} Q_P}}$$

$$\frac{d\eta_T}{d\omega} = 0$$

$$\Rightarrow \omega_M = \frac{\omega_S}{\sqrt{1 - \frac{1}{2Q_o^2}}}$$

$$\omega_M \in [\omega_S, \infty]$$

Best efficiency at frequency above ω_S.
This frequency is load dependent.

S/S Compensation Optimization

$$Q_L = \sqrt{\frac{L_S}{C_S}}\frac{1}{R_L}$$

$$Q_S = \sqrt{\frac{L_S}{C_S}}\frac{1}{R_S}$$

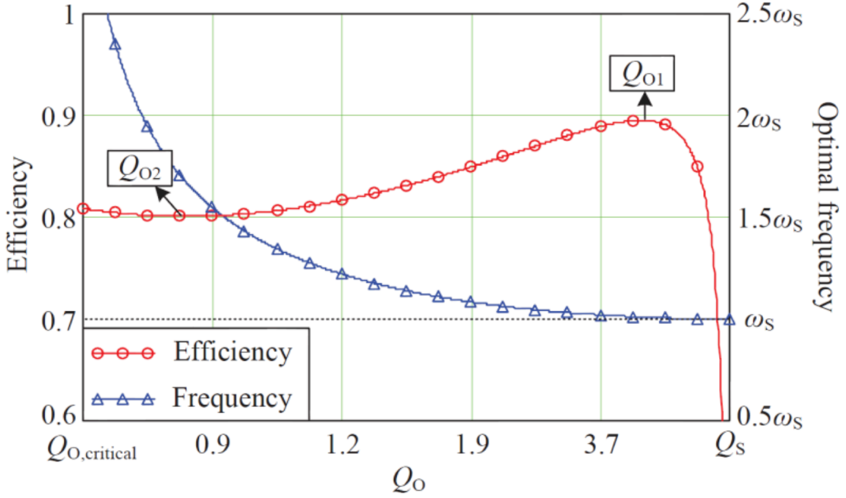
$$Q_O = \sqrt{\frac{L_S}{C_S}}\frac{1}{R_O}$$

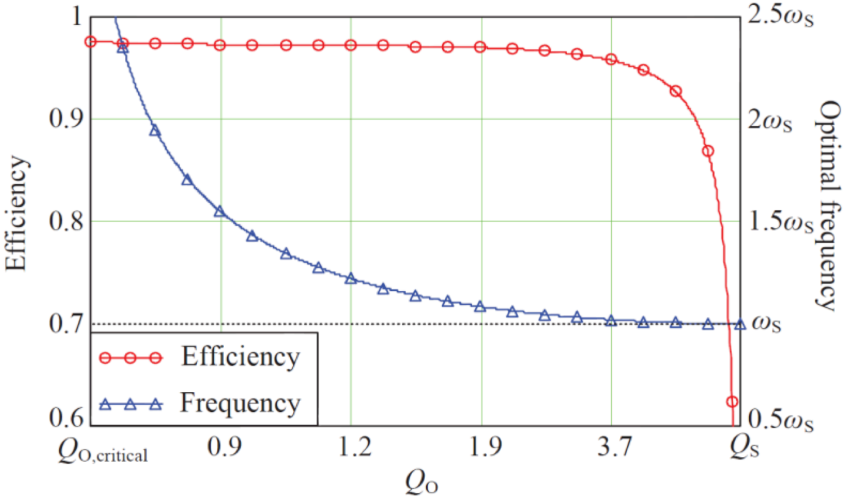
$$Q_P = \sqrt{\frac{L_P}{C_P}}\frac{1}{R_P}$$

$$\omega_P = \frac{1}{\sqrt{L_P C_P}}$$

$$\omega_S = \frac{1}{\sqrt{L_S C_S}}.$$

$$R_O = R_S + R_L$$





$$Q_{o1} = \sqrt{\frac{1}{2\lambda}(1+\sqrt{1-3\lambda})}\ ; \quad \lambda = k^2\frac{Q_P}{Q_S}$$

For $\lambda < 1/3$,

the optimal efficiency is at Q_{o1}.

For $\lambda \geq 1/3$,

the optimal efficiency increases monotonically as Q_o decreases.

S/S Compensation Optimization

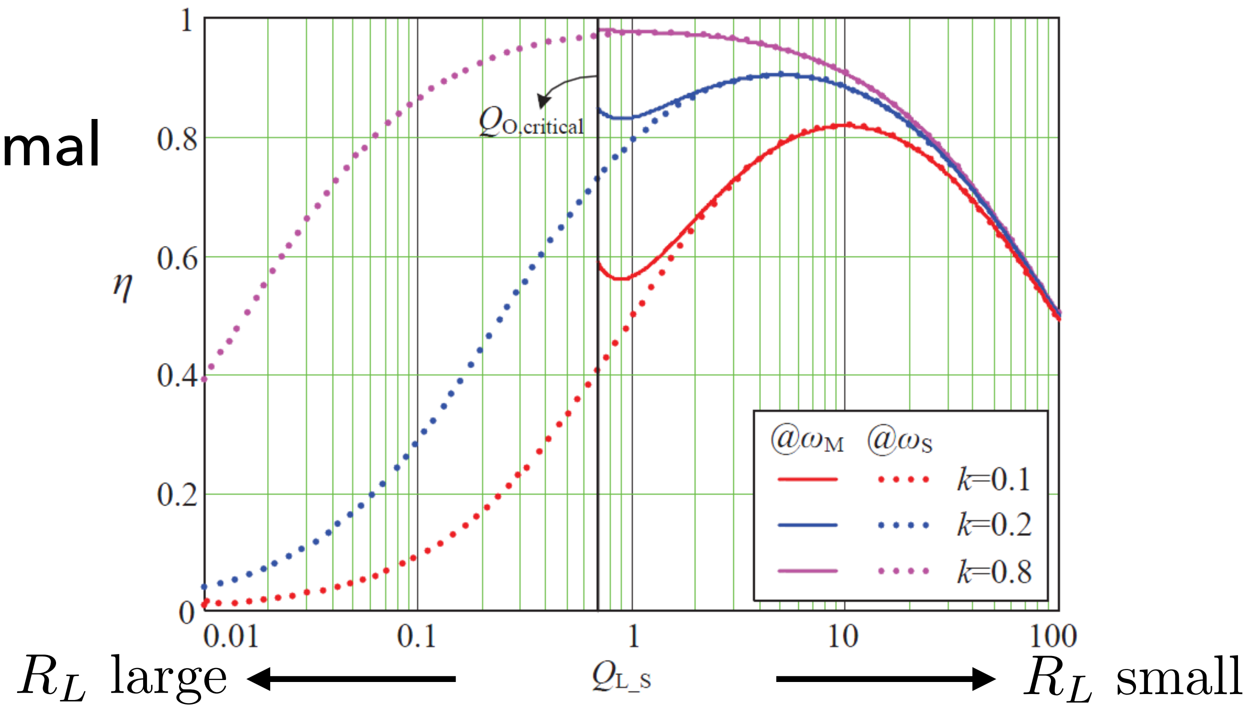
Key results: If $Q_P = Q_S$, then λ = 1/3 corresponds to k = 0.577.

When λ < 1/3, k < 0.577 (which is usually the case).

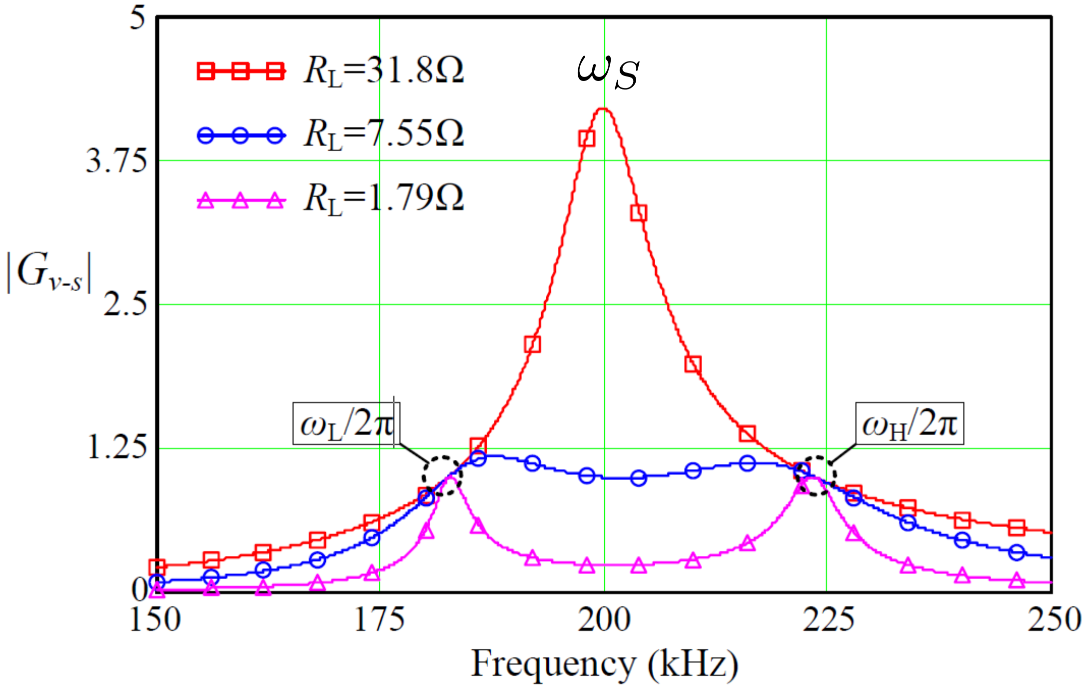
In this case, if the load is near Q_{o1}, ω_M is just slightly higher than ω_S.

We may say $\omega_M \approx \omega_S$,

and conclude that the optimal efficiency point is near ω_S.



S/S Voltage Gain



There are two cross points:

$$\omega_L = \sqrt{\frac{\omega_P^2 + \omega_S^2 + \sqrt{(\omega_P^2 + \omega_S^2)^2 - 4(1-k^2)\omega_P^2\omega_S^2}}{2(1-k^2)}}$$

$$\omega_H = \sqrt{\frac{\omega_P^2 + \omega_S^2 - \sqrt{(\omega_P^2 + \omega_S^2)^2 + 4(1-k^2)\omega_P^2\omega_S^2}}{2(1-k^2)}}$$

Clearly, we need to set the frequency at these points to get constant (load-independent) voltage output. **But ω_H > ω_S always !**

We can try to make ω_H and ω_S close to each other, so that we have constant (load-independent) voltage **and** high efficiency.

Optimal Efficiency

	$\lvert G_v \rvert$ Voltage Gain Cross Point	Optimal Efficiency Efficiency
S/S COMP	ω_H	$\omega_M \approx \omega_S$ (λ<1/3)

- $\omega_M \approx \omega_S$ must be **set by C_S** to optimize efficiency
- ω_H can be made closer to ω_S, so that operating at ω_S can also offer load-independent output current

$$\omega_H = \sqrt{\frac{\omega_P^2 + \omega_S^2 - \sqrt{(\omega_P^2 + \omega_S^2)^2 + 4(1-k^2)\omega_P^2\omega_S^2}}{2(1-k^2)}}$$

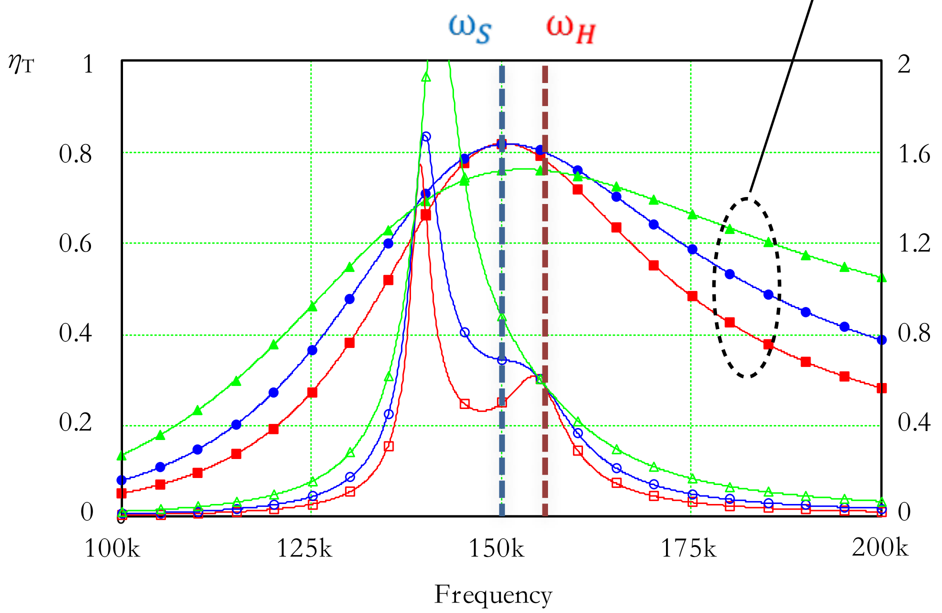
- ω_H can be **set by C_P** which sets ω_P.

Setting primary compensation capacitor for efficiency improvement (move ω_H close to ω_S)

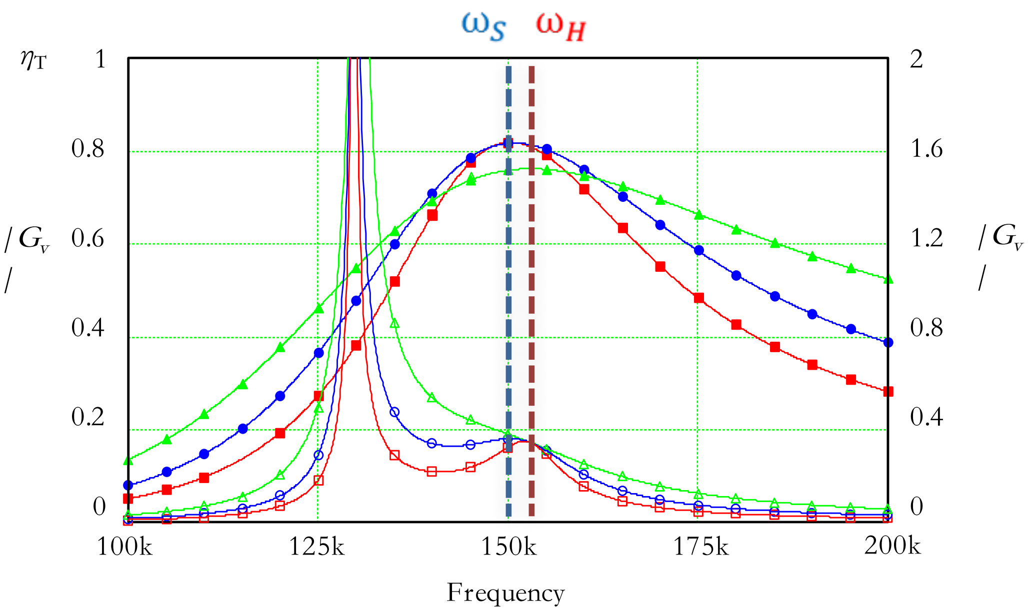
Optimal Primary Capacitance as Normal Capacitance

$$C_{Pn} = \frac{L_S C_S}{L_P}$$

But this does not make ω_H close to ω_S. So, try increasing C_p a bit, and see if ω_H may come down a bit as well.



$C_P = 1.1C_{Pn}$



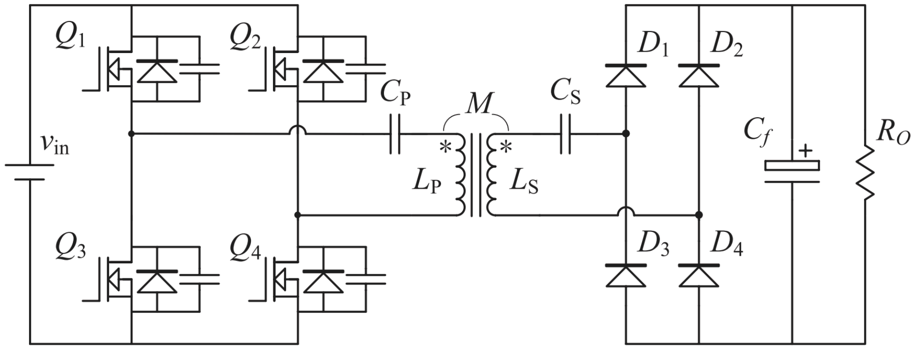
$C_P = 1.3C_{Pn}$

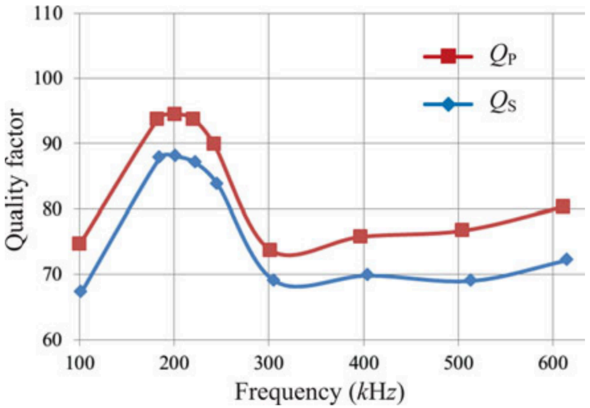
HK PolyU Results 2014

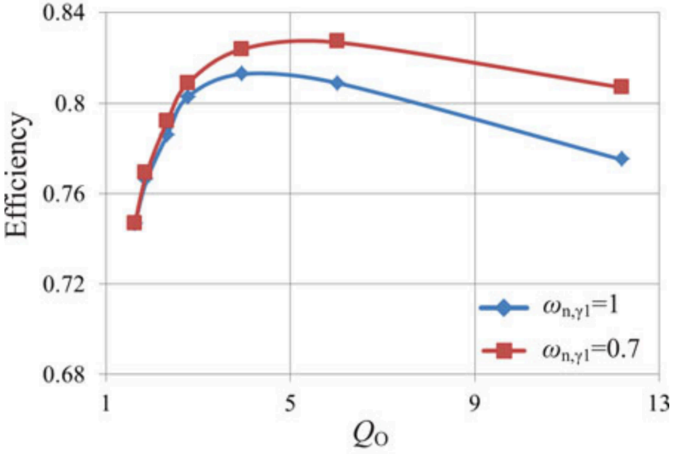
IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 29, NO. 1, JANUARY 2014 191

Design for Efficiency Optimization and Voltage Controllability of Series–Series Compensated Inductive Power Transfer Systems

Wei Zhang, *Student Member, IEEE*, Siu-Chung Wong, *Senior Member, IEEE*, Chi K. Tse, *Fellow, IEEE*, and Qianhong Chen, *Member, IEEE*







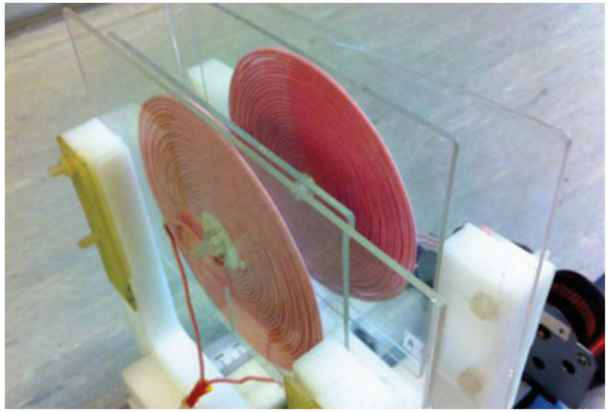
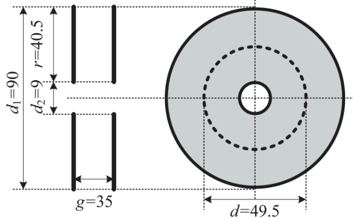
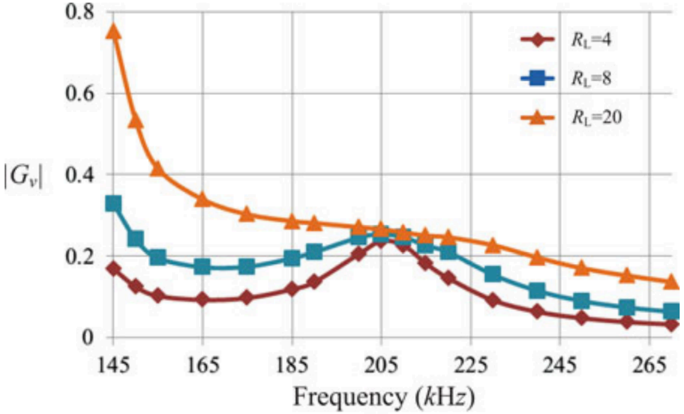


TABLE I
POWER COMPONENTS USED IN THE CONVERTER

Circuit components	Value
Power MOSFET Q_1-Q_4	IRF640N
Capacitance C_P	33.12 nF / 630V
Capacitance C_S	18.9 nF / 630V
Schottky diode D_1-D_4	STPS20H100CG
Capacitance C_f	220 μF
Loosely-coupled transformer	N_P=30 turns of Litz wire
	L_P=32.78μH Q_P =94.9@200 kH
	N_S=29 turns of Litz wire
	L_P=31.46μH Q_P =89.0@200 kH
	air gap = 35 mm
	k =0.182

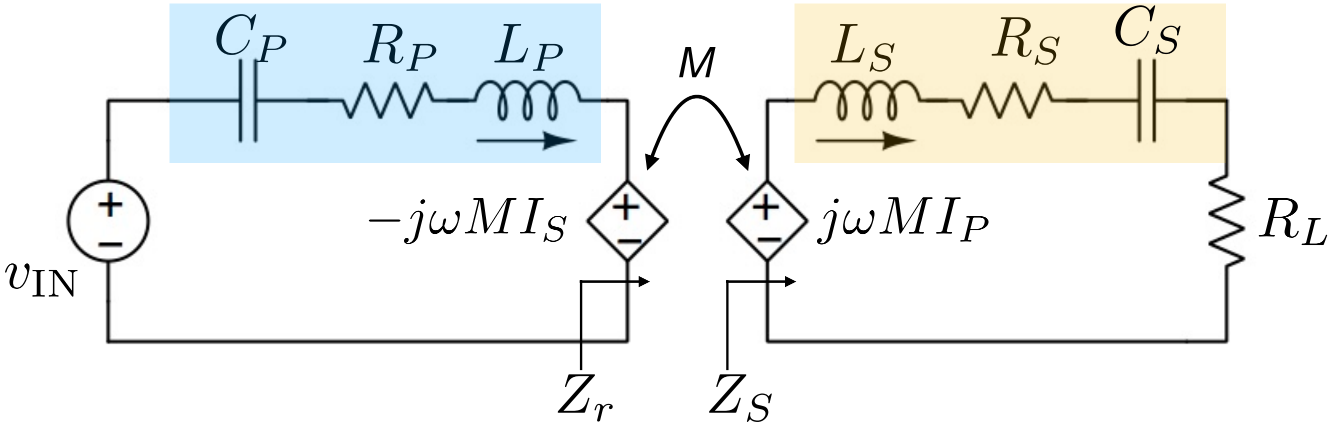


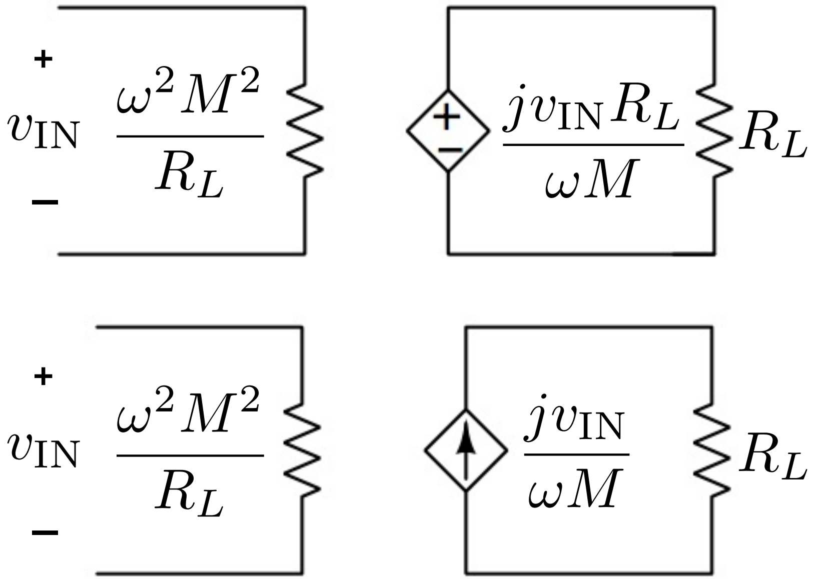


Design for Constant Current Output

Series-series resonance at primary and secondary sides:

- 😀 Input impedance is resistive, i.e., high power factor.
- 😀 Output current is constant, load-independent.
- 😀 Efficiency is optimal.



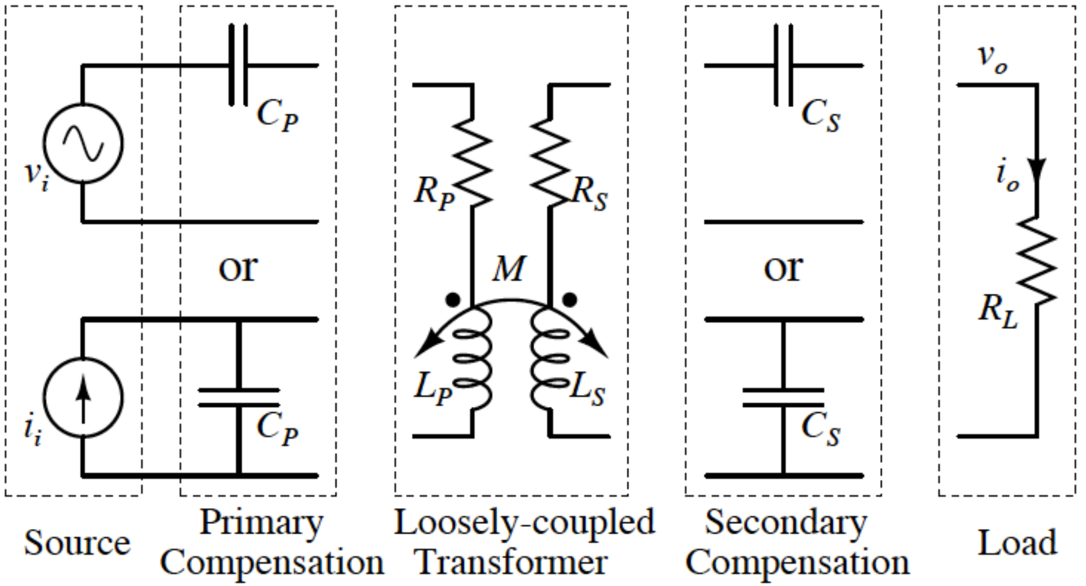


😫 Output voltage is proportional to load.

😫 Input current can be very high at light load or no load.

Optimal Design Guideline

GENERAL STRUCTURE



General Expressions

Topologies	G	Z_{in}	η
SS	$\frac{i_o}{v_i} = \frac{j\omega M}{Z_P Z_{S-S}+\omega^2 M^2}$	$Z_P + \frac{\omega^2 M^2}{Z_{S-S}}$	$\frac{\omega^2 M^2}{\lvert Z_{S-S}\rvert R_P+\omega^2 M^2}\frac{R_L}{R_S+R_L}$
PS	$\frac{i_o}{i_i} = \frac{\frac{M}{C_P}}{Z_P Z_{S-S}+\omega^2 M^2}$	$\frac{Z_P-\frac{1}{j\omega C_P}+\frac{\omega^2 M^2}{Z_{S-S}}}{j\omega C_P(Z_P+\frac{\omega^2 M^2}{Z_{S-S}})}$	
SP	$\frac{v_o}{v_i} = \frac{j\omega M\frac{R_L}{j\omega C_S R_L+1}}{Z_P Z_{S-P}+\omega^2 M^2}$	$Z_P + \frac{\omega^2 M^2}{Z_{S-P}}$	$\frac{\omega^2 M^2}{\lvert Z_{S-P}\rvert R_P+\omega^2 M^2}\frac{R_L}{R_S(1+\omega^2 C_S^2 R_L^2)+R_L}$
PP	$\frac{v_o}{i_i} = \frac{\frac{M}{C_P}\frac{R_L}{j\omega C_S R_L+1}}{Z_P Z_{S-P}++\omega^2 M^2}$	$\frac{Z_P-\frac{1}{j\omega C_P}+\frac{\omega^2 M^2}{Z_{S-P}}}{j\omega C_P(Z_P+\frac{\omega^2 M^2}{Z_{S-P}})}$	
$Z_P = j\omega L_P + R_P + \frac{1}{j\omega C_P}$, $Z_{S-S} = j\omega L_S + R_S + \frac{1}{j\omega C_S} + R_L$ and $Z_{S-P} = j\omega L_S + R_S + \frac{R_L}{j\omega C_S R_L+1}$.			

基本公式

Where does best efficiency occur?

Series-series compensation:

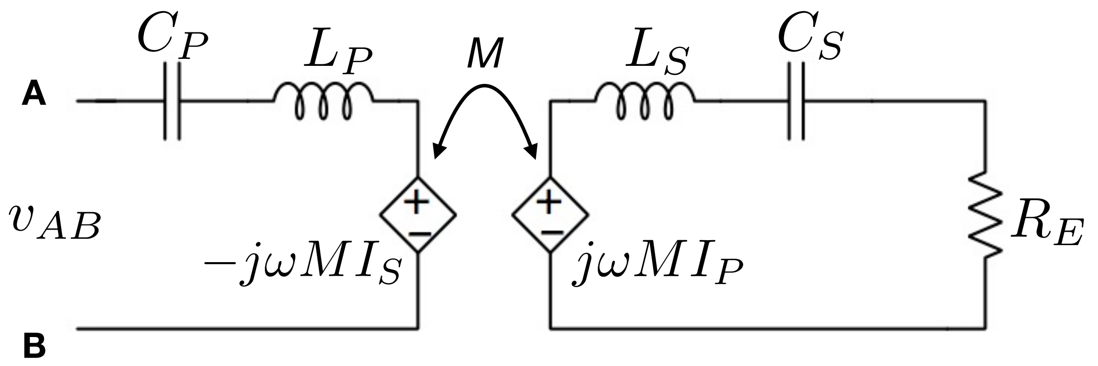
When primary self-inductance is compensated out, the output is constant current, which means constant transconductance. In this case, all reactive current is cancelled, and efficiency is optimal.

Thus, we can find the value of the transconductance at this compensation point:

$$G_i = \frac{i_o}{v_i} = \frac{1}{\omega_P M} \qquad \omega_P = \frac{1}{\sqrt{L_P C_P}} \quad \omega_S = \frac{1}{\sqrt{L_S C_S}}$$

and the resonant frequency is

$$\omega = \omega_S = \omega_P$$



Moreover, the max efficiency point is at a particular load, which can be found as

$$R_{L,m} = \omega_P M \gamma$$

where

$$\gamma = \sqrt{\frac{R_S}{R_P}}$$

Clearly, $R_{L,m}$ is *k*-dependent and hard to measure directly. A heuristic Perturb&Observe control is normally used for max efficiency tracking.

Where does best efficiency occur?

Series-series compensation:

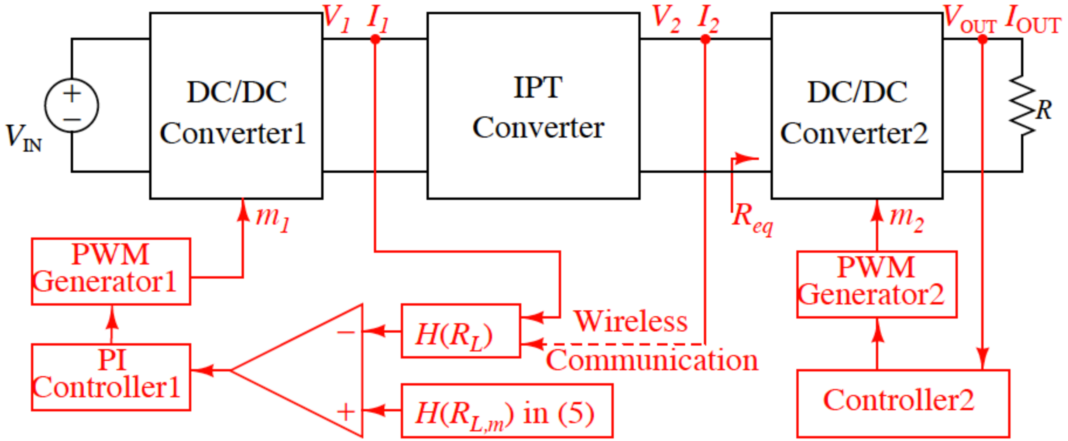
When the best efficiency happens, it has to be at $R_{L,m}$, and the operating frequency should be set for load-independent transconductance or output current.

But at this point, the voltage gain cannot be load-independent! We can find this gain as

$$H(R_{L,m}) = \frac{v_o}{v_i} = \gamma$$

Control

It is thus possible to achieve max efficiency by controlling the output relation to fit this $H(R_{L,m})$. By controlling the input voltage level, we can maintain this value of H and the load point at $R_{L,m}$. However, we will need another dc-dc converter for load change, as the power level is determined by the load.



MAX EFFICIENCY POINT	i_o/v_i	v_o/v_i	i_o/i_i	v_o/i_i
SS	LIC $G_i = \frac{1}{\omega_P M}$ $\omega = \omega_P = \omega_S$ $R_{L,m} = \omega_P M \gamma$	LIV $H_i = \gamma$		
SP	LIC $H_i = \frac{\gamma}{\omega_S L_S}$	LIV $G_i = \frac{L_S}{M}$ $\omega = \omega_S = \frac{\omega_P}{\sqrt{1-k^2}}$ $R_{L,m} = \omega_P M L_S^2/M^2\gamma$		
PS			LIC $G_i = \frac{L_P}{M}$ $\omega = \omega_P = \frac{\omega_S}{\sqrt{1-k^2}}$ $R_{L,m} = \omega_P M \gamma$	LIV $H_i = \omega_P L_P \gamma$
PP			LIC $H_i = \frac{L_P}{L_S}\gamma$	LIV $G_i = \omega_S M \frac{\sqrt{1-k^2}}{k^2}$ $\omega = \frac{\omega_P}{\sqrt{1-k^2}} = \frac{\omega_S}{\sqrt{1-k^2}}$ $R_{L,m} = \omega_S M \sqrt{1-k^2} L_S^2/M^2\gamma$

$$\omega_P = \frac{1}{\sqrt{L_P C_P}}$$

$$\omega_S = \frac{1}{\sqrt{L_S C_S}}$$

$$k = \frac{M}{\sqrt{L_P L_S}}$$

$$\gamma = \sqrt{\frac{R_S}{R_P}}$$

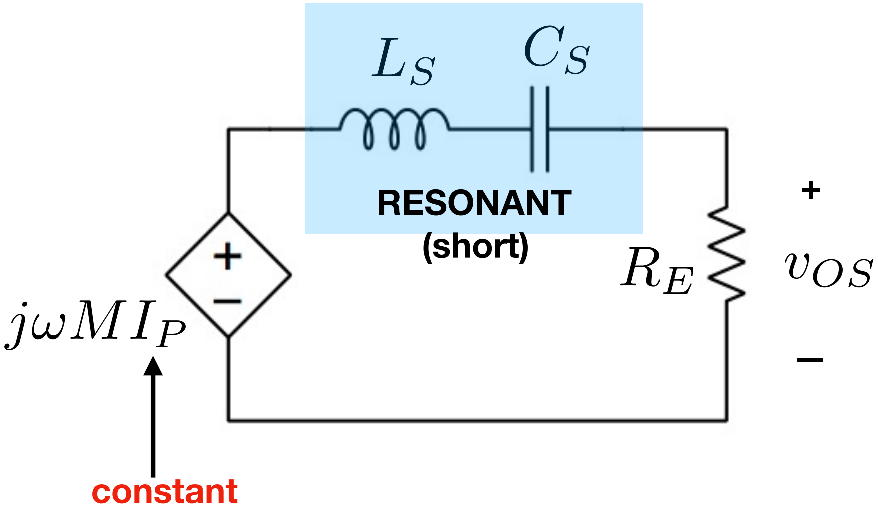
Higher Order Compensation

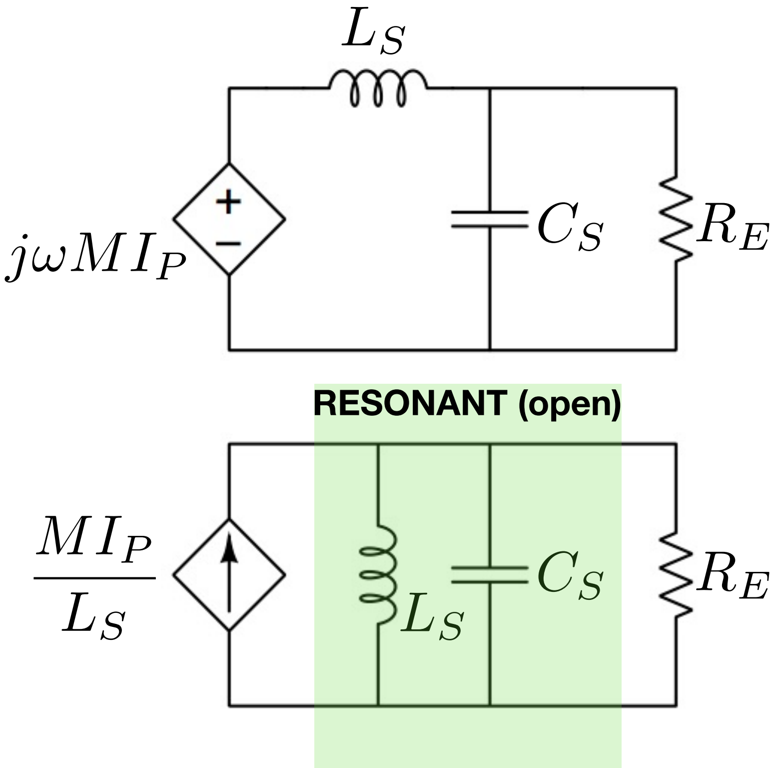
Trick to get constant output voltage or current:

First create constant primary winding current

With constant I_P

The secondary side becomes



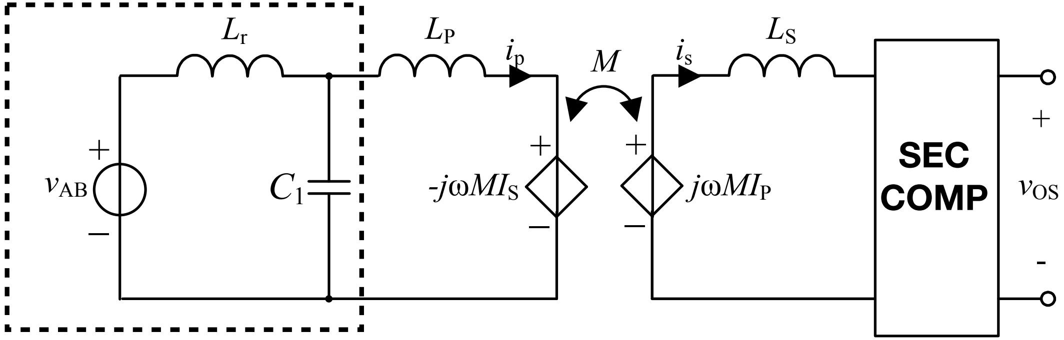


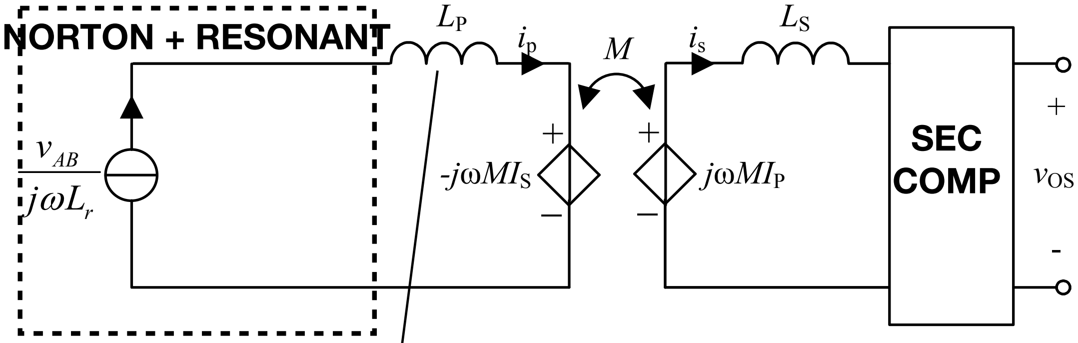
With secondary series compensation, we get constant output voltage.

With secondary parallel compensation, we get constant output current.

Realizing constant primary winding current (I)

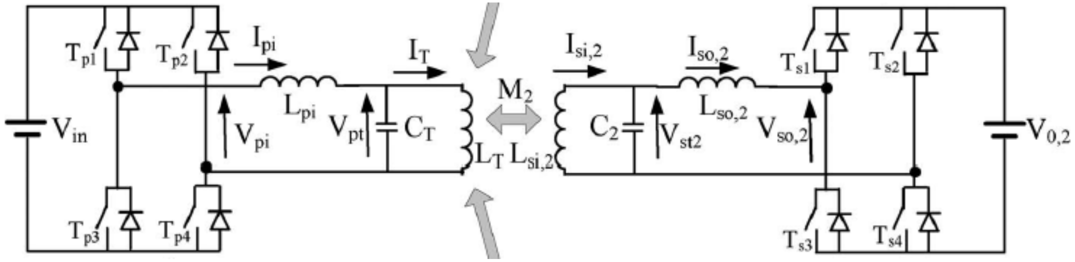
Auckland University, LCL primary circuit





Constant primary winding current

Lp does not matter if it is current source driven!



- 😀 Primary current and output current are load independent.
- 😀 Primary current being constant current source, hence suitable for multiple secondary design.
- 😀 Inverter only provides active power.
- 😀 L_P does not affect the primary current and the resonant frequency does not need to change even when coupling coefficient and self-inductance vary.

😫 LCL needs more components and cost.

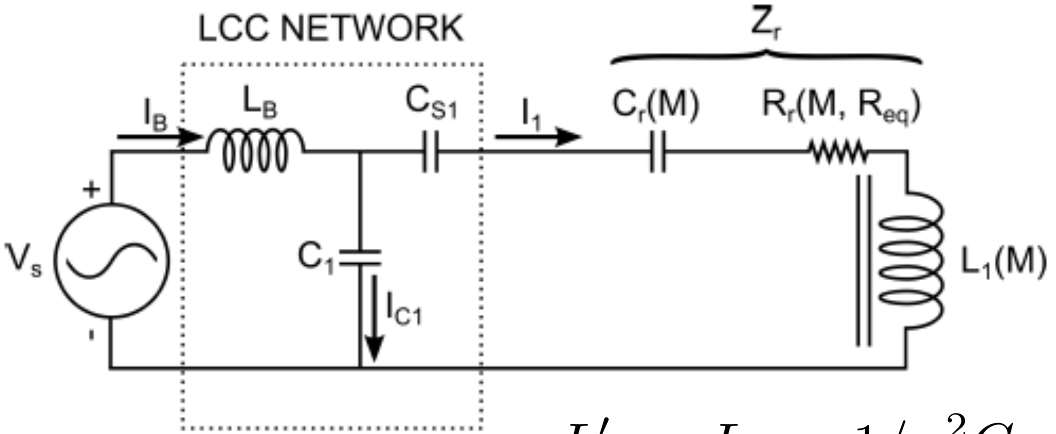
Realizing constant primary winding current (II)

Windsor University, LCC primary circuit

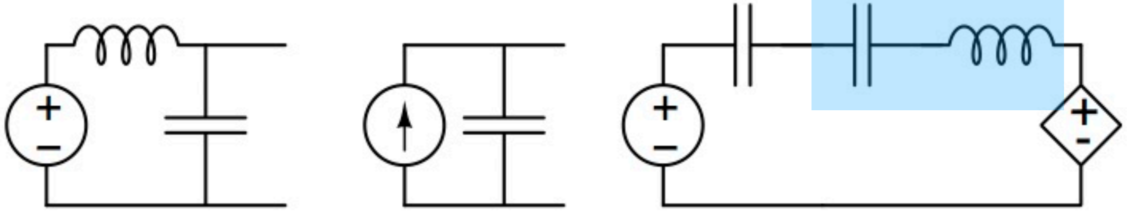
The added C_{S1} connected in series with the self inductance at primary will *<u>further cancel the self inductance</u>*, while the C_1 in parallel will create constant current, like in the previous LCL design.

😀 The LCC approach gives larger primary current and hence higher power transfer capability.

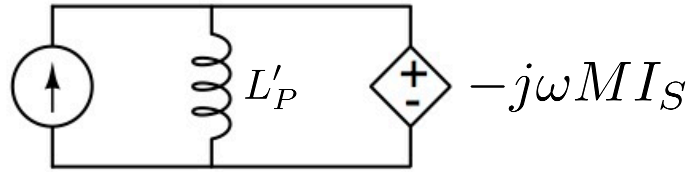
😀 Offers constant current over a wide operating range.



$$L'_P = L_P - 1/\omega^2 C_{S1}$$



$$I_{\mathrm{eqv}} = \frac{V_S}{j\omega L'_P}$$



Lp is partially cancelled, hence allowing greater current to be delivered.

WINDSOR UNIVERSITY, CANADA 2015

A Comparative Study of Power Supply Architectures in Wireless EV Charging Systems

Bryan Esteban, *Member, IEEE*, Maher Sid-Ahmed, and Narayan C. Kar, *Senior Member, IEEE*

***Abstract*—This paper examines two of the primary power supply architectures being predominantly used for wireless electric vehicle (EV) charging, namely the series LC (SLC) resonant and the hybrid series–parallel (*LCL*) resonant full-bridge inverter topologies. The study of both of these topologies is presented in the context of designing a 3-kW primary-side controlled stationary wireless EV charger with nominal operating parameters of 30-kHz center frequency, a range of coupling in the neighborhood of 0.18–0.26, and a parallel secondary pick-up with partial series coil compensation. A comparison of both architectures is made in terms of their design methodology, physical size, cost, complexity, and efficiency. It is found that the SLC architecture is 2.45% less costly than the *LCL* topology. On the other hand, it is observed that the *LCL* architecture achieves almost 10% higher peak efficiency at rated load and minimum coupling. The study also showed that the SLC topology suffers from poor light load efficiency, while the *LCL* topology maintains very high efficiency over its full range of coupling and loading. The study also revealed that the capacitor voltage stress is significantly higher in the SLC topology. Finally, it is also shown**

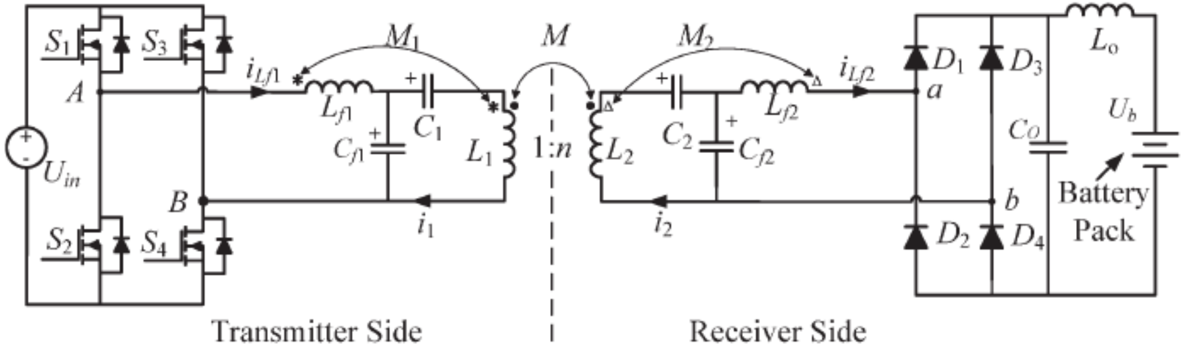
C_{S1}	Primary coil partial series tuning capacitor for *LCL* topology.
C_1	Primary resonant tuning capacitor.
C_B	HF transformer dc-blocking capacitor.
$L_{2\mathrm{eq}}$	Equivalent secondary inductance when partial series compensation is used.
$L_{2\mathrm{eq}}$	Equivalent primary inductance when partial series compensation is used.
ω	Operating angular frequency.
ω_0	Resonant angular frequency.
V_U	Utility input voltage.
V_S	Fundamental of inverter voltage.
Z_r	Reflected secondary impedance.
$R_r\,(M, R_{\mathrm{eq}})$	Reflected secondary resistance.
$C_r\,(M)$	Reflected secondary capacitance.
Q_{2t}	Overall tunned secondary quality factor.

Further extension - double LCC

IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 64, NO. 6, JUNE 2015 2261

A Double-Sided LCC Compensation Network and Its Tuning Method for Wireless Power Transfer

Siqi Li, *Member, IEEE*, Weihan Li, *Student Member, IEEE*, Junjun Deng, *Student Member, IEEE*, Trong Duy Nguyen, *Member, IEEE*, and Chunting Chris Mi, *Fellow, IEEE*

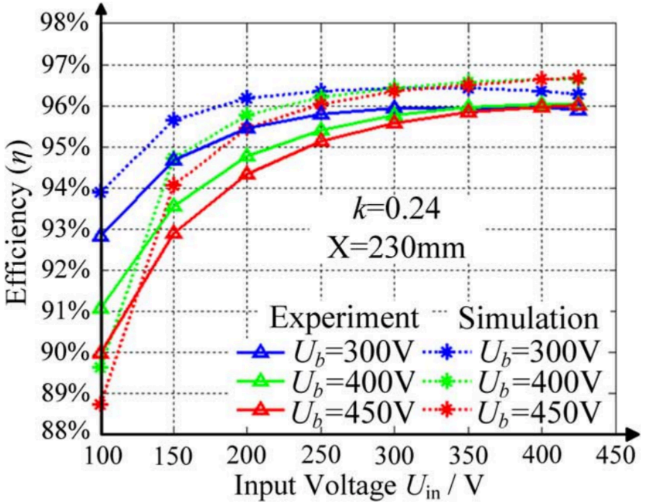


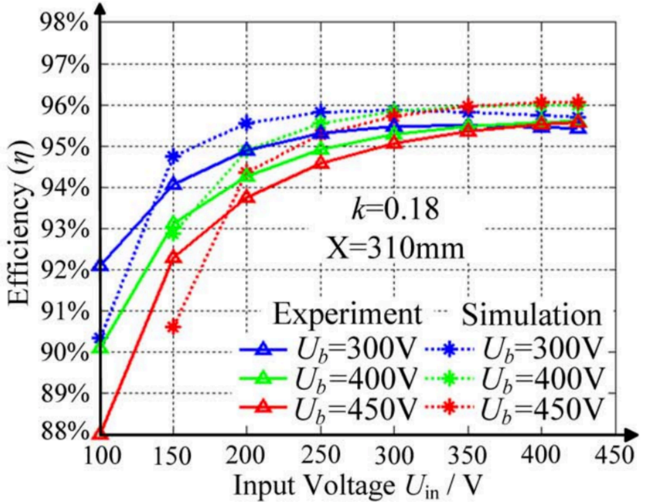
Michigan University at Dearborn, LCC primary and secondary circuits

😀 The LCC approach gives larger primary current and hence higher power transfer capability.

😀 LCC on both primary and secondary sides reduces the self-inductances, hence reduce the size of compensation capacitors. Overall system volume reduces.

😀 Wide operating range for constant output current.

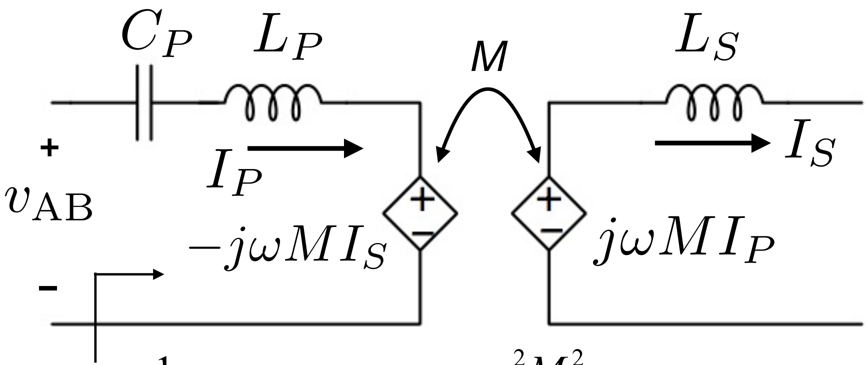




Large misalignment, poorly coupled

Under severe misalignment, *M* becomes very small (k is small).

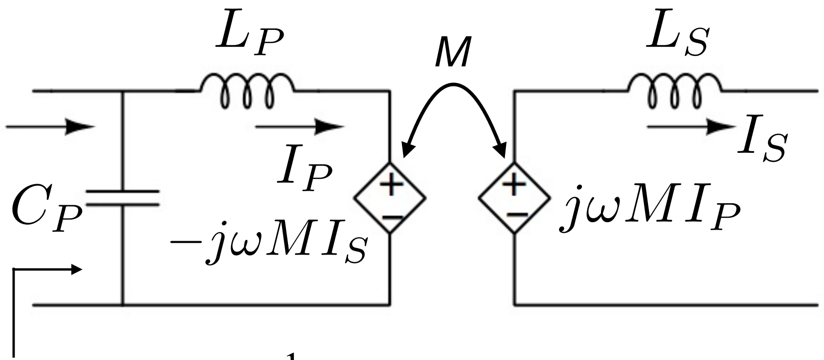
Primary series comp



$$Z_{in} = \frac{1}{j\omega C_P} + j\omega L_P + R_P + \frac{\omega^2 M^2}{Z_S}$$

As *M* becomes very small, I_P will rise rapidly and input current can be very large!

Primary parallel comp



$$Z_{in} = \frac{1}{j\omega C_P + \cfrac{1}{j\omega L_P + R_P + \cfrac{\omega^2 M^2}{Z_S}}}$$

As *M* becomes very small, I_P will drop rapidly, and power transfer reduces.

SP/S Compensation

Zaragoza University, SP/S compensation

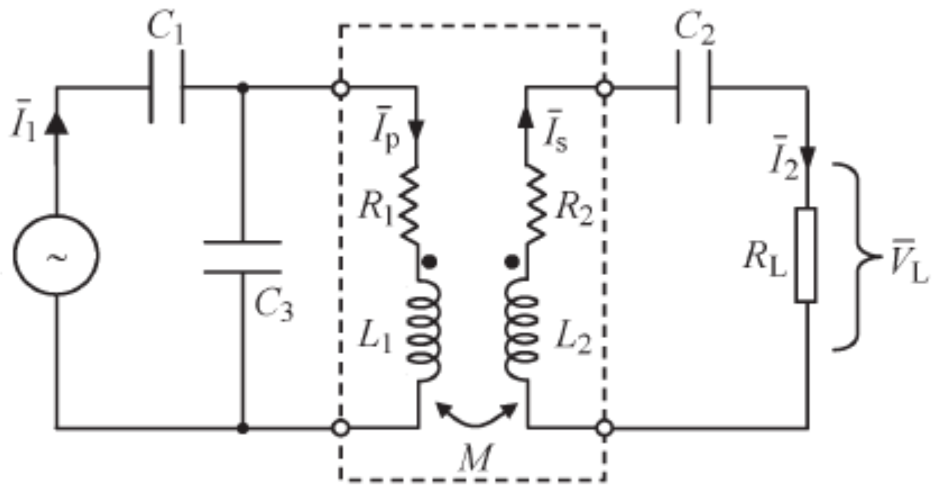
Without C_1 , the circuit is P/S compensation.

When K_C = 1, C_3 is exactly resonating with L_1 at ω_o.

But C_3 is deliberately chosen to be a bit smaller than needed for resonating with L_1 (K_C < 1). So, when misalignment occurs, M gets smaller, C_3 is not enough to resonate, making the whole $C_3 \| L_1$ actually inductive at ω_o. Then, C_1 is used to compensate this remaining inductance. Thus, even at large misalignment, reactive power is still not large, and the power transfer can still be high.

😀 Input is resistive.

😀 Insensitive to variation of M.



$$C_2 = \frac{1}{L_2\omega_o^2} \qquad C_{3\mathrm{PS}} = \frac{L_2C_2}{L_1 + \frac{M^4}{L_1L_2C_2R_L^2}}$$

$$C_3 = K_C C_{3\mathrm{PS}}$$

$K_C = 1$ means P/S compensation

Higher order compensation

In general, with more L and C, we can increase design flexibility as we have more parameter to manipulate.

But the circuit will be more complex to design and analyze.

394 IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 32, NO. 1, JANUARY 2017

Higher Order Compensation for Inductive-Power-Transfer Converters With Constant-Voltage or Constant-Current Output Combating Transformer Parameter Constraints

Xiaohui Qu, *Member, IEEE*, Yanyan Jing, Hongdou Han, Siu-Chung Wong, *Senior Member, IEEE*, and Chi K. Tse, *Fellow, IEEE*

***Abstract*—Compensation is crucial for improving performance of inductive-power-transfer (IPT) converters. With proper compensation at some specific frequencies, an IPT converter can achieve load-independent constant output voltage or current, near zero reactive power, and soft switching of power switches simultaneously, resulting in simplified control circuitry, reduced component ratings, and improved power conversion efficiency. However, constant output voltage or current depends significantly on parameters of the transformer, which is often space constrained, making the converter design hard to optimize. To free the design from the constraints imposed by the transformer parameters, this paper proposes a family of higher order compensation circuits for IPT converters that achieves any desired constant-voltage or constant-current (CC) output with near zero reactive power and soft switching. Detailed derivation of the compensation method is given for the desired transfer function not constrained by transformer parameters. Prototypes of CC IPT configurations based on a single transformer are constructed to verify the analysis with three different output specifications.**

nique is magnetic coupling of two physically separated coils of an IPT transformer across a predefined distance. When the ratio of the distance to the coil diameter increases, the coupled magnetic flux between the coils becomes smaller. The uncoupled magnetic flux appears as leakage inductance and causes significant reactive power. The reactive power will increase the ratings of the driver circuit and degrade the power transfer capability. Therefore, a compensation circuit is important in the IPT converter to improve the following transformer characteristics:

1) *Near zero input reactive power:* Without large reactive power and the associated circulating power losses, the converter efficiency can be increased. Given a set of power components with specified ratings, a properly compensated IPT converter can transfer more real power to the load. Zero input reactive power will imply a pure resistive input impedance to the driver circuit having *zero phase*

Interim Conclusion

- Compensation is the core design problem in IPT systems.
- Single capacitor compensation cannot achieve both lowest reactive power and highest power transfer capability.
- Two capacitors are minimal. One at primary and one at secondary.
- Theoretically, series-series compensation is the most efficient for V to I conversion after suitable compensation and optimization. Likewise, series-parallel is best for V to V, etc.
- Extended C or L will improve misalignment coupling or power capability, but with more complicated circuits.