Inductive Power Transfer

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The Hong Kong Polytechnic University
Part 1: Introduction
Electric Power Transfer

Potentially not safe!

Conventional method:

- Metal Conductor Soldering
- Electrical Plug and Socket
- Brush Metal Contact
Introduction

Conventional

Wireless
Roadmap of WPT

- **1831**: Tesla Coil
- **1891**: Faraday, Law of induction
- **1894**: First patent
- **1978**: MIT, lighten a 60 W lamp 2 m away
- **1987**: SHARP microwave airplane 1989-1996 USA PATH
- **1990s**: 1996-EV1, SAE J1773 HF IPT charging of EV
- **2007**: WPC established
- **2008**: WPC wireless charging standard Qi 2010
- **2010**: 2010 commercialized
- **2013**: SAE “J2954” for EV/PHEV
- **2014**: IEC61580 Communication standard for EV
- **2015**: A4WP & PMA merge
WPT classification

Inductive—inductive and resonant

- Inductive—Lower frequency, wider power
- Resonant—Higher frequency, longer distance

Capacitive

- Can penetrate metal, very short distance, high frequency and lower power

Long Range — Laser/Microwave

Long or very long distance
Capacitive coupling

Input voltage: 340V
Output voltage: 196V
Output current: 5.21A
Frequency: 540KHz
Efficiency: 83%
Air gap: 100um

Wireless Electric Vehicle Charging via Capacitive Power Transfer Through a Conformal Bumper
Jiejian Dai, Daniel C. Ludois, APEC 2015
WPT – Long Range

- Safety issue
- Occupy a lot of space
- Higher loss
## WPT Inductive Power Transfer

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Splashpower ▲ Germany Wampfler track IPT</td>
</tr>
<tr>
<td>2007</td>
<td>WiPower ▲ Mojo Mobility coils Japan Haneda Airport Bus IPT</td>
</tr>
<tr>
<td>2008</td>
<td>Seiko 0.5W IPT charger</td>
</tr>
<tr>
<td>2009</td>
<td>Seiko 2.5 W IPT</td>
</tr>
<tr>
<td>2010</td>
<td>Japan Airplane IPT</td>
</tr>
<tr>
<td></td>
<td>Fulton Innovation IPT</td>
</tr>
<tr>
<td></td>
<td>Powermat ▲ 东光 IPT</td>
</tr>
</tbody>
</table>

Now
WPT Inductive Power Transfer

Magnetic Resonant WPT

- MIT
- Intel
- Japan WPT
- Sony WPT

2007  2008  2009  2010  Now

- Less sensitive to transformer misalignment
- Safety Issue
- High frequency operation
3M—under ground positioning 0.6m-2m

Underground pipe detection

WPT application

HV

First international IPT standard;

Established from City University Hong Kong then the WPC (wireless power consortium) on Sept. 2015, WPC has 217 member.

Qi

Google “Nexus” and Nokia “Lumia” support this standard.
PMA (Power Matters Alliance) and Rezence (A4WP) have merged.

Initialized by Duracell Powermat;

on Sept. 2015, A4WP has 150 members including Qualcomm, Samsung, Broadcom and Intel.
## EV charging technology

<table>
<thead>
<tr>
<th>Country</th>
<th>Organization</th>
<th>Gap</th>
<th>Power</th>
<th>Efficiency</th>
<th>Announced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>Waseda</td>
<td>10cm</td>
<td>30kW</td>
<td>92%</td>
<td>2011</td>
</tr>
<tr>
<td>Korea</td>
<td>KIST</td>
<td>26cm</td>
<td>5*20kW</td>
<td>80%~85%</td>
<td>2013</td>
</tr>
<tr>
<td>China</td>
<td>ZTE</td>
<td>20cm</td>
<td>30kW</td>
<td>92%</td>
<td>2014</td>
</tr>
</tbody>
</table>
### EV charging technology

<table>
<thead>
<tr>
<th>Company</th>
<th>Gap</th>
<th>Power</th>
<th>Efficiency</th>
<th>Announced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idaho National Laboratory, USA</td>
<td>11cm</td>
<td>3.3kW</td>
<td>89.2%</td>
<td>2013</td>
</tr>
<tr>
<td>Qualcomm</td>
<td></td>
<td>7.2kW</td>
<td></td>
<td>2015</td>
</tr>
<tr>
<td>Witricity</td>
<td>Operating frequency : 85kHz</td>
<td>2kW</td>
<td>1.5 hours</td>
<td>2014</td>
</tr>
</tbody>
</table>

- **Idaho National Laboratory, USA**
  - Gap: 11cm
  - Power: 3.3kW
  - Efficiency: 89.2%
  - Announced: 2013

- **Qualcomm**
  - Gap: 
  - Power: 7.2kW
  - Charging Time: 1 hour
  - Announced: 2015

- **Witricity**
  - Operating frequency: 85kHz
  - Power: 2kW
  - Charging Time: 1.5 hours
  - Announced: 2014
Installation

ABB (Geneve Airport and Palexpo convention center), 15 second charging at 400 kW, from top of the bus.
Wireless Power Transfer System

- PFC Circuit
- Inverter
- Rectifier
- Driver Circuit
- Controller
- F/V converter
- Filter
- Secondary Feedback circuit
- Buffer
- VCO
- Battery pack
- Single or Three phase
- Primary
- Secondary
- Gap
- M
- Vo
- I
- T
- V
Critical Technology

Electromagnetic compatibility

A

B
Transformer Coupling

C
Control

D
Circuit Theory and Power Electronics

E
Safety

F
Material

G
Communication
Critical Technology

IPT system

Primary

PFC Circuit

Inverter

Rectifier

Secondary

Gap

Primary

Secondary

F/V converter

Filter

Controller

Driver Circuit

Gap

Secondary Feedback circuit

buffer

VCO

Tactic:

- Small Coupling Coefficient
- Large parameter variation

Inductances compensation

Optimization of Transformer

Effective control
Part 2: Basic Analysis

1. Introduction
2. Basic Analysis
3. Compensation Network
4. Transformer
5. Control
6. Design Example
Transformer Equivalent Model

Leakage inductance model

Coupling Model

Three parameter model

\[ L_P = L_{L1} + L_M \]
\[ L_S = L_{L2} + n^2 L_M \]
\[ M = \frac{k}{\sqrt{L_P L_S}} \]

\[ n' = \frac{L_S}{M} \]
\[ L'_L = \frac{L_{L1} L_S + M L_{L2}}{L_S} = \frac{L_P L_S - M^2}{L_S} \]
\[ L'_M = \frac{M^2}{L_S} \]

Equivalent n

\[ n^* = \frac{M}{L_P} \]
\[ L'_L = L_S - \frac{M^2}{L_P} \]
\[ L'_M = L_P \]
Part 3: Compensation network
Why compensation?

- Improve input power factor
- Reduce device rating
- Improve power transfer
- Improve efficiency
- Reduce sensitivity to transformer parameter variation

Primary Windings

Secondary Windings

Large leakage inductance and small mutual inductance
Circuit

Power source  Inverter  Compensation  Rectifier  Filter  Load

Primary
- Voltage source input
- Current source input

Secondary
- C Filter
- LC Filter
Phase of $v_{OR}$ and $i_2$ are identical, like a resistor.

Equivalent load resistor:

$$R_E = \frac{v_{OS}}{i_2} = \frac{4V_o \sin(\omega t)}{I_2 \sin(\omega t)} = \frac{4V_o}{\pi I} = \frac{8V_o}{\pi^2 I} = \frac{8}{\pi^2} R_L$$
C filter, output voltage assumed constant

\[ R_E = \frac{8}{\pi^2} R_L \]

LC filter, output current assumed constant

\[ R_E = \frac{\pi^2}{8} R_L \]
System Simplification

Square voltage

Square current

$T_r$

$C_f$

$L_f$

$R_{Ld}$

$R_E$
Resonant Compensation

Series resonant

Voltage across L C compensated to zero. When high Q, voltages across L and C can be higher than the input.

\[ Q = \frac{\omega L}{R} = \frac{1}{R} \sqrt{\frac{L}{C}} \]

Parallel resonant

Current flow through L and C cancelled out.

\[ Q = \frac{\omega C}{R} = \frac{1}{R} \sqrt{\frac{C}{L}} \]
Secondary Capacitor Compensation

Reflected $Z_r$:

$$Z_r = \frac{\omega^2 M^2}{Z_s}$$

Power transfer capability:

$$P = I_p^2 \cdot \text{Re}(Z_r)$$

$$\omega = \frac{1}{\sqrt{L_s C_s}}$$

<table>
<thead>
<tr>
<th>Compensation</th>
<th>Re(Zr)</th>
<th>Im(Zr)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series</td>
<td>$\frac{\omega^2 M^2}{R_E}$</td>
<td>0</td>
<td>Im(Zr)=0</td>
</tr>
<tr>
<td>Parallel</td>
<td>$\frac{M^2 R_E}{L_s^2}$</td>
<td>$-\frac{\omega M^2}{L_s}$</td>
<td>Capacitive load independent Im(Zr)</td>
</tr>
</tbody>
</table>
Parallel

Series

If $I_p$ constant

Output current is load independent

Output voltage is load independent

Can have load independent output.
Primary Capacitor Compensation

Series

Parallel

Suitable for driving large values of \( L \) to minimize input driving voltage.

Suitable for driving high winding currents to minimize input current.

We need primary and secondary compensations.
Primary and Secondary Compensations

(a) S/S compensation

(b) S/P compensation

(c) P/S compensation

(d) P/P compensation
Primary and Secondary Compensations

\[ C_{pn} = \frac{C_p}{\frac{C_s L_s}{L_p}}. \]

<table>
<thead>
<tr>
<th>Topology</th>
<th>Primary Capacitance ( C_p )</th>
<th>Normalized Primary Capacitance ( C_{pn} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>( \frac{C_s L_s}{L_p} )</td>
<td>1</td>
</tr>
<tr>
<td>SP</td>
<td>( \frac{C_s L_s^2}{L_p L_s - M^2} )</td>
<td>( \frac{1}{1 - k^2} )</td>
</tr>
<tr>
<td>PP</td>
<td>( \frac{(L_p L_s - M^2) C_s L_s^2}{M^4 C_s R + (L_p L_s - M^2)^2} )</td>
<td>( \frac{1 - k^2}{Q_s^2 k^4 + (1 - k^2)^2} )</td>
</tr>
<tr>
<td>PS</td>
<td>( \frac{C_s L_s}{M^4 L_p C_s L_s R + L_p} )</td>
<td>( \frac{1}{Q_s^2 k^4 + 1} )</td>
</tr>
</tbody>
</table>

![Graph showing normalized primary capacitance against magnetic coupling coefficient](image)

- SS
- SP
- PP
- PS

Normalized primary capacitance \( C_{pr} \)

Magnetic coupling coefficient (k)
Primary and Secondary Compensations

Resonant at 40 kHz

S/S voltage gain

P/P current gain

P/S current gain

Duality

Load independent output
**Resonant Compensation**

- Load independent output voltage
- Input inductive, current circulating loss
- Low input resistance, small reactance
- Load independent current output
- Even worse at light load
- Need open circuit protection

![Circuit Diagram]
S/S compensation

KAIST, output 27kW, gap 20cm, maximum efficiency 74%
Output voltage 408V, output current 66.2A
S/S Compensation Example

**KAIST**, output 27 kW, gap 20 cm, maximum efficiency 74%
Output voltage 408V, output current 66.2A

Spain, power 2 kW, gap 15 cm, maximum efficiency 82%
S/S uses less copper

---

S/P Compensation

L model

Input zero phase angle
Output load independent

C₁ design for voltage gain,
C₃ design for phase angle

 PLL control may fail due to high Q at light load

Voltage gain

Input phase angle

41
Japan, Output 30 kW, gap 10cm, Maximum efficiency 92%

Frequency 22 kHz

P/P Compensation

\[ i_1 \quad L_P \quad i_P \quad M \quad i_S \quad L_S \]

Input must be a current

Load independent output voltage

Input capacitive
Power: 300W, primary current 15A, 20kHz, load 6Ω, k=0.45, $Q_S=1.77$
P/S Compensation

Input must be a current source

Load independent current output

Input capacitive
P/S Compensation

\[ \frac{i_1}{j\omega C_1} + j\omega M L_1 \]  \quad \text{Current input}

\[ \text{C}_1 \text{ design for transfer function, C}_2 \text{ design for input phase angle} \]

\[ n' = \frac{M}{L_p} \quad \omega_p^2 = 1/L_p C_1 = 1/[ (L_s - M) C_2 ] \]

\[ \frac{1}{2} \]

\[ \text{Load independent current output} \quad \text{Input zero phase angle} \]
Load independent output and high efficiency

\[ \eta_T = \eta_P \eta_S \]

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

\[ \eta_S = \frac{R_O}{R_O + R_S} \]

\[ \text{Re}\{Z_r\} = \frac{\omega^2 k^2 L_P L_S R}{R^2 + X_S^2} \]

Set \( \frac{d\eta(\omega)}{d\omega} = 0 \)

\[ \omega_M = \frac{\omega_S}{\sqrt{1 - \frac{1}{2Q_O^2}}} \]

\( \omega_M \in [\omega_S, \infty) \)

Optimum frequency for maximal efficiency

Efficiency at $\omega_M$:

\[ Q_{O1} = \sqrt{\frac{1}{2\lambda}(1 + \sqrt{1 - 3\lambda})} \]

\[ \lambda = k^2 \frac{Q_P}{Q_S} \]

1. $\lambda < 1/3$

Efficiency maximized at $Q_{O1}$

2. For $\lambda \geq 1/3$

Efficiency increase with decreasing $Q_O$
When $Q_p = Q_S$

Efficiency at $\omega_S$ and $\omega_M$

With a known load, design a transformer such that $\omega_M \approx \omega_S$ to have maximum efficiency

When $\lambda < 1/3$ ($k < 0.577$), near load $Q_{O1}$, $\omega_M$ and $\omega_S$ are nearly identical

replace $\omega_M$ with $\omega_S$

$\omega_S$ is load independent

S/S Compensation optimization

Load independent output and high efficiency

S/S compensation voltage gain:

\[
\omega_L = \frac{\sqrt{\omega_p^2 + \omega_S^2 + \sqrt{(\omega_p^2 + \omega_S^2)^2 - 4(1 - k^2)\omega_p^2 \omega_S^2}}} {2(1 - k^2)}
\]

\[
\omega_H = \sqrt{\frac{\omega_p^2 + \omega_S^2 - \sqrt{(\omega_p^2 + \omega_S^2)^2 + 4(1 - k^2)\omega_p^2 \omega_S^2}} {2(1 - k^2)}}
\]

Load independent output and high efficiency

|                      | Load independent $|G_v|$ | Maximum Eff. |
|----------------------|------------------|--------------|
| Operating freq.      | $\omega_H$       | $\omega_M \approx \omega_S \ (\lambda < 1/3)$ |

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

$\omega_H$ cannot be $\omega_S$

$$\omega_S = \frac{1}{\sqrt{L_SC_S}} \quad C_S \text{ design for efficiency}$$

$$\omega_P = \frac{1}{\sqrt{L_PC_P}} \quad C_P \text{ design for efficiency, such that } \omega_H \text{ close to } \omega_S$$

Define: \( C_{Pn} = \frac{L_S C_S}{L_P} \)

\[ C_p = 1.1 C_{Pn} \]

\[ C_p = 1.3 C_{Pn} \]

**S/S Compensation optimization**

Load independent output and high efficiency

- Design \( C_p \) making \( \omega_H \) closer to \( \omega_S \) to have a higher efficiency
- maximize efficiency of S/S compensated converter to have load independent output

If a constant output current is needed, S/S compensation should operate at \( \omega_S \). Proper output open circuit protection should be given.
Realization of Load Independent Output

Voltage source output

Current source output
Realization of Input Current

Primary side LCL compensation
Primary and Secondary LCL Compensation

Auckland U.

- $I_T$ is load independent and so is $I_O$
- Suitable for multiple secondary windings application
- LCL need external indicator as large as $L_M$, lower system power density.
Compared with LCL compensation, LCC compensation can have higher injected current.

Current gain (normally less than 3 due to magnetics):

\[ Q_i = 1 + \frac{C_1}{C_{S1} - C_1} \]
Parallel capacitor $C_f$ reduce inductance $L_f$;
Load independent current output;

Magnetic coupling can improve power density.

Coupling Circuits

LCC Compensation-Integrated

Matching:

\[ L_{f1e} = L_{f1} + M_1 \]
\[ L_{f2e} = L_{f2} + M_2 \]
\[ L_{e1} = L_1 + M_1 - \frac{1}{(\omega^2 C_1)} \]
\[ L_{e2} = L_2 + M_2 - \frac{1}{(\omega^2 C_2)} \]
\[ C_{f1e} = C_{f1} / (\omega^2 M_1 \cdot C_{f1} + 1) \]
\[ C_{f2e} = C_{f2} / (\omega^2 M_2 \cdot C_{f2} + 1) \]

\[ L_{f1e} = L_{e1} \]
\[ \omega_0 = 1 / \sqrt{L_{f1e} C_{f1e}} = 1 / \sqrt{L_{f1} C_{f1}}. \]
\[ L_1 - L_{f1} = 1 / (\omega_0^2 C_1). \]
**SP/S Compensation**

Primary series compensation

\[
Z_{in} = \frac{1}{j\omega C_p} + j\omega L_p + R_P + \frac{\omega^2 M^2}{Z_S}
\]

Primary parallel compensation

\[
Z_{in} = \frac{1}{j\omega C_p} + \frac{1}{j\omega L_p + R_P + \frac{\omega^2 M^2}{Z_S}}
\]

Misalignment, coupling reduced

Primary series compensation + Primary parallel compensation = combine

\(I_P\) increases, can be over current. Is may also increases.

\(I_s\) increases, so as \(I_s\).

SP/S Compensation

Spain

\[ C_2 = \frac{1}{L_2 \omega^2} \]

\[ C_{3PS} = \frac{L_2 C_2}{L_1 + \frac{L_1}{L_2} C_2 R_L^2} \]

\[ C_3 = K_C \cdot C_{3PS} \]

原边串联电容将虚部补偿掉。


Input zero phase angle;

Insensitive to misalignment.

Input resistance change with output load.

\[
C_2 = \frac{1}{L_2 \omega^2}
\]

\[
C_{3PS} = \frac{L_2 C_2}{L_1 + \frac{M^4}{L_1 L_2 C_2 R_L^2}}.
\]

\[
C_3 = K_C \cdot C_{3PS}.
\]

**SP/S Compensation**

Spain

北京交通大学

中科院沈阳自动化所
S/S AND S/P COMPENSATION

S/S compensation

Voltage gain a function of \( n \) only

Input inductive

S/P compensation

Input resistive

Voltage gain a function of \( n \) and \( k \)

\[ \omega L_{l1} = \frac{1}{\omega C_1} \]

\[ \omega L_{l2} = \frac{1}{\omega C_2} \]

\[ n' = \frac{L_S}{M} \approx \frac{n}{k} \] (假设 \( \frac{L_P}{L_S} = \frac{1}{n^2} \))

S/SP COMPENSATION

Compensation: \[ \omega^2 = \frac{1}{L_{c1}C_1} = \frac{1}{L_{c2}C_2} = \frac{1}{n^2 L_M C_3} \]

😊 Voltage gain a function of \( n \) only

😊 Input resistive

**S/SP Compensation**

**Voltage gain**

\[ G_v(\omega) = \frac{8}{\pi^2} \times \left( \frac{\Delta}{j\omega C_1 C_2 L_M R_E} \right) \]

\[ \Delta = \omega^3 C_p C_s (n^2 L_M^2 - L_p L_s) + \omega^2 (L_p C_p + L_s C_s) - 1 \]

\[ \omega_i = \frac{1}{\sqrt{L_{11} C_1}} = \frac{1}{\sqrt{L_{12} C_2}} = \frac{1}{\sqrt{n^2 L_M C_3}} \]

\[ Z_{in} = j\omega L_p + \frac{1}{j\omega C_1} + \frac{\omega^2 M^2}{j\omega L_s + \frac{1}{j\omega C_2} + \frac{1}{j\omega C_3} || R_E} \]

\[ Z_{in}(\omega_i) = \frac{j\omega L_M R_E}{(-\omega^2 n^2 L_M C_3 + 1)R_E + j\omega n^2 L_M} = \frac{R_E}{n^2} \]

If 0, gain becomes load independent

If 0, then a pure resistor
Resonant frequency \( f_r = 40 \text{ kHz} \)

Compensation capacitor

<table>
<thead>
<tr>
<th>Transformer parameter</th>
<th>( C_1 = 48.89 \text{nF}, C_2 = 44.2 \text{nF}, C_3 = 51.4 \text{nF} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cm: ( k_{\text{max}} = 0.475, L_{ll} = 324.967 \mu\text{H}, L_{l2} = 362.56 \mu\text{H}, L_M = 310.948 \mu\text{H} )</td>
<td></td>
</tr>
<tr>
<td>20 cm: ( k_{\text{min}} = 0.231, L_{ll} = 435.275 \mu\text{H}, L_{l2} = 462.95 \mu\text{H}, L_M = 134.85 \mu\text{H} )</td>
<td></td>
</tr>
</tbody>
</table>

\( R_L_{\text{L}_{\text{min}}} = 100 \Omega, R_L_{\text{mid}} = 400 \Omega, R_L_{\text{max}} = 800 \Omega \)

Constant freq. control
Fundamental approximation is not able to keep up with the accuracy.

Lot of higher harmonics
Higher Harmonic Equivalent Circuit

Input voltage: \[ |V_{AB_m}| = \frac{4V_{in}}{m\pi} \]

Output current: \[ |I_{2_m}| = \frac{4I_o}{m\pi} \]
Higher Harmonic Equivalent Circuit

Voltage across $L_M$

$m=1$: $V_{LM \_1} = V_{AB \_1}$

$m=3,5,7,9,...$: $rac{V_{LM \_m}}{V_{AB \_m}} \approx k$

$v_{LM}(t) \approx (1-k)|V_{AB \_1}| \sin(\omega_s t) + kv_{AB}(t)$

 sine square

Secondary current

$m=1$: $I_{S \_1} = nV_{AB \_1} \left(j\omega_C + \frac{1}{Z_{E \_1}}\right)$

$m=3,5,7,9,...$: $I_{S \_m} \approx 0$

$i_S(t) = I_{S \_1} \sin(\omega_s t + \theta_1)$  sine
Waveforms of Resonant Circuit

\[ v_{LM}(t) \approx (1-k)|V_{AB-1}| \sin(\omega_s t) + kv_{AB}(t) \]

\[ i_s(t) = |I_{s-1}| \sin(\omega_s t + \theta) \]
Output Waveforms

Output current harmonics

Harmonic current and voltage
Experimental Comparisons

$P_o = 1.5 \, \text{kW}$

$P_o = 0.8 \, \text{kW}$

39.2 kHz

Input current

Voltage across parallel capacitor
S/SP Compensation

Result from calculation with Fundamental approximation

Result from calculation with higher harmonics

Experimental result

\( P_o(W) \)

\( \xi \)
Switching of Series or Parallel Compensation on the Secondary Side

Battery charging needs two stages:
- **Constant Current**, until battery reach a voltage level,
- **Constant voltage**, until current diminishing to nearly none.

- **Constant voltage**, S1 and S2 open, S3 connects RL to L2, forming a S/S compensation, \( L_s = L_1 + L_2 \) (dotted blue)
- **Constant current**, S1 and S2 close, S3 connects RL in parallel with \( C_{ssp} \), forming a S/P compensation, \( L_s = L_1 \) (solid red)

When there are variation of parameters, such as load, coupling and driving frequency, system compensation may deviate from optimal point.

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**Dynamic Tuning**

- Use extra inductor or capacitor;
- Need bidirectional current switch;
- Discrete alteration of capacitance or inductance.

---

**Three mode boost inductor secondary compensation**

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Part 4: Transformer Optimization

1. Introduction
2. Basic Analysis
3. Compensation Network
4. Transformer
5. Control
6. Design Example
Thank You!