非接觸式馬達驅動與伺服控制關鍵技術之開發
Study of Key Technologies for Motor Driver and Servo Control Using a Contactless Power System

Department of Electrical Engineering
National Changhua University of Education

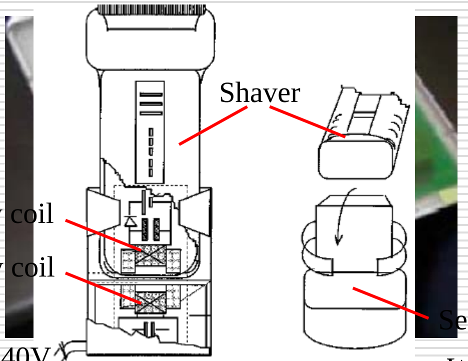
Ying-Shing Shiao

Outline

- Introduction
- Motivation
- System Configuration
- Simulation and Experimental Results
- Conclusions

Introduction

- ➢low power applications for portable electronic devices

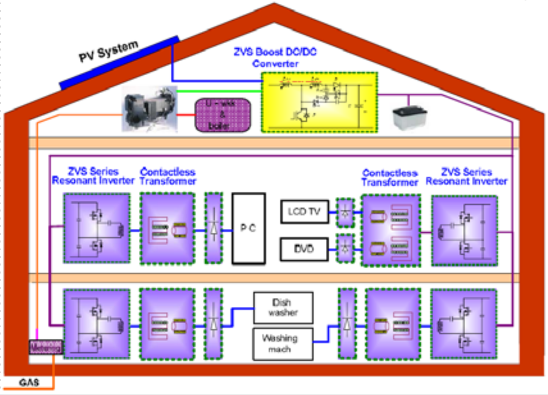


“Equivalent Circu … ar Winding Array of the Secondary Coil”

“A Noncontact Charger Using a Resonant Converter with Parallel Capacitor Structure for Use in a Universal Contactless Battery Charging Platform”

Introduction

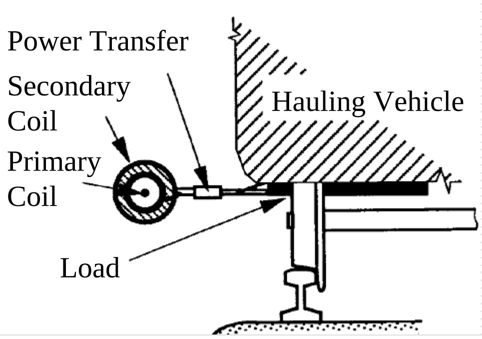
- ➢middle power applications for home electric systems



“A Contactless Power Supply for Photovoltaic Power Generation System”

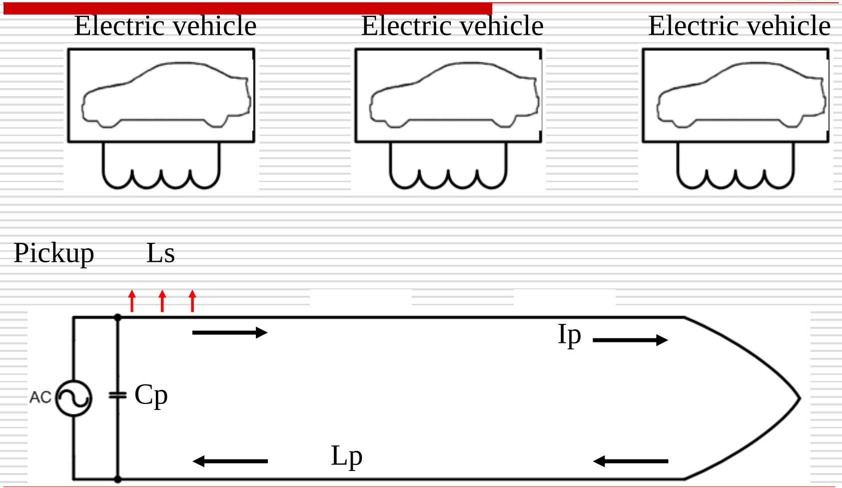
Introduction

- high power applications for public transport systems



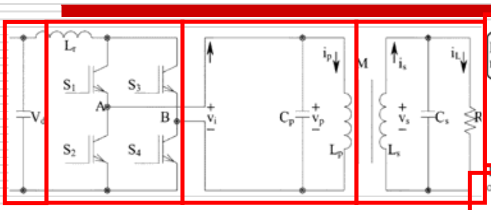
"Contactless Power Delivery System for Mining Applications"

Motivation

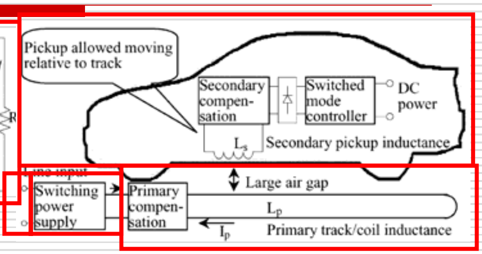


Primary track / coil inductance is buried in the ground

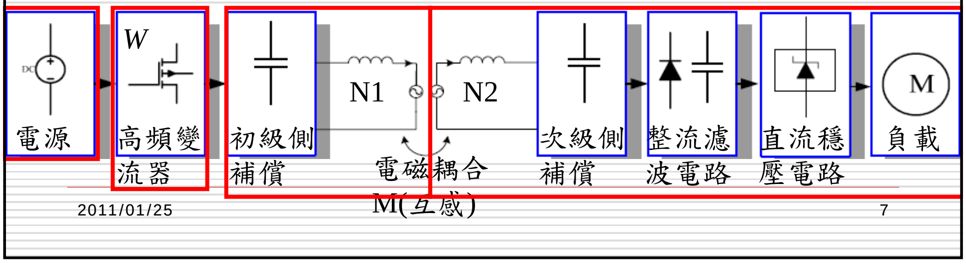
Contactless power transfer system (CPTS)



Circuit diagram of ICPT system



Structure of ICPT system



電源

高頻變流器

初級側補償

電磁耦合 M(互感)

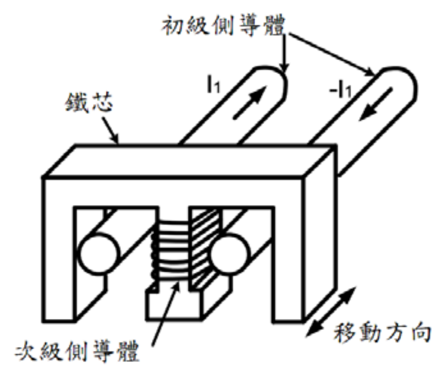
次級側補償

整流濾波電路

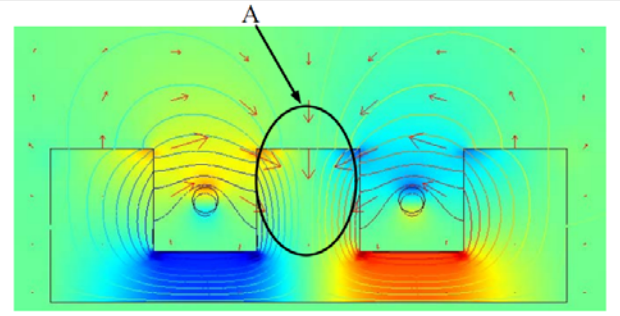
直流穩壓電路

負載

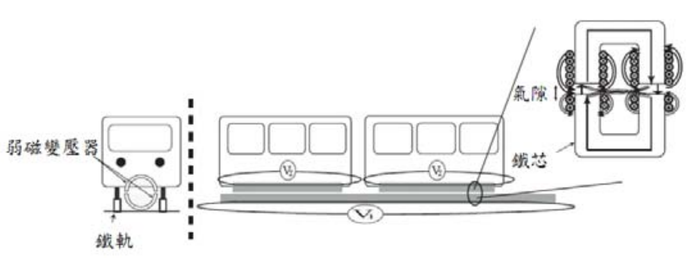
E型鐵芯變壓器



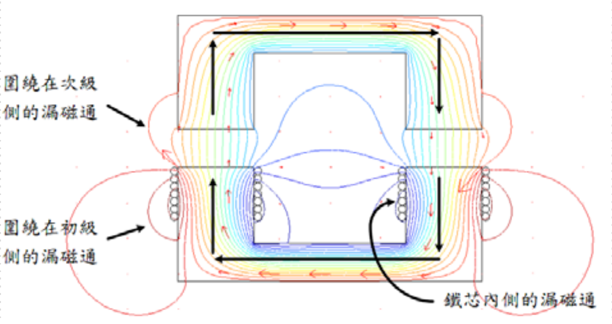
ECT的磁通分佈

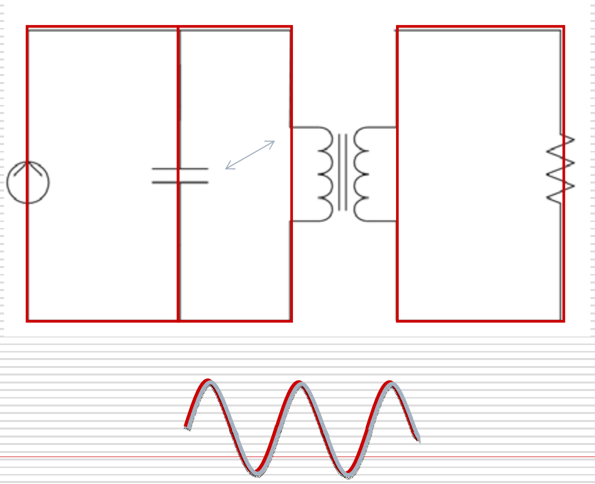


非接觸式U型鐵芯應用於運輸系統

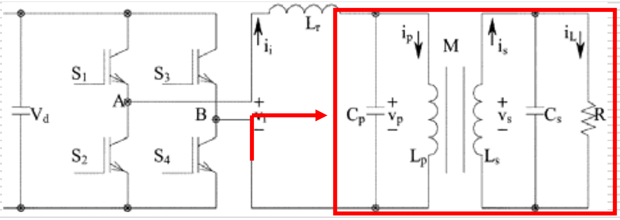


U型或C型鐵芯變壓器

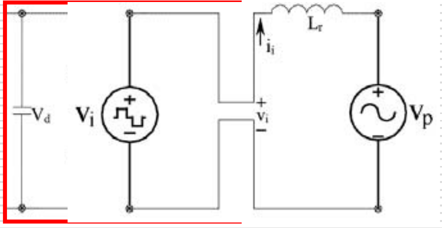


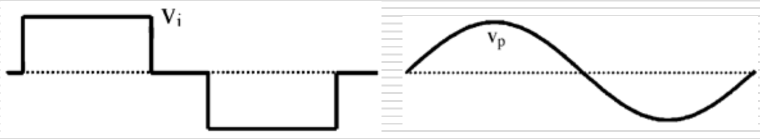


An LCL load resonant inverter

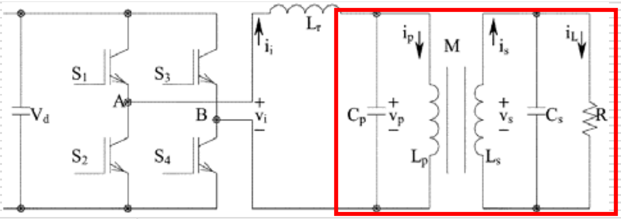


An LCL load resonant inverter

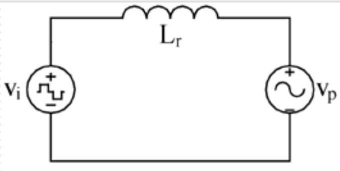


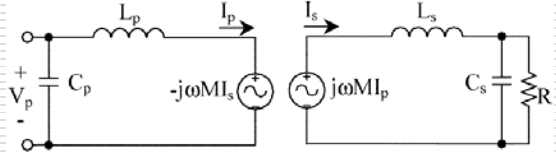


An LCL load resonant inverter



Circuit diagram of ICPT system driven by an LCL load resonant

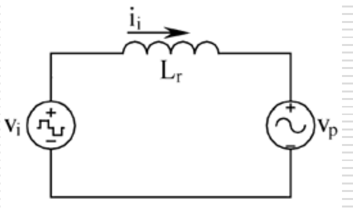


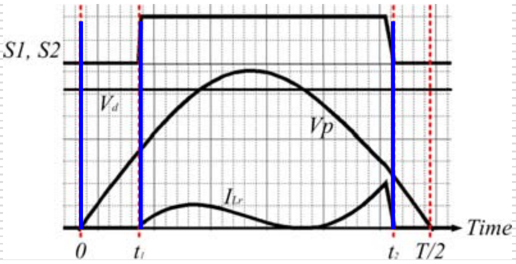


Inverter model

Resonant tank model

Inverter model





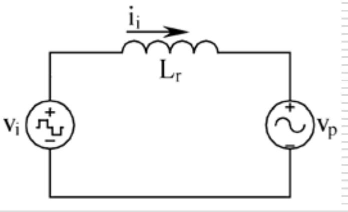
$$v_p(t) = \hat{V}_p \sin\omega t$$

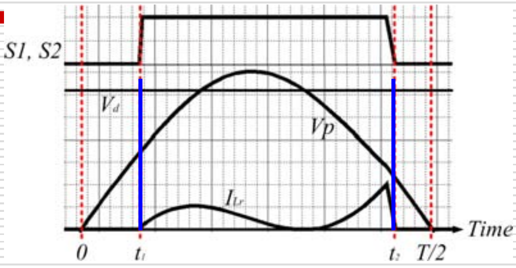
$$v_i(t) = \begin{cases} v_p(t) & 0 < t < t_1 \\ V_d & t_1 < t < t_2 \\ v_p(t) & t_2 < t < \frac{T}{2} \end{cases}$$

$$v_i(t) - v_p(t) = L_r \frac{di_i(t)}{dt}$$

$$i_i(t) = \frac{V_d}{L_r}(t - t_1) + \frac{\hat{V}_p}{\omega L_r}[\cos\omega t - \cos\omega t_1] \quad t_1 < t < t_2$$

Inverter model



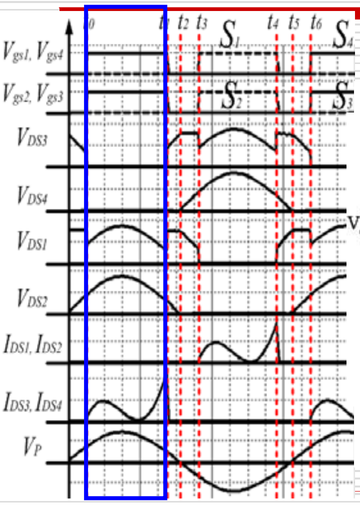


$$P_i = \frac{2V_d}{T}\int_{t_1}^{t_2} i_i(t)\,dt$$

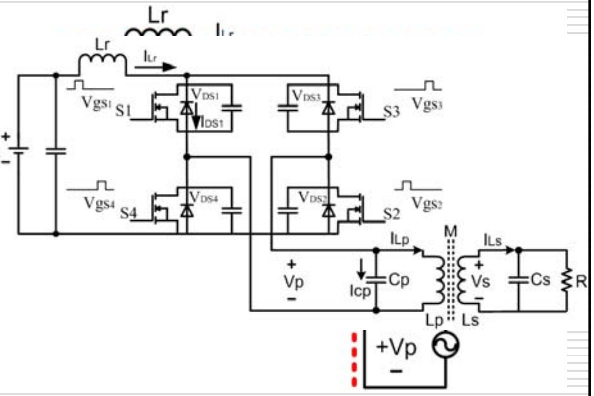
$$i_i(t) = \frac{V_d}{Lr}(t-t_1) + \frac{\hat{V}_p}{\omega Lr}\left[\cos\omega t - \cos\omega t_1\right] \quad t_1 \langle\, t \,\langle\, t_2$$

$$P_i = \frac{\omega V_d^2}{2\pi Lr}(t_2-t_1)^2 + \frac{V_d\hat{V}_p}{\pi\omega Lr}\left(\sin\omega t_2 - \sin\omega t_1 - \omega(t_2-t_1)\cos\omega t_1\right)$$

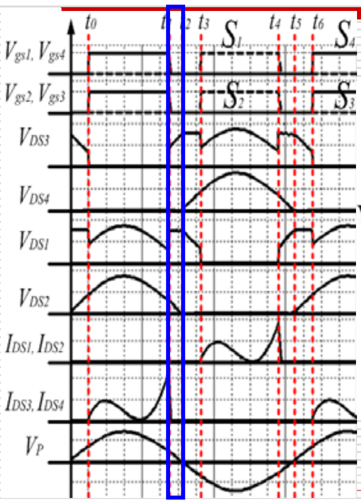
Timing sequence and waveform diagrams



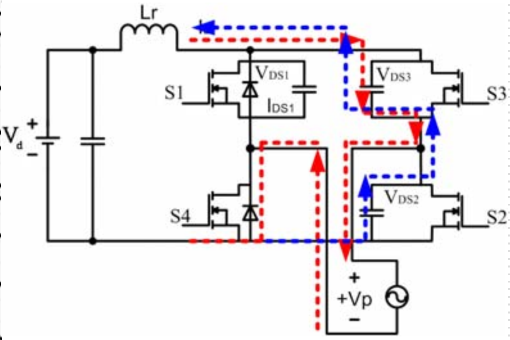
- Mode [a] t_0-t_1



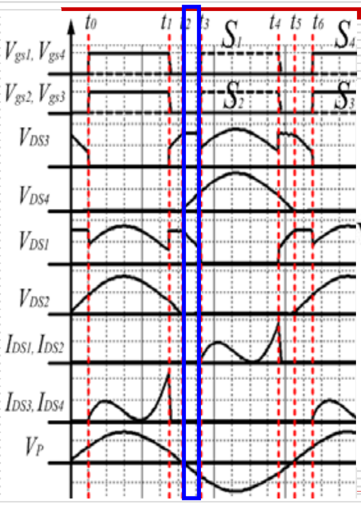
Timing sequence and waveform diagrams



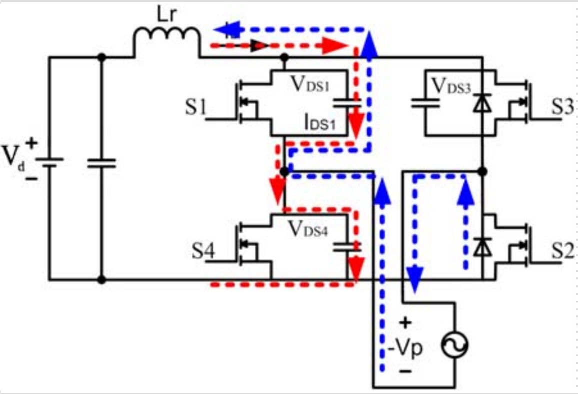
- ➢Mode [b] t_1-t_2



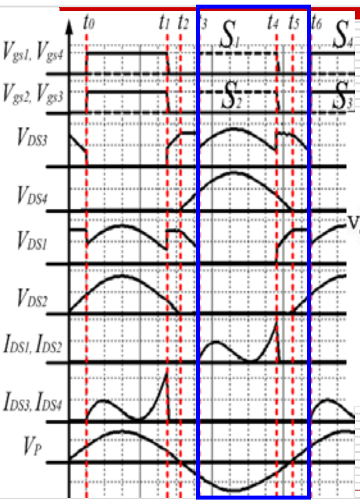
Timing sequence and waveform diagrams



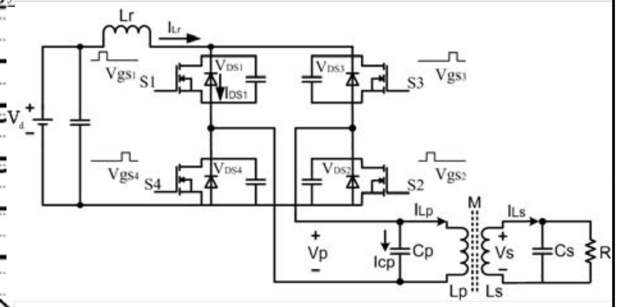
- ➢Mode [c] t_2-t_3



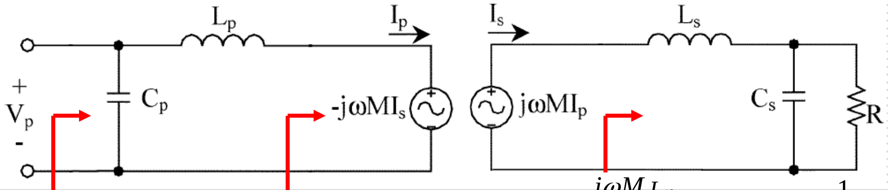
Timing sequence and waveform diagrams



- Mode [d-f] *t3-t6*



Resonant tank model



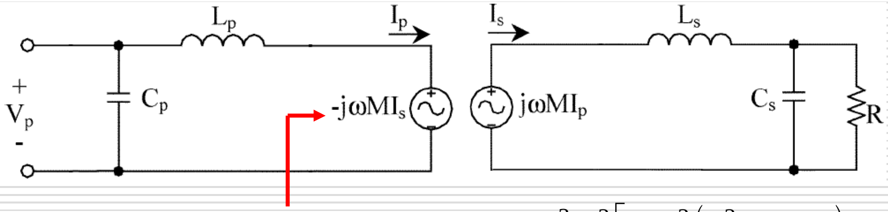
$$Z_s = \frac{j\omega M I_p}{I_s} = j\omega L_s + \frac{1}{j\omega C_s + \frac{1}{R}}$$

$$Z_r = \frac{-j\omega M I_s}{I_p} = \frac{\omega^2 M^2 I_s}{j\omega M I_p} = \frac{\omega^2 M^2}{Z_s}$$

$$Y_t = j\omega C_p + \frac{1}{j\omega L_p + Z_r}$$

$$P_c = (\mathrm{Re}\,Y_t)\frac{\left(\hat{V}_p\right)^2}{2}$$

Resonant tank model

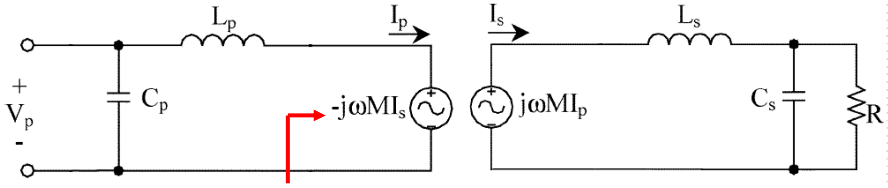


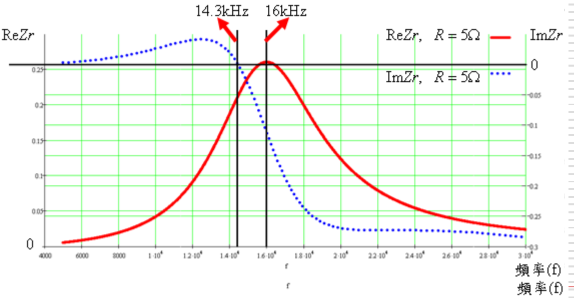
$$\operatorname{Re} Z_r = \frac{\omega^2 M^2 R}{R^2\left(\omega^2 C_S L_S - 1\right)^2 + \omega^2 L_S{}^2} \qquad \operatorname{Im} Z_r = \frac{-\omega^3 M^2\left[C_S R^2\left(\omega^2 C_S L_S - 1\right) + L_S\right]}{R^2\left(\omega^2 C_S L_S - 1\right)^2 + \omega^2 L_S{}^2}$$

- Parameters of the resonant tank circuit :

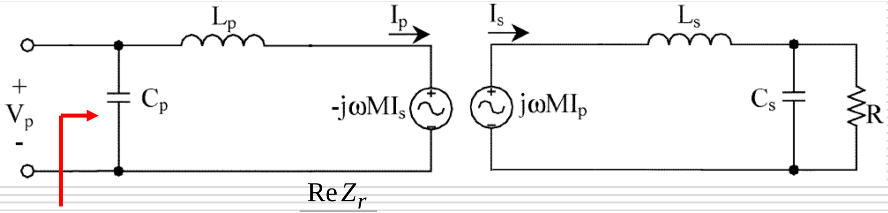
$L_P = 19.56\mu H,\ L_S = 21.29\mu H,\ M = 4.861\mu H,\ C_P = 5\mu F,\ and\ C_S = 4.648\mu F$

Resonant tank model





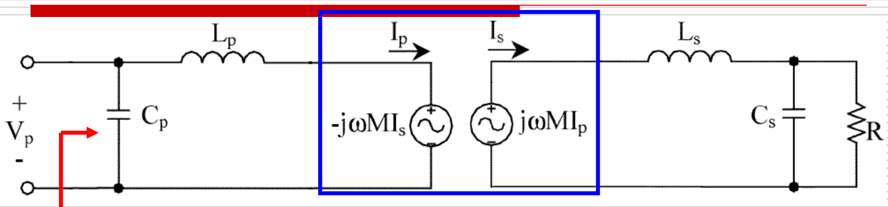
Resonant tank model

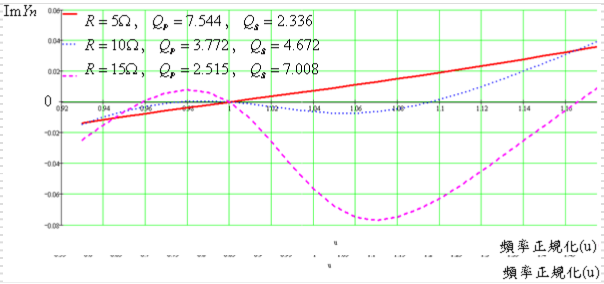


$$\operatorname{Re} Y_n = \frac{\dfrac{\operatorname{Re} Z_r}{\operatorname{Re} Z_{r0}}}{\left(\dfrac{\operatorname{Re} Z_r}{\operatorname{Re} Z_{r0}}\right)^2 + \left(\dfrac{\omega L_P}{\operatorname{Re} Z_{r0}} + \dfrac{\operatorname{Im} Z_r}{\operatorname{Re} Z_{r0}}\right)^2}$$

$$\operatorname{Im} Y_n = \omega C_P \left(\operatorname{Re} Z_{r0}\right) - \frac{\dfrac{\omega L_P}{\operatorname{Re} Z_{r0}} + \dfrac{\operatorname{Im} Z_r}{\operatorname{Re} Z_{r0}}}{\left(\dfrac{\operatorname{Re} Z_r}{\operatorname{Re} Z_{r0}}\right)^2 + \left(\dfrac{\omega L_P}{\operatorname{Re} Z_{r0}} + \dfrac{\operatorname{Im} Z_r}{\operatorname{Re} Z_{r0}}\right)^2}$$

Resonant tank model

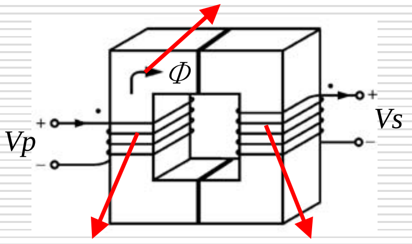




Inductive transformer

- Tightly coupled $k \approx 1$
- Loosely coupled $k \leq 0.8$

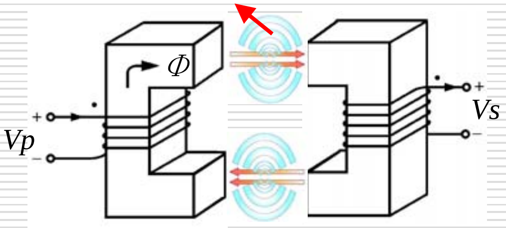
Power Transfer



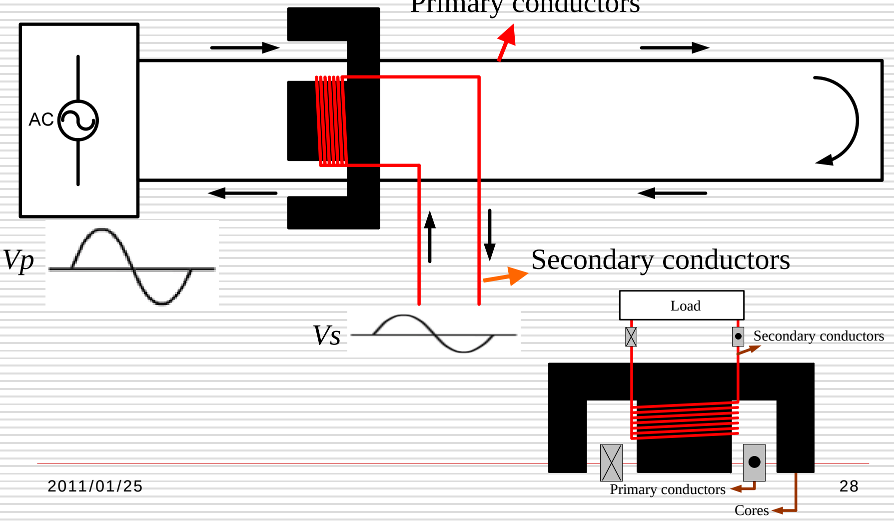
Primary Coil

Secondary Coil

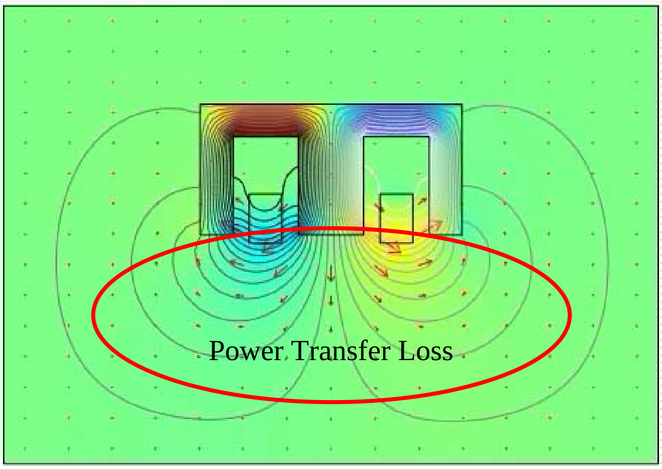
Power Transfer Loss



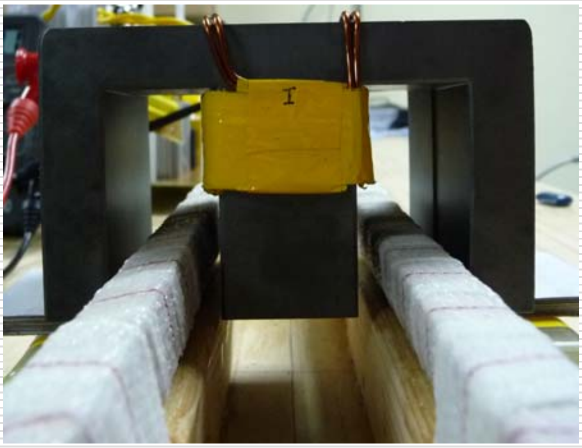
Proposed LCIT (2-1)



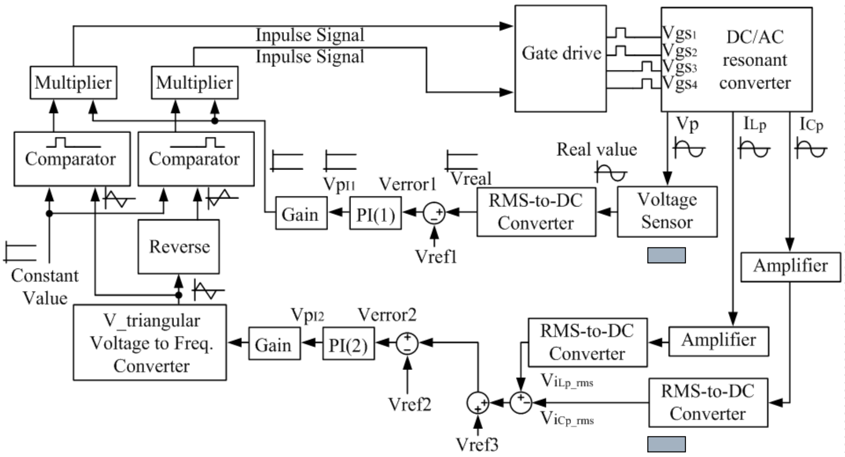
Proposed LCIT (2-2) $k \leq 0.5$



Prototype power pickup transformer



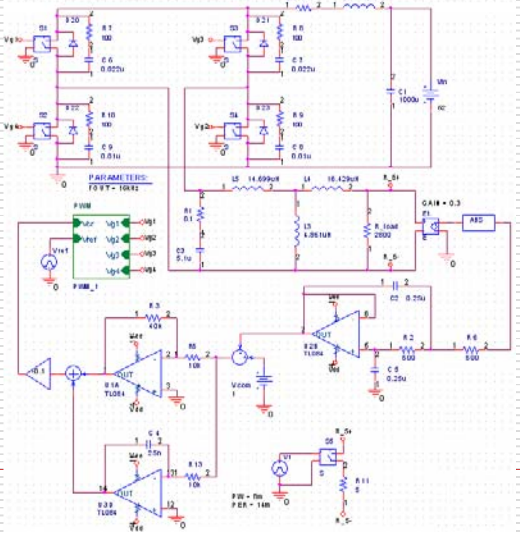
ControlSystem



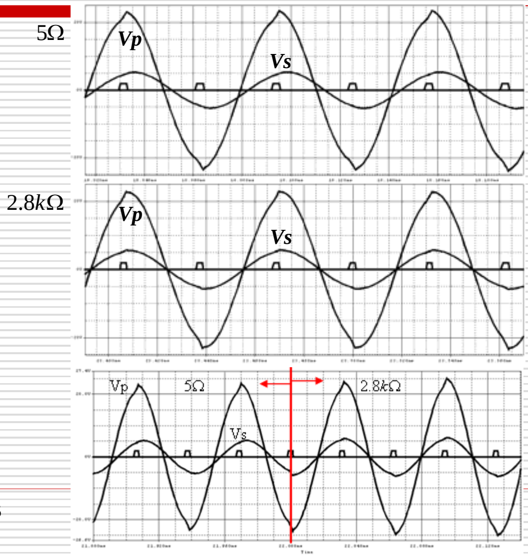
Parameters of the contactless power transfer system

Nominal frequency	16kHz(15k~17kHz)
Rated power	200VA
Rated load	5Ω
Primary inductance	19.56uH
Primary capacitance	5uF
Mutual inductance	4.861uH
Secondary inductance	21.29uH
Secondary capacitance	1.53uF
Magnetic coupling coefficient	0.238
Np	4
Ns	7
Air gap	20mm

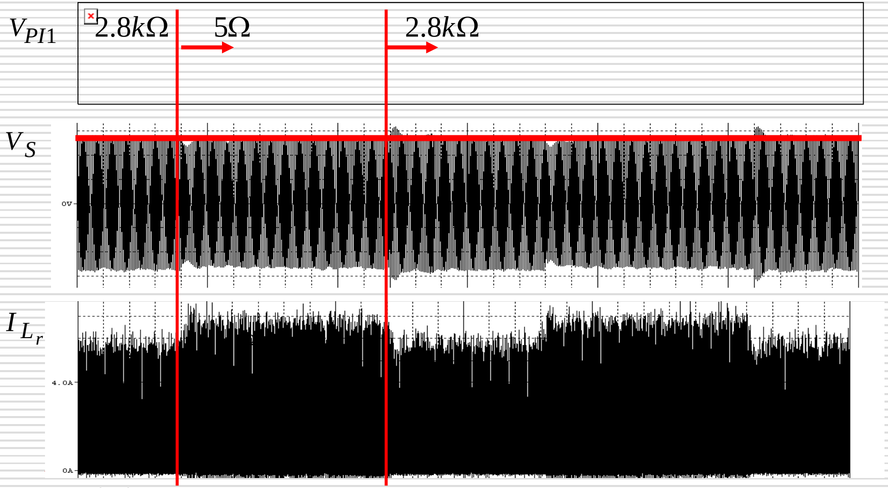
The simulation configuration of the proposed CPTS



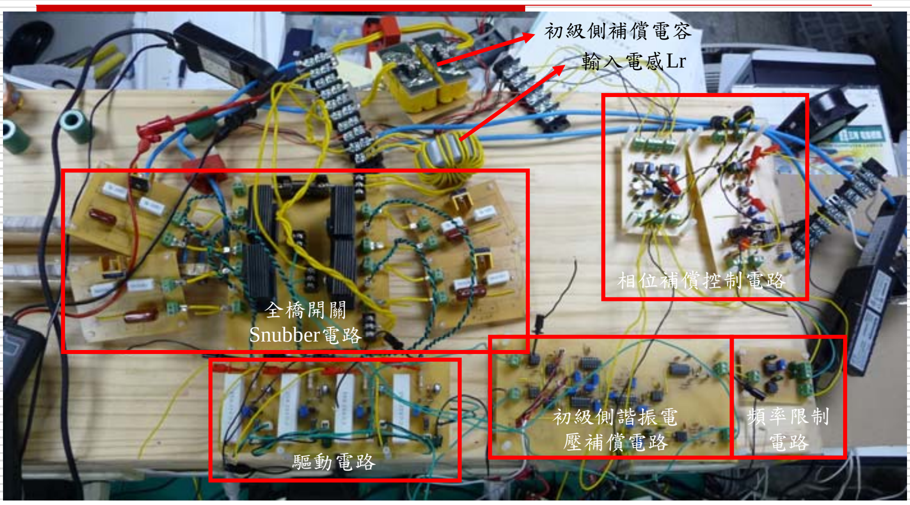
Simulation result –gate signal, primary and secondary side voltage (*Vp*, *Vs*)



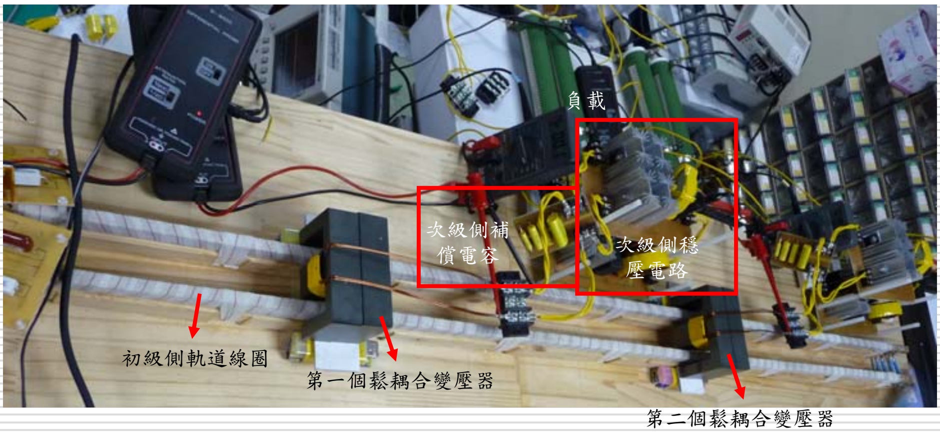
Simulation result –the transient responses



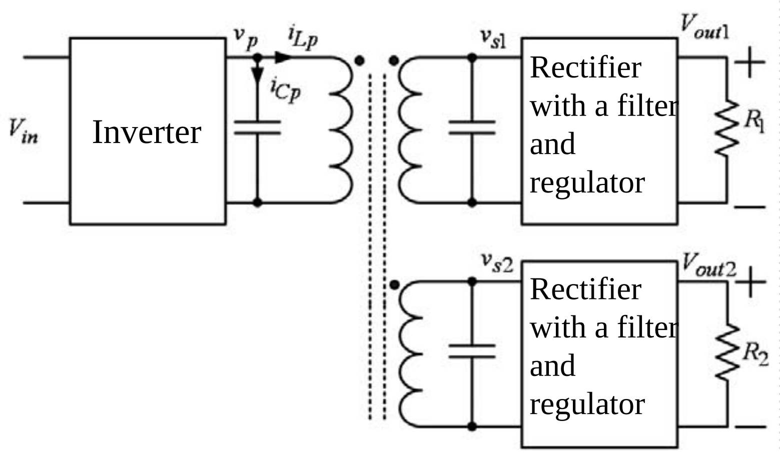
Photograph of a primary circuit



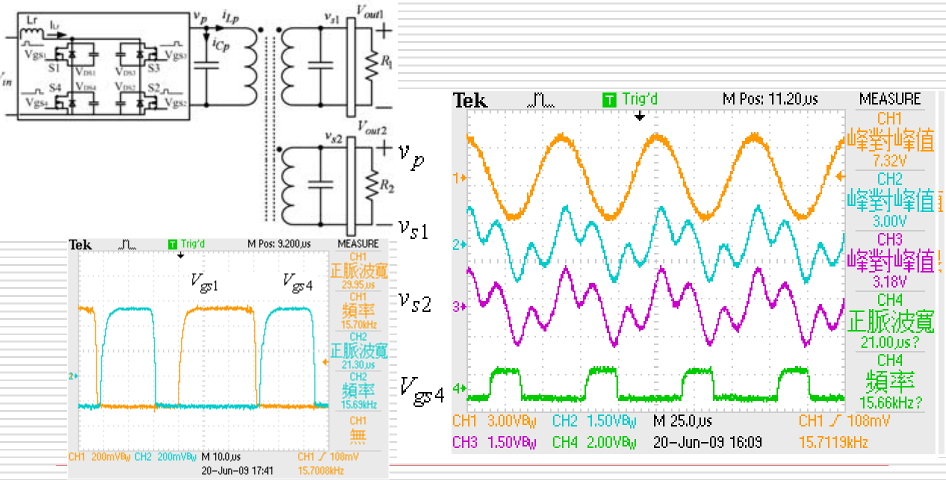
Photograph of two secondary network



Experimental results –with regulator (SEPIC)

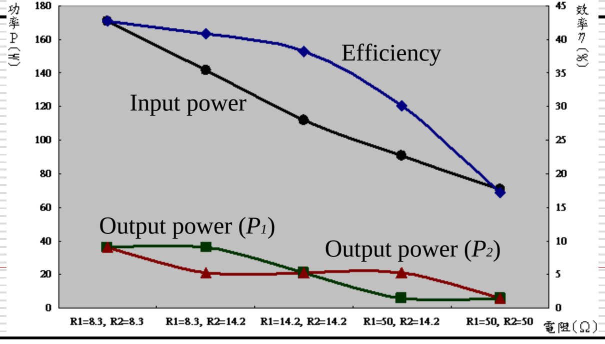


Experimental results –with regulator (SEPIC)

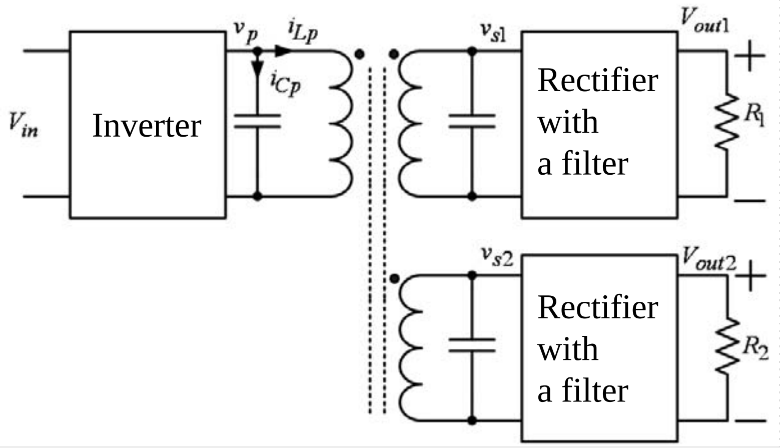


With regulator (SEPIC)

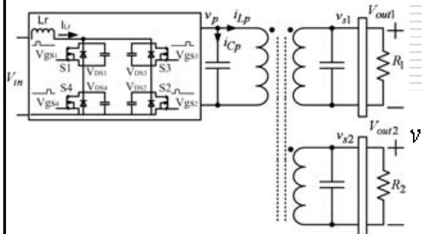
Load	$R_1=8.3\Omega$ $R_2=8.3\Omega$	$R_1=8.3\Omega$ $R_2=14.2\Omega$	$R_1=14.2\Omega$ $R_2=14.2\Omega$	$R_1=50\Omega$ $R_2=14.2\Omega$	$R_1=50\Omega$ $R_2=50\Omega$
Input power	170.8	141.52	111.63	90.89	70.76
Output power	$P_1=36.47$ $P_2=36.47$	$P_1=36.47$ $P_2=21.32$	$P_1=21.32$ $P_2=21.32$	$P_1=6.06$ $P_2=21.32$	$P_1=6.06$ $P_2=6.06$
Efficiency(%)	42.71	40.84	38.2	30.12	17.11

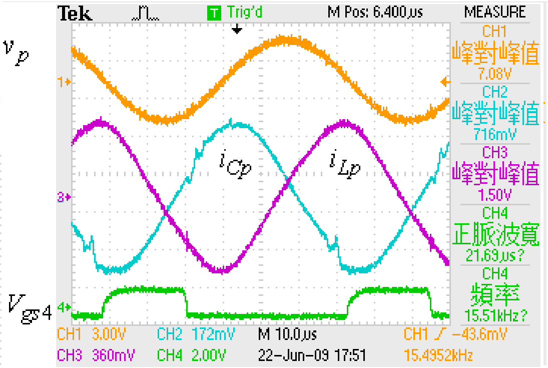


Experimental results –without regulator



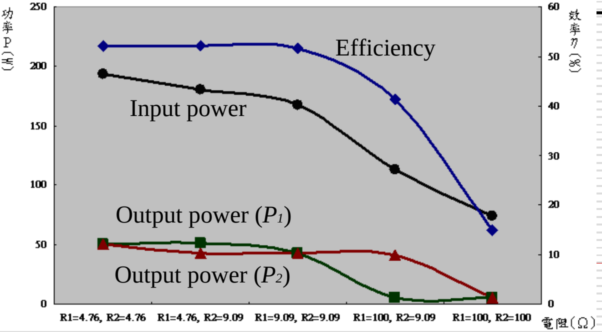
Experimental results –without regulator





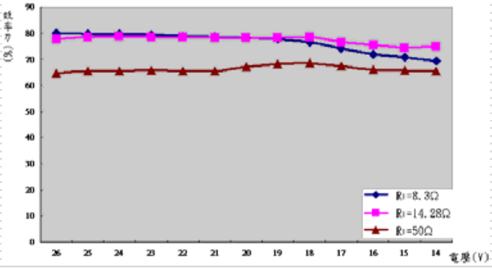
Without regulator

Load	$R_1 = 4.76\Omega$ $R_2 = 4.76\Omega$	$R_1 = 4.76\Omega$ $R_2 = 9.09\Omega$	$R_1 = 9.09\Omega$ $R_2 = 9.09\Omega$	$R_1 = 100\Omega$ $R_2 = 9.09\Omega$	$R_1 = 100\Omega$ $R_2 = 100\Omega$
Input power	193.37	180.56	167.14	112.85	73.81
Output power	$P_1 = 50.47$ $P_2 = 50.47$	$P_1 = 51.13$ $P_2 = 43.13$	$P_1 = 43.13$ $P_2 = 43.13$	$P_1 = 5.71$ $P_2 = 40.98$	$P_1 = 5.43$ $P_2 = 5.52$
Efficiency(%)	52.2	52.2	51.6	41.37	14.83

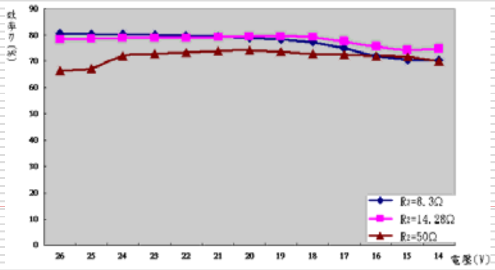


Converter efficiency

SEPIC(1)



SEPIC(2)

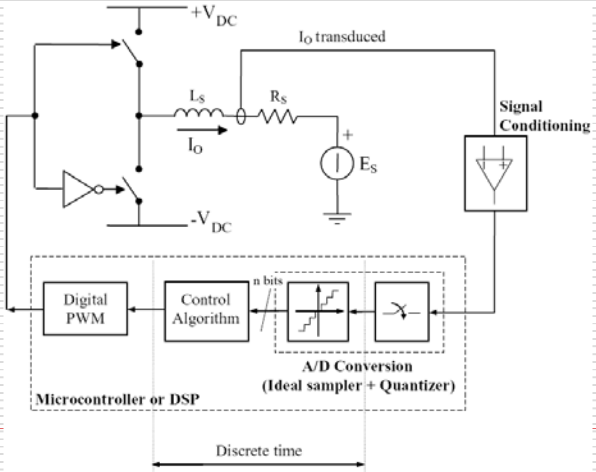


Conclusions

- Tracking the resonant frequency of coils connected with capacitors can improve the transmission efficiency.
- The system resonant voltage is regulated by a controller when the voltage is changed by the load.
- The overall efficiency is 42.71% in the case of the output current is 4.2A, output voltage is 17.4V, and air gap is 20mm, respectively.

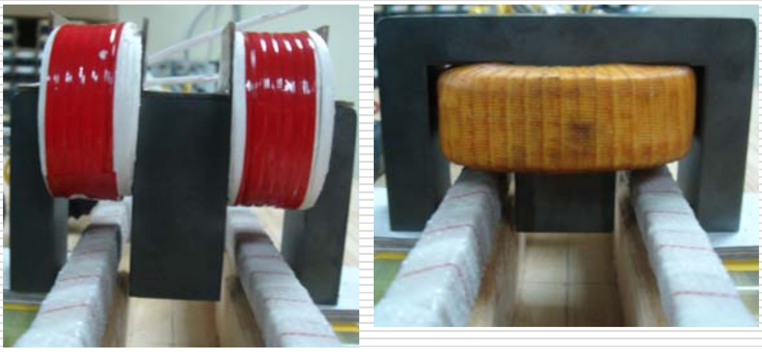
In further study

- Microcontroller



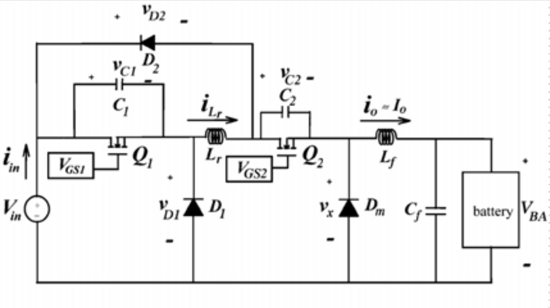
In further study

- ➢Different pickup

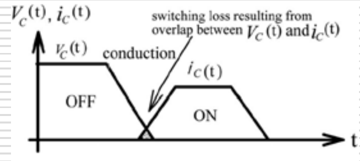


In further study

- ➢Employed soft switching



Developed charger with a ZVT soft-switching buck converter.



Switching losses in a soft-switching ZVT power switch.

Thanks for you attention !