2022 9th International Conference on Power Electronics Systems and Applications (PESA)

# Review and New Developments of Adaptive Tunning Technologies for Wireless Power Transfer


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Date： Sep 20, 2022

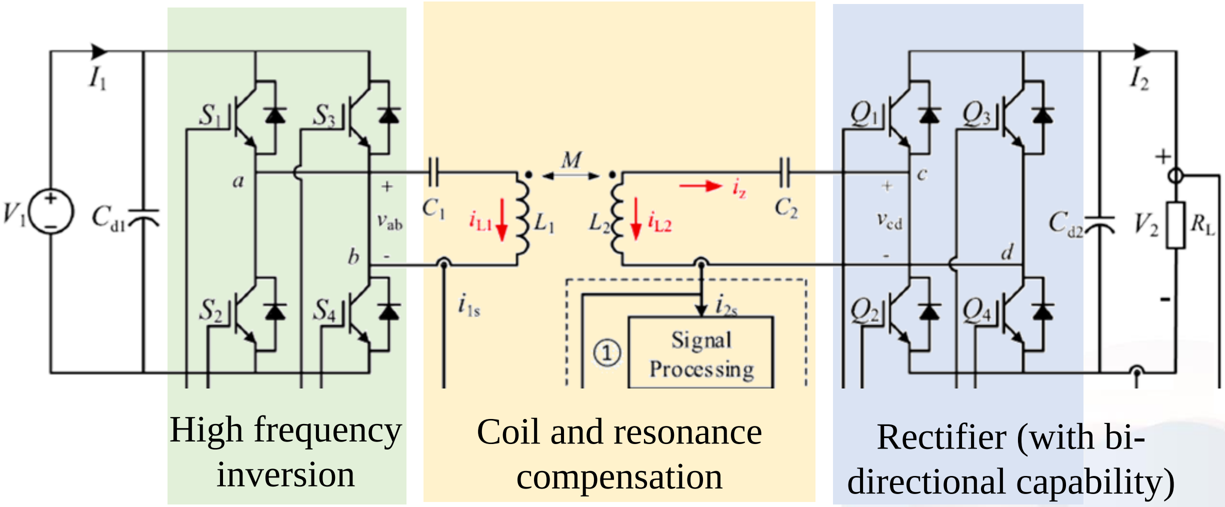
# Contents


Automated Guided Vehicle

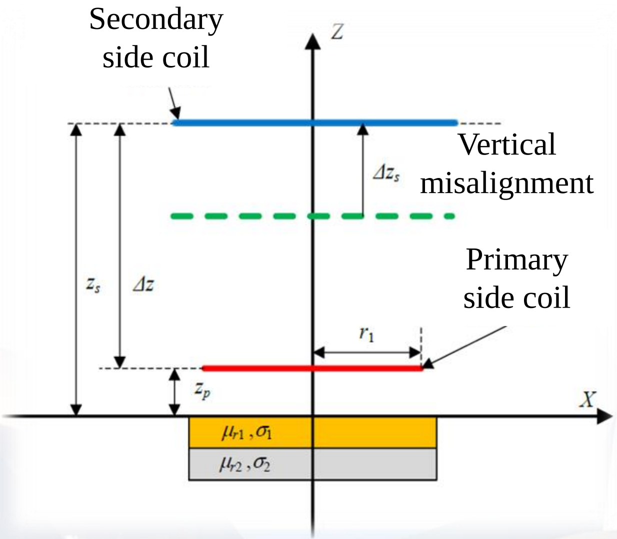
Unmanned Aerial Vehicle

Electric Vehicle

- Wireless Power Transfer (WPT) has the advantages of safe, reliable, convenient and flexible, and has been widely used in many fields.
- When the circuit operates in resonant state, the system has higher output power and higher power transmission efficiency.




A typical S-S resonance compensation based wireless power transfer diagram




Coil misalignment

- The relative position variation of the coupling coil and the equivalent impedance of the load will cause the offset of the resonant parameters such as the coil self-inductance, mutual inductance and coupling coefficient, which will lead to system detuning.

- The adaptive tuning technology solve the detuning problem by re-matching the resonance parameters so that the system can always work in the resonant state, ensuring the high efficiency and high-power transmission of the system.

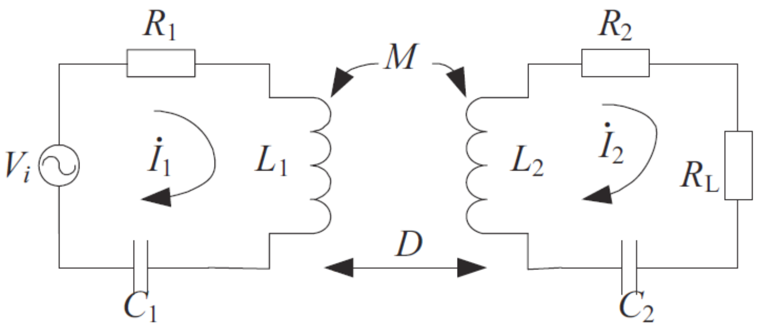
**Adaptive Tuning Technology**

- **Frequency tracking**
- **Dynamic compensation**
- Algorithmic control
- Hybrid control
- Additional coil measurement
- Coil structure changing

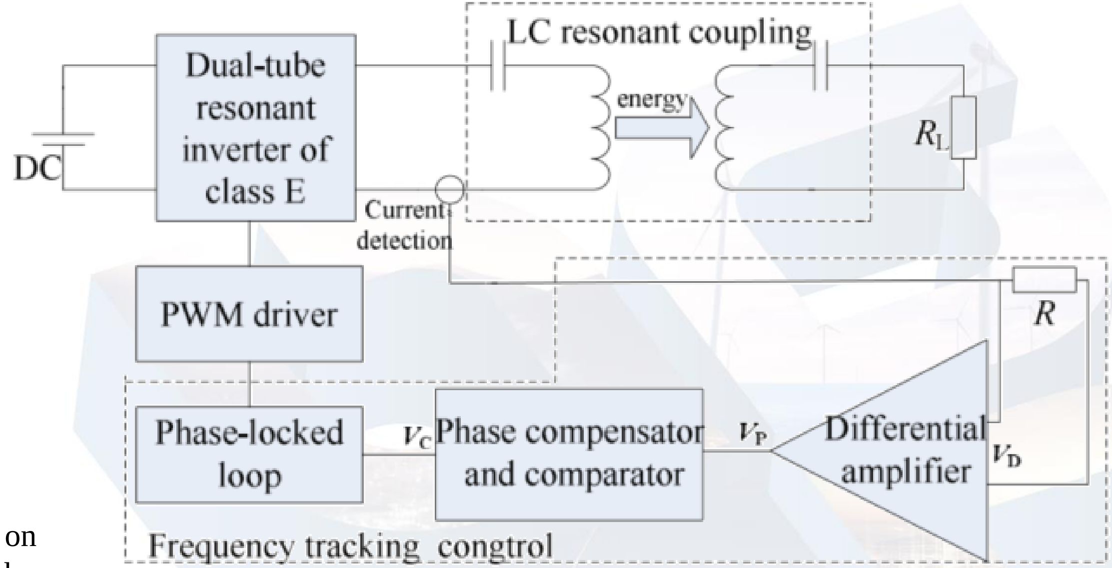

- Zhang Xin, Li Fangzhou, Li Chunzhi, et.al. Research Progress of Frequency Control Technology for Magnetically Coupled Wireless Power Transfer. Science Technology and Engineering, 2022, 22(09): 3416-3424.
- Jia Jinliang, Yan Xiaoqiang. Research Tends of Magnetic Coupling Resonant Wireless Power Transfer Characteristics. Transactions of China Electrotechnical Society, 2020, 35(20): 4217-4231.

# Contents

## 2.1 Frequency tracking based on phase-locked loop 74HC4046




Model of resonant coupling circuit

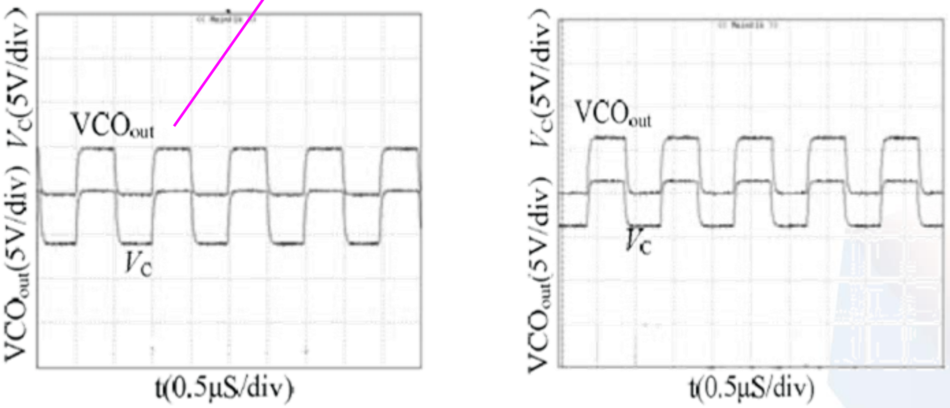



System principle diagram of frequency tracking

* Fu Wenzhen, Zhang Bo, Qiu Dongyuan. Study on frequency-tracking wireless power transfer system by resonant coupling. Power Electronics and Motion Control Conference. 2009: 2658-2663.

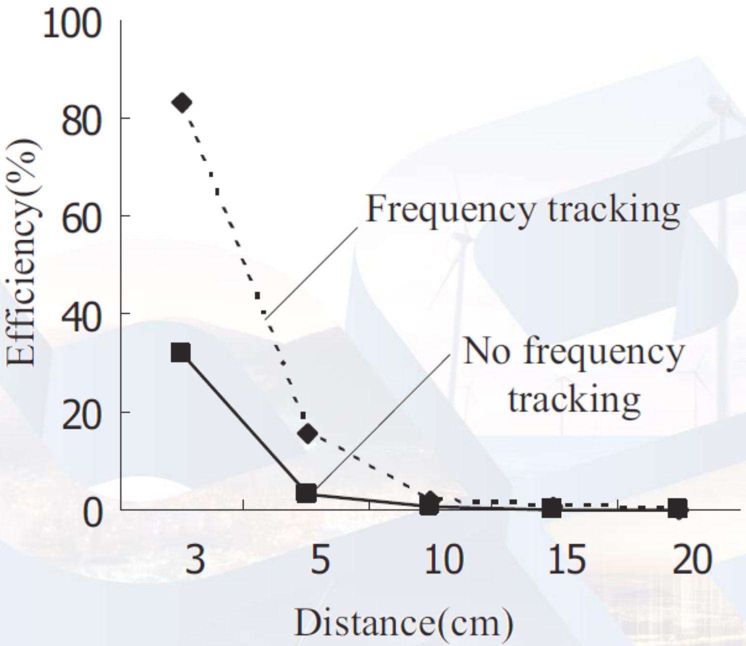
## 2.1 Frequency tracking based on phase-locked loop 74HC4046

phase-locked loop output $V_{CO_{out}}$




(a) f=0.993MHz (b) f=1.001MHz

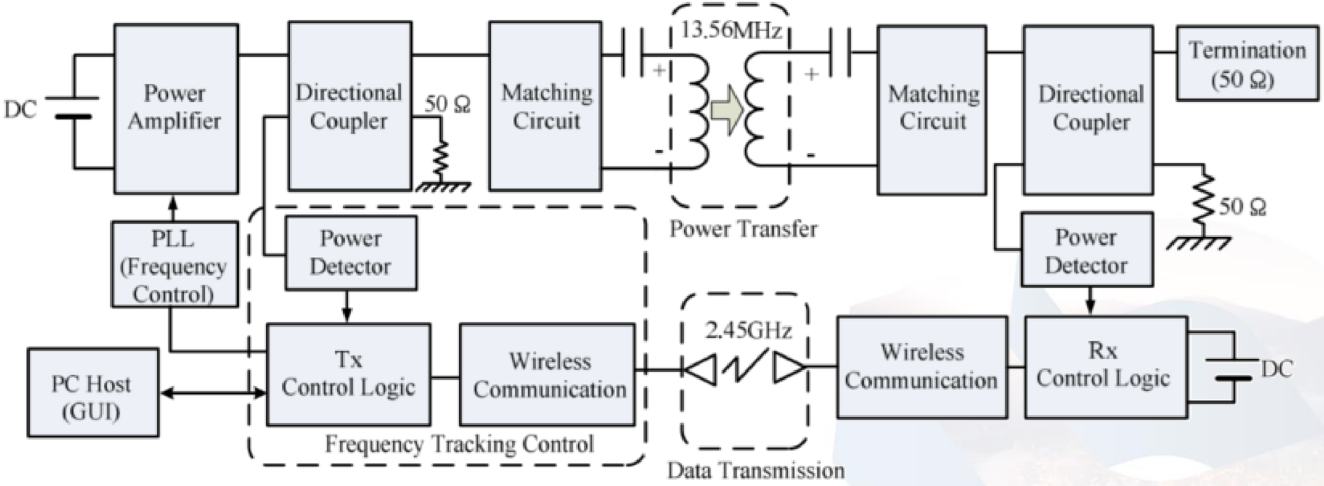
Effects of frequency-tracking at different frequencies

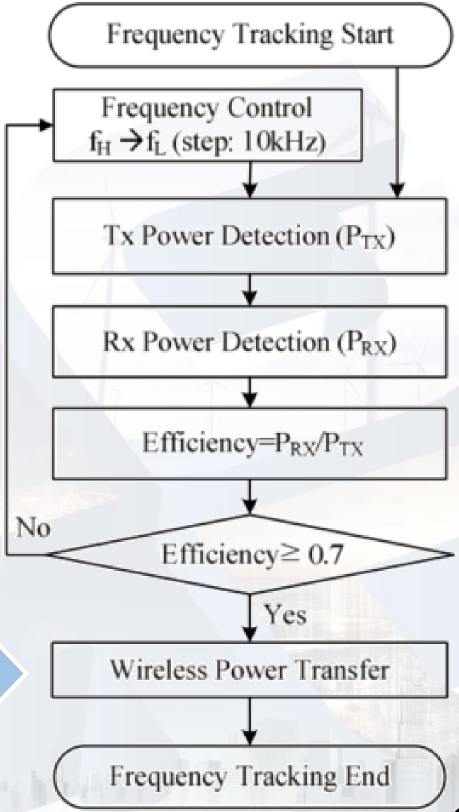



Efficiency comparison in different coil distance

* Fu Wenzhen, Zhang Bo, Qiu Dongyuan. Study on frequency-tracking wireless power transfer system by resonant coupling. Power Electronics and Motion Control Conference. 2009: 2658-2663.

## 2.2 Adaptive frequency tracking based on wireless communication



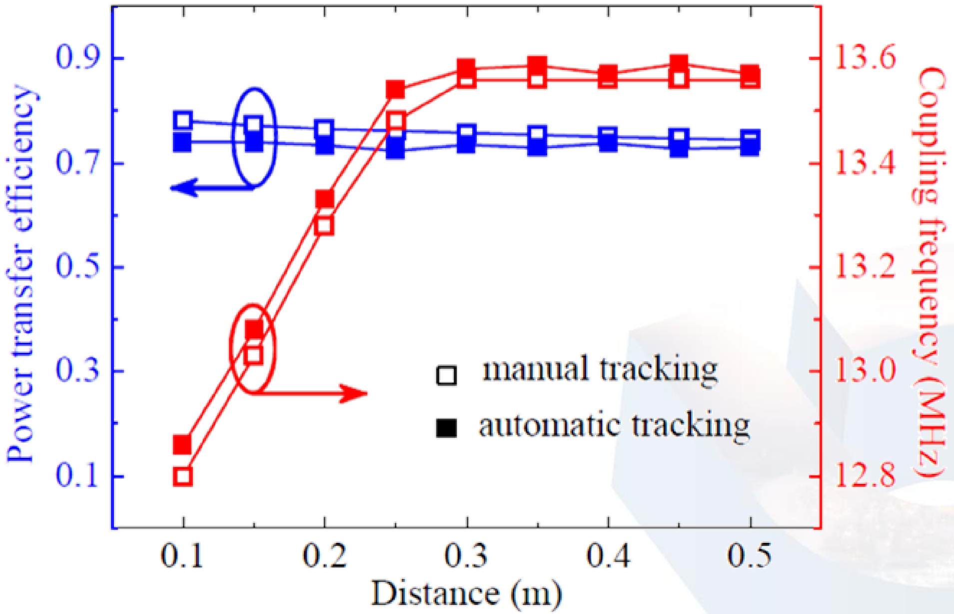




The featured schematic with wireless communication systems

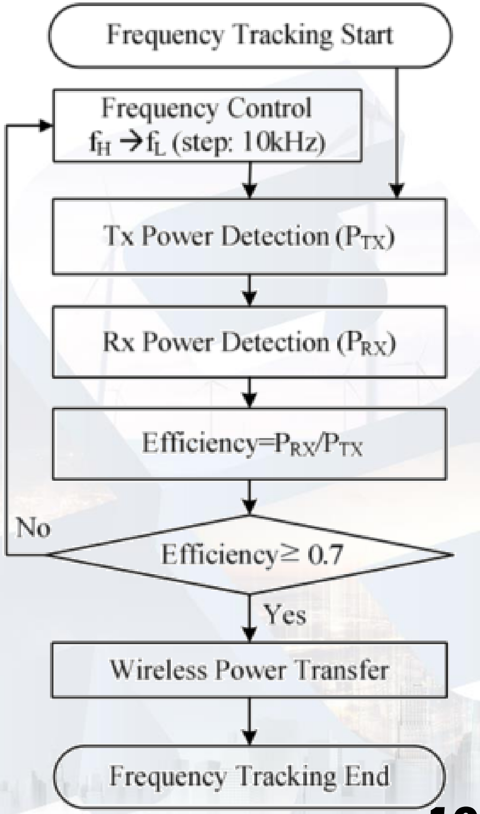
Flowchart of frequency tracking control algorithm

* Nam Yoon Kim K Y K Y, Yun-Kwon Park S K. Automated adaptive frequency tracking system for efficient mid-range wireless power transfer via magnetic resonant coupling. Proceedings of the 42nd European Microwave Conference, Amsterdam, Netherlands, 2012: 221-224.

## 2.2 Adaptive frequency tracking based on wireless communication

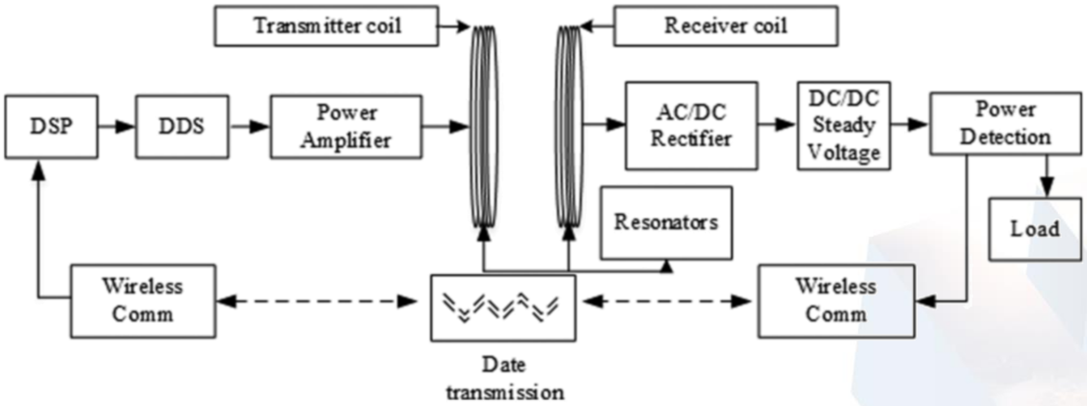



Measurement results of power transfer efficiency with automatically tracked resonant coupling frequency




* Nam Yoon Kim K Y K Y, Yun-Kwon Park S K. Automated adaptive frequency tracking system for efficient mid-range wireless power transfer via magnetic resonant coupling. Proceedings of the 42nd European Microwave Conference, Amsterdam, Netherlands, 2012: 221-224.

# 2.3 Based on Improved Ant Colony Algorithm (IACA)



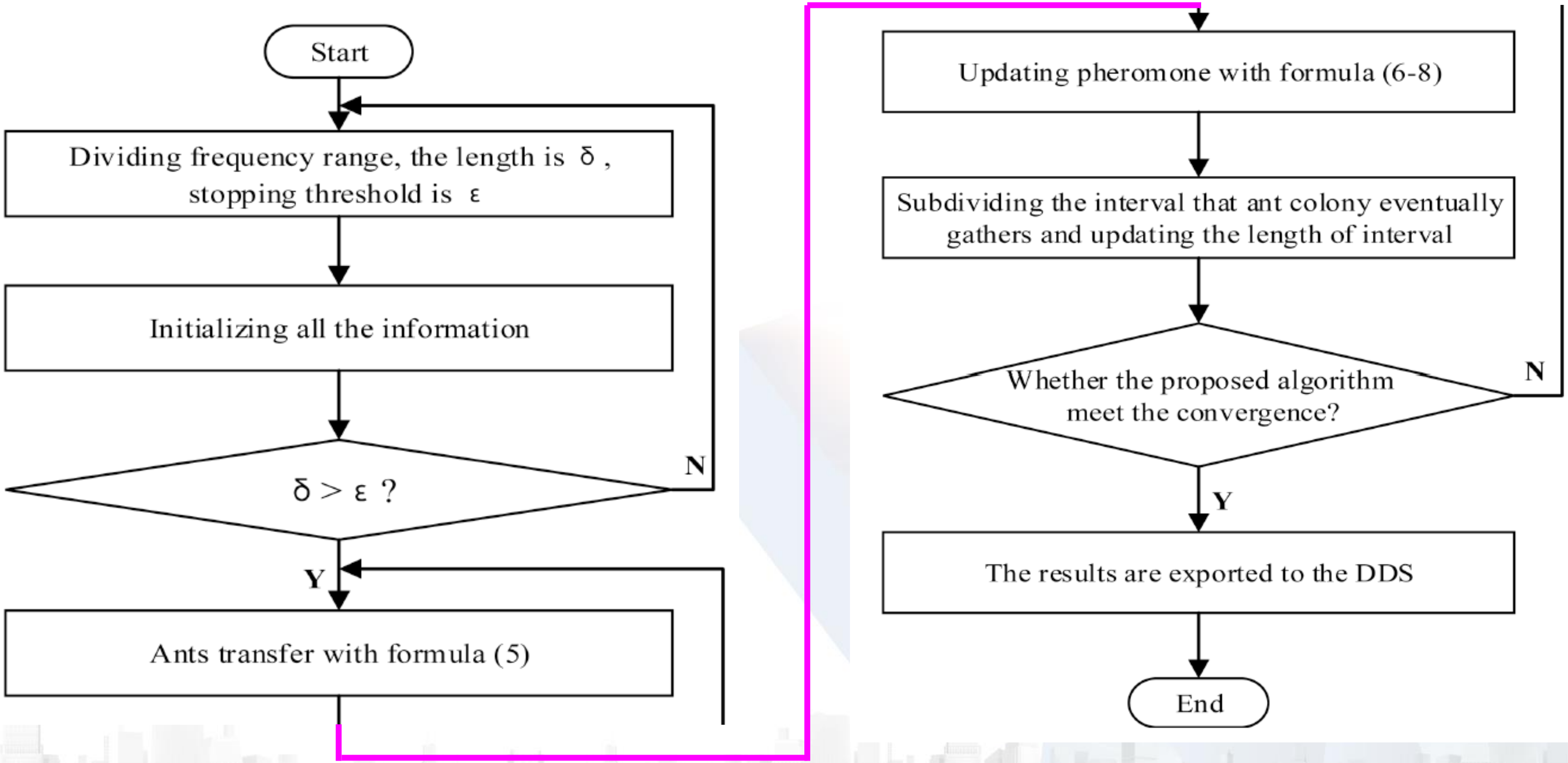

AFT WPT System


Frequency tracking experimental prototype

An improved ant colony algorithm (IACA) was proposed in AFTC to track the maximum power point in real time.

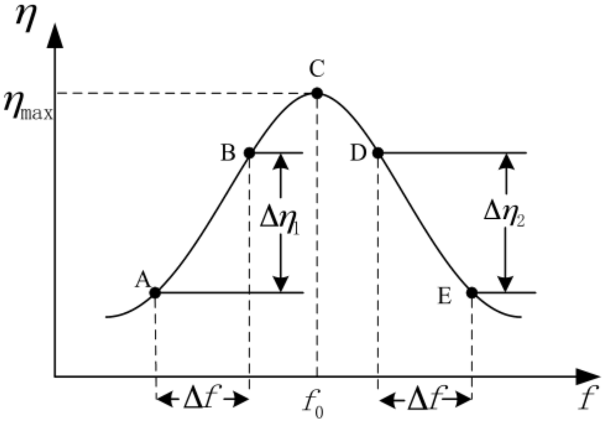
* Li Yang, Zhang Cheng, Yang Qingxin, et al. Improved ant colony algorithm for adaptive frequency-tracking control in WPT system. IET Microwaves, Antennas& Propagation, 2017, 12(1): 23-28.

# 2.3 Based on Improved Ant Colony Algorithm (IACA)

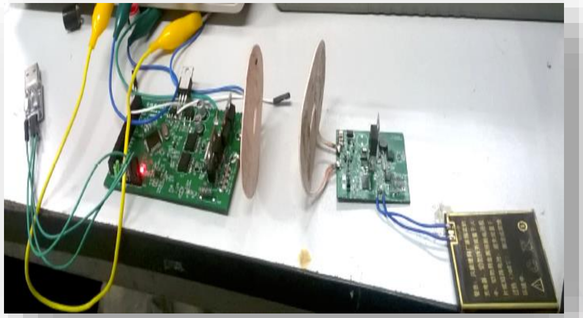


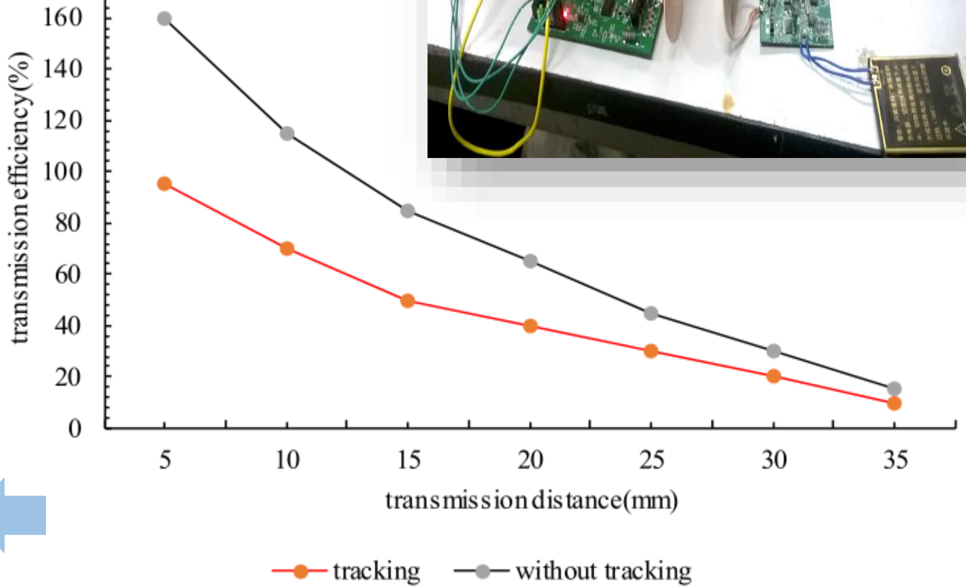

* Li Yang, Zhang Cheng, Yang Qingxin, et al. Improved ant colony algorithm for adaptive frequency-tracking control in WPT system. IET Microwaves, Antennas& Propagation, 2017, 12(1): 23-28.

## 2.4 Based on hill-climbing algorithm




Schematic of the climbing algorithm



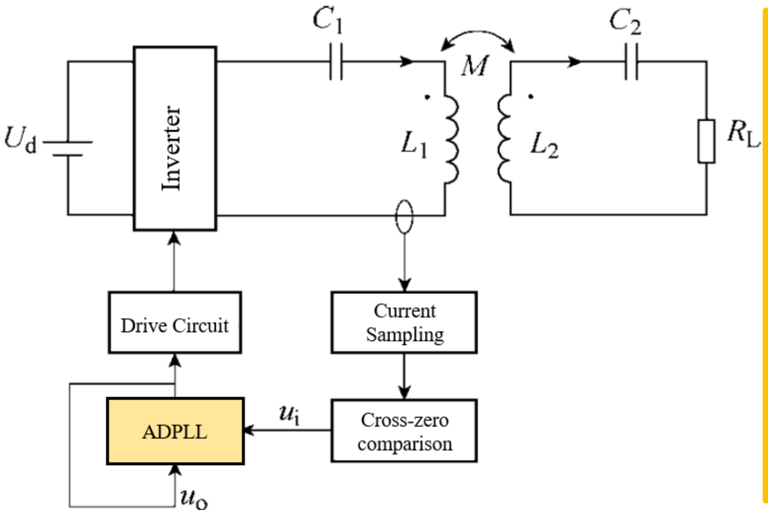



Transfer efficiency curve with and without tracking

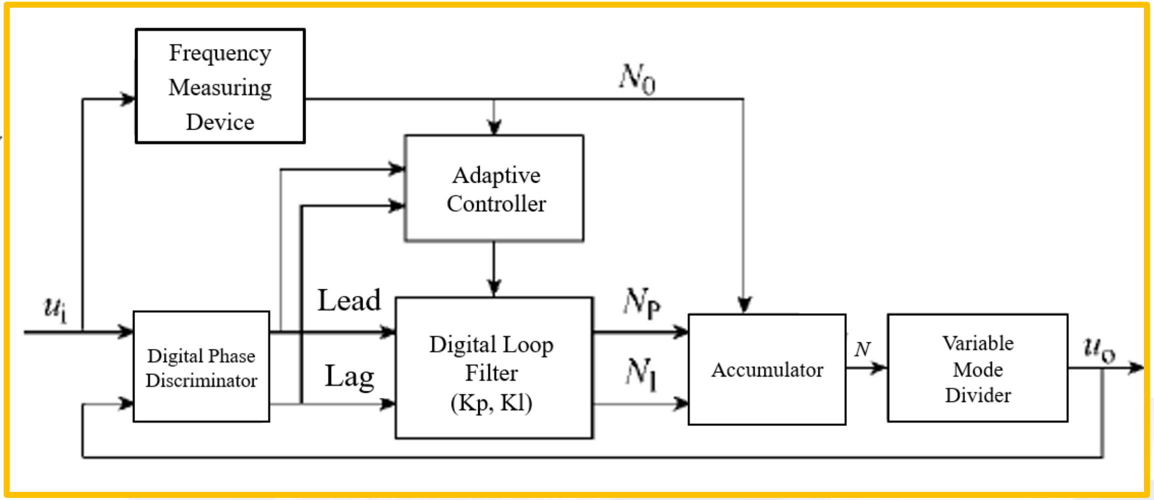
System transmission efficiency
When S = 10mm, 45.3% to 70.0%
When S = 20mm, 21.8% to 38.4%
When S = 30mm, 7.50% to 19.1%

* Li B, Xiang G, Chen L, et al. Detuning Mechanism and Frequency Tracking Algorithm for Wireless Power Transmission System. Journal of Engineering Science and Technology Review, 2017, 10(4): 100-108.

## 2.5 Based on adaptive PI control for variable mode all digital PLL




Structure of frequency tracking control system

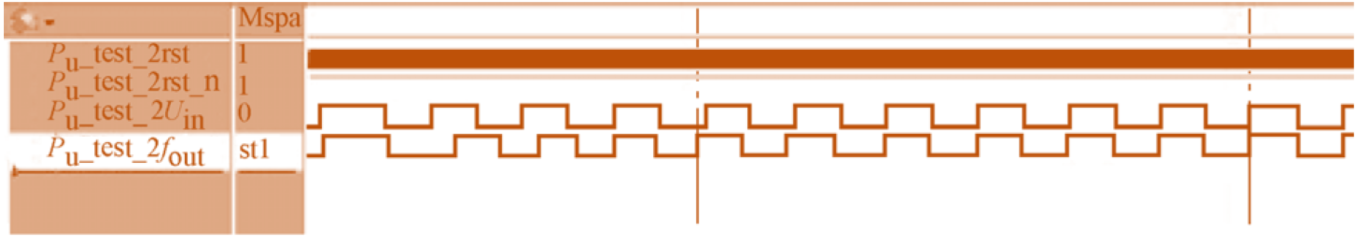



ADPLL Structure

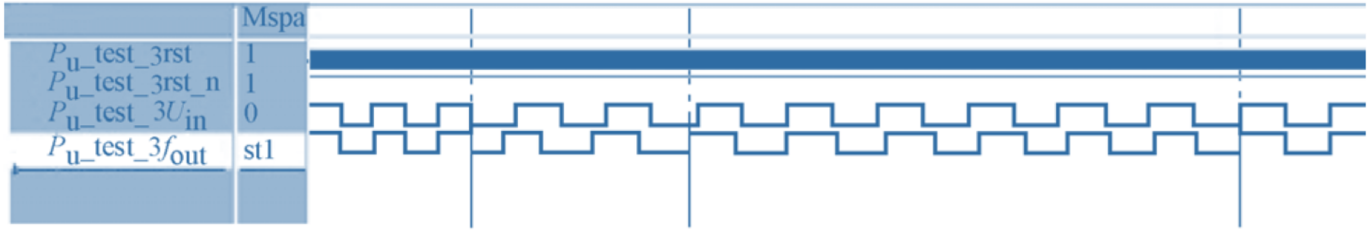
* Liu Guojin, Li Yixin, Cui Yulong, et al. Frequency tracking control of wireless power transfer via magnetic resonance coupling based on FPGA. Transactions of China Electrotechnical Society, 2018, 33(14): 3185-3193.

## 2.5 Based on adaptive PI control for variable mode all digital PLL

125 → 180 kHz



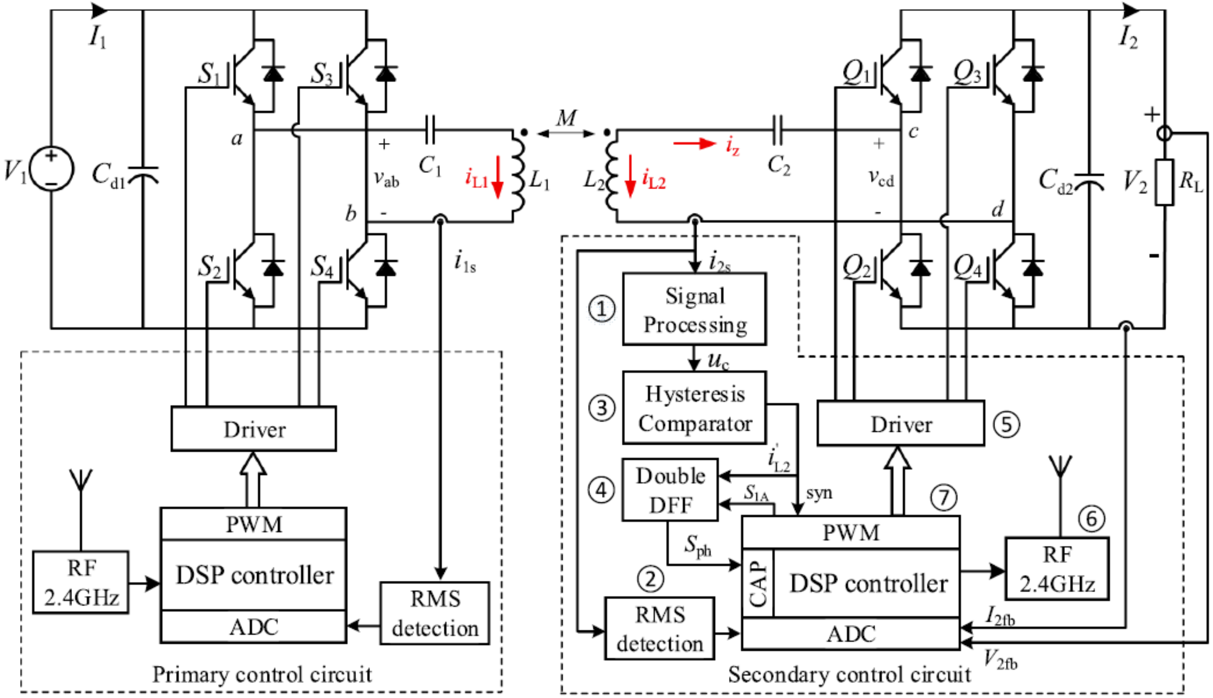

125 → 90 kHz

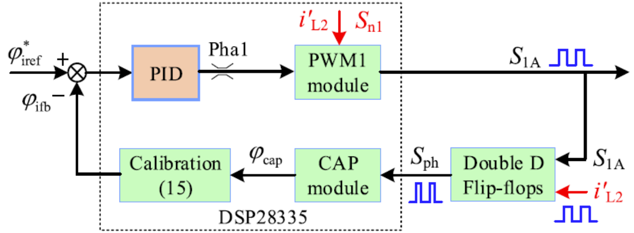



Frequency tracking process in experiments

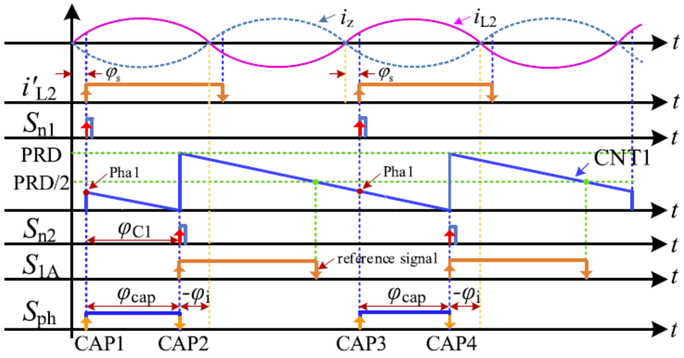
* Liu Guojin, Li Yixin, Cui Yulong, et al. Frequency tracking control of wireless power transfer via magnetic resonance coupling based on FPGA. Transactions of China Electrotechnical Society, 2018, 33(14): 3185-3193.

# 2.6 PLL combined with the chained trigger mode (PLL-CTM)




PLL control diagram

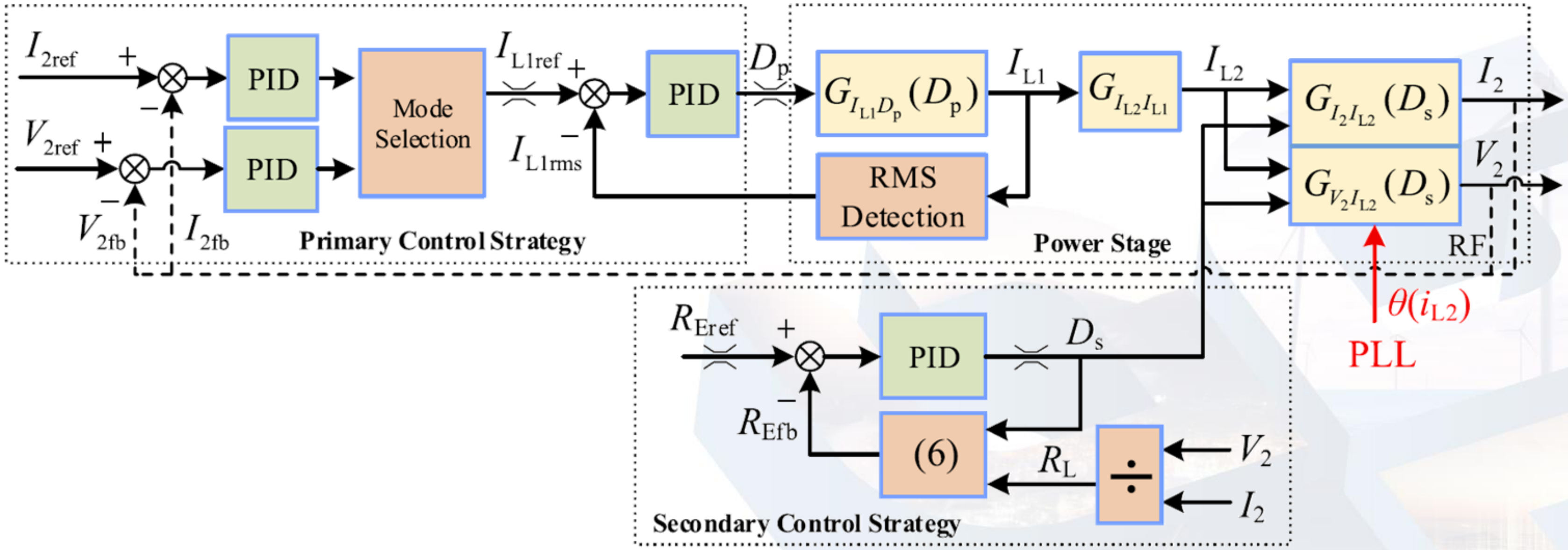



Overall structure

Operating principle

* Jiang Y, Wang L, Wang Y, et al. Phase-Locked Loop Combined With Chained Trigger Mode Used for Impedance Matching in Wireless High Power Transfer. IEEE Transactions on Power Electronics, 2020,35(4):4274-4285

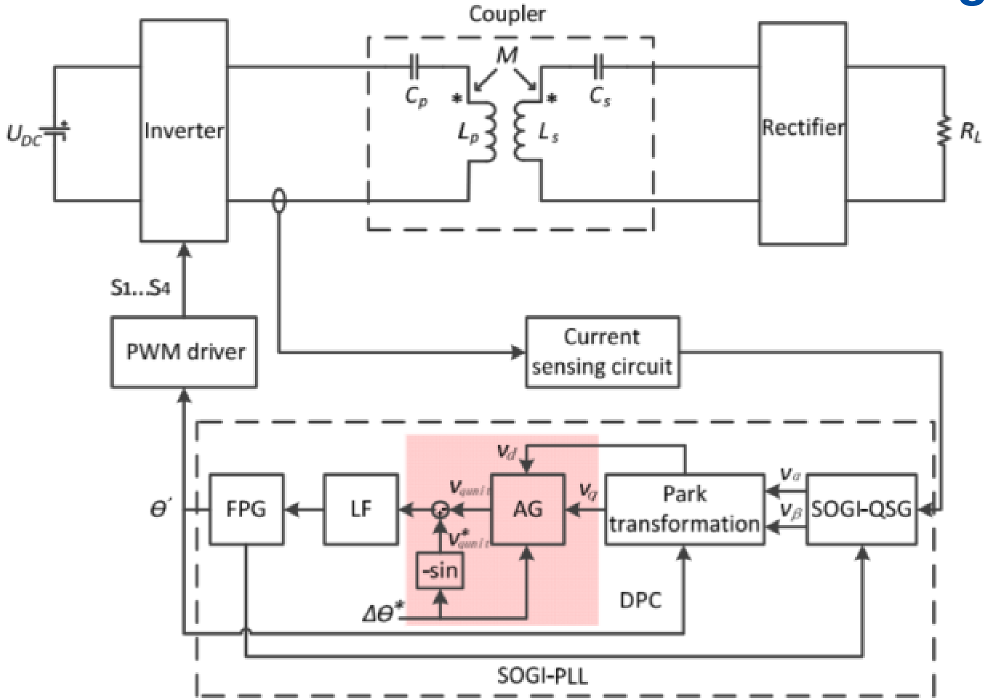
# 2.6 PLL combined with the chained trigger mode (PLL-CTM)




Control diagram of the WPTS

* Jiang Y, Wang L, Wang Y, et al. Phase-Locked Loop Combined With Chained Trigger Mode Used for Impedance Matching in Wireless High Power Transfer. IEEE Transactions on Power Electronics, 2020,35(4):4274-4285

# 2.7 Second-Order Generalized Integrator PPL



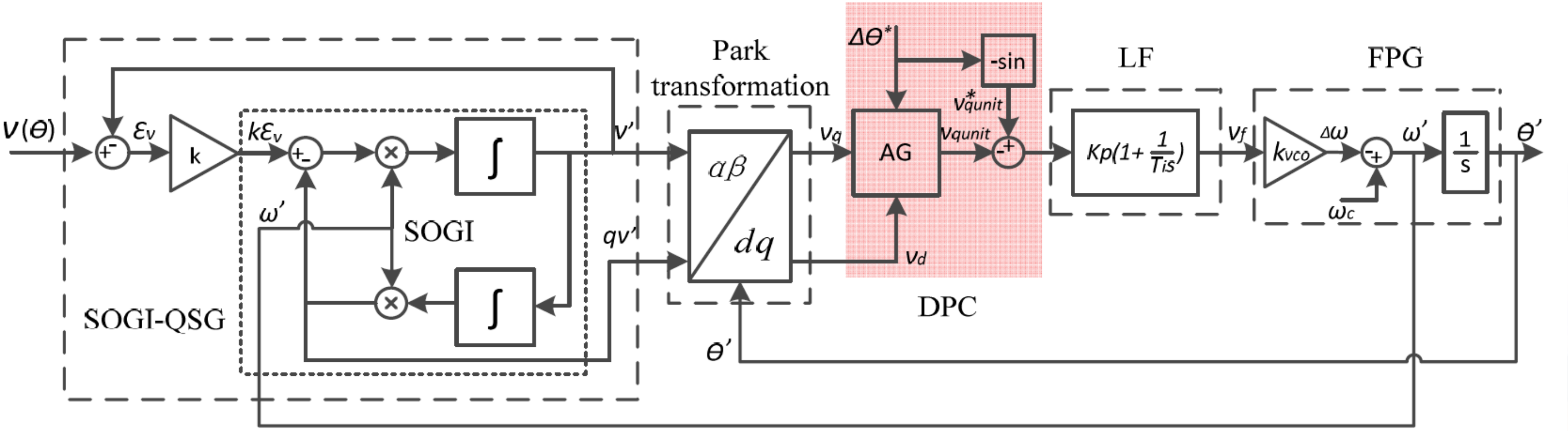

Schematic diagram of frequency-tracking

Second-Order Generalized Integrator Phase-Locked Loop (SOGI-PLL)

Direct Phase Control (DPC)

* Tan P, He H, Gao X, et al. A Frequency-Tracking Method Based on a SOGI-PLL for Wireless Power Transfer Systems to Assure Operation in the Resonant State. Journal of Power Electronics, 2016, 16(3): 1056-1066

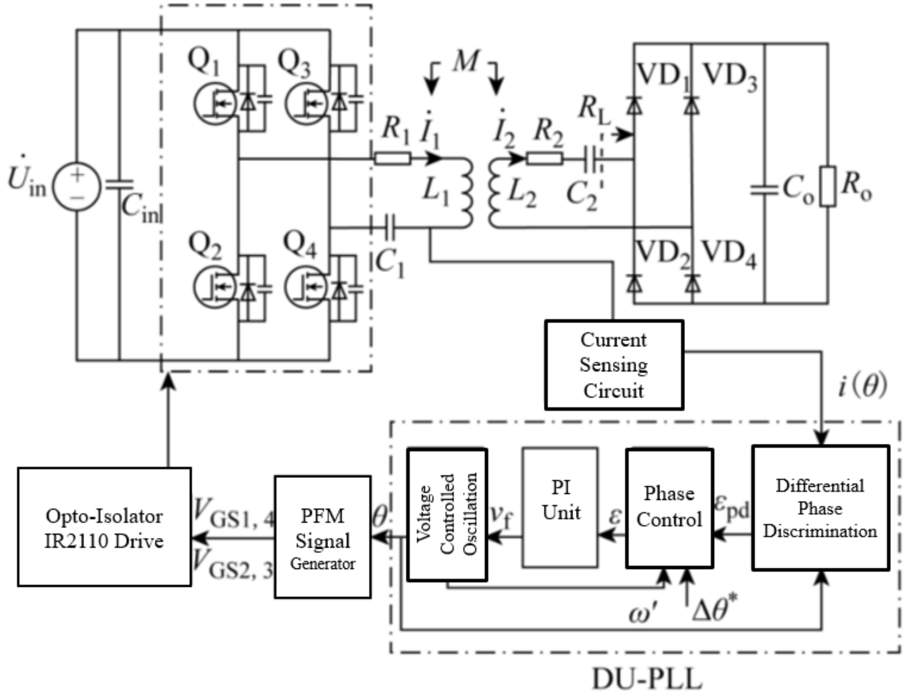
## 2.7 Second-Order Generalized Integrator PPL

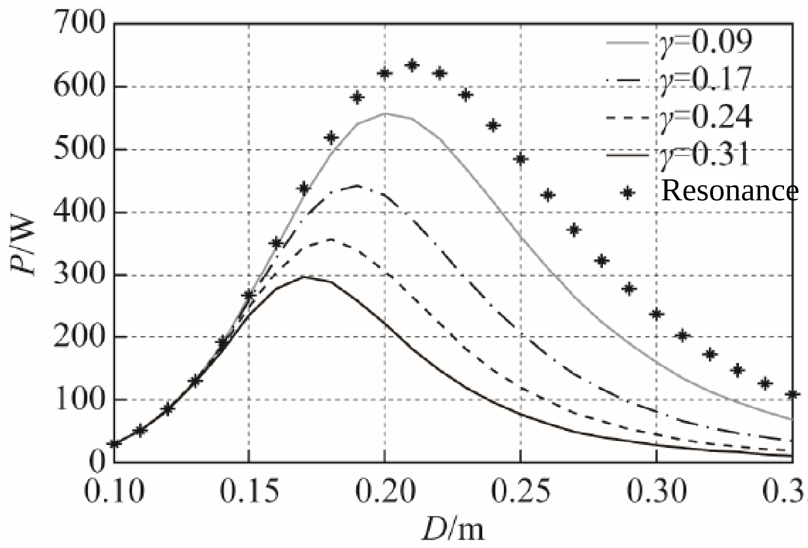



Five parts: the Second-Order Generalized Integrator Quadrature Signal Generator (SOGI-QSG), the Park transformation, the DPC, the Low-pass Filter (LF), and the Frequency/Phase-Angle Generator (FPG).

* Tan P, He H, Gao X, et al. A Frequency-Tracking Method Based on a SOGI-PLL for Wireless Power Transfer Systems to Assure Operation in the Resonant State. Journal of Power Electronics, 2016, 16(3): 1056-1066

## 2.8 Frequency Tracking Detuning Control of Magnetic Resonant WPT



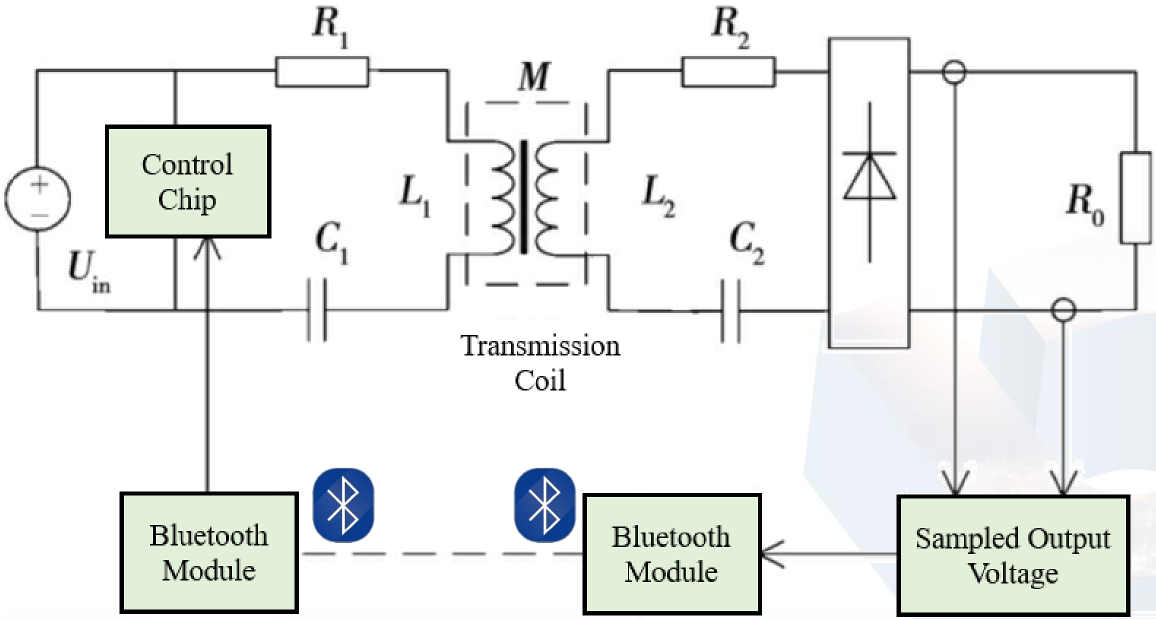




Frequency tracking detuning control strategy

Detuning coefficient, distance and power

* Huang Cheng, Lu Yimin. Frequency Tracking Detuning Control of Magnetic Resonant Wireless Power Transfer System. Transactions Of China Electrotechnical Society, 2019, 34(15): 3102-3111.

# 2.9 Frequency tracking based on maximum received voltage

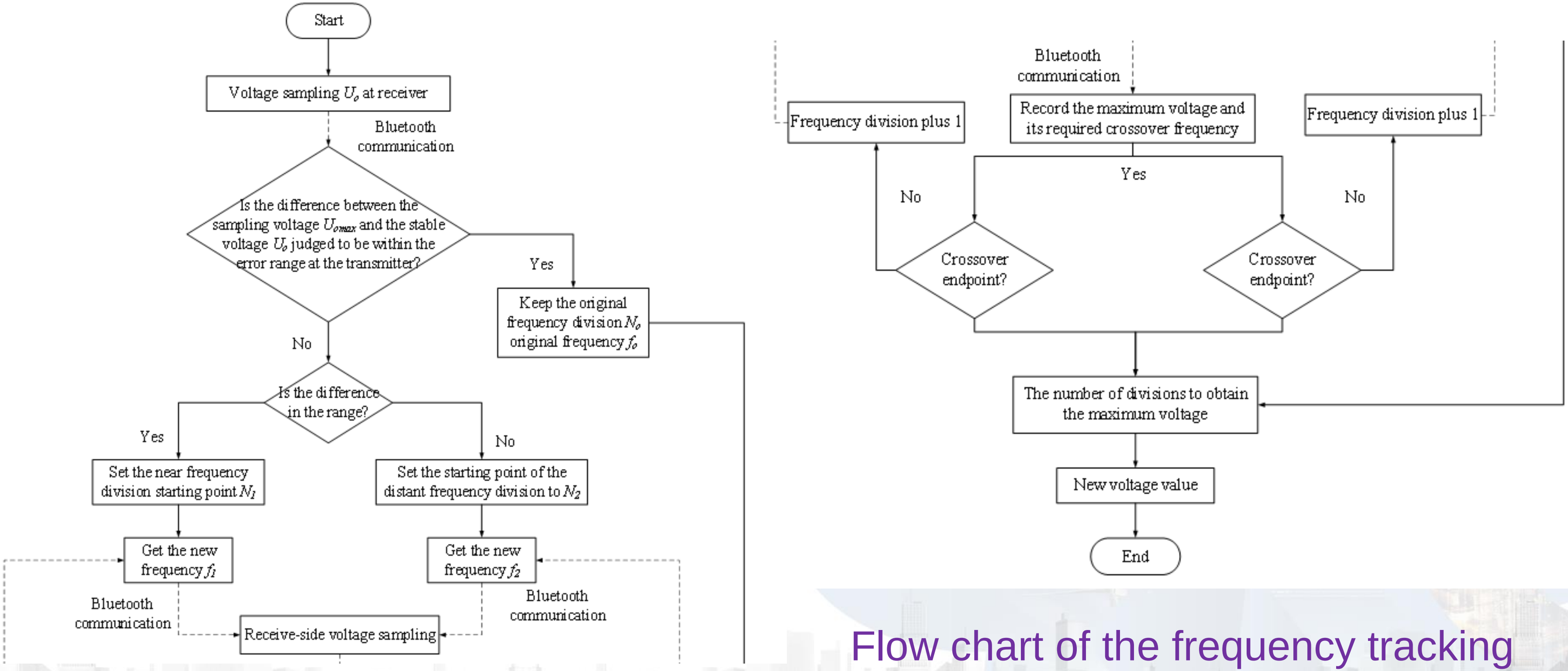



A frequency tracking and up-dating methodology based on the maximum received voltage was proposed.

Block diagram of the frequency tracking system control

* Zhao Yu, Yang Shiyou. Frequency tracking and controlling of wireless power transfer system. Electric Machines and Control, 2020, 24(9): 22-29.

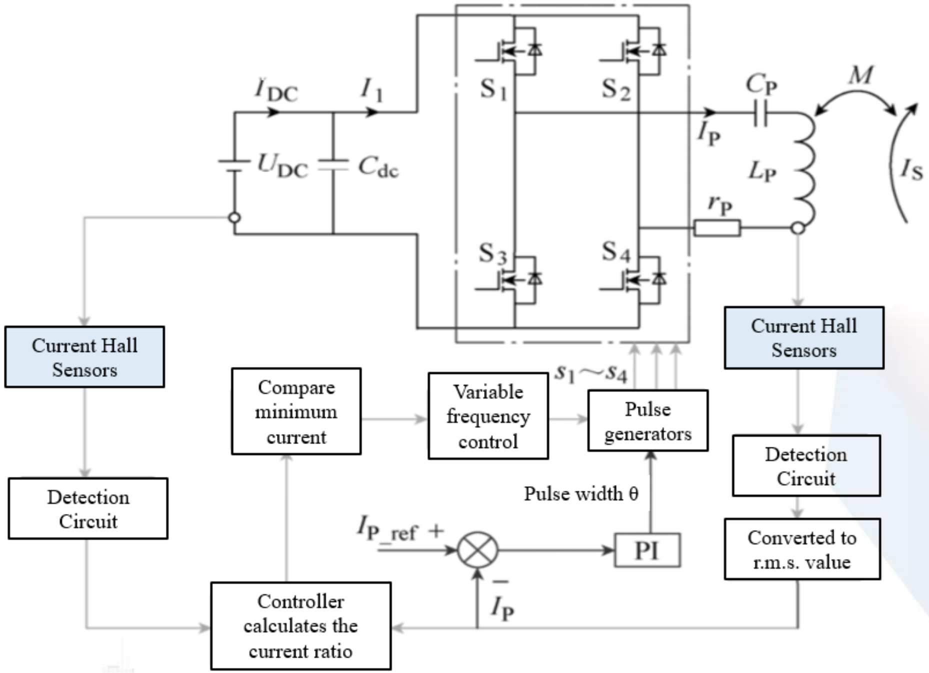
## 2.9 Frequency tracking based on maximum received voltage



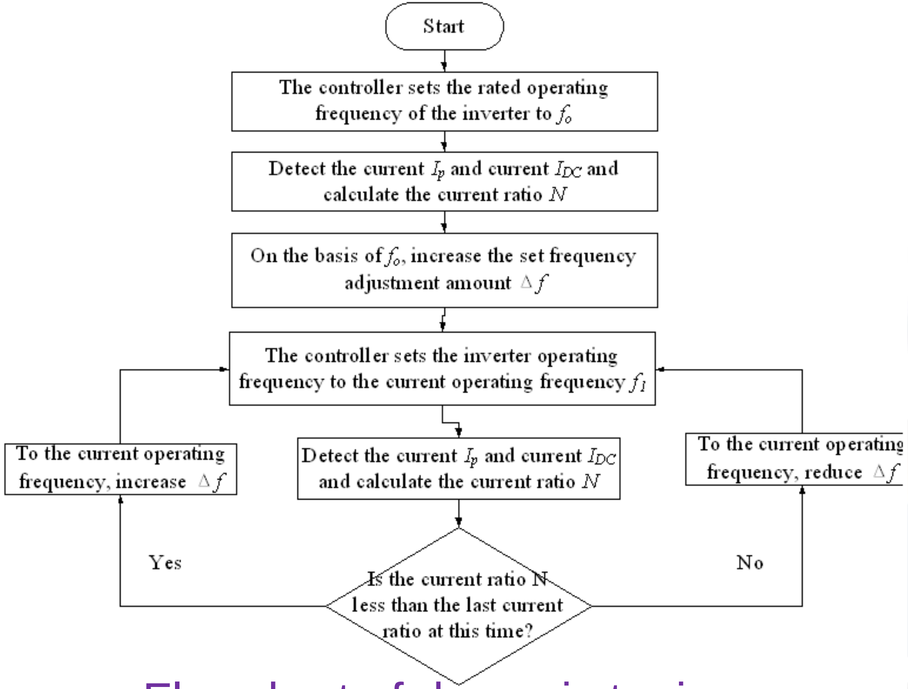

Flow chart of the frequency tracking

* Zhao Yu, Yang Shiyou. Frequency tracking and controlling of wireless power transfer system. Electric Machines and Control, 2020, 24(9): 22-29.

## 2.10 Frequency tracking based on minimum current ratio




Frequency tracking strategy

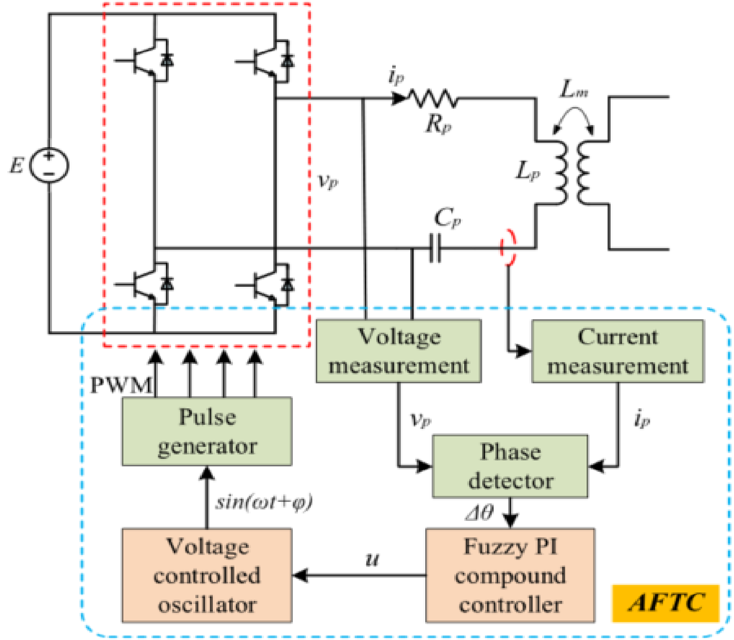



Flowchart of dynamic tuning

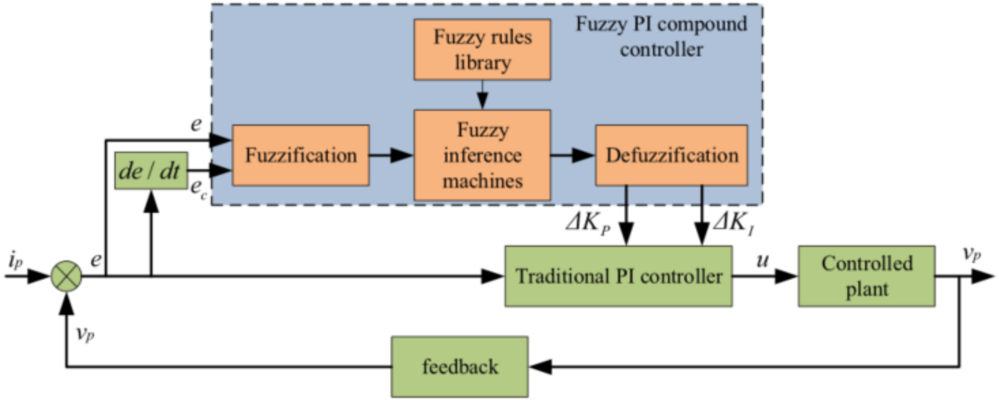
* Mai Ruikun Xu Danlu Yang Mingkai He, et al. Dynamic Tuning Method of Frequency Tracking Based on the Minimum Current Ratio for IPT System. Transactions Of China Electrotechnical Society, 2018, 33(6): 1276-1284.

# 2.11 Based on Fuzzy PI Compound Controller

- Adaptive Frequency Tracking Control (AFTC) with Fuzzy PI Compound Controller




Block diagram of the MCR-WPT with AFTC system




Block diagram of the fuzzy PI compound controller

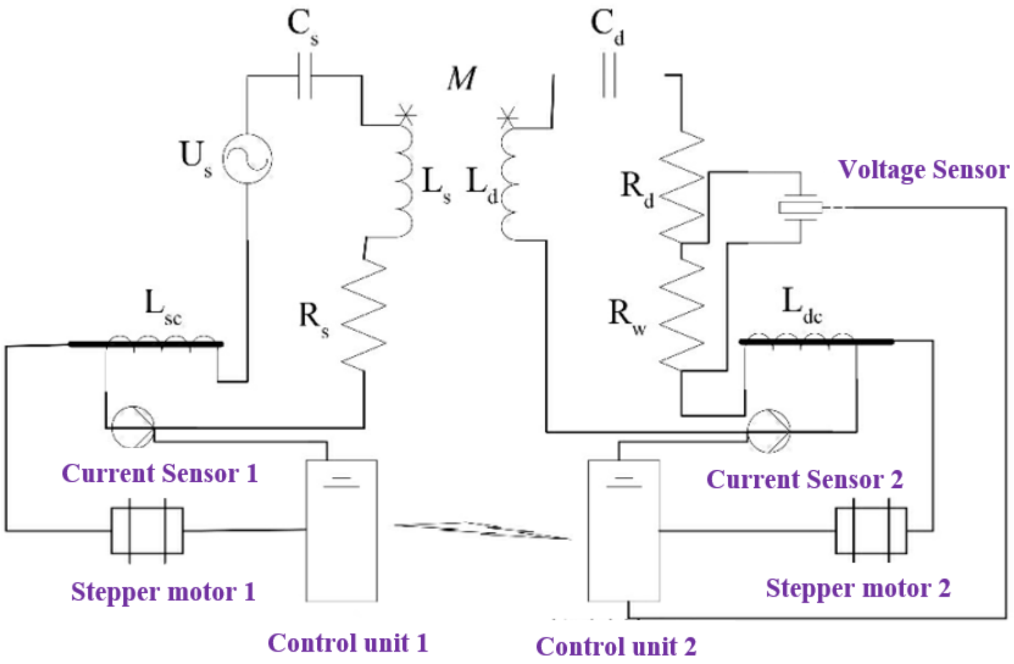
* Zheng Z, Wang N, Ahmed S. Adaptive Frequency Tracking Control with Fuzzy PI Compound Controller for Magnetically Coupled Resonant Wireless Power Transfer. International Journal of Fuzzy System, 2020(1): 1890-1903.

# Summary of frequency tracking technology

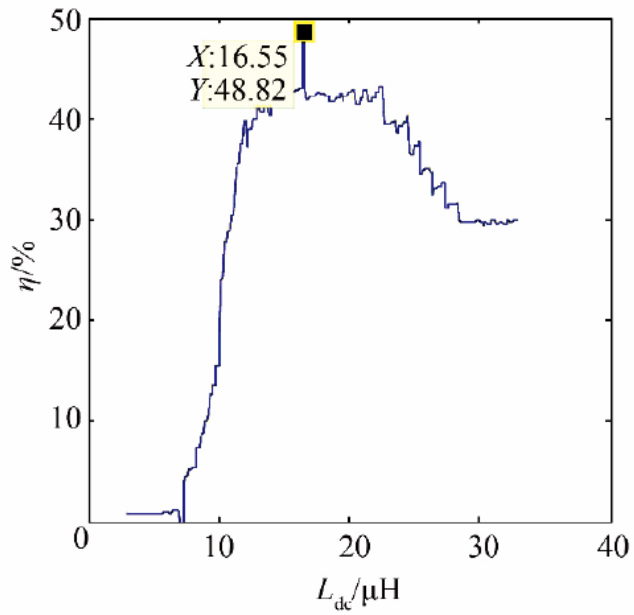
| | | |
|---|---|---|
| Minimum Current Ratio | All Digital Phase Lock Loop | Improved Ant Colony Algorithm |
| Maximum Received Voltage | Differential Phase Lock Loop | Hill Climbing Algorithm |
| Minimum Sampled Efficiency | Second-Order Generalized Integrator Phase Lock Loop | Fuzzy PI Control |

# Contents

# 3.1 Based on variable inductor



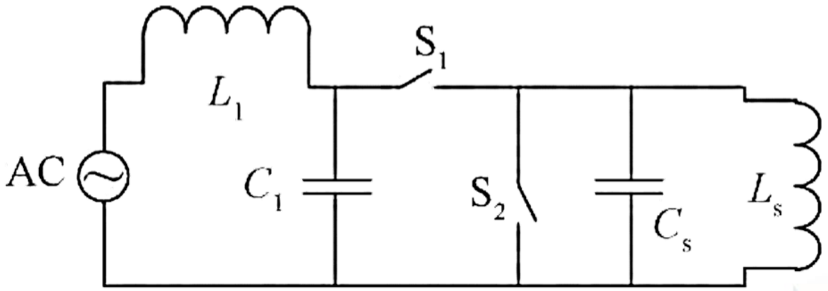

Tuning circuit diagram



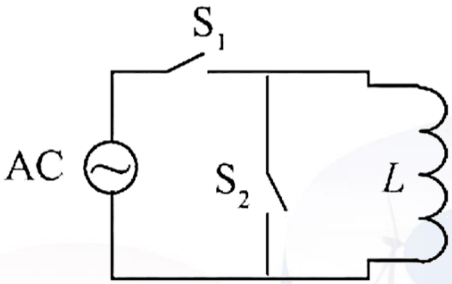

Efficiency vs the inductance

* Wang Yunhe, Liu Jiangtao, Deng Qijun, et al. Optimal design of wireless energy transmission system based on adjustable inductance. Wuhan University Journal: Engineering, 2018, 51(1): 85-90.

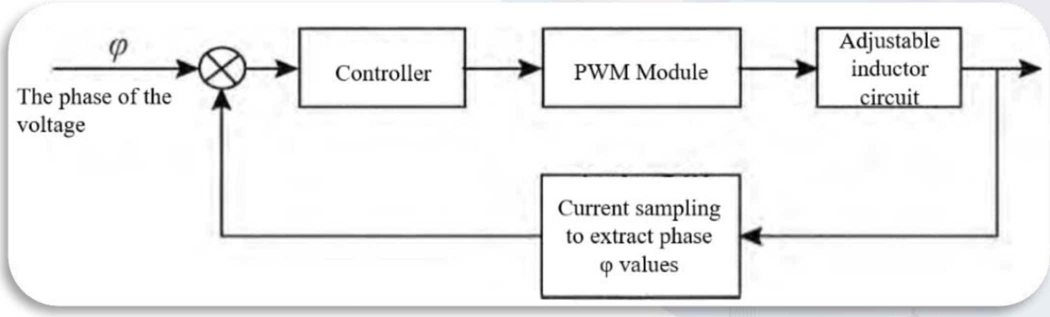
## 3.2 Variable inductor with PWM




Schematic diagram of an adjustable reactor based on PWM control



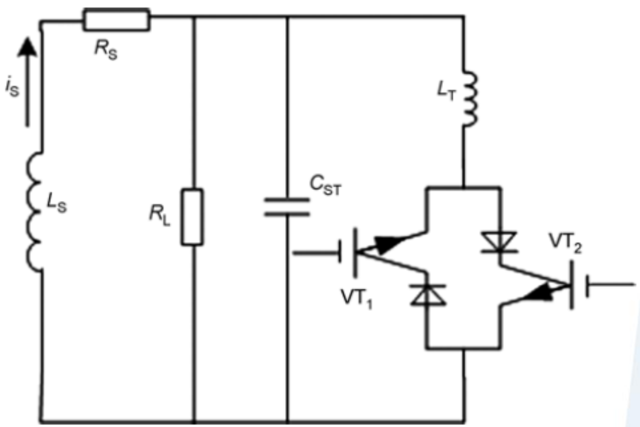

Equivalent circuit



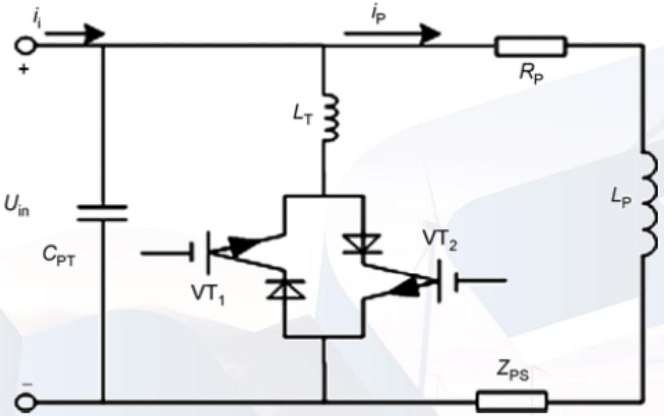

Adjustable choke control block diagram

* Yang Xu, You Linru, Wen Xiaoqin, et al. Resonant wireless charging technology based on pulse-width modulation controlled adjustable inductance compensation. Science Technology and Engineering, 2018, 18(3 ): 259-263.

## 3.3 Based on phase-controller inductor




Dynamic tuning secondary circuit of SP topology

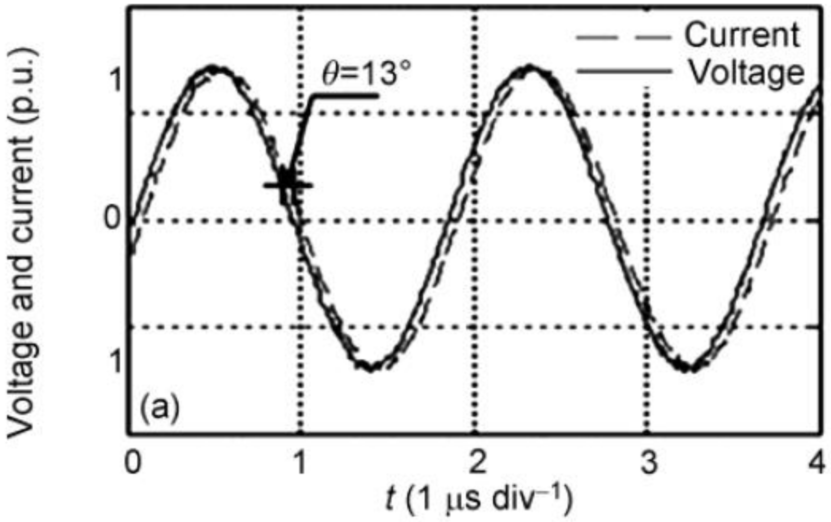



Dynamic tuning secondary circuit of PS or PP topology

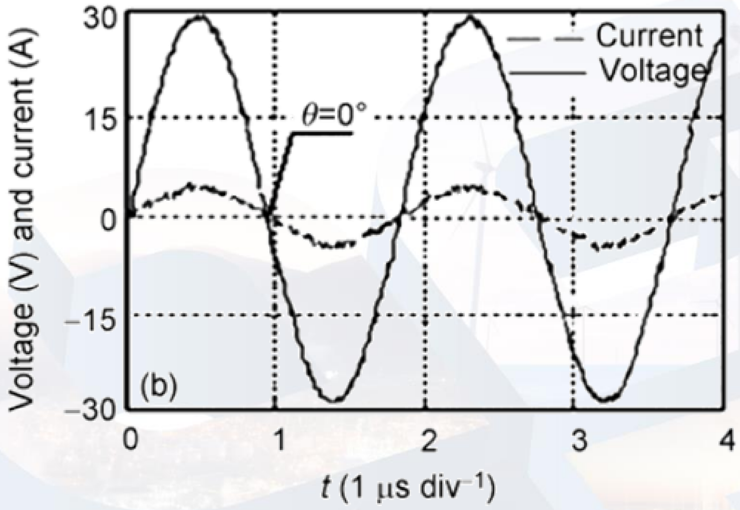
A phase controlled inductor circuit is proposed. By adjusting the triggering angle, the real-time dynamic tuning control can be achieved to guarantee maximum power transfer.

* Qiang H, Huang X, Tan L, et al. Achieving maximum power transfer of inductively coupled wireless power transfer system based on dynamic tuning control. Science China-Technological Sciences, 2012, 55(7):1886-1893.

# 3.3 Based on phase-controller inductor



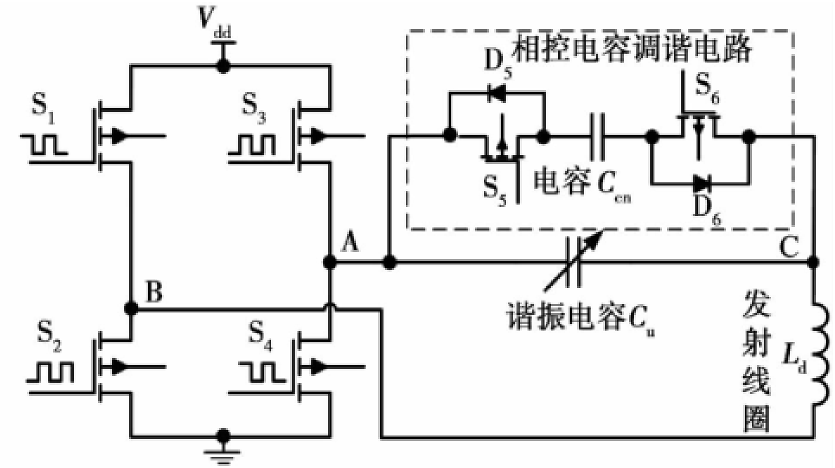

Without tunning



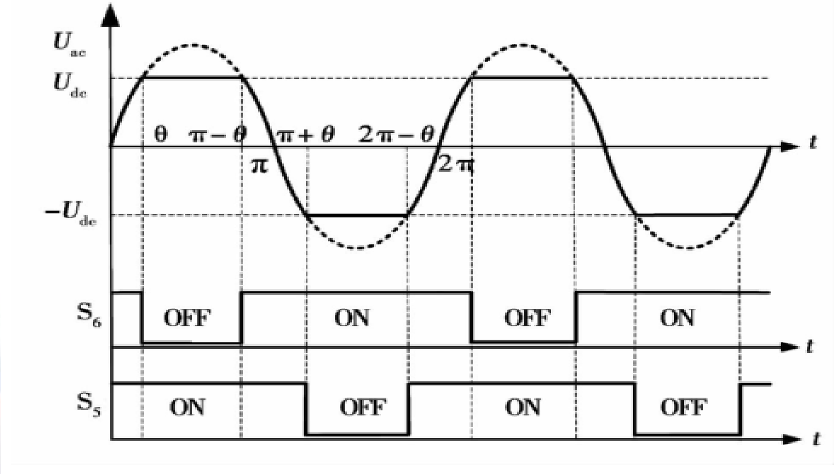

With tunning

* Qiang Hao, Huang Xueliang, Tan Linlin, et al. Achieving maximum power transfer of inductively coupled wireless power transfer system based on dynamic tuning control. Science China: Technological Science, 2012, 42(7): 830-837.

## 3.4 Based on phase-controller capacitor




Tuning circuit based on phase-control capacitor

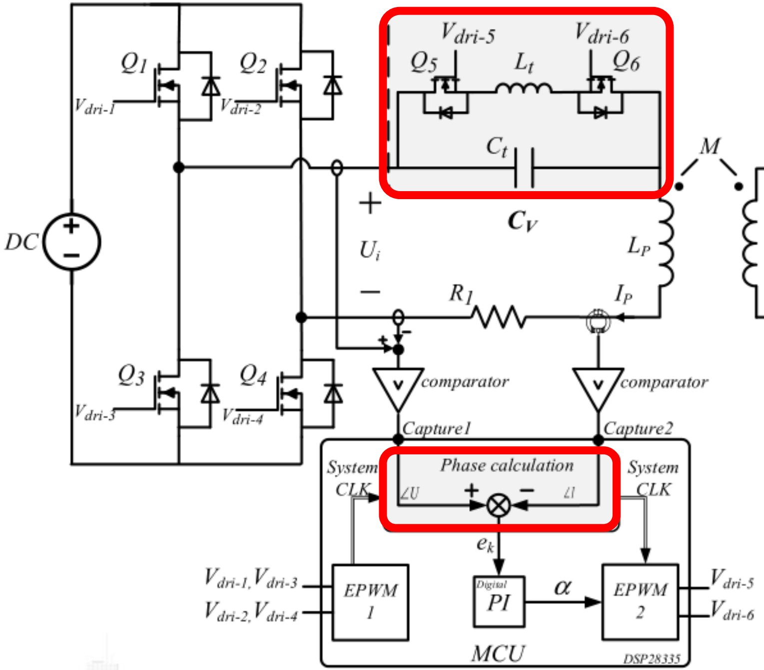



Waveform of phase controlled capacitor tuning circuit

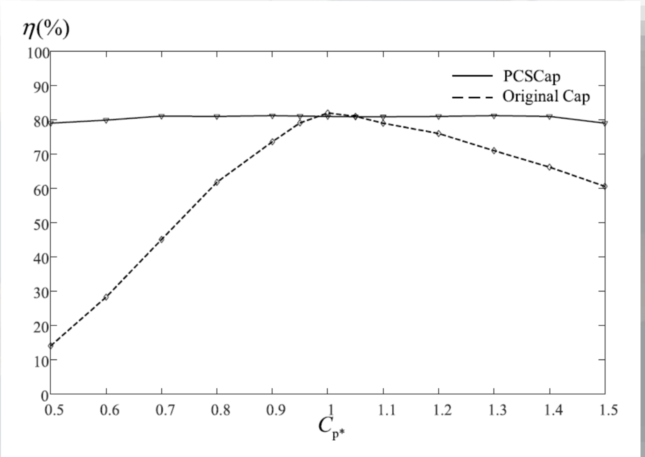
A turning method based on the phase-control capacitor was addressed, A controllable capacitor was achieved by adjusting the phase angle of recharging

* Xin Wenhui, Hua Dengxin, Cao Zhonglu, et al. Tuning method based on phase-control capacitor for magnetic resonant wireless power transfer. Electric Machines and Control, 2016, 20(12): 1-8.

## 3.5 Based on phase-controlled capacitor



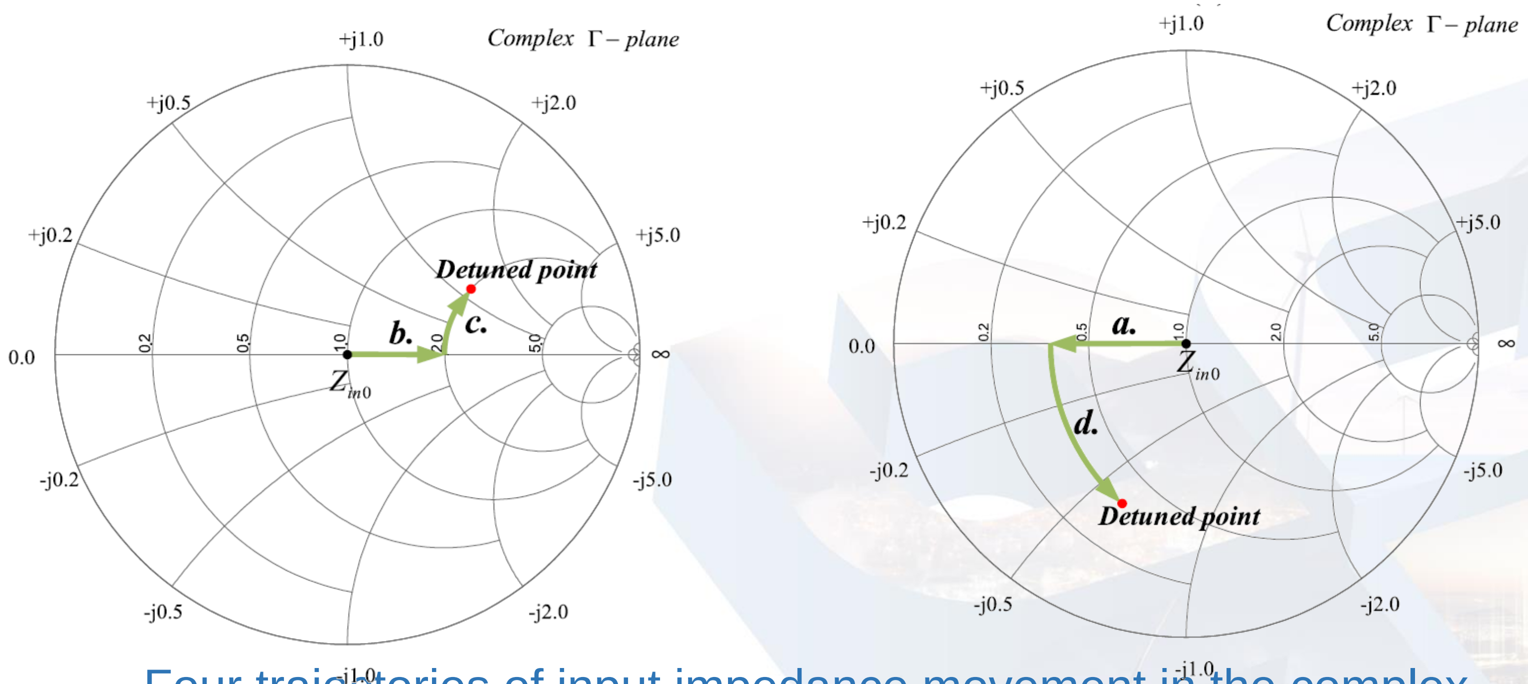

Topology of the proposed PCSCap-WPT system




Experiment results

* Shui H, Yu D, Yu s, et al. An autonomous impedance adaptation strategy for wireless power transfer system using phase-controlled switched capacitors. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2021, 9(2): 2303-2316.

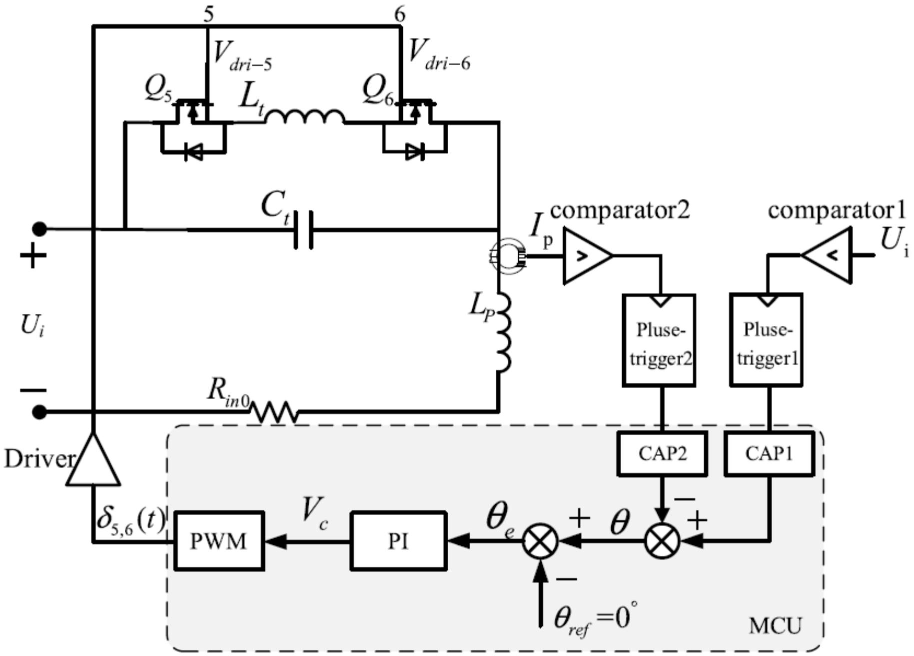
## 3.5 Based on phase-controlled capacitor



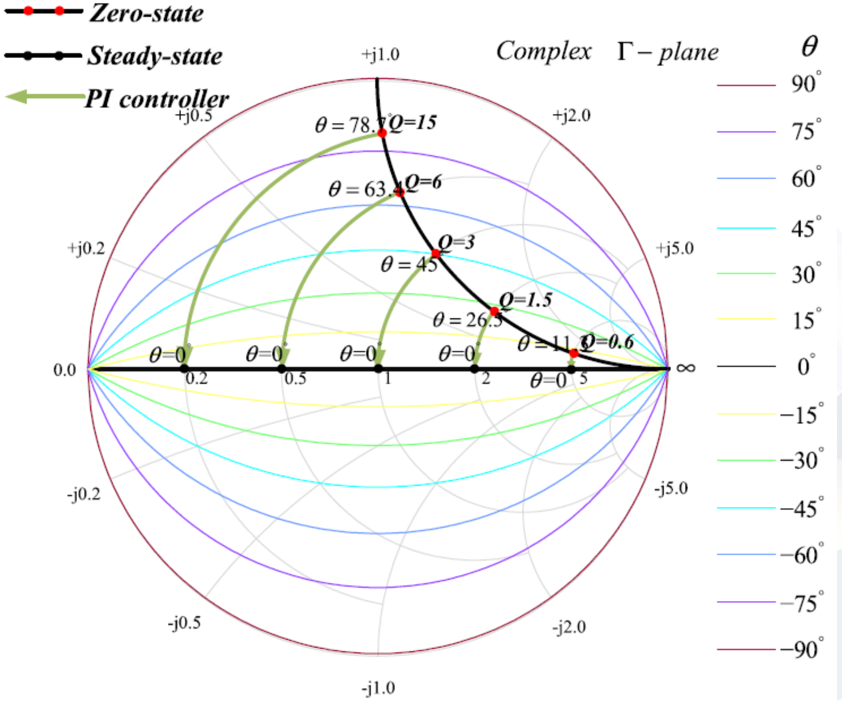

Four trajectories of input impedance movement in the complex Γ-plane considering potential parameter changes.

* Shui H, Yu D, Yu s, et al. An autonomous impedance adaptation strategy for wireless power transfer system using phase-controlled switched capacitors. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2021, 9(2): 2303-2316.

## 3.5 Based on phase-controlled capacitor



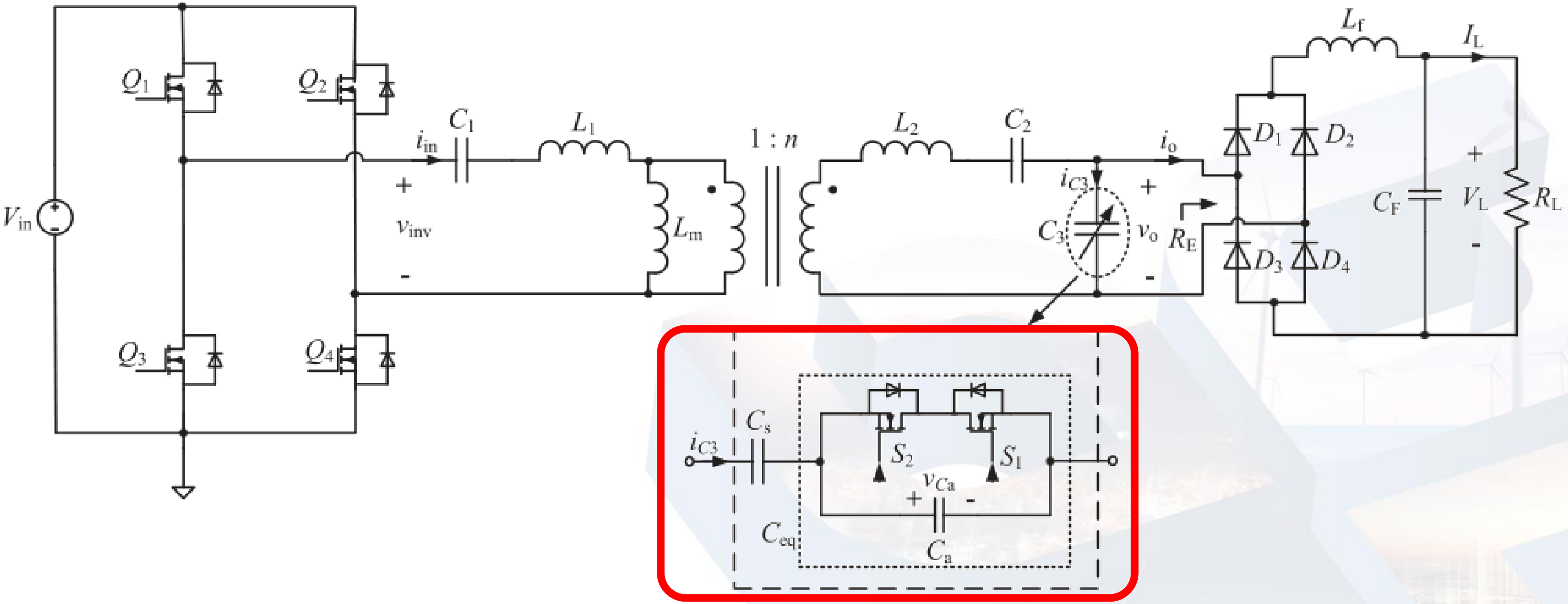

Proposed control scheme




Dynamic Autonomous Impedance Adaptation

* Shui H, Yu D, Yu s, et al. An autonomous impedance adaptation strategy for wireless power transfer system using phase-controlled switched capacitors. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2021, 9(2): 2303-2316.

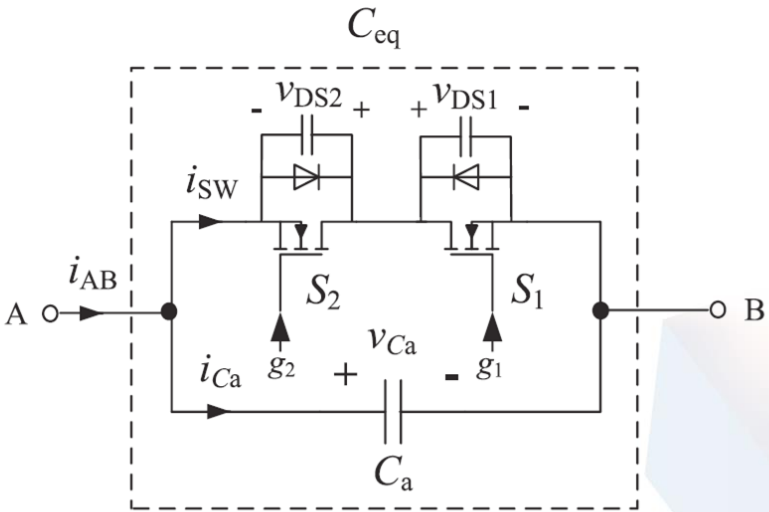
## 3.6 Based on switched capacitor



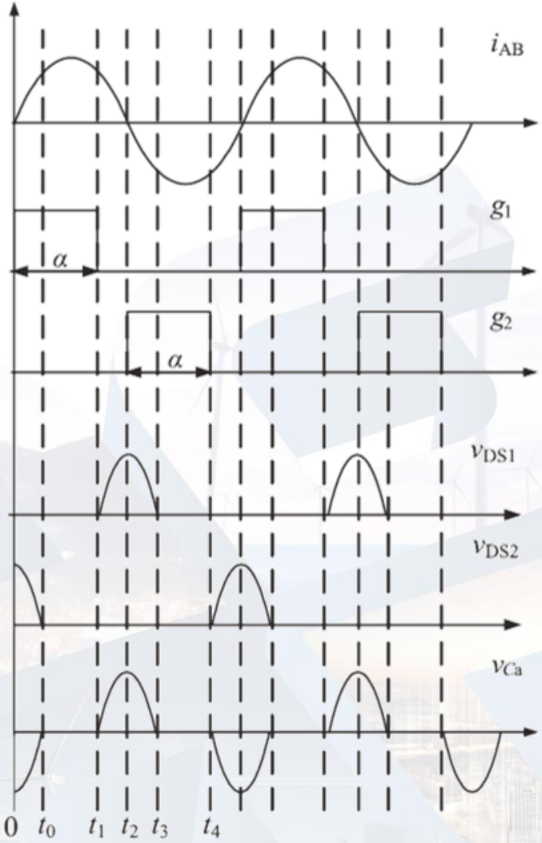

The proposed dynamic series/series–parallel compensation network based on a switch-controlled capacitor

* Wong C s, Chan Y P, Cao L. et al. A single-stage dynamically compensated IPT converter with unity power factor and constant output voltage under varying coupling condition. IEEE Transactions on Power Electronics, 2020, 35( 10): 10121-10136.

## 3.6 Based on switched capacitor

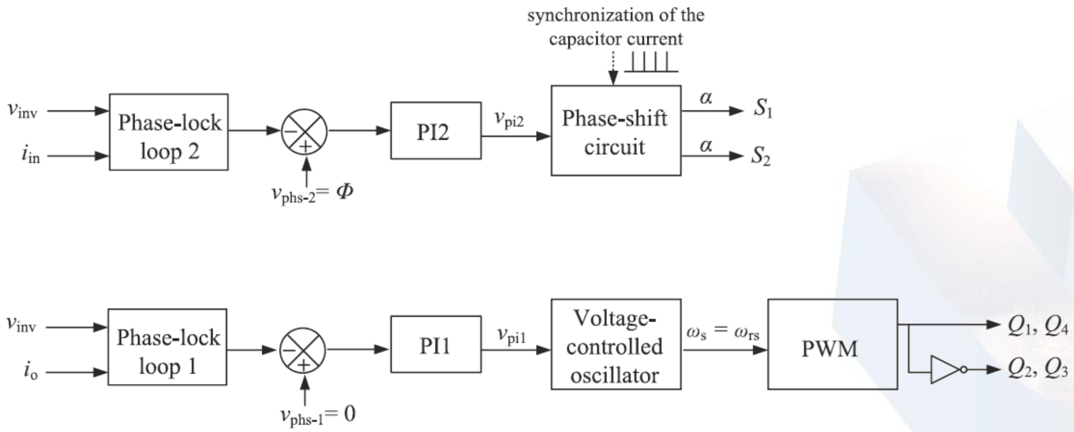



Schematic diagram of an switched controller capacitor and its key waveforms

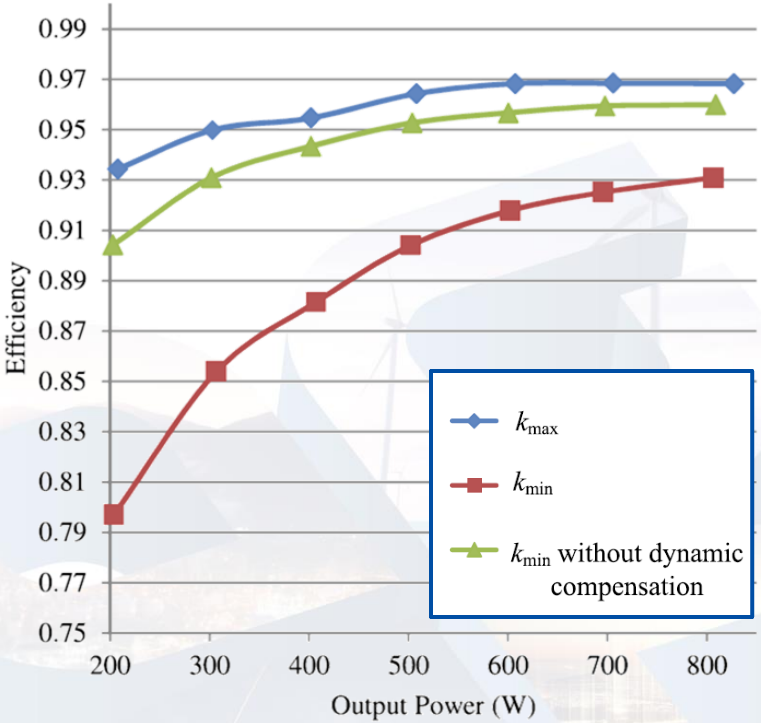



* Wong C s, Chan Y P, Cao L. et al. A single-stage dynamically compensated IPT converter with unity power factor and constant output voltage under varying coupling condition. IEEE Transactions on Power Electronics, 2020, 35( 10): 10121-10136.

# 3.6 Based on switched capacitor



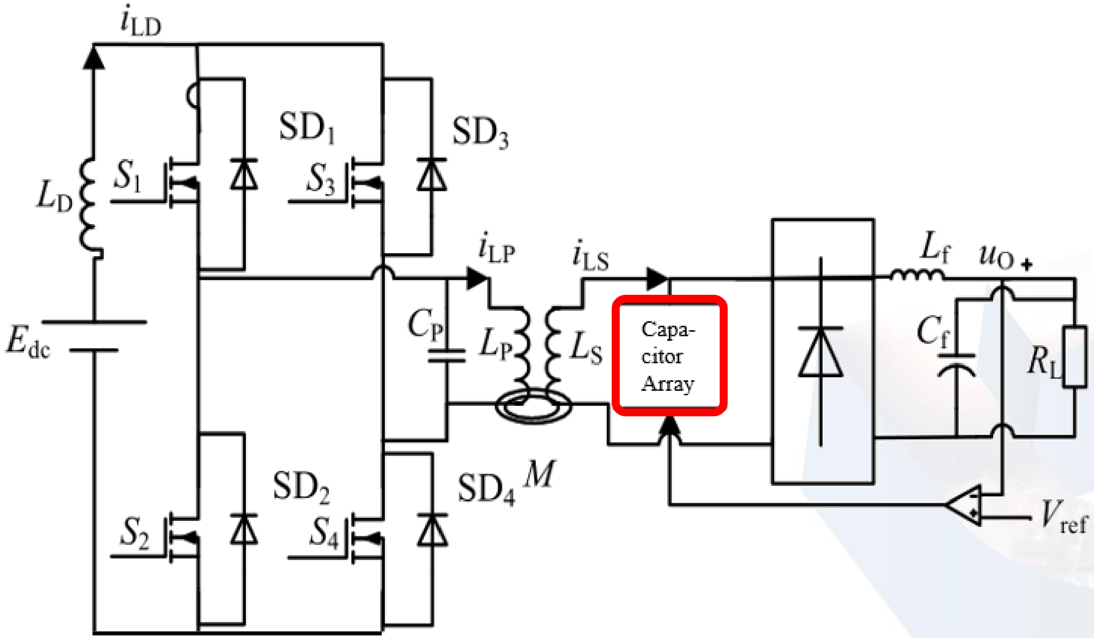

Block diagram of the implementation of the closed-loop control

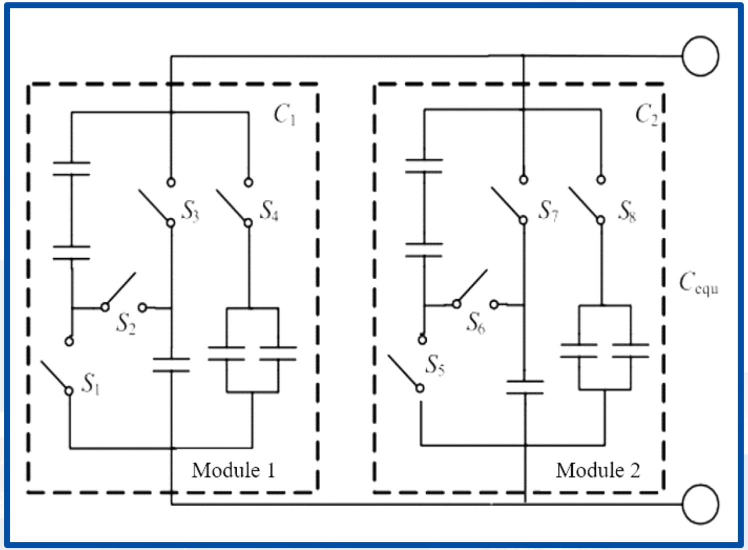



Efficiency comparison in experiments

* Wong C s, Chan Y P, Cao L. et al. A single-stage dynamically compensated IPT converter with unity power factor and constant output voltage under varying coupling condition. IEEE Transactions on Power Electronics, 2020, 35( 10): 10121-10136.

## 3.7 Based on capacitor array



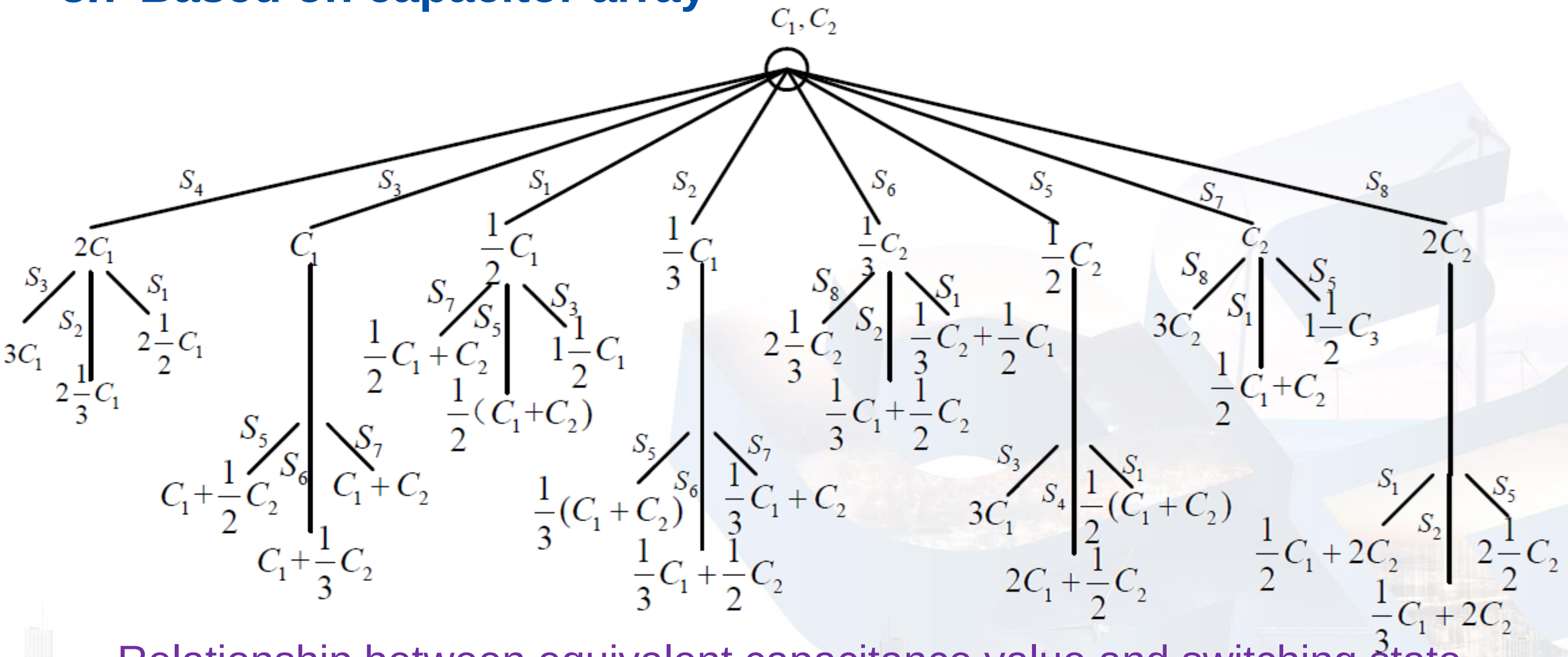




Circuit topology of CPT system based on resonant capacitor array

Resonant capacitor array

* Dai Xin, Zhou Jikun, Sun Yue. Study on output voltage stability of CPT system based on resonant capacitor array. Journal of University of Electronic Science and Technology of China, 2012, 41(5): 729-734.

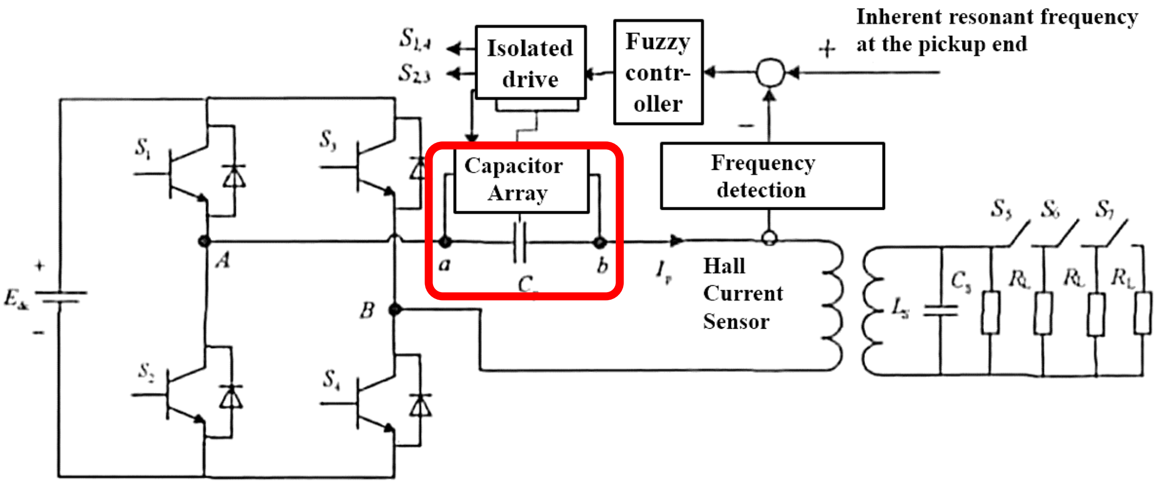
## 3.7 Based on capacitor array



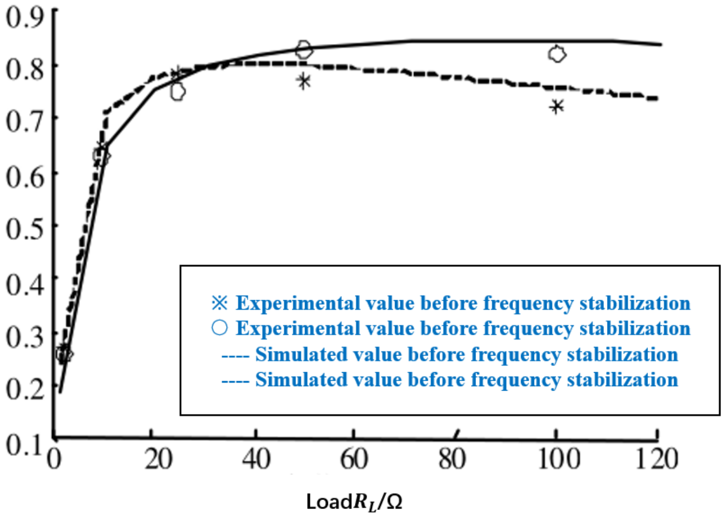

Relationship between equivalent capacitance value and switching state

* Dai Xin, Zhou Jikun, Sun Yue. Study on output voltage stability of CPT system based on resonant capacitor array. Journal of University of Electronic Science and Technology of China, 2012, 41(5): 729-734.

## 3.8 Based on capacitor array




Schematic diagram of frequency stabilization control

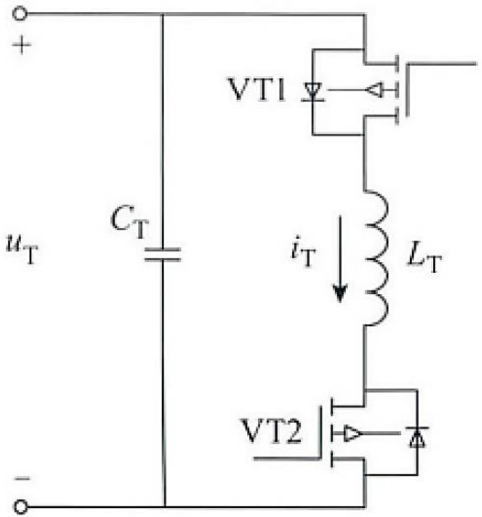



Simulation / experiment results

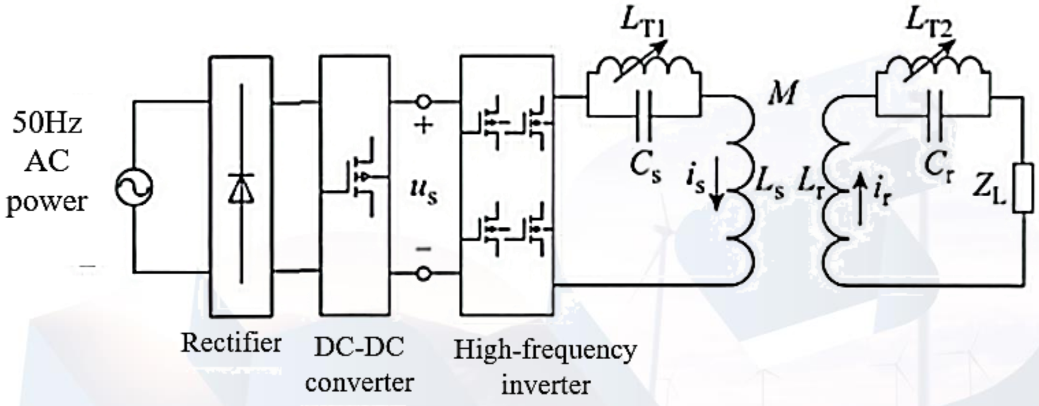
An improved fuzzy control strategy is designed to ensure the stability of the resonant operational frequency when the load changes by controlling the effective value of the primary resonant capacitor array.

* Sun Yue, Wu Jing, Wang Zhihui, et al. Frequency stabilization control method for ICPT system based on capacitor array. Journal of University of Electronic Science and Technology of China, 2014, 43(1): 54-59.

## 3.9 Phase-controller inductor and capacitor in parallel




Paralleled switching capacitor-inductor reactor

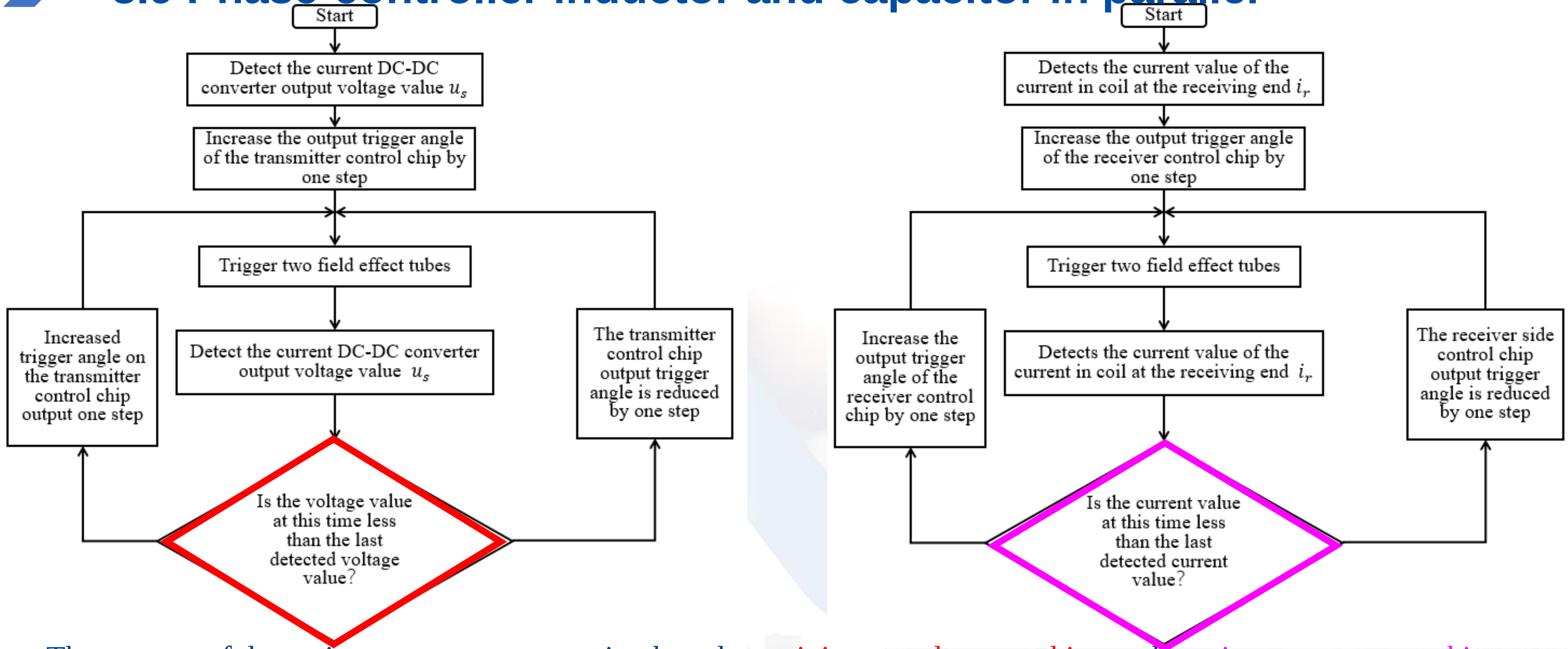



The dynamic resonant compensation diagram of IPT system

- compensation capacitance continuously adjustable

* Mai Ruikun, Lu Liwen, Li Yong, et al. Dynamic resonant compensation approach based on minimum voltage and maximum current tracking for IPT system. Transactions of China Electrotechnical Society , 2015, 30(19): 32-38.

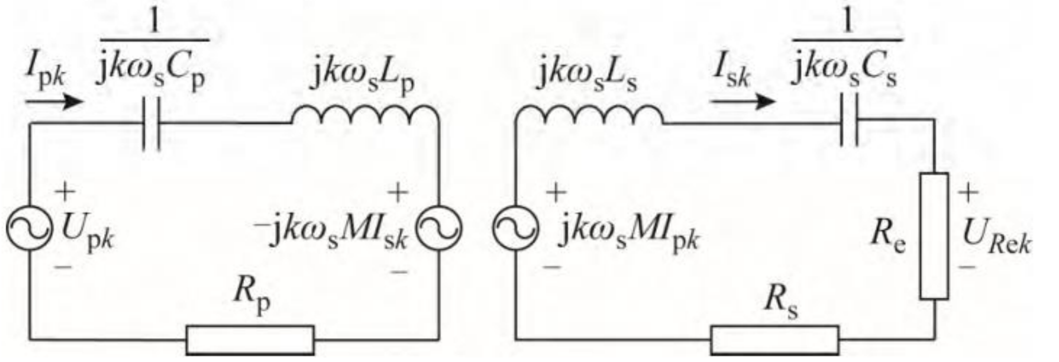
## 3.9 Phase-controller inductor and capacitor in parallel



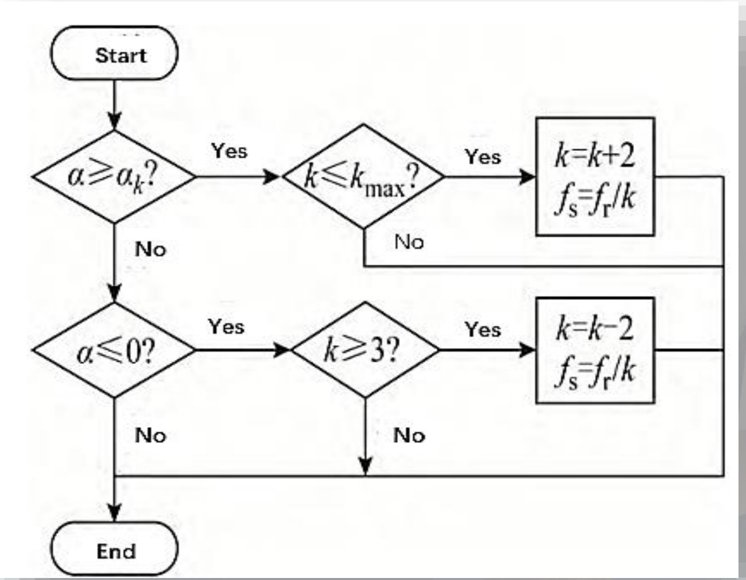

The process of dynamic resonant compensation based on minimum voltage tracking and maximum current tracking

* Mai Ruikun, Lu Liwen, Li Yong, et al. Dynamic resonant compensation approach based on minimum voltage and maximum current tracking for IPT system. Transactions of China Electrotechnical Society , 2015, 30(19): 32-38.

## 3.10 Phase-controller inductor and capacitor in parallel




The k-order harmonic equivalent model of ICPT




Flow chart of switching frequency controller

Harmonic based phase-shifted control (HPSC) is a novel power control method for wireless power transmission, which adopts harmonics to transmit power it overcomes the poor efficiency problem of traditional phase shift control at light load condition

* Cai Hua, Shi Liming, Li Yong, et al. The closed-loop control of harmonic based phase-shifted control in wireless power transmission. Transactions of China Electrotechnical Society, 2018, 33(S1): 1-8.

# Summary of dynamic compensation technology

- Impedance Matching
  - Variable Inductance
    - Variable inductor
    - Phase-controlled inductor
  - Variable Capacitance
    - Phase-controlled capacitor
    - Switched capacitor
    - Capacity array

# Contents

## Research status

- Adaptive tunning technology contributes to the high-quality-factor of resonance in WPT system, which enables higher power transmission with higher efficiency. The existing adaptive tuning technologies mainly include frequency tracking and dynamic compensation.

- Advanced algorithms are essential in frequency tracking, while switched-controller capacitors and phase-controlled capacitors are popular in dynamic compensation.

- The power transmission efficiency could be improved significantly with propose design of the adaptive tunning technology, while the power loss caused by the introduced additional circuits and devices are limited.

## Future trends

- The current obstacle and future research focus mainly include fasting tunning with simple control scheme as well as less wireless communication requirements.
- Faster wireless communication based on high-frequency-sampling sensors is still desired to achieve more accurate on-line adaptive tunning.
- Advanced schemes such as algorithms in artificial intelligence (AI) are research hot spots.
- Superconducting materials have great potential in WPT systems as they can make their resistance close to zero under special conditions, which is a key feature that the adaptive technology could take advantage of.

# Frontiers on Electronics (Industrial Electronics Section)

Frontiers in Electronics > Industrial Electronics > Research Topics > Wireless Power Transfer Techno...

## Wireless Power Transfer Technology in High degree of Freedom Applications

Abstract Submission Deadline 14 October 2022

Manuscript Submission Deadline 16 December 2022

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