ISIE 2020 TUTORIAL PROPOSAL

Title: System-Level Design and Optimization of Multi-Megahertz Wireless Power Transfer Systems

1. Presenter(s):

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2. Brief description:

Maxwell's equations mathematically predicted that electromagnetic waves, as an energy carrier, could propagate in space. This theory led to revolutionary development in wireless communications, which has changed modern society in many ways. Based on the same physics, a much greater amount of energy, compared to that representing digital bits in wireless communications, can also be transferred wirelessly. This concept of wireless power transfer (WPT) was first proposed by Nikola Tesla in 1904. In recent years, there has been a renewed interest in the research and application of WPT due to the urgent need to wirelessly charge many consumer electronic devices (e.g., smartphones, laptops, tablets, computer peripherals, medical implants, etc.). The end user wants to cut off the last wire (i.e., electrical charging wire) so that for the first time, information and power can be obtained ubiquitously through the air. WPT not only provides an easier and safer experience of daily charging processes, but also enables a new direction in the management of electrical power. Especially, it offers an alternative solution without the need for significant improvements in battery technology.

There are various WPT technologies for different applications, such as inductive coupling, microwave and laser radiation. Depending on the power level of interest, transfer distance, size and form factors, each technology may be more suitable for certain scenarios than other technologies. Microwave and laser radiation use far-field to wirelessly transfer electric power, while inductive coupling uses near field. In terms of safety, efficiency, and achievable power levels, the inductive coupling, such as the so-called magnetic resonance coupling, is being widely considered a promising candidate for wirelessly charging various electronic devices, i.e., applications requiring medium power transfer over a medium range. Conventional inductive coupling systems typically operate in the kHz band, which is largely in the field of classical power electronics. On the other hand, higher frequencies are often required to achieve a more compact and lighter WPT system with a longer transfer distance and a better tolerance to the coil misalignment. Meanwhile, regulations of the ISM (Industrial, Scientific and Medical) bands and the performance of today's power switching devices impose limits on the available operating frequencies, usually in the range of several megahertz (MHz), such as 6.78 and 13.56 MHz (i.e., multi-MHz).

In this tutorial, we plan to comprehensively summarize and explain our pioneer work on system-level approaches for high performance multi-MHz WPT systems. Operation in the MHz frequency band presents technical challenges due to possible increased power losses, strong nonlinearities of devices, and electromagnetic interference (EMI) problem. Special considerations are also needed for the robustness against variations in coil relative position and final load. All these challenges inherently require interdisciplinary efforts that combine the knowledge and insights in power electronics, radio frequency and microwave, circuit modeling, robust analysis, design optimization and control. As described in the following outline, this tutorial begins with an overview of the major challenges and limitations of the present multi-MHz WPT systems; then mentions the appropriate circuit topologies for the main components (power amplifiers and rectifiers) that provide high efficiency, low noise, and robust power conversion. The Class E topologies are especially useful for improving efficiency and facilitating optimization-based design. This tutorial continues to explain the analytical modeling and analysis of the multi-MHz WPT systems, providing the foundation for the following design and control efforts. It then comprehensively describes both the system-level passive design and feedback-based active control to improve the overall system performance in terms of efficiency, noise reduction, and robustness. Particular mention is made of the modeling, design and control aspects of the multiple-receiver WPT systems. Finally, this tutorial also reviews the recent developments in the multi-MHz WPT, such as new applications and dual-band design.

3. Outline:

As mentioned above, this tutorial is tentatively organized as follows:

1. Overview of Multi-MHz WPT

    1.1 Needs and Applications

    1.2 Technical Challenges

    1.3 Limitations of Conventional Approaches

2. High Frequency Power Conversions for Multi-MHz WPT

2.1 Power Amplifier and Rectifier Topologies

2.2 Constant Current and Load Independent Power Amplifier

2.3 High Efficiency and Low Harmonic Rectifier

3. Modeling, System-Level Design and Control

3.1 Analytical Modeling of Multi-MHz WPT systems

3.2 Design Problem Formulation and Solution

3.3 Optimal Load Tracking and Power Control

4. Multiple-receiver WPT systems

4.1 Modelling and Analysis of Coupling Mechanism

4.2 Time-Division Multiplexing-based Power Flow Control

4.3 Simultaneous WPT with Scalable Number of Receivers

4.4 Omnidirectional WPT Design

5. New Developments

5.1 Reactance Steering

5.2 Dual Band Design and Implementation

5.3 WPT-based Voltage Equalizer

5.4 Others

6. Conclusions and Future Prospects

4. Publications (note: relevant journal publications only):

1. **J. Song**, **M. Liu**, and **C. Ma**, "Analysis and Design of A High-Efficiency 6.78-MHz Wireless Power Transfer System with Scalable Number of Receivers", IEEE Transactions on Industrial Electronics, in press, 2019.

2. R. He, P. Zhao, **M. Fu** , Y. Liu, H. Wang, and J. Liang, "Decomposition and Synthesis of High-Order Compensated Inductive Power Transfer Systems for Improved Output Controllability", IEEE Transactions on Microwave Theory and Techniques, in press, 2019.

3. **M. Liu,** M. Chen: "Dual-Band Wireless Power Transfer with Reactance Steering Network and Reconfigurable Receivers", IEEE Transactions on Power Electronics, in press, 2019.

4. **M. Fu**, C. Fei, Y. Yang, Q. Li,and Fred C.Lee: "A GaN-Based DC/DC Module for Railway Applications: Design Consideration and High-Frequency Digital Control", IEEE Transactions on Industrial Electronics, in press, 2019.

5. J. Feng, Q. Li, Fred C. Lee, and **M. Fu**: "Transmitter Coils Design for Free-Positioning Omnidirectional Wireless Power Transfer System", IEEE Transactions on Industrial Informatics, in press, 2019.

6. **M. Fu**, C. Fei, Y. Yang, Q. Li, and Fred C. Lee: "Optimal Design of Planar Magnetic Components for A Two-Stage GaN-Based DC/DC Converter", IEEE Transactions on Power Electronics, vol. 34, no. 4, pp. 3329-3338, 2019.

7. **M. Fu**, Z. Tang, **M. Liu**, **C. Ma**: "Analysis and Optimized Design of Compensation Capacitors for A Megahertz WPT System Using Full-Bridge Rectifier", IEEE Transactions on Industrial Informatics, Vol. 15, No. 1, pp. 95-104, Jan. 2019.

8. S. Liu, **M. Liu**, X. Zhu, **C. Ma**: "Tunable Class E^2 DC-DC Converter with High Efficiency and Stable Output Power for 6.78 MHz Wireless Power Transfer", IEEE Transactions on Power Electronics, vol. 33, no. 8, pp. 6877-6886, Aug. 2018.

9. H. Yin, **M. Fu**, **M. Liu**, J. Song, **C. Ma**: "Autonomous Power Control in A Reconfigurable 6.78 Megahertz Multiple-receiver Wireless Charging System", IEEE Transactions on Industrial Electronics, vol. 65, no. 8, pp. 6177-6187, Aug. 2018.

10. **M. Fu**, C. Zhao, J. Song, **C. Ma**: "A Low-Cost Voltage Equalizer Based on Wireless Power Transfer and Voltage Multiplier", IEEE Transactions on Industrial Electronics, vol. 65, no. 7, pp. 5487-5496, Jul. 2018.

11. **M. Fu**, H. Yin, **M. Liu**, **C. Ma**: "A 6.78 MHz Multiple-Receiver Wireless Power Transfer System with Constant Output Voltage and Optimum Efficiency", IEEE Transactions on Power Electronics, vol. 33, no. 6, pp. 5330-5340, Jun. 2018.

12. **M. Liu**, **M. Fu**, **C. Ma**: "Battery Cell Equalization via Megahertz Multiple-Receiver Wireless Power Transfer", IEEE Transactions on Power Electronics, vol. 33, no. 5, pp. 4135-4144, May 2018.

13. **M. Liu**, S. Liu, **C. Ma**: "A High Efficiency/Output Power and Low Noise Megahertz Wireless Power Transfer System over A Wide Range of Mutual Inductance", IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 11, pp. 4317-4325, Nov. 2017.

14. **M. Fu**, H. Yin, **C. Ma**: "Megahertz Multiple-Receiver Wireless Power Transfer Systems With Power Flow Management and Maximum Efficiency Point Tracking", IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 11, pp. 4285-4293, Nov. 2017.

15. **M. Liu**, C. Zhao, J. Song, **C. Ma**: "Battery Charging Profile-Based Parameter Design of A 6.78-MHz Class E^2 Wireless Charging System", IEEE Transactions on Industrial Electronics, vol. 64, no. 8, pp. 6169-6178, Aug. 2017.

16. S. Liu, **M. Liu**, S. Yang, **C. Ma**, X. Zhu: "A Novel Design Methodology for High-Efficiency Current-Mode and Voltage-Mode Class-E Power Amplifiers in Wireless Power Transfer Systems", IEEE Transactions on Power Electronics, vol. 32, no. 6, pp. 4514-4523, Jun. 2017.
17. **M. Liu**, Y. Qiao, S. Liu, **C. Ma**: "Analysis and Design of A Robust Class E^2 DC-DC Converter for Megahertz Wireless Power Transfer", IEEE Transactions on Power Electronics, vol. 32, no. 4, pp. 2835-2845, Apr. 2017.
18. **M. Liu**, **M. Fu**, **C. Ma**: "Low-Harmonic-Contents and High-Efficiency Class E Full-Wave Current-Driven Rectifier for Megahertz Wireless Power Transfer Systems", IEEE Transactions on Power Electronics, vol. 32, no. 2, pp. 1198-1209, Feb. 2017.
19. **M. Fu**, H. Yin, **M. Liu**, **C. Ma**: "Loading and Power Control for A High-Efficiency Class E PA Driven Megahertz WPT System", IEEE Transactions on Industrial Electronics, vol. 63, no. 11, pp. 6867-6876, Nov. 2016.
20. **M. Liu**, **M. Fu**, **C. Ma**: "Parameter Design for A 6.78-MHz Wireless Power Transfer System Based on Analytical Derivation of Class E Current-Driven Rectifier", IEEE Transactions on Power Electronics, vol. 31, no. 6, pp. 4280-4291, Jun. 2016.
21. **M. Fu**, T. Zhang, X. Zhu, P. Luk, **C. Ma**: "Compensation of Cross Coupling in Multiple-Receiver Wireless Power Transfer Systems", IEEE Transactions on Industrial Informatics, vol. 12, no. 2, pp. 474-482, Apr. 2016.
22. **M. Fu**, H. Yin, X. Zhu, **C. Ma**: "Analysis and Tracking of Optimal Load in Wireless Power Transfer Systems", IEEE Transactions on Power Electronics, vol. 30, no. 7, pp. 3952-3963, Jul. 2015.
23. **M. Fu**, T. Zhang, **C. Ma**, X. Zhu: “Efficiency and Optimal Loads Analysis for Multiple-Receiver Wireless Power Transfer Systems”, IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 3, pp. 801-812, Mar. 2015.
24. **M. Fu**, **C. Ma**, X. Zhu: “A Cascaded Boost-Buck Converter for High-Efficiency Wireless Power Transfer Systems", IEEE Transactions on Industrial Informatics, vol. 10, no. 3, pp. 1972-1980, Aug. 2014.

5. Presenter’s biography:

- Hilight#1: Dr. Ming Liu and Dr. Chengbin Ma received Research Excellent Award from AirFuel Alliance (the leading global authority on high-frequency wireless power transfer), USA, in 2019 “for their work on high-efficiency and low electromagnetic interference full-wave rectifiers for AirFuel Resonant systems”. [Link: https://www.airfuel.org/2019/03/13/airfuel-alliance-presents-technical-leadership-awards/]

- Hilight#2: We are the world’s leading group in developing interdisciplinary approaches to achieve low-noise and high efficiency rectification, optimized design and robust control of MHz WPT systems, modeling and control of less-common multiple-receiver systems. Several of our original IEEE journal papers were listed by Essential Science Indicators (ESI) as top 1% highly cited papers in engineering and publication years. [Google Scholar Profile: https://scholar.google.com/citations?user=k_cBukkAAAAJ&hl=en] Our citation number in "megahertz wireless power" is also among the highest world widely, according to searching result of Web of Science.

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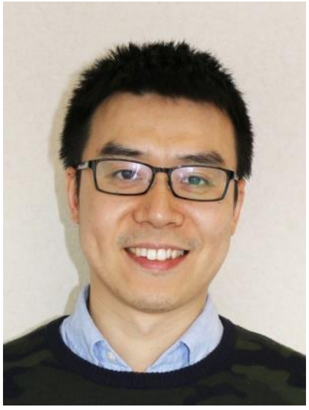
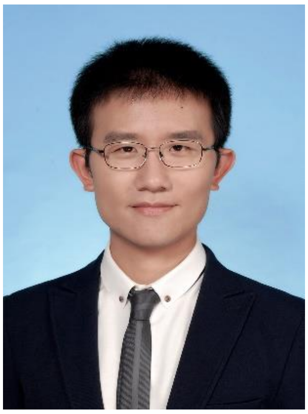


Ming Liu (S'15-M'17) received the B.S. degree from SiChuan University, Sichuan, China, in 2007, and the M.S. degree from the University of Science and Technology Beijing, Beijing, China, in 2011, both in mechatronic engineering, and the Ph.D. degree in electrical and computer engineering at University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, China, in 2017. He is currently a postdoctoral research fellow at Department of Electrical Engineering, Princeton University, Princeton, NJ, USA. Between 2012 and 2014, he was an assistant research fellow with Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China.

His research interests include circuit topologies and architectures, control strategies, parameters design and optimization of MHz wireless power transfer (WPT) systems as well as high frequency power electronics. He has conducted extensive research on the MHz WPT and has authored or co-authored over 30 IEEE journal and conference papers. He served as Session Chair of IEEE PELS WoW 2018 conference and Guest Editor of IEEE Trans. Industrial Informatics. He is Chair of the Wireless Charging Subcommittee of Energy Storage Technical Committee, IEEE Industrial Electronics Society. Dr. Liu received Top Ten Academic Star Award and Excellent PhD Thesis Award Nomination at Shanghai Jiao Tong University in 2016 and 2018, respectively, and Research Excellence Award from AirFuel Alliance, USA, in 2019.



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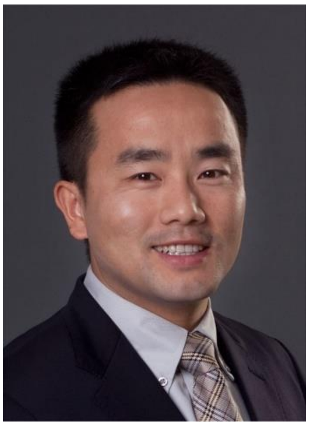
Minfan Fu (S'13-M'16) received the B.S., M.S., and Ph.D. degrees in electrical and computer engineering from University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, China in 2010, 2013, and 2016. He is currently an Assistant Professor at School of Information Science and Technology (SIST), ShanghaiTech University, Shanghai, China. Between 2016 and 2018, he held a postdoctoral position with the Center for Power Electronics Systems (CPES), Virginia Polytechnic Institute and State University, Blacksburg, VA, USA.

His research interests include megahertz wireless power transfer, high-frequency power conversion, high-frequency magnetic design, and applications of wide-band-gap devices. He has ten years of experience in Multi-MHz wireless power transfer (WPT) research. His first three IEEE journal papers on MHz WPT, which were published in 2014 and 2015, have been world widely cited 132, 118, and 100 times. At CEPS, he worked with Dr. Fred C. Lee, a National Academy of

Engineering member and IEEE Fellow, and extended his expertise to the field of high-frequency power electronics. He developed the next-generation GaN-based DC-DC module. Compared to the state-of-the-art products, the peak efficiency and power density have increased from 91% to 96% and from 88 W/inch^3 to 130 W/inch^3. He holds one US patent and has published 33 papers in prestigious IEEE journals and conferences, such as IEEE Trans. Industrial Electronics and IEEE Trans. Power Electronics. Currently, his total google scholar citations exceeds 660, and one of his first papers was listed by Essential Science Indicators (ESI) as top 1% highly cited papers in engineering and publication years.



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Chengbin Ma (M'05–SM'18) received the B.S. degree in industrial automation from East China University of Science and Technology, Shanghai, China, in 1997, and the M.S. and Ph.D. degrees in electrical engineering from The University of Tokyo, Tokyo, Japan, in 2001 and 2004, respectively. From 2004 to 2006, he was an R&D Researcher with the Servo Motor Laboratory, FANUC Limited, Japan. Between 2006 and 2008, he was a Postdoctoral Researcher with the Department of Mechanical and Aeronautical Engineering, University of California, Davis, USA. He joined the University of Michigan–Shanghai Jiao Tong University Joint Institute (UM-SJTU Joint Institute), Shanghai Jiao Tong University, Shanghai, China, in 2008, and currently an Associate Professor of electrical and computer engineering. His research interests include energy management, wireless power transfer, dynamics and motion control, and wide applications in electronic devices, electric vehicles, microgrids, smart grids, etc.

Dr. Ma is an IEEE senior member. He serves as Delegate of Energy Cluster, Chair of Energy Storage Technical Committee and Chair of Shanghai Chapter, IEEE Industrial Electronics Society. He is an Associated Editor for the IEEE Transactions on Industrial Informatics. He and his supervised students won many teaching and research awards at Shanghai Jiao Tong University, such as Koguan Top Ten Best Teacher Award in 2017 and Koguan Top Ten Research Group Award in 2014. He also received Research Excellence Award from AirFuel Alliance, USA, in 2019.
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