Proposal for ISIE 2021 Tutorial

Title of Tutorial:

Emerging Applications and Designs of High-Frequency Wireless Power Transfer Systems

Contact Information of Speakers:

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Background of Speakers:

Ming Liu
- High-frequency wireless power transfer
- High-frequency power electronics
- Battery management systems

Minfan Fu
- High-frequency wireless power transfer
- High-frequency power conversion and magnetic design
- Applications of wide-band-gap devices

Chengbin Ma
- High frequency wireless power transfer
- Energy storage and management
- Dynamics and motion control

Brief description of the tutorial (500 words max):

In this tutorial, we plan to comprehensively summarize and explain our leading work on the system-level approaches to high-performance multi-MHz WPT systems, with a particular focus on emerging applications and their design. First, we will give an in-depth overview of the high-frequency WPT operating at several MHz based on our intensive practice in recent years. Then, the following selected new developments will be explained in details.

1) Six-DOF Magnetic Field Shaping: In actual scenarios, the diversity and dynamics of the position / attitude of each receiving device have presented new needs and challenges for existing wireless power transfer systems, especially in terms of the transfer distance and angle. As a solution, we have proposed spatial six-degree-of-freedom magnetic field shaping based on the differential control of each coil in a transmitting coil array. Its major aspects will be systematically introduced, including modeling, position / attitude detection, optimal control and design, circuit topology and drive.

2) Multi-port Energy Router and Battery Equalizer: It is known that operating in the MHz bands helps eliminate magnetic cores, reduce coil size and increase the power density of energy routers and battery equalizer, but electromagnetic field analysis and power flow control become challenging. Without a magnetic core, the coil coupling coefficient in a MHz multi-port transformer is usually much lower than that of a conventional transformer. The multi-port transformer works closer to the inductive coupling coils in wireless power transfer systems, namely a multi-port wireless-coupled (MWC) transformer. In this tutorial, the system architecture, circuit topology and power flow control will be discussed to illustrate how to design and implement a high-performance wireless coupled multi-port energy router/battery equalizer.

3) Power Transfer through Metallic Structures: There are actual needs to wirelessly transfer power through metallic structures, such as powering a sensor separated by a metal barrier. A higher operating frequency is usually effective to improve the power transfer efficiency and minimize the size and weight on the receiving side. We will go through in detail a complete case study applying a 27.12 MHz operating frequency. The unique mechanism to transfer power through a large 3D-shaped metal sheet will be clarified and validated, which requires multidisciplinary knowledge in power electronics and radio frequency / microwave.

4) Capacitive Coupler Design and Compensation Synthesis: In addition to the near-field inductive coupling, capacitive coupling provides another solution for wireless power transfer, with many unique advantages, such as no need to worry

about eddy currents, low cost, and light weight. The proper coupler structure will help improve the power and efficiency performance under various misalignment conditions. This tutorial will discuss the coupling characteristics of several coupler structures, such as horizontal couplers, vertical couplers and interleaved couplers. Based on the duality between IPT and CPT, a systematic decomposition and synthesis method will be discussed to design high-order compensation networks. This general method is to realize coupling-independent resonance, load-independent output, and zero-phase operation at the same time.

Tentative Outline:

1. Overview of High-Frequency WPT
   1.1 Needs and Applications
   1.2 Technical Challenges
   1.3 Future Trends

2. Six-DOF Magnetic Field Shaping
   2.1 Purposes and Principle
   2.2 Coil Array Design and Optimization
   2.3 Circuitry and Results

3. Multi-port Energy Router and Battery Equalizer
   3.1 Architecture and Topology
   3.2 Multi-port Wireless-Coupled Transformer
   3.3 Multi-Way Power Flow Control

4. Power Transfer through Metallic Structures
   4.1 Challenges and Solutions
   4.2 Mechanism and Modeling
   4.3 Setup and Results

5. Capacitive Coupler Design and Compensation Synthesis
   5.1 Coupler Model
   5.2 Coupler Structure
   5.3 Coupling Variation
   5.4 Compensation Synthesis

6. Other New Developments

7. Conclusions and Future Prospects

<u>Biography:</u>

Dr. Ming Liu received the Ph.D. degree in electrical and computer engineering from the University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, China, in 2017. From 2017 to 2020, he was a Postdoctoral Research Fellow with the Department of

Electrical Engineering, Princeton University, USA. He joined the School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China, in 2020, where he is currently an Associate Professor of Electrical Engineering. His research interests include megahertz wireless power transfer, battery management systems, high frequency high performance power electronics for emerging applications. Dr. Liu was the recipient of Top Ten Academic Star Award and Excellent PhD Thesis Award Nomination from Shanghai Jiao Tong University in 2016 and 2018, and Research Excellence Award from AirFuel Alliance, USA, in 2019. He serves as Guest Editor of IEEE Transactions on Industrial Informatics and Chair of the Wireless Power Transfer for Energy Storage Charging Subcommittee of Energy Storage Technical Committee, IEEE Industrial Electronics Society.

Dr. Minfan Fu received the 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 198, 179, and 147 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/inch3 to 130 W/inch3. He holds 7 patents and has published over 50 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 1200, and one of his first papers was listed by Essential Science Indicators (ESI) as top 1% highly cited papers in engineering and publication years.

Dr. Chengbin Ma received the Ph.D. degrees in electrical engineering from The University of Tokyo, Tokyo, Japan, in 2004. 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. In 2008, he joined the University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, China, where he is currently an Associate Professor of Electrical and Computer Engineering. His research interests include energy storage and management, wireless power transfer, dynamics and motion control, and wide applications in electronic devices, electric vehicles, microgrids, smart grids, etc. Dr. Ma was the recipient of many teaching and research awards at Shanghai Jiao Tong University, such as Teaching and Education Award in 2020 and Koguan Top Ten Research Group Award in 2014. He also received Research Excellence Award from AirFuel Alliance, USA, in 2019. He is an Associated Editor for the IEEE Transactions on Industrial Informatics and IEEE Journal of Emerging and Selected Topics in Industrial Electronics. He serves as Delegate of Energy Cluster, and Chair of Shanghai Chapter, IEEE Industrial Electronics Society.

Brief description of the intended audience

The intended audiences are researchers and engineers engaged in wireless power transfer, high-frequency power electronics, battery and energy management, and related product development

Support technical committee in IES (if any)

1) IEEE/IES Technical committee on Energy Storage, Alfonso Damiano, damiano@unica.it
2) IEEE/IES Technical committee on Resilience and Security for Industrial Applications (ReSia), Federico Baronti, federico.baronti@unipi.it