INDUCTIVE POWER TRANSFER WITH MIMO TRANSMISSION

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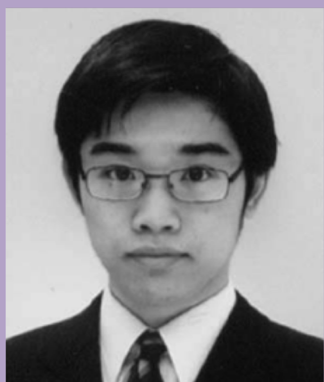

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Introduction on inductive power transfer

Inductive power transfer (IPT) [1] is a non-radiative type of energy transmission, where an AC driven coil induces electric voltage in another coil placed nearby. An IPT system can be seen as a transformer with steel core replaced by air or other dielectric material depending on where the system is deployed. IPT efficiency is sufficiently good in short transmission distance but it severely deteriorates with the transmission distance. Originally proposed by Nicola Tesla at the end of the 19th century, this technology only experiences primitive commercialization in late of the 20th century. IPT was used as contactless charger for toothbrush in 1981 by Panasonic Corporation, for an integrated card (IC) in 1995 by Sony Corporation, and for material handling robot in factories by Daifuku Corporation [2]. This technology starts to gain wide recognitions since the innovative invention on resonant inductive coupling introduced by a research group at MIT in 2007 [3]. The resonant inductive coupling electrically resonates the coils at the signal frequency to drastically improves power transfer efficiency and/or the transmission distance. The resonance concept enables a wide range of IPT applications, including biomedical implants, portable electronic devices, factory automation and electric cars. Today, wireless charger for smartphones can be found in any shop or pre-installed in new cars on sale. Stationary wireless charger for electric car battery is being developed by many car manufacturers and expected to be released soon. Dynamic wireless charging infrastructures for moving electric cars [4] have been widely developed in Japan, Korea, New Zealand, the United States, and Europe.

Research and development (R&D) activities on IPT so far mostly focus on the single-input single-output topology where one transmitting coil sends wireless power to one receiving coil. The next R&D trends may include investigations on larger topologies for better utilization of this technology to bring about more conveniences to everyday life. Single-input multiple-output (SIMO) topology can be introduced in large transmitting coil structure to enable simultaneous charging of multiple devices. Multiple-input multiple-output (MIMO) topology can be exploited to improve the power transmission capacity and realize effective high-power wireless charging. In this article, we would like to briefly introduce our research activities regarding this these IPT topologies.

SIMO IPT with elongated transmitting coil

We are studying wireless charging for material handling robots in factory automation [5][6]. The design objective is to enlarge the coverage area of IPT so that the system can effectively charge the robots while they move from place to place in the factory. Enlarging the coverage area usually comes with concern about electromagnetic interference to other electronic devices as well as impacts to human body. Fortunately, this is not a critical problem in factory application as the IPT system will be deployed in a closed space. Also, the robots are usually programmed to move on determined route, thus possible misalignments between the transmitting apparatus and the receiving coils installed on the robots may not be a critical problem. Here, the important task is how to simplify the transmitting coil structure as much as possible to reduce the manufacturing and maintenance costs.

To this end, we are simply elongating the transmitting coil instead of installing many small coils in an array. Our proposed design is parallel line feeder in Fig. 1, which is in fact a two-wire transmission line driven in the MHz band. The novelty of our design is not the shape of the transmitting coil but its high operation frequency compared to those of typical IPT systems. When elongating the transmitting coil, the coupling coefficient between the transmitting coil and each receiving coil decreases significantly due to severe leaked magnetic flux stemming from the imbalance in the coil sizes. The major purpuse of increasing the operating frequency is to improve the Q-factors of the coils and compensate for the low coupling coefficient. This is because the Q-factors, to some extent, increases linearly with the operating frequency. Another purpose is to simplify and reduce size of the circuitry as required circuit elements become smaller in higher frequency ranges.

On the contrary, our system suffers from standing wave effect as the sizes of transmitting coil becomes significant to the wavelength of the power-carrying signal. For instance, if our system operates at an ISM band of 13.56 MHz the signal wavelength is about 22 m while the feeder should have a length of several tens of meters or longer when deployed in factories. To address this issue, we are currently studying a method of periodically inserting capacitors in the feeder to make it electrically short, resulting in stable output powers for the robots during their operation along the feeder [5][6]. The remaining problem which usually arises in multiple receiver IPT system is the interaction among the receivers because they are coupling with each other via the feeder. During the charging process, load resistance at each receiver usually varies with time; and this variation changes the output voltages at the other receivers. To solve this problem, we employ a special resonant network consisting of an inductor and two capacitors, namely LCC circuit, at the transmitter side to stabilize the input current in the feeder, resulting in stable out voltages regardless of the load resistances.

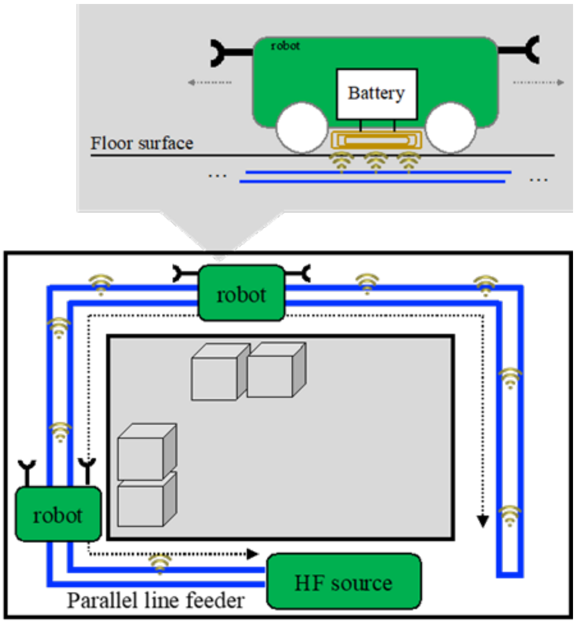


Fig. 1: SIMO IPT using parallel line feeder.

SIMO IPT using transmitting coil array

Another development direction is to realize an IPT system having large coverage area for simultaneous charging of portable devices, e.g., smartphones, table PCs, laptop PCS as shown in Figs. 2 and 3. This system would be installed on the surface of office tables or desks. As the system will be deployed nearby human body and many other communication devices, it should be sophisticatedly design to prevent leaked magnetic field as well as radiation to surrounding space. To this end, we employ a charging pad consisting of many small coils [7] instead of one enlarged transmitting coil as in the parallel line feeder system. An enlarged transmitting coil generates electromagnetic field over all the desk surface. Meanwhile, an array of many small coils is possible of effectively focusing magnetic flux towards the receiver locations by having each coil detect the receiver existence and activates when needed. Typically, a converter circuit is used to change the 50Hz/60Hz AC current to a DC, which then will be converted to higher frequency (kHz, MHz) signal to drive a coil. In implementing a large coil array system, power electronic redundancy becomes a critical problem because the numbers of converter and inverter circuits increase linearly with the number of the coils. To solve this problem, we are currently study a coil array system driven by a common RF feeder which needs only a pair of converter and inverter circuits [8] for activation.

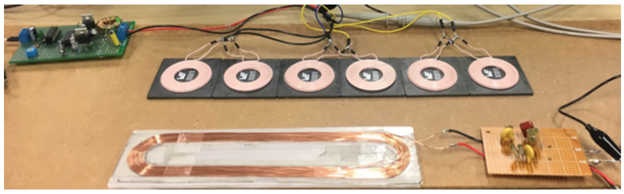


Fig. 2: IPT using coil array without a common RF feeder [7]

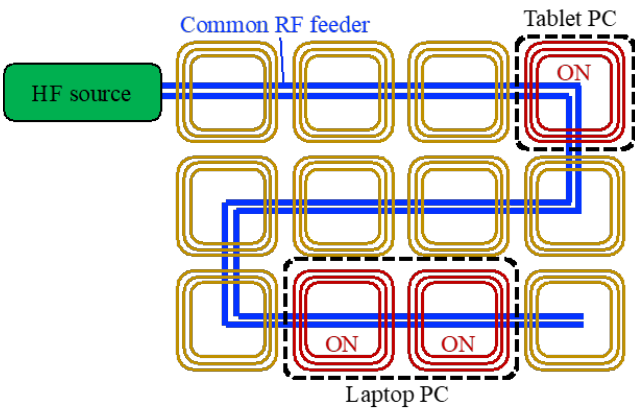
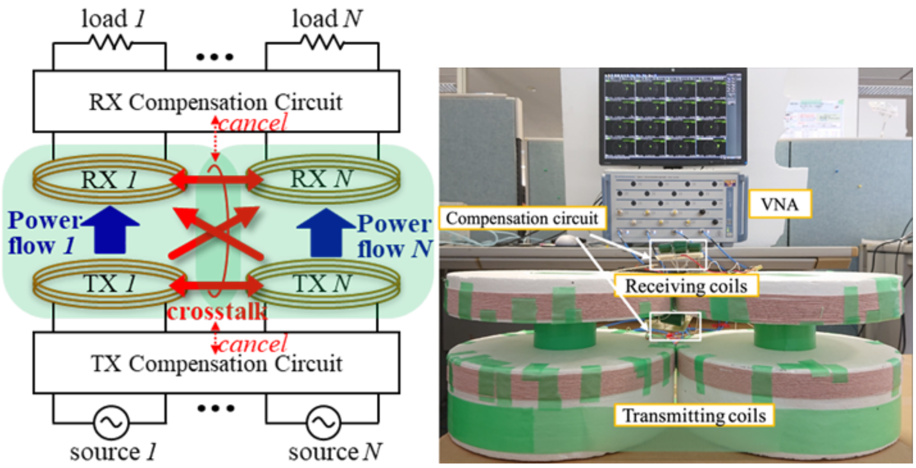


Fig. 3: SIMO IPT using transmitting coil array with common RF feeder

MIMO IPT for improving power transmission capacity

Researches on wireless charging are not only about efficiency and coverage but also about



(a)System model *(b) Experiments with 2x2 MIMO IPT [9]*

Fig. 4: MIMO-IPT for improving power transmission capacity

transferable power. As the power transmission capacity of SISO IPT is bound by physical limitations of materials of the coils and the current power electronic technologies, we are investigating the use of multiple-input multiple-output (MIMO) topology to simultaneously deliver a high power over N parallel flows. In the considered MIMO system in Fig. 4(a), the transmitter side uses a coil array of N elements, each of which is driven by an inverter circuit to deliver power to the receiving coil array having N elements at the receiver side. The MIMO configuration is expected to increase the power transmission capacity by about N times. But, with benefits come challenges. Due to space constraints, the element coils of each array are usually placed close to each other, resulting in inevitable mutual couplings among them. When the operation frequencies of the N inverters are set in the same frequency band to safe the frequency resource, crosstalk among the N power flows occurs and deteriorates the power increasing effect as well as the transfer efficiency. To address this problem, we are investigating compensation circuits for general MIMO-IPT system at any scale, placed in any arrangement and operates at any frequency. Our primitive study in [9] on 2×2 MIMO has shown that the solution effectively cancels the interference and achieves power flow isolation effect. Solution to the problem of N×M MIMO is currently developed and verified by experiments. Comprehensive results are expected to be published in the near future.

Summary

Since the groundbreaking invention of the MIT research group, R&D on the IPT technology has been undergoing a great progress and becomes promising in bring more conveniences to human life. In this article, we have briefly introduced our recent research activities focusing on MIMO transmissions for extending the coverage area, simplifying the power electronic as well as enhancing the power transmission capacity. Although still under development, our research activities will hopefully make contributions to the development of this important technique in the near future.

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