EVTeC 2023
6th International Electric Vehicle Technology Conference 2023

20231093

Efficient Multiple Input Multiple Output Wireless Power Transfer

Duong Quang Thang [1)] **Minoru Okada** [2)]

1) Nara Institute of Science and Technology, Ikoma, Nara, Japan

E-mail: thang@is.naist.jp

2) Nara Institute of Science and Technology, Ikoma, Nara, Japan

E-mail: mokada@is.naist.jp

ABSTRACT: This paper introduced a multiple-input multiple-output (MIMO) based wireless power transfer (WPT) system for supplying the power to moving vehicles. The conventional single-input single-output (SISO) WPT system has a problem in its flexibility and power transfer efficiency. The proposed MIMO-WPT system makes efficient use the multiple transmitters and receivers to optimize the power transfer efficiency. We can maximize the efficiency by controlling the input and output currents at the multiple coupler nodes, The numerical analysis shows that the proposed MIMO-WPT can drastically improve the power transfer efficiency. Furthermore, we extend the MIMO-WPT for moving vehicle application. The extended MIMO-WPT cancels the backward waves on the transmission line by making use of the RF generators implemented on the receiver side.

KEY WORDS: electric vehicle, wireless power transfer, multiple-input multiple-output, MIMO-WPT

1. INTRODUCTION

Wireless power transfer (WPT) is a promising technique for many applications such as electric vehicle (EV) battery charging.[1-3] However WPT has a problem in its power transfer efficiency. There have been many studies on maximization of the conventional single-input single-output (SISO) WPT system in the literature. Especially, the reference (4) reveiled that the maximum efficiency in terms of *kQ* product, where *k* is the coupling ratio and *Q* is the quality factor.

In a larger WPT network where many transmitters and receivers exists, however, the optimization of SISO WPT derived by the previous works cannot be applied. SISO-WPT also has a problems in its flexibility and power transfer efficiency.

In this paper, we introduce the MIMO-WPT for improving the power transfer efficiency. Furthermore, we propose an extended MIMO-WPT for moving vehicles. The extended MIMO-WPT cancels the backward waves on the transmission line by making use of the RF generators implemented on the receiver side.

2. MIMO WPT SYSTEM

Let us suppose M transmitters and N receivers in a WPT network as shown in Fig. 1. The $M+N$ couplers are electro-magnetically coupled with each other. In the following, the m-th coupler $(1 \le m \le M)$ is used as a transmitter and the n-th coupler $(M+1 \le n \le M+N)$ is for a receiver. V_l and I_l are respectively the voltage and current at the l-th coupler node $(1 \le l \le M+N)$.

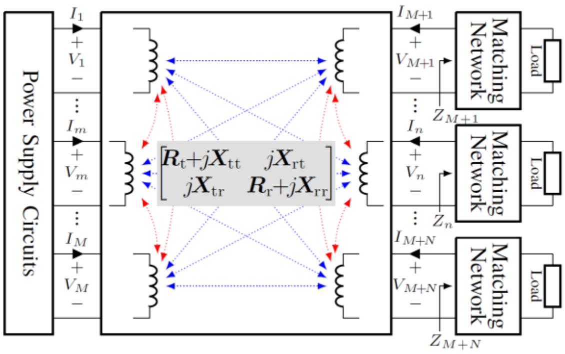

Fig. 1 $M \times N$ MIMO WPT System Model

The power transfer efficiency is given by

$$\eta = \frac{\sum_{n=M+1}^{M+N} I_n^* V_n}{\sum_{m=1}^{M} I_m^* V_m} = \frac{\boldsymbol{I}^H \boldsymbol{A} \boldsymbol{I}}{\boldsymbol{I}^H \boldsymbol{B} \boldsymbol{I}}$$

where $\boldsymbol{I} = [I_1, \cdots, I_l, \cdots, I_{M+N}]^T$ is a current vector and $\boldsymbol{I}^H$ is the Hermitian transpose of $\boldsymbol{I}$. $\boldsymbol{A}$ and $\boldsymbol{B}$ are the partial impedance matrices[5]. We can maximize the power efficiency by solving the equation:

$$\frac{\partial \eta}{\partial \boldsymbol{I}} = \boldsymbol{0}$$

In the following, we demonstrate the improvement in the power transfer efficiency by numerical analysis. Fig. 2 illustrates the configuration of the 2×2 MIMO-WPT system. In this system, we assume that two transmitter coils (coil 1 and 2) and two receiver coils (coil 3 and 4) are separated at the distance d. The system parameters are shown in Table 1.

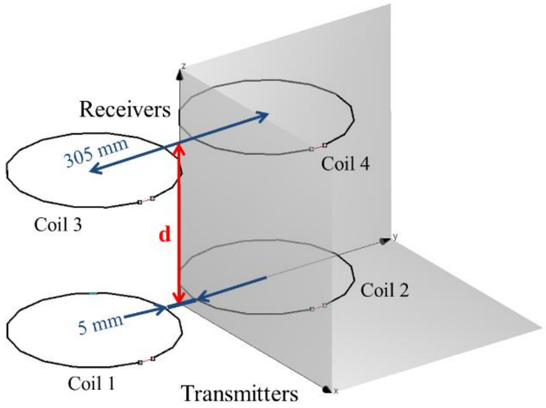

Fig. 2 2 × 2 MIMO WPT System Configuration

Table 1 System Parameters

parameter	value
frequency	13.56[MHz]
Analyzing method	Moment method
Radius of coil	150[mm]
Number of turns	1
Material of wire	Copper wire with φ2mm
conductivity	58[MS]

Fig. 3 shows the power transfer efficiency of the 2 × 2 MIMO-WPT system with and without optimization. The power transfer efficiency without optimization, or the conventional SISO-WPT based system, is around 10% at the distance between transmitter and receiver coils of 500mm. On the other hand, the proposed MIMO-WPT system gives the 50% of power transfer efficiency at the same distance.

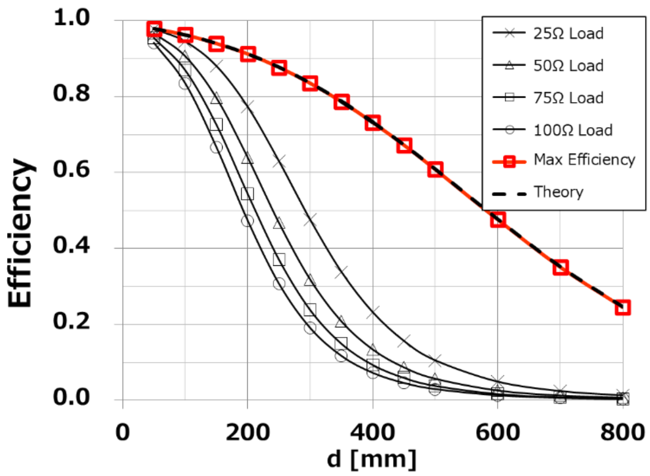

Fig. 3 Power transfer efficiency of the 2 × 2 MIMO WPT

3. MIMO FOR DINAMIC WPT

In this section, we extend the proposed MIMO-WPT system applicable to moving vehicles. Fig. 4 shows the extended version of the MIMO-WPT system. The parallel line feeder is implemented under the road. The RF generators are connected to the either end of the feeder. The two-port EM coupler is attached to the bottom of the vehicle. Each port is connected to the adaptive RF generator/load module. To control the adaptive RF generator modules to eliminate the backward waves on the parallel line feeder.

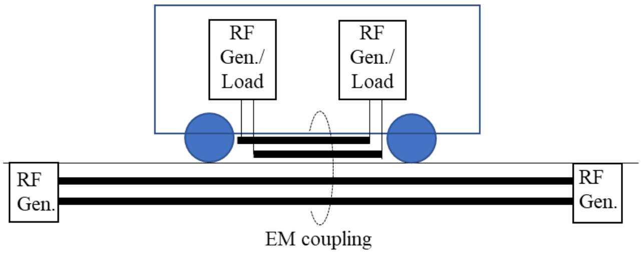

Fig. 4 Power transfer efficiency of the 2 × 2 MIMO WPT

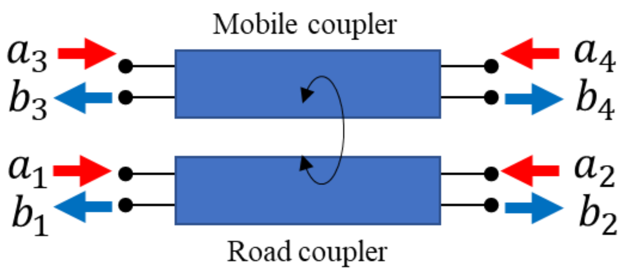

Fig. 4 MIMO Analytical Model

To explain the operation of the extended MIMO-WPT system, we use a four-port network model in Fig. 4. A pair of two-port couplers are electro-magnetically coupled. The overall network is considered as a four-port network. Let $\boldsymbol{a} = [\boldsymbol{a}_R \quad \boldsymbol{a}_M]^T = [a_1 \quad a_2 \quad a_3 \quad a_4]^T$ and $\boldsymbol{b} = [\boldsymbol{b}_R \quad \boldsymbol{b}_M]^T = [b_1 \quad b_2 \quad b_3 \quad b_4]^T$ be the forward and backward wave amplitude vectors, where $\boldsymbol{a}_R$ and $\boldsymbol{a}_M$ are the forward wave amplitude vectors for the road and the mobile nodes, respectively, and $\boldsymbol{b}_R$ and $\boldsymbol{b}_M$ are the backward wave amplitude vectors for the road and the mobile nodes, respectively.

The scattering matrix of the four-port network is given by

$$\boldsymbol{S} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & s_{14} \\ s_{21} & s_{22} & s_{23} & s_{24} \\ s_{31} & s_{32} & s_{33} & s_{34} \\ s_{41} & s_{42} & s_{43} & s_{44} \end{bmatrix} = \begin{bmatrix} \boldsymbol{S}_A & \boldsymbol{S}_B \\ \boldsymbol{S}_C & \boldsymbol{S}_D \end{bmatrix}$$

where

$$\boldsymbol{S}_A = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix}, \boldsymbol{S}_B = \begin{bmatrix} s_{13} & s_{14} \\ s_{23} & s_{24} \end{bmatrix},$$

$$\boldsymbol{S}_C = \begin{bmatrix} s_{31} & s_{32} \\ s_{41} & s_{42} \end{bmatrix}, \boldsymbol{S}_D = \begin{bmatrix} s_{33} & s_{34} \\ s_{43} & s_{44} \end{bmatrix}.$$

According to the definition of the scattering matrix, the backward wave amplitude can be given by

$$\boldsymbol{b} = \boldsymbol{S}\boldsymbol{a}$$

This equation can further be decomposed into the backward wave amplitude of the road and mobile nodes.

$$\boldsymbol{b}_R = \boldsymbol{S}_A\boldsymbol{a}_R + \boldsymbol{S}_B\boldsymbol{a}_M$$

$$\boldsymbol{b}_M = \boldsymbol{S}_C\boldsymbol{a}_R + \boldsymbol{S}_D\boldsymbol{a}_M$$

To solve the standing wave problem, the backward wave amplitude of the road $\boldsymbol{b}_R$ should be zero. When the RF generators on the mobile couple is controlled by

$$\boldsymbol{a}_M = \boldsymbol{S}_B^{-1}\boldsymbol{S}_A\boldsymbol{a}_R$$

This equation shows that we can remove the backward wave on the road coupler. This implies that we can remove the standing wave on the transmission line. It is known that standing wave causes unwanted radiation around the transmission line. So, we can reduce EMI (Electro-Magnetic Interference).

4. CONCLUSION

This paper proposed a MIMO-WPT system and showed that the proposed system is capable of improving the power transfer efficiency. Furthermore, we proposed an extended MIMO-WPT system for moving vehicle application. We can eliminate the backward waves on the transmission line implemented on the road by controlling the adaptive RF generators on the vehicle-side.

ACKNOWLEDGEMENT

This paper is based on results obtained from a project, JPNP21028, subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

REFERENCES

(1) Z. Zhang, H. Pang, A. Georgiadis and C. Cecati, "Wireless power transfer—An overview", IEEE Trans. Ind. Electron., vol. 66, no. 2, pp. 1044-1058, Feb. 2019.

(2) C.-S. Wang, O. H. Stielau and G. A. Covic, "Design considerations for a contactless electric vehicle battery charger", IEEE Trans. Ind. Electron., vol. 52, no. 5, pp. 1308-1314, Oct. 2005.

(3) J. Sallan, J. L. Villa, A. Llombart and J. F. Sanz, "Optimal design of ICPT systems applied to electric vehicle battery charge", IEEE Trans. Ind. Electron., vol. 56, no. 6, pp. 2140-2149, Jun. 2009.

(4) T. Ohira, "Angular expression of maximum power transfer efficiency in reciprocal two-port systems", Proc. IEEE Wireless Power Transf. Conf. Jeju South Korea, pp. 228-230, May 2014.

(5) Q. T. Duong and M. Okada, "Maximum Efficiency Formulation for Multiple-Input Multiple-Output Inductive Power Transfer Systems," IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 7, July 2018