Investigation and Simulation Model Results of High Density Wireless Power Harvesting and Transfer Method

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***Abstract*— The paper presents and provide simulation model results of a method for wireless power transfer by harvesting and/or transferring the switching ripple energy of the inductor current in a switching power converter. By placing a planar coil as a wireless power receiver (Rx) in the proximity of a power inductor of a power converter, wireless power can be received by the Rx coil because of the oscillating magnetic field generated by AC switching ripple of the inductor current. This yields a power converter with a wireless power transmitter (Tx) in addition to the original wired output of the power converter, therefore, eliminating the need for Tx side in an inductive wireless power transfer system. Using an example Buck-WPT system, which achieves step down power conversion for a wired output and WPT at the same time, this paper discusses the related operation principle and provide simulation model results.**

Index Terms — Wireless Power Transfer, Buck Converter, Consumer Electronics, Inductive Power Transfer, Maximum Power Transfer, Power Converter.

I. Introduction

Wireless Power Transfer (WPT) systems are increasingly being adopted or considered in new applications such as consumer electronics and electric vehicle charging, among others [1-5]. A conventional inductive WPT system normally includes a transmitter (Tx) side circuit, a Tx coil, a receiver (Rx) coil, and Rx side electronics/load. In most applications, a dedicated DC-AC power circuit is needed to drive the Tx coil in order to generate an oscillating magnetic field to transmit wireless energy/power to Rx [2-5].

A conventional DC-DC switching power converter, such as but not limited to buck and boost converters, supplies regulated voltage/current/power to a load from an energy source [6-9] through a wired (not wireless) connection. The power inductor is a critical part of most of these converters, which carry a current with a DC component and an AC switching ripple component [6-9]. This AC ripple/oscillating magnetic field is usually considered a disadvantage in terms of radiated electromagnetic interference (EMI) and conduction losses, but its potential for WPT has not been explored, until this paper.

This paper present a method to utilize this electromagnetic field as a result of the AC switching ripple which is a part of the current of the inductor in a switching power converter and utilizes it for WPT. By doing so, the power converter-WPT system achieves DC-DC power conversion (wired power transfer) and WPT function at the same time, which helps to eliminate the Tx side circuitry and Tx coil of the conventional WPT system and achieves size and cost reduction of the total system. Next section presents the operation principle of the proposed method based on an example Buck-WPT system (achieves step down DC-DC power conversion and WPT at the same time). Section III presents the simulation model results. Section IV gives the conclusion for the paper.

II. Operation Principle of the Buck-WPT System

Using Buck-WPT system as an example, this section presents the concept and operation principle of Power converter-WPT system that realizes DC-DC power conversion (wired power transfer) and WPT operation at the same time.

Fig. 1 illustrates the circuit diagram of the Buck-WPT system. The system has one input V_{in} and two outputs: one for WPT, which is referred to as V_{o_WPT}, and one for wired power transfer, which is referred to as V_{o_wired}. Fig. 2 illustrates the main operation waveforms for Buck-WPT system. The current of the inductor $i_l = I_o + i_{ripple}$ by superposition consists of the DC current component (I_o) and the AC ripple current component (i_{ripple}). V_{node} is the voltage at the phase node. In a Buck-WPT system, V_{o_wired} and V_{o_WPT} can operate simultaneously.

The wired power path has the same operation as the conventional buck converter without WPT. The power inductor L_1 and output capacitor C_o are used to form the LC low pass filter leading to V_{o_wired}. The WPT power path does not have a stand-alone Tx side driving circuit and Tx coil. Instead, it utilizes the buck converter power stage as the Tx side circuit and uses power inductor L_1 as the Tx coil. The AC component of the inductor current is used to achieve WPT. This is because the AC ripple of the current generates oscillating magnetic field in the proximity of the Tx coil with L_1, which can be used for inductive WPT to a receiver Rx.

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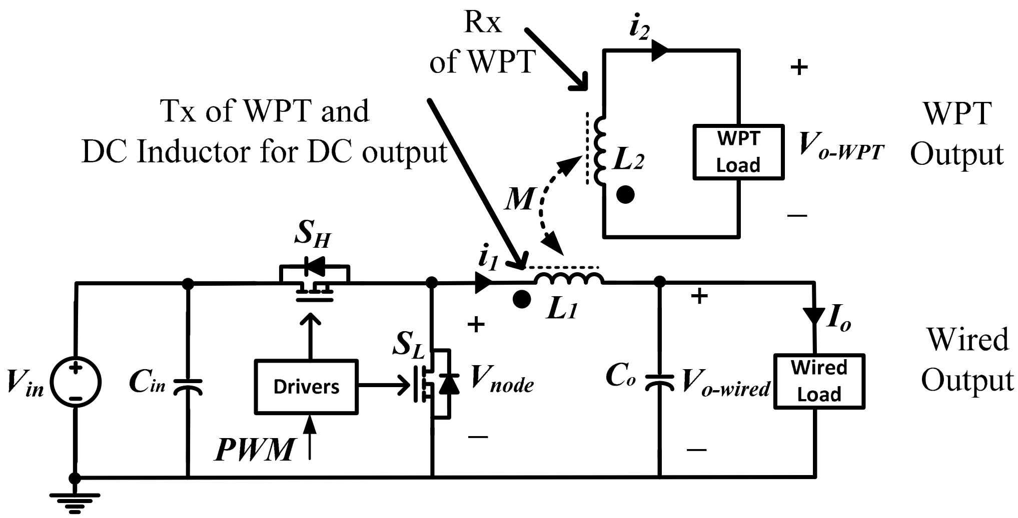

Fig. 1. Illustration diagrams of proposed Buck-WPT system

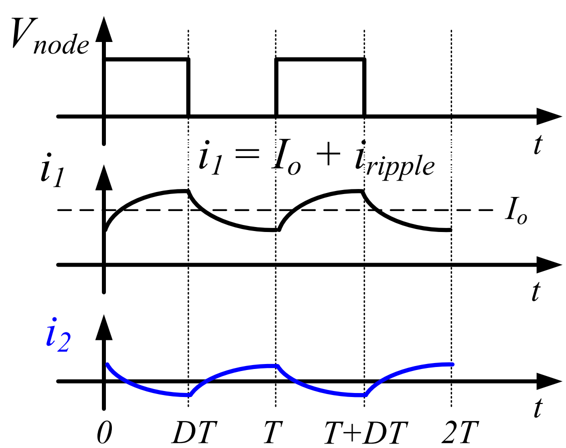

Fig. 2. Illustration for the main operation waveforms for Buck-WPT system.

When a planar receiver (Rx) coil with L_2 is placed in the proximity of the planar Tx coil, the Tx and Rx coils are coupled through a mutual inductance *M*. As a result, certain amount of power can be delivered to the WPT load (R_{WPT}). The Buck-WPT system eliminates Tx side circuitry and Tx coil compared with the conventional WPT system, which helps to reduce the size and cost of the total system.

III. Simulation Model and Results

An LTspice [10] model for Fig. 1 is developed with the main specifications shown in Table I. Fig. 3 through Fig. 5 show sample results waveforms as selected coupling factor k value varies, which simulates varying the distance between Tx and Rx. Fig. 6 shows a plot of the received average power at Rx side as a function of k (for $R_{WPT} = 2\ \Omega$). Fig. 7 shows a plot of the received Average power at Rx side as a function of R_{WPT} (for k = 0.8).

Table I. Simulation model main parameter specifications

Parameter	Value
V_{in}	12 V
$V_{o\ wired}$	5 V
R_{WPT} nominal load	2 Ω
Switching frequency	200 kHz
L_1	3 μH
L_2	9 μH
k	0.6 ~ 0.8

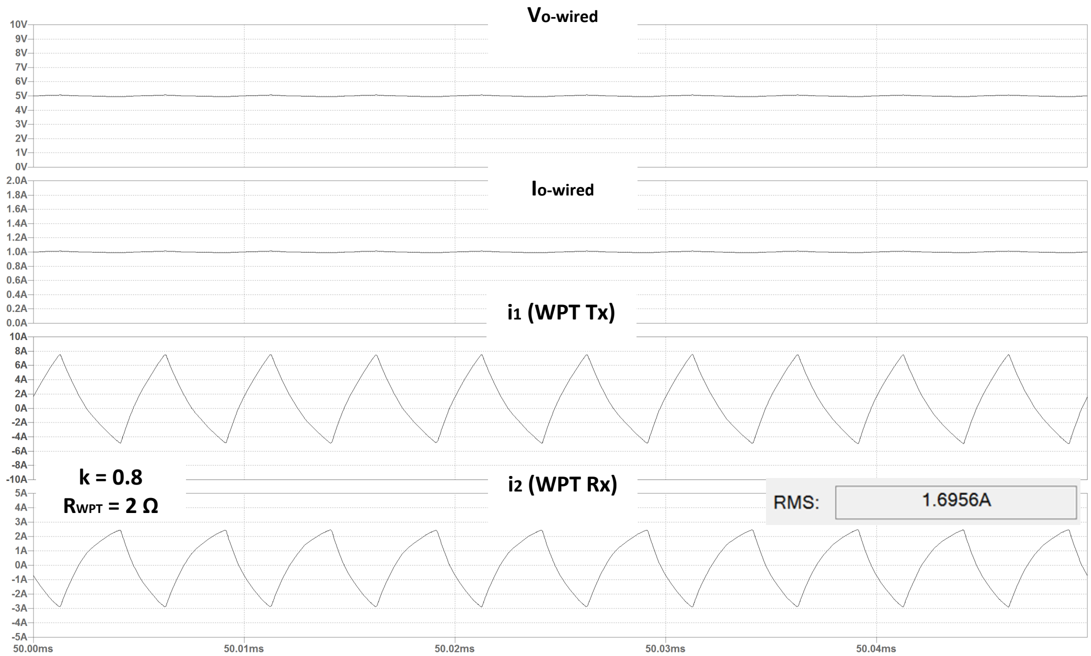

Fig. 3. Sample waveforms when coupling factor k = 0.8.

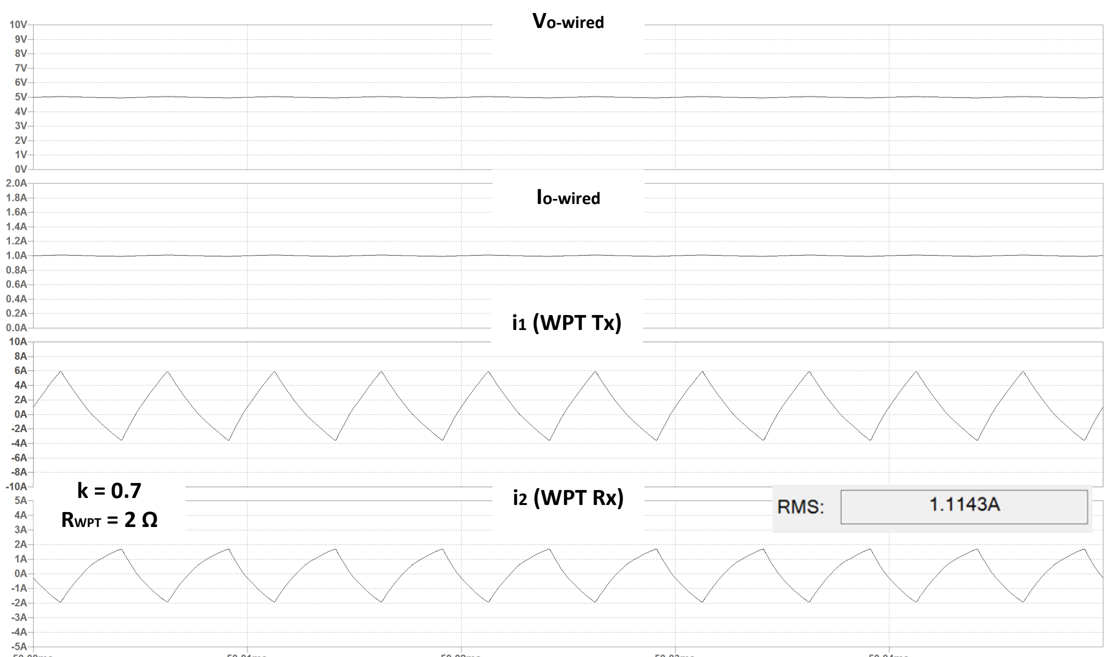

Fig. 4. Sample waveforms when coupling factor k = 0.7.

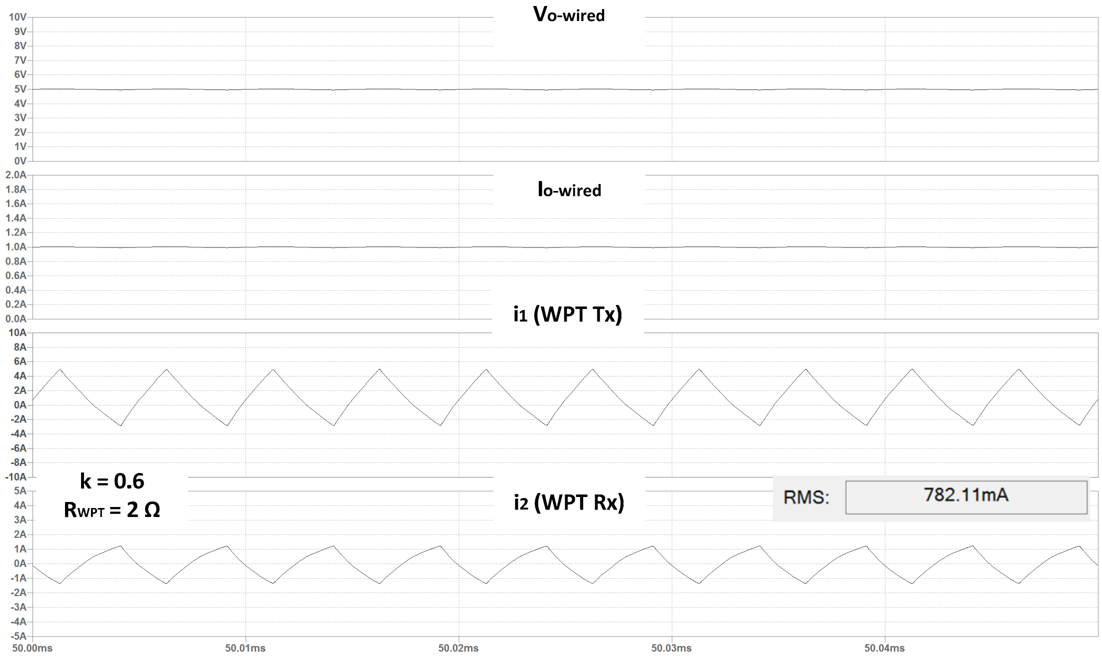

Fig. 5. Sample waveforms when coupling factor k = 0.6.

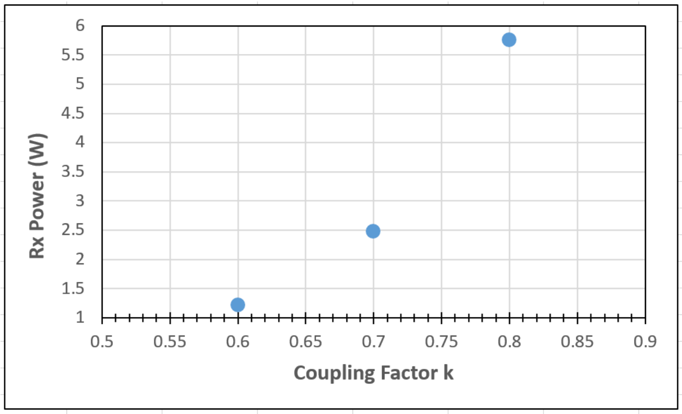

Fig. 6. Average power at Rx side as a function of k (for $R_{WPT} = 2\ \Omega$).

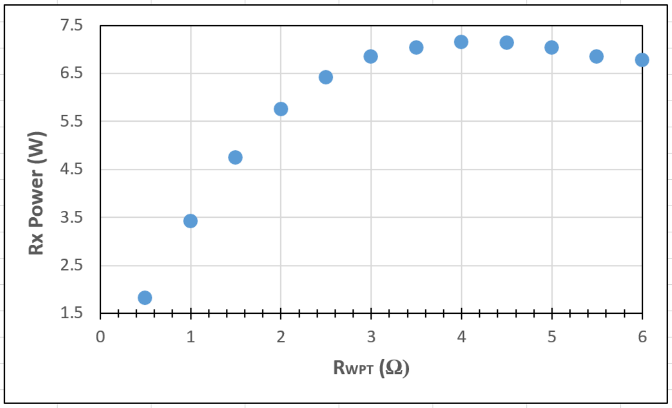

Fig. 7. Average power at Rx side as a function of R_{WPT} for k = 0.8.

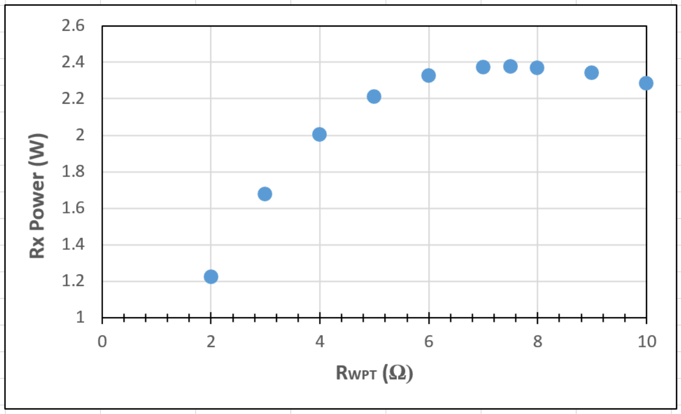

Fig. 8. Average power at Rx side as a function of R_{WPT} for k = 0.6.

Fig. 6 shows how the received power increases as the coupling factor k increases (one reason of coupling factor increase is reduction of distance between Tx and Rx). This also can be observed as the current rms value through R_{WPT} = 2 increases when k increases ($P_{WPT} = I_{2-rms}^2 \times R_{WPT}$).

Fig. 7 indicates that the maximum wireless power received when k = 0.8 occurs when the value of R_{WPT} is around 4 Ω. Fig. 8 indicates that the maximum wireless power received when k = 0.6 occurs when the value of R_{WPT} is around 7.3 Ω. However, the maximum power received when k is lower is smaller, which is expected.

IV. Conclusion

The simulation model results presented in this paper demonstrate the operation of a concept that allows the utilization of a switching power converter with a power inductor as a wireless power transmitter while maintaining the original operation of delivering a wired output. By taking a DC-DC buck converter as an example, the simulation model shows how a wireless output and a wired output are realized while keeping the number of components the same, i.e., two switches and a power magnetic device. The simulation model is utilized in this paper to study the effect of coupling factor and wireless power load on the operation and received power.

References

[1] N. Tesla, "System of transmission of electrical energy," U.S. Patent, No. 645576, Mar, 20, 1900.

[2] Z. Dang, Y. Cao and J. A. Abu Qahouq, "Reconfigurable Magnetic Resonance-Coupled Wireless Power Transfer System," IEEE Trans. Power Electron., vol. 30, no. 11, pp. 6057-6069, Nov. 2015.

[3] J. M. Miller, O. C. Onar, and M. Chinthavali, "Primary-side power flow control of wireless power transfer for electric vehicle charging," IEEE J. Emerg. Sel. Topics Power Electron., vol. 3, no. 1, pp. 147–162, Mar. 2015.

[4] Y. Cao., Z. Dang, J. A. Abu Qahouq and E. Phillips, "Dynamic efficiency tracking controller for reconfigurable four-coil wireless power transfer system," IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 3684-3689, March, 2016.

[5] D. Patil, M. Ditsworth, J. Pacheco, and W. Cai, "A magnetically enhanced wireless power transfer system for compensation of misalignment in mobile charging platforms," 2015 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 1286-1293, 2015.

[6] W. Huang, J. A. Abu Qahouq, and Z. Dang. "CCM-DCM Power-Multiplexed Control Scheme for Single-Inductor Multiple-Output DC-DC Power Converter with No Cross-Regulation," IEEE Trans. Ind. Applications, vol. PP, issue 99, pp. 1-1, 2016. DOI: 10.1109/TIA.2016.2630018

[7] Wangxin Huang and Jaber Abu Qahouq, "Input-Voltage Ripple-Based Sensorless current sharing auto-tuning controller for multiphase DC-DC converters," IEEE Transactions on Industry Applications, Vol. 52, No. 5, Page(s): 4117-4125, Sept.-Oct, 2016. DOI: 10.1109/TIA.2016.2570205

[8] Z. Dang and J. A. Abu Qahouq, "Permanent magnet coupled power inductor for multi-phase DC-DC power converters," IEEE Trans. Ind. Electron., vol. 99, pp. 1-1, 2016. DOI: 10.1109/TIE.2016.2626364

[9] Z. Dang and J. Abu Qahouq, "Evaluation of High-Current Toroid Power Inductor With NdFeB Magnet for DC–DC Power Converters," IEEE Trans. Ind. Electron., vol. 62, no. 11, pp. 6868 – 6876, Nov. 2015. DOI: 10.1109/TIE.2015.2436361

[10] Linear Technology, LTspice software, last accessed online November 15th 2016 at http://www.linear.com/designtools/software/.