Wireless Power Transfer Converter for Energy Hub Applications with Various Loads

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***Abstract* - A wireless power transfer (WPT) converter for'Energy Hub' system is proposed in home applications such as charge electric equipment. For high power factor capability, the proposed system adopts an additional secondary power factor correction (PFC) circuit. It can operate both of resistive load and resistive load with additional power circuit, which is multi-functional in the energy hub system. The proposed WPT converter can obtain high power factor without bulky components of passive or active PFC filter in the primary side. In addition, the proposed WPT converter can reduce the number of power stages to improve cost-effectiveness and increase power density.Using soft switchingcircuitsinstead of pulse generator, to improve performance and efficiency of proposed WPT converter without losses.**

Index Terms – Energy Hub, Impedance Compensation, Resonant Power Converter, Wireless Power Transfer

I.INTRODUCTION

For indoor power applications, wireless power transfer (WPT) technology can be adopted as the multi-functional converter for 'Energy Hub'. It can transfer electric energy to both of a single resistor which works as a heating equipment and other DC applications to charge electric equipment, so that it can be utilized as an energy herb in home. In order to be used as the indoor applications, the reliability of the converter should be high to guarantee safety within small manufacturing cost.

In precedent study, the WPT converter with the secondary side PFC is already shown in reference [1]. However, it was only focused on the operating feature and performance based on perspective of quality factor. Also there are many literatures to increase the power density of WPT converters [2-3]. They used advanced switching devices such as SiC and GaN to increase the switching frequency and decrease the size of passive components, however, it increased manufacturing cost.The proposed WPT converter has focused on reducing the number of power stages to increase cost-effectiveness and power density. The conventional WPT converter has a Power Factor Correction (PFC) circuit in primary side. On the other side, the proposed WPT converter does not contain the PFC circuit in the primary side. Also, a high frequency inverter adopted a Half-Bridge (HB) inverter to decrease the manufacturing cost. Due to the small number of power stagesand components, the proposed WPT converter can achieve high cost-effectiveness and power density. In addition, it can operate both of resistive AC load and capacitive DC load, so that it can be utilized as a multi-functional converter with cost reduction.

In this paper, the proposed WPT converter will be introduced and analyzed using an impedance analysis method in detail. In addition, the design considerations of the proposed WPT converter will be discussed, based on analysis results. The operation and performance of the proposed WPT converter will be verified using a 500 W prototype converter.

II.OPERATION OF PROPOSED WPT CONVERTER

The schematic of the proposed WPT converter is shown in Fig. 1. The proposed WPT converter can deal with both of resistive load and resistive load with additional power circuit. The basic operation of both modes is represented as the resistive load. The proposed WPT converter used a passive full-wave diode bridge with small LC input filter in input side to rectify the AC voltage.

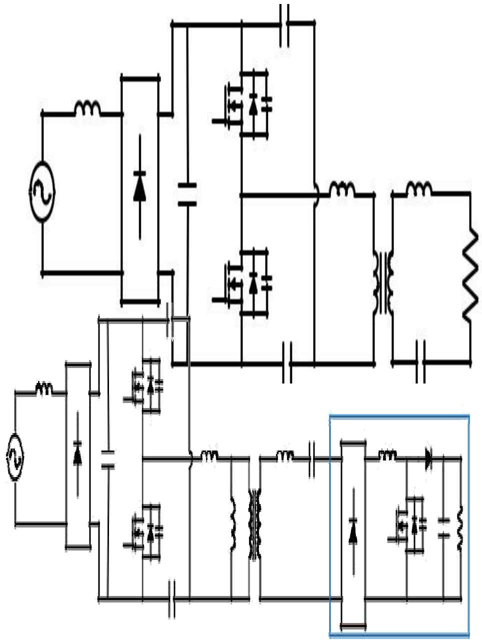
Due to passive rectifying circuit with small reactive components, it can increase high input power factor. The high frequency inverter uses the Half-Bridge (HB) resonant topology for the primary side power conversion to increase the cost-effectiveness. The resonant for compensating the leakage inductance of the coil is Series-Series (SS) in both of primary and secondary. The secondary side consists of resonant capacitor and PFC. The power capability of the primary side can be decreased due to the small input reactance of the PFC, because it does not have to deal with the high circulating current of the WPT converter from input impedance mismatch. Therefore, the primary current can be reduced compared with the conventional WPT converter.

PFC is normally achieved by the addition of capacitors to the electrical network which compensate for the reactive power demand of the inductive load and thus reduce the burden on the supply. There should be no effect on the operation of the equipment. To reduce losses in the distribution system, and to reduce the electricity bill, power factor correction, usually in the form of capacitors, is added to neutralize as much of the magnetizing current as possible.

Capacitors contained in most power factor correction equipment draw current that leads the voltage, thus producing a leading power factor.

CIRCUIT DIAGRAM

(a)



(a)

(b)

Figure 1.Schematic of the proposed WPT converter (a) Resistive load (b) resistive load with additional power circuit

The primary side rectifies the line frequency using a diode rectifier and a small capacitor, so the power-factor is almost unity. However, the line frequency cannot be rectified to pure DC voltage, the voltage transferred to the secondary side has multiple frequency components.The effect from line frequency can be analyzed by frequency-domain analysis. The output power which is affected by low line frequency component is derived as follows:

POWER FACTOR

Power factor is the ratio of real power flowing to the load to the apparent power. Apparent power is the product of the current and voltage of the circuit. Due to energy stored in the load and returned to source, or Due to a non-linear load that distorts the wave shape of the

$$P_{out}(\omega)=\frac{V_{in}^2}{R_0^2}\left[G_v^2(\omega-(\omega_s-\omega_{low}))+G_v^2(\omega-(\omega_s+\omega_{low}))\right]$$

$$\approx \frac{2}{R_0^2} V_{in}^2 G_v^2(\omega_s)$$

where V_{in} is the RMS value of the input voltage, G_v is the input-output voltage gain of the proposed WPT converter in frequency domain, ${}_s$ and ${}_{low}$ are the switching frequency and the line frequency respectively, P_{out} is the transferring power, and R_o is the output resistance.operating waveforms of the resistive load, and Fig. 5 and 6 show the operating waveforms of the resistive load with additional power circuit. The resonant frequency of each operating mode is performed by a range of solutioncurrent drawn from the source, the apparent power will be greater than the real power. A negative power factor occurs when the device (which is normally the load) generates power, which then flows back towards the source.

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III DESIGN CONSIDERATIONS

The proposed WPT converter shown in fig.1 can be simplified into its average model with a sinusoidal input based on First Harmonic Approximation (FHA), which is described in Fig. 3.1. Under an assumption that the PFC can regulate the voltage and current in phase perfectly in secondary side, it can be represented as a single resister Ro. The input-output voltage gain of the proposed WPT converter according to the frequency variation is analyzed to obtain proper operating region. In addition, the proposed WPT converter has an advantage that the primary side current is smaller than other HB topologies due to its resonant tank configuration. In order to utilize the advantage in the power stage design, the primary side current is taken into the analysis. Assuming the turn ratio of coil is 1:1, the input output voltage gain and Root Mean Squre (rms) value of primary side current can be calculated as (2) and (3) 4.

SIMPLIFIED CIRCUIT MODEL

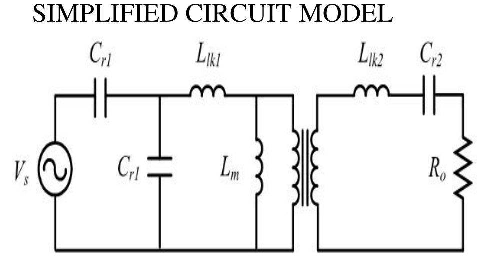

Figure 2.The simplified circuit model of the WPT converter

DERIVED EQUATION

$$G_v = \left[\left[1+2\frac{R_c}{R_0}+\frac{1-k}{k}\left(1+\frac{R_c}{R_0}\right)\left(1-\frac{1}{\omega^2}\right)\right]^2+\left[Q_{ac}\left(\omega-\frac{1}{\omega}\right)\left(1+\frac{1-k}{2k}\left(1-\frac{1}{\omega^2}\right)\right)\right]^2\right]^{\frac{1}{2}}$$

$$Q_{ac}=\frac{\omega_0}{R_0}(L_{lk1}+L_{lk2}),\omega_0=\frac{1}{\sqrt{2C_{r1}L_{lk1}}}=\frac{1}{\sqrt{C_{r2}L_{lk2}}}=2\pi f_0$$

$$I_{pri}=\frac{V_{in}}{Z_{in}}=\frac{V_{in}}{2Q_{ac}R_0}\left[\frac{Q_{ac}^2\left[\omega^2\left(1+\frac{2k}{1-k}\right)+\frac{2}{\omega^2}-\frac{3}{1-k}\right]^2+4\left(\frac{\omega}{1-k}-\frac{2}{\omega}\right)^2}{4\left(\frac{1}{1-k}-\frac{1}{\omega^2}\right)^2+Q_{ac}^2\left[\omega\left(1+\frac{2k}{1-k}\right)-\frac{1}{\omega^3}\right]^2}\right]^{\frac{1}{2}}$$

$$I_{pri,\min}\approx I_{pri}\left(\omega=\frac{1}{\sqrt{L_s C_{r1}}}\right)$$

where Q_{ac} is quality factor (Q-factor), f_o and $_o$ are the resonant frequency and the resonant angular frequency, C_{r1} and C_{r2} are the Primary and secondary compensation capacitors, L_s, L_{lk1} and L_{lk2} are the self-inductance, the primary and secondary leakage inductance of the WPT coil, andR_c is the practical resistance of the WPT coil, respectively.

Fig. 4 shows that the input to output voltage gain of the proposed WPT converter in accordance with the quality factor variation. In addition, zero voltage switching (ZVS) and zero current switching (ZCS) condition regions are given by the voltage gain curve 4-5. In the ZVS and ZCS regions, the switching loss of the converter can be minimum and the voltage gain can be monotonic enough to adopt a linear controller for regulating the output voltage and for making the power stage design clear. Fig. 4.2 (b) shows that the rms value of the primary side current in accordance with the quality factor variation. It shows that the minimum primary side current occurs the resonant frequency of the resonant capacitor and the self-inductance of the WPT coil. The reason of the minimum primary current is that the parallel resonance of primary resonant capacitor and the self inductance in the equivalent circuit in Fig. 4.1. It gradually increases according to the switching frequency increment.therefore the operation region is limited by the minimum point of the primary side current to minimize the conduction loss of the primary side. The proper operating frequency is limited by the minimum primary current and ZVS, ZCS region. Thus, the proper operating frequency region is between the resonant frequency of leakage inductance and self inductance with the resonant frequency. The proper operating frequency can be defined as shown in (4).

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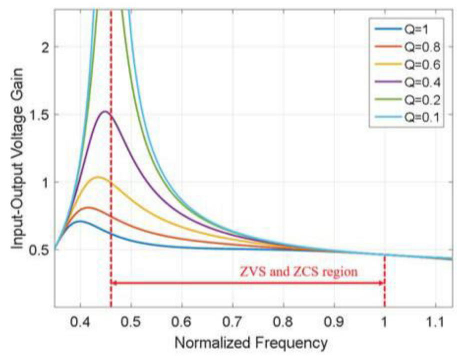
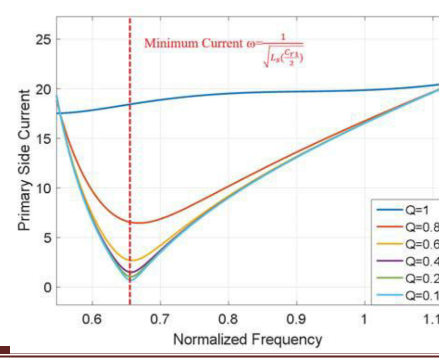
$$\frac{1}{2\pi\sqrt{L_s C_{r1}}}\le f_{sw}\le\frac{1}{2\pi\sqrt{L_{lk} C_{r1}}}$$

ANALYSIS RESULTS



(a)

The operating condition of proposed WPT converter can be changed from many issues, such as input voltage distortion and rapid load change. Despite of the variations, it should regulate the output voltage to keep high reliability of converter. The secondary PFC circuit regulates output voltage as a closed-loop control, the input voltage of PFC should be covered within the capable closed-loop control range. Therefore, the output voltage which is defined by input-output voltage gain of the proposed WPT converter should be fixed as (5) for its stable voltage regulation.



(b)

Figure 3. Voltage gain and primary current analysis results: (a) Input-Output Voltage Gain, (b) Primary current

$$V_{in,\min}G_v(\omega=1)\le v_{in,PFC}\le V_{in,\max}G_v\left(\omega=\frac{1}{\sqrt{L_sC_{r1}}},Q_{\min}\right)$$

where $V_{in,min}$ and $V_{in,max}$ are the minimum and maximum input voltage from the grid, $v_{in,PFC}$ is the designed input voltage range, respectively.

IV EXPERIMENTAL RESULTS

The proposed WPT converter's design specifications are listed in Table I. The steady state waveform of the proposed WPT converter at full load (500 W) is shown in Fig. 4-6. Fig. 4 shows the operating waveforms of the resistive load, and Fig. 5 and 6 show the operating waveforms of the resistive load with additional power circuit. The resonant frequency of each operating mode is the same frequency. Moreover, the operating waveforms of the resistive load shows that the output voltage of the proposed WPT converter has multi-frequency components, high switching frequency and low line frequency. Due to the secondary side PFC, the proposed WPT converter can rectify the AC voltage into the DC voltage at capacitive load operation. Fig. 6.shows the operating waveforms of the proposed WPT converter, specifically focused on the operation of PFC at full load. Due to small imaginary input impedance of the proposed WPT converter, the input current distortion is very small. Although the input voltage of PFC stage has multiple frequency components, which is shown in the resistive load operation, the PFC regulated into pure DC voltage. The output voltage ripple is around 30 V which is 10% of output voltage, but it can be solved by developing the performance of PFC.

The comparison of power factor and power transfer efficiency for each operating mode of the proposed WPT converter is shown in Fig. 7. Since the primary side of both operating modes are the same, the input power factor converges into a single curve and it achieved about 0.94 at full load condition (500 W). The power transfer efficiency shows different results each other. The capacitive load of uses additional power stage, which includes PFC circuit to regulate the output voltage, the capacitive load operating mode has lower power transfer efficiency then the resistive load. The resistive load achieved around 93% of power transfer efficiency at 400 W, and the capacitive load achieved around 90% at 500 W.

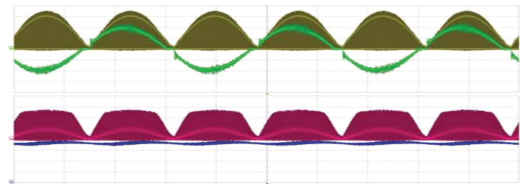
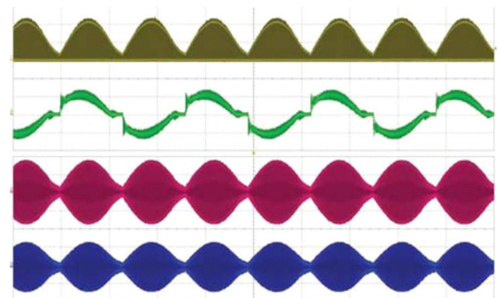
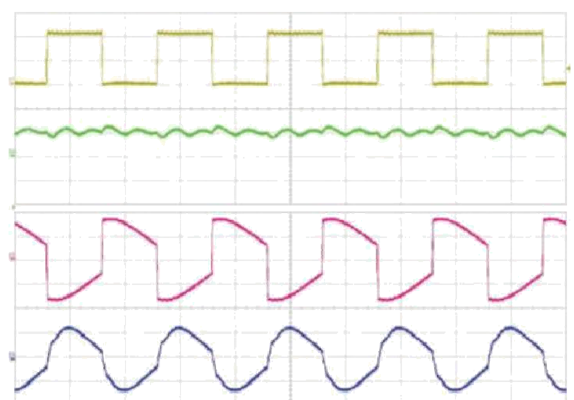


Figure 6. Experimental waveforms of PFC at the steady-state for the capacitive DC load (from top to bottom; V_{ds} 100 V/div, I_{in}5 A/div,$V_{in,PFC}$200 V/div,V_{out}100 V/div, 10 s/div)

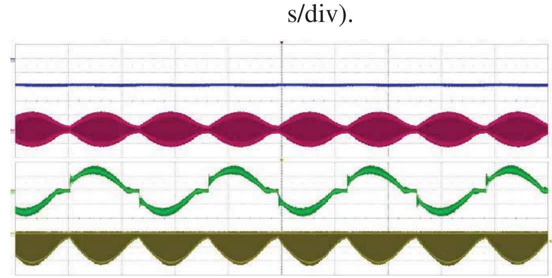


(a)

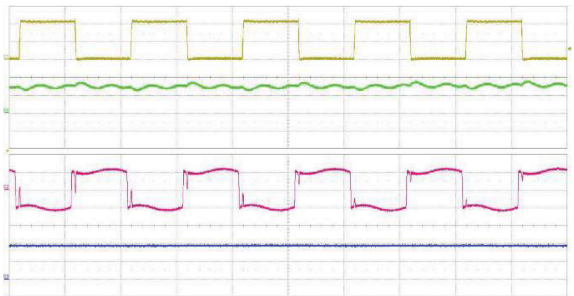


(b)

Figure 4. Experimental waveforms of the proposed WPT converter at the steady-state for the resistive AC load (from top to bottom; V_{ds} 200 V/div, I_{in} 2 A/div, $V_{coil,in}$ 200 V/div, V_{out} 200 V/div): (a) Line frequency scale waveforms (6.4 ms/div)(b) Switching frequency scale waveforms (10 s/div).



(a)



(b)

Figure 5.3 Experimental waveforms of the proposed WPT converter at the steady-state for the resistive load with additional power circuit (from top to bottom; V_{ds} 200 V/div, I_{in} 2 A/div, $V_{in,PFC}$ 200 V/div

IV CONCLUSION

In present applications, WPT converter proposed for the energy hub with high power density. Cost effectiveness, and power transfer performance. It reduces the number of power stages and components compared with the conventional WPT converter. In addition, it has smaller primary current due to the secondary side PFC circuit. The proposed WPT converter is tuned using the impedance network analysis in the frequency domain, and the input-output voltage gain and the primary current are also analyzed. Based on those analysis results, the design considerations of the proposed WPT converter is derived.

Modify the converter line and switching frequency pulses to improve performance and efficiency.

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