Characterization of Novel Inductive Power Transfer Systems for On-Line Electric Vehicles

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Abstract— **The Inductive Power Transfer System (IPTS) for On-Line Electric Vehicle (OLEV) developed at KAIST is fully characterized in this paper. The proposed IPTS includes Tesla's resonant transformers and show quite different characteristics comparing with conventional transformers. A current source instead of a voltage source is used for the IPTS at the primary side, and the system is fully resonated for maximum power delivery unlike other IPTS's. The proposed IPTS inherently has novel input/output characteristics. It is quite robust to abrupt the load change raised by the vehicle in-rush or power fluctuation. Furthermore the output voltage of the IPTS is nearly constant regardless of output power, and the output current may increase regardless of source current.**

It is shown in this paper that the IPTS is equivalently an ideal voltage source, hence the output current can be infinite theoretically. The limiting factors in practice are found to be the resonant frequency variation and the parasitic resistances. It is thoroughly verified by simulations and experiments.

I. INTRODUCTION

Electric Vehicles (EV) such as Plug-in Hybrid EV (PHEV) and Pure EV (PEV) have been widely developed to comply with CO_2 emission standards because transportation produces about 23 % of the global greenhouse gases, CO_2 [1]. However, they still have serious battery related problems. Battery weight of EV is very high, from 60 Wh/kg to 96 Wh/kg [2], so it exceeds 200 kg if a car requires 20 kWh. The price of battery is also high, about $1,000/kWh. Furthermore, the charging time of at least 10~20 minutes and charging frequency of every 100~200 km distance are quite inferior to conventional gasoline cars.

To overcome the problems of EV, KAIST has been developing OLEV [3], which stems from previous Road Powered EV [4]. The OLEV picks up power from roadway-buried power rails, therefore the battery capacity can be reduced up to 1/5. For practical application, the IPTS for OLEV has been developed to satisfy the following requirements:

1) Power and efficiency: 60 kW for a bus and 20 kW for a car with more than 70 % (83% achieved)
2) Air gap (the height of pick-up): larger than 12 cm in Korea (16 cm in Japan) for road regulation
3) Lateral displacement: larger than 20 cm for free driving on a road
4) EMF: less than 62.5 mG at 20 kHz for ICNIRP recommendation
5) Infra cost: less than $ 0.4 million/km for one way including inverters, and power rails.

To transfer high power to pick-ups and reduce voltage and current rating of the power supply, the IPTS should be in resonant mode. The IPTS operating like an ideal transformer by employing series-parallel resonant circuit was proposed [5]. However, the resonant frequency of the series-parallel resonant circuit varies by the load resistance change. So it cannot be applied to the IPTS requires a wide range of load variation such as OLEV.

In this paper, an innovative IPTS for OLEV is proposed, analyzed, and verified both by simulations and experiments. It is proved that the IPTS is simply an equivalent ideal voltage source by employing the full resonant circuit in pick-up's [9] and the constant current input source. Hence the output current can theoretically be infinite. The limiting factors in practice are found to be a resonant frequency variation and internal resistances. The proposed IPTS has been patented [6]-[8] since last year based on extensive field tests at KAIST in Korea prior to the results [5].

II. ANALYSIS OF FULL-RESONANT-CURRENT-SOURCE IPTS

A. Overall Configuration

The IPTS consists of a power inverter, power rails, and pick-up's as shown in Fig. 1. The power inverter developed has 380 V, 3-phase, 60 Hz input, and supply 20 kHz, 200 A current. To make the IPTS robust to the load change and

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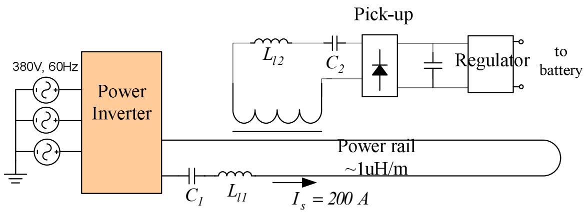


Fig. 1. Overall configuration of IPTS: inverter, power rail, and pick-up

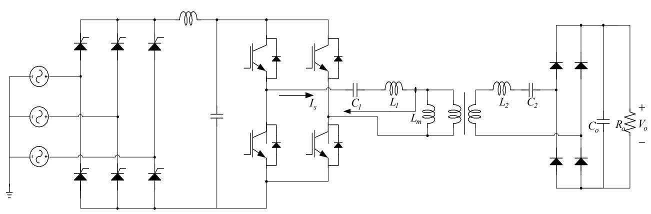
power fluctuation, a current source is used at primary side. The circuits of IPTS are also fully resonated for maximum power delivery with the inverter switching frequency (ω_s).

B. Current Source IPTS

The inverter proposed in this paper operates at the switching frequency (ω_s) higher than the primary resonant frequency (ω_c) where $\omega_c = \dfrac{1}{\sqrt{L_1 C_1}}$. The supply current is determined by residual inductance (ΔX_{L_1}) as follows:

$$I_s = \frac{V_{in}}{\Delta X_{L_1}} \quad (\because \Delta X_{L_1} = \omega_s L_1 - \frac{1}{\omega_s C_1}) \tag{1}$$

The current is so regulated that it becomes a constant current source as shown is Fig. 2, where V_{in} is the voltage difference between the input voltage (V_s) and the magnetizing inductance voltage (V_{L_m}).



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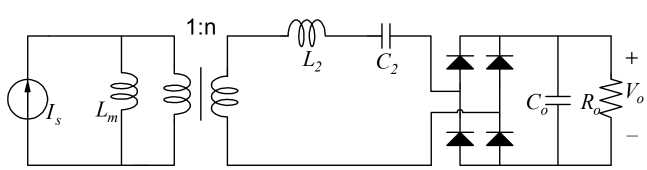


(b)

Fig. 2. Current control of IPTS (a) and its equivalent circuit(b)

C. Full-Resonant IPTS

Fig.3 shows an equivalent circuit from the primary side. A conventional IPTS of secondary-only resonance as shown in Fig. 4, where the impedances of pick-up leakage inductance and its compensation capacitance are same as determined (2), limits the output power capability as shown in Fig. 5.

$$\omega_s L_2 + \frac{1}{\omega_s C_2} = 0 \tag{2}$$

To overcome this drawback a full-resonant IPTS is proposed as shown in Fig. 4, where the capacitance (C_2) is given by:

$$\omega_s L_m + \omega_s \frac{L_2}{n^2} + \frac{1}{n^2 \omega_s C_2} = 0 \,, \tag{3}$$

where L_m is the magnetizing inductance, L_2 is the leakage inductance of a pick-up, and n is a turn ratio. From the equivalent circuit in Fig. 6, the output voltage and power are as follows:

$$I_o = I_o^* / n = \frac{jn\omega_s L_m I_s}{R_o} \tag{4}$$

$$V_o = nV_o^* = jn\omega_s L_m I_s \tag{5}$$

$$P_o = \frac{|V_o|^2}{R_o} = \frac{(n\omega_s L_m I_s)^2}{R_o} \tag{6}$$

The output voltage of the proposed IPTS is constant like an ideal voltage source, hence the output current may ideally increase infinitely. The phasor vector plots in Fig. 6 show that the output current leads the source current by $\dfrac{\pi}{2}$ and may increase much larger than the source current. These are unique characteristics of the proposed IPTS as well as the curious Tesla coils. On the other hand, the current and voltage of a conventional transformer highly depends on each other. Because of the phase difference between I_s and I_o, it is found that the active EMF cancellations for I_s and I_o should be separated from each other.

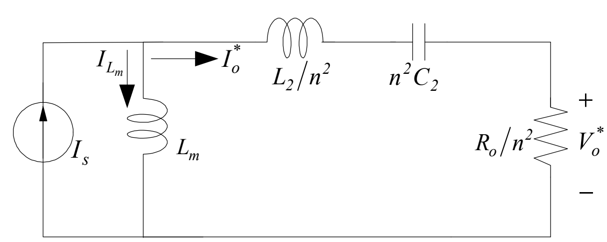


Fig. 3. Equivalent circuit from the primary side of IPTS (n is a turn ratio)

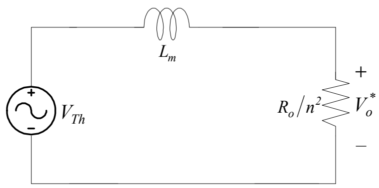
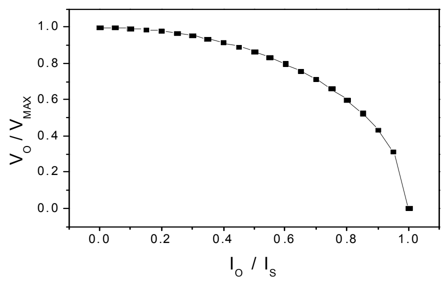


Fig. 4. Secondary resonant only circuit (V_{Th} is a Thevenin voltage)



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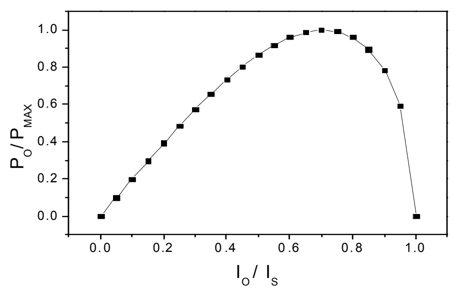
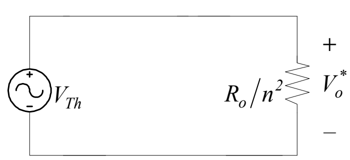


(b)

Fig. 5. Characteristics of V_o (a) and power (b) of IPTS of secondary-only resonance: simulation results



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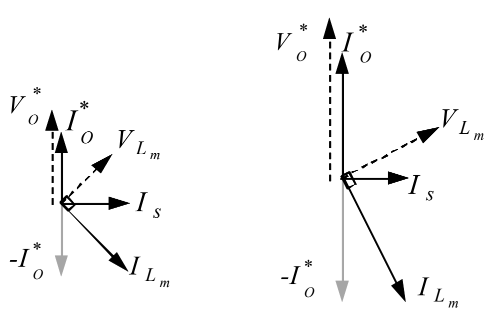
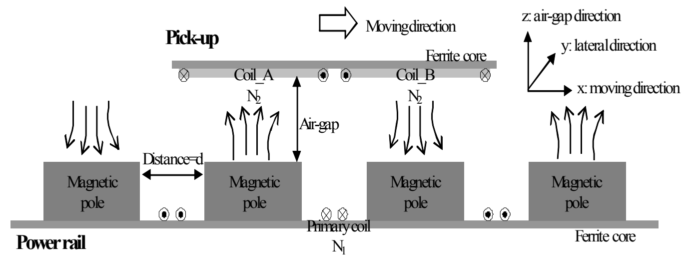


(b)

Fig. 6. Simplified equivalent circuit of the proposed full resonant IPTS (a) and the phasor vectors for light load (left) and heavy load (right) (b)



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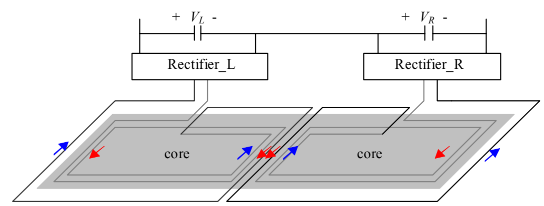


(b)

Fig. 7. Proposed narrow width power rail (a) and pick–up's (b)

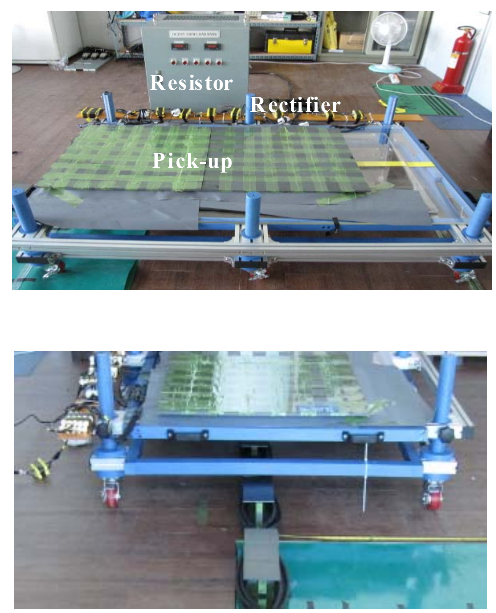


Fig. 8. The proposed IPTS for experiment: Power rail, Pick-up

III. EXPERIMENTAL VERIFICATION OF THE IPTS

The IPTS for experiment is shown in Fig. 7 and 8. The IPTS used here is a newly proposed I-type narrow-width power rail where the polarities of magnetic poles are alternating along with the roadway direction [5].

Simulations are performed for both the secondary-only resonance and the full resonance cases ignoring other parasitic components and internal resistances of the pick-up. Simulation results of Fig. 9 show that the output voltage abruptly decreases for the secondary-only resonance case, whereas it keeps constant regardless of output current for the proposed full resonance case as analyzed in previous section.

Experiment results also show that there is no abrupt voltage drop like the secondary-only resonance case until I_o=70 A. It is verified by the experiments that there are two categories of the voltage drop: the linear voltage drop, and the abrupt voltage drop as shown in Fig. 10. By changing the switching frequency, it is identified that the abrupt voltage drop is due to the resonant frequency variation of the IPTS for an excessive I_o. This abrupt voltage drop is alleviated when the switching frequency is appropriately changed from 19.79 kHz to 19.85 kHz to tune in the variant resonant frequency.

Fig. 11 shows the measured waveforms of the source current, the output current, and the output voltage when the IPTS is operating in a full resonant condition. The output current leads the source current by $\pi/2$, and the output current and the output voltage are in phase, which are well coincident with the phasor vectors shown in Fig. 6.

The linear voltage drop is due to the parasitic resistances such as internal resistances of pick-up's and the resistances of connector cables. The resistances are measured at 20 kHz with E4980A LCR meter, and the total sum of the resistances becomes 1.003 Ω. The measured resistance extracted from the slope of V_o vs. I_o of Fig. 11 is 1.038 Ω. The two resistances are well matched within 3.5 % error, which manifests itself the reason of linear voltage drop.

By adjusting the switching frequency in accordance with the variable resonant frequency, the abrupt voltage drop phenomenon disappears, and output power increases significantly up to 26.7 kW as shown in Fig. 11.

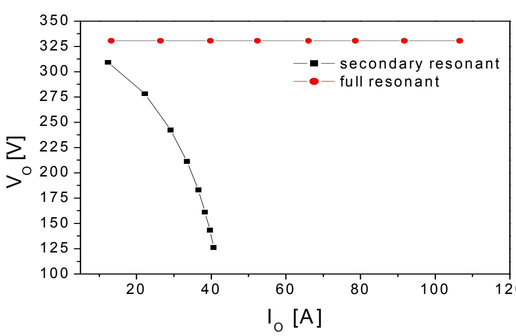


Fig. 9. Simulation results: V_o of Secondary vs. Full-resonance

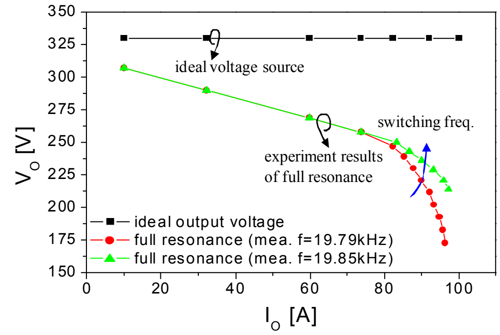


Fig. 10. Experiment results: large I_o limits V_o

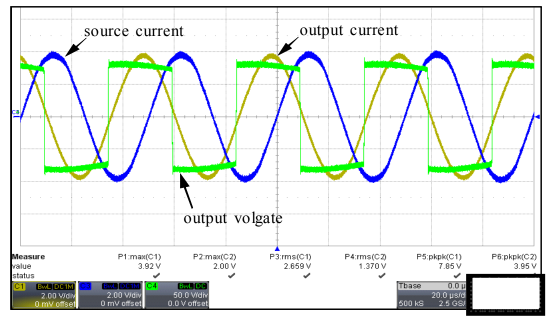
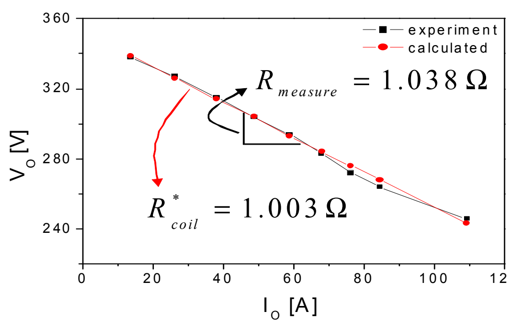


Fig. 11. Waveforms of full resonant IPTS



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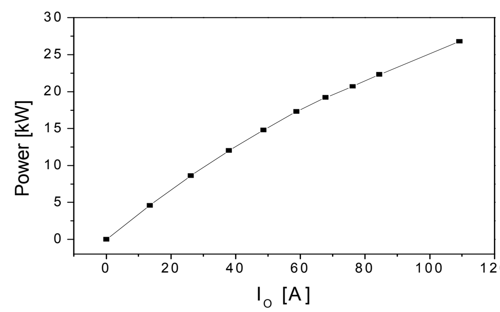

(b)

Fig. 12. V_o and P_o for variable resonant frequency: the output voltage drops linearly due to the parasitic resistances (a), and the output power increases significantly up to 26.7 kW (b).

IV. CONCLUSIONS

The full-resonant-current-source IPTS proposed in this paper has the ideal voltage source characteristics and quite robust properties, which are essential for practical use. The famous Tesla coil of "a resonant transformer" is fully analyzed, and found to be thoroughly different from the conventional transformer in terms of input/output currents and voltages.

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