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Efficient Wireless Power Transfer Topology for Phone Charging Application

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Abstract: Wireless power transfer scheme used on phone chargers are expected to have high efficiency, and reliability. However, existing AC-DC converter schemes were shown to be susceptible to leakage inductance and have lower regulation or excessive power losses. Output voltage regulation is a concern for wireless power converter topologies due to the need for additional shunt devices at DC output. In this paper, literature survey on various wireless power transfer scheme is performed with specific focus on phone charging applications. A modified topology using impedance matching transformer is presented with circuit analysis and LT spice simulation results. It is shown that the proposed topology can deliver better output voltage regulation at various coupling coefficients indicating a superior circuit performance for various separation distances between transmitting and receiving coil.
Keywords: Wireless, power, AC-DC, air gap, efficiency

I. INTRODUCTION

Wireless power transfer systems are increasingly adopted for various power transfer applications like electrical vehicle charging and smart phone chargers. In this paper, literature survey was performed on various wireless power transfer topologies. Based on the literature study, traditional design approach was seen to be susceptible to varying leakage inductance and magnetic coupling between primary transmitter coil and secondary receiver coil. In this paper, a simplified model with mathematical equation is discussed along with excel based analytical results. Circuit leakage inductance was seen to impact output voltage regulation. Since the power transfer system was susceptible to leakage inductance and lower magnetic coupling, a modified power topology with impedance matching transformer is proposed. In this paper, analysis of impedance matching transformer with wireless power transfer system is presented along with mathematical model and excel analysis. LT spice simulation results show that the proposed model improves output voltage regulation and retain zero voltage switching of power devices. Based on theoretical analysis and simulation results, the proposed model is well suited for wireless power transfer systems like phone charges, which required high reliability at low cost.

II. LITERATURE SURVEY

The magnetic induction based wireless power transfer scheme is quite popular in phone charges since the technology is best suited to transmit power between short distances. Although the implementation of power circuit can get extremely difficult, the magnetic resonance is able to transfer 60 W power is transferred at a 2-m distance [1]. As explained in [3], the high-frequency primary current will induce magnetic field, on the receiving coil and by resonating with the secondary compensation network, the transferred power and efficiency are significantly improved. A phone charger device was tested for a power transfer capability of 0.5W at 2.5meter distance [13]. Ultrahigh frequency of operation using split-ring loop design is shown to significantly increase the Q-factor and maximizing power transfer efficiency [5]. Studies also show that inductive magnetic coupling devices operating at non resonant frequencies are still able to achieve higher efficiency over long transmission distances [6]. To achieve higher power transfer efficiency through various load conditions, a compact planar & low-cost wireless power transfer link using matching circuit was analysed in [7]. Use of coupled capacitor based wireless power transfer topology was successfully verified [8]. Several theoretical models are also presented in literature including the leakage length models for E-core and U-core transformers with concentric windings [9]. Sensitivity studies were performed to accurately model leakage inductance using Finite element analysis [10]. Hardware testing with USB2.0 charging system, shows the effect of charging distance with the power generated from multiple transmitters and output DC power management circuit was required to ensure stable output [14]. A modified wireless power transfer topology was proposed using impedance matching LCC resonant circuit and 3.3 kW power was transmitted over 20cm distance with 92.7% system efficiency [20]. In this paper, a similar impedance matching technique is applied to low voltage wireless charging system and a power stage design is presented with mathematical analysis and simulation results.

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III. THEORETICAL MODEL AND SIMULATION

Figure 1. shows a theoretical model for AC-DC converter for a wireless power transfer system, between a transmitting side and receiver coil. Below analysis will refer to transmitting section as primary coil or winding, and receiver section as secondary coil or winding. Magnetizing inductance (Lm) is directly proportional to core (relative) permeability value, ranging from a value of several thousands (Ferrite core) to 1.0 (coreless or air).

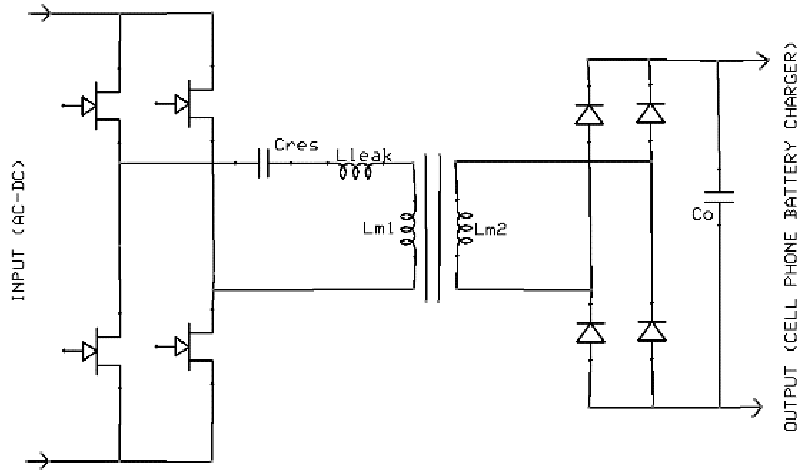

Fig. 1 Theoretical Model

As the primary and secondary side windings are spaced apart, the distance for magnetic flux path will increase resulting in a leakage inductance (Lleak) value several orders greater than magnetizing inductance (Lm) [4]. Figure 2. shows a simplified model with capacitor (Cres), which represents a resonant element, chosen to maximize resonant power transfer scheme while the resonant impedance (Z) is the primary side (reflected or equivalent) impedance [11].

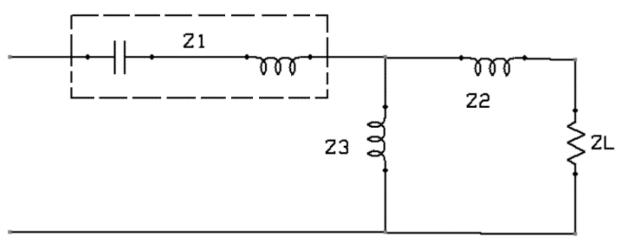

Fig. 2 Primary reflected Model

Using Figure 2, we can deduce voltage gain equation as follows,

Turns ratio, $N = N1/N2$ (1)

$Z1 = j\omega L11 + {}^{1}/_{j\omega Cr}$ (2)

$Z2 = j\omega N^2 L_{22}$ (3)

$Z3 = j\omega L_m$ (4)

$Z_L = (N^2 \times 8R)/\pi^2$ (5)

Voltage gain $= \frac{V_L}{V_i} = \frac{1}{N} \times \frac{1}{1+\frac{Z_1+Z_2}{Z_L}+\frac{Z_1(Z_2+Z_L)}{Z_3 Z_L}}$ (6)

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Assuming no air gap present between primary & secondary windings, voltage gain equation was plotted in Figure 3 (Frequency on X-axis and Voltage gain on Y-axis). Linear region of the plot indicates a stable operating range and limiting operation within this region will ensure highest power transfer efficiency.

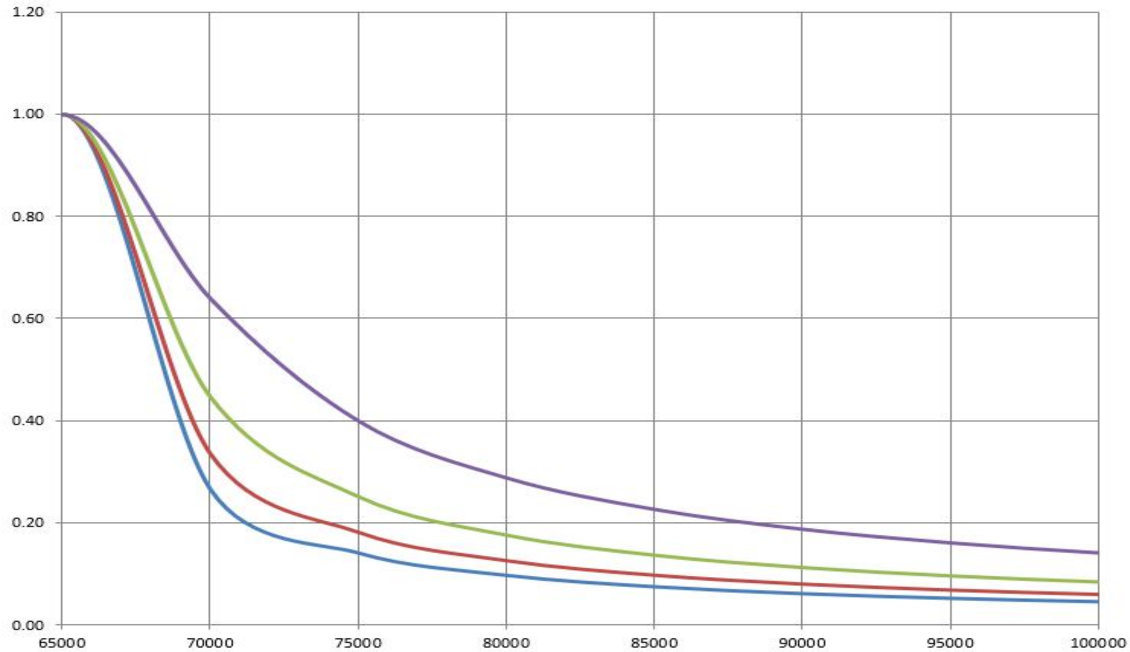

Fig. 3 Theoretical Model

As per the reluctance calculation [2], air gap length (lc) is directly proportional to the leakage inductance and an increase in air gap will reduce magnetic flux coupling between primary and secondary winding, thereby decreasing power transfer gain and deteriorate output voltage regulation. To demonstrate this effect, circuit simulation was performed in LT spice [12] with leakage inductance shifted from 0.5milliHenry (mH) to 0.6milliHenry (mH). Simulation parameters are 10nF (Cr) & 20Vdc input. Based on the results, leakage inductance (Lleak) was shown to impact output voltage regulation between light load (1440ohm) & full load (144ohm). Primary current waveform shows that, power device turnoff occurs at higher peak current, while turnon occurs at zero voltage (Fig 4).

TABLE 1. LT Spice results

Lleakage	0.6mH		0.5mH	
Pout	1	0.1	0.1	1
Rout	144	1440	144	1440
Voltage gain @ F= 65k	0.89	0.99	0.97	0.99
Voltage gain @ F= 66k	0.78	0.99	0.89	0.99
Voltage gain @ F= 67k	0.69	0.99	0.80	0.99
Simulation results				
	K = 0.95		K = 0.8	
Vout	7.6V@144ohm	18.5V@1440ohm	3.45V@144ohm	10.7V@1440ohm
Vdiff	10.9		7.25	

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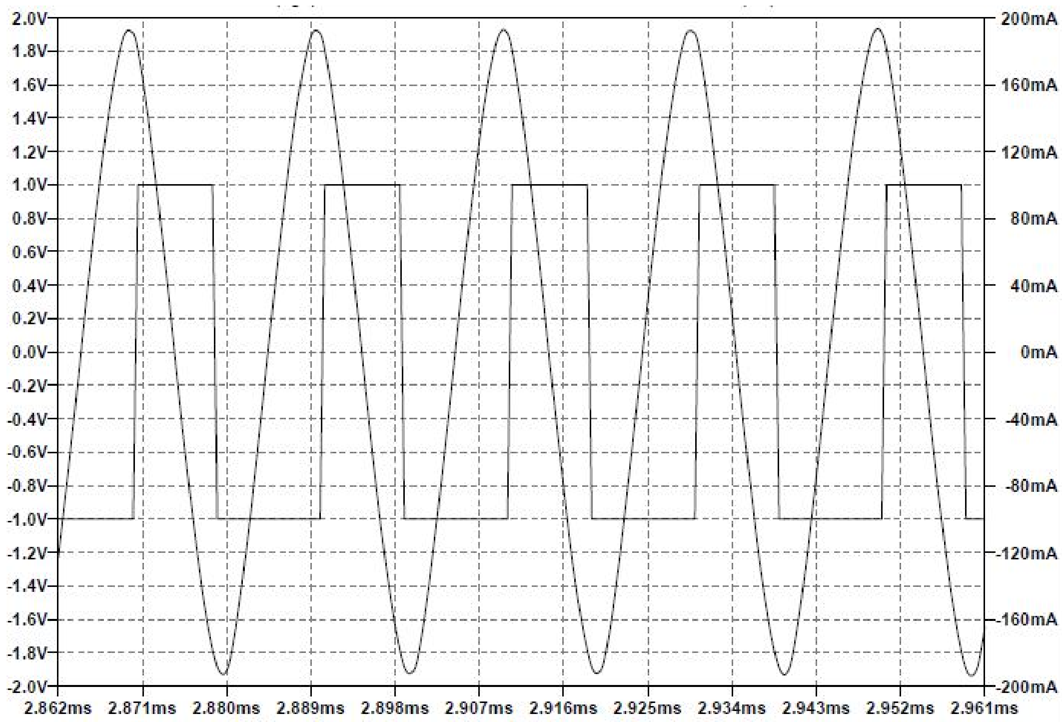

Fig. 4. Primary Current waveform, (K = 0.8).

We observe that varying leakage inductance causes resonant circuit to be susceptible to output voltage stability issues and additional safety measures are necessary at the converter output. A study published in [13] also shows an output voltage at 5 times the expected value and the use of Zener diode to achieve good output voltage regulation. To avoid such regulation issues which are inherent to wireless power transfer scheme (separation gap varies based on transmitter and receiver coil), an impedance matching transformer can help improve output regulation. In this paper, we analyse impedance matching transformer for low voltage phone charger application Figure 5 and associated model shown in Figure 6. Matching transformer is indicated by L_pri and L_sec, representing primary and secondary inductance. The leakage inductance of impedance matching transformer is shown as Lr. Impedance Z2' is the sum of matching transformer secondary inductance and leakage Z2. Z4 is magnetizing inductance of impedance matching transformer and Z1' indicates the total impedance of Cres and reflected leakage inductance of impedance matching transformer.

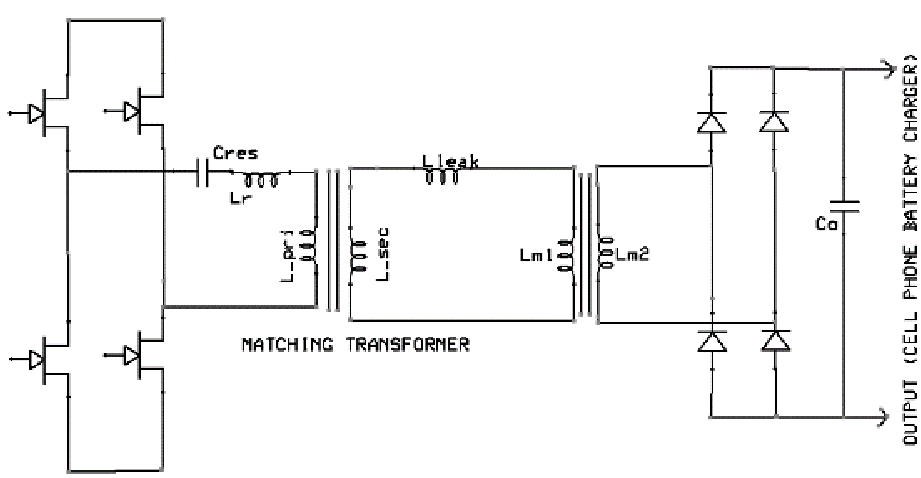

Fig. 5. Proposed Model with Matching transformer.

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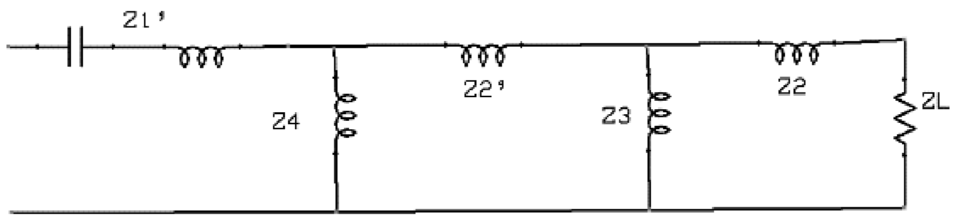

Fig. 6. Theoretical Model with Matching transformer.

Proposed model in Figure 6. was solved using excel and plotted at various frequencies. Analysis of proposed model shows that wireless power transfer system provides a tighter voltage regulation while still retaining soft switching of power devices. As shown in Figure 7 and Figure 8, the total voltage gain of wireless power transfer system is retained with impedance matching transformer both at no load and full load. At no load, the impedance matching transformer scheme can provide soft switching of power devices while retaining voltage gain very close to the original wireless transfer system. Plots shown in Figure 7 shows a slightly lower gain with the proposal model. A lower gain is usually preferable at no load since it simplifies voltage regulation and associated component stress with shunt regulation devices are reduced. This is also clearly established with simulation model results shown in Figure 9 and Figure 10.

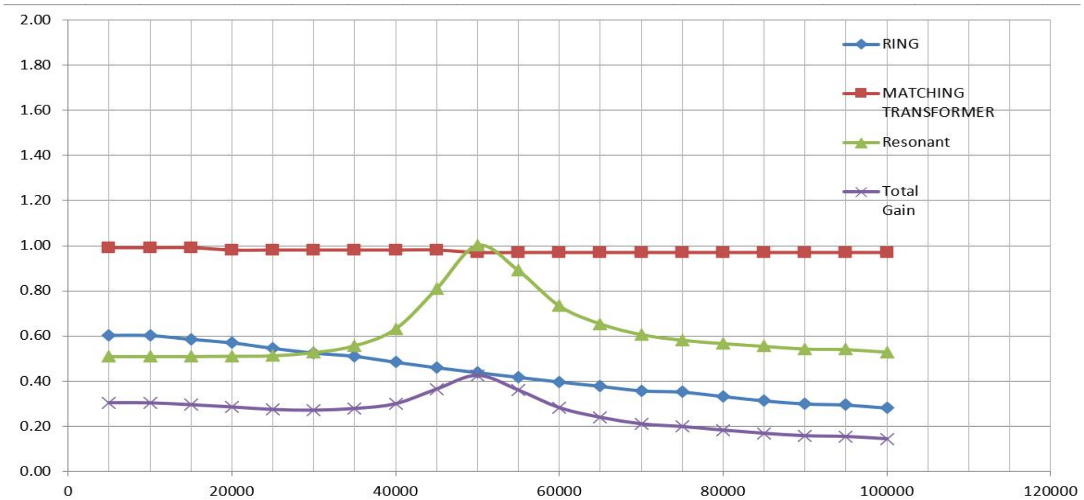

Fig. 7. Full Load Voltage gain of Impedance matching transformer.

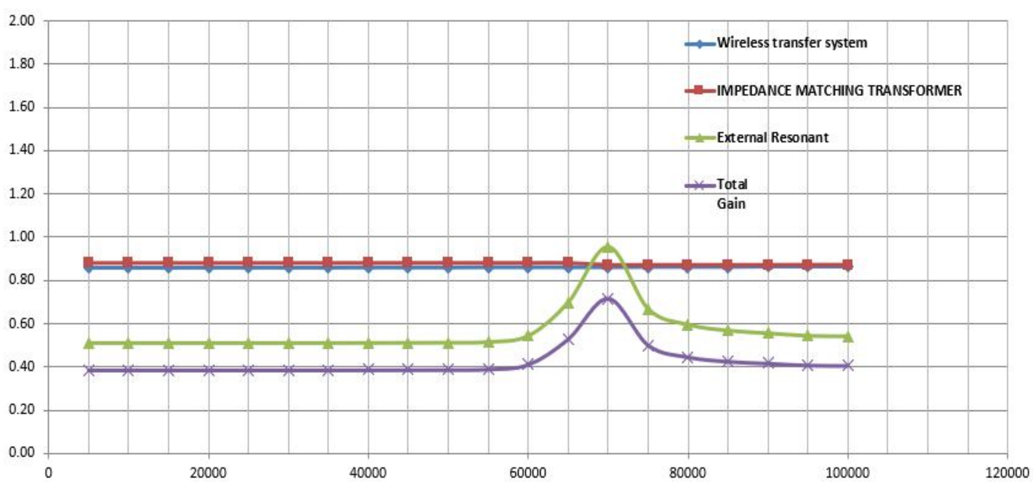

Fig. 8. No Load Voltage gain of Impedance matching transformer.

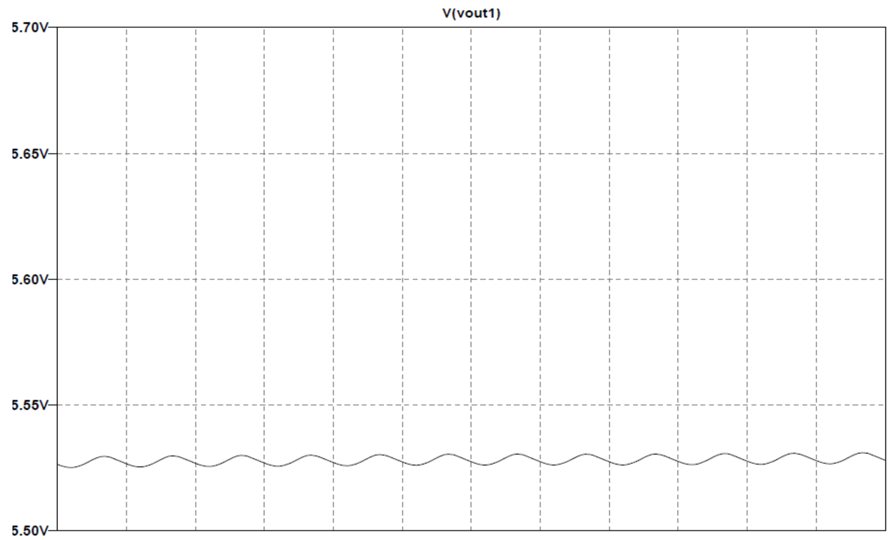

Fig. 9. No Load Waveform with Matching transformer

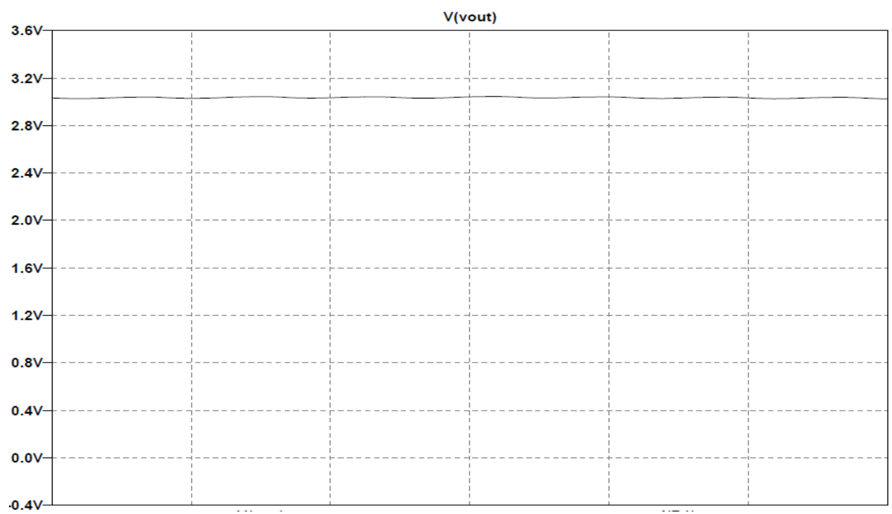

Fig. 10. Full Load Waveform with Matching transformer

Simulation results conducted in LT spice [12] show that voltage regulation with proposed model has improved by 20%, when compared to wireless power transfer system (Table 2 shows a value drop from 62% to 50%).

Table 2. Voltage Regulation

	K = 0.44	
	Wireless system	Proposed model
Output Voltage @No load (500 ohms)	8.1	5.48
Output Voltage @Full load (50ohms)	3.01	2.73
Output Voltage Regulation	62.84	50.18

Figure 11 illustrates the current waveform comparison and proves that matching transformer provides Zero voltage switching, thereby reducing turnon losses on power devices while the wireless power system has power devices turning on at larger peak current. Hence, proposed method is considered favourable and will significantly lower power device thermal stress.

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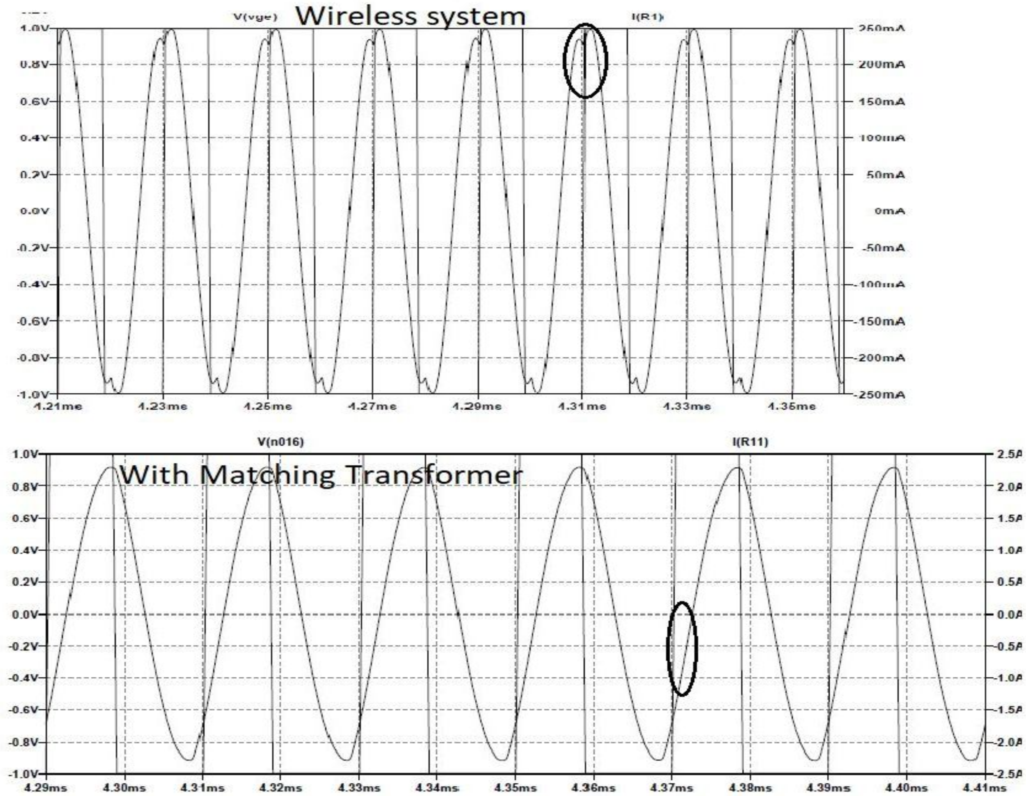

Fig. 11. Current waveform comparison

IV. CONCLUSIONS

As wireless charging applications, such as Electric Vehicle (EV) chargers and smartphone charges, become increasingly prevalent, the demand for efficient power transfer topologies rises. In this paper, we conduct a literature review to explore various techniques used for low voltage wireless power transformer scheme, including the effect of leakage inductance on circuit operation and voltage regulation. To achieve superior output voltage regulation, a theoretical model for an impedance matching magnetic circuit is developed and analyzed. To validate the effectiveness of the impedance matching method, a simulation model is developed, and empirical evidence provided. Device voltage and current waveforms were shown to retain soft switching operation, proving the effectiveness of the proposed impedance matching approach.

V. ACKNOWLEDGMENT

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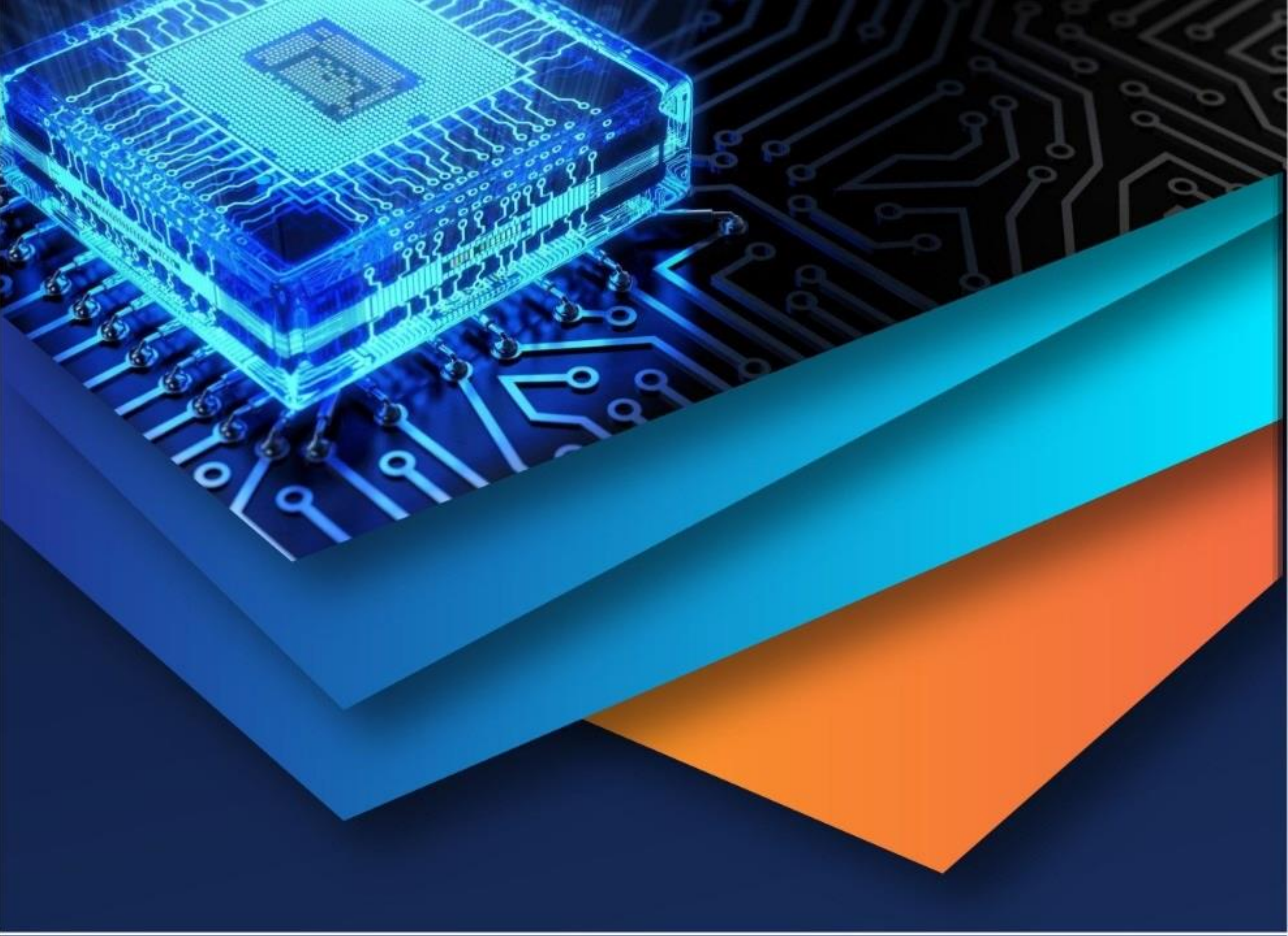

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