

INVESTIGATION OF ELECTRICAL PARAMETERS FOR PCB TRANSFORMER

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Abstract. Wireless transformer technologies are being utilized increasingly for many applications with a view to minimising production parts, reducing the weight through removal of metal based cores and ease in manufacturing. The current research involves the assessment of a printed circuit board (PCB) transformer, more specifically bi-polar designed boards. The boards were created with a view to centralizing the magnetic fields to the centre with the expectation that a more focused internal field would result in providing further transfer assistance to the resonant carrier field transferring energy from transmitter to receiver. Investigation is concerned with the flat PCB coils that are easy to produce and are inexpensive. Transference of the electrical energy is achieved through the creation of an electromagnetic field. The use of both two-wire and single wire excitation circuits has been applied in order to assess the feasibilities of both. Minimal voltage and ampere levels have been applied in order to assess the success of transfer without resorting to high current based electromagnetic fields, which can tend to exaggerate results and incur large flux linkage losses.

Keywords: printed circuit board, coil, energy transfer, wireless energy.

Introduction

Nowadays there is an ever increasing importance toward wireless energy transfer from electricity sources to the consumer. This applies especially to mobile equipment battery charging. Be it mobile phone, robotic vacuum cleaners or electric cars, they all require periodic charging and consumers are increasingly looking to the possibility of avoiding plugging the device into the mains socket, preferring wireless charging systems [1; 2]. It is especially important for robotic devices that need to find their charging spot autonomously or for scheduled electric vehicles used in public transportation, like on-route wireless charging of electric busses during their stops [3; 4]. This article is aimed at solution of this problem by examining possibilities of using PCB transformers.

Traditionally magnetic induction between two distant transformer coils is used for wireless transfer of electrical energy. The current paper examines electric parameters for transformers with primary and secondary coils produced as flat PCBs.

Use of PCB technologies is not a novel idea. It has been analysed for applications in mobile device charging already in several papers [2; 5; 6], however, usually within informal industry Q_i [7; 8] standard context, both as standalone [2] and array repeater configurations [5, 6], and thus feasible only if transmitter and receiver coils are in close proximity to each other [2]. In order to achieve further transfer distance, the coil setup was made outside the parameter set in Q_i specification [8].

Materials and methods

There are many different kinds of coils that are able to achieve wireless power transmission (WPT). Each coil is based on a specific technology and mathematical and physical models perform a specific WPT task. For example, if there is a need to achieve higher distance of WPT a circular monopole coil should be utilized, however, if a reduction in losses due to misalignment is required a good choice could be the bipolar coil.

The bipolar coil is essentially the merged combination of two coils and although the theories and maths of monopole coils can be approximated or adapted, precise models for bipolar coils are rare. The aim was the creation of a new coil type for WPT, with the primary consideration being a relatively inexpensive coil, able to self-resonate at reasonable frequencies and which at the same time could provide low skin-effect losses due to high frequencies and reduce the misalignment losses.

The PCB bipolar coil fits to these requirements to some extent but is not the final proposal. During design of the coil it became necessary to elaborate new mathematical models due to the lack of available mathematical models. In order to test the impact of configuration and to elaborate high quality mathematic model, it will be necessary to produce many coupled coils and each of them should have different features, such as the number of turns, clearance, open core size and it was a pre-requisite of the approach to maintain a maximum size of 210mm x 297mm (A4 size).

Maximum current calculated using formula(1):

$$I_{\max} = 0.48 \cdot dT^{0.44} \cdot A^{0.725} \quad (1)$$

where dT – maximum trace temperature at 33 °C;
 A – trace section area, m^2 .

The PCB coils utilize trace thicknesses of 70 μ m and variable trace width (trace width is a value in the range between 20 and 100 mils).

It is supposed that the voltage drop between winding traces in the case of coils with more than five and less than ten turnings (per monopole) will be lower than 48V and in case of coils with more than ten turnings the voltage drop between the winding trace (per monopole) will be lower than 36 V although the supply voltage is 300 Vpp.

To provide a safe coil with no unwanted interaction between winding traces, a trace to trace clearance higher than 25 mils and proper trace insulation are used.

Both coils were made identical with topography as shown in Figure 1. Measurement of resonant frequencies was performed.

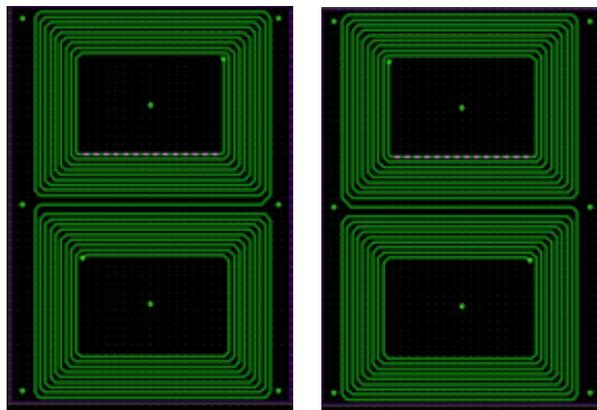


Fig. 1. PCB coil topography

The winding consists of two parts, which are wound in opposite directions. This creates a concentrated magnetic field at the center of the coil, which could let it extend farther. Construction of the transformer is shown in Figure 2.



Fig. 2. Transformer test configuration

The primary and secondary coil plates are positioned in parallel with a distance, l between them fixed with the help of four separators. Analysis of the transformer was performed using two types of connections:

1. As a traditional two-wire circuit;
2. As a single wire circuit.

Traditional two-wire circuit test set is shown in Figure 3.

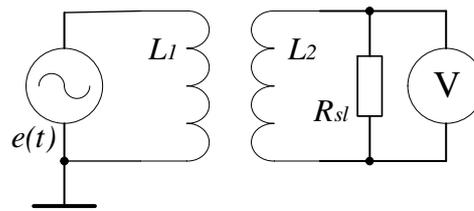


Fig. 3. Two-wire excitation circuit

Sinusoidal voltage source with adjustable frequency is connected to the primary coil, L_1 (Fig. 3). Load resistance R_L is connected to the exit of the secondary winding L_2 . Voltage drop on the resistance is measured with Voltmeter, V. Coils L_1 and L_2 are A4 size PCB with $n = 22 \times 2$ windings each. Their inductivity and loss resistances at frequency $f = 1$ kHz are $L_1 = 334 \mu\text{H}$, $R_{Z1} = 12.8 \Omega$ and $L_2 = 334 \mu\text{H}$, $R_{Z2} = 12.5 \Omega$. Measurements are made for two distances between the coils $l_1 = 60$ mm and $l_2 = 100$ mm.

Single wire circuit test set is shown in Figure 4.

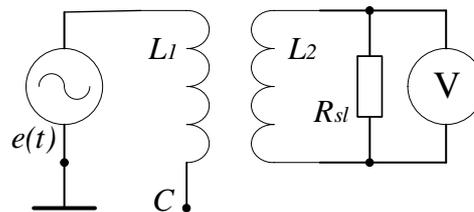


Fig. 4. Single wire excitation circuit

In this case the generator $e(t)$ is connected to one end of the primary coil while the other end is either unconnected or is connected to a small spatial capacitor C. The referred single wire electrical circuit has been studied in papers [9; 10].

Results and discussion

Measurements carried out showed that several resonances can be found at various frequencies. The data are presented in Table 1 and Table 2, and represent electrical parameters for the PCB transformer in a two-wire circuit configuration.

Table 1

Experiment settings and results, two-wire setup, distance 60 mm, under different load R_L

f , MHz	I_{in} , mA	U_{out} , V	I_{out} , mA	P_{out} , mW
$R_L = \infty, l = 60$ mm, $U_{in} = 10$ V				
1.90	2.9	48.2	0	0
4.19	15.6	33.8	0	0
5.36	5.9	6.2	0	0
$R_L = 3.2\text{k}\Omega, l = 60$ mm, $U_{in} = 10$ V				
4.08	11.3	7.8	2.44	19
5.24	5.0	3.4	1.06	3.6
$R_L = 1.0\text{k}\Omega, l = 60$ mm, $U_{in} = 10$ V				
4.11	12	10.1	10.1	102
5.34	5.6	3.9	3.9	15.2
$R_L = 330\Omega, l = 60$ mm, $U_{in} = 10$ V				
4.09	11.3	3.7	11.2	41.4
5.33	3.8	1.1	3.3	3.6
$R_L = 100\Omega, l = 60$ mm, $U_{in} = 10$ V				
4.09	14.7	1.4	14	19.6
5.33	6.3	0.4	4	1.6

The graph represented in Figure 5 presents the experiment results using the two-wire excitation method, at distance $l=60\text{mm}$. It indicates the relationship between the assessed resonant frequencies as they relate to the distance and the received power. The similarity is stated between the results with loads $R_L = 3.2\text{k}\Omega$ and $R_L = 100\Omega$.

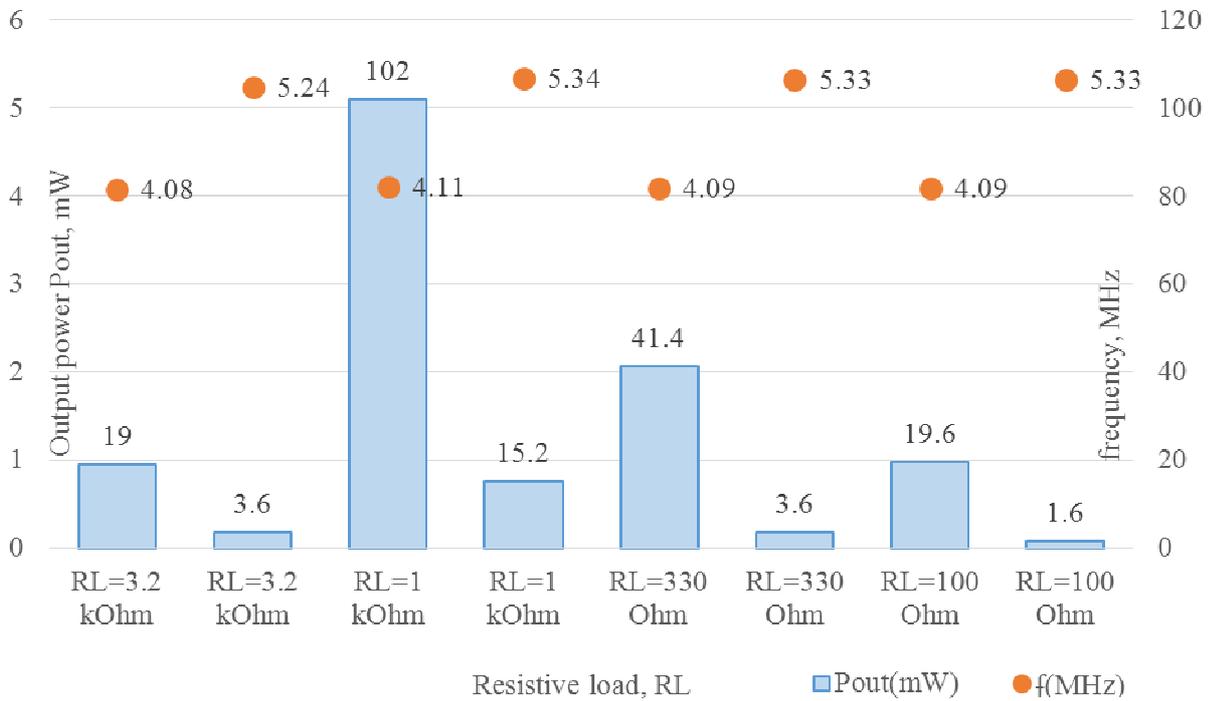


Fig. 5. Power output and resonance frequency at different load R_L , two-wire setup, distance 60 mm

Table 2

Experiment settings and results, two-wire setup, distance 100 mm, under different load R_L

f , MHz	I_{in} , mA	U_{out} , V	I_{out} , mA	P_{out} , mW
$R_L = \infty, l = 100 \text{ mm}, U_{in} = 10 \text{ V}$				
1.91	0.24	13.9	0	0
4.26	22.6	29	0	0
5.10	7.5	0.94	0	0
$R_L = 3.2 \text{ k}\Omega, l = 100 \text{ mm}, U_{in} = 10 \text{ V}$				
4.25	14.2	12.9	4.0	51.6
5.08	6.3	5.3	1.7	9.0
$R_L = 1.0\text{k} \Omega, l = 100 \text{ mm}, U_{in} = 10 \text{ V}$				
4.22	14.8	7.1	7.1	50.4
5.06	6.3	3.1	3.1	9.6
$R_L = 330 \Omega, l = 100 \text{ mm}, U_{in} = 10 \text{ V}$				
4.22	13.3	3.5	10.6	37.1
5.06	7.4	1.4	4.2	5.9

The results show that the first resonance frequency becomes negligible as load is added. The power transferred decreases as expected as the distance between the coils is increased.

The graph represented in Figure 6, still with the setup of coils using the two-wire excitation method with the increased distance $l = 100 \text{ mm}$, indicates the relationship between the assessed resonant frequencies as they relate to the distance and the received power. At load resistance $R_L = 100 \Omega$ output power has become negligible, and the similarity of the output results is observed for loads $R_L = 3.2 \text{ k}\Omega$ and $R_L = 1 \text{ k}\Omega$.

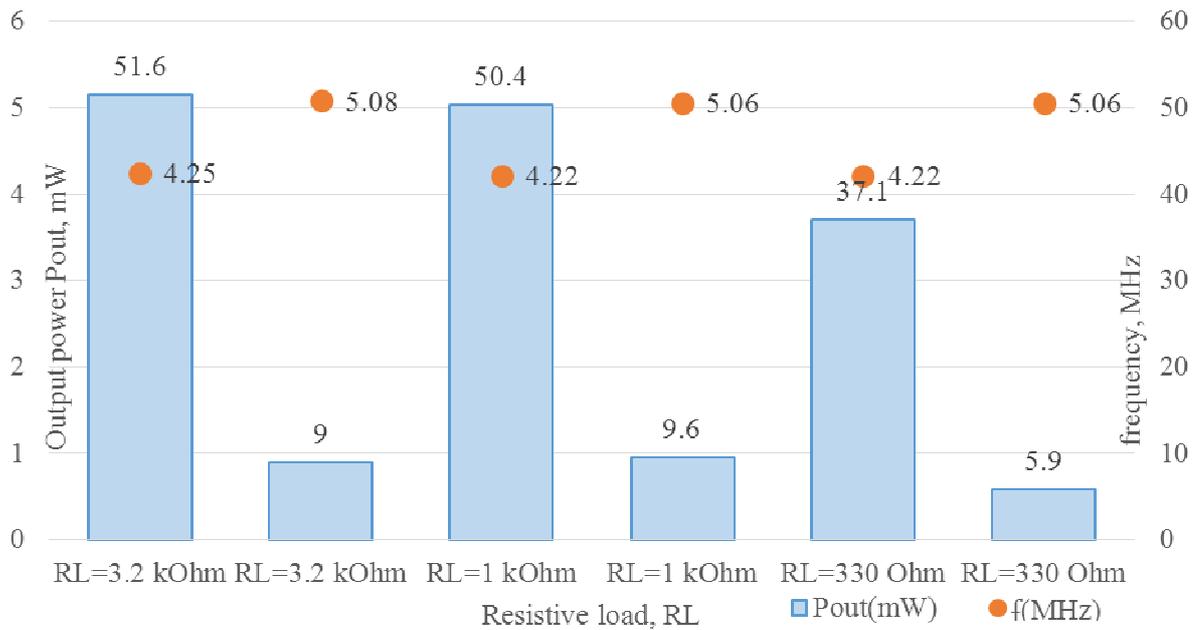


Fig. 6. Power output and resonance frequency at different load R_L , two-wire setup, distance 100 mm

The PCB transformer was analysed also in the single wire excitation circuit configuration.

The results of the experiments are shown in Table 3 and Table 4, and represent the electrical parameters for the experiment with the PCB transformer in a single wire circuit configuration.

Table 3

Experiment settings and results, single wire setup, distance 60 mm, under different load R_L

f , MHz	I_{in} , mA	U_{outs} , V	I_{outs} , mA	P_{outs} , mW
$R_L = \infty, l = 60\text{ mm}, U_{in} = 10\text{ V}$				
2.6	75	162	0	0
4.37	11.3	18.7	0	0
5.45	7.5	7.8	0	0
$R_L = 3.2\text{ k}\Omega, l = 60\text{ mm}, U_{in} = 10\text{ V}$				
2.47	20	23	7.2	165.6
4.38	9.4	8.4	2.6	21.8
5.43	5.0	7.8	2.4	18.7
$R_L = 1.0\text{ k}\Omega, l = 60\text{ mm}, U_{in} = 10\text{ V}$				
2.43	50	14.3	14.3	204.5
4.35	10	4.4	4.4	19.4
5.43	6.9	3.1	3.1	9.6
$R_L = 330\ \Omega, l = 60\text{ mm}, U_{in} = 10\text{ V}$				
2.44	50	7.8	23.6	184.4
4.34	9.4	2	6.1	12.2
5.43	6.3	1.4	4.2	5.9
$R_L = 100\ \Omega, l = 60\text{ mm}, U_{in} = 10\text{ V}$				
2.44	50	2.9	29	84.1
4.35	7.5	0.68	6.8	4.6
5.43	4.4	0.47	4.7	2.2

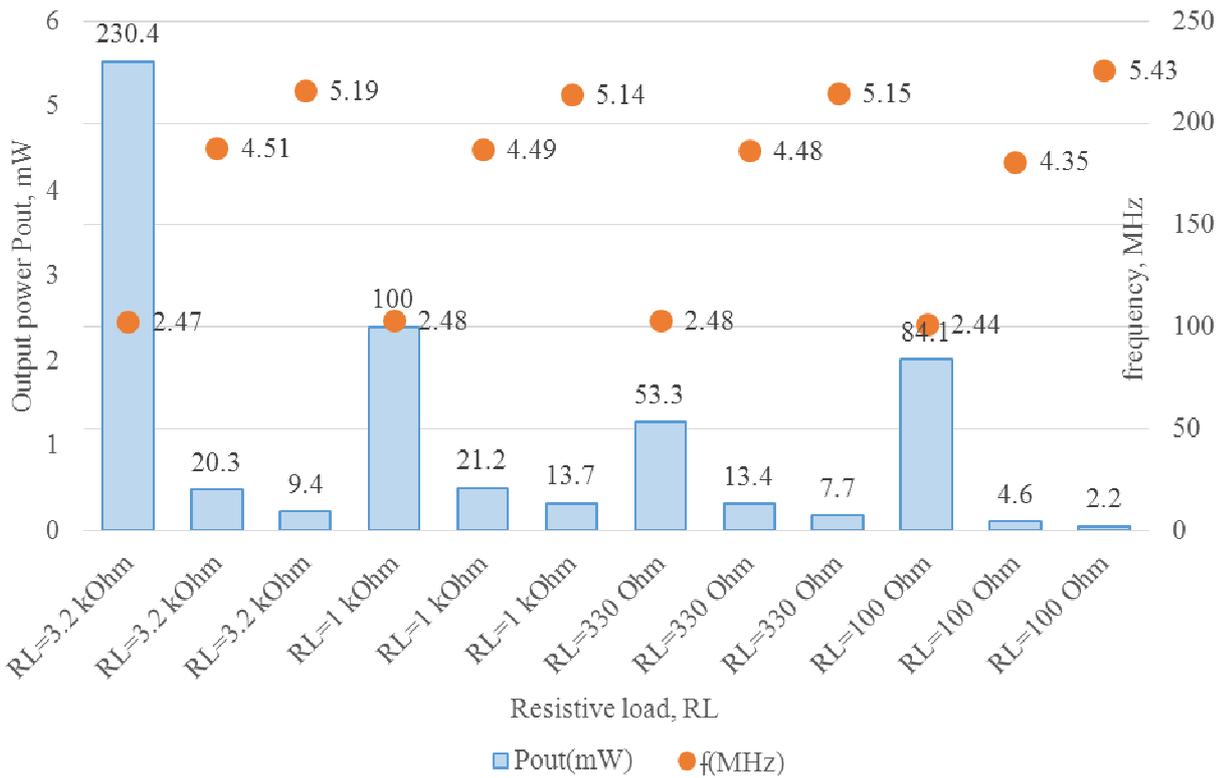


Figure 6. Power output and resonance frequency at different load R_L , single wire setup, distance 60mm

Table 4

Experiment settings and results, single wire setup, distance 100 mm, under different load R_L

f , MHz	I_{in} , mA	U_{out} , V	I_{outs} , mA	P_{outs} , mW
$R_L = \infty, l_1 = 100 \text{ mm}, U_{in} = 10 \text{ V}$				
1.86	16	187	0	0
2.53	95.5	152	0	0
4.53	8.0	17.3	0	0
5.19	6.5	10.0	0	0
$R_L = 3.2 \text{ k}\Omega, l_1 = 100 \text{ mm}, U_{in} = 10 \text{ V}$				
2.47	30	27.1	8.5	230.4
4.51	8.1	8.1	2.5	20.3
5.19	4.5	5.5	1.7	9.4
$R_L = 1.0 \text{ k}\Omega, l_1 = 100 \text{ mm}, U_{in} = 10 \text{ V}$				
2.48	38.5	10	10	100
4.49	7.7	4.6	4.6	21.2
5.14	6.9	3.7	3.7	13.7
$R_L = 330 \text{ }\Omega, l_1 = 100 \text{ mm}, U_{in} = 10 \text{ V}$				
2.48	38.4	4.2	12.7	53.3
4.48	8.4	2.1	6.4	13.4
5.15	6.5	1.6	4.8	7.7

The data presented in Tables 3 and 4 show that in the case of the single wire circuit the transformer has more resonant frequencies than in the two-wire circuit. Also the power transfer in the single wire circuit is approximately twice as high as in the two-wire circuit.



Fig. 8. Single wire excitation circuit, $l_1 = 100$ mm, $U_{in} = 10$ V

Conclusions

1. The experiments show that the value of transferring energy is dependent on the size of load and has an optimum that is around 1 k Ω when using the PCB transformer.
2. The results of the testing assure that wireless electrical energy transfer using PCB coils takes place, and power transfer is substantial (in the experiment – maximum power reached more than 50 mW).
3. The measurements indicate few resonance frequencies, which can be used for efficient wireless energy transfer using PCB transformers.
4. Single wire excitation of the PCB transformer resulted in rather efficient wireless energy transfer – maximum power reached more than 230 mW.

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References

1. Tiwari H.D., Park H.-G., Lee K.-Y. Communication controller and control unit design for Qi wireless power transfer (2013) Digital Signal Processing: A Review Journal, vol. 23(4), pp. 1322-1331.
2. Waffenschmidt E. Wireless power for mobile devices, in: IEEE 33rd International Telecommunications Energy Conference (INTELEC), 2011, pp. 1-9.
3. Kim J., et al., “Low Frequency Electromagnetic Field Reduction Techniques for the On-Line Electric Vehicle (OLEV)”, IEEE International Symposium on Electromagnetic Compatibility, 2010, pp. 625-630.

4. Graurs I., Vizulis A., Rubenis A., Laizāns A. (2014) Wireless energy supply to public transport units with hybrid drive – trends and challenges. *Transport and Telecommunication*, vol. 15(1), pp. 67-76.
5. Waffenschmidt E. Free positioning for inductive wireless power system, in IEEE Energy Conversion Congress and Exposition: Energy Conversion Innovation for a Clean Energy Future, ECCE 2011, Proceedings 6064239, pp. 3480-3487.
6. Mori K., Lim H., Iguchi S., Ishida K., Takamiya M., Sakurai T., Positioning-free resonant wireless power transmission sheet with staggered repeater coil array (SRCA) (2012) IEEE Antennas and Wireless Propagation Letters, 11, art. no. 6417946, pp. 1710-1713
7. van Wageningen D., Staring T. “The Qi Wireless Power Standard”, 14th International Power Electronics and Motion Conference (EPE-PEMC 2010), Ohrid, Macedonia, 6.-8. Sept. 2010
8. “System Description Wireless Power Transfer, Volume I: Low Power, Part 1: Interface Definition”, Version 1.0.2, Wireless Power Consortium, April 2011.
9. Voitkāns J., Greivulis J., Voitkāns A. Single Wire and Respective Double Wire Scheme Equivalence Principle. 7th International Scientific Conference „Engineering for Rural development”, Jelgava, 2008.
10. Voitkans J., Voitkans A. “Tesla Coil Theoretical Model and its Experimental Verification”. The Scientific Journal of Riga Technical University “Electrical, Control and Communication Engineering” ECCE, 2015. vol. 7.