Thermal Analysis for Temperature Robust Wireless Power Transfer Systems

Kiwon Hwang, Sanghoon Chung, Uooyeol Yoon, Manho Lee, and Seungyoung Ahn

***Abstract*—This paper reports thermal analysis of a 35kW wireless power transfer (WPT) pickup module to keep the system's efficiency at different temperatures. Temperature effects are first considered by looking at change in efficiency of the system which is influenced by change in resistance and capacitance at different temperatures. Then, we introduce methods to improve the overall performance of a high powered WPT system by utilizing appropriate wires and capacitors, and cooling the device by means of an optimized heat sink.**

***Index Terms*—Wireless Power Transfer (WPT), Thermal analysis, Resistance, Capacitance, Resonance frequency, Efficiency, Heat sink, Optimization**

I. INTRODUCTION

As more attention has recently been brought to WPT technologies, many attempts to improve the wireless concept have been performed in various institutions and companies [1] [2]. Also, since thermal heat loss in electronic devices causes unexpected problems in the systems, there are many research papers and projects on electronic equipment such as transformers, and inductors [3] [4]. However, no active thermal research on current WPT systems on the market has been done yet. Effect of heat dissipation of a WPT system device can be minute if the machine deals with low power. But as power and frequencies increase in the system, serious power loss can occur due to characteristics of WPT systems (such as proximity effects by many turns of wiring, and sensitivity to resonance frequencies).

In this paper, we propose methods to make a WPT system robust against heat dissipation. Analysis of an equivalent circuit model and its components (resistors, and capacitors) are first performed, and then, realistic solutions to possible thermal problems are introduced with the help of commercial software packages such as Ansys Icepak, Maxwell, and Matlab.

II. TEMPERATURE EFFECTS ON WPT SYSTEM EFFICIENCY

To see how temperature change in a WPT system influences efficiency of the whole system, we first introduce an equivalent circuit for a typical wireless power transfer system.

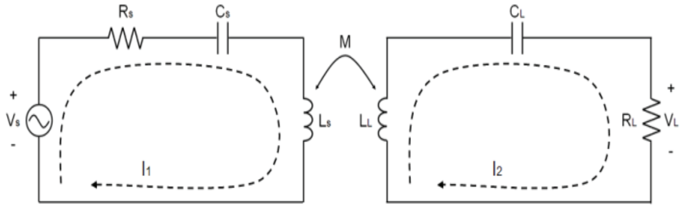


Fig. 1. An equivalent circuit model for a WPT system.

Fig. 1 shows an equivalent circuit to be analyzed. In the following analysis, sinusoidal waves are assumed, and rms magnitudes are employed. With these assumptions and Kirchhoff's voltage law, we can derive the following equation [5].

$$\frac{\mathbf{S}_L}{\mathbf{S}_S} = \frac{\boldsymbol{I}_2 \cdot R_L}{\left(\frac{(R_L + \boldsymbol{Z}_{CL} + \boldsymbol{Z}_{LL})}{\boldsymbol{Z}_M}\right)^* \boldsymbol{V}_S}$$

$$= \frac{\frac{\boldsymbol{Z}_M \cdot R_L}{(R_S + \boldsymbol{Z}_{CS} + \boldsymbol{Z}_{LS})(R_L + \boldsymbol{Z}_{CL} + \boldsymbol{Z}_{LL}) - \boldsymbol{Z}_M{}^2}}{\left(\frac{(R_L + \boldsymbol{Z}_{CL} + \boldsymbol{Z}_{LL})}{\boldsymbol{Z}_M}\right)^*}$$

$$= \frac{Z_M{}^2 \cdot R_L}{(R_L + \boldsymbol{Z}_{CL} + \boldsymbol{Z}_{LL})^* \left\{(R_L + \boldsymbol{Z}_{CL} + \boldsymbol{Z}_{LL})(R_S + \boldsymbol{Z}_{CS} + \boldsymbol{Z}_{LS}) - \boldsymbol{Z}_M{}^2\right\}} \tag{1}$$

where

$$\boldsymbol{Z}_{CS} = \frac{1}{j\omega C_S}, \ \boldsymbol{Z}_{LS} = j\omega L_S, \boldsymbol{Z}_M = j\omega M,$$

$$\boldsymbol{Z}_{CL} = \frac{1}{j\omega C_L}, \boldsymbol{Z}_{LL} = j\omega L_L \tag{2}$$

S indicates complex power, and subscripts $_S$ and $_L$ mean source and load respectively. By defining a power transfer function K, we can obtain

$$|\mathbf{K}| = \left|\frac{Z_M{}^2 \cdot R_L}{(R_L + \boldsymbol{Z}_{CL} + \boldsymbol{Z}_{LL})^* \left\{(R_L + \boldsymbol{Z}_{CL} + \boldsymbol{Z}_{LL})(R_S + \boldsymbol{Z}_{CS} + \boldsymbol{Z}_{LS}) - \boldsymbol{Z}_M{}^2\right\}}\right| \tag{3}$$

With |**K**|, we can compare efficiency of WPT systems having temperature varying components such as R and C components.

A. Decreasing Efficiency Occurred by Change in Resistance with Rising Temperature

In this and next subsections only, we take the values in Table I to analyze change in efficiency of the introduced WPT circuit model. The values of capacitors and inductors are determined to have a resonance frequency of 20kHz in both the source and

---

Seungyoung Ahn and Kiwon Hwang are with the Cho Chun Shik Graduate School for Green Transportation, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea (e-mail: sahn@kaist.ac.kr, origin11@kaist.ac.kr).

Sanghoon Chung, Uooyeol Yoon are with KAIST Wireless Power Transfer Research Center, Daejeon, South Korea (floecist@kaist.ac.kr)

Manho Lee is with Dept. of Electrical Engineering, KAIST, Daejeon, South Korea (manho@kaist.ac.kr)

978-1-4673-5010-5/13/$31.00 ©2013 IEEE

the load, and resistors and mutual inductance (M) are appropriately assumed for the current WPT system. It is further assumed that the initial values in Table I are obtained at room temperature of 25 °C.

According to Robert *et al.* [6], the resistivity (ρ) varies from $1.724*10^{-8}\Omega$-m at room temperature to $2.3*10^{-8}\Omega$-m at 100°C. Since $R = \rho * l/A$, where l and A are the length and the surface area of a coil, we can obtain source resistances (R_S) and load resistances (R_L) at different temperature states (see Table II).

TABLE I
INITIAL RLC AND M VALUES WITH A RESONANCE FREQUENCY OF 20KHZ AT ROOM TEMPERATURE

	R_S (mΩ)	C_S (uF)	L_S (uH)	R_L (Ω)	C_L (uF)	L_L (uH)	M (uH)
Value	30	3.7	17	30.3	0.021	3000	19.9

TABLE II
VALUES OF Ρ, R_S, R_L, AND |K| AT DIFFERENT TEMPERATURES

T(°C)	$\rho(10^{-8}\Omega m)$	R_S(mΩ)	R_L(Ω)	|K| at 20kHz considering R
25	1.724	30	30.3	0.8726
35	1.801	31.34	31.65	0.8626
45	1.878	32.68	33.01	0.8523
55	1.955	34.02	34.36	0.8419
65	2.032	35.36	35.71	0.8314
75	2.109	36.70	37.07	0.8206
85	2.186	38.04	38.42	0.8098
95	2.263	39.38	39.77	0.7989

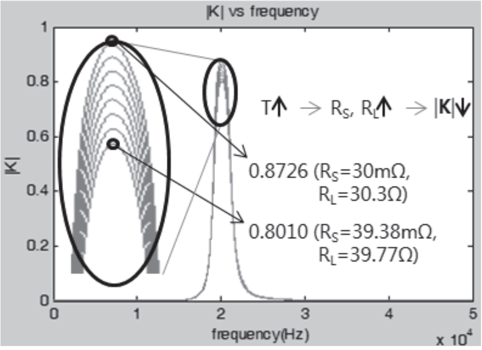


Fig. 2. Change of |K| at different temperatures (different values of R_S, and R_L).

By substituting corresponding R_Ss and R_Ls into Eq. (1), we can obtain Fig.2 by means of Matlab. Fig. 2 illustrates the relationship between |**K**| and resistors all of which are dependent upon temperature. In both cases, |**K**| decreases as resistance increases with rising temperature. This means that efficiency of the WPT system diminishes as the system temeprature rises. Note that we only considered the DC case by using $R = \rho * l/A$ for a simple explanation, however; in practice, the temperature effects may become much worse due to other AC related problems such as proximity effects and electromagnetic interference (EMI).

B. Decreasing Efficiency Occurred by Change in Capacitance with Rising Temperature

It is crucial to have stable capacitance in WPT systems since most of the current WPT systems utilize the concept of resonance (see Section 2). However, all capacitors change in capacitance if their surrounding temperature departs from room temperature [7]. Accordingly, this temperature dependence of capacitors causes some decrease in system efficiency while wirelessly transferring power from the primary coils to the secondary pickup modules. Fig. 3 shows an example of capacitance value change over temperature [7].

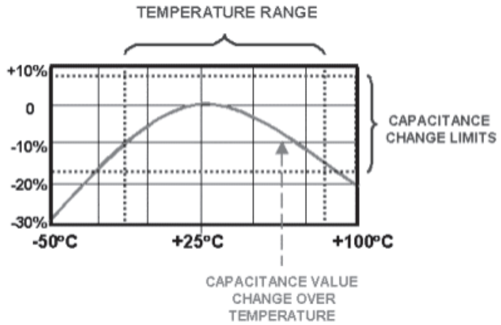


Fig. 3. An example of capacitance change over temperature ranging from -50° C to 100°C [7].

For the sake of temperature dependency demonstration, we analyze efficiency of the WPT system by taking different capacitance values as temperature rises and the capacitance change is assumed to be linearly proportional to the rising temperature. General capacitors are known to have, at most, a 15% offset within an operating temepratute range of 25°C ~ 85°C [7]. Table III shows two sets of changing capacitance (one in the source circuit, the other in the load) in the WPT system depending on temperature.

TABLE III
VALUES OF C_S, C_L, AND |K| AT DIFFERENT TEMPERATURES

T(°C)	C_S(uF)	C_L(uF)	|K| at 20kHz considering C	|K| at 20kHz considering R & C
25	3.7	0.021	0.8726	0.8726
35	3.7925	0.021525	0.8660	0.8566
45	3.885	0.02205	0.8428	0.8219
55	3.9775	0.022575	0.7867	0.7429
65	4.07	0.0231	0.6475	0.5939
75	4.1625	0.023625	0.4583	0.4286
85	4.255	0.02415	0.3072	0.3027

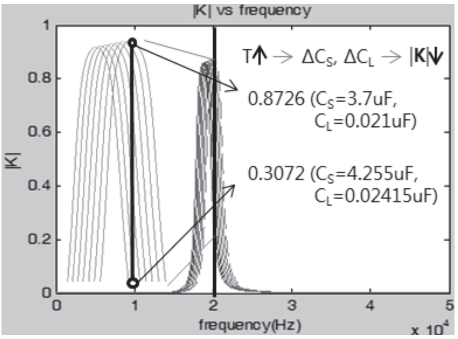


Fig. 4. Change of |K| at different temperatures (different values of C_S, and C_L).

As you can see in Fig. 4, |**K**|, which indicates efficiency of the system, dramatically falls as temperature rises. This is because the resonance frequency shifts from 20kHz as the capacitors in the system change. Simply put, resonance frequencies of both sides (source and load)do not match each other so that |**K**| values at 20kHz plummet. From this result, we can conclude that temperature dependant capacitors not only cause poor efficiency but also destabilize the system.

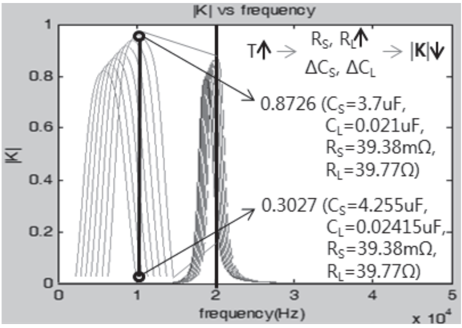


Fig. 5. Change of |K| at different temperatures (different values of R_S, R_L, C_S, and C_L).

Fig. 5 includes the previously considered resistance change because, in reality, change in resistance and capacitance occurs together as temperature rises. In this case, the fall of |**K**| values become worse because not only resonances in the system mismatch by capacitors but also the resonance peak decreases by resistors.

In practice, additional problems may occur due to system's complexity. For example, resonance peaks can split into two (or more) maximum points because change in RLC values occur at different rates in the source and the load (so the source and the load have different resonance frequencies).

III. METHODS TO STABILIZE WPT SYSTEMS

From the previous section, we have learned that change in resistance or capacitance occurred by temperature rise causes problems in terms of efficiency and stability of a WPT system. Since both elements (R, C) depend on the same factor (temperature), it is more likely that the temperature effect on a WPT system is worse in a real situation as they both deteriorate simultaneously. In this section, we look at two different approaches to solve the problem.

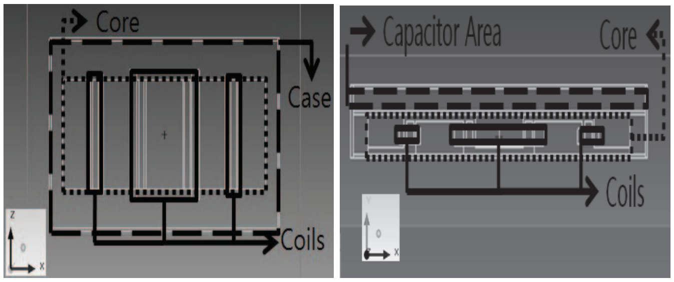
A. Improving Coil Performance & Choosing Temperature-Robust Capacitors

To solve a problem in engineering, we can make the system robust to the problematic factor, or just eliminate the main culprit. In this subsection, we discuss the former. Firstly, using advanced Litz wires [8], such as Teflon Litz Wire [9], can reduce the thermal power loss because it is known to reduce EMI as well as the total resistance of a wire. Secondly, choosing temperature independent capacitors is another option to take. Class 1 capacitors are known to be accurate, temperature-compensating [10] [11]. Also, these capacitors have very low electrical losses and no significant aging processes in addition to independence from applied voltages [10] [11]. Nevertheless, Class 1 capacitors have very low volumetric efficiency compared to other types of ceramic capacitors. Therefore, it is too bulky to apply especially when it comes to WPT vehicles.

However, it is still good practice to use Class 1 capacitors for WPT systems due to its lower temperature dependence. So if space for capacitors is enough and the WPT system is not sensitive to weight, Class 1 capacitors are highly recommended. In other cases, we suggest that one use a combination of Class 1 and Class 2 capacitors since Class 2 capacitors are well-known to have a better volumetric efficiency (but less accuracy and stability) [10]. WPT system manufacturers can place Class 1 capacitors where temperature occasionally changes while Class 2 is located in a comparatively temperature stable space. This way, one can reduce volume and weight of capacitors while ensuring stability and efficiency of their WPT system.

B. Controlling Temperature by Applying a Heat Sink

Apart from utilizing temperature robust components (resistors, and capacitors), keeping the surrounding area at an operating temperature by applying a heat sink can be an alternative. With the help of Ansys Icepak, we compare and analyze temperature of pickup modules for a typical WPT with various heat sink geometries. In this study, three variables are taken into consideration (fin numbers, fin thickness, and base thickness). We chose a 35kW pickup module to be analyzed because this type is one of WPT applications that is currently available to high power vehicle operations such as OLEV [12]. It is undeniable that thermal analysis be conducted for such high powered, inductive resonance systems. Fig.6 shows geometries of our model to be analyzed.



(a) (b)

Fig. 6. 35kW pickup module demonstration which includes a core, three coils, and a surrounding case: (a) view from above, (b) front view.

Before applying a heat sink on top, we first need to check whether the applied heat sink causes additional heat with a penetrating electromagnetic field inside. We first consider displacement and thickness of a plate and calculate P_{loss} generated inside the plate. Via Maxwell, we obtain the results in Table IV & Table V. With a few calculations, we conclude that the applied plate does not generate much heat (2~4 W). Furthermore, since current density J decreases as thickness of the plate increase, it is clear that applying a heat sink, which is thicker, does not cause influential heat energy loss. In addition, we apply a heat sink right on top of the pickup module because displacement of the applied plate does not have an impact on J (see Table IV).

To observe effects of a heat sink, we compare maximum temperatures in the core and an area where capacitors are placed. The area is indicated in Fig. 6 (b). The applied heat sink is sized to fit into the space between the case and the pickup module (see Fig. 8). In this example, the pickup module is supposed to have over 90% efficiency and we assume that most of the power loss in the system is due to heat loss (7% of the total power). The initial number of fins, fin thickness, and base thickness are 6, 10mm, and 10mm respectively. The results are listed in Table VI

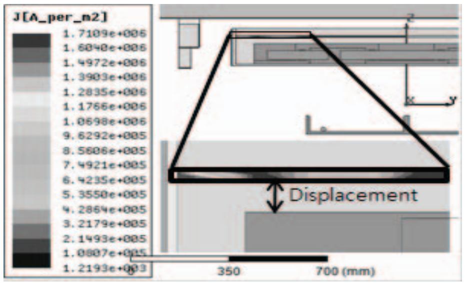


Fig. 7. Current density distribution throughout a 5 mm thick aluminum layer with 30 mm displacement.

TABLE IV

MAXIMUM CURRENT DENSITY J WITH DIFFERENT DISPLACEMENT

Displacement (mm)	*0*	*10*	*20*	30
J_{MAX} (10^6*A/m^2)	1.9732	1.9972	1.5191	1.7109

TABLE V

MAXIMUM CURRENT DENSITY J WITH DIFFERENT THICKNESS OF THE APPLIED LAYER

Thickness of the layer (mm)	*2*	*5*	*10*	20
J_{MAX} (10^6*A/m^2)	5.0551	1.9732	1.0404	0.5286

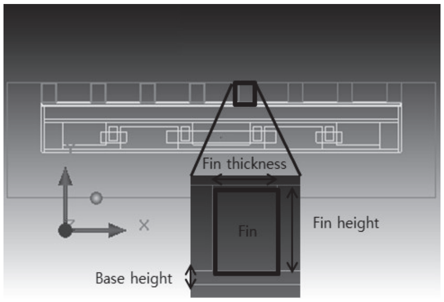


Fig. 8. Pickup module demonstration with a heat sink on top.

TABLE VI

A COMPARISON OF TEMPERATURES WITH DIFFERENT HEAT SINK TYPES

Types (fin #, fin thickness, base thickness)	T_{MAX} of all (°C)	T_{MAX} of CapArea (°C)	ΔT_{MAX} (°C) of	
			all	CapArea
No heat sink	105.9	72.37	-	-
6, 10mm, 10mm	105.3	59.49	-0.6	-12.88
8, 10mm, 10mm	105.3	59.46	-0.6	-12.91
10, 10mm, 10mm	105	58.71	-0.9	-13.66
12, 10mm, 10mm	105	58.41	-0.9	-13.96
14, 10mm, 10mm	105	58.59	-0.9	-13.78
12, 5mm, 10mm	105	58.45	-0.9	-13.92
12, 15mm, 10mm	105	58.33	-0.9	-14.04
12, 20mm, 10mm	105	58.23	-0.9	-14.14
12, 25mm, 10mm	**104.8**	**57.76**	**-1.1**	**-14.61**
12, 30mm, 10mm	105.2	58.9	-0.7	-13.47
12, 25mm, 5mm	105.1	58.73	-0.8	-13.64
12, 25mm, 15mm	104.8	58.13	-1.1	-14.24
12, 25mm, 20mm	105.2	59.19	-0.7	-13.18

As can be seen in Table VI, there exists an optimum size for a heat sink. To gain the optimum, we first changed the number of fins while keeping the same thickness of the fin and base. After finding an appropriate value for the fin number (12 for this example), fin thickness was changed with the same fin number and base thickness. Likewise, we gave variety in the base thickness, and finally found decent values for a heat sink to apply to the pickup module. By applying the optimized heat sink, we were able to improve the |K| value up to 0.7106 from 0.4679; almost 25% efficiency improvement. (Note that we applied quite dependent capacitors and assumed all capacitors in the system are influenced by the maximum temperature to see the worst effects of rising temperature. Current 35kW pickup modules on the market may have higher power transfer efficiency.) Therefore, we conclude that there is a definite advantage in applying a heat sink on top of a pickup module with dimension optimization.

IV. CONCLUSION

We have demonstrated that temperature dependent elements (resistors and capacitors) can deteriorate resonance-based WPT system performance. Analysis of a 35kW WPT system indicates that we can stabilize WPT systems by choosing temperature-robust elements (for example, using Litz Wire, and appropriately placing a combination of Class 1 & Class 2 capacitors) and applying a heat sink to the surface where most heat is generated. With an optimized heat sink, we found that system temperatures can be kept under 58°C which is within a safe operating temperature range.

REFERENCES

[1] iSuppli, “Wireless Charging Market Set to Expand by Factor of Nearly 70 by 2014”, Jun. 2010.

[2] S. Kong, M. Kim, K. Koo, S. Ahn, Bumhee Bae, and J. Kim, “Analytical Expressions for Maximum Transferred Power in Wireless Power Transfer Systems,” IEEE International Symposium on Electromagnetic Compatibility, pp. 379-383,2011.

[3] P. L. Dowell, “Effects of eddy currents in transformer windings,” Proc. Inst. Elec. Eng., vol. 113, no. 8, Aug. 1966.

[4] J. P. Vandelc and P. Ziogas, “A Novel Approach for Minimizing High Frequency Transformer Copper Losses,” IEEE Power Electronics Specialists Conference, 1987 Record, pp. 355-367.

[5] Kiwon Hwang, Seonghwan Kim, Seongkyu Kim, and Seungyoung Ahn, “Design of Wireless Power Transfer System for Railway Application.” International Journal of Railway, Vol.5, No. 4 / December 2012, pp. 167-174.

[6] Robert W. Erickson, Dragan Maksimovic, “Fundamentals of Power Electronics,” 2nd ed., Kluwer Academic Publishers, 2001, p. 508.

[7] http://www.niccomp.com/Products/TC_Ceramics.pdf, 15. Jan. 2013

[8] Terman, Frederick E. (1943), Radio Engineers' Handbook, McGraw-Hill, pp. 37, 74, 80

[9] http://www.litz-wire.com/products.html, 15. Jan. 2013

[10] Otto Zinke, Hans Seither (2002) (in German), Widerstände, Kondensatoren, Spulen und ihre Werkstoffe (2. ed.), Berlin: Springer, ISBN 3-540-11334-7

[11] W. S. Lee, J. Yang, T. Yang, C. Y. Su, Y. L. Hu, Yageo: Ultra High-Q NP0 MLCC with Ag inner Electrode for Telecommunication Application. In: Passive Components Industry, 2004, page 26ff

[12] Sungwoo Lee, Jin Huh, Changbyung Park, Nam-Sup Choi, Gyu-Hyeoung Cho and Chun-Taek Rim (2010). “On-line electric vehicle using inductive power transfer system”, in IEEE Energy Conversion Congress and Exposition (ECCE), pp. 1598-1601.