Thermal Integration of a High Power Polyphase Inductive Coil Assembly

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Abstract— **As inductive wireless power transfer reaches higher power levels; thermal management becomes essential. To address these concerns, past works have demonstrated the benefit of encapsulating coil assemblies with thermally conductive materials and integrating backside liquid cooling into coil assemblies. This work adds to these developments by considering the thermal analysis and construction of a liquid-cooled high power polyphase wireless power transfer ground assembly intended for long duration operation at high power levels, aiming towards hundreds of kW or even 1 MW.**

Keywords— Thermal, liquid-cooling, high-power, polyphase, wireless power transfer, encapsulation, coil design

I. Introduction

Inductive wireless power transfer (WPT) continues to mature for electric passenger vehicles, trucks, and buses with increasingly high-power levels and power densities. Some electric passenger vehicles fast charge at hundreds of kilowatts already, and the larger batteries on electric trucks and buses enable charging at even higher power levels over longer durations. As the power levels of the WPT systems increase, so do the losses in the power electronics, conductors, and magnetic materials which may be constrained by volume, weight, or cost requirements. If coil assembly losses are not dissipated through cooling, the temperatures of components will increase, possibly exceeding the temperature limits of the wire insulation or enclosure. Below these ultimate limits, other thermal effects such as thermal cycling stress and increases in conductor resistance must be considered for their impact on reliability and efficiency. Therefore, active cooling methods have been applied to maintain lower steady-state temperatures and increase the operating duration, lifetime, and power density of WPT systems.

For many low-power WPT systems, passive cooling or forced air cooling is enough to effectively cool the system. However, the coil assemblies of these systems may be buried or fully enclosed for ingress protection, reducing the possibility of passive or forced-air heat transfer as shown in [1], [2]. Instead, in [3] liquid cooling can be integrated into the ground assembly (GA) and vehicle assembly (VA) enclosures to actively cool the coil conductors, ferrite, and resonant components. The integration of liquid coolant loops within the GA and VA must be done carefully: metal tubing exposed to alternating magnetic field will develop eddy current losses and additional heat. The liquid coolant itself, which is often inhibited glycol-water coolant in electric vehicles, may also contain and accumulate impurities through corrosion and be too conductive for direct contact with voltage carrying elements or magnetic fields [4]. Therefore, the coolant loops are placed on the backside of the ferrite which shields the coolant from the magnetic fields generated by the coil current. This sort of indirect cooling places encapsulation materials, ferrite, and litz wire in the primary heat transfer path. The heat transfer of a similar path is analyzed in [5], where the transverse thermal conductivity of the litz wire is shown to vary according to the bundling and number of strands and is on the order of 1-2 W/(m-K).

This work considers the application of backside indirect liquid cooling to a high-power polyphase inductive coil assembly. In [6], a polyphase version of the bipolar coil geometry was proposed. The fields of the three-phase bipolar coils are similar to the fields of bipolar coils but revolve each period such that the field at any radial point resembles the peak field from a bipolar structure when excited by three-phase currents. This allows the peak flux magnitudes in the coil ferrites and coil current density to be more-uniformly distributed than the bipolar geometry, potentially reducing the thickness of the ferrite and coil hotspots and increasing the power density of the system. This work introduces a backside liquid cooling system to a high-power polyphase WPT system, aiming towards hundreds of kW or even 1 MW capacity and long operating

This manuscript has been authored by Oak Ridge National Laboratory, operated by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy.

durations. This cooling system enables these very high power levels with smaller wire gauges and less number of wires in parallel by significantly increasing the current carrying capacity of litz wires. For example, instead of the typical 80-90 A ampacity for 4 AWG litz wire without cooling, 160-170 A current levels may be achieved with cooling. This enhancement not only improves current density but also promises substantial cost and weight savings. In Section II, a straightforward analysis of the thermal performance is outlined and confirmed by finite-element analysis (FEA) simulations and then the mechanical implementation of liquid cooling is detailed in Section III. Conclusions are provided in Section IV.

II. Modeling of Coil Assembly Heat Transfer

A. Heat Transfer in Coil Assembly Layers

To better understand the impact and requirements for cooling high-power WPT coil assemblies, the losses and heat transfer of the assemblies must be modeled. The area-related heat generation of a coil assembly is a function of the coil-to-coil power level *P*, the coil quality factor *Q*, and the coupling coefficient of the coils *k*. The coupling coefficient is strongly a function of the geometric mean length (GML) of the coil geometry l_{GM} relative to the airgap. l_{GM} is defined as the square root of the product of the outer dimensions of the coil, which is the area for rectangular coils, or the outer diameter for circular coil geometries. As often derived in the literature, at optimum loading with matched coils, the coil-coil efficiency η can be calculated as [7]

$$\eta = \frac{k^2Q^2}{\left(1+\sqrt{1+k^2Q^2}\right)^2} \approx 1 - \frac{2}{kQ}. \quad (1)$$

Therefore, for a given power level and area-related heat transfer coefficient h_T, the surface temperature increase ΔT is expressed by:

$$\Delta T = \frac{P}{kQh_T l_{GM}^2}. \quad (2)$$

To achieve higher power levels, high h_T is needed to limit the temperature rise. For conductive cooling, the heat transfer is governed by the thermal conductivity of the material, κ_{th}, and thickness, *t*, as [8]

$$h_T = \frac{\kappa_{th}}{t}. \quad (3)$$

The thermal resistance R_{th} of each layer of area *A* is then

$$R_{th} = \frac{1}{h_T A} = \frac{t}{\kappa_{th} A}. \quad (4)$$

For indirect backside cooling with 20 mm of ferrite in the ideal case, 175 W/m^{2}K is the upper limit for h_T given the 3.5 W/mK thermal conductivity of the material as given in Table I and Table II. This relatively high heat transfer potential through the ferrite further motivates the backside liquid cooling of the coil through the ferrite as implemented in this work.

TABLE I - Area-Related Heat Transfer Coefficients [8]

Heat Transfer Type	Typical Heat Transfer Coefficient (W/m^{2}K)
Natural Air Conv. Vertical Wall	5
Forced Air Conv. at 5 m/s	30
Forced Air Conv. at >30 m/s	100
Conduction through 20 mm 3C95 Ferrite (3.5 W/mK)	175
Water at 2 m/s over a Flat Plate	590
Water at 19 m/s through 20 mm I.D. Tube	34500

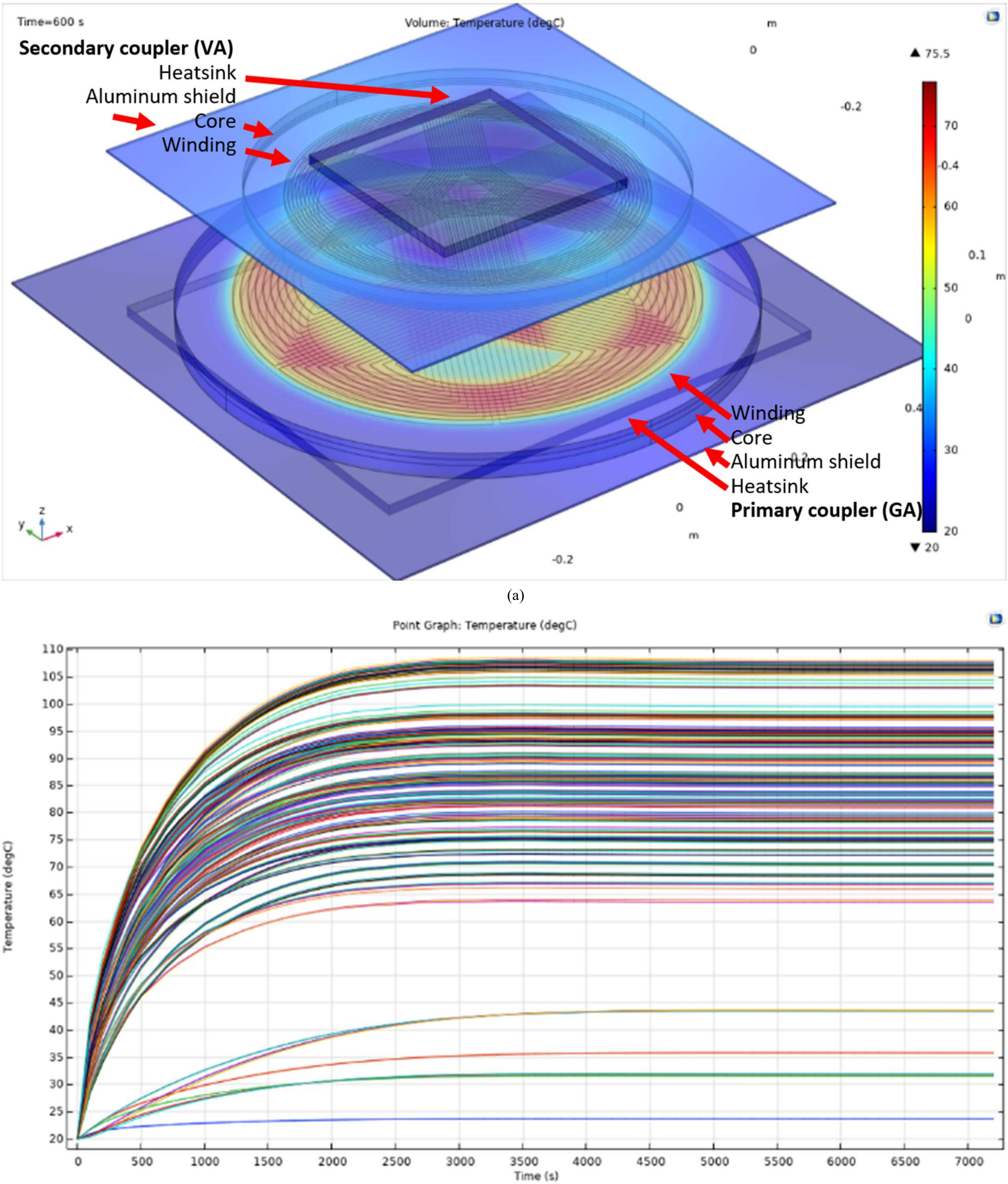
TABLE II - FEA Simulation Parameters

Layer Description	Modeled Loss	Thickness (mm)	Thermal Conductivity (W/mK)
Aluminum	N/A	3.1 mm	167 W/mK
MnZn Ferrite [9]	1.3 kW	20 mm	3.5 W/mK
Cooltherm SC-320/ 4 AWG/42 Litz Wire	1.9 kW 507 A(rms) per phase 169 A(rms) per wire Three wires/phase	18.5 mm	3.0 W/mK

B. Finite Element Analysis of Coil Assembly Heat Transfer

Thermal analysis of a high-power polyphase coil GA with a 20 mm ferrite layer and aluminum shield was conducted using the COMSOL finite element analysis (FEA) simulation software. The simulation settings are summarized in Table II. The polyphase GA is simulated with a wire current of 169 A(rms). There are three 4 AWG equivalent litz wires with 42 AWG strands in parallel per phase equating to an overall 507 A(rms) per phase and three phases overall in the bipolar polyphase coil geometry. Depending on the inverter DC-link voltage, deadtime, and phase, this equates to hundreds of kilowatts for lower DC-link voltages or 1 MW for a DC-link voltages of around 800 V.

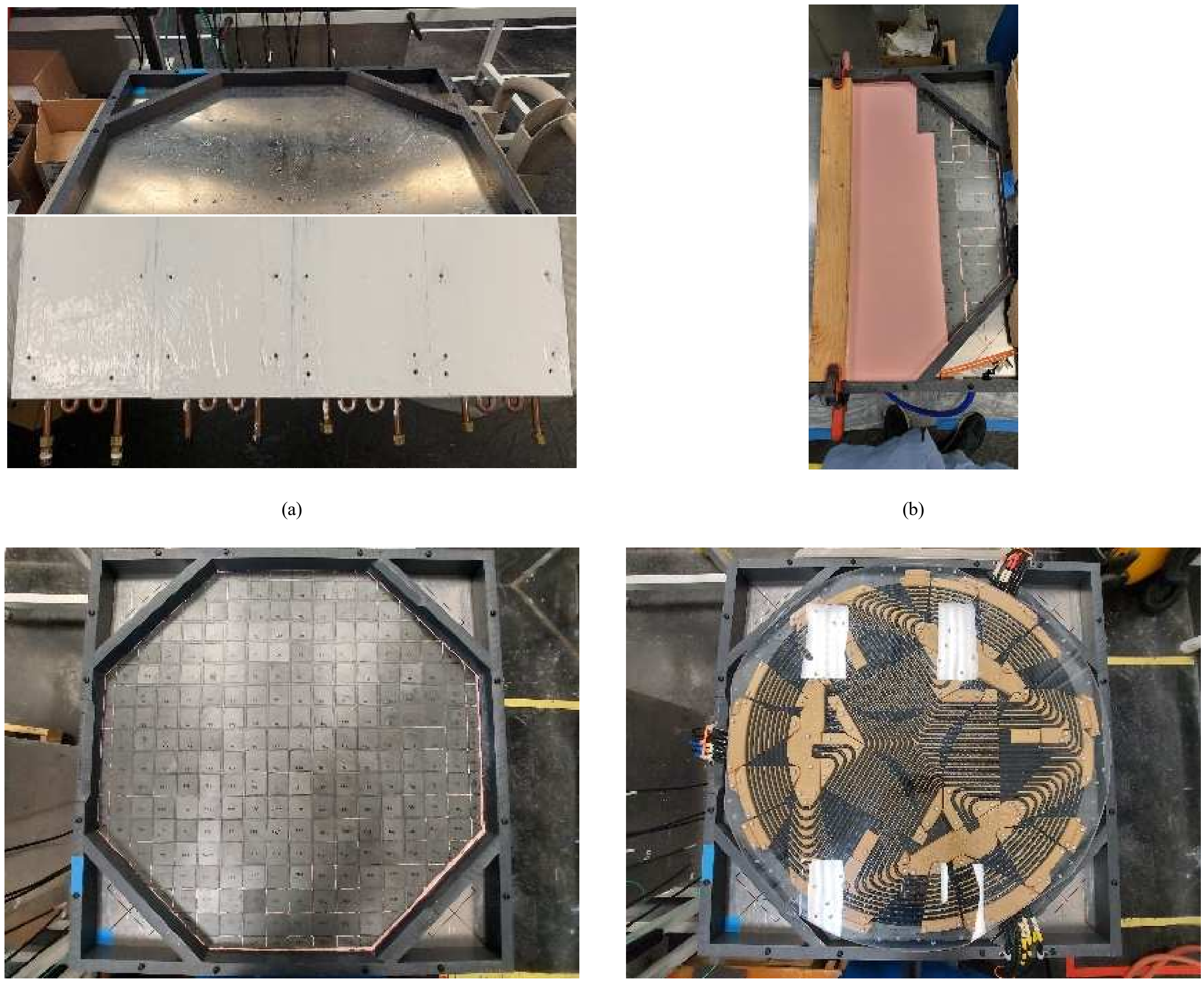
The thermal design of the polyphase coupler involved the utilization of Cooltherm SC-320 as the cooling medium around the coil windings. As depicted in Fig. 1 (a), beneath the polyphase wire windings, a 20 mm-thick ferrite material was employed on top of a 3.1 mm thick aluminum shield. Cold plates with copper tubing were placed under the aluminum shield to facilitate efficient liquid cooling and maintain the desired operating temperature with a constant temperature boundary of 20°C. The FEA simulation results, presented in Fig. 1 (b), predict that the GA's innermost center experiences the most significant thermal stress, reaching a maximum temperature of



(a)

(b)

Fig. 1. Thermal analysis of a high power polyphase ground assembly (shown with vehicle assembly for context): a) COMSOL finite-element analysis simulation set-up with thermal integration, b) simulated temperature of vertices within the coil assembly with the highest temperatures at the coil center.



(a) (b) (c) (d)

Fig. 2. The process of thermal integration of the polyphase system: (a) alumunium shield with PVC frame and backside heatsinks, (b) placement of ferrite on spread encapsulant, (c) completed ferrite layers with cured encapsulant, and (d) mounted coil assembly with strain reliefs.

108°C. These findings provide crucial data for optimizing the system's design and ensuring its safe and efficient operation in high-power, high-current applications over long durations.

III. CONSTRUCTION OF THE LIQUID COOLED POLYPHASE COIL ASSEMBLY

The construction of the liquid-cooled polyphase coil assembly, as illustrated in Fig. 2, involved a meticulous and methodical approach to ensure optimal performance and thermal management. Four heatsinks were strategically fastened to the aluminum shield using tapped holes in the heatsinks and countersunk bolts. Thermal grease was used between the aluminum shield and heatsinks to eliminate any potential air gaps and lower the interfacial thermal resistance. Additionally, the ferrite tiles were carefully cut, laid out, and dry-fit for a precise fit within the frame. To accommodate the lead wires, the edges of PVC frame were chamfered and rounded at three locations. Strain relief clamps were also installed by tapped holes on the frame, providing a secure means to attach the wires to the frame. Furthermore, meticulous organization was maintained throughout the assembly process, with each ferrite piece numbered and arranged in order beforehand within designated boxes to control the tolerances of the tiles during assembly. The Cooltherm encapsulant was evenly distributed between the layers of ferrite using a notched adhesive spreader to ensure consistent thickness. As in Fig. 2 (b), the GA was partitioned into two sections with a temporary border to account for the working time of the Cooltherm encapsulant for both the first and second layers of ferrite. This detailed construction process was crucial to achieve an orderly and a repeatable assembly process.

IV. Conclusions

In conclusion, this work presents a thermal analysis of a high-power polyphase ground assembly with integrated indirect liquid cooling using COMSOL FEA at high current and power levels. The construction of the cooled ground assembly is also detailed with details of the assembly process, fastening method, and encapsulant application. The thermal modeling predicts that the proposed thermal management system can facilitate continuous operation of the high-power polyphase coil assembly with high current at hundreds of kilowatts or even 1 MW power levels. The proposed indirect backside liquid cooling enhances the current carrying capacity of litz wires to enable the utilization of smaller wire cross-sectional areas and fewer wires in parallel for high power systems. Specifically, for the proposed system cooling significantly increases the current carrying capacity of litz wires, from the typical 80-90 A for a 4 AWG litz wire without cooling to 160-170 A with cooling. This enhancement not only improves current density but also promises substantial cost and weight savings. This innovation underscores the feasibility and effectiveness of advanced thermal management solutions for high-power applications, promising enhanced efficiency and reliability in future MW-level wireless power transfer systems.

Acknowledgements

This research used the Power Electronics and Electric Machinery Research Center at the National Transportation Research Center, a DOE EERE User Facility operated by the Oak Ridge National Laboratory (ORNL). The authors would like to thank Lee Slezak (U.S. Department of Energy) for their support and guidance on this work.

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