A NOVEL DESIGN FOR A 22KW TRANSFORMER FOR A 3 PHASE FULL BRIDGE LLC EV ONBOARD CHARGER FOR SMALLER SIZE, LOWER COST AND IMPROVED PERFORMANCE

Abstract

As power levels increase, powertrain system engineers are already moving to a three-phase full bridge LLC topology but this in turn brings challenges for heat dissipation and symmetrical operation of the transformer. These challenges have limited the performance of existing magnetic integrations. A novel transformer construction for symmetrical operation is presented that also reduces the size and cost compared to the multi transformer approach. This paper introduces the concept and presents the finite element modelling (FEM) and SPICE results used to optimize the design. Finally, the concept is validated through prototyping and evaluation in a 22kW on-board charger (OBC).

Benefits and Challenges of Magnetic Integration

Earlier generation OBC's have utilized multiple LLC transformers to reach power levels up to 6.6kW and beyond. Figure 1 illustrates one such solution, a 52x51x40mm PQ50/35 3.3kW transformer [1]

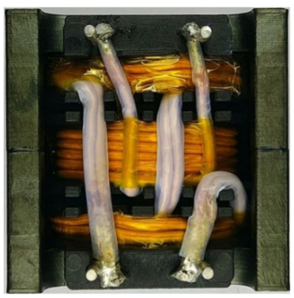

Fig. 1: 3.3kW LLC transformer

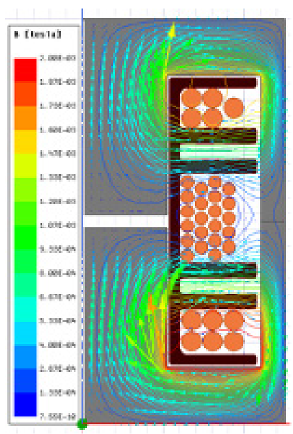

Fig 2: FEM of the primary winding flux path

This transformer was designed with a core gap location that provides a high reluctance to the primary flux linking with the secondary winding, while simultaneously providing a low reluctance to the secondary flux linking with the primary winding. This resulted in a concentration of the leakage inductance (i.e., reduce flux linkage) in the primary side of the transformer. It was sufficient to replace the need for an external resonant inductor.

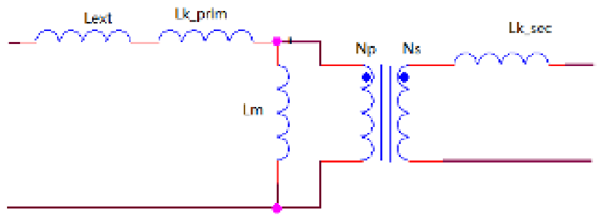

Fig 3

Fig 3: Transformer equivalent circuit with L_{prim} available to replace the L_{ext} external resonant inductor.

However, even with this first level of magnetic integration, 2 large components are still required to reach 6.6kW of throughput power. Along with their associated cooling requirements, these existing solutions occupy a significant volume (2x106cm3) and PCB board real estate.

Hardware engineers have looked to three phase systems to reduce the size of their OBC solutions when dealing with power ranges from about 7kW. Figure 4 shows an example of a ladder core construction EE70 transformer solution. At 86x54x32mm (148cm3), it is already 30% smaller and less expensive than the above 3.3kW x 2pcs magnetic solution.

However, with this magnetic integration, two limitations become evident when scaling this approach for higher power.

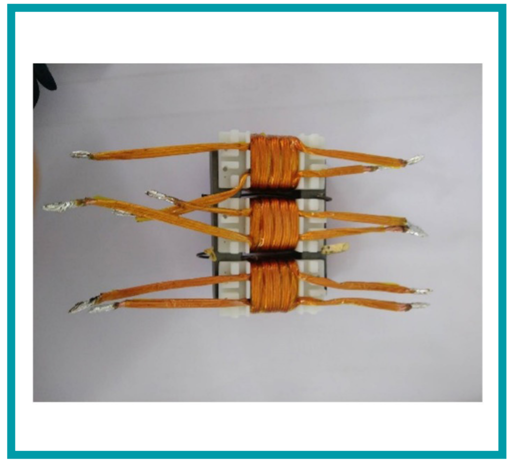

Fig. 4: 7kW, 3 phase LLC transformer

1 With the E core construction, the hot spot temperature is in the winding over the center leg air gap. Here, the resistive losses of the winding and the air gap related eddy current losses combine with the core losses in an area where it is difficult to introduce a high thermal conductivity interface for cooling.

2 The different magnetic resistance seen by the center and outer leg windings result in unbalanced flux paths between the transformer phases which result in asymmetrical current waveforms and flux density. Besides the obvious impact on the dissipated losses within the transformer and in other circuit components due to imbalanced currents, this also presents EMC challenges due to higher ripple currents.

The second limitation is further explained by considering the equivalent magnetic circuit of the E core construction and resistance paths of each core leg

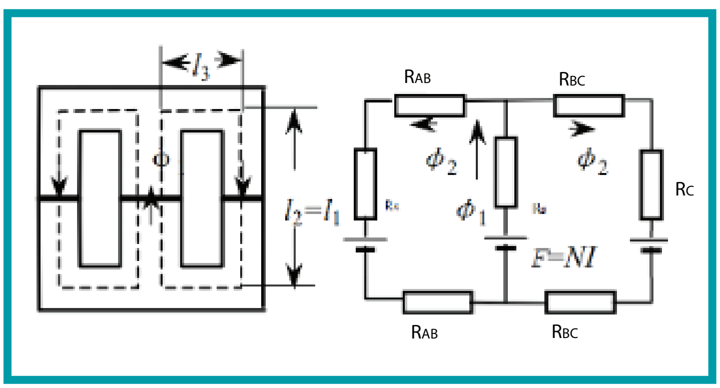

Fig. 5: E core equivalent circuit model

The magnetic resistance R_m denoted as

$$Rm = \frac{Le}{\mu * Ae} \qquad (1)$$

Where -

L_e is the effective path length
μ is the effective permeability of the core
A_e is the core cross sectional area

The equivalent magnetic resistance of each phase is calculated as

$R_{phaseA} = R_A+2*R_{AB}+R_B //(2*R_{BC}+R_C)$ (2)
$R_{phaseB} = R_B+(2*R_{AB}+R_A)//(2*R_{BC}+R_C)$ (3)
$R_{phaseC} = R_C+2*R_{BC}+R_B //(2*R_{AB}+R_A)$ (4)

As $R_{AB} = R_{BC}$ and $R_A = R_B = R_C$, these can be simplified to

$R_{phaseA} = R_A+2*R_{AB}+R_A //(R_{AC}+R_C)$ (5)
$R_{phaseB} = R_A+R_{AB}+R_A/2$ (6)

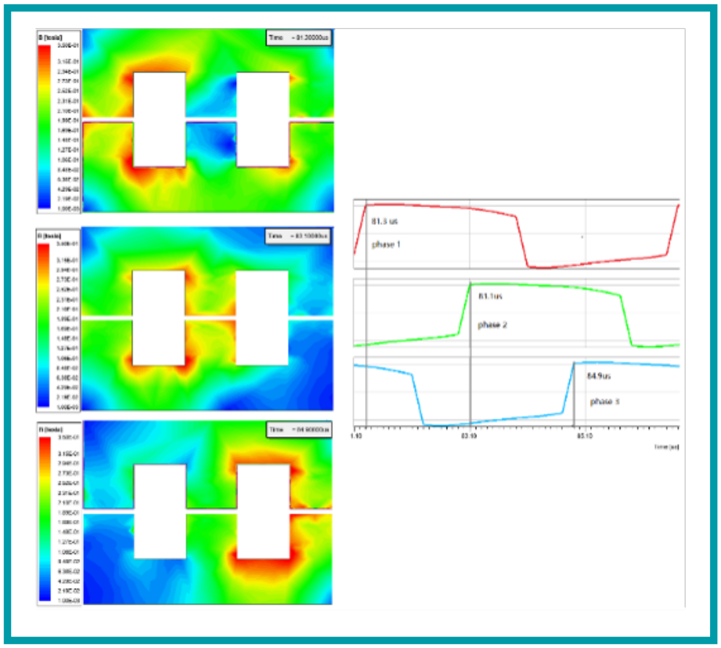

Fig. 6: E core flux driven by each phase.

With $R_{phaseC} = R_{phaseA} > R_{phaseB}$, the different magnetic resistances result in an unbalance flux flow as shown in Figure 6.

Spice modelling of the OBC circuit using this magnetics model confirms the current imbalance. Figure 7 shows the simulated three phase currents with these on each other after the phase 2 and phase 3 current are 1/3 and 2/3 phase shifted respectively for comparison purpose.

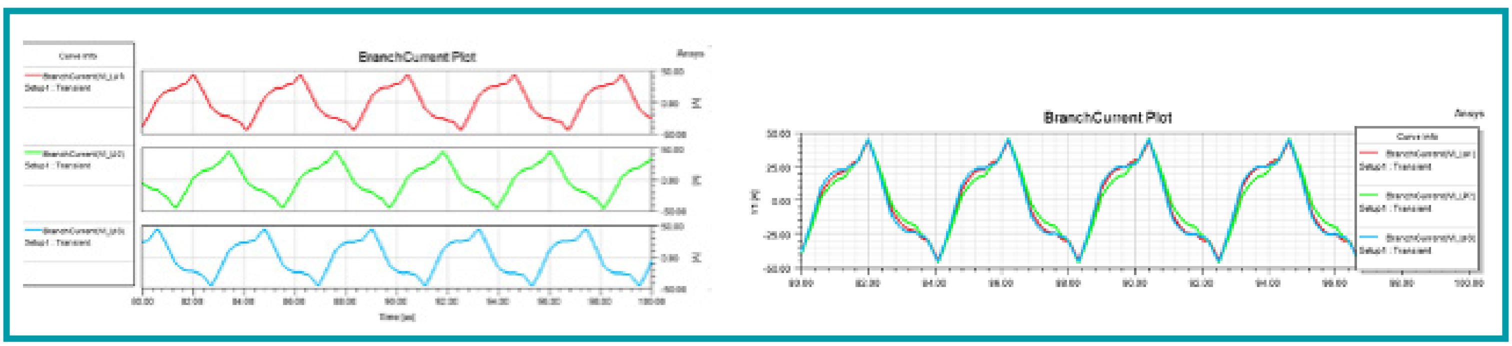

Fig. 7: Simulation and superimposition of the current waveforms for E core construction.

A New Three Phase Transformer Construction

A key requirement for a new transformer construction, to overcome the limitations of the E core solution, in for a core design that facilitates a balanced coupling between each phase. The design also needs to allow for the required leakage inductance between phases to eliminate the need for an external resonant inductor.

Maxwell Ansys is a powerful tool 3D finite element analysis modeling tool that allows for the simulation of various alternate core constructions. By analysis of the balanced flux generate by one winding through the two other core legs, the concept of the triangular shaped core construction shown in Figure 8 was developed.

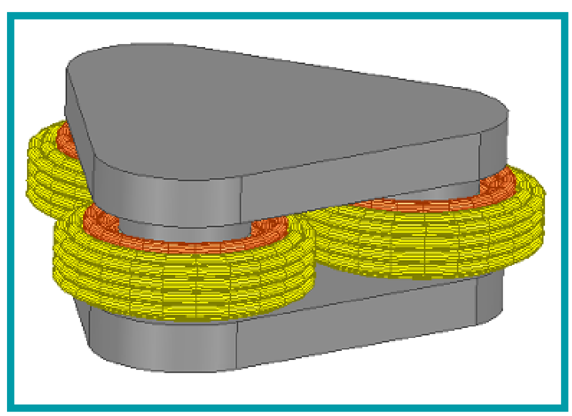

Fig. 8: Triangular core transformer

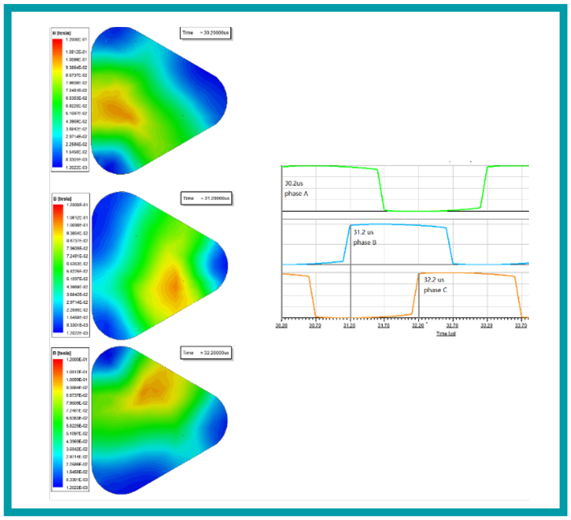

Fig. 9: Triangular core with balanced flux

Repeating the equivalent magnetic circuit analysis, we now have equal magnetic resistance in each phase. The related flux modeling shown in Figure 9 demonstrates that an equalized coupling between the transformers in each phase has been achieved

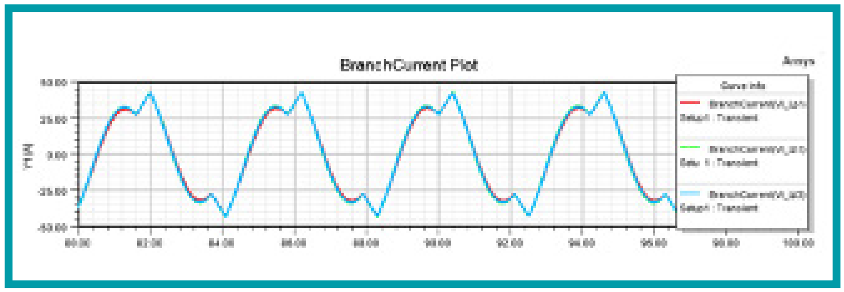

Fig. 10 Balanced triangular core current

A significant benefit of this new construction is that it now eliminates the inner leg and its associated hot spot temperature. Additionally, the large upper and lower core surface area allows for a much better thermal interface with the OBC cooling system, reducing the component size for a given power compared to the traditional E core construction.

Further Spice modelling of the OBC circuit using the magnetic model for this core construction, with a superposition of simulated currents, reveals that the currents are now well balanced.

22kW CLLC Transformer Design

The magnetics requirements of a 22kW, 3 phase CLLC topology was selected for product design [2].

- Input voltage: 600V-850V
- Output voltage: 540V-765V
- Switch frequency: 250KHz-400KHz
- Np:Ns = 10:9
- Lm = 19.8uH
- Lrp = 3.8uH, Lrs = 3.1uH

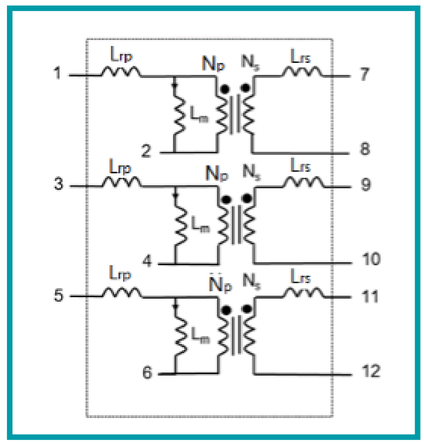

Fig. 11: 22kW CLLC transformer

Figure 11 summarizes the requirements for the integrated magnetic component, with the goal to once again use the transformer leakage inductance to eliminate the need for external resonant inductors Based on an 97.5% target efficiency for maximum output power conditions, an initial core size and cross-sectional area was selected for sufficient heat dissipation of the core and winding losses. This resulted in a starting point for a winding design for the targeted leakage inductance values.

Unlike the earlier LLC transformer where concentrated primary side leakage inductance was the target, the CLLC topology requires both primary and secondary side resonant inductors. Therefore, a more traditional winding construction could be adopted for balance leakage inductance. FEM techniques were once again used to arrive at two segment winding design to achieve the target leakage inductance.

Finally, a mechanical design was selected for board mounting and securing the safety requirements, as illustrated in Figure 12.

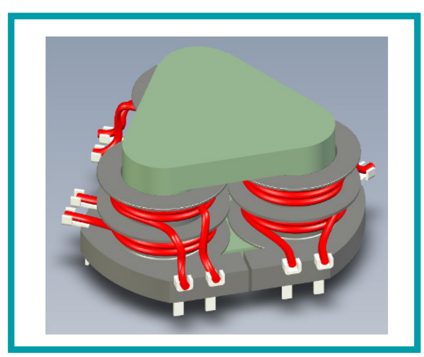

Fig. 12 22kW CLLC Transformer 3D Model

Product Realization and In Application Testing

A 112 x 110 x 46.5mm transformer design (Volume ~ 280cm3) was selected for product prototyping using machined cores and 3D printed coil formers. This is 35% smaller and less expensive that the earlier 7kW x 3 pcs magnetic solution.

Centre leg gapping of the core was used to achieve the target open circuit inductance, with fine tuning to the bobbin segment separation to fulfil the target leakage inductance requirement.

Fig. 13 22kW CLLC Transformer prototype sample

The prototype transformer was tested in a client's 22KW OBC application with positive results. Client confidentiality precludes the sharing of their measured data, but it can be confirmed that the current waveform is well aligned with the simulated waveform in Figure 10, contributing to a higher than expected fully load efficiency (97.9%). Although temperature hot spots remain in the winding area over the core gaps, these are now equally distributed over the three legs and the core design is efficient in dissipating that generate heat through the large top and bottom areas, reducing the overall component temperature rise. The client confirms a superior performance compared to the E core solution of similar magnetic size where the efficiency is compromised by the current imbalance, with greater component temperature due to its localized hotspot.

Conclusion

This paper discussed the benefits of integration is multi-KW OBC applications. Building on an earlier single-phase LLC design where the primary side leakage inductance replaced a discrete resonant inductor, a novel construction for a three phase CLLC transformer was presented to address the limitations of traditional solutions. A 22KW CLLC transformer was tested in a OBC application to confirm a balanced current waveform operation that resulted in higher efficiency and reduced hot spot temperatures.

References

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