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Rubrik på rapporten

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Författare
Datum
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Innehåll

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Instruktioner för slutrapport

- *Instruktioner är skrivna med brun kursiv text – alla sådan text tas med fördel bort innan redovisning sker.*
- *Ingen begräsning finns för antalet sidor*

1. Sammanfattning

Kort sammanfattning, max 5 000 tecken.

Denna tekniska rapport beskriver de teoretiska och experimentella arbeten som utförts av kraftelektronikgruppen vid Mittuniversitetet i samarbete med Huawei R&D Sweden om projektet nr "52703-1" med titeln "Optimering av plana magnetiska enheter för en 22 kW Bidirectional On-kortladdare för att uppnå 98 % verkningsgrad, 4,6 kW/L och 35 $/kW" under perioden 2021-11-01/2022-06-30.

Projektet är en förstudie för att undersöka och validera nya designmetoder för induktiva komponenter för att öka effektiviteten och effekttätheten hos den högfrekventa induktiva komponenter som används i en 22 kW ombordladdare för EV-applikationer.

Projektet är en del av programmet Fordonsstrategisk forskning och innovation (FFI) och det finansieras av Energimyndigheten.

2. Executive summary

Executive summary ska vara en komprimerad version av rapporten, inte enbart en översättning av den svenska sammanfattningen.

This technical report details the theoretical and experimental works conducted by the power electronics group at Mid Sweden University with the collaboration of Huawei R&D Sweden of the project No "52703-1" entitled "Optimization of Planar Magnetic Devices for a 22 kW Bidirectional On-board Charger to achieve 98% efficiency, 4.6 kW/L and 35 $/kW" during the period 2021-11-01/2022-06-30.

The project is a preliminary study to investigate and validate new design approach of magnetics in order to increase the efficiency and the power density of the high frequency magnetics employed in a 22 kW On-board-charger for EV application.

The project is part of the Vehicle strategic research and innovation (FFI) program and it is funded by the Swedish Energy Agency.

3. Bakgrund

The automotive market is witnessing a radical change from the conventional vehicle to the electric vehicle (EV). In order the increase the penetration of the Electric Vehicle (EV) into the automotive market and improve its competitiveness with the petrol car, the FFI and the US-road map have raised up the requirements that concerns the power electronics systems and the electrical traction motors. Among the power electronics requirements, the ones that concern the on-board charger (OBC) which is a central part of the EV charging system. Specifically, the 2025 US-drive road maps have set the target to achieve OBCs with the following requirements: 98% efficiency, 4.6 kW/L power density and 35 $/kW cost.

Magnetics, which are a central part in the OBC, remain the main obstacle that hinders to improve the efficiency and the power density. They are the bulkiest components and they degrades the total efficiency of the OBC due to their high loss. With the very slow advancement in the development of efficient magnetic materials, design optimization is still considered nowadays as the solely solution to improve the efficiency and the power density of the magnetic components. The optimization of the magnetic components deals principally with the minimization of the core loss and the winding loss. In the literature, there are several approaches, methods and techniques developed for this objective. In recent years, with the emerging of the Wide-Band-Gap devices like GaN and SiC, increasing the switching frequency to the MHz range is the most adopted solution in order to improve the performance of the high frequency magnetic components. This solution has brought a considerable improvement for the efficiency and the power density, however it still faces several problems mainly the thermal constraint.

The need for a new magnetic design approach is of great necessity in order to overcome the limitations of the magnetics. In this project, we will explore and investigate two complementary solutions for this problem. The first solution is to use a complete new magnetic design based on an unbalanced-flux distribution instead of the well-known balanced-flux design. The second solution is to use Genetic Algorithms and Pareto front concept in order to find the optimal solution for the two objective functions: efficiency and power density.

4. Syfte, frågeställningar och metod

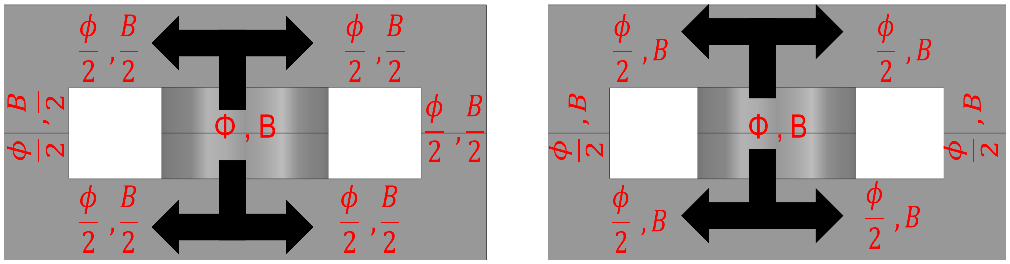
The fundamental approach adopted in this project in order to increase the efficiency and the power density of the magnetic components is the following:

First, we have developed new magnetics based on an unbalanced-flux distribution. The validation of this concept was proven in first step analytically and then verified experimentally by measuring the core loss of the developed magnetics and compare them with the results of the balanced-flux magnetics and with the core loss data given in the manufacturer datasheets. The measurement of the core loss was performed using a fast colorimetric technique using a Peltier device because of its high accuracy and low measurement time. This technique was developed in our research group. In order to enhance the results, we have also performed FEA simulation to calculate the core loss and the winding loss.

Second, we have used GAs and the Pareto front concept to perform the bi-objective optimization of the loss and the volume of the magnetic components for a 22 kW OBC.

A. Unbalanced-flux magnetics

We have proposed a new concept to design the magnetic devices in order to improve their efficiency and power density. The principle of the proposed concept is based on an unbalanced-flux distribution within the magnetic core. The key difference between the proposed concept and the conventional one is highlighted in Fig.1. As it can be seen the magnetic flux density within the outer part of the unbalanced flux concept is lower than the magnetic flux density within the central part. This idea will reduce the core loss and increase its thermal performance because the outer part volume is more 80% the total core volume. The details of this approach are given in [1].



(a) Proposed (unbalanced) design

(b) Conventional (blanced) design

Fig. 1. Φ and B distribution for (a) unbalanced design and (b) balanced design

B. Bi-objective optimization

The bi-objective optimization of the power density, the efficiency of the magnetic devices for 7.2 kW LLC converter of the on-board charger was performed using Genetic Algorithms and Pareto front concept. The objective to determine the optimal solution in the loss and volume design space. There two objective functions (loss-volume) and the design problem includes 24 optimization variables. The optimization tool GOSET developed at Perdue University was used, as it has the ability to solve optimization problems that include mixed-integer variables. The principle of the optimization tool is described in Fig.2. The variation of the optimum solutions of the two objective functions are depicted in Fig.3. The optimal solution is defined as the closed solution to the ideal one.

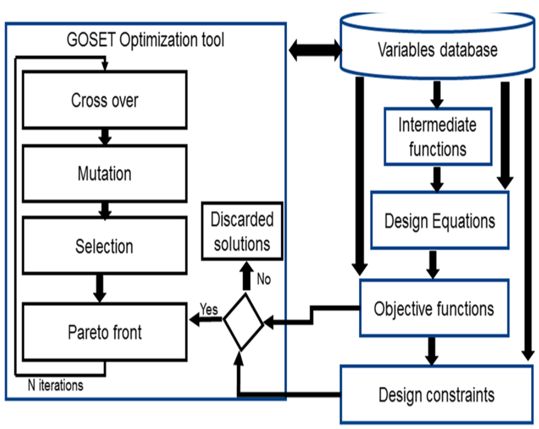


Fig. 2. Principle of GOSET optimization tool

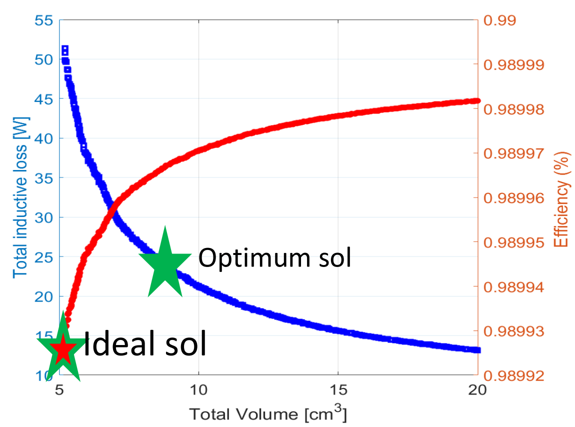


Fig. 3. Optimal solution in the volume-loss design space

5. Mål

The Overall objectives of the project are the following:

1. To optimize the design of the high frequency magnetic devices using an unbalanced-flux design approach
   a. Investigate the effect of the unbalanced-flux design approach on the efficiency and the power density of high frequency magnetics
   b. Verification of the proposed design in a 1kW LLC converter
   c. Verification of the design for 7.2 kW module of a 22 kW OBC

2. To perform a bi-objective optimization of the magnetic components for a 22 kW OBC using Genetic Algorithms and Pareto front concept
3. Experimental measurement of the core loss and the temperature rise of the designed prototype

6. Resultat och måluppfyllelse

The methodology adopted in this project is to firstly verify the proposed approach low power application, typically 1 kW power, and then apply the design for the implementation of the magnetic components for a 22 kW OBC. Consequently, Prototypes of both design applications were implemented to validate the proposed approach. The first design is the transformer and the resonant inductance for 1 kW LLC converter. The second design the transformer of 7.2 kW module of the DC-DC resonant converter for the 22 kW OBC. The optimization of the loss and the volume for both designs were carried out using GAs and Pareto front concept.

1. *Results of the magnetic components for 1 kW LLC converter*

The designed transformer and the resonant inductance for the 1 kW LLC converter are core2 and core3 respectively shown in Fig.5. To verify the proposed magnetics design, the performance of the two unbalanced-flux magnetic cores (core2 and core3) are compared to a balanced-flux magnetic core (core1) (Fig. 5). As it can be seen in Tab. I, to achieve a reasonable comparison of the proposed method, we have chosen core1 with approximately same volume as core1 while core3 has twice the volume of core1.

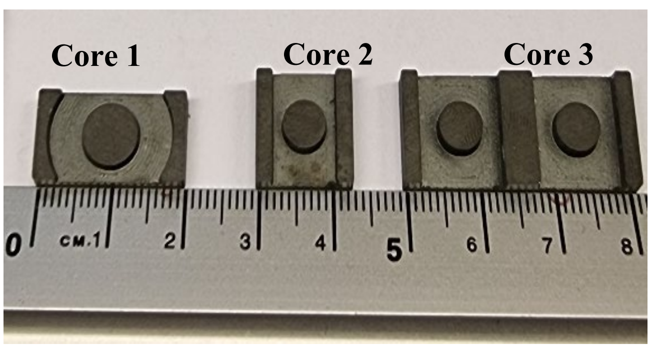


Fig. 5. Photo of the tested core.

TAB.I GEOMETRY CHARACTERISTICS OF THE TESTED MAGNETIC CORES

	Core 1	Core 2	Core 3
Flux	balanced	unbalanced	
Volume(mm^3)	1284	1114	2254
A_c (mm^2)	47.8	28.3	2*28.3
A_o (mm^2)	24.75	28.3	2*28.3
δ	0.9	0.97	0.97
Base area (mm^2)	226.5	192.7	384

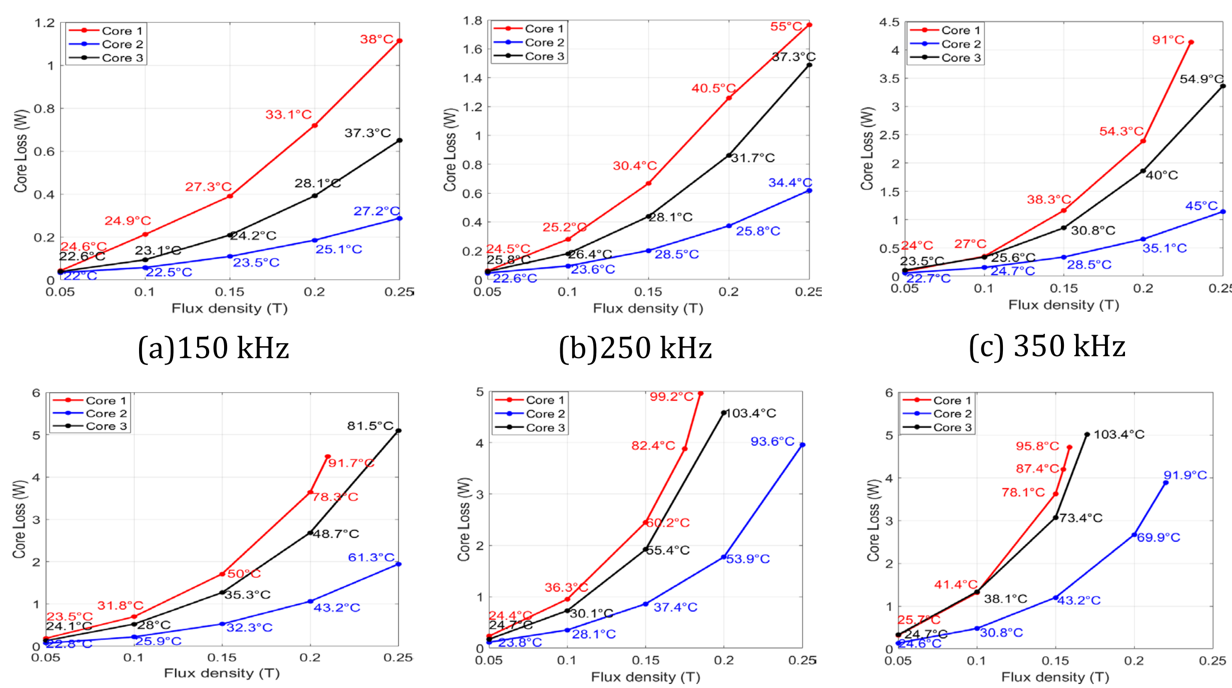
a. *Evaluation of the Core loss and the temperature*

• ***Core1 VS Core2***: despite that core2 and core1 has approximately the same volume, it can be seen in Fig that the unbalanced-flux design (core2) has much lower core loss than the balanced-flux design (core) over all the magnetic flux density and frequency ranges. Fig. shows the core loss density ratio between both designs. It can be clearly seen that the core loss for core1 is 2 to 3.4 times the core loss of core2 in the flux density range [0.1-0.2] T.

Concerning the thermal behavior, it is also clear that the core2 has achieved much better thermal performance than core1. For instance, in case (f) for B=0.15 T, the registered temperature for core2 is 43.2°C, however it peaks at 78.2°C for core1. It should be clearly noticed that the main reason, for the low temperature registered for core2, is the low core loss and certainly is not because of having lower thermal resistance. This can be synthesized by comparing the temperature of both cores at equal core loss. For instance, we can take the case (0.15T, 650 kHz) for core2 and the case (0.1T, 650 kHz) for core1, in which both cores have approximately the same core loss and nearly same temperature.

•***Core1 VS Core3***: in general, core3 has achieved lower core loss and lower temperature rise despite its volume is twice the volume of core1. Fig.7 (b) shows that the core loss density ratio between the balanced and the unbalanced flux designs varies between 2 and 3.5 times in the interval [0.1-0.25] T. Three exceptions are registered for 0.1T at 650, 150 and 350 kHz, which could be due to some measurement errors. it can also be seen that core has achieved lower temperature than core1 at same core loss. As an example, at (0.1 T, 650 kHz), the core loss are same, but the temperature for core1 and core3 are 41.4 °C and 38.1 °C respectively. This means that core3 has lower effective thermal resistance than core1 despite that core1 has a higher outer surface-to-volume ratio.

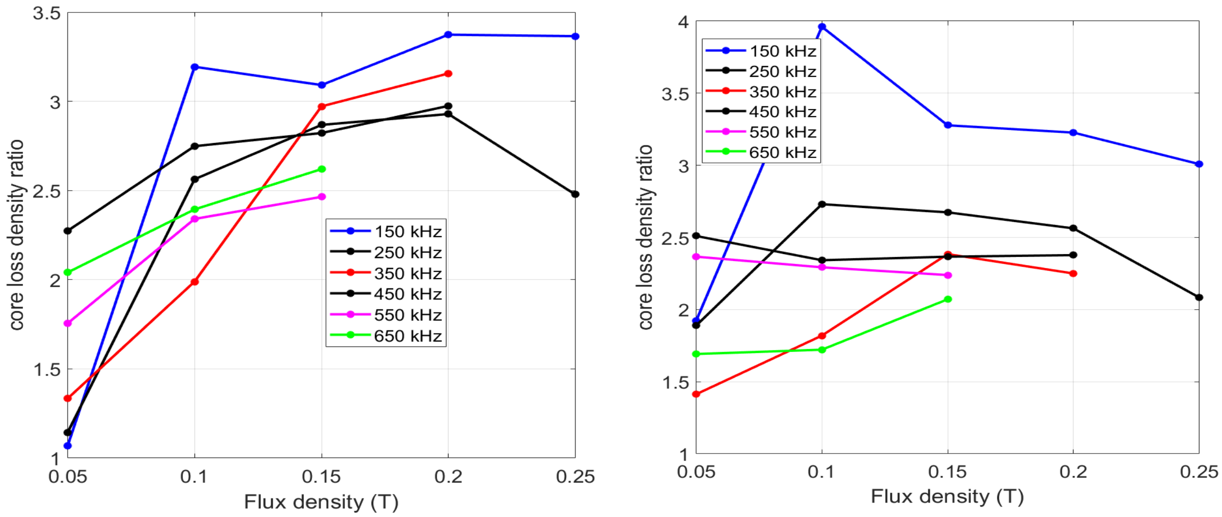
In the previous comparison cases, the registered core loss density ratio, at 0.05 T, is smaller than 2. This is due to the core loss behavior at low temperature and low flux density. We can also notice that the loss density ratio depends on B and f. this aspects are very important and will be furtherly investigated in future works.



(a)150 kHz (b)250 kHz (c) 350 kHz

(d) 450 kHz (d) 550 kHz (d) 650 kHz

Fig. 6. Measured core loss and temperature of the tested cores.



(a) Core1/Core2 (b) Core1/Core3

Fig. 7. Core loss density ratio between balanced and unbalanced flux designs

b. Magnetic power factor (MPF) and Safe operating area (SOA)

In order to characterize the maximum power capability and the safe operating area, the different cores were tested until they reaches the thermal saturation or the flux saturation defined respectively as 100°C and 0.25 T. the maximum power capability is proportional to the maximum magnetic power factor defined as follows:

$$MPF_{max} = f\ {B_m}^2$$

The core loss for core1, core2 and core3 are measured over the frequency range [0.15-0.65] MHz and the corresponding MPF and SOA are given in Fig.8 and Fig.9. The obtained results show that the unbalanced-flux method enables to increase significantly the MPF. The MPF_{max} of core2 and core3 peaked at 34.4 MHz.B^2 and 28.1 MHz.B^2 respectively compared to 19.8 MHz.B^2 for core1. This means that core2 has 73% more power capability than core1 despite it has lower base surface and slightly lower volume. Additionally, despite the previous advantages accounted for core1, core2 has achieved much better performance such as, lower core loss, higher MPF and larger SOA. Fig.8 shows the limits of the SOA for core2 and core1. Similarly, Fig.9 shows the SOA for core3 to core1. As it can be seen, the SOA has been considerably increased which gives the designer more freedom to select the suitable combination of (B, f) in order to meet with the design requirements. Higher MPF and larger SOA definitely enable to reduce the number of turns, which in turns can bring down the winding loss.

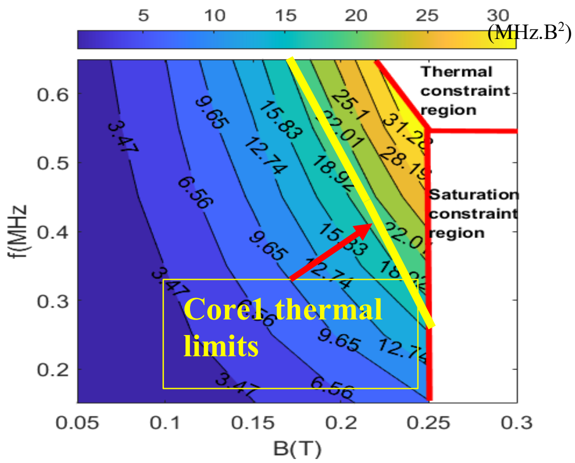


Fig. 8.Working range and power capability of core2 in the (B. f) space.

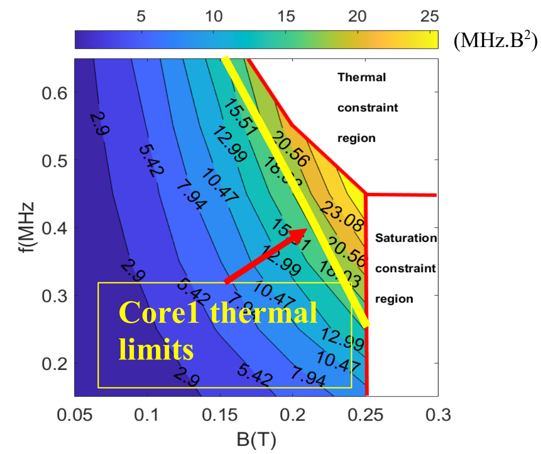


Fig. 9. Working range and power capability of core 3 in the (B. f) space.

2. Results of the HF transformer for 7.2 kW LLC converter

The DC-DC converter of the 22 kW OBC is composed by 3 modules. Each module has a power capability of 7.2 kW. The specifications of the converter are summarized in Tab. I.

Tab. I. LLC Converter specifications

Total power (kW)	**22**
Power per module (kW)	7.2
Voltage (V)	400/800
Frequency (kHz)	340

a. FEA Simulation and PCB design

The optimal solution of the transformer core is shown in Fig and Fig and its dimensions are summarized in Tab. The magnetic flux density, the core loss and the winding loss for different winding structures are investigated using FEA.

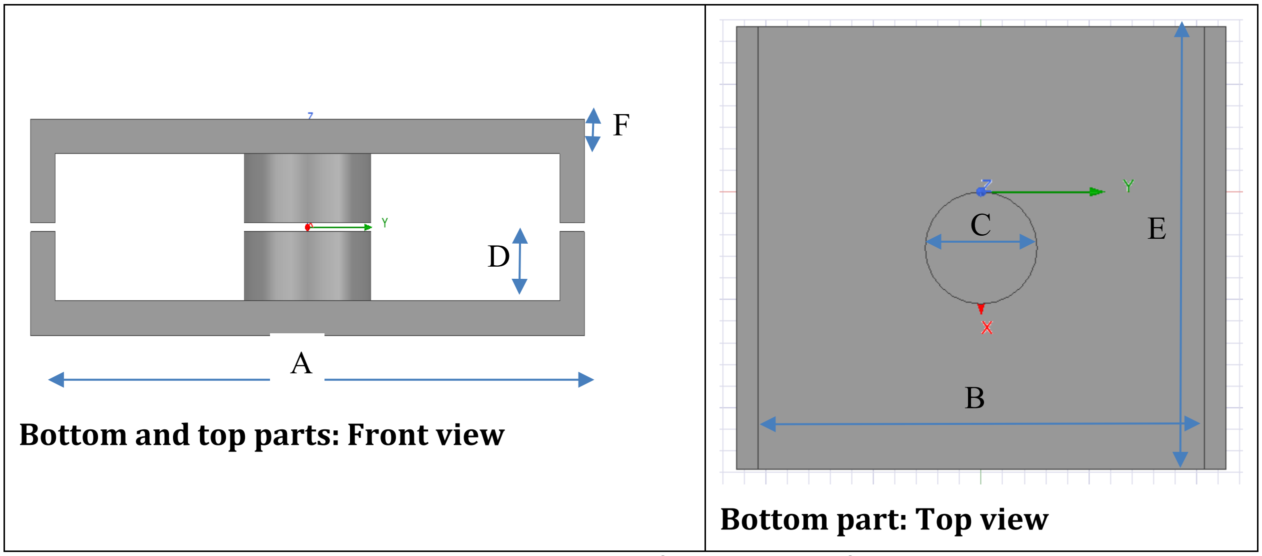


Fig. 10. Front and Bottom view of the designed transformer.

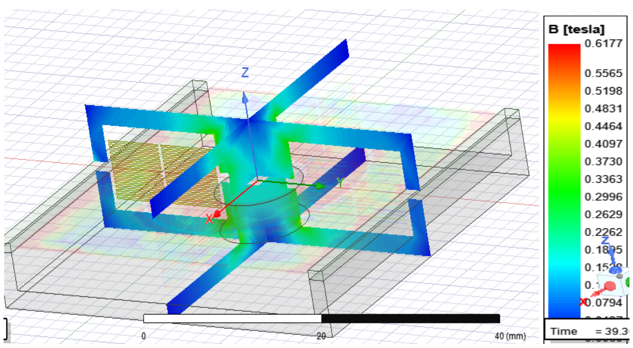


Fig. 11.Magnetic flux density of the designed core.

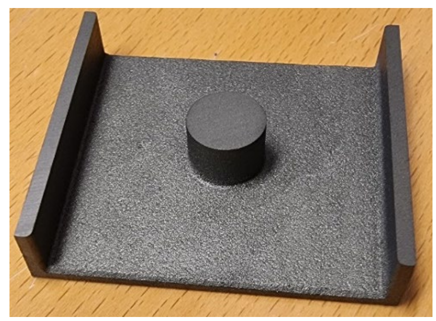
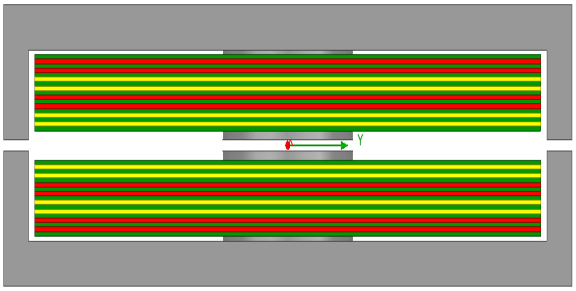
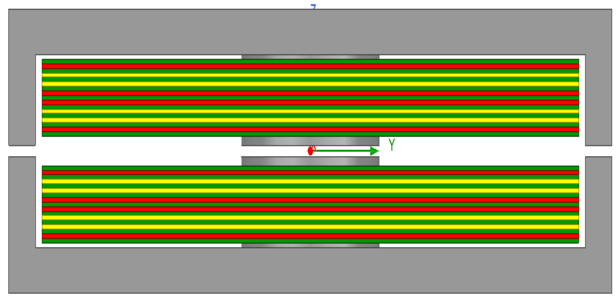


Fig. 12. Sample of the designed unbalanced-flux magnetic core for 7.2 kW.

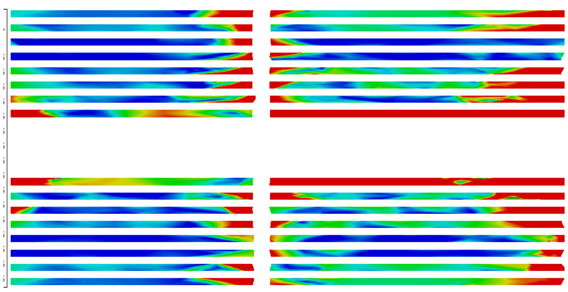
As it can be seen in Fig., the magnetic flux density in the central leg (.02T) is twice the magnetic flux density in the outer part (0.1 T) and that is the principle of the unbalanced-flux density.
Fig. shows the winding loss for different winding arrangements. It is clear that by increasing the interleaving can reduce significantly the winding loss.



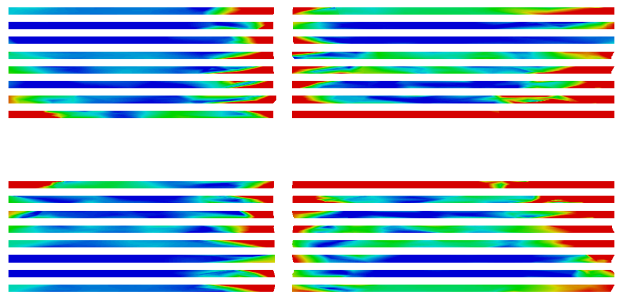
(a) Winding arrangement (A)



(b) Winding arrangement (B)



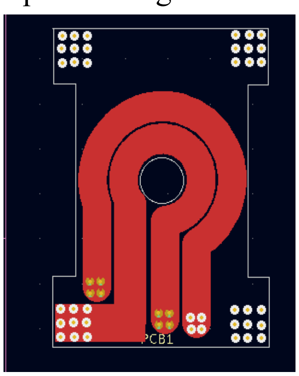
(c) Copper loss for arrangement A in the Z-Y plan



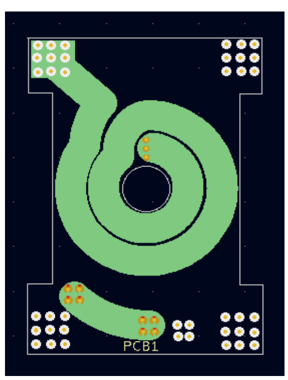
(d) Copper loss for arrangement B in the Z-Y plan

Fig. 13.Winding loss calculation with FEA for different winding arrangements.

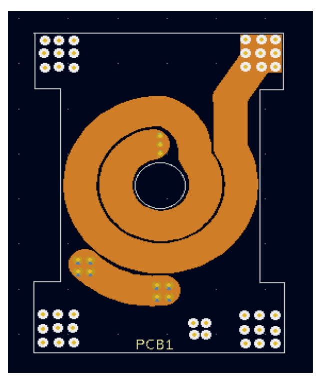
The designed magnetic core is shown in Fig12 and Fig.13. The dimensions are depicted in Tab.2. The final optimal solution of the transformer winding has two primary windings connected in parallel and two secondary windings connected in series (Fig.16). Each primary and secondary is made using two 4-layer PCBs (Fig.15). Each layer has two turns. The 4-layers PCB is chosen over 8-layer PCB due to the manufacturing constraints in making buried vias in the 8-layers PCB. Fig.14. shows the designed PCBs (PCB1 and PCB2). Four PCBs will stacked up to achieve the required design.



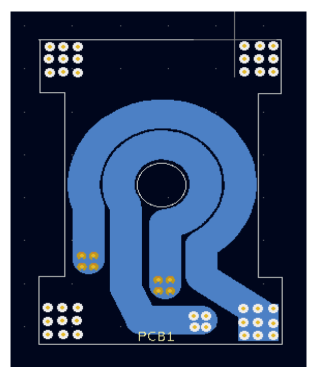
Layer N1: primary



Layer N2: secondary

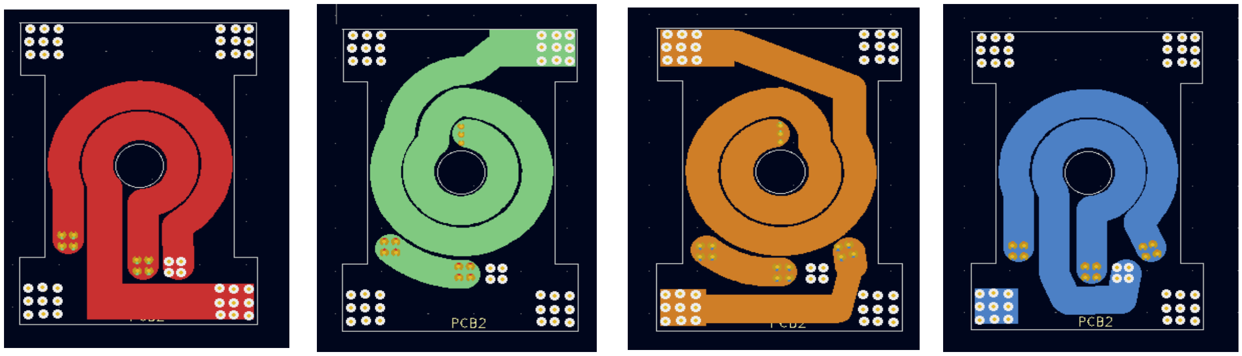


Layer N3: secondary



Layer N4: primary

PCB1



Layer N1: primary | Layer N2: secondary | Layer N3: secondary | Layer N4: primary

PCB2

Fig. 14.designed PCB winding of the transformer.

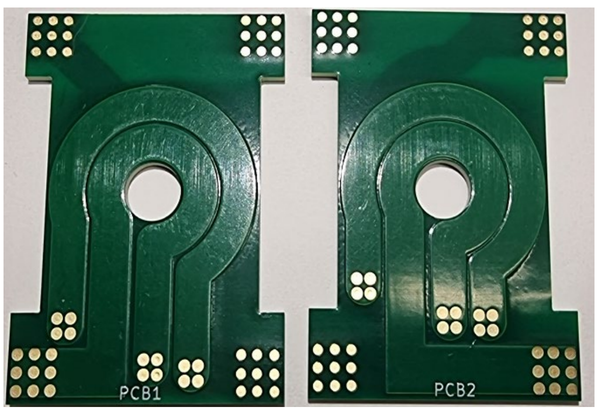


Fig. 15. Designed 4-layer PCBs for one primary and one secondary windings

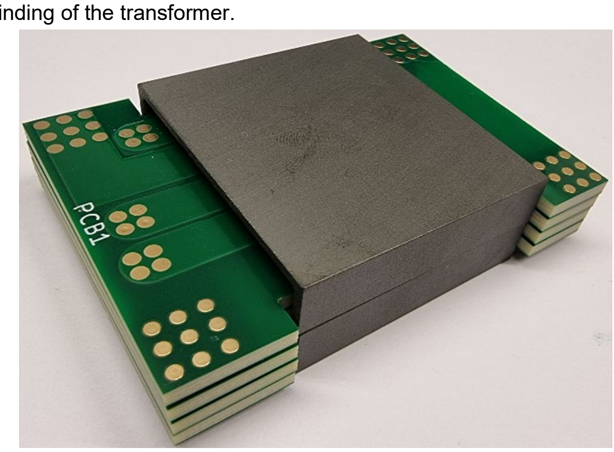


Fig. 16. Two transformer windings 16:16 formed by 4 stacked 4-layers PCBs.

b. Core loss measurement results

The core loss test of the designed core was performed using the calorimetric measurement technique as shown in Fig.17. The voltage waveform is generated using a Half-Bridge circuit using the Infineon evaluation board []. The magnetic flux density is set by measuring the voltage across the transformer. The temperature is measured using a thermocouple device. The magnetic core is isolated so that all the heat is converted into electric energy using a Peltier device. The Peltier voltage is measured using a high precision voltmeter. More information about the principle of this measurement technique can found in [].

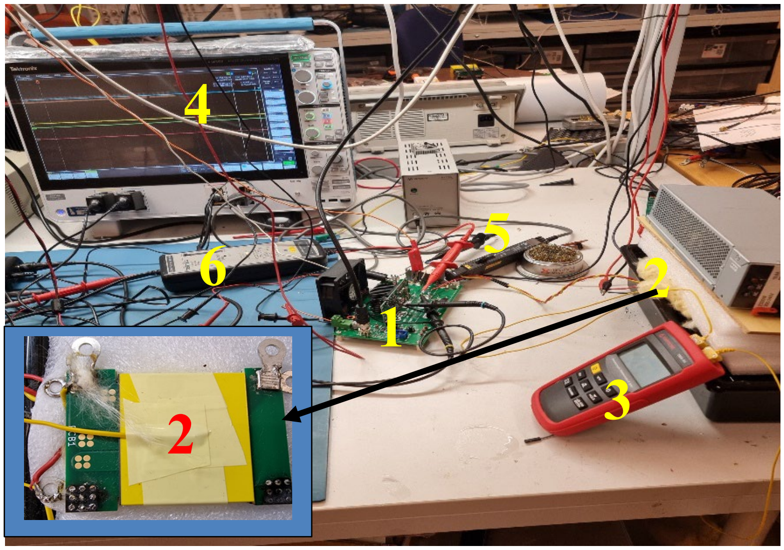
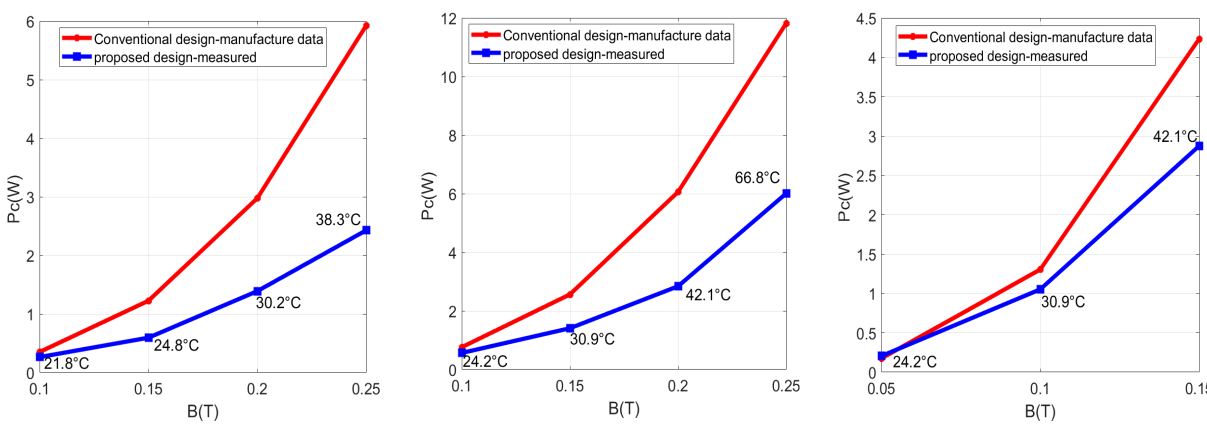


Fig. 17. Loss measurement test set-up: (1) Half-bridge circuit, (2) DUT, (3)Thermocouple, (4) Oscilloscope, (5) current probe, (6) voltage probe, (7) Peltier device.

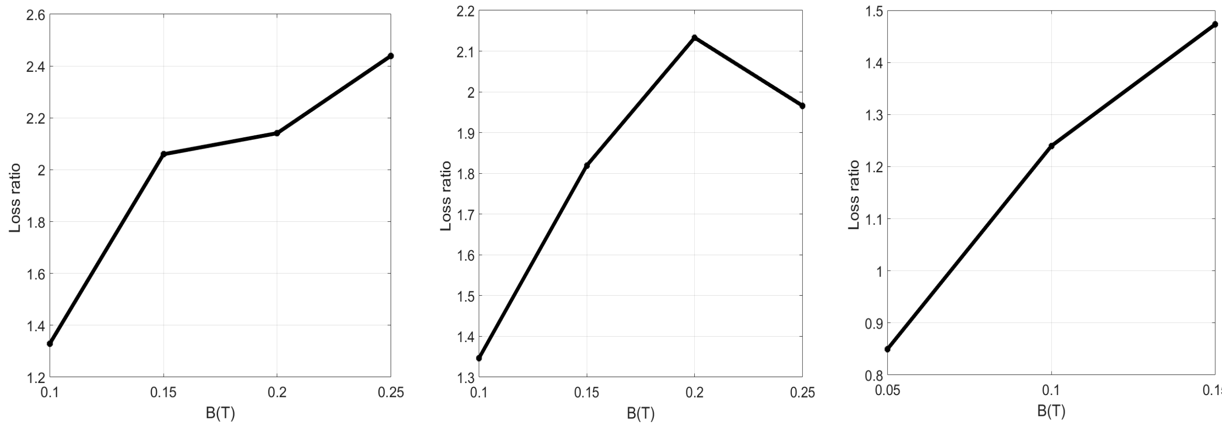
The core loss results are compared with the manufacturer loss data. The test was performed for wide range of frequency and magnetic flux density. The results shows that the core loss of the designed core is much lower than the core loss of a similar conventional design (same volume) obtained from the manufacturer datasheet. The loss ratio between both designs increases as the magnetic flux density. As it can be seen in Fig, the loss ratio between the conventional and proposed design increases as B increases. As an example, at 100 kHz, the loss ratio increases from 1.4 for B=0.1T to 2.4 for B=0.25 T.

To conclude, the proposed design has enabled to reduce the core loss by approximately 50% compared to the conventional design. This reduction in loss will have a significant impact on the efficiency and the power density.



100 kHz 150 kHz 200 kHz

Fig. 17. Measured core of the designed core (blue) and calculated loss for the conventional design (red)



100 kHz 150 kHz 200 kHz

Fig. 18. Core loss ratio between the conventional design and the proposed design

7. Spridning och publicering

7.1 Kunskaps- och resultatspridning

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	X	En konferensbidrag accepterat samt ytterligare en artikel i manuskript
Föras vidare till andra avancerade tekniska utvecklingsprojekt	X	En ansökan till Energimyndigheten för att konstruera en komplett omvandlare
Föras vidare till produktutvecklingsprojekt	X	Interna utvecklingsprojekt inom Huawei
Introduceras på marknaden	x	Produktifieras om inte några hinder inte några allvarliga hinder påträffas i ett senare skede.
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut		

Finns kopplingar till andra interna/externa projekt som kan påskynda introduktion eller ge större genomslag?

We have submitted a funding application to the Swedish Energy Agency for the extension of this project. The future project will focus on the development of the full 22 kW OBC. The proposed magnetics design approach will be used to increase the efficiency and the power density of the complete converter.

7.2 Publikationer

1. S. Barg, K. Bertilsson, G. Torrico, "A Novel Concept to Optimize Core Loss in Planar Magnetic Based on an Unbalanced-Flux- Approach", 24th European Conference on Power Electronics and Applications, September 5-9, 2022 - Hannover, Germany

7.3 References

1. S. Barg, K. Bertilsson, G. Torrico, "A Novel Concept to Optimize Core Loss in Planar Magnetic Based on an Unbalanced-Flux- Approach", 24th European Conference on Power Electronics and Applications, September 5-9, 2022 - Hannover, Germany

8. Slutsatser och fortsatt forskning

Conclusions:

- A new magnetics approach based on an unbalanced-flux distribution is developed which reduces the core loss by approximately 50% compared to the conventional magnetics
- The loss reduction can increase the power capability and the safe operating by two to three times of the magnetic compared to the conventional approach. Eventually, the efficiency can be improved and the power density can be increased by the same rate.
- The increase of the efficiency and the power density of the magnetic components will have a significant impact in increasing the efficiency and the power density of the On-board chargers

Future research:

- Application and validation of the proposed magnetic design in real circuits like the OBCs
- Establish the fundamental basics of the modeling, optimization and design of the unbalanced-flux magnetics
- Extension of the idea for the solid-state transformer in high voltage application

9. Deltagande parter och kontaktpersoner

(infoga gärna deltagande parters loggor)

organization	Contact person	logo
Mid Sweden University	Kent Bertilsson	Mittuniversitetet MID SWEDEN UNIVERSITY
Huawei	Dr. Grover Torrico	HUAWEI