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EXTENDED SUMMARY

RESEARCH ON OPTIMIZATION OF ELECTRONIC POWER MODULES

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List of abbreviations

BH – notation that refers to the hysterezis loop

DC – Direct Curent

FR4 – Flame Retardant 4

MOS – Metal – Oxide – Semiconductor

PCB – Printed Circuit Board

PWM – Pulse Width Modulation

Chapter 1

Introduction

1.1. Presentation of the thesis field

Along with the increasing of working frequencies in DC to DC converters, the complexity of losses in the magnetic materials and conductors follow an ascending path. Although the loss phenomenon can not be completely eliminated but only reduced, the selection of a magnetic core is in a strong relation with the working frequency, the total power that needs to be transformed and the losses that appear in conversion process.

1.2. Purpose of thesis

The present thesis purpose is to identify methods for improving magnetic components used in switching power supply systems taking into consideration the efficiency of the power transfer. In this context, high – frequency planar magnetic structures are proposed, near the MHz region.

1.3. The content of the thesis

The work consists of 6 chapters, the first one being refered as the description of the thesis technical domain and also its purpose.

The second chapter is an introduction in the magnetic materials and it indicates several aspects like the behavior of the materials that are exposed to magnetic field, the classification that is in relation with the application type and also it describes properties of the magnetic materials used in switching power supplies.

Chapter 3 is dedicated to the operating theory of the power transformer that works at high frequencies. Here in chapter 3 are described the physical phenomena associated with the real world transformer. Winding losses and magnetic core losses are investigated.

Chapter 4 is an approach regarding the thermal effect in planar core power transformers. Magnetic core heat sources are investigated, the stress over the windings and the relation between magnetic core properties and temperature.

Further in chapter 5, configurations of planar transformers are presented, simulation tools are used to indicated the influence of sinusoidal waveform along with high frequency values. Experimental results are presented.

In chapter 6 conclusions regarding to experimental results are presented and both author contributions and further research aspects are indicated.

Chapter 2

Magnetical materials for switchmode power supplies

2.1. Behavior of materials in the presence of magnetic field

Within magnetic fields, the existing forces tend to turn the magnetic moments in the direction of the field lines.

Depending on the magnetic behavior, all materials have properties that can be classified as follows: *diamagnetics, paramagnetic, ferromagnetic, antiferromagnetice and ferrite*.

2.2. Classification of magnetic materials regarding the application purpose

The main purpose of a magnetic core is to ensure „proper enviroment" for the magnetic flux to transfer energy between to coupled windings [1]. One of the most important property of a magnetic material that defines the efficiency of a power transfer is the *magnetic remanence*. The magnetization of a material is a ireversibil phenomenon.

2.2.1 Soft magnetic materials

Due to the cristalin structure of certain composites the hysteresis loop is been triggered using lower values of the magnetic flux intensity *H*. An ideal soft magnetic material has a null value of the coercitiv field (H_c), a greater amplitude of the saturation flux (B_{sat}), zero losses caused by hysteresis and also huge values for permeabilies $\mu_{r,max}$ şi $\mu_{r,i}$.

2.2.2 Hard magnetic materials

An ideal hard magnetic material has greater values for the coercitiv field than a soft magnetic material. Material properties recommend the use in strong magnets applications.

2.3. Magnetic material properties used in power conversion

2.3.1 Permeability

Permeability is a property that characterizes th alloy composition the technological methods used in the fabrication process.

All the magnetic materials have the permeability in a dependence relation with: *magnetic field intensity H*, *the frequency f*, *the temperature T* and *the magnetic material type* [2].

2.3.2 Saturation flux density

The total allowed magnetic flux density value is the product of peak induction and core area, without crossing the saturation threshold, even in transient conditions [3]. Moreover, the gratest induction values are obtained with metal alloys [4].

2.3.3 Curie temperature

All magnetic materials lose their properties when the Curie temperature point is achieved. Magnetic cores may have different values for Curie point. The temperature thresholds are not linked with geometrical shapes.

Chapter 3

Power transformer at high frequency conversion

3.1 Losses in the real-world power transformers

The present paragraph describes losses in power transformers that are used in switchmode power supplies. The approach goes natural to planar core transformers.

3.1.1 Skin effect

The skin effect is a consequence of current distribution to the conductor surface. Eddy currents are produced by the main current across the conductor.

3.1.2 Proximity effect

Two nearby conductors that are crossed by a high frequency current, generate magnetic fields that concentrate the maximum current density in the conductor contact area.

3.1.3 Losses in the magnetic core

Magnetic core losses refer to the hysteresis loop and eddy currents. The choice regarding a core or another is related to the hysteresis loop. The squareness of the B-H loop depends on the magnetic intensity field.

Eddy currents are responsible for losses per unit volume $J^2\rho$. The parameter that defines the specific resistance of core material is ρ.

3.2 Aspects regarding the design of planar core power transformer

3.2.1 Considerations of planar winding implementations

The high frequency current flow is pushed to the conductor surface, therefore only a certain depth will depth will be used. The parameter that defines this physical effect is the penetration depth.

Due tot the skin effect no improvement would be obtained by increasing the conduction area. This will decrease the DC resistance but it will increase the AC resistance.

3.2.2 Planar magnetic cores and the windings current distribution

The purpose of the present study is the comparative estimation regarding the losses in two types of transformer that use an ER and EI planar magnetic cores [5]. Both models have gaps.

Simulation was made by considering the frequency value of 700 KHz and a 10A across a solid conductor.

The high-frequency current crosses the conductor near the magnetic core edge and creates high current density areas (Fig. 3.12 and 3.13).

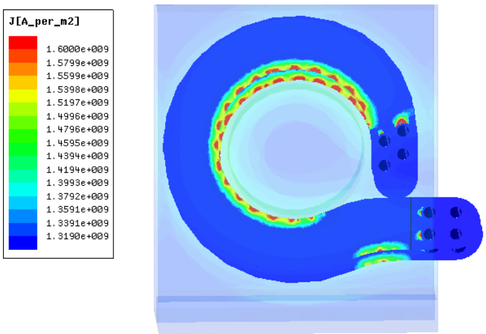


Fig.3. 12 *Current distributionon the secondary winding of ER transformer.*

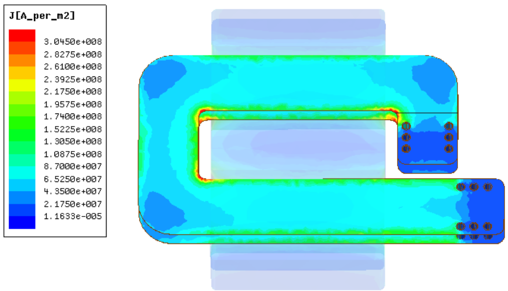


Fig.3. 13 *Current distribution on the secondary winding of EI transformer.*

Moreover, because of the magnetizing force that appears on the core gap, eddy currents will be generated on the core inner edge and will affect the current distribution on the winding.

3.2.3 A comparison simulated study regarding the behavior toroidal and planar magnetics at high frequencies

In case of transformer, the equipotential surfaces provide high current density near the gap. This will generate a higher AC resistance. In this model, the toroidal core has a gap that is similar to a “distributed reluctance”, along the the magnetic flux path.

Figure 3.16 indicates the simulation results considering the distribution of current density.

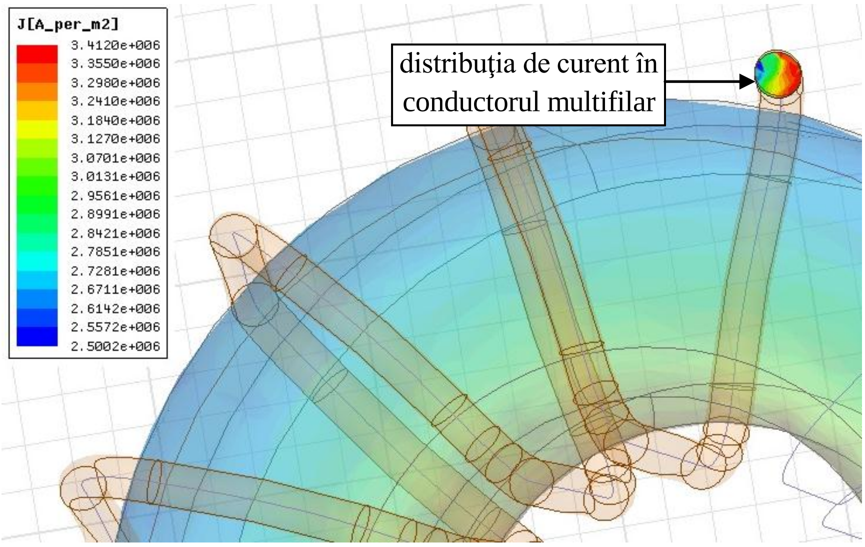


Fig.3. 16 *Current density distribution within the toroidal wired conductor (900 KHz).*

The transformer model was simulated at 900 KHz and a current of 10A.

3.3 Determination of magnetic parameters

3.3.1 Magnetic core selection

Magnetic core selection takes into account the values of core area (A_e), the input voltage (U) and frequency f. The maximul induction value can be calculated usind the expression below. The obtained value offers the maximul flux swing.

$$B_{max} = \frac{U \cdot \sqrt{2}}{2\pi \cdot f \cdot N \cdot A_e} \left[V \cdot \frac{s}{m^2}\right] \tag{3.12}$$

3.3.2 Duty cycle

Duty cycle is defined as the period of time in which the switching element is in conduction state in relation with the allowed conduction period. The control loop adjusts the duty cycle D in inversely proportion to input voltage V_{IN} in order to maintain the output voltage V_O.

3.3.3 General design of power transformers

The design of the transformer is performed starting from the ratio of the input and output voltages as well as from conduction time of the switching element.

The main condition for the transformer to have an efficient energy transfer is given by:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \tag{3.20}$$

where V_p – primary voltage,
V_s – secondary voltage,
N_p – primary winding number of turns,
N_s – secondary winding number of turns.

The magnetic design takes into consideration that the working frequency is 200 KHz and the skin depth does not generate losses in the windings.

From calculations it results that T = 5 μs.
In relation with the mentioned aspects the values of the input parameters are as follows:

N_s = 1 turn,
V_p = 400 V,
V_s = 12 V,
N_p = to be determined.

By using (3.14) for the usual converter working conditions the following expression takes place:

$$V_p \cdot t_{ON} = B \cdot A_e \cdot N_s \tag{3.16}$$

For B = 200 mT. Using equation (3.16) it results:

$$400V \cdot 5\mu s = 200mT \cdot A_e \cdot 33\ spire \tag{3.24}$$

The core area section is determined and is given by the following expression:

$$A_e = 303\ mm^2 \tag{3.25}$$

The closest value from the product catalog will be chosen.

The equation that verifies the ratio between the peak value of the field intensity and the current across the winding is given by [6].

Chapter 4

Thermal management in planar magnetics

In applications representing switching supplies, the main aspects related to the use and limitation of the magnetic core refer to the permeability, magnetic material saturation, as well as to the losses in core considering one or more frequencies. The flux swing is in a strong relation with the mentioned aspect.

4.1 Sources of thermal stress over the transformer windings

The used parameter in thermal modelling, θ_{JA}, is the thermal impedance that starts from the electronic component junction and ends into the environment [7]. The equation that describes the behaviour takes place:

$$\theta_{JA} = \frac{T_{joncțiune} - T_{ambient}}{Puterea\ disipată} \tag{4.3}$$

Thermal junction is represented by the assembly heat source and this is the copper trace.

The first dissipation branch is starting from the secondar winding through the magntic core and ends up in the environment by radiation and convection.

The second heat conduction path has the same starting point and crosses the FR4 insulation, it intersects again the core surface and it goes in the environment by radiation and convection.

In the following a simplified model with thermal resistance is presented and its goal is to illustrate the two ways for heat dissipation into a planar transformer (Fig.4.2).

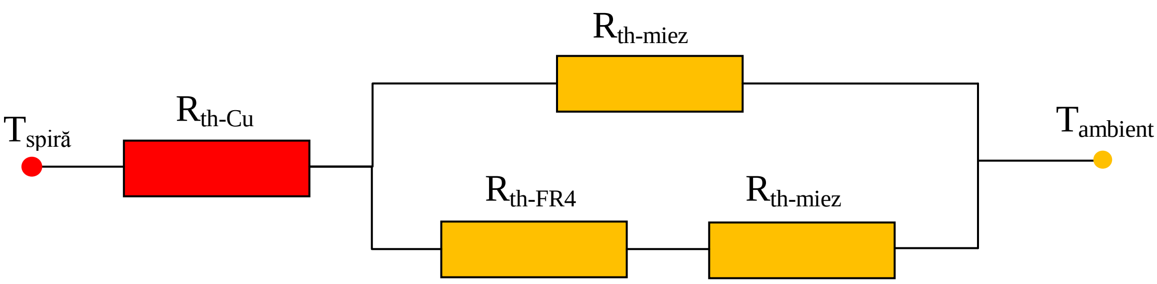


Fig.4. 1 *Simplified model with thermal resistances for a planar transfromer.*

The proper placement of viases between layers has an important contribution over the entire magnetic component efficiency. A minimum electrical resistance is required for the viases according to the current needs.

4.2 Heat sources in planar transformers

In order to study the losses that appear in a planar transformer, in the following are explained steps that need to be done in the design approach [8].

Transformer calculation started by considering the primary input voltage V_{prim} = 15V, secondary voltage V_{sec} = 5V and frequency f = 1MHz.

Based on the calculation was chosen the magnetic core that has A_e = 78,5 mm^2 with H_{max}= 540 A/m. The core model is E22/6/16 and the obtained value is near saturation.

În figure 4.9 and table 4.2 are indicated results for 1MHz.

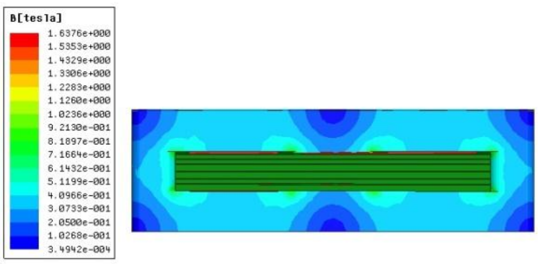


Fig.4. 2 *Distribution of magnetic induction in E22/6/16 at 1MHz.*

Tabel 4. 1 *Simulation results for 1MHz*

Parametru	**Valoare**
Average magnetic flux density [T]	0.35
Secondary losses [W]	0.69
Secondary current [A]	10.27
Secondary resistance [mΩ]	6.90
Secondary inductance [μH]	5.20

From the simulation results interpretion it seems that no saturation is achieved for 1 MHz at the core proximity edges.

New simulations were made for 1.3 MHz and 1.5 MHz. The dissipated power between the first and the third simulation is 0.56W.

The heat transfer between the magnetic core and environment takes place by convection. The equation that describes this transfer is as follows:

$$Q_{conv} = h \cdot A(T_s - T_\infty) \tag{4.8}$$

where h is the heat transfer coefficient by convection, A is the object surface area that is crossed by the fluid, T_s is the temperature of the object surface and T_∞ is the environment temperature.

In order to analyse the thermal behavior of the simulated model it is necessary to assign material properties, as it is indicated in table 4.5.

Tabel 4. 2 *Material properties for thermal simulations*

Material	**Mass density (kg/m3)**	**Thermal conductivity (W/m·k)**	**Specific heat (J/kg· K)**
Mn – Zn ferrite	4700	4	800
Copper	8900	390	390
FR4	1850	0.5	1200

In the next image is presented the thermal simulation results for 1 MHz working frequency (Fig.4.13).

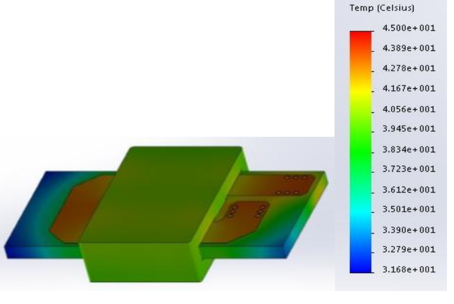


Fig.4. 3 *Temperature distribution in the transformer model for 1 MHz.*

Chapter 5

Development of planar power transformers. Magnetic structures

5.1 The DC – DC converter. Topology

In certain applications the chosen converter topology will have a significant contribution in achieving the objective. The aspects that are taken into consideration when developing converters refer to: isolated or non-isolated topology and excessive use of switching elements.

5.2 Modeling and simulation of magnetic components

5.2.1 Finite Element Method and modeling applications

Due to the specific requirements of conversion application and also taking into consideration the physical phenomena that occur, simulation tools were developed for both solving electromagnetic and thermal.

Finite Elemente Method (FEA) is an algorithm that is able to transform a geometrical structure into a multitude of discrete elements. These elements contribute to the generation of solutions for the algebraic equations.

5.2.2 Proposed planar transformers

Taking into account the results obtained from the transformer calculation steps, a printed circuit board was designed in a matter that covers section area of 78.5 mm^2 (Fig. 5.9). The simulation tool (Ansys Maxwell) uses a default and impossible to change excitation waveform and that is sinewave.

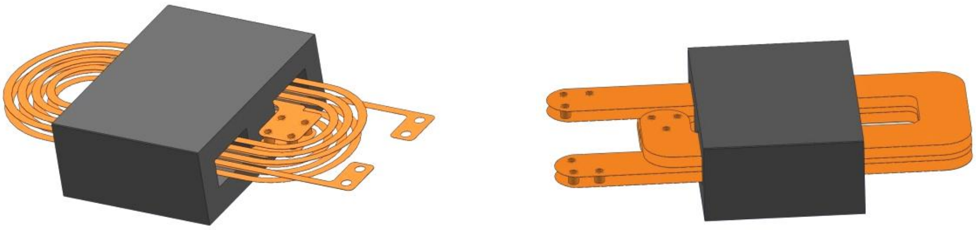


Fig.5. 1 *T1 planar transformer model.*

Following the analysis performed over the losses in the magnetic core, it has been observed that for an oscillating frequency of 500 KHz, the average value is under the 20 KW/m^3 threshold. At 1 MHz the average value is about 60 KW/m^3.

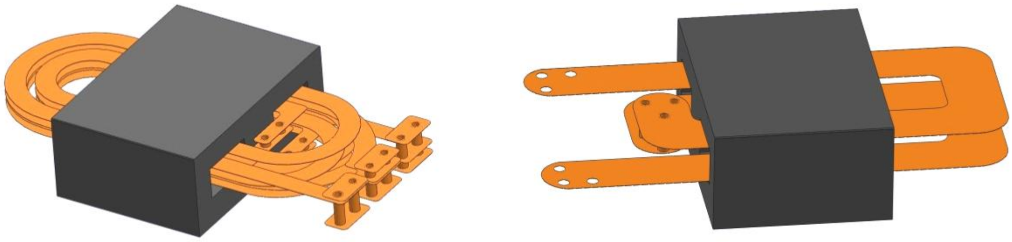


Fig.5. 2 *T2 planar transformer model.*

The same simulation conditions were followed also for the second transformer. (Fig. 24). Both primary windings are parallel connected and a 5A current crosses them.

In order to compare both simulations, by losses, the same range values were used. The conclusions indicate that different induction values were obtained and this result shows variations in the hysteresis loops.

5.2.3 Study of energy storage in planar transformers. Magnetomotive force

An ideal transformer that is part of the energy conversion chain does not store energy. The entire input power is transferred to the output with no delay.

In a real life situation, a transformer working at high frequencies stores an amount of energy that is found in loss inductances and mutual inductances.

As much as the magnetic flux crosses the secondary winding the amplitude of the magnetizing force decreases linearly down to zero. The following expression takes place $Np \cdot Ip = - Ns \cdot Is$ (Fig.5.40).

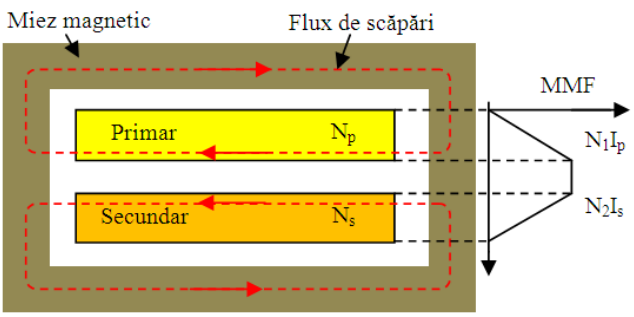
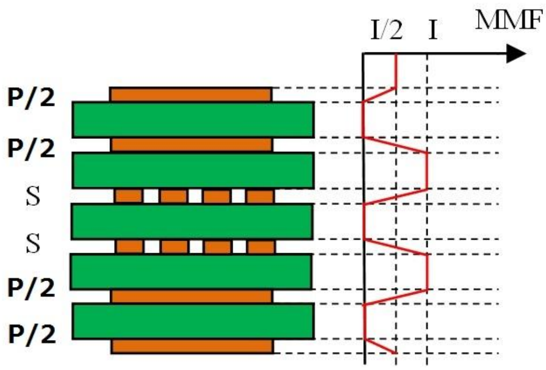


Fig.5. 3 *Stray inductance and the magnetomotive force* **[9]**

In Figures 5.46 and 5.47 layers of the transformers T1 and T2 are indicated. Also, the magnetomotive force amplitude is illustrated in ratio with the distribution of winding within layers.



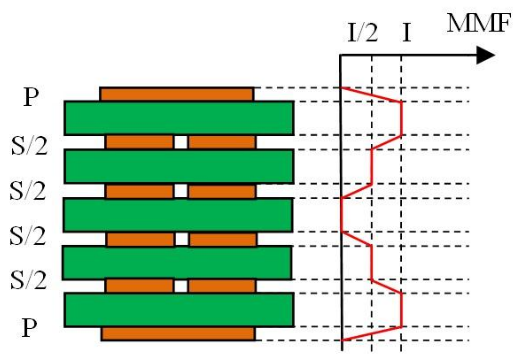


Fig.5. 4 *Magnetomotive force distribution for T1 model.*

Fig.5. 5 *Magnetomotive force distribution for T2 model.*

5.3 Testing platform for planar transformer

By developing the testing platform, planar transformers were analysed both from electromagnetic and thermal aspects. It was chosen a hard-switching topology that follows an MHz frequency domain.

5.3.1 Description of the converter schematics

The converter schematic was developed using facilities offered by the PWM controller UC3825. The circuit is able to control two stage outputs with high currents generated by the capacitive loads in the MOSFETs gates. The feedback circuit is driven by a current loop.

5.3.2 Push-pull converter analisys. Measurements

The proposed schematic that drives the two planar transformers covers a ratio of 1 to 4 from primary to secondary.

Taking into account the oscillation conditions it was observed that both transformers the stability of the circuitry is near by 970 KHz.

5.4 Effects of losses in planar transformers. Thermal distribution

From the simulation operations that took place in sinusoidal waveform conditions it results that the structure that has the secondary winding arranged in two layers and four turns (T1) has a lower efficiency than the other (T2 with 4 turns and 4 layers).

From calculations it was obtained that saturation current for both transformer models is around 9A.

Figures 5.66 and 5.67 indicate screenshots taken from the scope. To the primary windings of the transformers sinusoidal and PWM waveforms were applied.

The area from the first quadrant changes according to values of *B* and *H*.

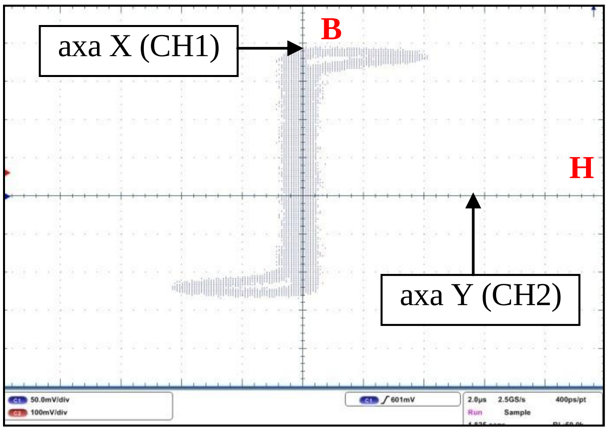


Fig.5. 6 *Magnetizing loop obtained at 970 KHz for squared impulse.*

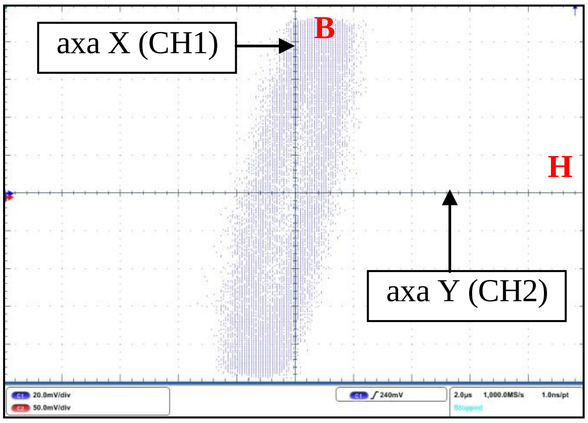


Fig.5. 7 *Magnetizing loop obtained at 970 KHz for sinusoidal input signal.*

In order to put into evidence the losses generated by thermal effect, the testing platform was exposed to a thermovision camera. Temperature increases were observed both at the surface of the magntic core and also at the surface of the switching controller. These results were compared with with simulate transformer models. In Figure 5.63 the thermal simulation result for T1 is presented.

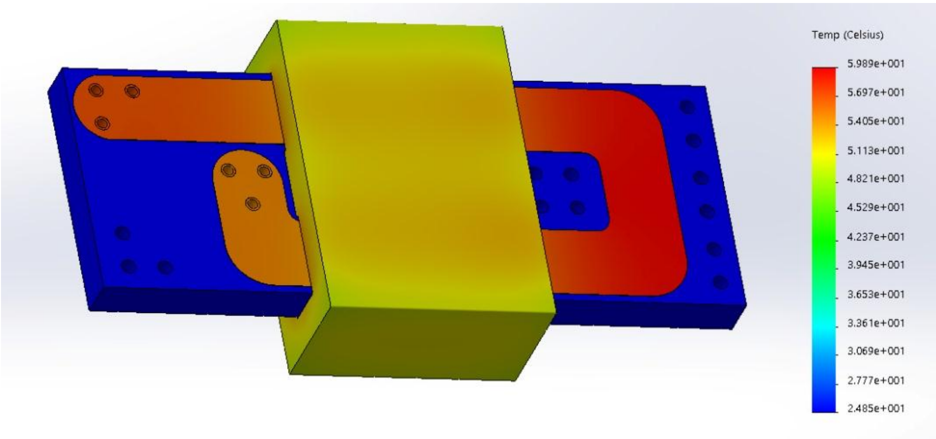


Fig.5. 8 *Temperature distribution acros the transformer T1.*

Along with this approach, that is intended to obtain improvements at high frequencies, the study performs new ways of analysis regarding magnetic components size and reducing and also efficient conversion.

By analysing the thermal distribution illustrated in Figure 5.71 it can be observed that temperature at the controller surface is higher in comparison with core surface. In this context, the input transformer waveform (provided through MOSFETs) widths were compared and differences were found.

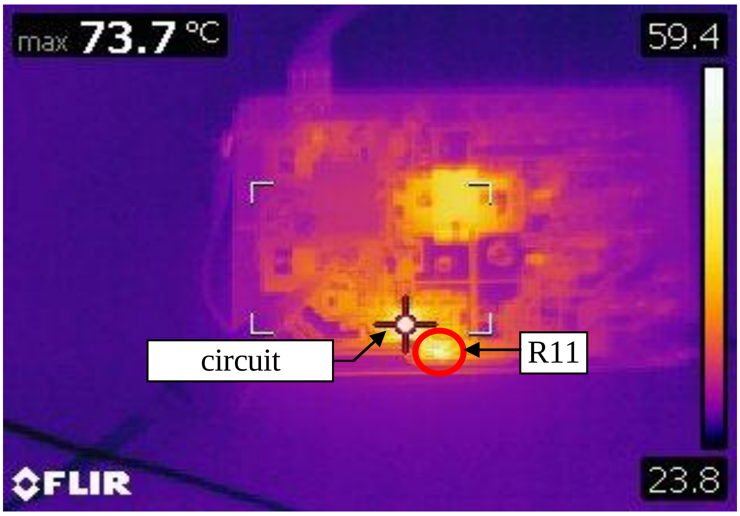


Fig.5. 9 *Temperature measured at the surface of UC3825 controller.*

The different width of the two control signals may be a consequence of the board routing layout or an unapropriate control feedback of the controller.
The primary winding of the transformer is considered a load for the two PWM controller outputs. Thus, the incorrect length of the copper traces along with the capacitive gate effects, can generates cross conduction for short moments of time in both windings (Fig.5.72).

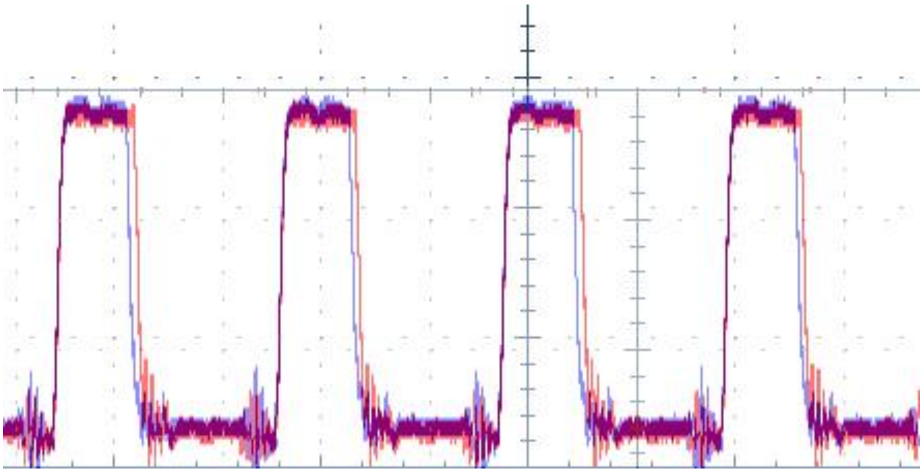


Fig.5. 10 *Potential cross conduction Overlapping of waveforms at the transistors gates (circuit version1).*

Chapter 6

Conclusions

During the present work, the importance of the magnetic material was mentioned due to the fact that an important source of losses is realy the magnetic component.

6.1 Results

In the first chapter of the present thesis a presentation of the research domain was made, in order to obtain a better understanding over the loss sources.

Chapter 2:

- Characteristics of materials in relation with the magnetic field were presented. Also, material magnetization effects were taken into consideration by relating them with magnetic remanence;

Chapter 3:

- Losses analyses were made, both in conductors that form windings and magnetic cores used in transformer applications.

Chapter 4:

- The results of losses obtained after electromagnetic simulations were used as input data for thermal analysis.

Chapter 5:

- Achievements were made regarding losses in magnetic components working in the MHz region.

6.2 Personal contributions

During the doctorate thesis several original contributions were releaved and those are presented in the following:

[1] A virtual 3D planar transformer model was created which was simulated with an electromagnetic tool. The magnetic core model has similar dimensions with an available product (E32/6/20). The obtained simulation results contributed to the evaluation approach considering working frequencies between 1MHz and 1.5 MHz.

[1,2,3] A thermal comparative analysis was made, considering the heat dispersion in both magnetic cores and the windings. The analysis is just a part of a larger electromagnetic analysis that was previous published and took into consideration the MHz region. Based on results observed in the winding layout, estimations were made over the distribution of heat in PCB and magnetic core.

[4] Using modeling and simulation tools a comparative analysis was made over two types of planar transformers that had different core shape. It was revealed the current distribution in the windings and also the source of losses depending on the available structure (ER or EI cores).

[5] Two virtual transformer models were modelled, the first one who had a planar structure and a second one with a toroidal shape. Following electromagnetic investigations sources of losses were found in both structures and conclusions have been presented.

[6] A comparative study regarding the stored energy in the planar magnetic components was made. Two types of winding layout were used. This investigation has revealed the impact of the magnetomotive force over over the magnitude of losses in planar transformers. A transformer structure with a lower magnetomotive force impact was proposed.

[6,7] Investigation over the behaviour of two transformers being exposed to transients.

[8] A testing platform developed in order to test two experimental models of

planar transformers. Taking into consideration that the working frequency is near 1 MHz, several aspects are presented as follows:

- ✓ the electromagnetic behaviour of the two models of planar transformers under sinusoidal excitation (using a simulation tool);
- ✓ the influence of control signal waveform (sinusoidal versus squared) and the estimation of losses impact by analysing the hysteresis loops;
- ✓ the consequence of routing choise based on the fact that the new circuit will work near 1 MHz;
- ✓ the validation of simulated an experimental results based on the losses magnitude;
- ✓ the distribution of thermal effect in both transformer models but also in the entire converter;

6.3 List of published papers

[1] Constantin Ropoteanu, Paul Svasta and Iulian Buşu, „High – Frequency Power Loss Investigation of a Planar Ferrite Core Transformer", 21st International Symposium for Design and Technology in Electronic Packaging (SIITME), pages 61 – 64, **IEEE**, 2015.

[2] Constantin Ropoteanu, Norocel – Dragoş Codreanu and Ciprian Ionescu, „Thermal Investigation of a Planar Core Power Transformer", 39th International Spring Seminar on Electronics Technology (ISSE), pages 112 – 115, **IEEE**, 2016.

[3] Bădălan Drăghici Niculina, Ropoteanu Constantin and Marghescu Cristina, „Investigation of Heat Dissipation Limits for High Power LEDs", 8th International Conference on Electronics, Computers and Artificial Intelligence (ECAI), pages 1 – 4, **IEEE**, 2016.

[4] Constantin Ropoteanu, Paul Svasta and Ciprian Ionescu, „Electro – Thermal Simulation Study of Different Core Shape Planar Transformer", 22nd International Symposium for Design and Technology in Electronic Packaging (SIITME), pages 209 – 212, **IEEE**, 2016.

[5] Constantin Ropoteanu, Paul Svasta and Ciprian Ionescu, „A Comparative Simulation Analysis of Toroid and Planar Magnetic Core Near MHz Region", 23rd International Symposium for Design and Technology in Electronic Packaging (SIITME), Pages 259 – 262, **IEEE**, 2017.

[6] Constantin Ropoteanu, Paul Svasta and Ciprian Ionescu, „A Study of Losses in Planar Transformers with Different Layer Structure", 23rd International Symposium for Design and Technology in Electronic Packaging (SIITME), pages 255 – 258, **IEEE**, 2017. **Lucrare premiată cu „Excellent Poster Award for Young Scientist**".

[7] Constantin Ropoteanu, Paul Svasta and Ciprian Ionescu, „Planar Core Transformers Analysis for a Power Distribution Network Concept", 24th International Symposium for Design and Technology in Electronic Packaging (SIITME), pages 339 – 342, **IEEE**, 2018. **Lucrare premiată cu „Excellent Poster Award for Young Scientist**".

[8] Constantin Ropoteanu and Paul Svasta, „Effects of Excitation Waveform on Developing Planar Core Transformers", 25th International Symposium for Design and Technology in Electronic Packaging (SIITME), 2019.

[9] Constantin Ropoteanu and Paul Svasta, „Influence of Core Temperature on the Efficiency of a Planar Transformer", 43rd International Spring Seminar on Electronics Technology (ISSE), **IEEE,** 2020.

6.4 Further development aspects

The investigations taken over the planar transformers revealed the necessity for additional studies both on the direction of research and also the results presented in the thesis. These additional study references can be defined as objectives for further investigations. Objectives are presented as follows:

1. A more detailed analysis over the losses that characterise 3F4 magnetic material for working frequency close to 2 MHz.

2. Investigation of losses as part of the layer to layer traces that form planar transformer structures.

3. Investigation of losses and disturbing factors within a supply system with power distribution facilities that include planar magnetics working in the MHz region.

The major objective which can be considered the endline of this research is represented by the implementation of a power supply, having a high power density and highly efficient (over 98%).

Annex

A1. Magnetic domains. Magnetization

Magnetic forces are generated by electrically charged particles that are in motion. These magnetic forces can overlap with other predominant electrostatic forces. The concept of magnetic field is usually associated with magnetic forces.

By analogy with the influence of the electric field on the electric poles, it is noted that the magnetic dipoles are influenced by the magnetic field.

The subject of the present doctoral thesis mainly included the study of the phenomenon of losses associated with ferrite-type magnetic materials. In the structure of such a material the electrons rotate around their one spin. Their electrostatic charge does have a magnetic moment.

In the initial state, the elementary domains are oriented in the direction given by the existing low energy level. The application of an external energy determines the alignment of the moments in the direction of the applied field.

The mechanical deformation of the material crystals creates accentuated non-uniformity which can be seen at the microscopic level by the deformation of the separation edges between the domains. In this context, the magnetization is performed unevenly in the material (due to the increase of the anisotropy), and the demagnetization with the help of an external field becomes much more difficult due to the decrease of the permeability.

Figure A1.2 shows in a simplified way the phenomenon of magnetization of a material crystal. Figure A1.2a shows the shape of an ideal crystal whose domains are bounded by straight edges, and which has no magnetic field applied. In the case of position b) a magnetic field with a relatively low intensity H was applied, which reversibly orients the magnetic moments. The influence of the magnetic field is given by the thickness of the Bloch walls. This is the situation in which the beginning portion of the magnetization curve is outlined.

Under the pressure of the magnetic field whose intensity continues to increase, the Weiss magnetic domains expand (passing through steps c, d and e), bringing the magnetization curve to the threshold where the induction has a maximum value. At this stage the magnetization is irreversible and maintaining the field will generate the rotation of the moments until the orientation of all domains and reaching the saturation threshold (Figure A1.2f) [10].

In practical meanings, magnetization is strongly influenced by the granulation of the material, the size of the domains as well as the temperature.

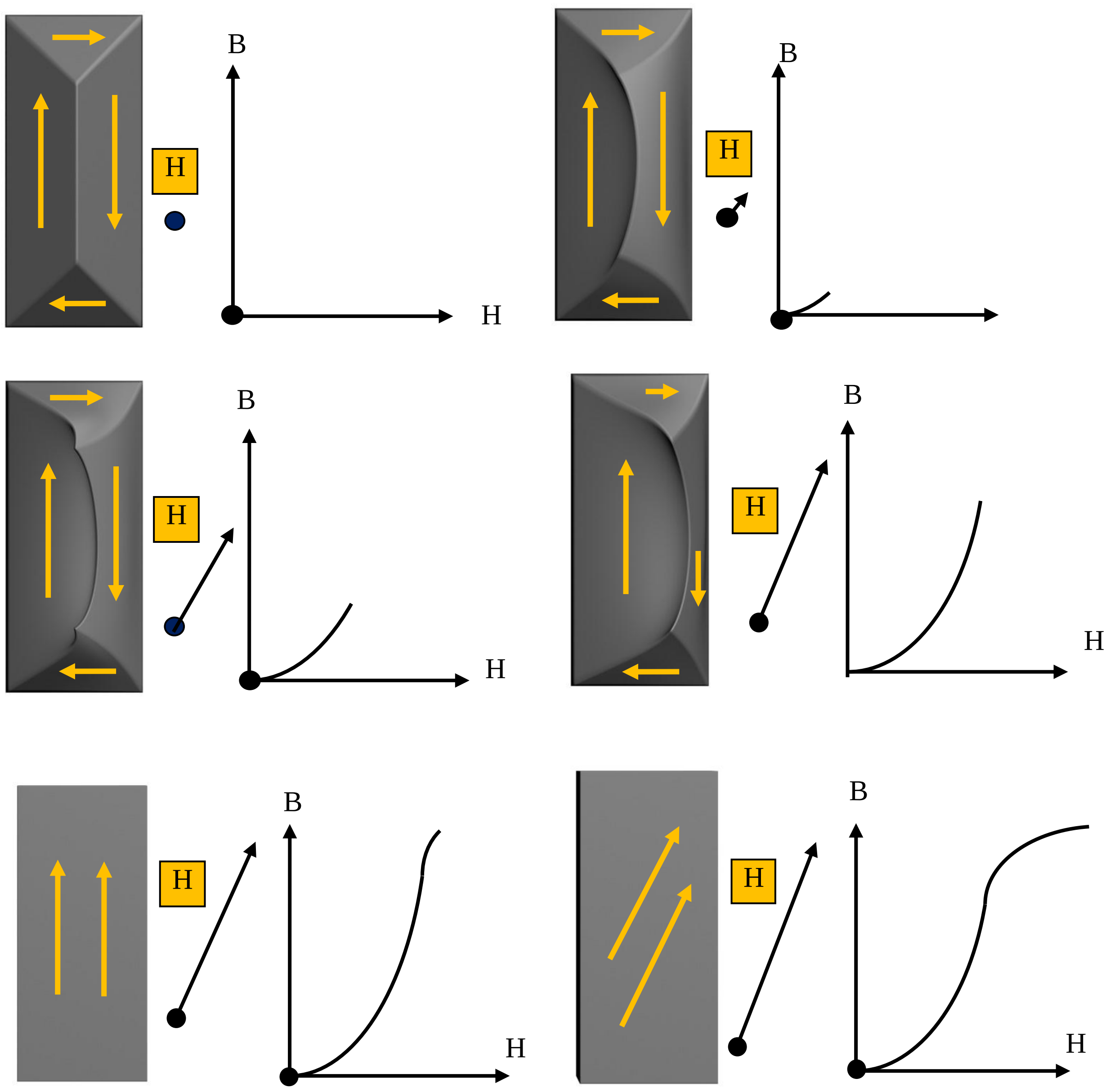


***Fig.A1. 2** Simplified display of the domain magnetization.*

A.2 Control schematics part

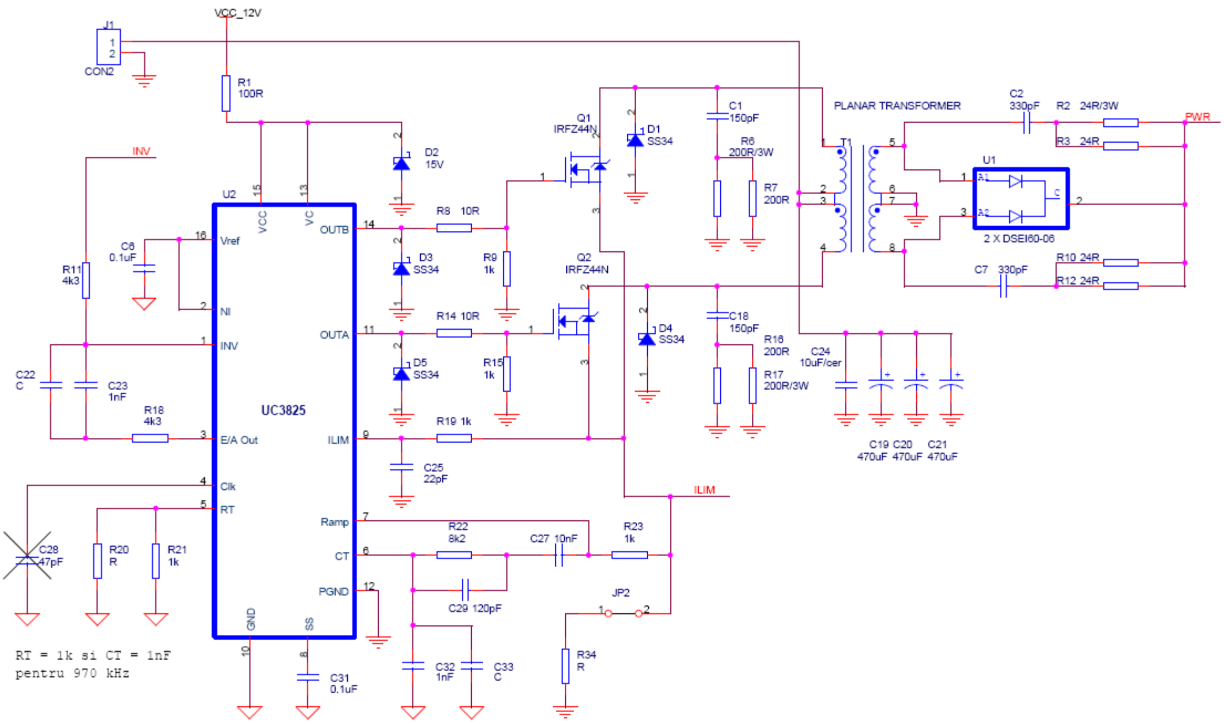


Fig.A2. 1 *Converter schematic – power transformer and control loop.*

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