Integration Planar Transformer for Reducing Volume, Leakage Inductances and Improve EMC Disturbances of a Radar Power Supply

Sega Gueye, Brayima Dakyo, Sylvain Alves, Joël Cordier, Philippe Eudeline

***Abstract*— ** This article deals with EMC (Electromagnetic Compatibility) disturbances caused by leakage inductances and stray capacitances of the internal transformer from a power supply unit for a radar subset. A measurement in emissive conductance shows that their frequencies are critical facing the military standard MIL-STD-461E EMC. To cancel their disturbances, reduce the volume and the weight, the planar technology is used. A new interleaving techniques layers of a planar transformer, is used to further reduce the leakage inductances.

***Keywords*—** PFC, MMF, AC/DC, DC/DC.

I. Introduction

The increasingly need of compact system development makes that we must develop a compact, robust power supply and control the interaction between the various parts of the power supply while avoiding the electromagnetic disturbances coming from the external environment and/or the internal circuits to the radar module.

Manuscript submitted March 28, 2012: This work was supported in part by the THALES AIR SYSTEMS Company and the Regional Council of Upper Normandy.

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The radar module is composed among others by the power part which provides the supply voltages of the hyperfrequency part. The hyperfrequency part is composed by hyperfrequency transistors and power amplifiers which provide the radar signals. These signals depend among others on the supply voltages. A poor quality of the supply voltages can lead to pulse to pulse instability of the radar. A radar instability may cause signature errors and/or the risk of false alarms. The radar signals (Amplitude, Phase) from the power transistors must be as closed as possible and not disturbed. The main possible causes of radar stability degradation are : the thermal phenomena of power transistors, the power supply voltage ripples and electromagnetic disturbances (EMC). It's very important to reduce the thermal phenomena, the voltages ripples and the electromagnetic disturbances of the radar power supply to the acceptable levels in order to guarantee a pulse to pulse stability. This article deals with how to reduce the electromagnetic disturbances caused by transformer of the AC/DC part. The other phenomena of causes of radar stability degradation are not taken into account.

Previous works had shown some drawbacks of the transformer windings wound (classical transformer). These drawbacks are among others the disturbances and the magnetic losses caused by its leakage inductances, its volume and its magnetic radiation. The magnetic radiation can directly or indirectly cause failure from radiation-sensitive components. The need of increasing switching frequencies in the goal to reduce the volume of passive components (inductors, capacitors,...), limit the use of the classical transformers (windings wound). In recent years, planar transformers have emerged to meet these needs. With their low volume, their ability to operate under high powers, their low loss, low costs and low serial leakage inductances, planar transformers occupy a prominent place in the comity of switching power supplies.

The aim of works carried out in [2] is initially to characterize, to identify electromagnetic disturbances sources of the radar power supply. Once these disturbances sources identified, the idea is in the second time, to propose solutions for reducing and improving EMC disturbances of the radar power supply performances. This article presents a solution allowing to reduce the weight, the volume, the size and disturbances caused by the leakage inductances of the classical power transformer. A technical interleaving of layers of the planar transformer, will be presented further in the goal to reduce the leakage inductances.

II. Synoptic of the Module

As shown in Fig 1, the radar power supply is composed by the input network, the AD/DC and DC/DC parts and the power amplifier. The input network provides the input voltages (230 VAC), The power supply uses a front head Power Factor Corrector (PFC), electrically insulated from the power converters that provide secondary voltages, supplying high power microwave modules. The power supply is characterized by two modules. These two parts are isolated electrically. Nevertheless electromagnetic coupling paths exist and allow disturbances propagation from one part to the other.

The AC/DC part or PFC (Power Factor Corrector) Fig 1 is composed by a converter which uses a switching transformer which manages the energy transferred between the network and the DC/DC converters. The switching transformer is an classical transformer windings wound as shown in Fig 5.

This transformer is susceptible to be source and/or victim of disturbances by wire crosstalk (by its inductances and stray capacitances), by common impedance coupling field to wire and loop.

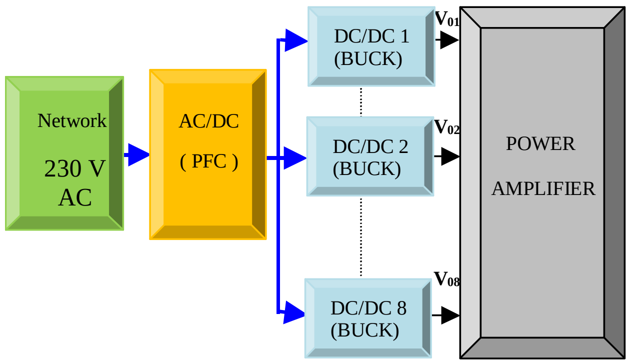

Fig. 1 Synoptic of the radar power supply

III. Problems

The work carried out in [2] had shown that the main disturbances sources of the AC/DC part were mainly the leakage inductances, the stray capacitances of the transformer and the smoothing circuit inductance. The transformer field lines are also found on the input network wires of the module, as shown in Fig 2.

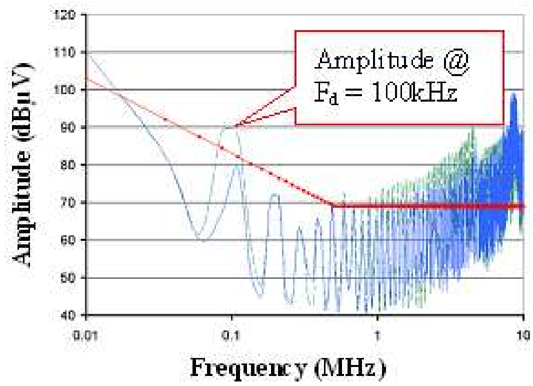

Fig. 2 Spectrum measurement in emissive conduction of the power supply input

- Level of the MIL-STD-461E EMC standard,
- Spectrum measurement with shielded the input filter,
- Spectrum measurement of the power supply input filter.

Measurement in emissive conduction according to the standard MIL-STD-461E Fig 2 shows the switching frequency (100kHz) and the resonance frequency between leakage inductances and the stray capacitances of the transformer highlighted in [2]. Fig 2 also shows that the amplitude levels at these frequencies are over the level of this standard. To attenuate these amplitude levels, one of solutions is to use an external filter, but this solution is not compatible with our objective of reducing the power supply volume.

The high voltage insulation prevents close coupling between transformer windings. The resulting leakage inductance is large and its circuit location directly in series with their inductances causes delays, voltage spikes and difficulty energy recovery problems. The energy stored in the leakage inductances creates disturbances in the terminals of the switching MOSFET power supply Fig 3. The leakage inductance also increases the switching losses and therefore reduces the efficiency.

Fig. 3 Disturbances in terminals of the Drain-Source V_{DS} of the power M0SFET.

One of solutions carried out in [2] to reduce the leakage inductances and the stray capacitances is to use the planar technology. The planar transformers are often manufactured with several separate components, with multiple tracks on several layers or multilayer Fig 4, or integrated into the PCB of the power supply. The planar technology presents advantages listed below:

- Very low profiles,
- Low leakage inductance,
- Good MTBF,
- Increasing of the power density.

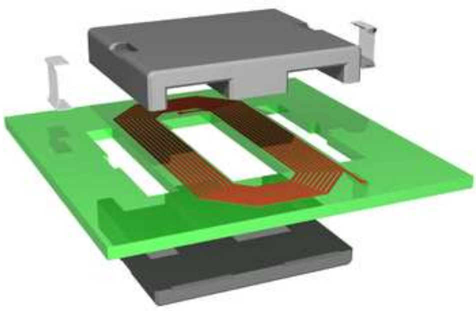

Fig. 4 View of a planar transformer

The increasing of switching frequency of power supplies sometimes limits the planar transformers performances. Beyond certain operating frequencies (>100kHz), losses caused by the skin effect, increase with the frequency and can reduce planar transformer performances. To guarantee a better planar transformer performance, the operating frequency is fixed at 100kHz. The other motivation to use planar technology is to reduce the volume, the weight, the height of the classical transformer and cancel their wires connection as shown in Fig 5. The classical transformer wires can moreover collect disturbances resulting from outside by coupling field, this external field can be found in the magnetic circuit and slow down the energy transferred between primary and secondary windings and thus increase the leakage flux then the leakage inductances.

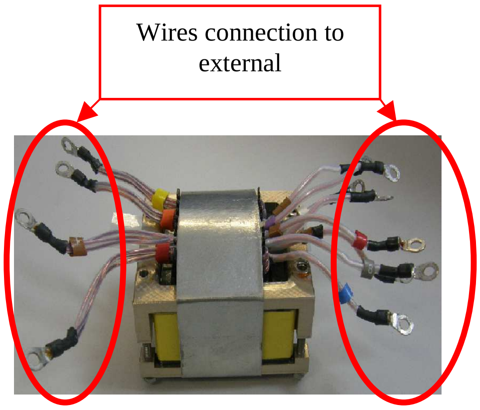

Fig. 5 Actual transformer use in the radar power supply

IV. Reducing the Leakage Inductances

The comparison of the classical and planar technology Table.1 shows that, with the planar technology, the serial resistances of windings , the leakage inductances, the size, and the volume of the classical transformer can be reduced but the drawback of this technology is the increasing capacitance between windings.

Table. 1 Comparison of classical and planar technology

Designation	Classical transformer	Planar transformer
Leakage Inductances	+	-
Serial resistances of windings	+	-
Size and Volume	+	-
Capacitance between layers	-	+

The leakage inductances are difficult to estimate analytically, that's why they are often estimated by short circuit measurement. As in [3], the leakage inductances are estimated based on the distribution of the Magneto Motive Force (MMF) Fig 6.

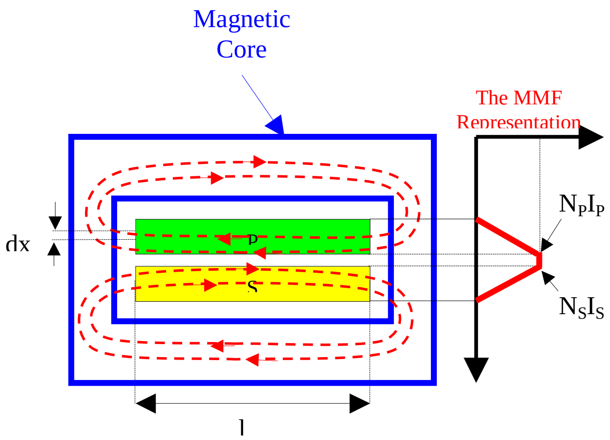

Fig. 6 Representation of the MMF of one primary and secondary winding

dx : Variation of the copper thickness,
Np, Ns : Primary and secondary turns respectively,
Ip, Is: Primary and secondary current respectively.

The MMF variation Fig 10 was plotted by assuming that the planar transformer turns ratio is equal to 1 and the total number of turns is 24. In reality, the planar transformer turns ratio is equal to 0.25 and the numbers of primary and secondary turns are equal to 32 and 16 respectively. The planar transformer design is not presented in this article, but the techniques of interleaving layers are presented to improve the leakage inductances of the planar transformer. The calculation of the energy stored in the primary and secondary windings is based on the formula below :

$$E = \frac{1}{2}\int B.H.dV = \frac{1}{2}.L_f.I^2 \quad (1)$$

B : Magnetic flux density,
H : Magnetic flux strengh,
dV: Volume variation,
L_f : Leakage inductance,
I : Rms current

Based on the MMF distribution Fig 10, the leakage inductance of primary and secondary are obtained by the following formula.

$$E = \frac{\mu_0}{2} L.l \left[\begin{array}{l} 8\int_0^{h_P}\left(\frac{I.x}{l.h_P}\right)^2 dx + 4\int_0^{h_S}\left(\frac{I.x}{l.h_S}\right)^2 dx + \left(\frac{I}{l}\right)^2 h_I + \\ \left(\frac{I}{l}\right)^2 (2h_p + h_s + 2h_I) + \left(\frac{2I}{l}\right)^2 h_I + \\ \left(\frac{2I}{l}\right)^2 (2h_p + h_s + 2h_I) + \left(\frac{3I}{l}\right)^2 h_I \\ + \left(\frac{3I}{l}\right)^2 (2h_p + h_s + 2h_I) + \left(\frac{4I}{l}\right)^2 h_I \end{array} \right]$$

$$E = \frac{\mu_0}{2} L.l \left[\begin{array}{l} \frac{8.I^2}{l^2}.\frac{h_p}{3} + \frac{4.I^2}{l^2}.\frac{h_s}{3} + \\ \left(\frac{I}{l}\right)^2 \left[49h_I + 28h_p + 14h_s\right] \end{array} \right]$$

$$E = \frac{1}{2}\frac{\mu_0 L}{l}\left[\frac{8h_p + 4h_s}{3} + 28h_p + 14h_s + 49h_I\right].I^2$$

By identification with (1)

$$L_f = \frac{\mu_0.L}{l}\left[\frac{92.h_P + 46h_S}{3} + 49.h_I\right] \quad (2)$$

h_p,h_S : Copper thickness of primary and secondary tracks respectively,
h_I : Insulation thickness between layers,
L : Total lenght of primary and secondary tracks,
l : Width of primary and secondary tracks.

The lengths of primary and secondary layers are respectively 295.3 mm and 299 mm. The width of the primary and secondary tracks is equal to 2.8 mm. The thicknesses of primary and secondary copper, the insulation between the primary and secondary layers are equal to 200 µm. Using (2), the primary and secondary leakage inductances are L_{fp} = 20.1µH and L_{fs} = 10.2µH respectively.

For industrial feasibility reasons, the planar transformer PCB is made by two circuits of 5mm each and paste them Fig 7.

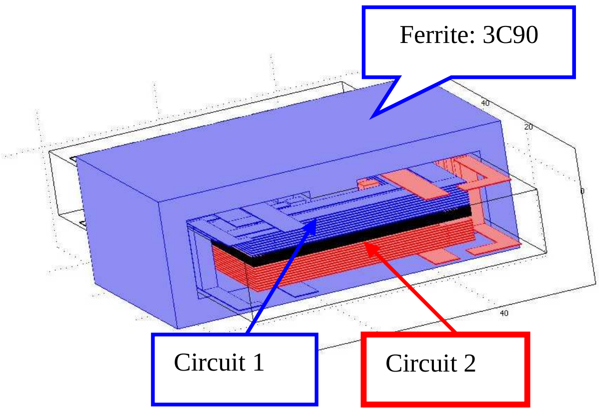

Fig. 7 2D view of the planar Transformer

The leakage inductances of the two circuits are in parallel. The equivalent primary and secondary leakage inductances are equal to half the leakage inductances calculated above and then become L_{fp} = 10.1µH and L_{fs} = 5.1 µH respectively. Fig 8 and Fig 9 show an example of primary and secondary tracks.

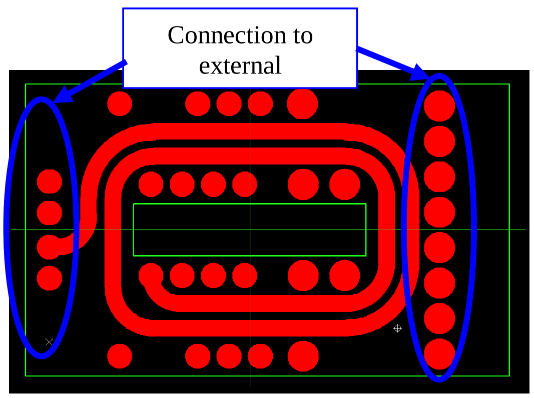

Fig. 8 Example of primary tracks

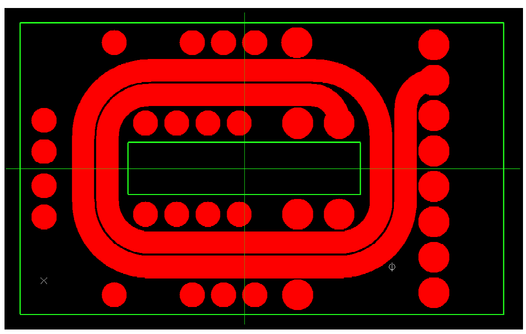

Fig. 9 Example of secondary tracks

The comparison of Fig. 8 and Fig. 5 shows that our objective to cancel the extenal wires connexion of the classical transformer is achieved. With this new connexion system, the disturbances resulting from outside by coupling field will be reduced. The comparison of Fig 3 and Fig 11 shows that the oscillations on the Off phase of the MOSFET are cancelled with the planar transformer. This is mainly due to reduced leakage with planar technology.

Table. 2 Comparison of two transformers

Designation	Weight (g)	Height (mm)	Volume (cm^3)
Classical Transformer	684	54	301
Planar Transformer	324	21	100

Table 2 shows that, the weight, the height and the volume of the classical transformer are almost divide by two as shown in Fig 12 and Fig 13. The aim to reduce the volume, weight and leakage of the transformer is reached.

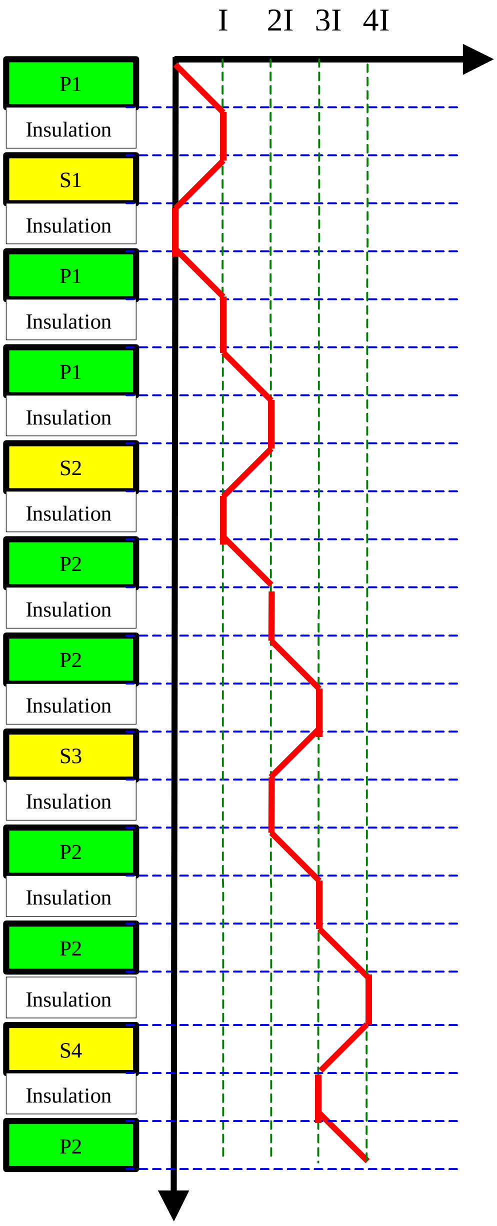

Fig. 10 Magneto Motive Force (MMF) variation of the circuit 1 of the planar transformer

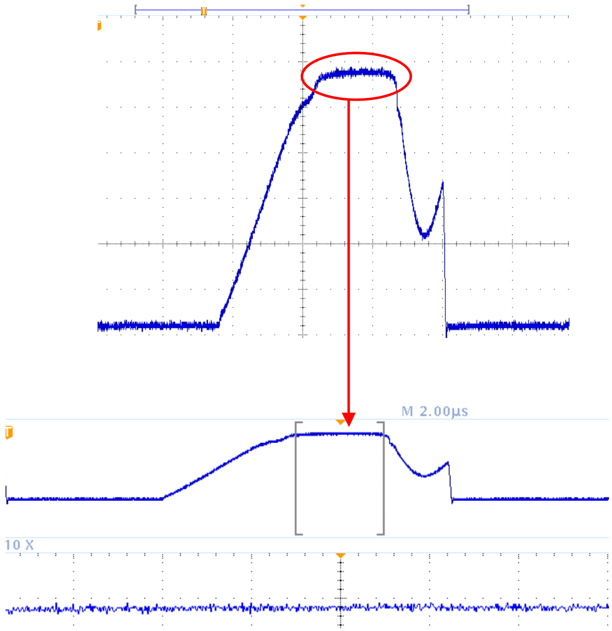

Fig. 11 Drain- source voltage V_{DS} of the switching MOSFET.

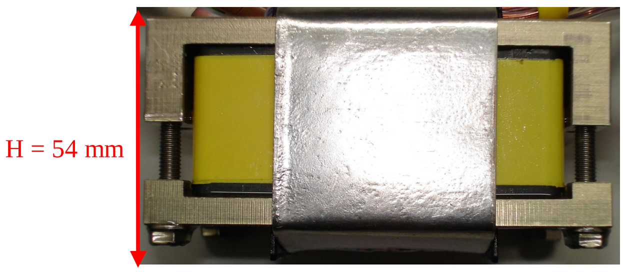

Fig. 12 Height of the classical transformer

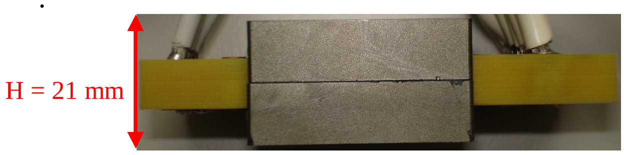

Fig. 13 Height of the planar transformer

V. Improving the Leakage Inductances

To reduce the primary and secondary leakage inductances of the planar transformer, a new technical interleaving is next presented. The complete interleaving of primary and secondary layers PSPPSPPSPPSP used in the design of the planar transformer has reduced the leakage inductance of the classical transformer. In the case of the number of primary turns is much higher than the secondary ones (32>16), to reduce the leakage inductances, the following interleaving technic can be applied when the ratio between primary and secondary windings is important. That is when the primary turns are above or below the secondary turns and vice versa.

This technique is to put the layers that have more turns near the ferrite to reduce leakage inductances. This technique is to put the layers that have more turns near the ferrite to reduce leakage inductances. This arrangement technique layers is applied to the planar transformeris above. The interleaving of primary and secondary layers PSSPSSPPPPPP is shown below.

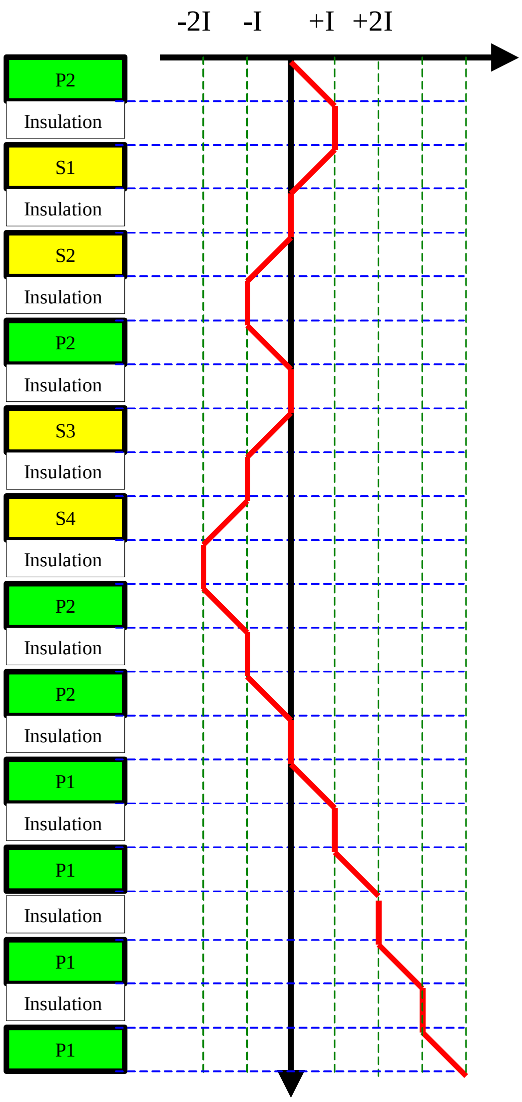

Fig. 14 New variation of the Magneto Motive Force (MMF) of the circuit 1 of the planar transformer

The calculation of the primary and secondary leakage inductances associated with this technique gives :

$$E = \frac{\mu_0}{2} L.l \left[\begin{array}{l} 8\int_0^{h_P} \left(\frac{I.x}{l.h_P}\right)^2 dx + 4\int_0^{h_S} \left(\frac{I.x}{l.h_S}\right)^2 dx + \left(\frac{I}{l}\right)^2 h_I \\ + \left(\frac{I}{l}\right)^2 (h_p + h_I) + \left(\frac{2I}{l}\right)^2 (h_p + h_I) + \\ \left(\frac{3I}{l}\right)^2 (h_p + h_I) + \left(\frac{I}{l}\right)^2 h_I + \\ \left(\frac{I}{l}\right)^2 (2h_I + h_s + h_p) \end{array} \right]$$

$$E = \frac{1}{2} \frac{\mu_0.L}{l} \left[\frac{8h_p + 4h_s}{3} + 18h_I + 15h_p + h_s \right]$$

By identification with (1)

$$L_f = \frac{\mu_0.L}{l} \left[\frac{53.h_P + 7h_S}{3} + 18.h_I \right] \quad (3)$$

Using the same values of width, length and insulation of the planar transformer above, the primary and secondary leakage inductances are respectively L_{fp} = 8µH and L_{fs} = 4µH. The equivalent primary and secondary leakage inductances becomes 4µH and 2µH respectively. This techique of interleaving greatly reduces the leakage inductance.

VI. Conclusion

The objectives to reduce the volume, the weight, the leakage inductances and the oscillations at the terminals of the power MOSFETs, are achieved. The next step of our works is to realize the planar transformer and validate the new technique of interleaving that we developed in this paper.

Acknowledgment

The authors would like to thank the Regional Council of Upper Normandy.

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