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Sizing a Single Phase and High Frequency Transformer for a Conversion String of Photovoltaic Energy

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Abstract— **In order to minimize the size, weight and cost of a PV micro-inverter board, we adopted a very specific architecture and a design for a product of high reliability and very small physical dimensions. We sized a high frequency transformer that meets the criteria of reliability and miniaturization. In this paper, we formulated a structured algorithm and design of single-phase and high frequency transformer, for a photovoltaic application. We then developed an application with a graphical interface enabling the user to execute the sizing algorithm as he want with a different parameters**.

Key Words— **Single-phase and high frequency transformer, Photovoltaic Micro-inverter, Sizing, Simulation, Test, Calculation algorithm, Data base, Graphical interface.**

I. INTRODUCTION

There are many years, the small transformers for miniaturized electronic applications costing quite expensive, so that when an assembly is realized, it was necessary to wind the transformer himself.
This is not the same case today, because the costs are not higher as before, and for four or five Euros, we can find these small pieces of about four to eight VA of power.

For higher powers, the prices go up very quickly and they have become unapproachable, especially for the "toric" Transformers (wound on a magnetic ring without air-gap). Why write an article for it then? Simply, because in the most cases the standard and trade transformers are technically inappropriate. First, voltages, currents delivered, frequency and applications are different and secondly the issue of galvanic isolation. Naturally the "tailor-made" exists, but is not applicable for some individual cases. This article discusses the design of high frequency transformers for a particular application of the smart PV micro-inverter.

II. MODELING :

After analyzing the system we propose the architecture of *Figure 1*. In this figure, a first block converts the voltage input to a high frequency AC voltage. This is passed through a high frequency transformer. At its output we get a voltage of 311V as a maximum value to get a RMS voltage of 220V in the end of the chain. This voltage is rectified before being corrugated again, this time at a frequency of 50Hz. A second channel is added to charge the battery of 12V. In this article we will look at the design of high frequency transformer block. *(See fig.1)*

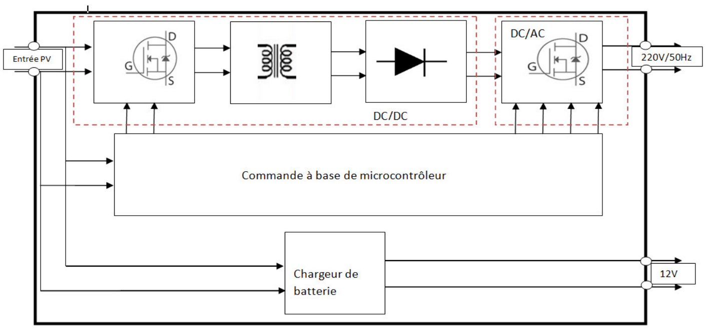


Fig.1: block diagram of the system.

A. *Theoretical Aspect*

TABLE 1
QUANTITIES USED

f	Electrical current frequency	**Hz**
B	Magnetic induction	T
H	Magnetic field	A/tr
Φ	Magnetic flux	Wb
L	Inductance	H
δ	Electrical current density	A/m²
ρ	Resistivity of the material	Ω.m
K_b	Winding coefficient	SI
S_b	Winding area	mm²
K_c	Copper area	mm²
$S_f(A_e)$	Iron section (magnetic circuit)	mm²

μ_0	Air Permeability	SI
μ_r	A relative permeability material	SI
N	Number of turns	Trs
A_l	Coefficient of inductance	nH/trs²

The HF transformer sizing consists to determine the following:

TABLE 2
THE ELEMENTS TO MODEL AND THE CONSTRAINTS TO BE TAKEN INTO ACCOUNT.

Elements	**Constraints**
➢ The transformer size	- The transformer power
➢ The magnetic core material	- Saturation of materiel (Bmax < Bsat of material) - The sufficient area for winding
➢ The winding wire (coil wire)	- The number of turns in primary and secondary - The section and type of winding wire.

1) *Magnetic Material*

- *Available Material :*
  - ✓ Iron sheets used in industrial frequency (16.66 to 400Hz)
  - ✓ Magnetic ferrite or ceramic used in high frequency in power electronics.
  - ✓ Air used in very high frequency ;

We choose the ferrite materials which have a high resistivity (10^2 to 10^8). So, it has low losses due to Foucault currents. It also has a high permeability for obtaining small transformer. Their saturation induction is about 0.5T (we use Bmax =0.3T (experimental value)).

2) *Transformer Size Depending on Its Power*

- *Total Winding Area*
  S_b is the sum of the area of the primary and secondary coil.
  $$S_b = n_1 \frac{I_1}{\delta} K_1 + n_2 \frac{I_2}{\delta} K_2 = n_1 \frac{I_1}{\delta}(K_1 + K_2)$$
  [1]
- *Core Section* S_f

$$E = n_1 . S_f . \frac{dB}{dt} \Rightarrow S_f = \frac{E \alpha T}{n_1 B_{\max}}$$

- $S_b . S_f$

$$S_b . S_f = \frac{E \alpha T}{n_1 S_f} . n_1 \frac{I_1}{\delta}(K_1 + K_2) \ [1]$$

We have to show up before the input power P_e of the system to highlight the relationship between the power transformer and its size. $P_e = E I_1 \sqrt{\alpha_{\max}}$

$$S_b . S_f = \frac{P_e \sqrt{\alpha_{\max}}}{B_{\max} \delta f} . n_1 \frac{I_1}{\delta}(K_1 + K_2) \ [1]$$

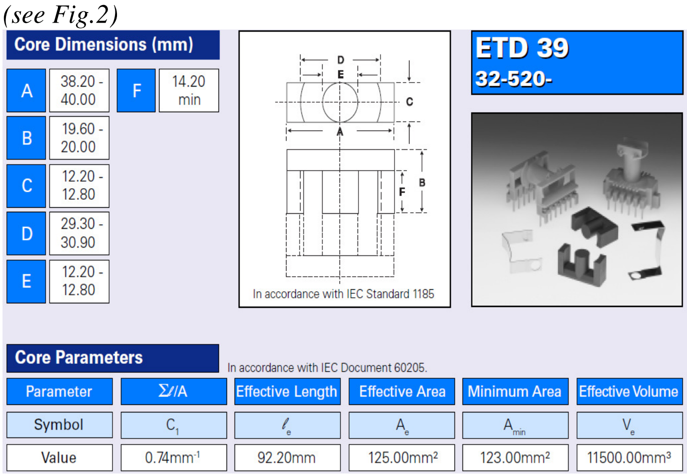
K_1 And K_2 are respectively the filling factor of the primary and secondary. We take K_1 =5; K_2 =2, $B_{\max} = 0.3T$, $\alpha_{\max} = 0.75$ $\delta = 4A/mm^2$ ($5A/mm^2$ maximum)

$S_b . S_f = 25259.07 mm^4$

- *Core Selection*

We choose a core whose cross section and the winding area are greater than $S_b . S_f = 25259.07 mm^4$

We take the pot from the ETD series. $S_b . S_f = 25259.07 mm^4$ Reference ETD 39 32-520- [2] *(see Fig.2)*



Parameter	Σl/A	Effective Length	Effective Area	Minimum Area	Effective Volume
Symbol	C_1	l_e	A_e	A_{min}	V_e
Value	$0.74 mm^{-1}$	92.20mm	125.00mm²	123.00mm²	11500.00mm³

Fig.2: The reference of the ferrite core in the catalog ETD [2]

- *Turns Number*
  We want from an input voltage of 30V, have an output voltage of 311V. It is known that:
  $$V_s = \frac{m . V_e}{1 - \alpha} \Rightarrow m = \frac{V_s (1 - \alpha)}{V_e} = 2.59$$

To consider the voltage losses in the components, especially the transformer, we will take $m = 5$ (experimental value). From the previous relationships we deduce that:

$$n_1 = \frac{E\alpha_{\max}}{f.S_f.B_{\max}} = 12 \text{ turns; so } n_1 = 12 \text{ turns}$$

So $n_2 = 60$ turns.

- *Winding Wire Selection :*

The winding wire selection has an impact on the resistance of each winding, on the size and weight of the transformer.

- *Skin Effect.*

The skin effect is an electromagnetic phenomenon in which the density of a high frequency electric current is very high at the conductor surface than inside. This creates a layer on the surface in which the current flows: is the skin effect e_p [4].

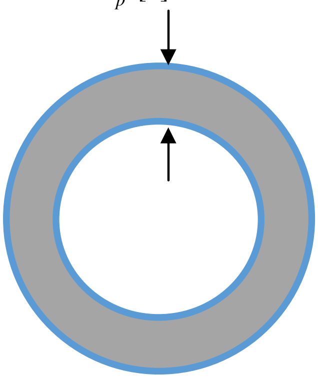


Fig.3: Electrical wire in high frequency

$e_p = \sqrt{\frac{\rho}{\mu\pi f}}$. To optimize a cable, its radius should therefore not exceed the thickness of skin. We note that the wire section is:

$$S_{fil} = \pi r^2 = \frac{I}{\delta} \quad \Rightarrow \quad I = \delta\pi e_p{}^2 \qquad [1]!$$

The *table 3* gives e_p for the copper.

TABLE 3
THICKNESS SKIN FUNCTION OF FREQUENCY [3]

F(KHz)	e_p **(mm)**	**I(A)**
5	1	15
10	0.7	7.5
20	0.5	4
50	0.3	1.5
100	0.22	0.8

Because we work in 50 KHz, the section of wires should not exceed 0.3mm². This leads us to use a Litz or an enamelled wire (copper) of, at least 6 strands, each one has at most 0.3mm² of section and it can support a current of 1.5A for the primary (I_e).

Regarding the secondary we should have one wire of section of, at most, 0.3mm² is enough ($I_s = 0.8A$).

B. *Theoretical Results:*

TABLE 4
RESULTS OF THEORETICAL CALCULATION

Elements	**Caractéristics**	**Ref**
Core	Ferrite core	ETD 39 32-520-
Winding wire	Copper wire consists of 6 strands of section 0.3 mm² each one.	enamelled copper wire 0.70 mm of diameter

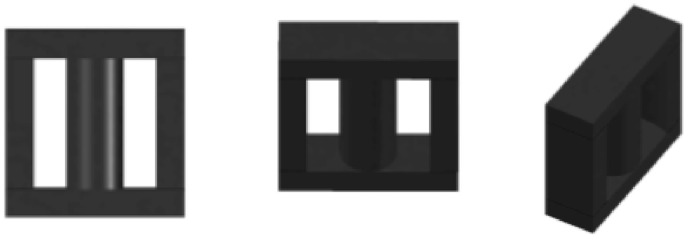


Fig.4: General view of the ferrite core (drawn on AutoCAD 2011).

C. *Simulation Results :*

The simulation of the assembly of fig.5, the ISIS simulation software, gives the following result: *(see Fig.6)*

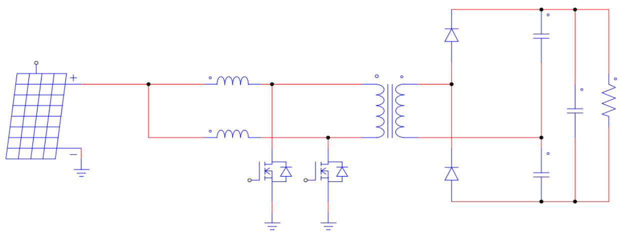


Fig.5: simulation schematic

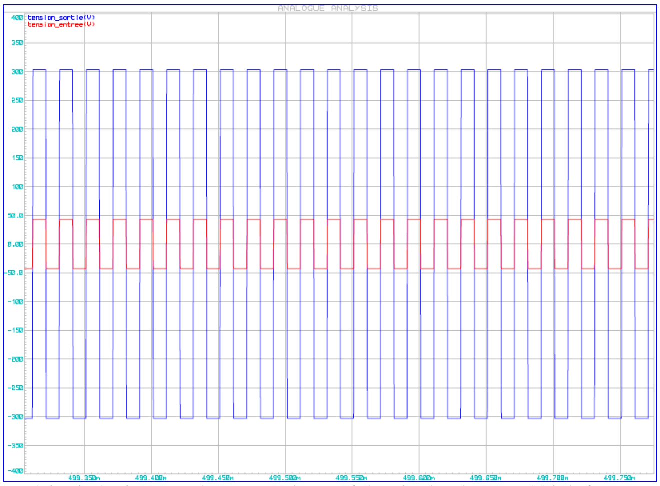


Fig.6: the input and output voltage of the single-phase and high frequency transformer for a duty cycle of 45%.
Red: Input voltage of transformer
Blue: output voltage of the transformer

With a duty cycle of 45% we had, for an input (red) voltage of 48V, an output voltage (blue) AC 306V. (*See Figure 6*). In this test example, we can see that the voltage obtained at the output (306V) is close to the value of the voltage that we set at the beginning (311V).

After several tests with various values of the duty cycle, we found that we can have at the high frequency transformer output a voltage of 311V ± 10% regardless the voltage of the photovoltaic panel. That means the load is all time supplied by a voltage between 198V and 242V.

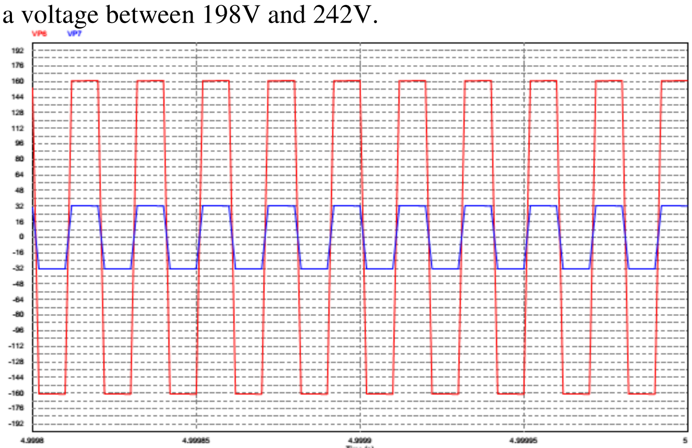


Fig.7: the input and output voltage of the single-phase and high frequency transformer for a duty cycle of 45%.
Red: Input voltage of transformer
Blue: output voltage of the transformer

For this example, we gave an input voltage of 32V and we had in the transformer output a voltage of 160V for the same value of the duty cycle made in figure 6.
160/32 = 5 so we well keep the theoretical ratio of transformation.

III. Conclusion

In order to facilitate the procedure and execute quickly the design algorithm of such a high frequency transformer, we made an application with a graphical interface allowing to the user to enter the required data (the power of input Pe, the duty cycle α, the input voltage Ue, the output voltage Us, the operating frequency F ...) to perform the calculation and sizing of the high frequency transformer in a very short time. With a database that we predefined in our system, the application provides to the user a list of references ferrite cores with their characteristics (magnetic and electric ones), their physical design, prices, winding area…. All information relating to winding wire also (number of turns, section, surface winding, number of strands, the type of wire ....)

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