INNOVATIVE CONTACTLESS SLIP RING

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ABSTRACT

To provide electrical power and signals to a rotating part of an instrument, a mechanism or a satellite, a slip ring or a cable wrap (for limited rotation) are commonly used. In these two cases, even if the development seems to be under control, the qualification is always a tricky issue in particular the long duration life demonstration, like for radiometers…

The paper hereby proposed presents an original design of a contactless slip ring studied in the frame of CNES Research and Development program.

First of all, we would like to introduce the principle chosen for this electrical transmission and for which the brushes have been removed, to avoid friction torque and wear.

The core part of this paper describes the optimization of the electrical ratio, mass and volume, with the main electrical parameters.

Afterwards, the prototype realised and the characterization tests results obtained on this model would be presented.

In conclusion, the advantages but also some drawbacks of this new kind of mechanism component and the lessons learned from this study would be highlighted.

1. INTRODUCTION

The signal transmission with standard slip ring used in spatial mechanisms is based on friction between brushes and rings. The main drawback of this principle is the occurrence of contacts degradation by wear during the orbit life. This phenomenon could induce growing friction torques, higher electrical contact resistance (line losses) and arcing risk. And so, the slip ring very long duration life qualification is always a tricky issue.

The purpose of the activities performed in the frame of Research and Development program was to avoid this problem by removing the mechanical contacts.

Analyses in contactless power transmission lead us to use induction transmission in a transformer. The main interest is the failure risk removal associated to contact degradation. Meanwhile, the transmission efficiency is lower than for a "mechanical" slip ring and it needs a more complex electronics.

This equipment is functioning only with AC voltage. So we have to convert the input DC voltage in AC shape by a converter, transmit the electrical power in the transformer and convert the voltage in continuous shape thanks to a rectifier.

Some remarks on rotating transformer

It's necessary for rotating transformer to have an air gap between primary (core, coils) part and secondary part.

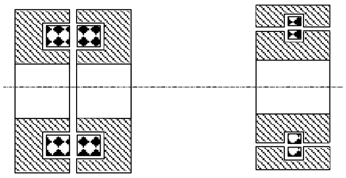

Figure 1 : standard transformers (axial or radial gap)

This air gap leads to transformer characteristics degradation which not allows the standard converter use without drawbacks (over voltage, high losses during commutations and high no-load current).

Indeed the air gap induces a low magnetising inductance on the one hands and the windings separation implies a high leakage inductance on the other hand. Only resonant converters could be used in this case [1].

One of the study objectives was to reduce these drawbacks. Thanks to led analyses and chosen design, the leakage inductance reached a value close to the one of a static transformer and we have obtained an acceptable magnetising inductance value with a reasonable over sizing of the transformer (high magnetising inductor need with air gap). These characteristics are very interesting and allow again classical converters use especially flyback converter. In this case over sizing is avoided thanks to the lower magnetising inductor need.

Some comments on capacitive transmission

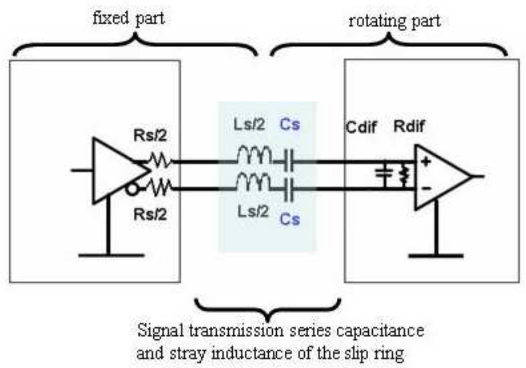

figure 2 : capacitive transmission model

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The capacitive transmission is corresponding to the model fig 2. From this model we obtain the transmission transfer function shown fig. 3. The frequency broadband width must be adapted by modifying the input inductance, differential capacitance and gain.

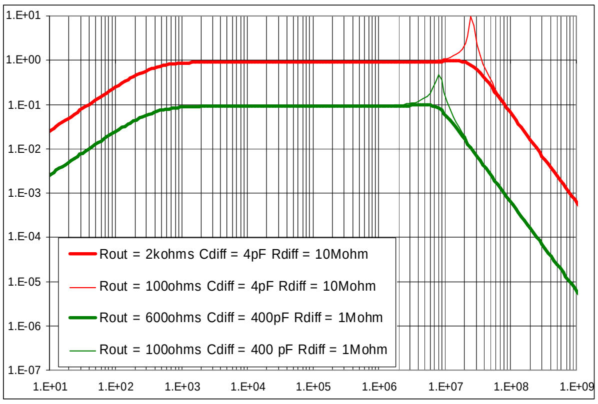


figure 3 : theoretical transmission transfer function for different line parameters

2. PRELIMINARY STUDY

For mechanical and machining considerations we tried to design the transformer with magnetic alloy core. The study shows that the eddy current losses that are proportional to the frequency square become a major disadvantage.

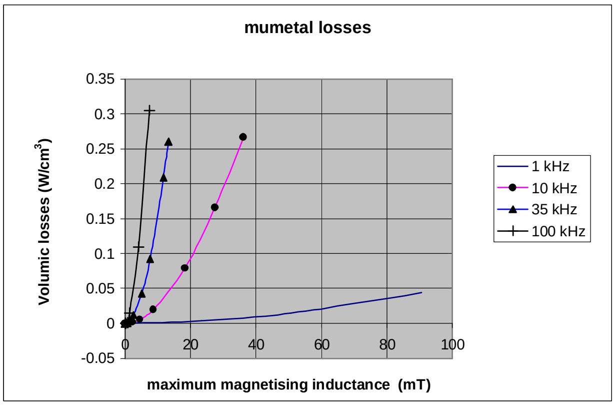


figure 4 : losses versus magnetising inductance

To reduce this effect, we can use laminated material alloys but that leads to a more complicated machining. The second way is the reduction of the working frequency but the overall dimensions of the transformer become very important. This solution is rejected.

The other solution which is based on a ferrite core has been validated for electrical behaviour with a mock-up. The calculation process for electrical performance and structure dimensions has been demonstrated.

3. DESIGN AND OPTIMIZATION

After this first study we had a design and optimization phase

The concept of the slip ring had to take into account the specifications hereafter.

	Nbr of channels	Frequencies	Impedance	Voltage - current
Power	1	100 to 200kHz square signal	Leakage inductance < 5µH. Magnetising inductance : 100 µH	input 40-20 V output 30 V, 1.2A
Signals	8	3 to 1MHz square signal	TBD	0-50 V

Transferred electrical power : 30 W
Overall dimensions : 30 mm x 30 mm x50 mm
Weight : < 100g

Electrical main hypotheses

Magnetising inductance will be around 100 µH and the ratio between magnetising inductance and leakage inductance would be around 400.

Current density max allowed : 6 A/mm²

Triangular current : Max current : 6 A

Two configurations have been analysed : disc design or tubular design.

3.1. Disc design

The disc configuration slip ring calculated from these hypotheses lead to the design hereafter.

The disc configuration volume is about 243 cm3 without the ball bearings. The disc internal part is devoted to the signals transmission and the outer part to the transformer.

Magnetising inductance

100 µH

Gap between coils

0.06 mm

Conductor thickness

0.45mm

Bmax : 100mT

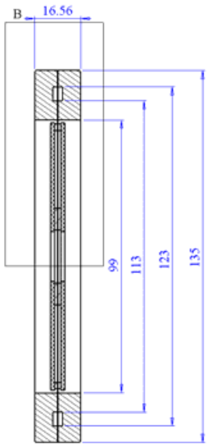


Figure 5

Because of overall dimensions, this configuration has been abandoned.

3.2. Tubular design

A parametric calculation on a simplified model has shown that the tubular configuration is less bulky than the disc configuration.

Transformer design

The transformer is constituted by two L shape tubular ferrites. The ferrites are positioned as on fig. 6.

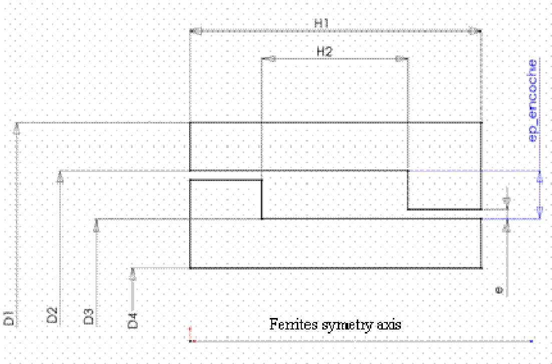


figure 6 : L shape tubular ferrites

The goal of the parametric optimization was to obtain the best design according to some parameters.

- External diameter impact

From the following equations and hypotheses [2]

Current density chosen = 3A/mm² - rms current = 6A

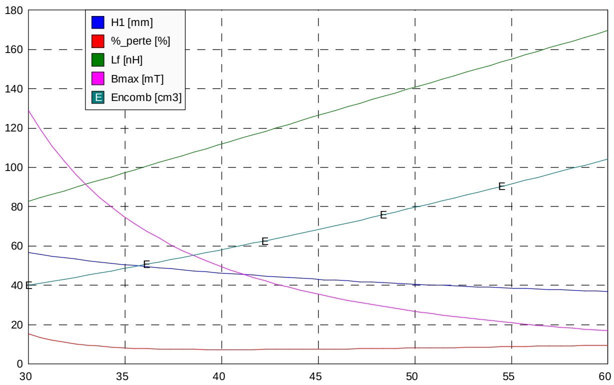
Magnetising inductance Lm = 100 µH area

$$Lm = \frac{n^2 . \mu_0 . S}{2e}$$ with $S =$ air gap cross section of the two gaps.

Leakage inductance $$Lf = \frac{\pi \mu_0 . n^2 .(D2 + D3) \cdot d}{2 \cdot H2}$$

$$n \cdot S = \frac{\text{max input flux}}{B\max}$$

We calculated the evolution of Lf, H1, Bmax ; losses, volume according the external diameter.



X-axis in mm

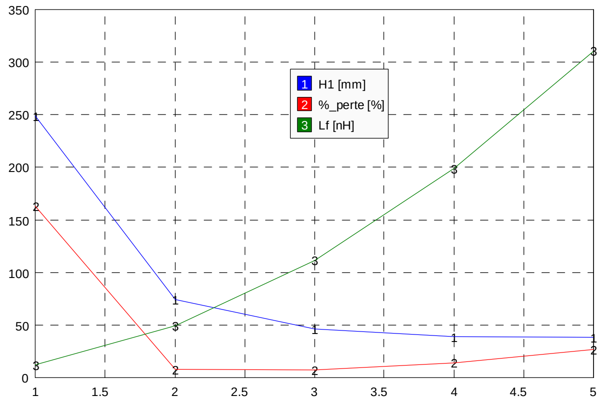
figure 7 : external diameter impact

The curves show that the optimum diameter to minimize the losses is around 40 mm.

- Turns number impact

We note on the graph fig. 8 that the increase of the number of turns leads to minimise the length (H1) of the transformer and increase the losses. The optimum for the losses seems to be 3 and it's a good compromise for the transformer bulk.

For this calculation : Lm = 100µH and
The external diameter D1= 40mm



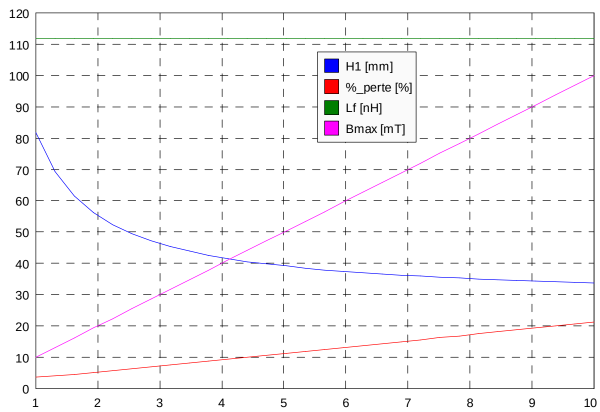
X-axis is the turns number

figure 8 : Turns number impact

- Current density effect

The calculations have been done with Lm =100mH and D1 = 40 mm.

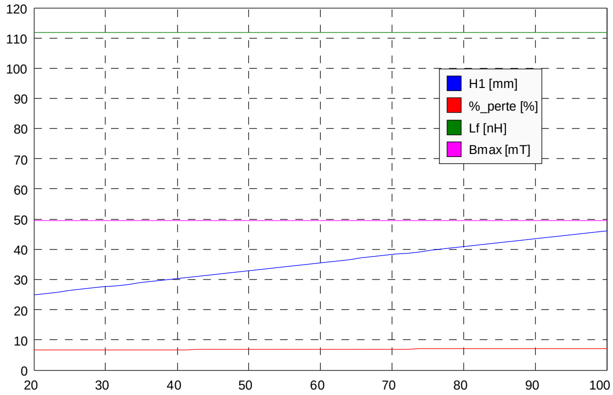
We note that the increase of the current density implies an increase of the losses and a diminution of the transformer length. It seems that a density current about 3 A/mm² is a good compromise.



X-axis in A/mm²

figure 9: Current density effect

- **Magnetising inductance (Lm) effect**



X-axis in µH

figure 10 : Magnetising inductance effect

The calculations have been done with D1 = 40 mm.

The transformer length follows the magnetising inductance increase. The losses are independent from Lm evolution. On the other hand the losses of the assembly (converter + transformer) are affected by Lm.

With this geometry, we can easily adjust the magnetising inductance by moving the ferrites one with respect to the other.

Signals transmission

Chosen design and main dimensioning equations

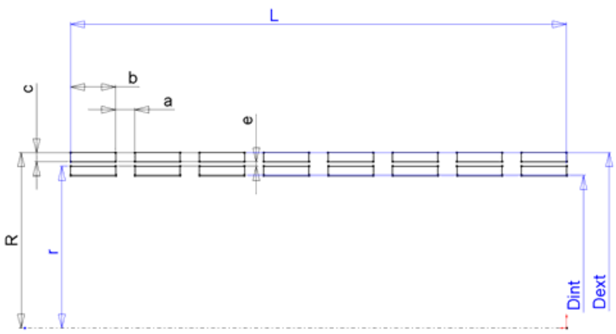


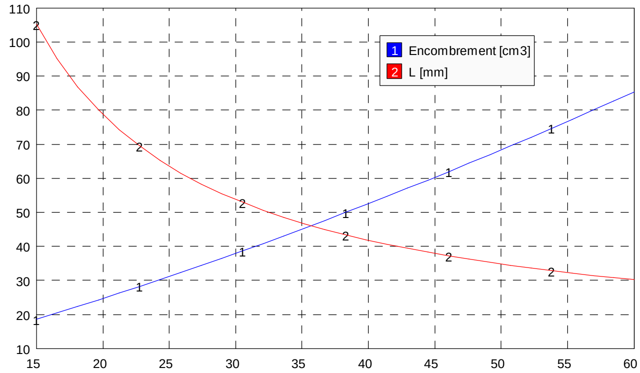
figure 11: Capacitive transmission scheme

Transmission capacitance $Cu = \dfrac{\varepsilon_0 . S}{e} = 100$ pF

Stray capacitance $Cp = \dfrac{\varepsilon_0 . \varepsilon_r . S'}{a}$ and $Cp < 10\%$ Cu

With $S = 2 . \pi . r . b$ and $S' = \pi . (R^2 - (R-c)^2)$

- **External diameter effect**

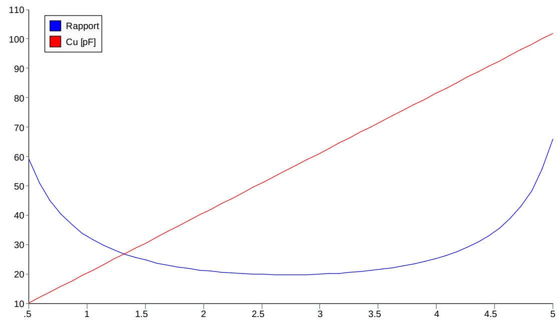


X-axis in mm

figure 11 : External diameter effect

We see that the global volume increases with the outer diameter. We will choose a “side by side” configuration with a 40 mm diameter.

- **Stray capacitance and conductor width optimization**



X-axis is the conductors width in mm

figure 12 : Parameters optimization

To have a good ratio between Cu and Cp we chose a 4 mm width for a conductor. In this case, Cu =80 pF and the ratio is about 2.5%. This value allows having a good signal/noise ratio.

The sensitivity and trade-off analyses led us to the design shown in figure 13.

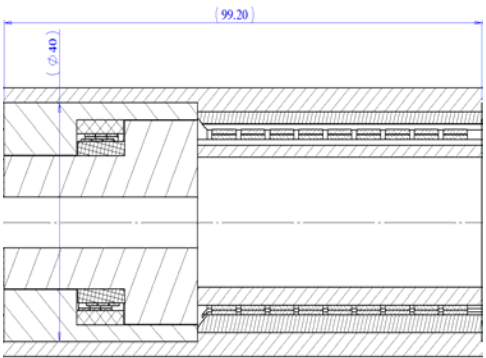


figure 13 : Transformer scheme

4. DESIGN DESCRIPTION

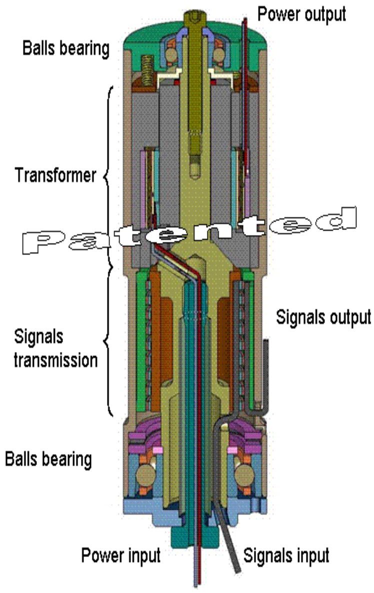


figure 14 : Slip ring cut-away view

The rotating part is composed of a shaft on which are fixed the inner ferrite and capacitors. The shaft is made of titanium to minimise differential thermal expansion with respect to the ferrite. In order to take into account the wire routing, the ferrites and the shaft have been machined.

Because of the ferrites brittleness, to avoid heavy loads created by the vibrations and thermal expansion solicitations, the ferrites holding forces are applied by springs.

The power coils could be done with flat or cylindrical wire. The flat wire dimensions are : 4.44 mm width ; 0.45 mm thickness. The spacing between the turns is around 1mm.

figure 15 : transformer coils in machining

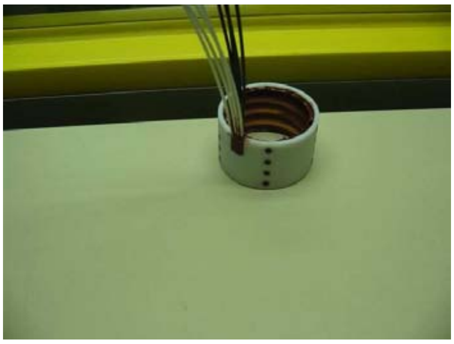


figure 16 : Transformer coils glued in housing

The transmission capacitors are copper rings. The thickness is 0.8 mm, width is 4 mm and the spacing between two rings is 1.7 mm.

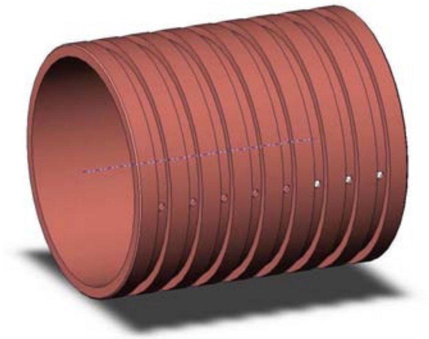


figure 17: Inner capacitors

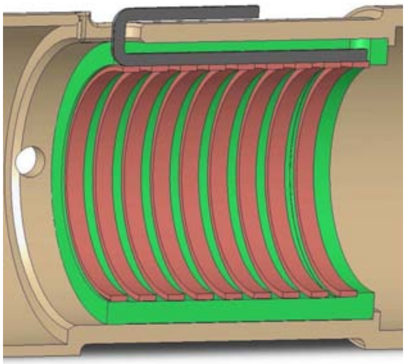


figure 18 : Outer capacitors

The nominal gap between transformer rotor core and stator core which is about 0.06 mm is guaranteed by machining.

The correct centring is guaranteed by a pair of skew angle balls bearings. The two bearings are preloaded by elastic washers or springs.

Two screws one at each side allow to preload the bearings and so maintain the slip ring.

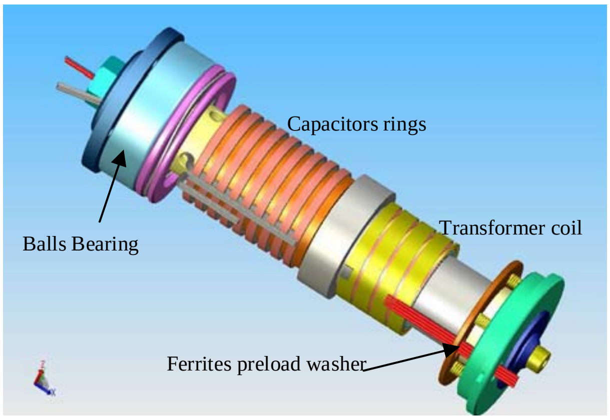


figure 19: Slip ring internal view

5. SLIP RING TESTS

A test bench has been realised to characterise the transformer in functional conditions and also to verify that the signals transmission isn't disturbed when the transformer is on-load.

The test bench is composed of a tension generator to supply the transformer and electric charge to simulate a standard functioning. The high frequency with high voltage and current makes the test bench realisation difficult.

To supply the voltage, two elements have been used: an adjustable direct voltage generator which determines the voltage square amplitude and an inverter to generate the square signal.

The charge is realised with a fixed capacitance and a variable inductance.

- Measurements

The measurements are realised with the 100µH slip ring.

<u>Magnetising inductance and losses :</u>

Measurement done at 50 kHz

RMS voltage (V)	RMS current (A)	Losses (W)	Inductance (µH)
5	0,46	0,1	
10,1	0,7	0,46	
15	1,03	1,12	46

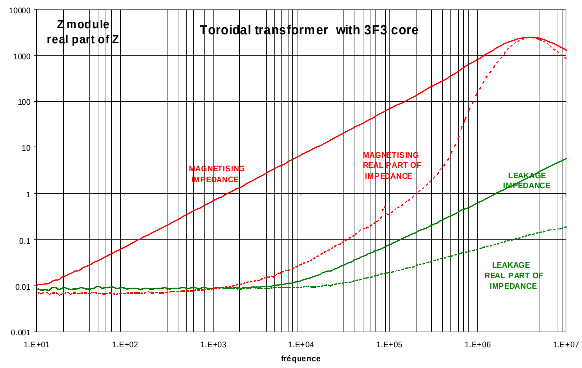
Measurement done at 100 kHz

RMS voltage (V)	RMS current (A)	Losses (W)	Inductance (µH)
5	0,184	0,06	
10,1	0,368	0,28	
15	0,54	0,66	
20,2	0,72	1,22	45

Measurement done at 200 kHz

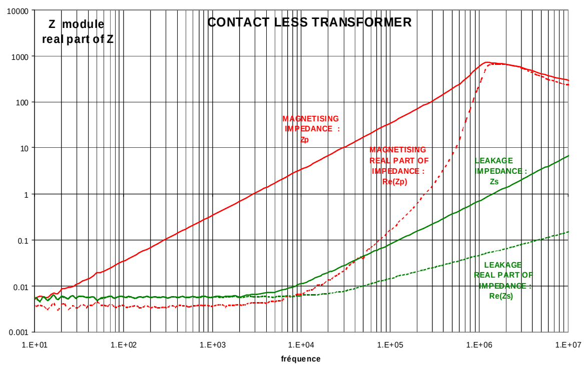
RMS voltage (V)	RMS current (A)	Losses (W)	Inductance (µH)
10,1	0,192	0,14	
20,1	0,378	0,64	43

<u>low signal frequency characteristics measurements :</u>



X-axis in Hz – Y axis in ohms

Figure 20 : Static transformer (measurements)



X-axis in Hz – Y axis in ohms

Figure 21 : rotating transformer (measurements)

The fig. 19 and 20 show the transformer impedance evolution in accordance with the input signal frequency variation.

The losses calculation is done with :

Open circuit losses ~ Re(Zp) .V^2 /Z^2p

Series losses ~ Re(Zs) .I^2

These two charts show that magnetising inductance, leakage inductance and losses are quite the same for a static transformer and our rotating transformer (in spite of the air gap). The analyses and the optimization of the design seem to be confirmed by these measurements. The rotating transformer behaviour is close to the one of a static transformer.

At this moment we don't have consistent signal transmission measurements. They will be done for the symposium.

6. LESSONS LEARNED

During the mock up development, we have encountered some difficulties. After the design optimization and to have the most compact possible slip ring, the main problem was the components machining.

Due to their brittleness, the ferrites tooling was not very easy and it's impossible to do a complicated shape.

Another problem was the coils manufacturing. We needed some tries to machining the inner coils transformer. Some of them have been destroyed during the machining.

During prototype slip ring assembling some problems occurred.

- A ferrite has been broken, it was re-glued. We have noted that the magnetic losses were higher for this prototype than for the others.
- Friction points appear during functioning and the electrical characteristics were bad. After visual inspection, we had to re-tool the coils.

At the moment, the main drawback is the slip ring weight (about 800 g). Indeed, to have a homogeneous thermal behaviour, we have chosen titanium alloy for the housing. The next step is to replace titanium by polymer material to reduce the weight. Moreover if some parameters like magnetising inductance are less stringent, the transformer dimensions will decrease.

This kind of slip ring has to be associated with electronics at each side. This is more complex than the slip ring with contact and these electronics must be developed and qualified.

The main advantage of this slip ring is the remove of the friction contacts for transmission. Duration life tests are not necessary to prove the slip ring dimensioning.

The signals transmission will not be degraded by the evolution of the mechanical contacts during the orbit life.

7. CONCLUSION

The design of the slip ring, patented by CNES, is nowadays validated through breadboard good tests results. The optimization has allowed obtaining a good losses / transmitted power ratio.

The manufacturing problems have been solved. Some processes have to be improved (like coils manufacturing and machining).

The next step is to minimize the physical characteristic of the equipment by degrading the specifications or by replacing the materials used.

The final objective is to qualify the slip ring to be able to propose it to a flight mission.

Acknowledgements: we wish to thank the CSTM Company for their slip ring design work under R&D contract. We also wish to thank the SUPELEC electrical laboratory for their participation to theoretical study and the test bench realisation.

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