Magnetic coupling design

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Abstract
This paper describes the construction of magnetic coupling for use with a high-speed electric machine with 1 Nm at 60 000 rpm. Starting with the technology review it continues with calculations of the torque created by the coupling with multiple configurations, especially the number of poles. Finally, the magnetic coupling is drawn, and mechanical parameters are calculated.

Keywords: Magnetic coupling, Design, FEM, Magnet, CATIA V5, Attraction force, Torque, High-speed, Matlab

1. Introduction

In a very disturbing environment (vibration, heat, lubricant for the saft, …), it can be useful to isolate different systems of a product. In a case of turbine who drive an alternator, there is on side with a lot of vibrations and heat (turbine's side), and one side with just a few excitations. Indeed, in the context of a student project a development of a high-speed PMSM unit with a model turbine engine is made. The high speed PMSM can be generator or engine.

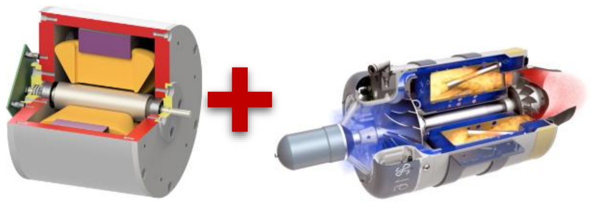

Figure 1. *High speed PMSM and the turbine used for the project [6] and [7]*

The implantation of a magnetic coupling between these two sides (PMSM motor and turbine) will allow to isolate the two environments and to not spread the local's constraints to the whole system. Moreover, the advantages of this type of coupling, compared to mechanical couplings, is the self-protection against the overload (pull-out torque) and a big tolerance against the shaft misalignment.

Among the advantages of this type of coupling compared to mechanical couplings is the self-protection against the overload (pull-out torque). Moreover, magnetic couplings tolerate shaft misalignment ([1] page 6).

2. Description of the case of study

Indeed, this paper speaks about an implantation of a magnetic coupling on a shaft who transfer a torque from a turbine to an alternator. The magnetic coupling will permit to have an air gap between the two shafts and not spread the vibration and heat to the other shaft, and so the whole system.

It will also be studying the possibility to uncouple the two shafts, in a goal to control the torque who goes to the alternator.

3. Different possible Design

Among all the different designs possible, two will be presented in this chapter. The selected designs are the only who showed relevant in our case (small, lightweight, easy design and cheap). Indeed, the magnetic coupling need to transmit at least 1 Nm at 60 000 rpm. Moreover, one side will undergo the turbine's vibrations and heat. In addition to the environment, the design must be small and lightweight because of the high rotational speed and the little diameter of the shaft (6 mm). To fill all this condition, this is the two designs who are pertinent in our study case.

3.1. Co-Axial Coupling

The Co-Axial Coupling is made up of one inner rotor and one outer rotor. An air gap between the two rotors is present, like in an electric motor. The series of opposing magnet poles creates a torque. Indeed, when, the two opposite poles are aligned, the attraction force prevents a relative movement between the two rotors. If an offset angle appears, the next magnet, who is the opposite pole, will repulse the rotor to close the offset angle.

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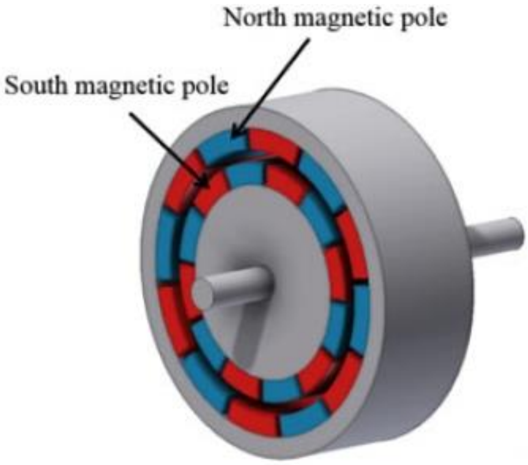

Figure 2. *Schema of a Co-Axial Coupling [2]*

This type of coupling presents the advantage to be compact and easy to balance which result of a design that can support high rpm naturally. However, the close difference of diameters between the outer and inner rotor requires to have a high manufacturing precision. The two shafts are not in contact and need to have a perfect alignment.

This design is therefore very relevant for this case of application, but the nature of the project (student project) force us to find if there are other cheaper solution that can be applicated and fulfilled our requirements.

3.2. Disc Coupling

The Disc coupling is made of two discs mounted on two different shafts. On each disc, there is an even number of magnets with the aim that there is an opposition of pole between the magnets which follow one other. Like in Co-axial coupling, the alignment of two opposite magnets creates a force that prevents a relative displacement between the two discs. If an offset angle still appears, the repulsive force create by the next same pole magnet, will close the offset angle.

This type of coupling presents the advantage to be very simple and allow lots of misalignment without loss too much torque ([1] page 5). Moreover, the magnet used is cheaper and easier to find compared to the concentric radial arc one used by the Co-axial coupling. The drawback of it is that is harder to balancing this design because the diameter of the discs is bigger than the outer router for the same torque, which is result by a bigger development to reach the high rpm requirement.

Figure 3. *Schema of a Disc Coupling [2]*

4. Magnetic Calculation

4.1. Analytical analysis

4.1.1. Principe of the 2D analysis

After having chosen our design for our magnetics couplings, we need to do some calculation with the objective to have a device the smallest and lightweight as possible. There are two ways to reach our goal: dimension our mechanical part at the limit (1Nm with the attraction force of the magnet) with some FEM calculation, and do some magnetic calculation to have the smallest number of magnets with the smallest diameter of the disc. However, to do the FEM simulation, we need our attraction force of the magnet. That means the scheme and number of the magnet need to be chosen before. This chapter will be interested in this part.

After reading a lot of paper and documentation, a protocol has been funded to determinate the number, type and spacing of the magnets. The calculation is a 2D approach who shows some results very close to the reality *(Figure 4).* However, the paper does a comparison of two methods: between a 2D, 3D approach, and the experiences results:

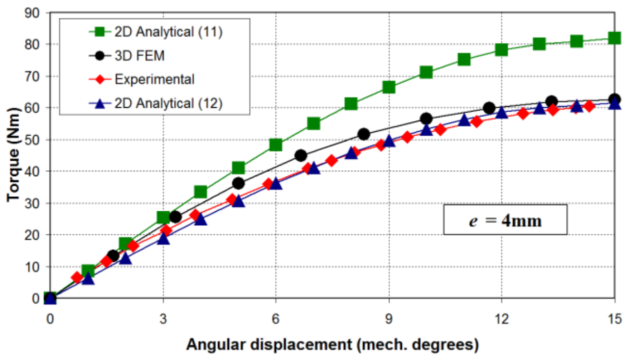

Figure 4. *Graphic to compare the different analytical methods with the reality [1]*

On this graph, there are two 2D Analytical, the "11" and the "12", the reason is that the 12 is the 11 with a correction factor to be closer to the reality. This correction factor is always the same during all the paper, and the analytical 12 is always very close to the reality

$$T_{\max c} = k_c T_{max} \quad with \quad k_c = 0{,}75 \qquad (12)$$

The 2D analytical calculated a force between two pairs of opposite poles. The magnetic characteristic of the magnet is needed, but easily findable on the provider website. By knowing that, we can calculate a torque with the magnet's distance from the center of the disc.

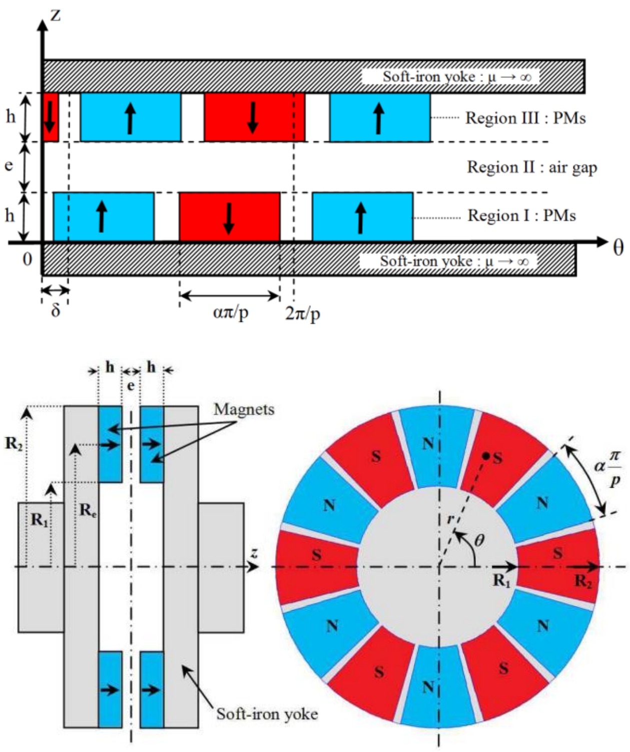

Figure 5. *Layout of the 2D analytical analysis [1]*

4.1.2. Adaptation of the formula for disc magnet

The problem that we can see on the layout, is the used magnet is a concentric radial arc's one. To simplify the design, the stock availability and the reduce the price, the disc magnet has been chosen. So, it is now necessary to adapt the calculation of T_{max}.

$$T_{\max} = \frac{16}{3\pi}\frac{B_r^2}{\mu_0}R_2^3\left(1-\left(\frac{R_1}{R_2}\right)^3\right)\sin^2\left(\alpha\frac{\pi}{2}\right)\frac{\sinh^2(a)}{\sinh(2(1+\nu)a)} \quad (11)$$

The most important to have reliable result is to keep the same surface aera of the magnets. Moreover, the space between each magnet $(\frac{\alpha\pi}{p})$ is not the constant in function of where you are in the disc unlike to concentric radial arc magnet. We will do an average to be the closest to the reality.

Table 1. *Input value for the first simulation.*

Symbol	Quantity	Value
R_1	Inner radius of the magnets	8,7 mm
R_2	outer radius of the magnets	17,3 mm
R_e	Mean radius of the magnets	13 mm
h	Magnet thickness	6 mm
e	Air gap lenght	variable
α	PMs Pole arc to pole pitch ratio	$\frac{57{,}5 \times 6}{360} = 0{,}958$
p	Pole pars number	3
B_r	Remanence of the magnet	1,32 T

Disc magnets of 12mm diameters has been taken. We now need to adapt R_1, R_2 and α. The surface of one magnet is:

$$S = \frac{\pi d^2}{4} = \frac{\pi 12^2}{4} = 113\ mm^2 \qquad (1)$$

With the chosen numbers the surface aera of equivalent magnet is:

$$S_t = \pi \times (R_2^2 - R_1^2) \times \frac{57{,}5}{360} = 112\ mm^2 \qquad (2)$$

57,5° is chosen because of the layout. We just adapt R_1 and R_2 to have the same surface.

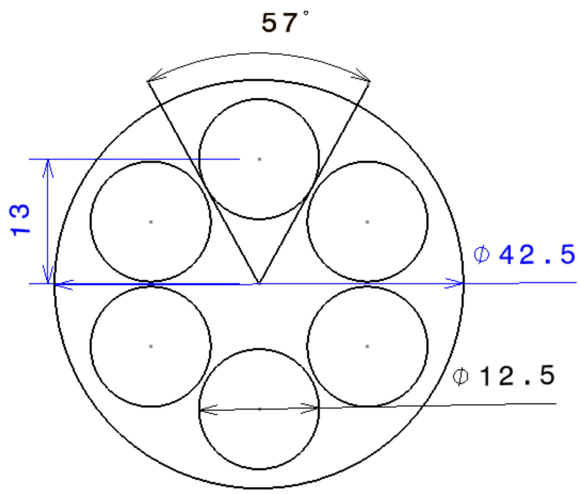

Figure 6. *Layout of the disc for the first calculation*

4.2. Optimisation

4.2.1. Result of the first calculation

After programming the formula in Matlab, we obtained this result:

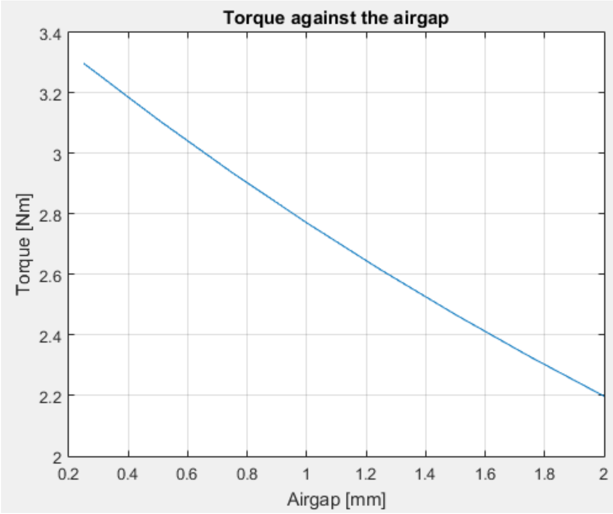

Figure 7. *Result of the first calculation*

In the case of study of this paper, the air gap can be chosen between 0,5 and 1 mm. Even with a strong security coefficient, the maximum torque is overdesigned. This means that less magnet or smaller can be used, and the R_e can be reduced.

4.2.2. Result for 2 poles pairs

After some Matlab iterations, some relevant results were obtained with 2 poles pairs and the same magnet. Moreover, the distance between the center of the magnet and the disc's one had decreased a lot allowing to have a lightweight and low inertia design. This is the parameters who have changed:

Table 2. *Input values who are different for the second simulation.*

Symbol	Quantity	Value
R_1	Inner radius of the magnets	5,8 mm
R_2	outer radius of the magnets	14,2 mm
R_e	Mean radius of the magnets	10 mm
α	PMs Pole arc to pole pitch ratio	$\frac{77{,}4 \times 4}{360} = 0{,}860$
p	Pole pars number	2

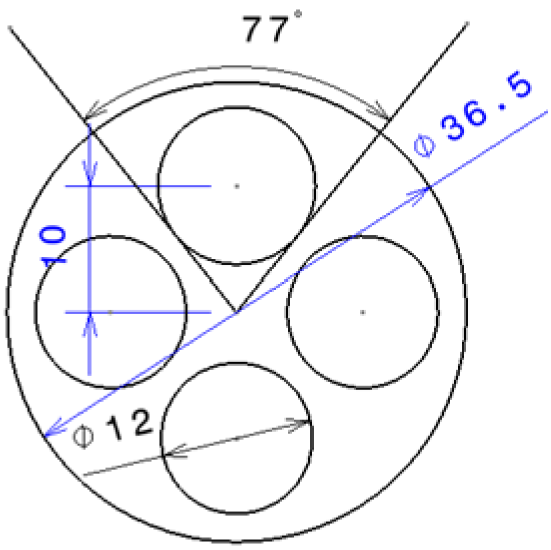

Figure 8. *Layout of the 2 poles pairs design*

With the chosen numbers, the surface of equivalent magnet is:

$$S_t = \pi \times (R_2^2 - R_1^2) \times \frac{77{,}4}{360} = 113\ mm^2 \qquad (3)$$

77,4° is chosen because of the layout. We just adapt R_1 and R_2 to have the same surface.

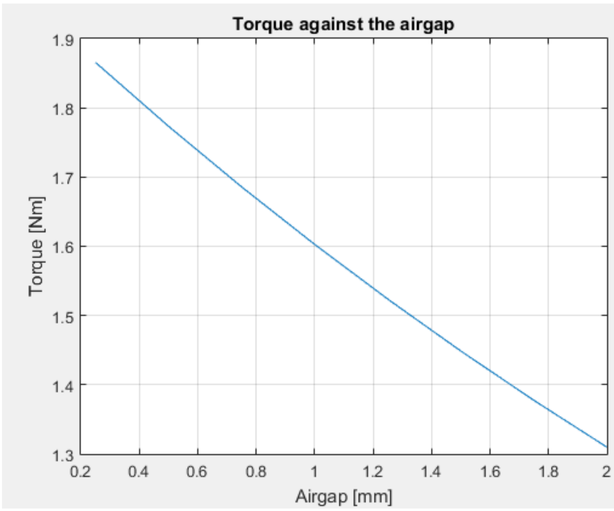

Figure 9. *Result of the two poles pairs simulation*

For an air gap at 0,75 mm, we have a torque of 1,7 Nm. So, we have a security factor of 1,7 to balance with the parameters that has not been considered (high rotational speed, heat, vibration, and other phenomenon can decrease the magnetic torque).

The magnetic design is now dimensioned, the disc to transmit the torque from the magnet to the shaft need now to be dimensioned.

5. Mechanical Design

5.1. Magnet's Fastening

The magnet's location and shaft's location has already been determined. However, the fastening method has been ignored for the moment. In a goal to have the simplest design, magnet will be maintained on the disc with an epoxy glue. It is a type of "strong glue" very efficient on metals (34,6 Mpa). According to the manufacturer, each magnet can produce a force of "4,5 kg". We understand here 44 N. With two discs of four magnets, there is an attraction force of 352 N.

$$P = \frac{F}{2 \times p \times S} = \frac{352}{2 \times 2 \times 113E-6} = 1{,}11\ Mpa \quad (4)$$

$$c_{glue} = \frac{P_{glue}}{P} = \frac{34{,}6}{1{,}11} = 31{,}2 \quad (5)$$

The security factor for the glue is equal to 31,2.

5.2. Disc's Fastening

The Disc needs to be attached to the shaft. However, the small diameter of the shaft (6 mm) makes impossible the machinery of it. It means that the use of key, pin, dowel, or lock nuts is impossible. The set screw is the only relevant, simple, and cheap solution that exists for this case. The principal difficulty is to implant set screw without unbalancing the disc, which would be annoying because of the high rotational speed.

A high number of set screws will promote a good balancing of the shaft but will increase the mechanical stress. How many set screws who will be used will be decided during the FEM simulation to have the best balancing with a stress under the elastic limit. Because of the low torque (1 Nm), even 1 screw will be enough to fix the disc on the shaft. A calculation of friction between the shaft and the screw is therefore useless. The threading will be design thanks to "*Guide du dessinateur industriel – Chevalier"* [3] who present all the different rules and law on it.

5.3. Disc's design and FEM

In the Disc's design, all the previous constraints need to be respected, in addition to find a good combination between a high number of set screw, a lightweight material and a stress under the elastic limit. Obviously, an acceptable security factor (2 for example) needs to be applied on each calculus to have a reliable design. This number may decrease in the future if the experiment shows that no problem appears after a lot of working time.

A first design has been drawn on Catia V5. The chosen material is Aluminium with an elastic limit of 95 Mpa (cheap aluminium). The number of set screw is 3, and their location is on an extension of the disc which aims to guide it. A distributed force of 352 N and a moment of 1 Nm is applied when the tapping is fixed. The result of the FEM is presented in *Figure 10*.

The maximum stress that the disc will have to undergo will be 34 Mpa according to the simulation. A security coefficient of 2,8 is therefore adopted.

6. Remaining tasks

The next step is to build a prototype with the aim to validate all the theory and previous calculations. Then a dynamic study will be done to view the answer of the coupling device to sudden change of speed, torque, and vibrations. If all the tests are successfully passed, some other prototype smaller and lighter can be designed. A test with Co-Axial coupling is also possible to compare the two designs and be sure that we made the best choice previously. The only goal is to provide the best magnetic coupling design for our case of study at the end of the project.

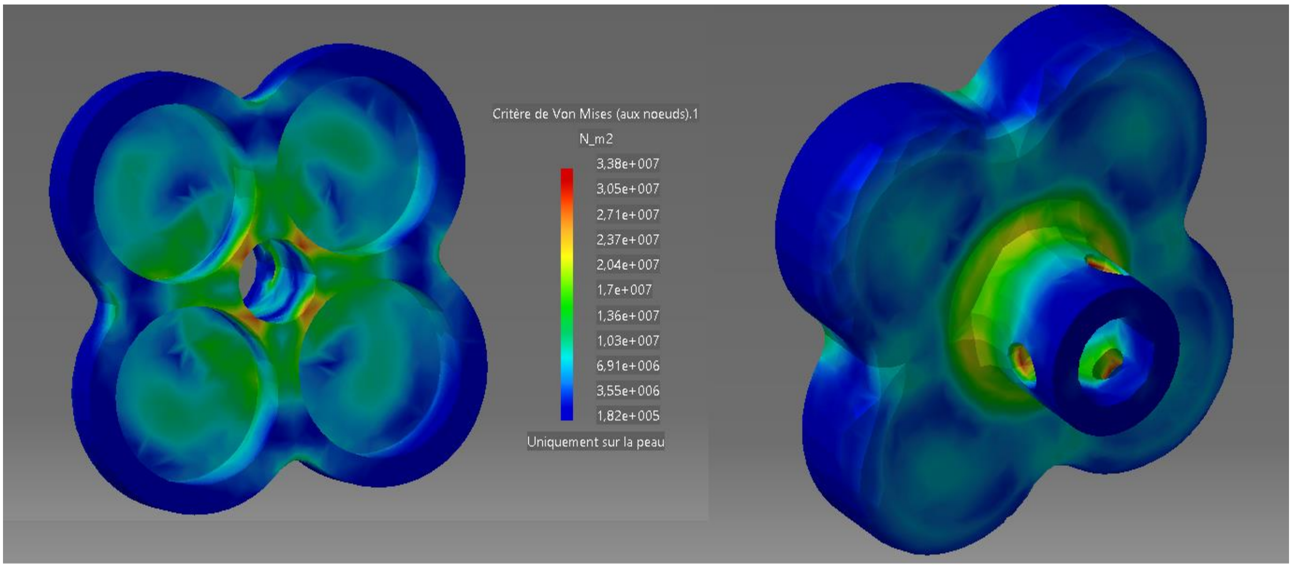

Figure 10. *FEM result of the first design*

7. Conclusion

By using magnetic calculation and FEM analysis, a lot of time and money can be saved. The work of people like Thierry Lubin, Smail Mezani or Abderrezak Rezzoug [1] are crucial for engineers to develop theories and calculation methods. The magnetic coupling is an uncommon device and only a few papers speak on it. However, it present lot of advantages to isolated two environments and not propagate the constraint of one to another to have a global design easier. This paper uses the magnetic coupling system for a very special case of study, but this device can be used in a lot of various cases.

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