

# Effects of manufacturing tolerances of permanent magnets in fractional slot permanent magnet synchronous machines

eISSN 2051-3305  
Received on 25th June 2018  
Accepted on 30th July 2018  
E-First on 14th May 2019  
doi: 10.1049/joe.2018.8199  
www.ietdl.org

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**Abstract:** The fractional slot permanent magnet synchronous machines are well-known for their low torque ripple. However, in mass-production machines, not all the permanent magnets are identical due to the manufacturing tolerances and new torque harmonics could appear. In addition, the magnetic field is modified and unbalanced magnetic pull (UMP) could happen. Apart from that it is important to study the effect on vibrations since the magnetic field is no longer ideal. So, here, a study of the effect of unevenly magnetised permanent magnet distribution on torque ripples, unbalance magnetic pull, and vibrations is proposed. Apart from that, the tolerance grade sensitivity is studied. Finally, experimental tests show good agreement with finite element analysis.

## 1 Introduction

Nowadays, the electric drive manufacturers tend to minimise the life cycle cost of their products. Furthermore, comfort and compactness are also becoming important requirements. Within this framework, direct-drive systems based on permanent magnet synchronous machines (PMSM) are presented as one of the best solution to fulfil all these requirements. Fractional slot concentrated winding (FSCW) PMSMs are well known for their low torque ripple. Hence, in applications where the comfort is an important key point, this type of machines may be very suitable. Nevertheless, when the machines are produced in mass, mass-production tolerances may lead to additional torque ripples or to amplification in already existing torque ripple components, [1–3].

Depending on the machine topology and the manufacturing tolerance grade, the experimental torque ripple may be very different from the ideal pattern without tolerances. Not only might torque ripple be different, but vibrations may be higher as well. In addition, assuming that the machine is no longer ideal, the machine could be magnetically unbalanced, creating by this way unbalanced magnetic pull (UMP). Depending on the frequency of the new harmonics created due to the manufacturing imperfections, the comfort grade may be reduced. Thus, in order to assure a good comfort performance, the effect of mass-production tolerances on the torque ripple, vibrations or UMP forces must be analysed in detail.

In [1, 2, 4–7], the effects of the manufacturing tolerance only on cogging torque are studied. On the other hand, in [8], the effect of unevenly magnetised magnets distribution on the cogging torque and on load torque ripple is analysed. In [9], the repercussion of manufacturing tolerances of modular machines on the cogging torque and the stator flux is studied. The effects of stator and rotor tolerances on the cogging torque, on load torque and the back electromotive force, are analysed in [3, 10]. In addition, in [11], an analytical model of the magnetic pressure, the UMP, and torque is presented taken into account the manufacturing tolerances.

However, a research, which takes into account, the cogging torque, the on load torque, the UMP, and the vibrations at the same

time, under different unevenly magnetised magnets distributions and grades of tolerance, is not already published. Among the manufacturing tolerances, this paper focuses only on magnets remanence tolerance. The torque ripple (cogging and electromagnetic torque), UMP, and vibrations will be analysed by FEM and experimentally under different magnet tolerances and distributions. The machine under study is an 18-slot/14-pole FSCW.

## 2 Analysis of tolerance effect by FEM simulation

Permanent magnets, PM, have the following tolerances, [5].

- Thickness tolerance.
- Width tolerance.
- Position tolerance.
- Tolerance of magnetic remanence.
- Magnetisation direction tolerance.

In this work, not all the tolerances are taken into account, only the tolerance of magnetic remanence. The reason is because according to [5], this tolerance is the one which has the highest impact on torque ripple. As it can be seen in several works, [1, 2, 4–7], PM's tolerances could create new additional harmonics multiples of the number of slots,  $Q$ , in the torque ripple and in the UMP, [11]. Apart from that, the modification of the air-gap magnetic field due to PM's tolerances could create new resonant frequencies in the stator and the vibration of the machine may be different from the ideal case [11].

In this section, the effects of PM's remanence tolerance on the torque ripple and UMP are studied by finite element method (FEM). Different distribution patterns and tolerances grades are considered. In all cases, the mean magnetic remanence of the rotor is the same. The machine design under study is an 18-slot/14-pole FSCW, whose characteristics are described in Table 1.

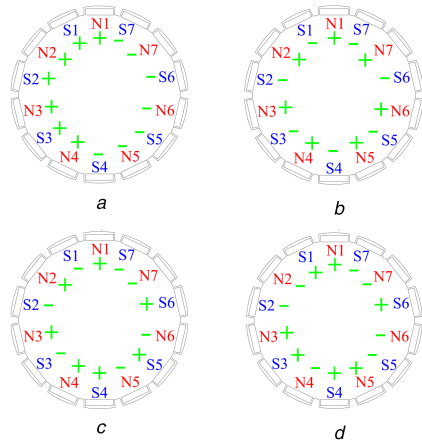
### 2.1 Distribution effect

The aim of this study is to analyse how the amplitudes of the new harmonics change depending on the magnet distribution pattern. One-half of magnets are defined with 5% more remanence and the other half with 5% less.

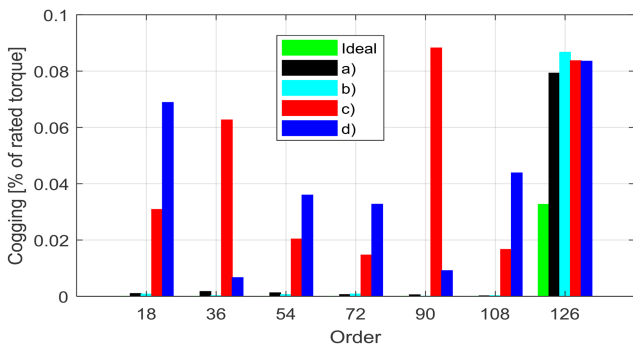
Four different distribution patterns are studied, Fig. 1:

**Table 1** Characteristics of the machine

number of slots [ $Q$ ]	18
number of poles [ $P$ ]	14
mean magnetic remanence [ $Br$ ]	1.1234 T



**Fig. 1** Distribution patterns  
 (a) All more magnetised magnets following each other, (b) All north magnets more magnetised, (c) Distribution in which the  $2Q$ th harmonic has its highest amplitude, (d) Distribution in which the  $Q$ th harmonic has its highest amplitude



**Fig. 2** Cogging torque with different distributions

- (a) All more magnetised magnets following each other.
- (b) All north magnets more magnetised.
- (c) Distribution in which the  $2Q$ th harmonic has the highest amplitude.
- (d) Distribution in which the  $Q$ th harmonic has the highest amplitude.

The worst distribution for each additional harmonic of cogging torque, in which the highest amplitude is obtained, can be calculated according to (1), [6]

$$K = \sum_{i=1}^p B_i e^{jn(\frac{2\pi Q}{p})(i-1)} \quad (1)$$

where  $B_i$  is the magnetic remanence of each PM,  $n$  is the order of the additional harmonic multiple of  $Q$ ,  $P$  is the number of poles and  $K$  is the unbalance grade for that harmonic.

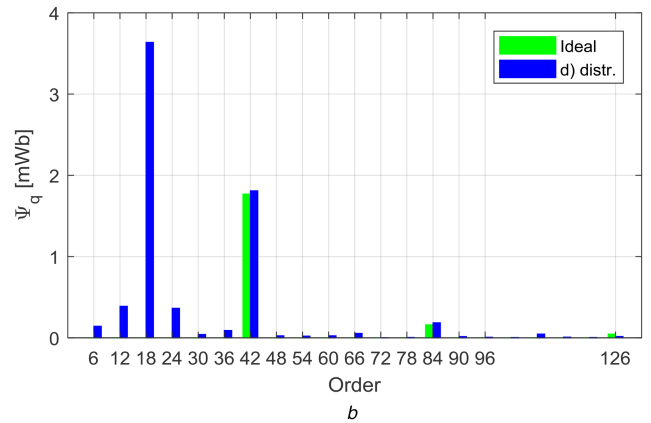
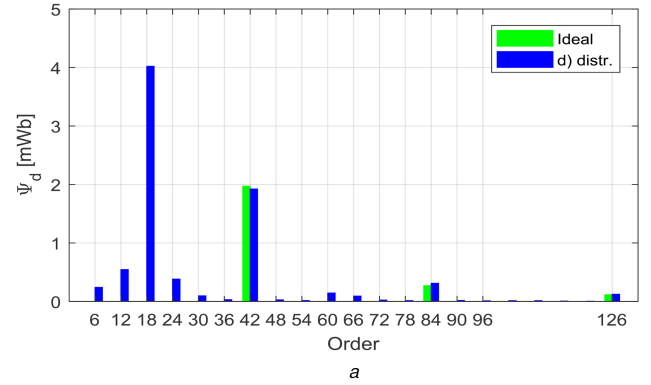
Hence, the worst distribution for each additional harmonic is achieved when  $K$  is maximum.

So, for the c) case, where the 2nd additional harmonic,  $2Q$ th mechanical harmonic, has its highest amplitude, the PMs distribution should be as it can be seen in Fig. 1c.

For the d) case, where the 1st additional harmonic,  $Q$ th mechanical harmonic, has its highest amplitude, the PMs distribution should be as it can be seen in Fig. 1d.

**2.1.1 Cogging torque:** In Fig. 2, it can be seen that the highest amplitude of the 1st additional harmonic,  $Q$ th, is achieved in d) distribution. While 2nd additional harmonic,  $2Q$ th, is achieved in c) distribution.

Apart from that, another conclusion is that in a) and b) distribution, the amplitudes of the additional harmonics are practically negligible, even with unevenly magnetised PMs. This is



**Fig. 3** Magnetic fluxes  
 (a)  $\psi_d$ , (b)  $\psi_q$

because according to (1), the unbalance grade of each harmonic is not very high.

**2.1.2 On load torque ripple:** The on load torque is the sum of the cogging and the electromagnetic torque, [12]. As it has been seen in the cogging torque, new additional harmonics could appear due to unevenly magnetised PMs. Hence, in the on load torque, the same will happen.

The order of the additional harmonics will be different from the ones created in the cogging torque. The reason resides in the additional harmonics of the magnetic flux due to unevenly magnetised PMs. The electromagnetic torque,  $T_{em}$ , in rotational reference frame,  $dq$ , is calculated by (2), [12].

$$T_{em} = \frac{3}{2} \frac{(d\psi_d/dt)i_d + (d\psi_q/dt)i_q}{\omega_m} + \frac{3}{2} p(\psi_d i_q - \psi_q i_d) \quad (2)$$

where  $\psi_d$  and  $\psi_q$  are the magnetic fluxes in direct and quadrature axis, respectively,  $\omega_m$  is the mechanical speed,  $p$  is the number of pole pairs and  $i_d$  and  $i_q$  are the currents in direct and quadrature axis, respectively.

In Fig. 3, it can be seen that when all PMs are not identical, new additional harmonics multiples of 6 appear in the magnetic fluxes. Therefore, in the electromagnetic torque these orders will appear, too.

In Figs. 4–6, the FEM results of the on load torque are exposed. As it can be seen, the additional harmonics that appear in the on load torque are the same that appear in the fluxes. In addition, it is shown that only the harmonics multiples of 6 appear when the machine is on load. On the other hand, in Fig. 6, it is shown how the additional torque harmonics increase their amplitude with the load. The ones that suffer with the load a greater amplitude modification are the ones that have a bigger magnetic flux amplitude.

**2.1.3 UMP:** The UMP exerted on the machine can be calculated by the integration of the magnetic pressures over the surface of the rotor, [13]. If the machine is ideal, it is balanced and the integration

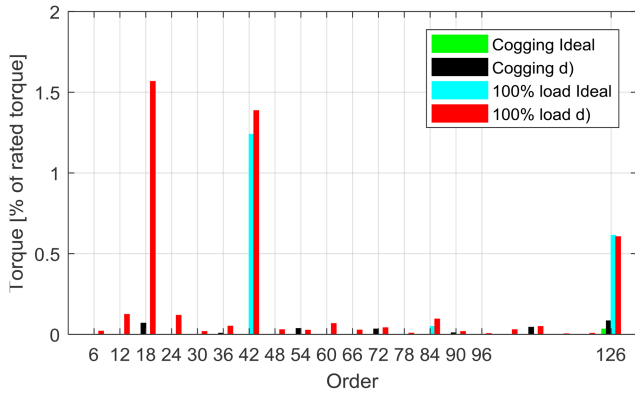


Fig. 4 Cogging and on load torque with ideal and d) distribution

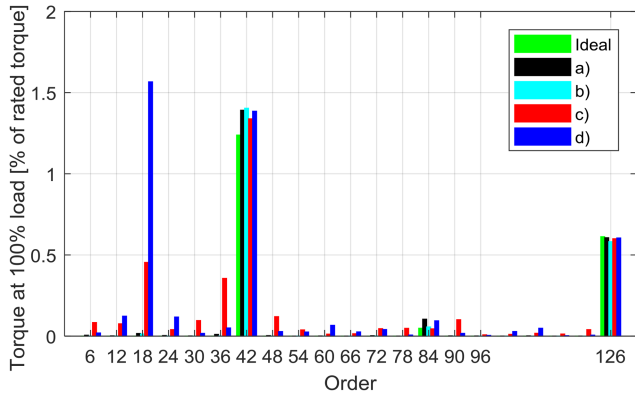


Fig. 5 Nominal torque with ideal, a), b), c) and d) distributions

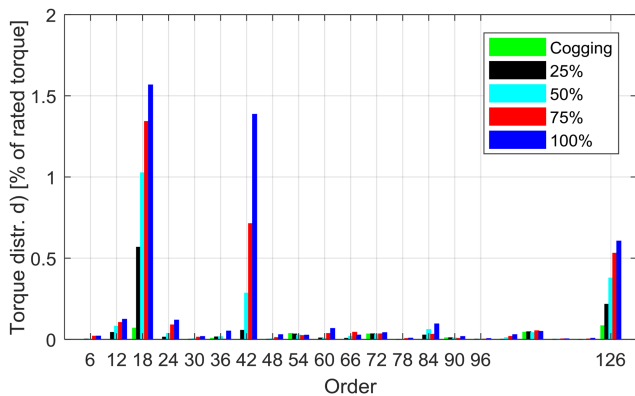


Fig. 6 Torque at different load with d) distribution

of all pressures around the rotor contour is zero. However, when the magnets are unevenly magnetised, the machine could be no longer magnetically balanced and the integration of all pressures may not be zero. So, UMP would appear, supposing a decrease in the life cycle of the machine and a source of vibrations, [14].

In a), c), and d) distributions, the air-gap magnetic field is unbalanced due to the tolerances of the PMs. However, in b) distribution, the air-gap magnetic field is balanced, even with unevenly magnetised PMs. In order to know if the magnetic field is balanced (3) is used.

$$D = \sum_{i=1}^p B_i e^{j(2\pi/p)(i-1)} \quad (3)$$

If  $D$  is not zero, the air-gap magnetic flux is unbalanced and UMP will exist. Apart from that, the phase of  $K$  shows the direction of the UMP. While the rotor moves, the mean value of the UMP will be also rotating.

In Fig. 7, it is shown the UMP of the different distributions and their direction. As it can be seen, the amplitude and phase of UMP is in function of  $D$  value. The higher value of  $D$ , the higher UMP.

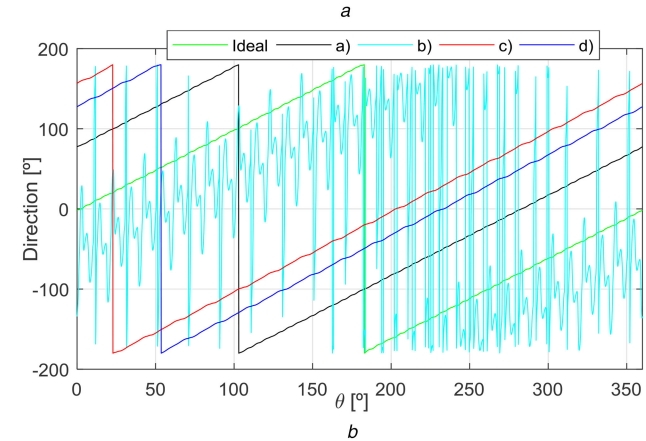
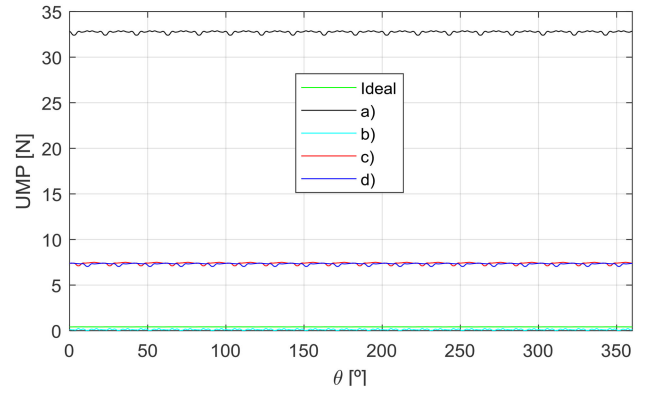


Fig. 7 UMP  
(a) Magnitude, (b) Direction

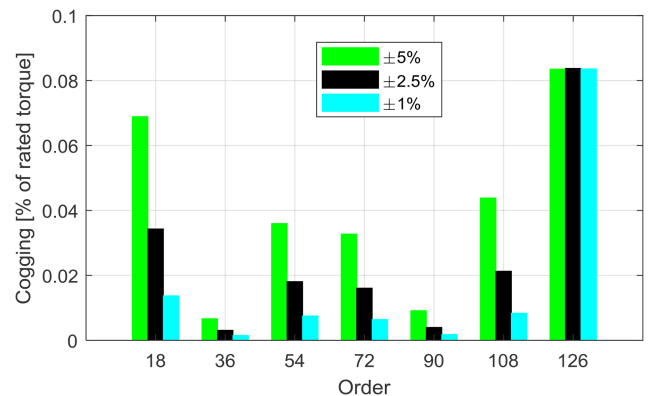


Fig. 8 Cogging torque with d) distribution and different grades of tolerances

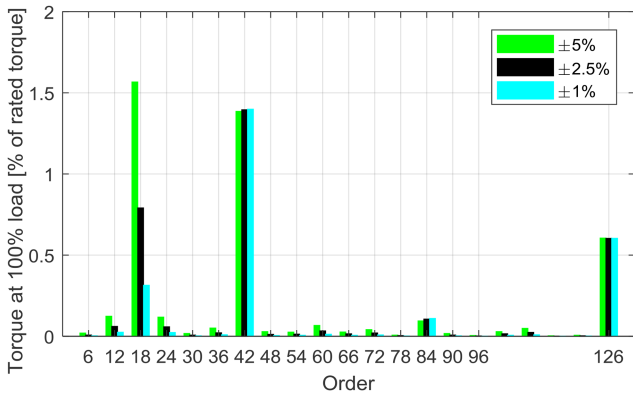
## 2.2 Tolerance grade effect

The aim of this study is to analyse the effect of the tolerance grade on the amplitude of the additional harmonics. The research is performed with d) distribution, the one in which the 1st additional harmonic,  $Q$ th, has its highest amplitude.

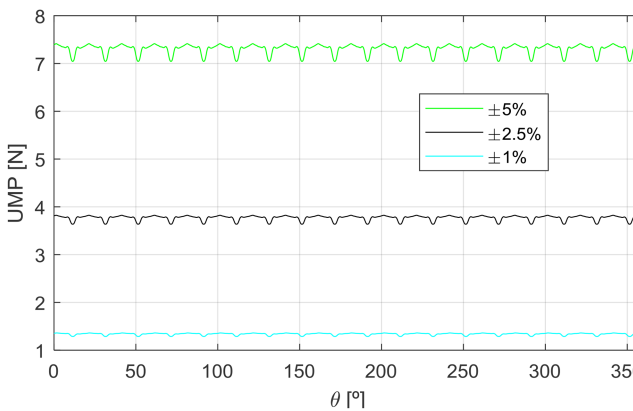
The difference in relation to last section is that in this case, the tolerance is variable and in the previous section, it was  $\pm 5\%$ . The tolerance grades analysed are  $\pm 5$ ,  $\pm 2.5$  and  $\pm 1\%$ .

**2.2.1 Cogging torque:** In Fig. 8, it can be seen that in all tolerance grades, the same additional harmonics appear. Regarding to the amplitude, all the additional harmonics show a linear tendency with the tolerance grade. Therefore, the effects of the tolerance increase linearly with the grade.

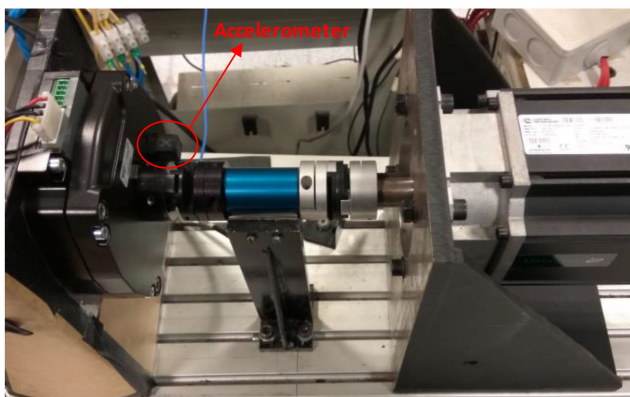
**2.2.2 On load torque ripple:** The same phenomenon as in the cogging torque happens in the on load torque ripple, as it is observed in Fig. 9. The tolerance grade amplifies the effects linearly.



**Fig. 9** Nominal torque with *d*) distribution and different grades of tolerances



**Fig. 10** UMP with *d*) distribution and different grades of tolerances



**Fig. 11** Test bench

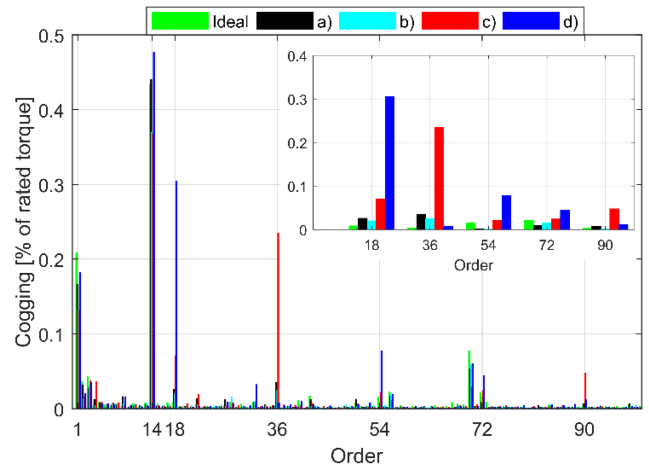
**2.2.3 UMP:** The UMP, as well as torque ripple, suffers the same phenomenon. The tolerance grade amplifies the UMP linearly, as it can be seen in Fig. 10.

### 3 Experimental results

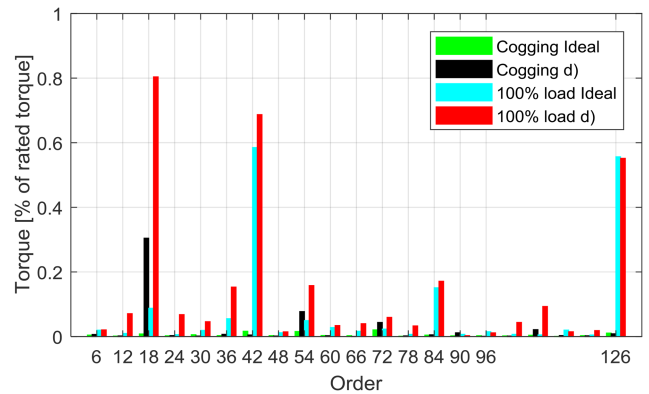
A single prototype has been built in order to experimentally validate the simulation results. In Fig. 11, it can be seen the test bench for the experiments. The prototype is connected back to back with a load machine and between them, a torque sensor is coupled.

For measuring the torque ripples, specifically the cogging, the load machine is controlled in speed mode and the prototype is in open circuit. For measuring the on-load torque ripple, instead, the prototype is controlled in current mode. A low speed is set, 7 rpm, in order to minimise the effect of the inertia. In this way, the real amplitudes of the torque ripples are not modified by the low-pass filter effect of the inertia.

On the other hand, for measuring the vibrations, a tri-axial accelerometer is placed in the prototype housing. Concerning to the control, both machines are controlled in the same way as when



**Fig. 12** Experimental cogging torque with different distributions



**Fig. 13** Experimental cogging and on load torque with ideal and *d*) distribution

measuring torque ripples. Therefore, at the same time, torque ripples and vibrations are captured.

In order to avoid the effects of manufacturing tolerances of the stator and rotor sheet as well as any kind of assembly tolerances, the same machine is used for each test. In this way, all tests have the same rotor and stator geometry and the same mechanical parts. Only the remanence value of the PMs and their location are changed for doing the tests.

For testing the distribution effects, first, a test is done with all PMs with the same remanence value. Then, seven PMs are 5% more magnetised and the rest, 5% less and the same distributions analysed by FEM are tested experimentally.

In Fig. 12, the cogging torque with different distributions is shown. As it can be seen, the same harmonics as in FEM analysis, Fig. 2, appear, except 14th harmonic. This could be due to the stator sheet tolerances, [3]. Apart from that, as in FEM, in *d*) distribution the amplitude of 18th harmonic is maximum and in *c*) one, the 36th. As well, *a*) and *b*) distributions show the same tendency as in FEM.

Regarding to the on-load torque ripple, in Figs. 13–15, it can be seen the same tendency as in simulation, Figs. 4–6, respectively. The amplitudes of the additional harmonics increase with the load. With respect to the vibrations, Fig. 16 shows that there is not a major change when not all PMs are identical.

Finally, the tolerance grade as in simulation, Fig. 8, modifies linearly the effect on the torque ripple as it can be seen in Fig. 17.

### 4 Conclusions

Here, a study of the effects of different tolerance grades and PM distributions on torque ripple, UMP, and vibrations is done. It has been seen that some distributions do not originate any additional harmonics in the torque ripple, neither UMP, even with unevenly magnetised PMs. Furthermore, it has been identified what distribution is the most sensible for each additional torque



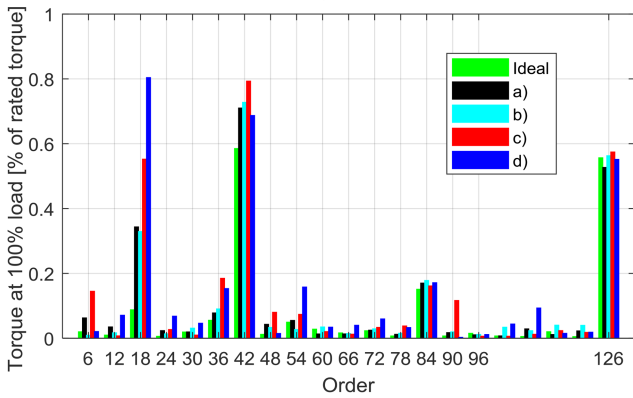


Fig. 14 Nominal torque with ideal, a), b), c) and d) distributions

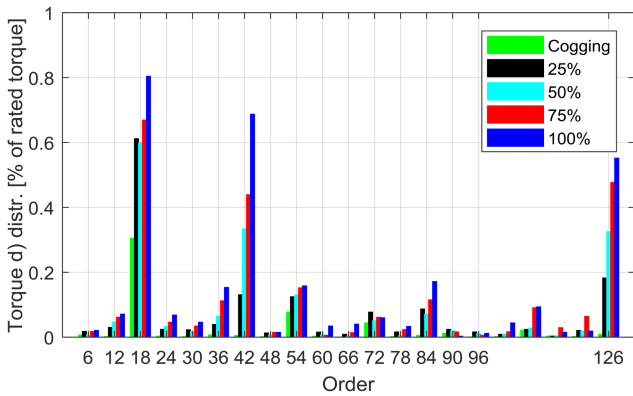


Fig. 15 Experimental torque at different load under d) distribution

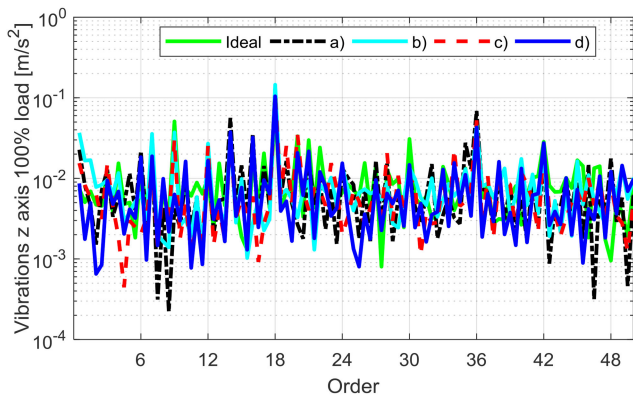


Fig. 16 Vibrations with  $\pm 5\%$  tolerance and different distributions

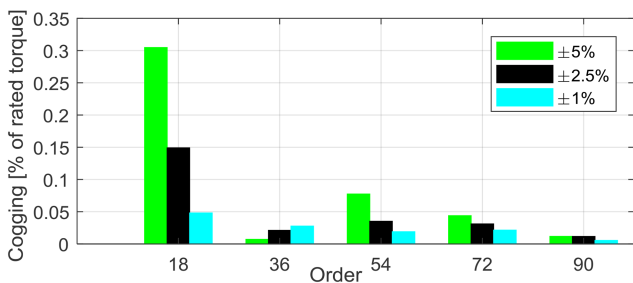


Fig. 17 Experimental cogging torque with different tolerance grades

harmonic. Apart from that the relation between the tolerance grade and the amplitude of the additional harmonics is linear.

With respect to the vibrations, it has been seen that there is not a high modification respect to the ideal case at least with  $\pm 5\%$  of tolerance.

Finally, experimental results have shown good agreement with the simulation results.

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