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Research Article

Dummy Slots Effect on the Torque Ripple and Electromagnetic Forces for Small Permanent Magnet Brushed DC Motors

Mohamed Ali Ben Hamed, Thierry Tollance, Michel Hecquet*, Frederic Gillon and Abdelmounaim Tounzi

Laboratory of Electrical Engineering and Power Electronics Lille (L2EP), Ecole Centrale de Lille, 59651 Villeneuve-d'Ascq, France

Abstract

Permanent magnet brushed DC motors are used in several applications such as home automation or automotive industry. This is mainly due to their lightweight, low cost and compact structure. Thus, the importance to study the sources of noise and vibration in these motors, which is often complicated and can be attributed to many factors. In this paper, the cogging torque and electromagnetic forces are studied in the case of a small permanent magnet brushed DC motor with 2 poles and 3 slots. Addition of dummy slots on the rotor side is described with its effect on the evolution of both aspects. The aim of this study is to give the quantitative effect about torque ripple and radial forces for each harmonic in relation with these dummy slots.

Keywords: Permanent Magnet Brushed DC Motor; Electromagnetic forces; Dummy slots; Cogging torque

Introduction

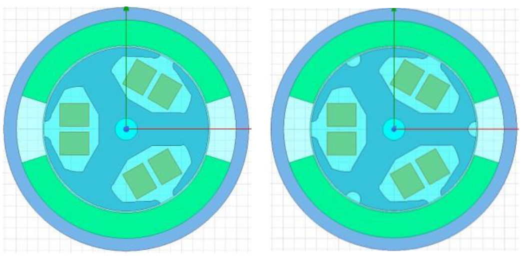
Low noise and vibration in electrical machines became an essential requirement in many applications. The vibro- acoustic aspect is no longer neglected during the design stage of motors to ensure more comfort and less annoyance to the user. However, it should be noted that only few articles and studies dealt with vibro-acoustic of PM-DC (permanent magnets direct current) brushed motors [1,2].

Cogging torque represents one of the main drawbacks of PM motors [3,4] as it causes high torque ripple and undesirable vibrations and prevents smooth rotation [5]. This is especially more annoying at low speeds [6]. Therefore, in order to reduce electromagnetic noise, some papers give the advantages and disadvantages of the dummy slots [6,7] but no quantitative study is given.

The LCM (Least Common Multiplier) between the number of poles 2p and the number of slots Zs and the GCD (Greatest Common Divider) between (2p, Zs) are well-known and used to evaluate the motor performance in terms of torque ripple (LCM) and lowest order of the radial force (GCD) and vibration and noise of the machine [8,9].

The study [10] on the noise of a PM-DC motor with 2 poles and 3 slots during running-up shows that the unbalanced radial magnetic field in the air gap (due to the odd number of slots) is one of the main contributors to the noise. Thus, one way to balance the radial magnetic field and reduce the related noise is to use dummy slots on the rotor (Figure 1).

In this paper, using 2D finite element method (FEM), models with and without dummy slots is built. F.E. analysis is used to compare both topologies in terms of torque and radial pressure harmonics that are linked to the vibration and noise. Study of the dummy slot effect is carried out on the cogging torque, torque ripple but also on the radial pressure level. In addition, few measurements are made on 2 poles and 3 slots motor. The aim of this study is to give a quantitative study about torque ripple and radial forces for each harmonic.



a b

Figure 1: (a) Standard motor, (b) Motor with 3 dummy slots.

Studied Machines

The considered application concerns a low power DC motor, a PM-DC motor with 2 poles and 3 slots (Figure 1(a)) whose main specifications are given in the Table 1.

The proposed topology by adding dummy slots is shown in (Figure 1(b)). As it can be seen, the 3 added dummy slots are symmetrically distributed and have the same slot opening width as the initial ones. Thus, this new topology of PM-DC motor can be considered as 2 poles and 6 slots.

Cogging Torque and Steady State Torque

The effect of the dummy slots is studied on the cogging torque and radial pressure level. As shown in (Figure 2) the magnitude of the cogging torque has significantly increased in the case of the second

Rated speed/fs	5000 rpm/84 Hz
Rated voltage	12 V
Rated power/torque	12 W/20 mNm
Outer diameter	<25 mm

Table 1: Main specifications.

***Corresponding author:** Michel Hecquet, Laboratory of Electrical Engineering and Power Electronics Lille (L2EP), Ecole Centrale de Lille, 59651 Villeneuve-d'Ascq, France, Tel: +33320335432; E-mail: michel.hecquet@centralelille.fr

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structure which is also visible in the waveform of the electromagnetic torque at steady state (Figure 3).

The cogging torque magnitude is directly linked to the LCM of the pole (2p) and slot number (Zs). Classically, in

case of PM machines [8,9] to reduce the cogging torque, it is required to maximize the LCM (2p, Zs) but this is not related to the GCD (2p, Zs) value Table 2.

By adding the 3 dummy slots, the LCM is maintained the same as LCM (2,3) is equal to LCM (2,6) equal to 6. However, the torque ripple increases. Thus, the increase of the cogging torque by adding the dummy slots can be explained by the increase of GCD (2p, Zs):

- First machine: GCD (2, 3)=1 with LCM (2, 3)=6;
- Second machine: GCD (2, 6)= 2 with LCM (2, 6)=6.

A Fast Fourier Transform on one period of the torque at steady state is performed for both topologies yielding to the results shown in (Figure 4). All the harmonic orders are multiples of 6.fs with a

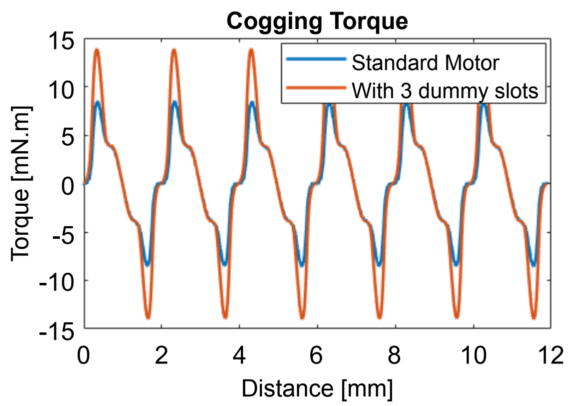

Figure 2: Cogging torque.

Motors		Standard	With dummy slots
Cogging torque magnitude (mN.m)		8,5	13,8
Mean torque at steady state (mN.m)		19,17	19,22
Torque harmonics at steady state	1st harmonic (% of the mean torque)	6.fs (24.6 %)	6.fs (34.9%)
	2nd harmonic (% of the mean torque)	12.fs (10.3%)	12.fs (12,5 %)

Table 2: Standard motor and motor with 3 dummy slots comparison.

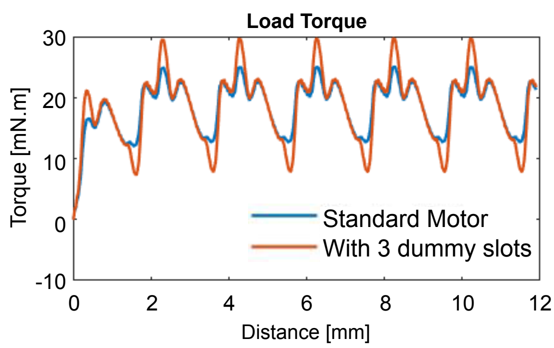

Figure 3: Torque ripple at load.

significant increase of their magnitude when adding the dummy slots (48.8% more for the harmonic at 504 Hz).

From these results, the effect of the dummy slots is not beneficial as they increase the magnitude of the cogging torque and the torque ripple.

Radial Magnetic Field and Pressure

From the global air-gap radial flux density versus time and space, the air-gap radial Maxwell pressures can be calculated using the following relation (1):

$$\sigma_{rad}(t,\theta) = \frac{B_r^2(t,\theta) - B_t^2(t,\theta)}{2\mu_0}\ [N.m^{-2}] \quad (1)$$

Then, the spatial and frequency orders can be defined with the help of 2D Fast Fourier Transform (FFT):

$$\sigma_{rad}(t,\theta) = \sum_{f,r} P_{fr} e^{j(2\pi f t - r\theta + \varphi_{fr})} \quad (2)$$

Where (r,f) represent the number of waves (r: spatial order) and the frequency (f), P_{fr} the harmonic amplitude and φ_{fr} the shift phase [9,11,12].

From F.E simulations, only the radial component (Br) of the air-gap flux density is considered to calculate the Maxwell pressure as the tangential component (B_t) has a less significant magnitude. The radial flux densities Br(t,θ) for motor operating at load are calculated and presented.

The radial magnetic field in the air gap is asymmetrical between the positive and negative alternations, which results in unbalanced radial magnetic pulls on the rotor [6] as shown in Figure 5 (standard motor).

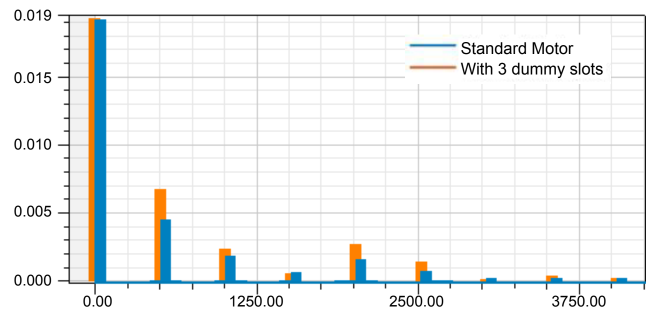

Figure 4: Torque FFT at load.

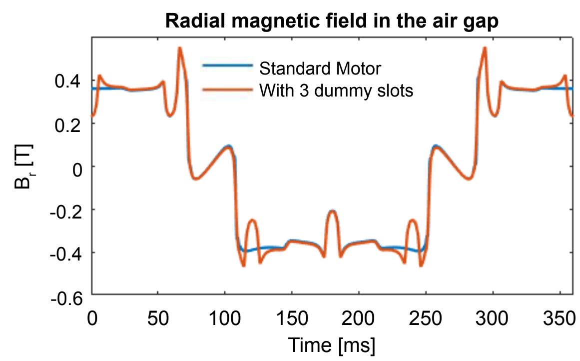

Figure 5: Radial magnetic field Br (T) in the air gap for the standard motor and motor with 3 dummy slots.

One way to balance the radial magnetic field and therefore the radial pressure is to add 3 dummy slots on the rotor located between each two slots. Thus, there will be 6 distributed peaks (or disturbances) equally spread out between the positive and negative field sides which will ensure the balance of the field as shown in (Figure 5). With 3 dummy slots.

Figure 6 shows an FFT-2D (formula 2) of the radial pressure in log scale for the standard motor. It shows many harmonics with different orders corresponding to the frequencies multiples of 3.fs, which is expected as the frequency orders of the important harmonics of the radial pressure are multiple of the number of slots [1,11,12]. An orange dashed line marks (Figure 6) the most intense harmonics.

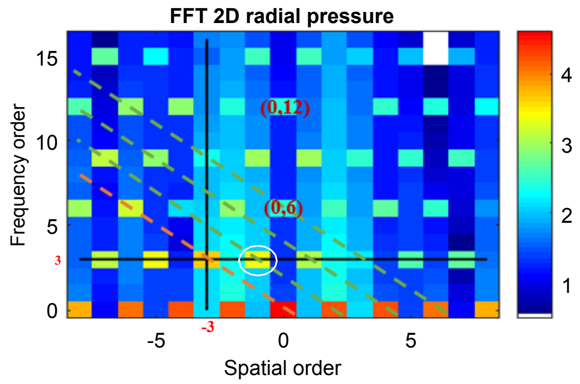

Figure 6: Standard motor radial pressure FFT2D in log scale.

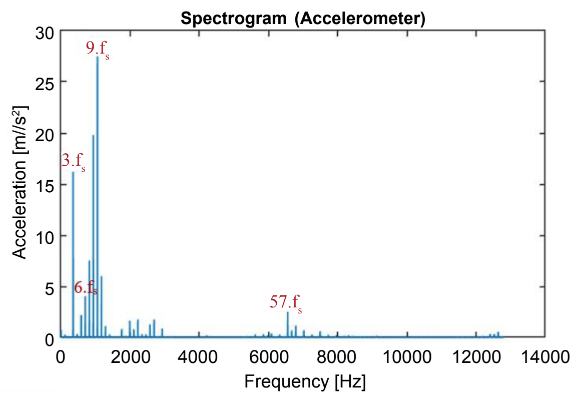

Figure 7: Standard motor no-load spectrogram of vibration.

The spatial (r) and frequency (f) orders of each harmonic are:

- r=+/-k (the sign is related to the direction of the force wave)
- f=3.k.fs

With k ∈ N. The main harmonic of radial force corresponds to r=-3 at 3.fs (black lines intersection).

The smallest spatial order is equal to GCD (2, 3)=1.

The first order can be clearly seen (white circle).

Figure 7 shows the vibration measurements that were realized on the standard motor at no load. The important harmonics for theses frequencies are multiples of 3.fs.

Different papers give the advantages of dummy slots. One way to balance the radial magnetic field and therefore the radial pressure is to add 3 dummy slots on the rotor situated between the slots opening. By adding the dummy slots, there is no global tendency in the evolution of the radial pressure harmonics. As some decrease, others increase significantly Table 3.

In the case of the studied machine, the harmonic related to the cogging torque (0, 6.fs) increases by 42% as expected.

However, the main interest of using dummy slots is to balance the radial magnetic field responsible for the odd spatial order harmonics. As such, there is a magnitude reduction for the odd spatial order harmonics especially for those of orders 1 and 3 (-20.5%).

To conclude, the spatial and frequency orders of each harmonic of radial force are the same and for this case, some harmonics with high spatial order and zero-order are increased. These high spatial orders have no influence on the noise as the latter is proportional to 1/(spatial order) 4 but this is not the case of the zero-order. A modal analysis is then very important to know the natural frequency for each mode.

A modal analysis model was used to determine the natural frequencies of the motor for the different circumferential modes Table 4. It showed that the first circumferential mode has a small resonance frequency (2.fs) which can cause an important noise as the radial pressure FFT2D shows an important close harmonic for the spatial order 1 and frequency order 3.fs. Due to that, the dummy slots are very interesting as they reduce the magnitude of the first mode harmonics which will lead to mitigate the noise.

Conclusion

The effect of adding dummy slots on the rotor side were studied for a motor with 2 poles and 3 slots on the torque ripple and on radial forces linked to the vibro-acoustic level. As it was described, for the radial

Radial force N/m² (standard motor)	Radial force N/m² (with dummy slots)	Frequency order	Spatial order	Evolution rate (%)
2400	2288.93	3	-1	-4,63
4732.39	3758.55	3	-3	-20,58
2069.39	1742.85	3	-5	-15,78
255.74	363.14	6	0	+42
849.73	516.76	6	-2	-39,19
1486.16	3573.56	6	-6	+140,46
988.84	1392.08	6	-8	+40,78
2666.78	2417.5	9	-9	-9.35
4638	7983.95	12	-12	+72.14

Red: main harmonic of radial force (-3.k, 3.k.fs)/Green: related to the torque ripple/Black: other important harmonic

Table 3: Standard motor and motor with 3 dummy slot radial pressure's comparison.

Mode	Resonance Frequency (Hz)
0	57024,3 (679.fs)
1	173,1 (2.fs)
2	4826,26 (58.fs)
3	13650,7 (163.fs)
4	26174,1 (312.fs)
5	42329,1 (504.fs)

Table 4: Natural frequencies of the motor.

pressure harmonics responsible of noise, the dummy slots reduced some annoying odd spatial orders harmonics magnitudes, especially the first spatial order harmonics, which are close to the corresponding circumferential modes' natural frequency of the motor structure.

However, the spatial and frequency orders of each harmonic of radial force are the same and for this case, some harmonics with high spatial order and zero-order are increased. These high spatial orders are not influential for the noise but it's not the case of the zero-order.

In addition, for the cogging torque, adding dummy slots increased its magnitude remarkably, which increased the torque ripple too. That will lead to more vibrations or noise and will depend on the mechanical load.

Finally, the impact of the dummy slots can be beneficial but it depends on the machine configuration and a quantitative study is needed to understand the interest of these dummy slots.

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