Effect of tooth tips on the electromagnetic performance of PM fractional-slot modular machines using grain-oriented electrical steel

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Abstract: The effect of tooth tips on the performance variations due to using grain-oriented electrical steel (GOES) stator laminations in permanent magnet fractional-slot modular machines is studied in this work. It is concluded that the electromagnetic performance is further improved using GOES in machines with tooth tips compared to machines without tooth tips. This is due to a higher increment on the flux density in the airgap. The acoustic behaviour variations due to using GOES are predicted by analysing several mechanical- and acoustic-related parameters. It is predicted that implementing GOES improves the acoustic behaviour in machines without tooth tips. Furthermore, the effects of GOES in machines with tooth tips are slightly improved compared to machines without tooth tips. However, in order to determine the real mechanical and acoustic behaviours, further analysis is needed.

1 Introduction

Noise emitted in permanent magnet (PM) machines is a major concern for electrical machine designers [1]. Several techniques have been proposed to reduce radial forces in the airgap, torque ripple and cogging torque which are some of the major contributors to vibrations and thus noise. A common solution is to modify the machine design where solutions like skewing [2–4], selecting a suitable pole and slot number combination [4–9], selecting an adequate winding type [2, 10], magnet shaping [3], magnet positioning [2, 9, 11–13], adding dummy slots and teeth [2, 9, 11, 14] or reducing the slot opening [9, 15, 16], have been proven to be the most effective techniques for this purpose. These modifications on the design can also be applied combined to produce larger improvements on the acoustic performance.

The slot opening is reduced by adding tooth tips to the stator design which reduces the permeance variations along the airgap decreasing the influence of the slots [16, 17]. This solution has been proven to have several advantages and a few drawbacks. From a mechanical point of view, tooth tips help to hold better the windings in the slots [17]. Moreover, the presence of tooth tips also has electromagnetic advantages like reducing cogging torque, reducing the no-load back-EMF harmonics as well as the on-load torque ripples and increasing the output average torque [16, 18, 19]. It has been also found out in [16] that smaller slot openings reduce the slot harmonics and therefore the eddy currents in the magnets.

One of the main drawbacks of installing tooth tips in the stator is the increase of iron losses which lead to a decrease on the efficiency [16, 17, 20]. This is due to tooth tips absorb the high frequency harmonics of the flux density in the airgap leaving the fundamental component to flow through the tooth yoke. This leads to an increment on the iron losses in the tooth tip as they are proportional to the frequency. In [16, 17], it is highlighted that the presence of tooth tips on the machine stator also increases the slot leakage flux and therefore the slot leakage inductance. Moreover, very small slot openings can lead to a decrease on the no-load back-EMF and on the output average torque. This also has the inconvenience of leaving less space for cooling the windings [19].

The use of GOES laminations in the stator of PM fractional-slot modular machines has been studied in [1] where an accurate yet simple model to simulate the behaviour of anisotropic materials in this type of machines is proposed. The technique is based on the flux line distribution in a module and consists of breaking each module down into smaller isotropic segments each one working with a different BH curve. A comparative analysis between using non-GOES and GOES stator laminations is also carried out. It is proven that the use of GOES increases the flux density in the airgap compared to non-GOES laminations. Consequently, flux linkage, back-EMF and average torque also increase leading to conclude the use of GOES laminations is beneficial for the electromagnetic performance of PM modular machines.

In this paper, the effect of tooth tips on the electromagnetic variations due to the use of GOES is studied. In addition, the acoustic performance is predicted by analysing several mechanical- and acoustic-related parameters in both machines with and without tooth tips.

2 Models to be compared

The effect of using tooth tips on the electromagnetic performance variations due to using GOES in PM fractional-slot modular machine is carried out by analysing a 12-slot/10-pole (12s/10p) machine. Its cross section is shown in Fig. 1 and its design parameters in Table 1.

Before carrying out the analysis, the tooth tip dimensions are obtained by getting the optimised values at the condition of maximum average torque at the rated conditions presented in Table 1. As can be seen in Fig. 2, a stator tooth tip can be characterised by two parameters, the span angle ($\alpha_{agT}$) and its thickness ($e$).

Four models of the 12s/10p machine obtained from combining the cases of with/without tooth tips and with/without GOES in the stator are compared. They all can be seen in Fig. 3. Models A and C have isotropic or non-GOES steel installed in the stator whereas models B and D have GOES. Moreover, models A and B do not have tooth tips installed whereas models C and D do. The effect of using GOES in machines without tooth tips is analysed by comparing models A and B whereas the effect of using GOES in machines with tooth tips is carried out by comparing models C and D. The FE model used in models B and D to simulate the behaviour of anisotropic materials is the one proposed in [1], which is based on the flux line distribution in a module. Each module is divided into smaller segments where each one work with a different BH curve according to the direction of the flux lines relative to the rolling direction. Moreover, as it is highlighted in [1], the back-iron length when using GOES needs to be larger than...
when using non-GOES to avoid saturation. The selected back-iron thicknesses for both isotropic (ISO) and anisotropic (AN) models are presented in Table 1.

The performance characteristics to be analysed have been split into two categories. The first group are electromagnetic-related characteristics including flux density in the airgap, flux linkage, back-EMF and average torque. On the other hand, radial forces in the airgap, back-EMF harmonics and torque ripple have been classified as acoustic-related parameters. Both electromagnetic and acoustic analyses are carried out in the following sections.

## 3 Electromagnetic performance

### 3.1 Flux density in the airgap

The radial ($B_{\text{rad}}$) and tangential ($B_{\text{tan}}$) harmonic components of the flux density in the airgap are analysed in the four models and shown in Fig. 4. It is concluded that the presence of GOES in both machines with and without tooth tips increase the fundamental value of the radial component and does not affect the tangential component. This is beneficial from an electromagnetic point of view. The presence of tooth tips is also beneficial from an electromagnetic point of view as it increases the radial component and decreases the tangential component.

![Fig. 4](image)

**Fig. 4** Harmonic spectra of the flux density in the airgap for the four models studied

(a) Radial components, (b) Tangential components

By using the fundamental values of $B_{\text{rad}}$ and $B_{\text{tan}}$, the flux density magnitude ($B_{\text{mag}}$) and its direction relatively to the tangential axis ($\theta$) are calculated following (1) and (2), respectively.

The results in Fig. 5 show how the flux density in the airgap changes when adding tooth tips to the stator (C–A), when using GOES in machines with tooth tips (D–C), and when adding both tooth tips and GOES to the stator (D–A). These differences are obtained following (3). It is shown that both adding tooth tips and using GOES to the stator affect in a similar way the flux density in the airgap. Both design modifications increase the flux density magnitude and orient it towards the radial direction. However, the variations on the radial component, the flux density magnitude and the orientation towards the radial direction are larger when adding tooth tips than using GOES. Furthermore, adding tooth tips also decreases the tangential component of the flux whereas the presence of GOES keeps it constant. When both design modifications are applied together, the flux density is further increased and oriented towards the radial direction. Consequently, further improvements in the electromagnetic performance can be achieved.

![Fig. 5](image)

**Fig. 5** Differences on the flux density in the airgap when adding tooth tips to the stator (C–A), when using GOES in machines with tooth tips (D–C), and when adding both tooth tips and GOES to the stator (D–A)

### Table 1 Design parameters of 12s/10p machine

| Parameter                        | Value         |
|----------------------------------|---------------|
| Number of slots [Ns]             | 12            |
| Tooth tip angle                  | 9°            |
| Number of poles [2p]             | 10            |
| Flux gap width                   | 0 mm          |
| Number of phases                 | 3             |
| Airgap length                    | 1 mm          |
| Rated current                    | 30 arms       |
| Magnet thickness                 | 3 mm          |
| Speed                            | 400 rpm       |
| Resistance torque                | small         |
| Stator outer diameter            | 100 mm        |
| Winding type                     | concentrated  |
| Tooth width                      | 7.1 mm        |
| Number of layers                 | single-layer  |
| Back-iron width (ISO)            | 3.7 mm        |
| Turns per phase                  | 132           |
| Back-iron width (AN)             | 4.3 mm        |
| Q                                | 0.29          |
| Segment angle                    | 60°           |
| GCD                              | 2             |
| Tooth tip thickness              | 1 mm          |
| LCM                              | 60            |

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and without tooth tips. This shows the electromagnetic performance could be further improved by using GOES in the stator of machines equipped with tooth tips.

3.2 Flux linkage, back-EMF and average torque

The flux linkage, back-EMF and average torque for the four-studied models are presented in Fig. 7. As can be seen increasing the flux density in the airgap due to changing the stator laminations from non-GOES to GOES also has an effect on the flux linkage, back-EMF and torque fundamental components. The three of them increase due to the increment of flux in the airgap.

The effect of tooth tips in the stator design has a similar effect to installing GOES laminations. It increases the flux linkage, back-EMF and torque fundamental components. Fig. 8 shows the variations of these three parameters, given by (3), when adding tooth tips to the stator design (C–A), when replacing the stator laminations from non-GOES to GOES (D–C) and when implementing both design modifications (D–A). The same conclusion made on the flux density in the airgap study can be applied here. The effects of installing tooth tips are larger than using GOES. Consequently, both changes in the machine design are suitable and constitute a good combination to improve the electromagnetic performance of the machine.

Fig. 9 compares the effects of using GOES on a 12s/10p machine with and without tooth tips. As it happened in the flux density in the airgap, the electromagnetic benefits are larger if these materials are installed in machines with tooth tips.

From this electromagnetic analysis, several conclusions can be made. It has been proven that GOES and tooth tips behave in a similar way in terms of improving the electromagnetic performance of the machine. They both get the flux density in the airgap oriented radially with the only difference that the tangential component is kept equal when using anisotropic materials and decreases with the presence of tooth tips. Although they both improve the electromagnetic performance, electromagnetic improvements due to the presence of tooth tips are larger than the ones obtained by using GOES. This difference in the relative increments is due to the tangential component behaviour of the flux in the airgap. Nevertheless, it is concluded that adding both tooth tips and GOES to the stator of a PM fractional-slot modular machine is recommended combination to improve the electromagnetic performance.

In addition to this, it can be also concluded that the benefits obtained when changing the stator laminations to GOES are further increased if the anisotropic materials are installed in machines with tooth tips. This is due to a larger increment on the flux density in the airgap which leads to a further increment on the flux linkage, back-EMF and torque fundamental components.
Acoustic performance prediction

4.1 Radial forces in the airgap

The radial component of the force in the airgap is calculated semi-analytically by using the Maxwell stress tensor given by (4) where the flux density in the airgap components were obtained by FEA numerical methods

\[ f_{\text{rad}} = \frac{B_{\text{rad}}^2 - B_{\text{tan}}^2}{2\mu_0} \]  

The force density values were calculated along a line in the middle of the airgap as calculating them in that position has been proved to be the best place as flux focusing effects on the tooth surfaces are avoided. The obtained values are the ones at time step zero and at a position where the machine is synchronised. The total force was calculated analytically from the force density values using the machine stack length and the distance along the airgap. Results of this analysis for the four studied models are presented in Fig. 10.

The results in Fig. 10 show that the presence of GOES increases all the harmonic orders and the harmonic content given by the total harmonic distortion (THD) for both machines with and without tooth tips. This is also the case in the main harmonic components which are the 0th, 10th and 12th. The reason of this is due to the increment on the radial component of flux density in the airgap and the tangential component staying constant. This is not desirable from an acoustic point of view.

Fig. 11 shows the effect of adding tooth tips to the stator, adding GOES and implementing both design modifications at the same time.

4.2 Back-EMF harmonics

The back-EMF harmonic orders for the four cases studied are presented in Fig. 13. It is shown that some of the harmonics are increased and some others decreased which lead to conclude harmonic content (THD) could either increase or decrease depending on the case.

Fig. 14 shows the effects of installing GOES in machines with and without tooth tips on the back-EMF harmonic content. As can be seen, it is more desirable to implement GOES in machines without tooth tips as the THD is decreased whereas in machines with tooth tips the harmonic content increases. This is mainly due to the fifth-harmonic variations. Consequently, it could be more beneficial to install GOES in machines without tooth tips from a back-EMF harmonic point of view.

4.3 Torque ripple

Torque ripple waveforms and harmonic spectra are presented in Fig. 15. As can be seen the peak-to-peak component (sixth) and the harmonic content (THD) are increased when implementing GOES in machines without tooth tips but decreased when doing so in machine with tooth tips. This makes GOES to be more desirable to be installed in machines with tooth tips from a torque ripple point of view.
6 Conclusions

In this paper, the use of GOES in machines with and without tooth tips is studied from electromagnetic and acoustic points of view. It has been concluded that the effect of GOES on the electromagnetic performance is analogous to the effect of tooth tips both producing benefits due to an increase of the flux density in the airgap. However, it has been shown that the benefits obtained due to the presence of tooth tips are larger than when using GOES. Consequently, it is suggested that tooth tips and GOES are two machine design modifications and can be combined to improve the electromagnetic performance considerably.

From an acoustic point of view, it has been shown that using GOES in the stator could also improve the acoustic behaviour of the machine. The presence of tooth tips showed slightly higher benefits compared to employing them in machines without tooth tips. However, in order to determine the real mechanical and acoustic behaviours further analysis is needed.

7 References

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