

Use of fractional-conductor windings and semi-magnetic slot wedges in synchronous machines

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Abstract: This paper discusses two methods of altering the harmonic content of the spatial air-gap flux density waveform in synchronous machines (generators and motors). First, fractional-conductor windings are analysed for adoption as a replacement for a conventional distributed winding arrangement, their advantages and disadvantages briefly discussed and an example design scenario presented. Second, analysis and discussion regarding the use of semi-magnetic slot wedges as a replacement for glass-fibre type wedges is presented to complement the choice of winding in synchronous machines. Both methods are shown to benefit machine performance under certain circumstances.

1 Introduction

This paper explores the impact of adopting fractional-conductor distributed winding arrangements and/or the use of semi-magnetic slot wedges on the various design and performance criteria of wound field synchronous machines (Fig. 1). Particular emphasis is on exploiting any potential performance improvements in large synchronous generators and electrically excited automotive traction motors. It has been shown in the literature that the wound field synchronous machine can provide superior performance to permanent magnet or reluctance machines for long-range electric vehicles [1], and is now a very active research area, with this technology being adopted by Renault [2] in their electric vehicle range. Also, it is well known that the wound field synchronous generator is also the traditional choice for diesel-generator sets and low-speed turbine-driven power generation [3]. The synchronous machines in both applications are typically wound with distributed stator windings of appropriate design/construction commensurate with their voltage level. The salient pole synchronous machine has a power range between a few VA and 1000's of kVA with widespread use mainly in power generation due to its reliability and low maintenance coupled with high efficiency, which is particularly the case with the 'brushless' variant. It is noted that the Renault traction motor is of the 'brushed' type. The use of fractional conductor windings has received little attention in the literature with the few studies that exist showing positive results [4]. Semi-magnetic wedges have also been subject to some study but are lacking widespread adoption despite their apparent benefits [5]. This paper explores these two technological advances in both application contexts and seeks to demonstrate the usefulness of those technologies, while discussing challenges to their adoption. Two-dimensional finite element analysis is employed here and manufacturer's data are used where available and appropriate. The aim of this paper is to explore the adoption of these two technologies in synchronous machines and draw general conclusions regarding their advantages and/or disadvantages against set performance criteria, as outlined in the next section.

2 Performance indicators

With respect to the adoption of stator winding modifications and semi-magnetic slot wedges, certain performance indicators should be defined. The following generic figures of merit are used for comparative evaluation of these technologies:

- Winding factors (fundamental and harmonic)

- Air-gap flux density spatial harmonics

Both synchronous generators and motors can be considered, with the application-specific performance criteria are of concern. In motoring, torque ripple and mean torque production are of importance in the design, where as in synchronous generator design, the key design criteria are low field current (to reduce losses) and low armature voltage THD [6]. Losses are of importance in both cases, such as the field winding losses and rotor pole surface losses, however, these are tolerated in a traction motor scenario as they are outweighed by the extra control variable for high-efficiency field weakening [1].

3 Fractional conductor windings

A number of special windings have been considered in electrical machines, among the most popular at present is the *fractional slot-concentrated winding* or *single-tooth winding* [7]. These are not employed in synchronous generators for many reasons, such as the increased harmonic content in the air gap [5]. Another type of winding is a variation of the conventional distributed winding, the *fractional conductor winding* is a distributed winding scheme that does not constrain mean number of conductors per slot to a positive integer [4], it is very similar in construction (end windings and assembly) to conventional distributed windings where all coil sides have the same number of conductors. By assigning differing numbers of conductors from the same phase to different slots, it is possible to achieve the condition where the mean number of conductors per slot is fractional – coils having different number of integer conductors can be used in a phase group of coils. There is little to be found in the literature on these windings, though some studies do exist [4, 8, 9]. As an example, consider Fig. 2.

Now, as the coil number of turns and placement in the slots dictates the winding factors (fundamental and harmonics), therefore, by the stator magnetomotive force wave (MMF) pattern, it is clear that by using fractional conductor windings, the air-gap MMF could be finely controlled so that the magnitudes of applicable harmonics can be further refined. Fine-tuning through the use of fractional conductor windings can positively affect both the magnetising and leakage reactances of the machine, through control of the winding factors [4]. In Fig. 2, some coils have a number of turns $N_1 = 5$ and some with $N_2 = 6$ turns. In an m -phase fractional conductor winding, the number of slots per pole per phase q can be expressed [4];

$$q = q_1 + q_2 = \frac{Q_s}{2mp} \quad (1)$$

where Q_s and p are the number of stator slots and rotor pole-pairs, respectively. Note that q_1 is the number of coils in half a slot with N_1 turns, q_2 the number of coils in half a slot with N_2 turns, implying a double layer winding. The effective number of turns per slot for a winding with number of layers n_l can be defined;

$$N_{se} = n_l \frac{q_1 N_1 + q_2 N_2}{q} \quad (2)$$

Conventionally, distributed windings are simply defined by the number of slots per pole per phase and the value is either fractional or an integer. With a fractional-conductor winding, the shape of the air-gap MMF wave can be finely adjusted, giving a more sinusoidal distribution and leading to reduced harmonic content or acting to increase the fundamental winding factor. However, if a fractional conductor winding is inappropriately selected, even harmonics could potentially occur. In [4], the theoretical details such as the air-gap MMF harmonics, winding factors and applicable windings are discussed. Leakage inductances are explored in [8] and the design process in [9]. Here, it is sufficient to summarise the key findings:

- (i) Use of fractional conductor windings can minimise selected spatial harmonics spectrum of a winding
- (ii) In some cases, a marginally higher fundamental winding factor can be achieved
- (iii) Even harmonics can be generated if certain phase group patterns are utilised
- (iv) The best results are generally achieved with the q_2 coils placed either side of the phase group

Therefore, although fine-tuning of the machine parameters may be possible with fractional conductor windings, the overall scheme of the winding remains identical to that of the conventional distributed winding (long overlapping end windings).

As an example (adapted from [4]), a two pole $p=1$ machine with $Q_s=36$ is considered. The suggested arrangement is chosen such that the q_2 coils are placed either side of the phase group. With $N_1=2$ and $N_2=1$ and for $q=6$ and $q_2=2$, an effective or mean number of conductors per slot is calculated as $N_{se}=10/3$. The winding factors are compared to a conventional winding of $q=6$ in Table 1.

If this is a synchronous generator, the machine will have a higher fundamental armature voltage capability as the fundamental winding factor has been increased by 1.46%. However, the 5th and 11th harmonics have increased, though the 7th and 13th have reduced. Fig. 3 shows a comparison of the armature voltage waveforms and the resulting harmonics of both windings.

In this particular case, despite the rise in the fundamental and the tuning-out of some of the harmonics, the increased 5th harmonic increases the total harmonic distortion of the voltage waveform from 7.1 to 11%. This is clearly unacceptable as the BSI standard 60034 states that up to 5 kHz the THD must be <5% for generators. The fractional conductor winding could be more useful if 'good' slot-pole and conductor ratios were to be found for a given machine. As such, further research is required (Fig. 4).

4 Semi-magnetic slot wedges

The use of fractional conductor windings can modify (fine tune) the winding factors of the synchronous machine. These winding factors feed-forward to the air-gap flux density wave via the armature reaction MMF wave. Altering the winding factors has no effect on the stator slot permeances that have a large influence on the resulting air-gap flux density wave. The stators of large generators are usually designed with open slots and closed with a high temperature plastic or glass-fibre slot wedge to assist with keeping the coils in place. Open slots reduce the output voltage quality of generators and also degree the performance of motors –

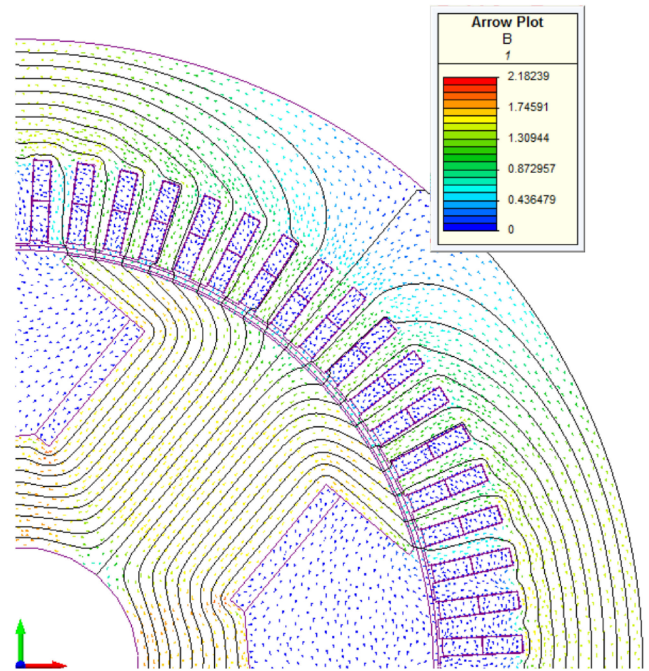


Fig. 1 No-load FEA plot of a wound field synchronous machine

	SLOT 1	2	3	4
a)	B-	A+	A+	A+
	A+	A+	A+	C+
b)	B-	5	6	5
	5	6	5	C+
c)	B-	5.5	5.5	5
	5	5.5	5.5	C+

Fig. 2 Example fractional conductor winding arrangement for a phase group of phase A of a two pole 18 slot double layer winding

(a) Winding arrangement, (b) Number of conductors per coil-side, (c) Mean number of conductors per slot, assuming that the B- and C+ coils have 5 conductors each

Table 1 Winding analysis

	Conventional	Fractional conductor	Change
q	6	6	—
q_2	0	2	—
k_{w1}	0.956	0.97	+1.46%
k_{w5}	0.19	0.35	+84.20%
k_{w7}	0.14	0.02	-92.85%
k_{w11}	0.11	0.13	+18.18%
k_{w13}	0.09	0.05	-44.44%

pole face losses increase significantly due to the increased air-gap harmonic content [6]. Fig. 5 shows the wedge placement in a parallel tooth synchronous machine.

There are commercially available semi-magnetic slot wedges [5]. These wedges have >1 relative permeability in the range $2 \leq \mu_r \leq 10$ and have been shown in single-tooth wound synchronous reluctance motors to reduce the harmonic content in the air gap by modulating the flux density wave via the permeances. It is possible

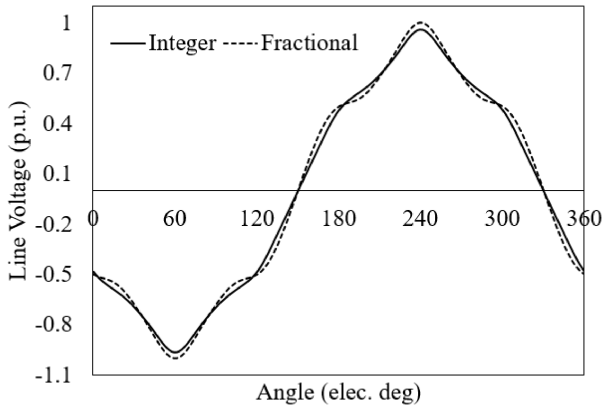


Fig. 3 Armature EMF waveforms

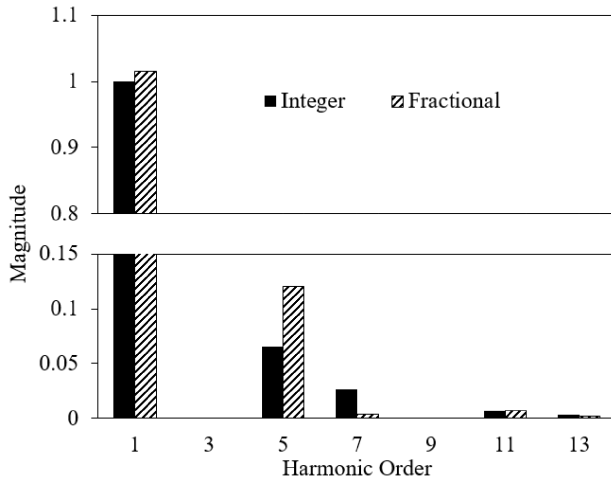


Fig. 4 Armature EMF harmonics

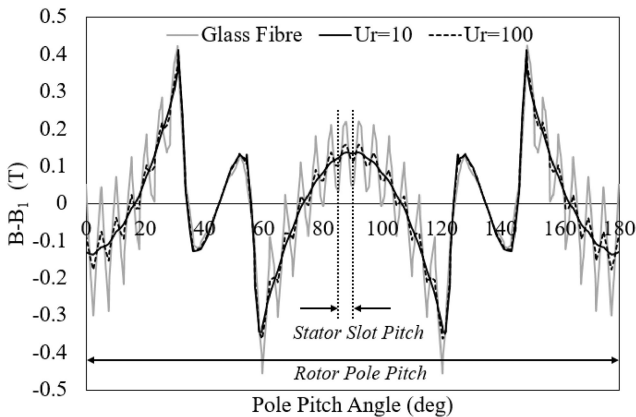


Fig. 8 Residual magnetic flux density over a rotor pole pitch

that combination of reduction in pole shoe surface iron losses, reduced voltage THD, reduced field current, and improved efficiency energy conversion efficiency can be achieved by adopting correctly designed semi-magnetic slot wedges – this is explored in Section 5. Again, little literature is found on the use of semi-magnetic slot wedges. Fig. 1 shows a synchronous machine that is now analysed.

Finite element studies can be used to determine the radial component of the air-gap flux density. The slot wedges shown in Fig. 5 have their relative permeability modified accordingly; 1 (normal wedge) $\leq \mu_r \leq 100$ (high permeability wedge). Transient motion analysis is also performed to determine the eddy-current losses in the pole face of the salient rotor poles. Fig. 6 shows the resultant radial air-gap magnetic flux density plots across a single rotor pole pitch in machine with different wedges, Fig. 7 shows the radial flux density harmonic decomposition, Fig. 8 the residual

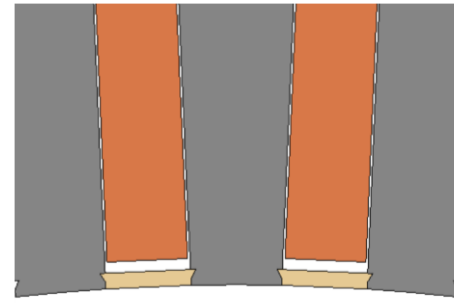


Fig. 5 Slot wedge position at air-gap periphery in a synchronous machine with parallel teeth

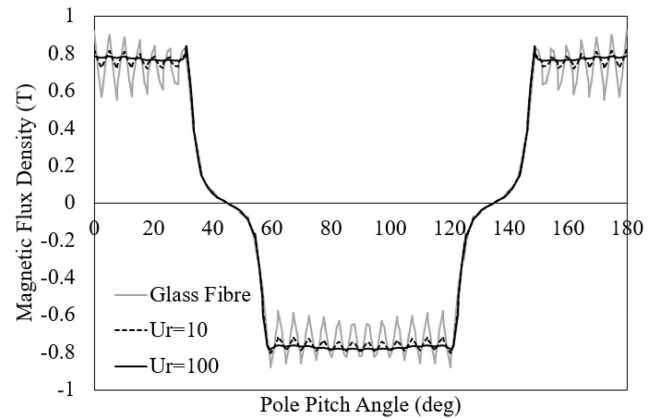


Fig. 6 Magnetic flux density plots across a single rotor pole pitch in machine with different wedges

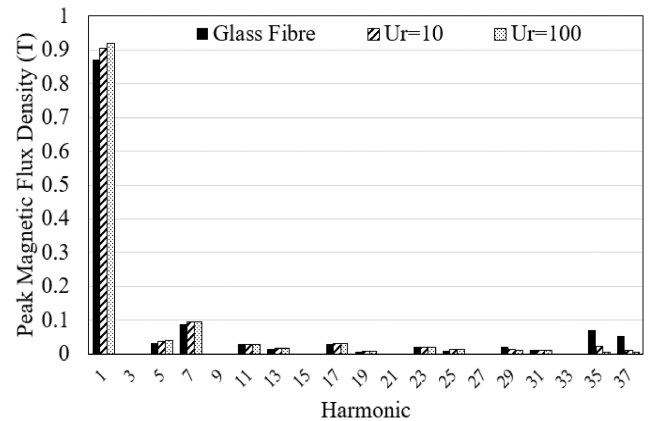


Fig. 7 Radial flux density harmonics

magnetic flux density over a rotor pole pitch and Fig. 9 the eddy-current distribution over half a rotor pole pitch.

As is clearly evident from Fig. 6, the stator slotting permeance (if damper bars existed there would also be a rotor permeance variation) causes significant variation of the air-gap flux density over the rotor pole face.

This leads to harmonic losses in the rotor pole surface and increased armature voltage harmonics, both of which are undesirable. By introducing the semi-magnetic wedges (here we must note that the wedge permeability is much less than the stator lamination steel), there are two observations;

- (i) Increased fundamental flux
- (ii) Reduction in the high frequency slotting harmonics

The increase in the fundamental flux is attributed to the shortening of the effective air gap, the Carter factor for the stator is reduced, and hence the effective air gap is smaller. The Carter factor is usually computed via conformal mapping assuming that the steel has infinite permeability and the stator slot opening has a relative

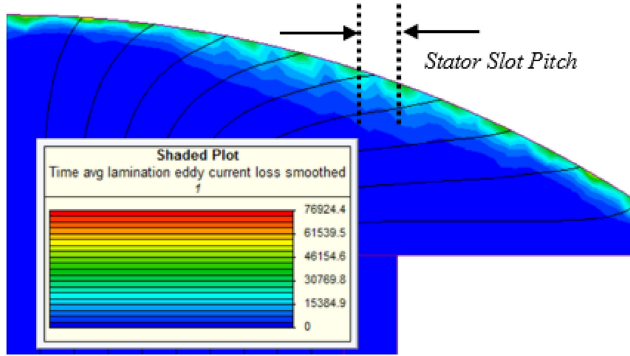


Fig. 9 Eddy current loss in rotor (no wedges, 1500 rpm)

permeability of one, this effectively enlarges the air gap – this effect is reduced with semi-magnetic slot wedges.

As a consequence, the fundamental voltage capability for the machine will increase slightly, or the required field current for rated air-gap flux will reduce along with the associated loss and temperature rise. Second, due to the reduction of the discontinuity of permeability in the slot opening, the stator slotting permeance function becomes less pronounced, reducing the high-frequency slotting visible in the air-gap flux density waveform for a machine with conventional wedges.

If the air-gap flux density residuals are plotted; $B(\theta) - B_1(\theta)$, removing the fundamental (Fig. 8), it is seen that the high-frequency ripple is clearly related to the stator slot pitch. These residuals are ripple flux densities that vary in time over the rotor pole face and hence cause surface iron losses. By introducing higher permeability material into the slot opening, the residuals reduce; for a slot wedge of $\mu_r \leq 10$, it is found that the time averaged rotor surface iron loss can be reduced by >75%, in this case (reference Fig. 9). While an increase in fundamental flux complemented by harmonic reduction can be achieved, the stator slot/tooth tip leakage inductance will increase and there will be associated magnetic losses in the wedges if they have sufficient electrical conductivity. This is recommended for further research; however, CIGRE reporting on use of magnetic slot wedges in very large hydro-generators [10] agrees with the general results presented here.

5 Discussion

The use of fractional conductor winding and semi-magnetic slot wedges has been briefly explored here due to a lack of available literature. Both methods are used to affect harmonic reduction and/or elimination in the air-gap flux density and voltage waveforms. The use of fractional conductor windings is useful in fine-tuning the armature voltage, E , in synchronous machines, which can be written;

$$E = \sum_{v=1}^{\infty} E_v; E_v \propto k_{wv} \quad (3)$$

Hence, the use of fractional conductor windings, as with sort pitching and distributing the coils of a conventional distributed winding, will reduce the armature voltage harmonics E_v if the harmonic winding factors k_{wv} can be fine-tuned.

It is important to note that the resultant air-gap field is due to both the stator and rotor MMF waves and both permeance functions. Use of fractional conductor windings or short pitching can only reduce one aspect of the harmonic generation in the machine. In terms of synchronous motors, any air-gap field harmonics (caused by any generating mechanisms) can lead to torque ripple, as described in [11].

$$T_{\theta} \propto \sum_{k=1}^{\infty} |B_r^k| |B_{\theta}^k| \cos(\varphi_d^k) \quad (4)$$

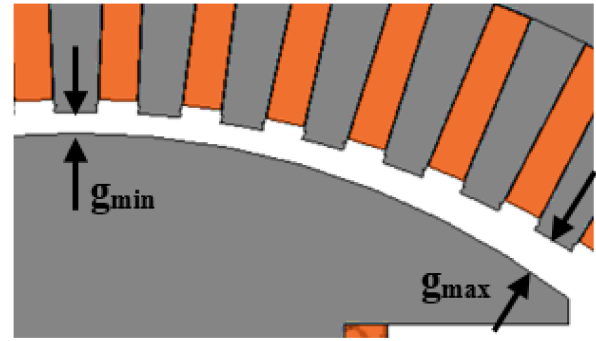


Fig. 10 Graded air gap in a wound field synchronous machine

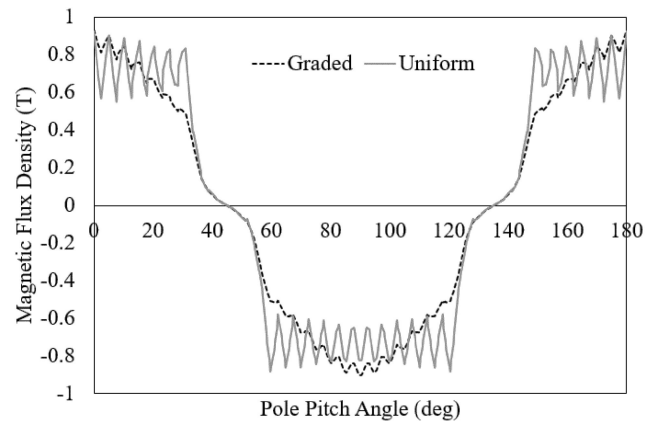


Fig. 11 Magnetic flux density plots across a single rotor pole pitch in machine with uniform and graded air gaps

Hence, the resultant torque T_{θ} at a particular time instant t is the sum of the product of $|B_r^k|$ the magnitude of the radial field k th harmonic; $|B_{\theta}^k|$ is the k th harmonic of the tangential field, and φ_d^k is the phase angle between the k th harmonic fields. Thus, in a synchronous motor, the use of semi-magnetic slot wedges aids in the reduction of torque ripple [5].

Use of these techniques requires further investigation and an investigation of their technical disadvantages of their adoption, coupled with the practical and economic engineering decisions to be made by the design engineer. This is the focus of further work.

6 Use of graded air gaps

An alternative to the adoption of fractional-conductor windings and to the use of semi-magnetic slot wedges is the 'graded air gap', or in some cases tapered pole shoe tips. Here, the air gap across the salient rotor pole face is not uniform, thus the graded air gap is defined as an increased air gap at the rotor pole shoe tip, see Fig. 10 for a continuously graded air gap. This type of air gap has been considered since very early in the design of synchronous machines [12] where it is shown that the air-gap flux density THD is reduced as the air gap is graded [13] (see Fig. 11 for the magnetic flux density plot and Fig. 12 for the harmonic decomposition). The disadvantage here is that this technique is likely only to be used for new designs or designs in which capital investment is justified due to lamination stamping tooling costs.

With graded air gaps, the *effective* air gap is increased which leads to increased field current requirement and, therefore, winding losses and an associated rotor temperature rise. Despite this, there are some other advantages that are evident, such as lower rotor pole face losses (due to increased rotor-stator separation at the rotor pole shoe tips) and lower armature reaction. Thus, this is an additional technique in which the desired performance improvements can be achieved in synchronous machines – its adoption is likely benefited from the adoption of semi-magnetic slot wedges to reduce the effective air gap, potentially mitigating,

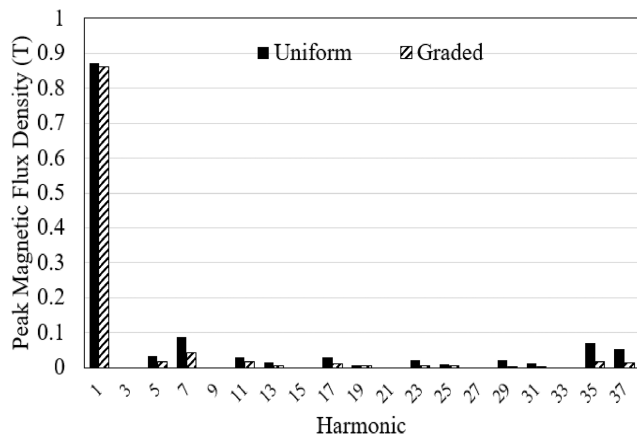


Fig. 12 Magnetic flux density plots across a single rotor pole pitch in machine with uniform and graded air gaps

wholly or partially, the disadvantages of graded air gaps. This is an area of further research.

7 Conclusions

This paper explores two methods that can be used to modify the stator air-gap flux density distribution in synchronous machines where there is a lack of literature; both can lead to machine performance gains if adopted correctly. Care must be taken in the design of fractional conductor windings as while some harmonics may be significantly reduced, others may increase, increasing the overall THD of the armature voltage. Further work is required to ascertain the ‘good’ design combinations for adoption.

Semi-magnetic wedges can be useful for reducing pole face losses and can act to reduce the stator air-gap Carter coefficient, effectively reducing the rotor DC current required for rated flux. There are disadvantages of both methods that deserve further exploration and one avenue of research is to couple these methods with graded air gaps to obtain the optimal solution for reduced armature voltage harmonics, reduced rotor iron loss, reduced torque ripple, and reduced rotor field current, all of which act to improve machine performance and efficiency.

We must note that any rotor damper bars will also affect the distribution of flux density from the rotor side permeance variation; this has not been explored in this work.

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9 References

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