SPEED TUTORIAL B10

7 Aug 2004

UNIVERSITY
of
GLASGOW

Airgap or slotless windings in *PC-BDC*

Objective

To introduce the basic principles and characteristics of airgap windings (slotless windings) and illustrate their calculation in *PC-BDC*. This tutorial intersperses sections of design theory with examples from *PC-BDC*. The examples show the comparison between a slotless motor and a conventional slotted motor.

Background

By removing the iron teeth from the stator of a brushless permanent-magnet motor, the open-circuit cogging torque is eliminated. Removing the teeth decreases the airgap flux-density, decreasing the torque constant and the EMF constant. On the other hand, the extra space available for ampere-conductors can be used to compensate the reduction of flux.

Definitions

Slotless motor	A motor in which the stator winding is not laid in slots. The stator iron has a smooth bore and no teeth.
Airgap winding	A winding not laid in slots but directly in the smooth bore of an unslotted stator.
Encapsulated winding	A prefabricated winding that may be inserted into the smooth bore of the stator as a single monolithic component.

Knowledge required

Basic theory of brushless permanent-magnet machines.

Further reading : *SPEED's Electric Motors*, chapter 2; the *WinSPEED* manual; *An Introduction to WinSPEED*. For the basic operation of the *PC-BDC* program, see tutorial B01.

1. Airgap or Slotless Windings

By removing the iron teeth from the stator of a brushless permanent-magnet motor, the open-circuit cogging torque is eliminated.[1]

Removing the teeth decreases the airgap flux-density, decreasing the torque constant and the EMF constant. On the other hand, the extra space available for ampere-conductors can be used to compensate the reduction of flux. To maintain the same torque for the same rotor diameter and length, the product of "magnetic loading" and "electric loading" must be kept constant.[2]

It may be advantageous to design slotless motors with a larger rotor diameter, so that for the same total winding area and the same stator outside diameter, the radial depth of the winding (and therefore the effective airgap) is reduced. The larger rotor diameter can be used to accommodate a thicker magnet, which not only increases the flux but also raises the magnet operating point higher up the demagnetization curve, increasing the permeance coefficient and reducing the risk of demagnetization.

The reduction in airgap flux-density is caused by the increase in the effective airgap length when the teeth are removed. The reduction is least for a 2-pole motor, and increases so rapidly with the number of poles that slotless motors with more than 4 poles may be difficult to design with acceptable torque per unit volume, unless the ratio of rotor diameter to stator diameter is significantly increased compared to the normal practice with slotted motors. The reduction is less severe in the exterior-rotor configuration, but then the cooling of the windings may be more difficult.

Higher-order space harmonics in the magnet field and in the armature-reaction field are liable to attenuate very rapidly with radial distance away from their respective sources.[3] For this reason the slotless motor lends itself well to the generation of sinusoidal EMF, while the possibility of local demagnetization due to armature reaction is reduced.

In recent years the development of magnets with very high coercivity and remanence has made it possible to achieve acceptable levels of magnetic loading in spite of the large effective airgap, although the magnetic loading cannot equal the level achievable in a slotted motor having the same magnet dimensions. Without such magnets the slotless motor would hardly have any hope of competing with conventional motors, particularly in respect of torque per unit volume.

It was shown many years ago that for 2-pole machines a helical winding could be designed with less copper than in a conventional machine having straight conductors and conventional end-windings[4]. In the helical winding each conductor has 180° of skew, so that the end-windings are completely eliminated. Although the low skew factor reduces the EMF considerably, the saving in end-winding copper (and therefore in copper loss) makes the concept attractive, especially for high-speed machines, and it also results in a short axial length. Evidently the manufacture of a helical winding requires special processes different from those used for conventional windings.

Because of the large effective airgap, the slotless machine is susceptible to much more "axial fringing" (variation of magnetic field along the axial length) than the slotted machine. Since most of the design equations for EMF, inductance etc. depend on 2-dimensional theory (including the finite-element calculations), the results will not be as accurate as for slotted machines. The 2-dimensional theory can be taken to apply at the central plane of the machine, so that estimates of flux and torque will probably be low by 10–20% depending on the length/diameter ratio.

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[1] "Cogging torque" is produced by the interaction of the magnets and the slot openings at the bore of the stator, and is usually understood to relate to the open-circuit condition: in other words, it does not include any "electromagnetic torque ripple" arising from the interaction of the magnets and the stator *currents*.

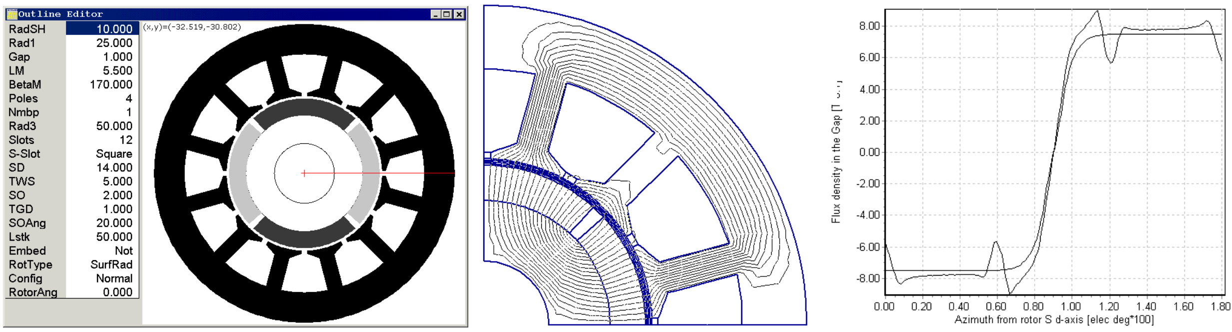
[2] "Magnetic loading" is the average open-circuit airgap flux-density around the airgap. "Electric loading" is the RMS ampere-conductors per metre around the airgap. For equations relating these parameters to the torque per unit volume, see *SPEED's Electric Motors*, Ch. 1. The equations contain factors that depend on the magnet flux *distribution* and the winding factors.

[3] See Hughes A and Miller TJE (1977), Proceedings IEE, **124**, pp. 121–8.

[4] See Ross, JSH, UK Patent 1,395,152 (1971)

2. What happens when we remove the teeth

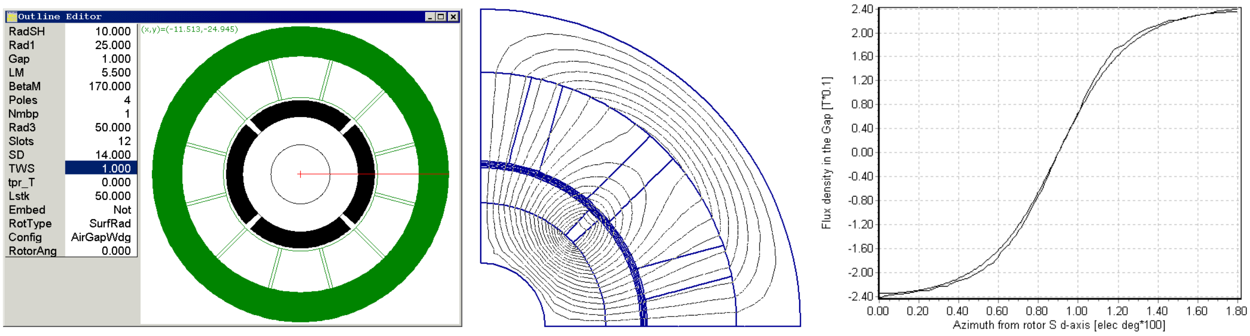
Let's take a standard example [**Alt+1**] in *PC-BDC* and see what happens when we remove the teeth. The following figures show the outline, the flux-plot on open-circuit, and the airgap flux-density distribution computed with the finite-element GoFER and *PC-FEA*. The magnet is NeIGT30H with B_r = 1·12 T.



RadSH	10.000
Rad1	25.000
Gap	1.000
LM	5.500
BetaM	170.000
Poles	4
Nmbp	1
Rad3	50.000
Slots	12
S-Slot	Square
SD	14.000
TWS	5.000
SO	2.000
TGD	1.000
SOAng	20.000
Lstk	50.000
Embed	Not
RotType	SurfRad
Config	Normal
RotorAng	0.000

Outline, flux-plot and airgap flux-density distribution for conventional slotted motor

Now let's see what happens when we remove the teeth (**Config** = AirgapWdg):



RadSH	10.000
Rad1	25.000
Gap	1.000
LM	5.500
BetaM	170.000
Poles	4
Nmbp	1
Rad3	50.000
Slots	12
SD	14.000
TWS	1.000
tpr_T	0.000
Lstk	50.000
Embed	Not
RotType	SurfRad
Config	AirGapWdg
RotorAng	0.000

Outline, flux-plot and airgap flux-density distribution for slotless motor

We can make the following comparison from the above figures:

- The airgap flux distribution in the slotless motor is more sinusoidal
- The peak flux-density and the flux/pole are both reduced in the slotless motor
- There is less iron in the slotless motor, so the iron losses will be much lower
- In the slotted motor, most of the flux passes through the teeth and not through the windings. In the slotless motor, flux passes directly through the windings. Moreover, the flux-density in the winding decreases with radius, being maximum at the stator bore and minimum at the bore of the yoke.[5]

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[5] The flux distribution in the slotless motor is taken at the middle of the winding r = 32 mm, whereas the mid-gap radius of the slotted motor is 25.5 mm

Data from the design sheets gives a more precise comparison:

	Slotted	Slotless	Slotless/Slotted
Peak airgap flux-density **BgOC**, T	0·759	0·237	0·312
Flux-density in the magnet **BmOC**, T	0·893	0·398	0·446
Peak yoke flux-density **Bsy**, T	1·444	0·527	0·365
Fundamental flux/pole **PhiM1**, mWb	1·217	0·490	0·403
Slot area **Aslot**, mm^2	157	242	1·54
Product **PhiM1** × **Aslot**, mWb × mm^2	191	119	0·62

- The fundamental flux/pole in the slotless motor is only 40% of the value in the slotted motor
- The magnet is working at a much lower point on its demagnetization curve (0·4T compared with 0·9T)

In order to compensate the reduction of magnetic loading, we would need to increase the electric loading (ampere-conductors/metre) by 1/0·4 = 2·5 times. But the slot area in the slotless motor is only 54% larger than in the slotted motor. The product of flux × slot area gives an idea of the relative torque/rotor volume of the two machines, and the slotless motor has only 62% of the capability of the slotted motor.

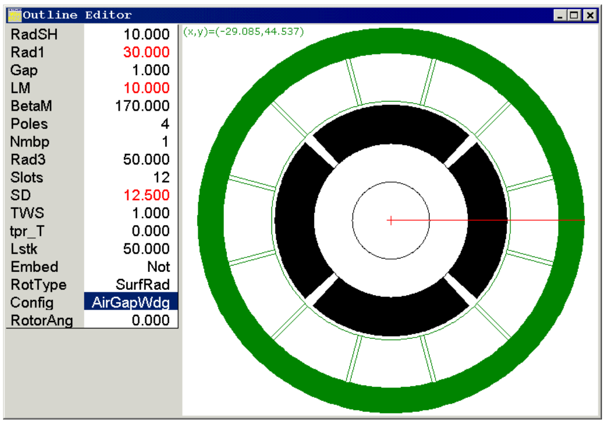
This leads us to conclude that simply removing the teeth will not produce any advantages. We need to modify the slotless design to accommodate its special features.

3. How to modify the slotless motor to compensate for the removal of the teeth

To increase the magnetic loading, the obvious steps to take are:

- use a more powerful magnet
- increase the magnet thickness
- reduce the thickness of the stator winding

With the [**Alt+1**] slotless example, try these to see if you can restore the product **PhiM1** × **Aslot** to the same value it had in the original slotted design. For example, changing **Rad1** from 25 to 30, **LM** from 5·5 to 10, and **SD** from 14 to 12·5 gives the design shown below (with no change in the magnet material):



RadSH	10.000
Rad1	30.000
Gap	1.000
LM	10.000
BetaM	170.000
Poles	4
Nmbp	1
Rad3	50.000
Slots	12
SD	12.500
TWS	1.000
tpr_T	0.000
Lstk	50.000
Embed	Not
RotType	SurfRad
Config	AirGapWdg
RotorAng	0.000

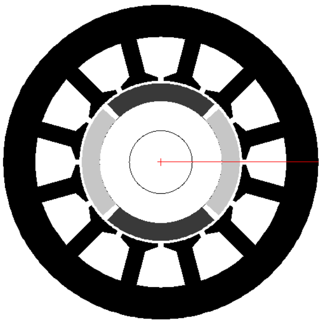
The comparison with the slotted motor is now:

	Slotted	Slotless	Slotless/Slotted
Peak airgap flux-density **BgOC**, T	0·759	0·350	0·46
Flux-density in the magnet **BmOC**, T	0·893	0·587	0·66
Peak yoke flux-density **Bsy**, T	1·444	1·478	1·03
Fundamental flux/pole **PhiM1**, mWb	1·217	0·888	0·73
Slot area **Aslot**, mm^2	157	244	1·55
Product **PhiM1** × **Aslot**, mWb × mm^2	191	217	1·13
Magnet weight **wt_Mag**, kg	0·269	0·549	2·04
Copper weight, **wt_Cu**, kg	0·775	0·751	0·97
Product **PhiM1** × **Aslot** × Rotor diameter (indicative of torque)	9550	13020	1·33
Inertia, kg-m^2 × 10^{-4}	2·23	4·54	2·0

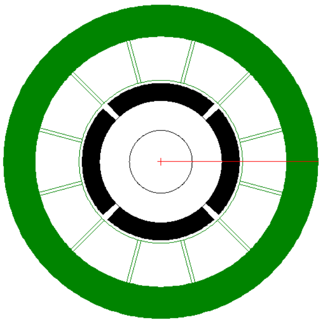
The rotor diameter is 18% greater, and the magnet weight is doubled, but the product of flux/pole and slot area is now 13% greater in the slotless motor. (When spacers and slot insulation are taken into account, the ratio will be closer to 1·0). All this means that the same torque should be achievable with no change in the winding current-density. The number of turns will be greater in the slotless machine, approximately in the ratio of the relative values of the fundamental flux/pole **PhiM1**, i.e. 1/0·73 or 1·37. Correspondingly, a smaller wire size will be needed in the slotless machine. This will help to reduce eddy-current losses in the conductors, which are exposed to the full magnet flux, being no longer shielded by the teeth.

The increase in rotor diameter will produce a further 18% increase in torque, with no change in the magnetic and electric loadings, suggesting that this slotless motor can produce 33% more torque per stator volume than the original slotted motor. However, its inertia is twice that of the slotted motor, so the torque/inertia ratio is lower in the ratio 1·33/2·0 = 0·67.

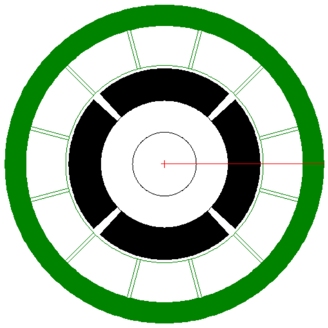
The figure shows the comparison between the original slotted motor, the slotless motor obtained by removing the teeth, and the final slotless motor.



Original slotted



Teeth removed



Final slotless

4. Inductance

When the iron teeth are removed, the effective airgap increases, and we would expect the inductance to decrease. This would be valid if the winding remained the same, with the same distribution and the same number of turns.

However, the open-circuit flux is reduced by removing the teeth, so the number of turns must be increased to compensate. Since the inductance depends on (turns)^2, it is not obvious that the inductance will necessarily end up smaller than in the slotted machine. The following table shows the comparison of inductance between the original slotted motor and the slotless design, together with a slotless motor whose turns have been increased by 37% as noted above. With this increase in the number of turns, the inductance of the slotless motor is not appreciably smaller than that of the original slotted motor.

	Slotted	Slotless	Slotless/turns adjusted
Phase self-inductance **Lph**, mH	0·299	0·142	$1{\cdot}37^2 \times 0{\cdot}142 = 0{\cdot}266$

5. Heat transfer

Cooling of the slotless motor winding is likely to be more difficult than in the slotted motor, because

- the contact area at the sides of the teeth is lost, so that heat transfer by conduction to the stator steel is reduced. The reduction of contact area is very roughly in the ratio 1/(1 + **SD** × **Slots**/**Rad2**) where **SD** = slot depth, and **Rad2** = radius of bore of stator yoke. For the example motor, this ratio is approximately 0·22 — a significant loss of heat transfer area.
- the coil sides are likely to be significantly larger in the slotless motor, increasing the thermal diffusion distance across the coil and increasing the ratio between the winding hot-spot temperature and the mean winding temperature.

6. Torque ripple

While cogging torque is eliminated in the slotless motor, electromagnetic torque ripple can still arise through the interaction of harmonics in the the ampere-conductor distribution and the magnet flux distribution. However, these space harmonics attenuate fairly rapidly with radial distance away from the winding or the magnet surface, so the problem is likely to be less severe in the slotless motor than in the slotted motor. Very likely, no special precautions need be taken to reduce electromagnetic torque ripple aside from the usual measures of assuring a sinusoidal EMF and a sinusoidal current.

7. Eddy-current losses in stator conductors

The stator conductors are exposed to the full magnet flux, and are not shielded by teeth as they are in the slotted motor. Therefore they are liable to additional eddy-current losses, and stranding may be necessary to limit these losses.

The basic criterion for avoiding eddy-current loss is to make the individual strand diameter less than the skin-depth d at the frequency at which the eddy-currents are induced. The fundamental eddy-current frequency due to rotation of the magnet is the same as the fundamental frequency of the inverter supply to the motor, but any space-harmonics in the magnet field will induce eddy-currents at a multiple of the fundamental frequency corresponding to the order of the space harmonic.

Suppose, for example, we have a 4-pole motor rotating at 6,000 rev/min and the magnet field contains significant harmonics up to the 7th. Then the highest eddy-current frequency of concern is 6,000/60 × 2 × 7 = 1·4 kHz. At this frequency the skin-depth in copper conductors is

$$d = \sqrt{\frac{2\rho}{\mu_0 \omega}} = \sqrt{\frac{2 \times 1{\cdot}7 \times 10^{-8}}{4\pi \times 10^{-7} \times 2\pi \times 1400}} = 1{\cdot}75 \quad \mathrm{mm}$$

so the wire diameter should ideally be a fraction of this value.

Induced currents in parallel paths

A further problem can arise when the winding has parallel paths, if the parallel paths do not all have exactly the same inductance and the same flux-linkage with the magnet. In this case circulating current will flow between the parallel paths, and since the impedance in such loops is inevitably very small, the currents could be large enough to cause significant extra losses. The only way to prevent this is to ensure that when parallel paths are used, the winding is made with complete symmetry and a high degree of precision.

8. Finite-element analysis

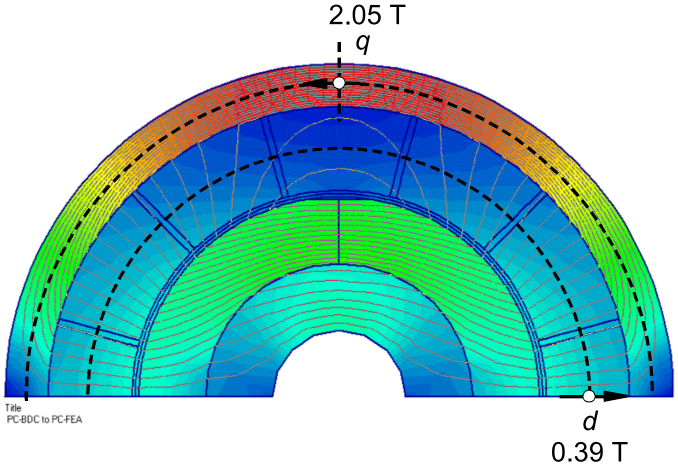


Fig. 5 Finite-element analysis with 2-pole magnet

Fig. 5 shows the open-circuit flux calculated by the finite-element method using the Bgap GoFER with *PC-FEA*. Note that the 4-pole magnet has been replaced by a 2-pole magnet, with parallel magnetization (**RotType** = SurfPll), and **BetaM** = 160°; **EMFCalc** = HBMethod.

With airgap windings *PC-BDC* treats the stator yoke as infinitely permeable. It calculates the peak airgap flux-density **BgOC** at the point *d* in Fig. 5, at the mean radius of the winding. With a NeIGT30H magnet the result is 0·44T. When we compare this with the *PC-FEA* value, 0·39T, it appears that by neglecting the yoke MMF drop, *PC-BDC* is overestimating the flux by about 12%.

Evidently in this type of motor the saturation of the yoke does not make a very large difference to the airgap flux-density **BgOC**. The reason is that relatively little MMF is required to saturate the yoke, compared with the MMF required to force the flux across the airgap and the magnet.[6] In the light of the finite-element result we can adjust *PC-BDC* by setting **XBrT** = 0·88, and then **BgOC** comes out equal to 0·39 T. (It is best to use the **MatchFE** utility in *PC-BDC* to match the finite-element result.)

In contrast, the error in *PC-BDC*'s value of the yoke flux-density **Bsy** is much greater. This is calculated by dividing the yoke flux **PhiSY** by the yoke cross-section area. **PhiSY** is calculated by integrating the radial flux-density over the inside surface of the stator yoke, and dividing by 2. With no adjustment factors **Bsy** = 3·15 T, and even with **XBrT** = 0·88 it is 2·78 T; both values being clearly too high. The finite-element result is 2·05 T, as shown in Fig. 5 at point *q*). Here is a case where **Bsy** needs to be adjusted or corrected in the light of the finite-element result, and the way to do it is to set **XSyoke** = 2·78/2·05 = 1·36 in *PC-BDC*, which is the same as defining an "effective magnetic thickness" 1·36 times the actual yoke thickness. Unsatisfactory as it may seem, this simple calibration is the only way to adjust *PC-BDC*'s result to account for the yoke saturation, because the particular classical analytical equations used for airgap windings are too complex to allow for the details of saturation — only the finite-element method can do this correctly.

With **XBsy** = 1·36 and **XBrT** = 0·88, *PC-BDC* returns a value of 2·04 T for **Bsy**, and the iron losses will be calculated more accurately with this value.

The degree of adjustment required is much greater with 2-pole motors than with motors of higher pole-number, because the fringing or pole-to-pole leakage is much less in 2-pole motors. Note that if the stator yoke is longer than the magnet in the axial direction, the yoke flux will spread in the axial direction, relieving the yoke flux-density to a certain extent, and making a more-than-proportional reduction in the MMF absorbed by the yoke. The gap flux also spreads or bulges in the axial direction, and for exact comparisons with 2-D finite-element calculations, **ufz** should be set equal to 1.

From these arguments we can further infer that the saturation of the yoke will make relatively little difference to the inductance — probably of the order of the correction needed in **XBrT**, which even in this severe case is only of the order of 10 – 12%.

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[6] Although *PC-BDC* ignores the MMF required in the yoke, it is doing a good job of estimating the field in every other respect. If a **MatchFE** comparison is run with an unsaturated yoke, the basic accuracy of *PC-BDC* can readily be verified.