Brushless DC Motor

Calculating Air Gap Flux with MagNet

Introduction

A quantity of significant interest in the design of any machine is the magnetic flux density in the air gap, both as a function of position and in terms of its harmonic content.

This tutorial will outline the methods for calculating the magnetic flux density *B,* both in terms of orthogonal components and in the radial direction in the machine's air gap, and for obtaining the harmonic analysis of the flux wave.

MagNet's 2D Static Solver is used and the machine is analyzed in an unexcited state.
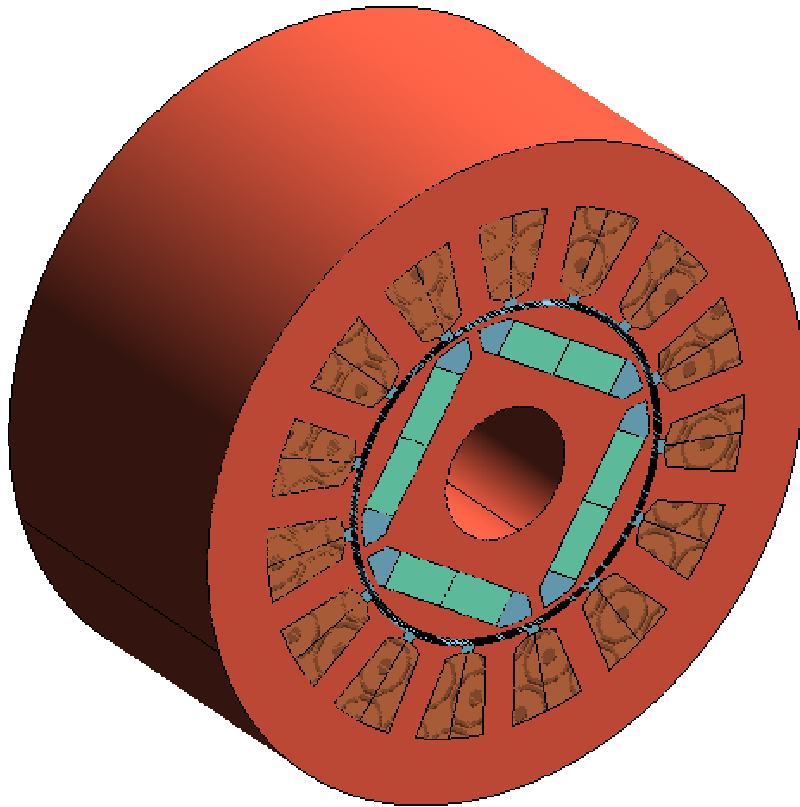
Figure 1: MagNet model of BDC motor

Creating the Model

Viewing the Mesh Refinement

Open the *BDCTutorial.mn* model and you will see that our motor is a single-barrier interior permanent magnet (IPM) machine with 15 stator slots and 4 rotor poles.

To ensure a good solution, some mesh controls have already been assigned to the model. Using *View→Initial 2D Mesh*, you can see how the mesh is refined in the air gap regions.
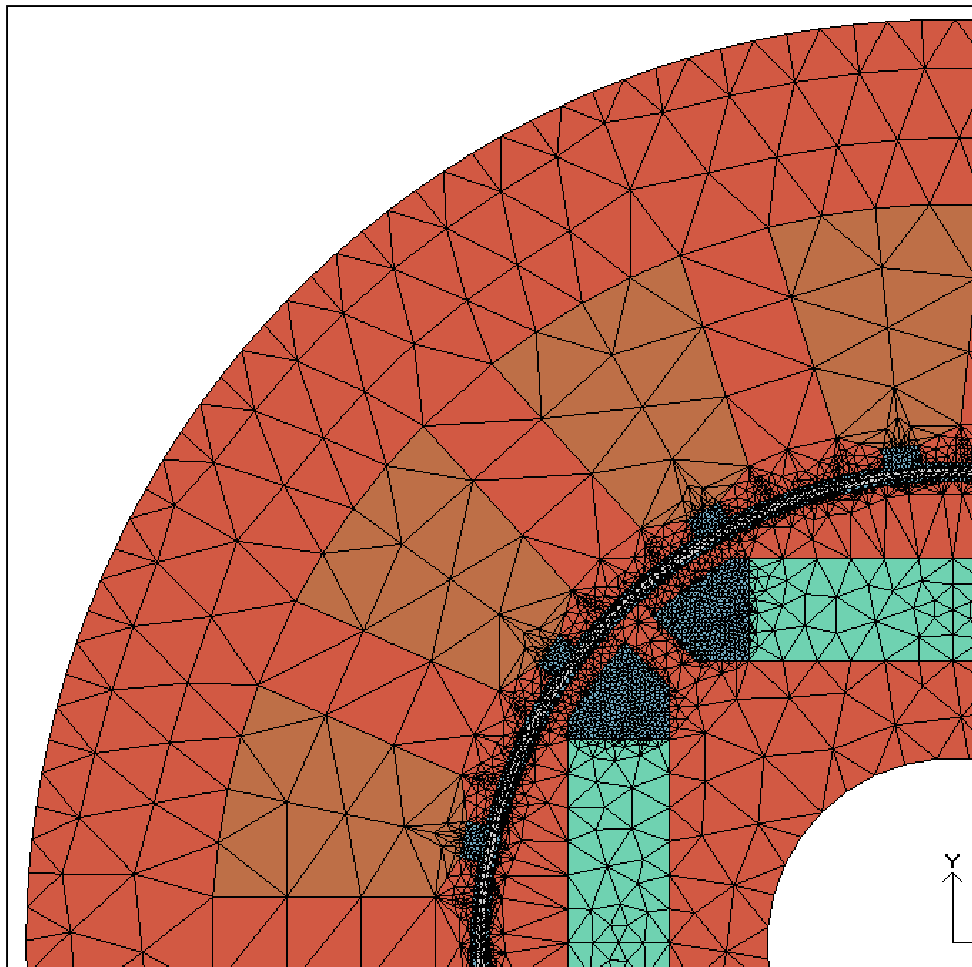

Figure 2: Quarter-model of BDC machine showing mesh refinement

Open up the Properties page for various components to see the mesh controls (specifically, the Maximum Element Size) applied.

Zoom in on the air gap region to see the special treatment applied here. For accurate machine analysis and calculations, air gaps in machines should be set up this way:

- Split the air gap into four layers.

- Assign the material "Virtual Air" to the layers closest to the stator and rotor.

- Assign the material "AIR" to the two other layers.

To calculate forces, MagNet must evaluate the field in the layer of AIR elements adjacent to the component. If this procedure is not done, MagNet will evaluate the field immediately adjacent to sharp corners where there is a potential for error. This method ensures that MagNet will calculate the forces and torques with accurate field values.
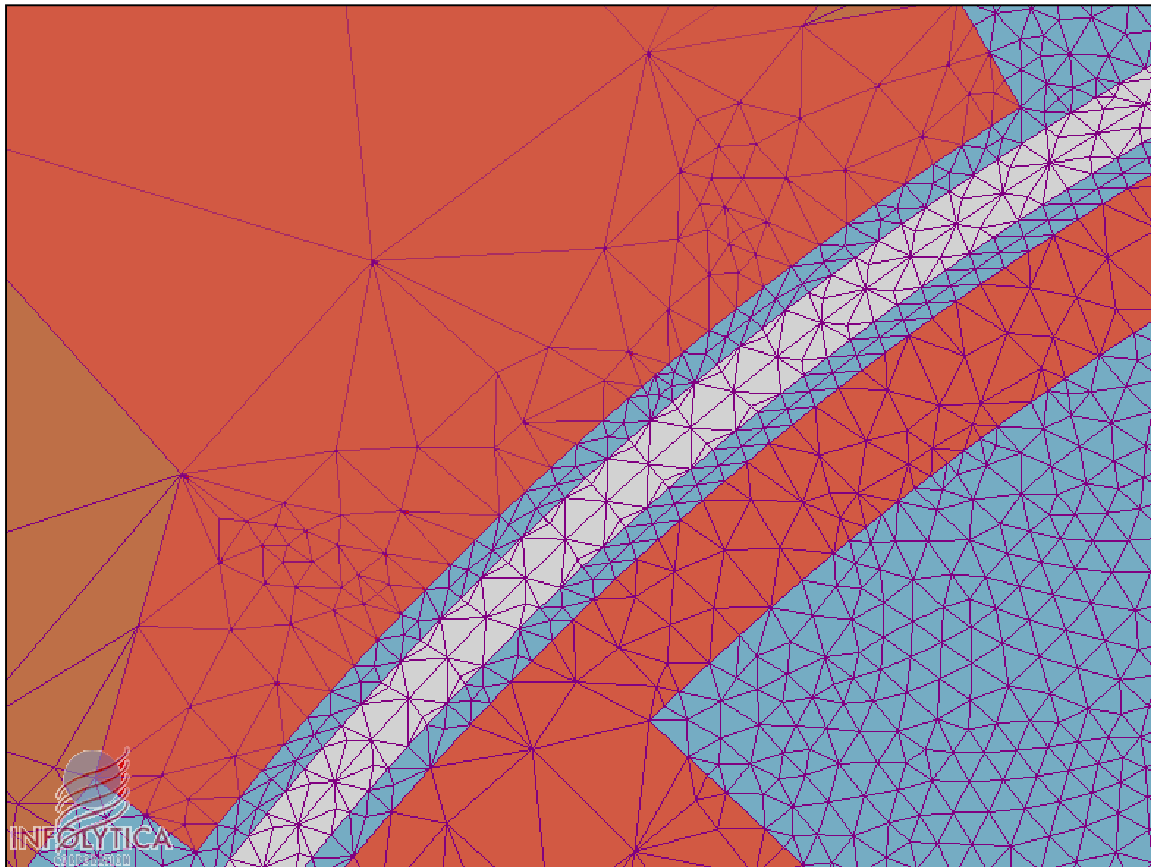

Figure 3: Air gap layout for optimal torque calculations

Solving and Post-Processing

Solve the problem using the *2D Static* solver.

On the *Field* tab, select the *Arrow* tab, choose |**B**| and click *Update View* to display an arrow plot of the |B| field.

The initial arrow plot will be rather confusing due to the large sizes of the arrows and the fact that they are all the same colour. Modify the default settings to make the arrow plot easier to understand.

Under the *View* tab, right click the *Arrow Plot* option and select *Properties.*

Make the following changes to the settings:

- Size Multiply Factor: 0.075
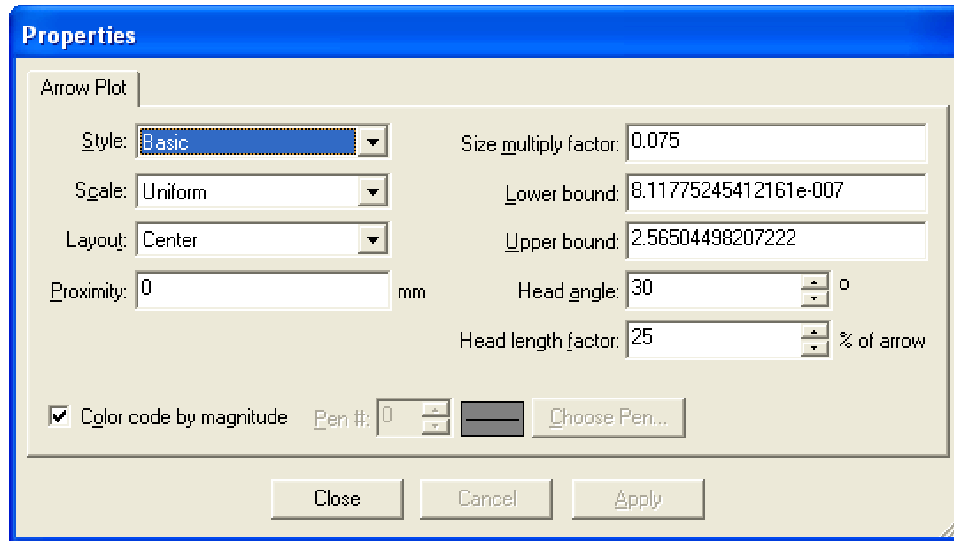- Color code by Magnitude: Checked

Figure 4: Arrow Plot Options Dialog Box

The plot should look now something like this. You may want to zoom in on the air gap region for better clarity.
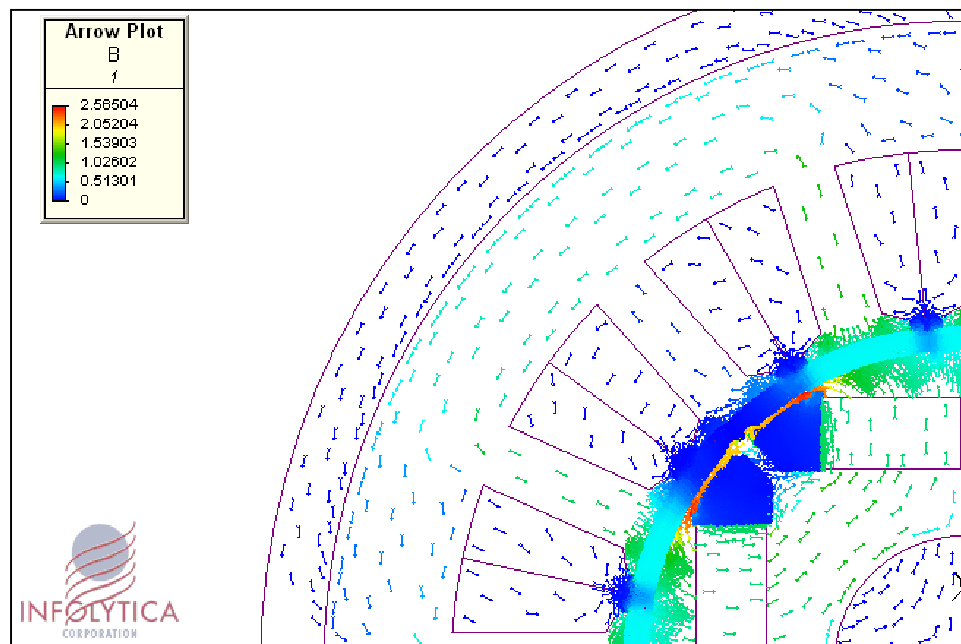

Figure 4: Arrow Plot of B

After the solve is complete, the *Field Sampler* and *Field Arc Graph* tools will be used to obtain the value of *B* in the air gap.

The mean diameter of the air gap is 25.5 mm and the machine's geometry is centered about the origin (0, 0).

Under the *Tools* menu, select the *Field Circle Graph* tool.

Ensure the *Keyboard Input Bar* is visible and enter (0, 0) for the centre point, and (25.5, 0) for a point on the circle's radius.

A graph window similar to the one below should appear.

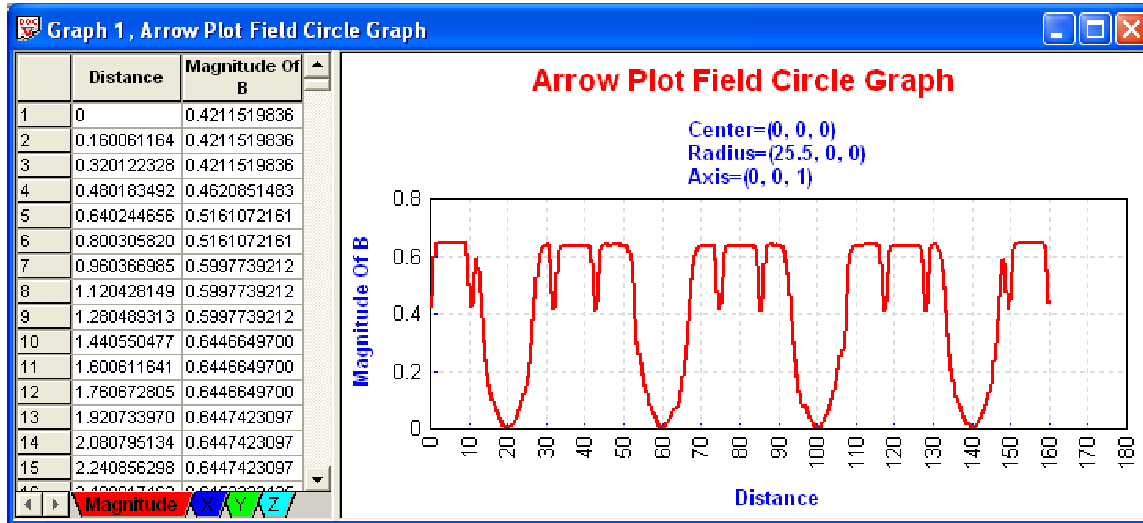**Figure 6: Graph of |B|**

Note the four tabs on the bottom left to display the magnitude as well as the three components (X, Y and Z) of **B**. Click to display the X and Y components (the Z component will be zero).
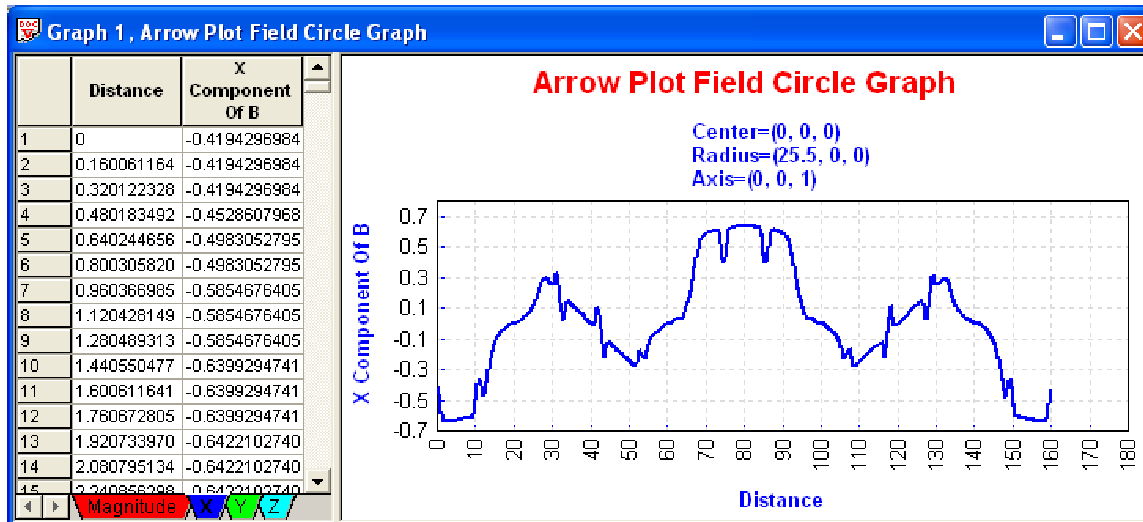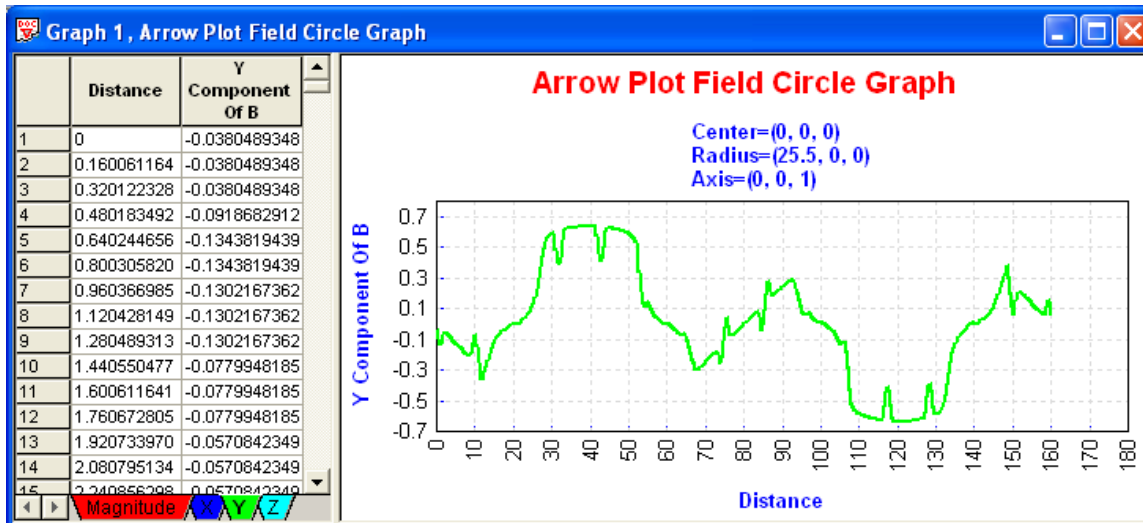

Figure 6: Graph of B$_x$

Figure 6: Graph of B$_y$

The next step is to obtain the radial component of the flux density.

Post Processing with Infolytica's Air Gap Flux tool

Infolytica provides an executable for the extraction of the radial air gap flux data and the calculation of the Cartesian and radial/tangential components, starting from 2D field solutions.

This tool requires the specification of the center point of the motor (the origin for the model investigated here), the mean radius of the air gap, as well as the start and end angle (in mechanical degrees) for the air gap computation.

The user is presented the option of extracting the Cartesian components (x and y) or radial and tangential components. Once the air gap flux waveform is extracted, the harmonic content can be calculated.

Extract Air Gap Flux

Sampling Contour

Sampling Radius   25.5   mm

Starting Angle   -90   Degrees

End Angle   90   Degrees

Harmonics

Maximum Harmonic   21

Poles   4

Harmonics	Amplitude	Phase
1	.7118734	179.9741
2	.0009384	22.28899
3	.0326238	.31633
4	.0063595	.01605
5	.0783803	-.27234
6	.0274005	-.44078
7	.0539942	-179.87628
8	.0192732	.29611
9	.0343801	.62894
10	.0150851	179.60749
11	.0317802	.37109
12	.0100466	-179.12924
13	.0163432	-179.43974
14	.0282692	.08905
15	.0040536	-2.96625
16	.0281969	.5213
17	.0136307	.35287
18	.0080961	179.81054
19	.0037889	176.78701

Go   Create Graph   Print   Save File   Exit

Figure 7: Air Gap Flux Tool

The tool requires the user to enter the following data:

- Sampling radius (the mean radius of the air gap, which for this model is 25.5 mm)

- Starting angle and end angle (measured counter-clockwise from the positive *x*-axis) (for this machine, use −90 to +90, respectively)

- Maximum Harmonic: the maximum harmonic for the calculation of harmonic content

- Number of poles (4)

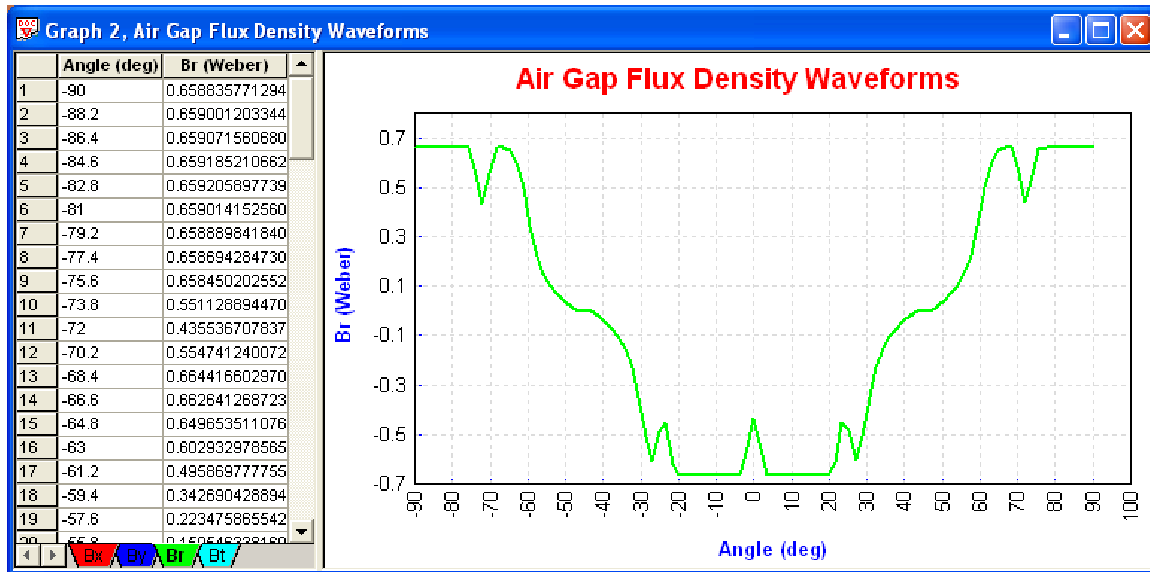Enter the data as shown above and press GO.

Figure 8: Graph of Air Gap Flux (radial) as a function of Mechanical Angle

The resulting graph shows the radial flux component as a function of angular position around the air gap. The dips in the curve occur in regions where a rotor magnet is located near a stator slot. A close-up of this area (corresponding to just over 90 degrees on the graph) is shown below.
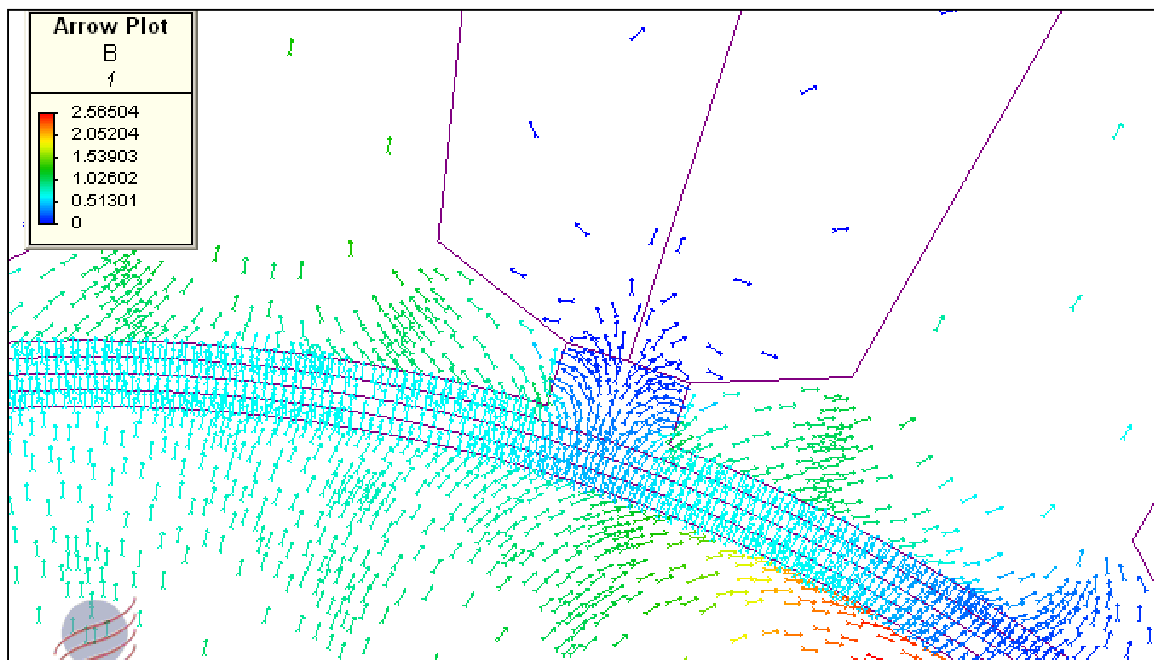
Open Circuit Voltage

Once the flux waveform is known, it can be used to calculate the open-circuit voltage of the motor while spinning.

For a single loop of wire encircling a time-varying magnetic flux $\phi(t)$, the voltage can be calculated as:

$$V = \frac{d\phi}{dt} = \frac{dB}{dt} A$$

where B is the magnetic flux density and A is the area of the loop.

For the BDC machine considered here, the area A is equal to the stack length, multiplied by the radius of the air gap, multiplied by the angle spanned by the winding (in this case, two slots).

The flux density can be approximated by a sinusoidal function equal to $-0.638 \cos(2\delta)$, where δ is the mechanical angle around the air gap.

This fundamental can be found as the first (fundamental) term of a Fourier series expansion. This can be obtained using Infolytica's Air Gap Flux tool, or third-party tools such as those found in Microsoft Excel or MATLAB, and the method is detailed in Appendix A.
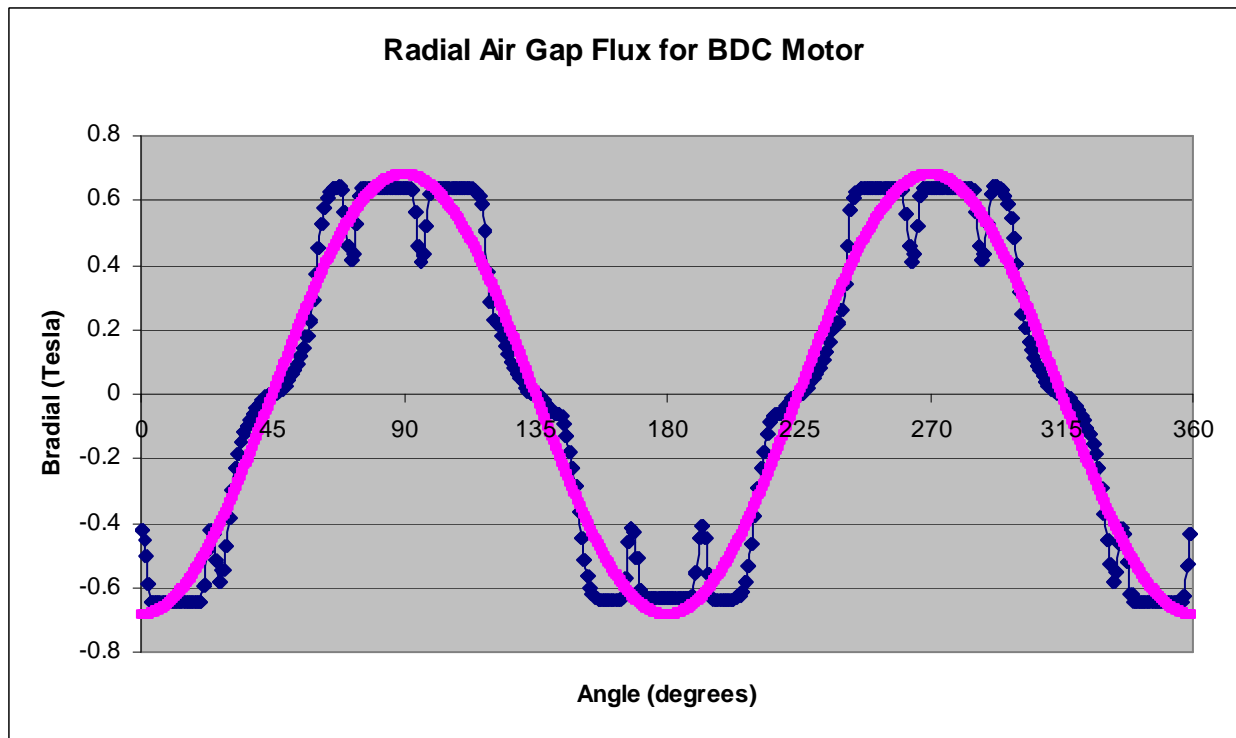
A plot of this approximation is shown below.

Figure 11: Plot of B_x

If the rotor is rotating, then from any reference point, the flux in the air gap at that point as a function time is expressed as $(-0.638 \cos \omega t)$, where ω is the angular frequency of rotation of the rotor.

Only the fundamental of the flux density is considered. For a more complex treatment of the air gap flux harmonics and a more accurate computation of open circuit voltage, refer to Appendix A.

The only remaining term is the number of turns in each winding *N*.

$$V_{oc} = N \cdot 2\omega \cdot l \cdot r_{gap} \cdot \delta \cdot (0.638 \sin 2\omega t)$$

For this motor:

- $l = 48.5$ mm

- $r_{gap} = 25.5$ mm

- $\delta = 24°$

- $N = 600$

Therefore, the final expression would be equal to 0.397 cos 2ω*t*.

There are actually five windings per phase in series, so the phase voltages are then multiplied by five, or 1.983 cos 2ω*t*.

Appendix A – Fourier Transform of Flux Function

In the air gap of the motor, the radial flux density is a time-harmonic function with a varied amount of harmonic content dependent upon the geometry of the motor. It is the radial flux that cuts the plane of the stator windings and is the cause of the back EMF generated as the rotor spins.

The open circuit voltage (as a function of rotational speed) is dependent upon this flux waveform, and the magnetic harmonics manifest themselves as electrical harmonics in the voltage waveform.

Often, however, an approximation can be made using simply the fundamental or a small number of lower-order harmonics to model the flux in the air gap.

This can be done using Infolytica's Air Gap Flux tool. This tool can be downloaded from Infolytica's website in the free add-ons section.

The tool will require you to enter the centre point of the motor (by default the origin, although any point can be used), the mean radius of the air gap and the start and end angles, measured from the positive x-axis and increasing in the counter-clockwise direction, and the number of sample points to be used. A sweep of 360 degrees will always give an appropriate answer but as a rule, a span of only one pole pair (two poles for this four pole machine, or 180 degrees) is needed. A tabular view of the radial and tangential air gap flux can be generated.

The tool will perform a spectral analysis on the air gap flux and compute the harmonic content of the flux waveform. This is useful in minimizing acoustic noise and torque ripple through the optimization of the rotor and stator configurations. The first value is the fundamental and in most case should be the largest of any of the harmonic components, and can be used to approximate the no-load voltage/speed relationship in the machine, as was done in the final part of this tutorial. The spectrum analysis can be viewed or exported.