INFOLYTICA
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Brushless DC Motor

Calculating Torque vs. Advance Angle

Introduction

In the design of the control scheme for a brushless DC machine, an important consideration is the advance angle γ. This is the angle (in electrical degrees) between the rotating magnetic field caused by the sinusoidal excitation of the stator windings and the rotating magnetic field due to the permanent magnets on the rotor. When the machine is operating as a motor, and the load torque is non-zero, the stator field will *lead* the phase of the rotor field by the angle γ.

As the advance angle is controlled by the drive circuitry attached to the motor, the designer is free to select an angle that provides an optimal motor operation.

This tutorial will outline the method for computing the performance of the machine at a given advance angle using MagNet.

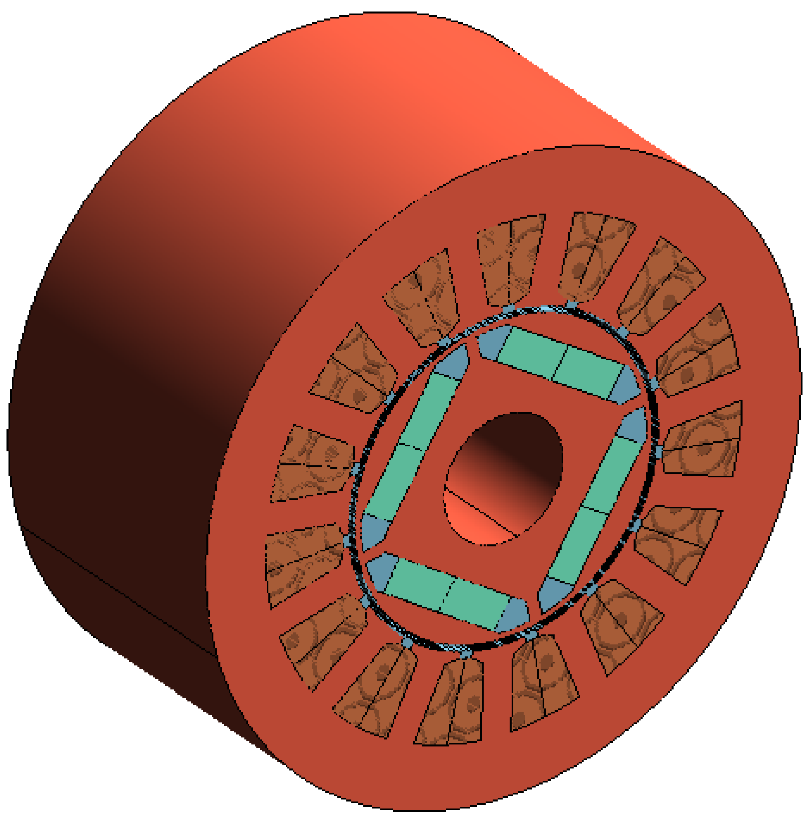

Figure 1: MagNet model of BDC motor

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.

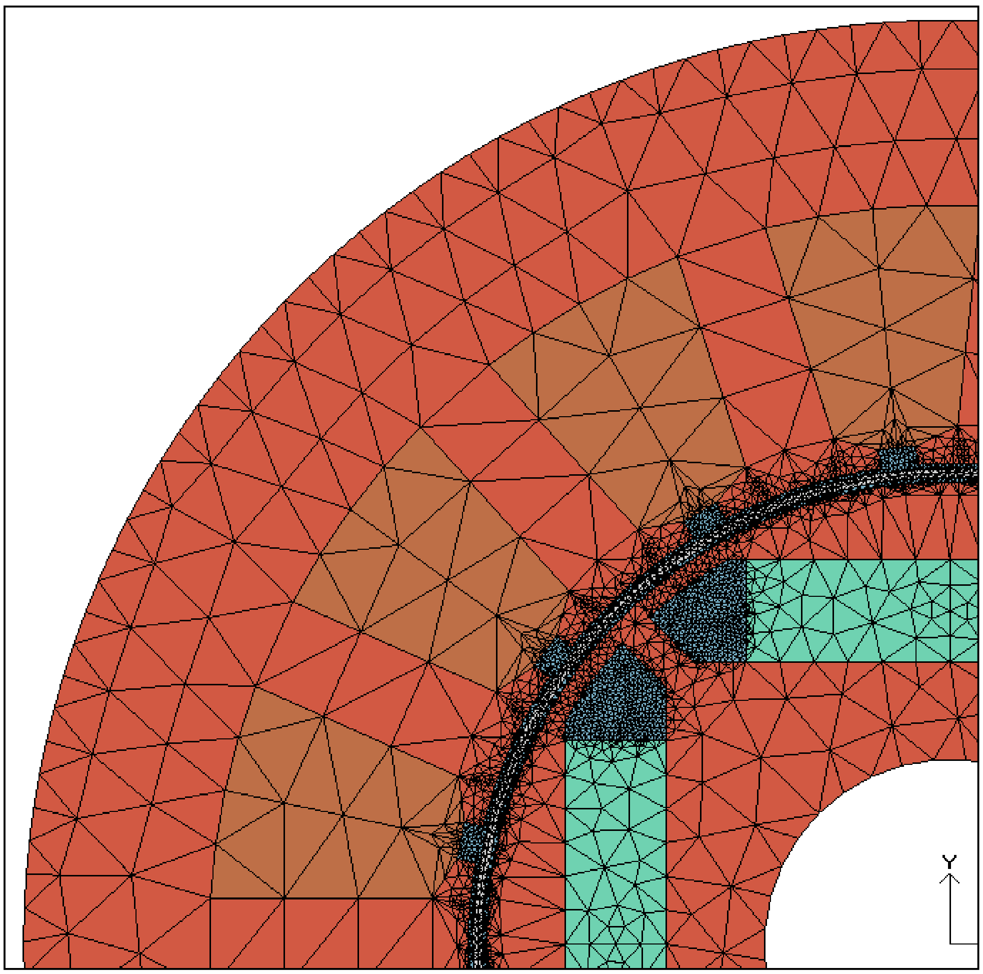

Figure 2: Quarter-model of BDC machine showing mesh refinement

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 torque and force 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.

When calculating the running torque for a given advance angle, to obtain an accurate representation of the torque ripple, it is important to set up this type of structure in the air gap to obtain good results.

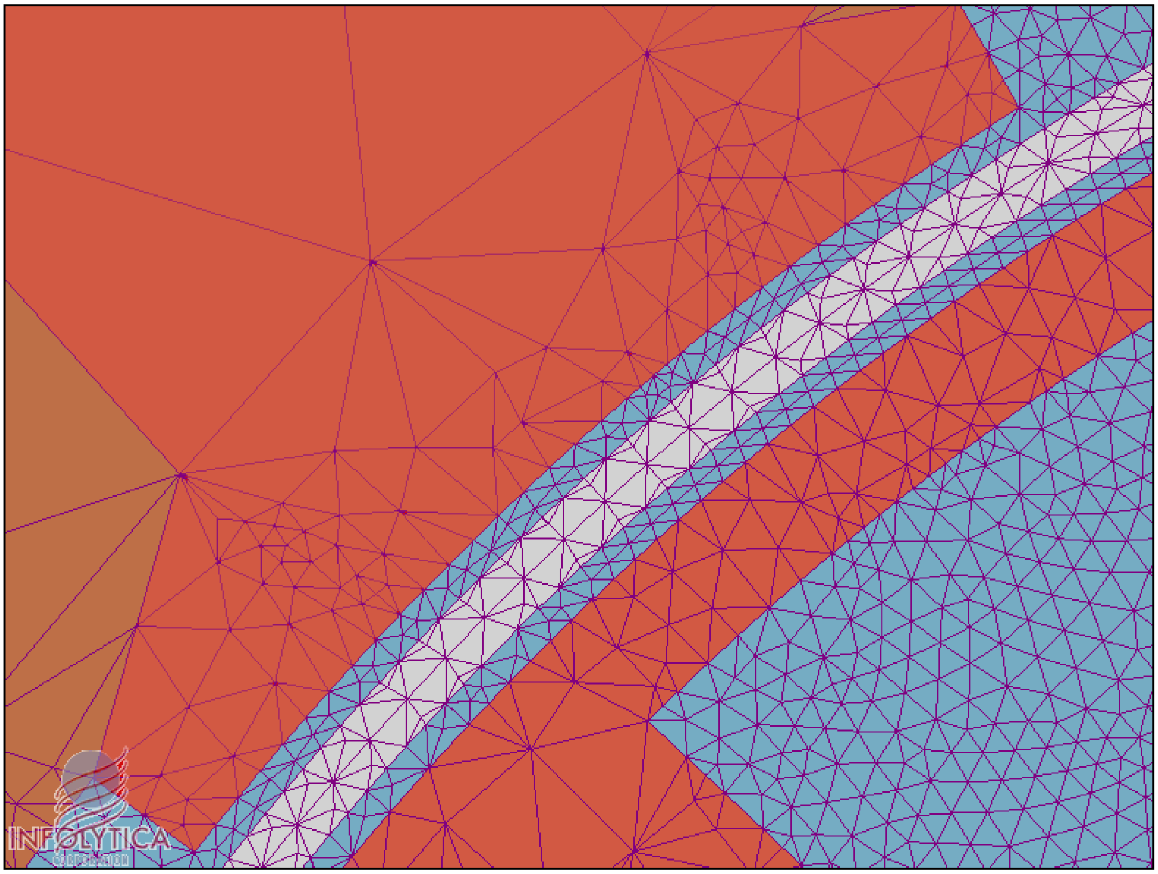

Figure 3: Air gap layout for optimal torque calculations

Torque, Advance Angle and Torque Ripple

The stator consists of a three-phase winding. A sinusoidal excitation will be applied to each of the windings, 120° apart.

Assume we consider a “snapshot” of the motor’s operation. The sinusoidal excitations are frozen in time. The rotor is then allowed to rotate freely to a point where there is no net torque acting upon it. This can be considered a reference point where the magnetic fields of the stator and rotor are aligned, no net torque is produced, and $\gamma = 0$. Assuming the motor was completely unloaded (zero torque), if the sinusoidal excitations were to begin varying again, the stator and rotor magnetic fields would rotate together in the same relative positions.

Considering the ‘snapshot’ again, but now assume the rotor is locked mechanically. Then imagine the sinusoidal stator excitations are advanced slightly by the advance angle γ. The stator magnetic field rotates a few degrees and is no longer aligned with the rotor. A torque is produced which attempts to rotate the rotor into alignment. As γ increases, the torque increases as well.

If the sinusoidal excitations begin varying again, the motor will rotate. If there is a load torque applied, the rotor and stator field rotate at the same speed, but with an offset of γ. As γ increases, the motor torque rises and then begins to decrease, up to the point where the rotor begins to lose synchronization with the stator field (pull-out torque). The machine will lose synchronism when $\gamma > 90°$.

The goal is to select the advance angle for optimal motor operation.

There is one more effect to consider. Because of the saliency (non-uniform shapes of teeth and pole faces), the distributions of magnetic flux due to the rotor and to the energized stator are not perfectly sinusoidal. Therefore, there are periodic interactions that occur as the motor rotates which lead to variations in the torque. Therefore, one ‘snapshot’ is not enough, as if the entire frame (both rotor and stator field) is rotated by the same amount, the torque may change. As far as the motor’s ability to drive a load, the quantity of interest is the average running torque. This must be obtained from a number of solutions obtained for different mechanical angles (however with the same relative position of rotor and stator field). However, the variations with changing mechanical angle (torque ripple) are also of concern as they can lead to unwanted vibration and noise.

Torque ripple is similar to cogging torque, however the cogging torque is measured with the machine unexcited, and does not consider the effects of the flux produced in the stator as a result of the stator excitations.

Setting up the Excitations

Some parameters will be added to the model as follows:

- **RotorAngle**: The rotor will be displaced from the initial position by this angle.
- **AdvanceAngle**: The stator magnetic field will be *further* displaced from the rotor position by the advance angle (i.e. total stator field displacement = **RotorAngle** + **AdvanceAngle**
- **Stator Current:** The peak current per turn in the stator windings.
- **Poles:** The number of rotor poles (4).
- **PolePairs**: The number of rotor pole pairs (2).

The current in the three phase windings will be specified as:

- Phase A: cos (**PolePairs** * **RotorAngle + AdvanceAngle)**
- Phase B: cos (**PolePairs** * **RotorAngle + AdvanceAngle – 120°)**
- Phase C: cos (**PolePairs** * **RotorAngle + AdvanceAngle + 120°)**

The factor of 2 is the conversion from mechanical to electrical degrees (equal to 2 for a 4 pole machine)

On the *Coil* page, click on **PhaseACoil** and assign the following parameters:

Current: %StatorCurrent * cos(%RotorAngle%deg + %AdvanceAngle%deg)

For **PhaseBCoil** and **PhaseCCoil**, assign

%StatorCurrent * cos(%PolePairs * %RotorAngle%deg + %AdvanceAngle%deg) – 120%deg

%StatorCurrent * cos(%PolePairs * %RotorAngle%deg + %AdvanceAngle%deg) + 120%deg

Note: Although there is a parameter for **Phase,** it only applies when using the Time-Harmonic solvers. This problem is solved using the MagNet Static 2D solver, and what we are inputting is the value of the sinusoidal current at a single point in time. The Time-Harmonic solver assumes all quantities are perfectly sinusoidal, meaning all materials must be necessarily linear. As magnetic saturation is one of the principles that enable an interior permanent magnet machine to operate, it is not possible to make this assumption and use the Time-Harmonic solver. Also, since at steady state operation, the rotor and stator fields are synchronized, there is no time-varying magnetic flux wave in the air gap (the flux varies only with position, in a rotating reference frame). Synchronous machines cannot be analyzed with the Time-Harmonic solver.

Furthermore, the analysis performed here neglects motion effects (motion induced currents) and also ignores eddy currents produced by time-varying fields. To include the influence of these effects, the MagNet Transient 2D solver can be used to obtain the eddy currents induced by time-varying fields, and the Transient with Motion 2D solver can be used to include the motional effects.

Parameterizing the Rotor Position

These calculations will require a series of solutions with the rotor in various angular positions.

The following steps will lead you through the assignment of the various parameters

1. Select the “RotorSteel#1” component and open the *Properties* page.
2. Under the *Parameters* tab, locate the parameter called **RotationAngle** and set the *Expression* to %RotorAngle %deg. This will cause the rotor steel component to be rotated by **RotorAngle** for each of the problems.
3. Repeat Step 4 for RotorAir, RotorInnerAir#1 - #8, and Magnet #1-#8. You may want to make use of the script form *ManageParameters.frm* to make this task easier. This script form is available on Infolytica’s website (www.infolytica.com) in our documentation center at Scripting → Samples and Utilities → Modeling→ Managing Parameters.

Aligning the Rotor and Stator Field

We wish to analyze the motor under normal, steady-state running conditions. This implies that the rotor and stator fields are aligned at zero torque, and displaced by the angle γ as the load increases. Therefore it is necessary to determine the relative position of rotor and stator so that the fields are aligned and the torque is zero when $\gamma = 0$.

If this step is not done, the simulation will reflect the performance of the machine in an unsynchronized state.

This can be done in a number of ways. For simple machines and/or experienced designers, a zero-torque position may be obvious from observation of the model, such as in the simple 4-pole, 4-slot machine below. With a more complex geometry, it may not be as obvious.

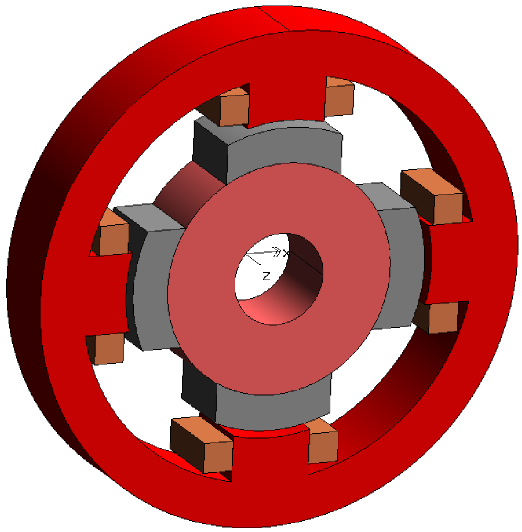

Figure: 4-pole, 4-slot machine aligned at a zero-torque position

Generally, γ is considered zero when the *d*-axis of the rotor is aligned with the centerline of one of the poles of the phase A windings.

If a plane of symmetry can be observed in the machine at a given rotor position (with respect to both geometry, excitation and permanent magnet polarity), the net torque on the machine will be zero. It may help to solve the problem and view a shaded plot of Jz to see the symmetry in the excitations.

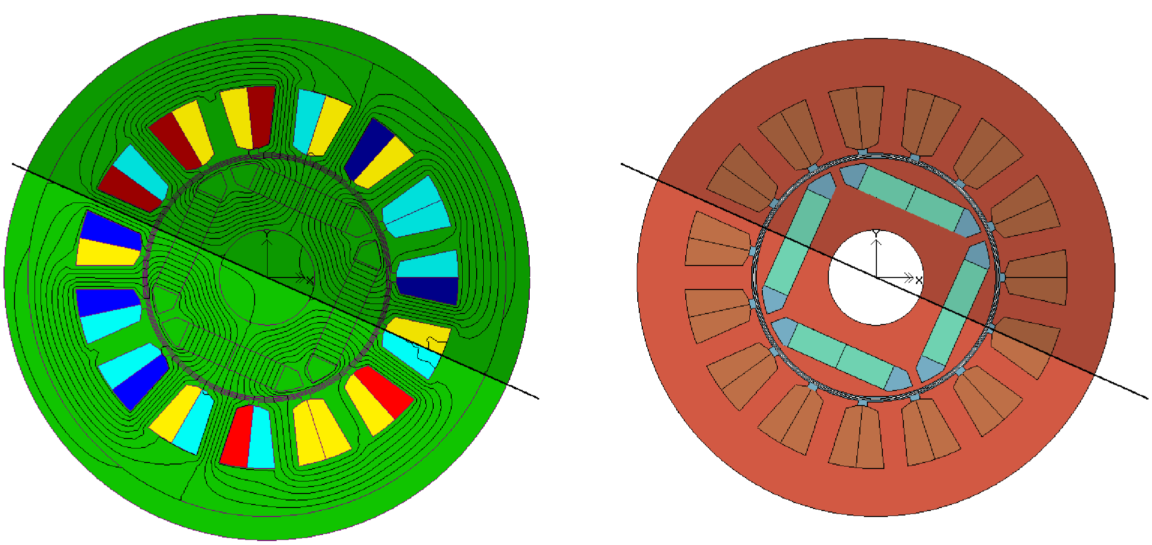

Figure 4a,4b: Motor geometry and current density showing symmetry plane.

In Figure 4b, the red and blue coil pairs correspond to Phase A. Remember that because of this machine's fractional slot winding, there are two slot pairs for the stator pole in the upper-left part of the motor.

It may be easier to excite only the phase A coils and align the rotor with the resulting field. Viewing a shaded plot of J_z, combined with a flux-function contour plot will allow you to see the stator "poles" and rotate the rotor into alignment with the stator field which is produced.

If still no solution can be found, the following procedure should be followed:

- Set the **RotorAngle** to a position where a pole axis of the rotor aligns with either a tooth center or slot center. This will ensure the motor is geometrically symmetric.
- Set a number of values for the **AdvanceAngle** parameter.
- Solve the problem and view the rotor torque for various values of the advance angle (there is no need to go more than 180°). Find a zero crossing with a negative slope—this will correspond to the location of a zero-torque point. It may be necessary to refine the solution around this point to get more accurate results.

The following graph shows a sample results from the final method. The advance angle is parameterized from 0° to 90° in increments of 10 degrees.

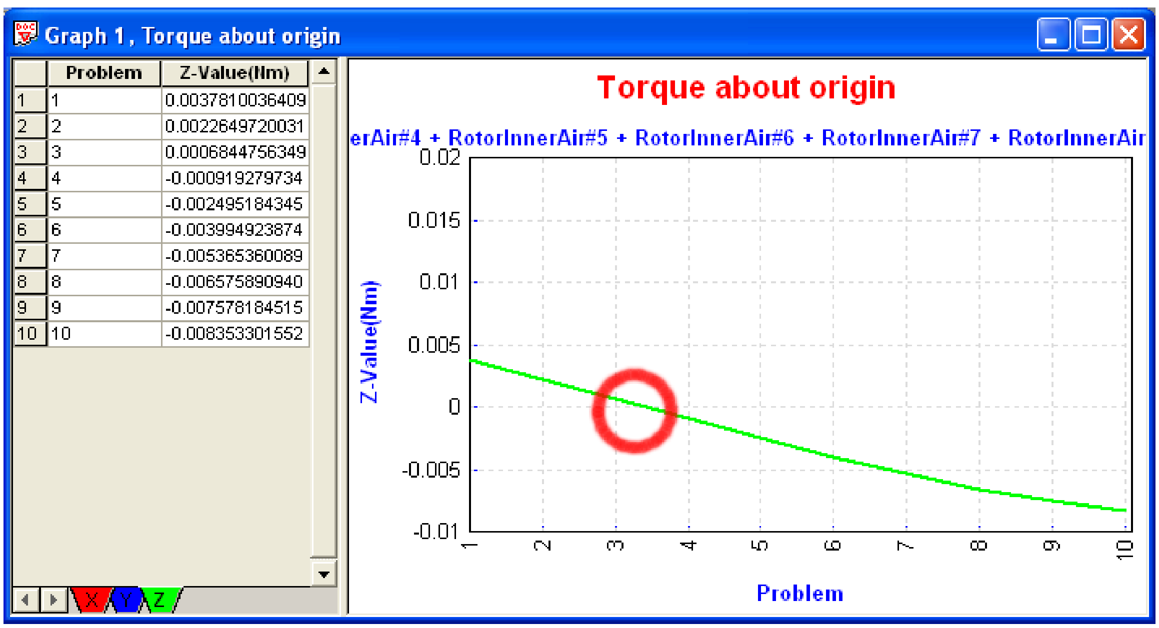

Figure 5: Torque vs. Current Advance Angle, finding a zero-torque point

The negative slope zero torque position represents $\delta = 0$.

Once this position is found, it is usually easier to add offsets to the **RotorAngle** and **AdvanceAngle** to prevent confusion, such that when **RotorAngle** is zero, and the motor is unexcited, the motor is at a zero-torque point, and that when **RotorAngle** and **AdvanceAngle** are both zero, the energized motor is also at a zero-torque point.

To set the symmetric rotor position as the baseline position, you can either rotate the entire rotor using geometric transformations, or add another parameter, which will be added to **RotorAngle**.

For the excitations, it is easiest to add a second parameter, with a name like **AdvanceAngleOffset.** Then, in the *Coil* parameters, change all instances of %AdvanceAngle to %AdvanceAngle + %AdvanceAngleOffset.

For this model here, follow these steps to align the rotor and stator fields.

1. On the *Coil* page, select the **PhaseACoil** to highlight its windings.

2. Note that there is a stator pole lying just below the positive x-axis. We will choose this as a starting point and align the rotor there.

3. Select all of the rotor components, and using *Model→Transform Components*, rotate them all 24 degrees clockwise (-24 degrees)

4. Solve only the first problem (**RotorAngle** = 0). Also ensure that the AdvanceAngle is 0. The resulting torque should be nearly zero (of the order 10^{-5} or so).

Note that the opposing pole is made up of two pairs of windings (as the motor is wound with a fractional slot pitch). Fractional slot windings may mean that some of the stator and rotor poles do not line up (in this case, the q-axis rotor poles only align approximately with the stator poles)

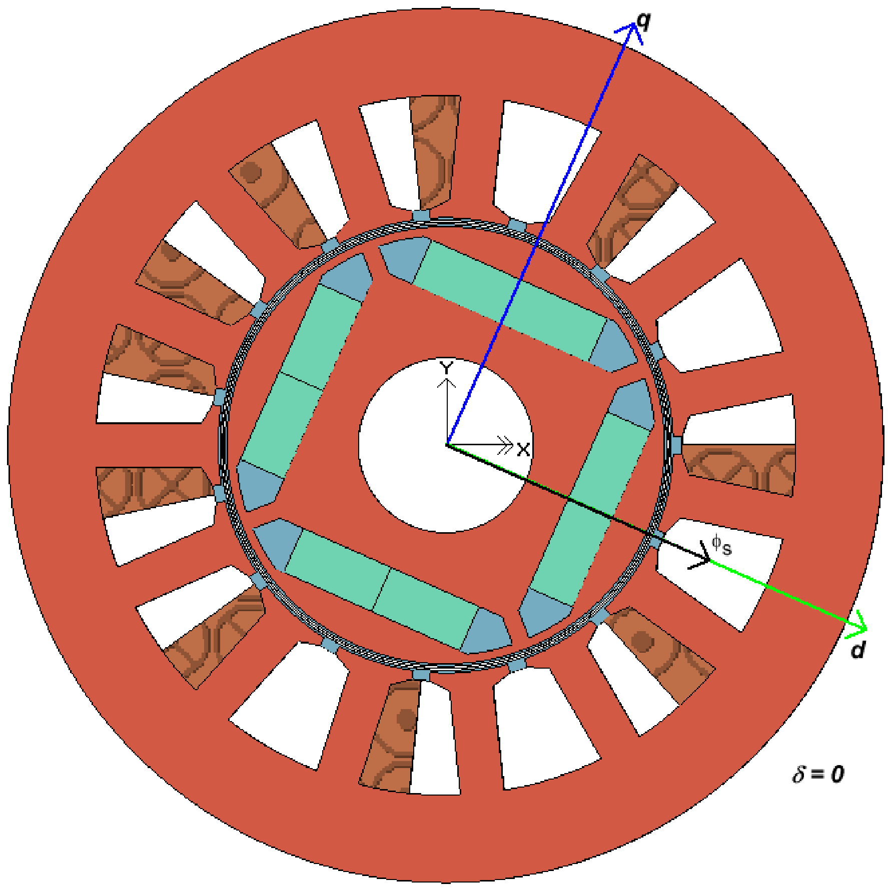

Figure 6: d-q axes and stator flux plot for aligned stator/rotor fields (phase A coils shown only)

Setting the Solver Options

To ensure accurate solutions for torque, the solver tolerance settings must be tightened from MagNet's default settings. Under *Solve→Set Solver Options*, make the following changes:

- Polynomial order: 2
- CG Tolerance: 1e-4% (or 0.0001%)
- Newton Tolerance: 1%

Setting up the problem to find the running torque

Now that the position and excitations corresponding to δ = 0 have been found, a series of solutions can be performed to find the average torque as the rotor position varies. This analysis is performed at a constant advance angle.

The torque analysis will be performed over a 45-degree sweep, with a solution every 1 degree for a total of 46 positions.

Follow these steps to set up the parameterization that is needed.

1. In the *Object Page*, open the *Properties* page for top level model.
2. Create the following parameters on the *Parameters* tab:

Parameter	Type	Expression
RotorAngle	Number	0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20, 21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37, 38,39,40,41,42,43,44,45

3. View a few problems and verify that the rotor is turning.

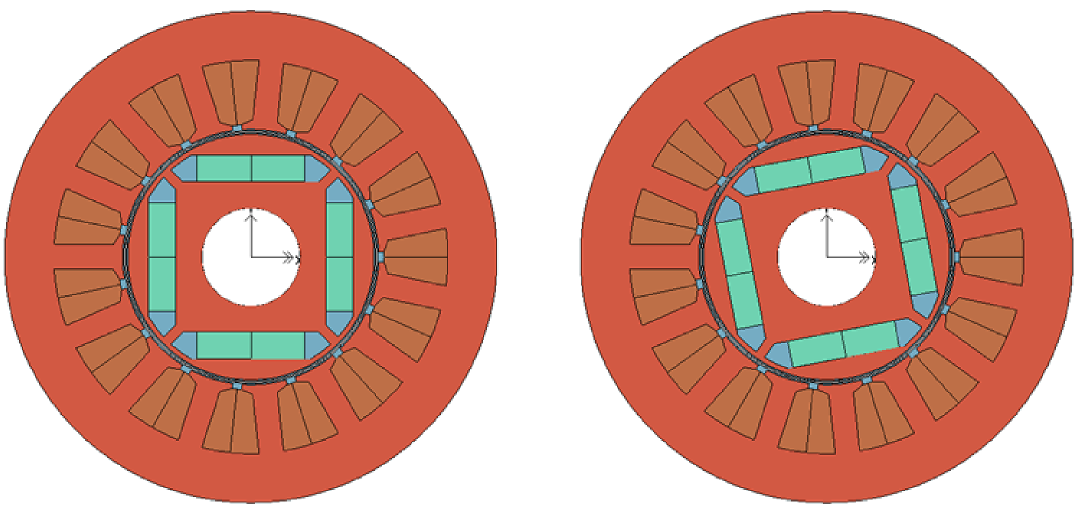

Figure 7a, 7b: Rotor parameterized position

4. Set the **AdvanceAngle** parameter to 12 degrees ("12%deg").
5. The problem can now be solved for all 45 problems.
6. The rotor torque can be viewed from the *Post-Processing Bar* as a function of rotor position.

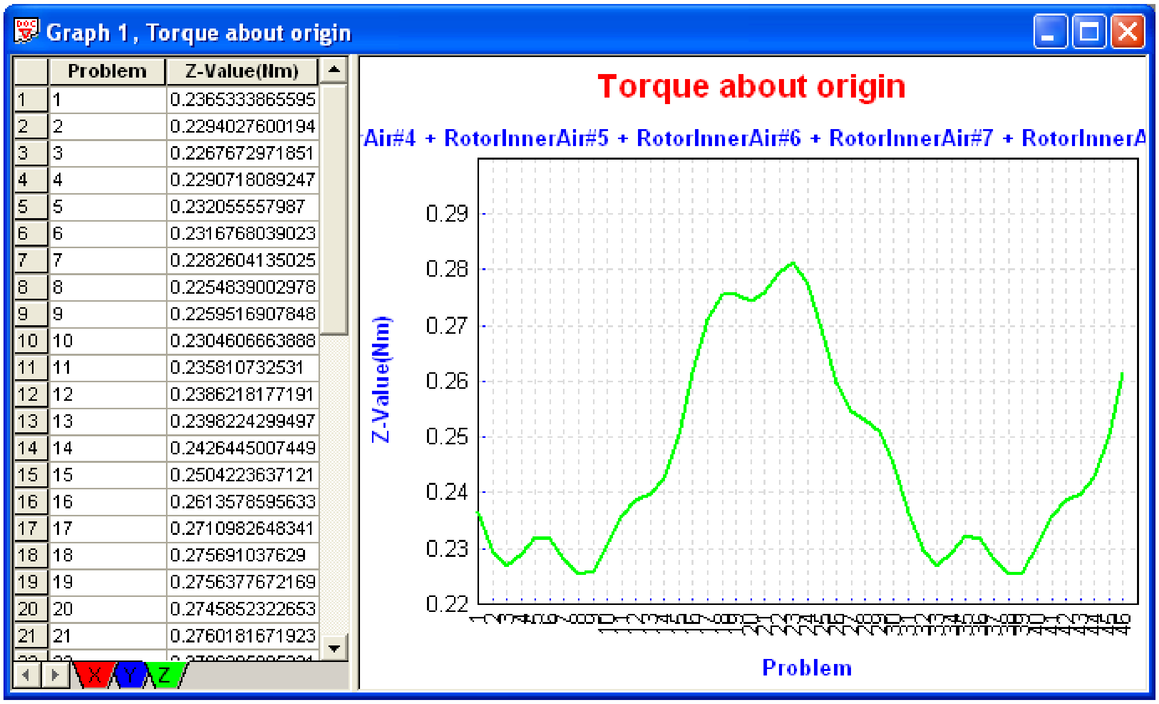

Figure 8: Running torque for δ = 12°

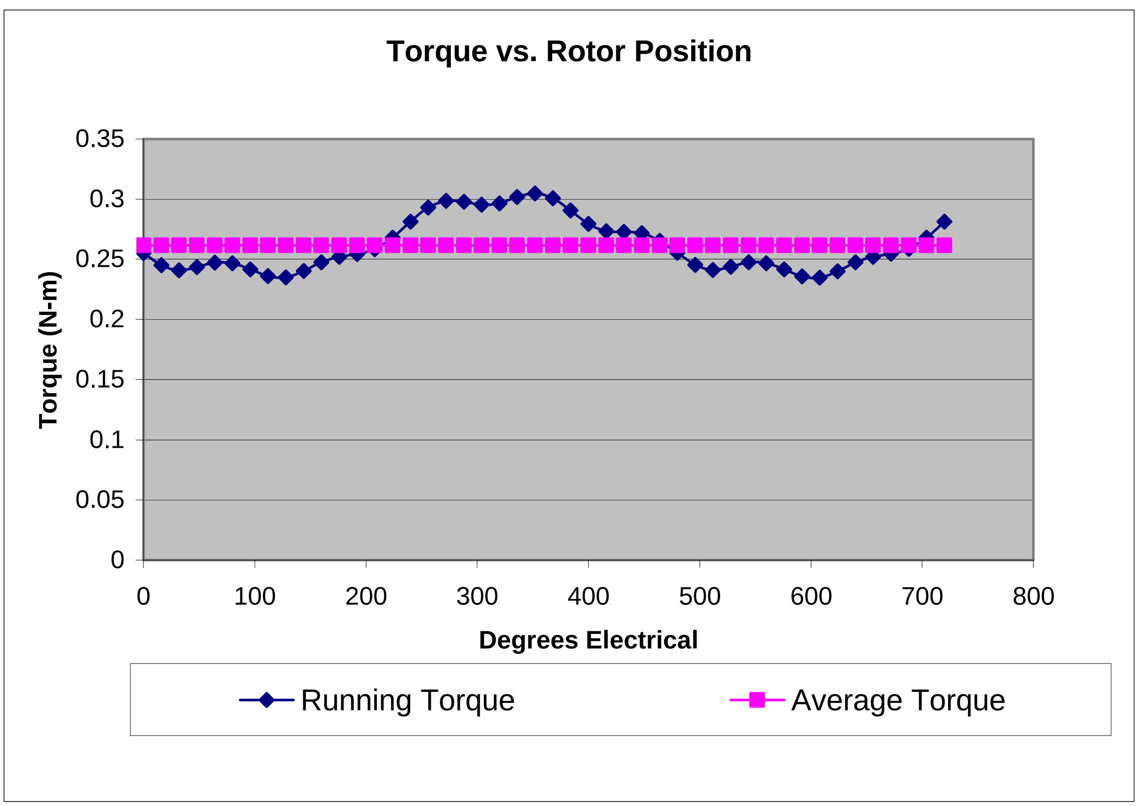

Figure 9: Average and Running Torque for δ = 12°

From the previous graph and associated data, the motor has an average running torque of 0.261 N-m, and a peak-to-peak torque ripple of 0.070 N-m.

This can be repeated for various advance angles to determine the effects of the value of δ on the peak torque available from the motor.

The following curves are plotted for δ = 12,30,45 and 90 degrees. As a rule, the maximum torque appears somewhere near 90°, but this varies depending on the winding resistance and other factors.

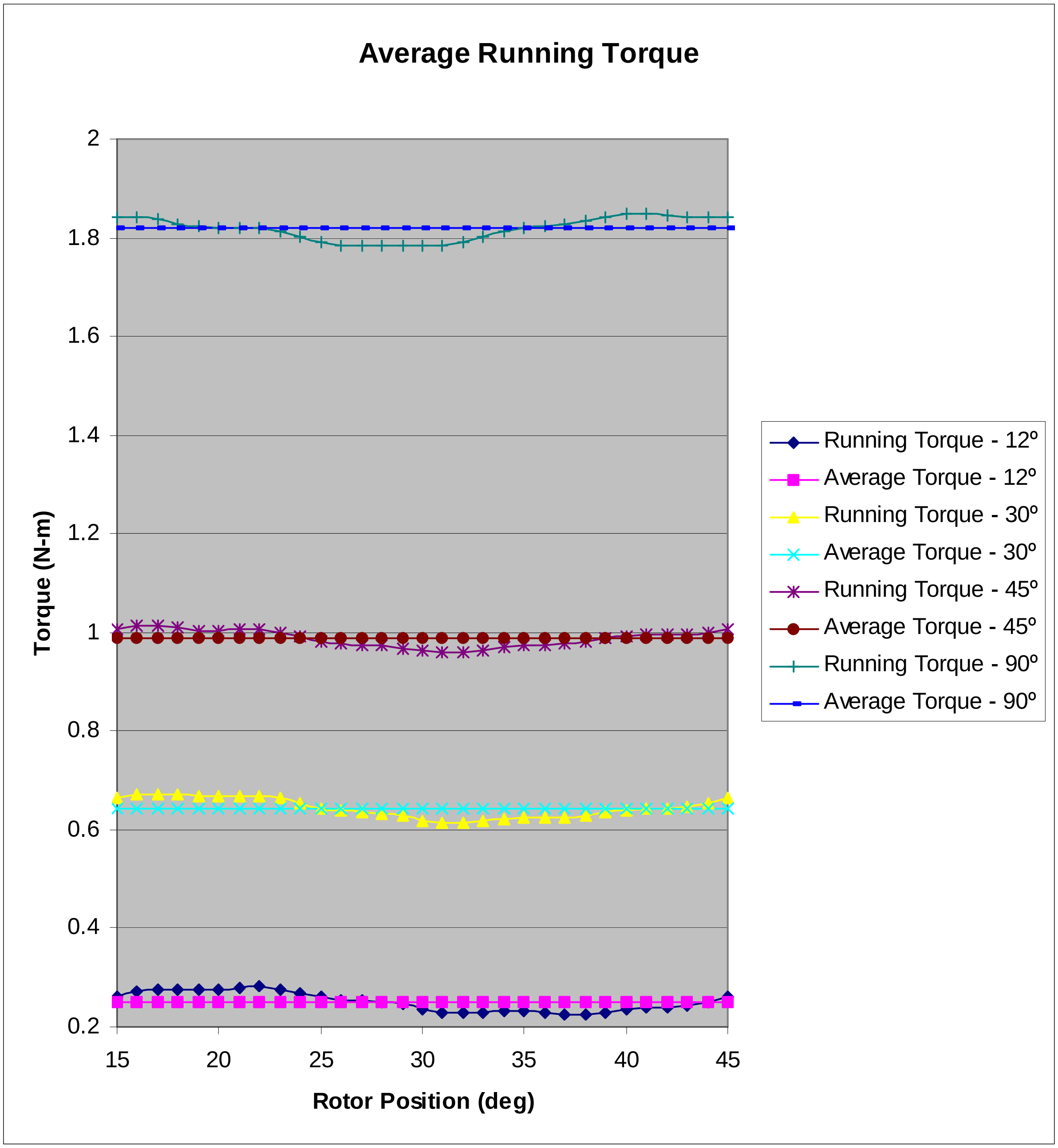

Figure 10: Torque vs. Rotor Position for δ = 12°, 30º, 45º and 90º