Instructor’s Guide

Electromagnetics in Power Engineering
Maxwell 3D Simulations of a Residential Wind Generator

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Introduction

These activities were designed for upper-level undergraduate engineering or physics students, and electromagnetic concepts were emphasized, but of course an instructor could modify the activities or use the resulting simulations for a wide range of audiences or purposes. The cost of the Ansoft/Ansys Maxwell 3D software ranges from a few thousand to several thousand dollars per year for academic institutions, depending upon the number of licenses and other options. The cost is much higher for commercial organizations. The software is quite advanced and is widely used in the motor/generator industry, and the students will gain fundamental CAD skills and an understanding of issues involving numerical simulations that would apply more generally. In addition, NAU has created other activities in which students use Maxwell 3D simulations to explore a range of other electromagnetic concepts, with power engineering as the unifying theme or application. The Maxwell 3D User’s Guide contains additional tutorials. In total, these may help you justify the software’s recurring costs.

As stated above, the software is advanced, which translates into many possible difficulties or errors that students may face during lab time. We tried to embed tips, warnings, checklists, example results, and so forth throughout the procedures to guide students in preventing and troubleshooting any errors, and to reduce their frustration and the debugging burden on the instructor. However, it’s always a good idea to test procedures at least once, well ahead of lab time. You’re encouraged to contact the author (Dr. Allison Kipple, allison.kipple@nau.edu) with any problems, concerns, recommended changes, ideas for or links to additional simulations, etc. Many minds are better than one!

Since we embedded the “tips and tricks” into the procedures, this core of this guide will include example answers to the concept and design questions. You may choose to assign a subset of these questions. To save time, you may also choose to cut some activities from Session III.

Session I - Modeling the Air-X Rotor and Stator

Summary of Specific Information Requested for the Lab Report

From the Ansoft/Ansys Maxwell 3D Software:

1. Screen shots and comparisons of three cores from the list of User Defined Primitives.
   - Common differences between core types include the use of electromagnets (i.e., coils) compared to permanent magnets to produce the magnetic field (or, in the case of the induction motor using the SquirrelCage core, no active excitation on the rotor); permanent magnets
mounted internal to vs. around the edge of the rotor; salient vs. non-salient coil windings; orientation of the coil windings (e.g., different in the ClawPoleCore).

2. Measurement of the gap between two magnets when the rotor’s Embrace parameter is 0.8, and the final Embrace value which made the gap approximately 1.0 \( \text{mm} \), along with the final gap measurement.
   - The original gap is \(~2.2\ \text{mm}\) wide. An Embrace value of 0.86 gives a gap that is 0.98 \( \text{mm} \) wide, while an Embrace value of 0.85 gives a 1.19 \( \text{mm} \) gap.

3. The value of the rotor’s Offset value which made the magnets’ edge thickness approximately 5.0 \( \text{mm} \), and the model’s measurement of that thickness.
   - An Offset of 5 \( \text{mm} \) produces a magnet edge thickness of 5.04 \( \text{mm} \). Figure 8 lists this value and an Embrace of 0.86.

4. Screen shot of your rotor model.
   - It should look similar to Figure 7.

5. Screen shot of a SlotCore SlotType other than #3.
   - (A few possibilities.)

6. Screen shot and example application of skewed slots (or skewed coils).
   - The squirrel cage rotor of an induction motor often has skewed coils. An internet image search on “squirrel cage induction motor” brings up several examples; fans and vacuum cleaners are common applications.

7. Screen shot of your selected ferromagnetic material’s hysteresis curve. Discuss whether the data indicates that the material has linear or non-linear magnetic properties, and whether it is a soft or hard magnetic material.
   - The graph is nonlinear, indicating nonlinear magnetic properties. The hysteresis curve is narrow, the material changes magnetization easily, indicating a soft magnetic material.

8. Two screen shots showing different views of your combined rotor / stator model.
   - (Many possibilities.)

**Concept and Design Questions:**

1. Why might permanent magnets be a better design choice for creating the Air-X rotor’s magnetic field, rather than electromagnets? What is an application where electromagnets might be the better choice? Explain.
   - Electromagnets require current and therefore power to create a magnetic field. In an off-grid setting, any additional use of power is problematic. The electromagnets also create a lot of heat which would need to be dissipated; this could be especially problematic when the wind isn’t blowing. However, electromagnets can dynamically change the strength of the magnetic field and hence the power output when the rotor’s speed is constant, which is particularly useful for synchronous utility-scale power generation.

2. Describe one benefit and one drawback of using neodymium magnets in the Air-X design, rather than another type of permanent magnet.
Neodymium magnets are much stronger than most other permanent magnets. Therefore, the changing magnetic fields through the stator’s coil are stronger, so the resulting EMF and power produced by the generator is greater. However, neodymium magnets are relatively expensive, can chip or break easily, and can be dangerous to handle (e.g., because they have such a strong attractive force with each other, and can pinch your skin when they pull together).

3. In what country are most of the rare earth magnets, such as those used by the Air-X, made? Find and briefly summarize a recent article that discusses issues with using rare earth magnets in electric generators, which may or may not relate to the magnet’s country of origin.
   - Most neodymium mines are located in China, and China manufactures most neodymium magnets. Students may find articles about the environmental effects of neodymium mines, export/import restrictions, high costs that have caused engineers to seek other solutions, etc.

4. What do you think is the purpose of the band that wraps around the Air-X magnets?
   - It helps to hold the magnets in place at high rotor speeds.

5. What is the effect of attaching magnets to a stainless steel rotor core? How is stainless steel different from, say, copper in terms of its behavior around magnets?
   - Stainless steel will become magnetized such that the magnets will have a strong attractive force to the rotor core, helping to keep the magnets in place. In many other rotor configurations, a ferromagnetic core will have a strong effect on the resulting magnetic field passing through the stator as well.

6. List one advantage and one disadvantage of using a smaller diameter wire in a coil.
   - A smaller wire will have larger resistive losses, but you can wrap more loops of a smaller wire through a given volume to get a higher EMF across the coil. Smaller wires are easier to coil, but the resulting “floppy” coils may cause problems (e.g., may get caught in the spinning rotor).

7. Discuss the rationale for coating magnet wire and coils with enamel.
   - If magnet wire (i.e., thin wire used to create magnets) weren’t coated in enamel, it would short to itself rather than following the coiled path, so no magnetic field or a much smaller magnetic field would be produced. The coils are often covered with another enamel coating to stiffen the coils and provide extra protection against the wires being chaffed and shorted.

8. Why are plastic inserts placed around each slot in the stator? Why is a plastic insert placed into the slot’s opening?
   - The plastic inserts protect the wire from being scraped and then shorted against the sharp slot edges, both while the coils are being wound and during use. The inserts in the slot’s opening keep the coil from vibrating out of the slot and getting caught in the spinning rotor.

9. One end each phase’s wire is connected to the Air-X circuit board, while the other ends of the three coils are soldered together. What is the name for this type of three-phase connection?
   - Wye connection

10. Most stators are made of a “soft” magnetic material with a high relative permeability. Explain why.
    - The material has a high relative permeability so that it strongly enhances the magnetic field produced by the rotor. The material is soft so that it can easily change direction, following the changing magnetic field produced by the spinning rotor.
11. In your report, explain the rationale for using laminated sheets for the stator’s core, and explain in terms of physics phenomena why stacking the sheets in the Z-direction is the best option. Also discuss why engineers often construct larger cores from a specialized form of steel, labeled M19, even though it’s more expensive.

- Current cannot flow across the laminations, so the induced eddy currents and their associated losses are prevented in the stator core. When the laminated sheets are stacked in the Z-direction, they’re easier to fabricate and stop the eddy currents near each coil. If the sheets were stacked in the X-direction, eddy currents would not be stopped in places where the sheets were in a similar plane as the stator coil.

- About M19 steel: “When low carbon steel is alloyed with small quantities of silicon, the added volume resistivity helps to reduce eddy current losses in the core. Silicon steels are probably of the most use to designers of motion control products where the additional cost is justified by the increased performance. These steels are available in an array of grades and thicknesses so that the material may be tailored for various applications. ... The grades are called out, in increasing order of core loss by M numbers, such as M19, M27, M36 or M43, with each grade specifying a maximum core loss. ... The higher M numbers (and thus higher core losses) are progressively lower cost, although only a few percent is saved with each step down in performance. M19 is probably the most common grade for motion control products, as it offers nearly the lowest core loss in this class of material, with only a small cost impact, particularly in low to medium production quantities.” (From http://www.protolam.com/page7.html)

12. Include a picture of a lap coil and a wave coil for reference.

- The following is one example, from http://www.powerelectricalblog.com/2007/03/armature-and-its-windings.html
**Session II – Setting Simulation Parameters**

**Summary of Specific Information Requested for the Lab Report**

*From the Ansoft/Ansys Maxwell 3D Software:*

1. Screenshot and discussion of the model after splitting it across the XZ plane.
   - This question was mainly designed to make students aware of what they were doing, rather than blindly following procedural steps. The answer isn’t difficult: the model was split across the XZ plane, with the positive side being saved after the split.

![Split Model](image1.png)

2. Screenshot of the final reduced model, 1/12 of the original model.
   - The screenshot should look similar to Figure 16 in the procedures.

3. Screenshot of the Band object. Discuss the purpose of the Band object.
   - The screenshot should look similar to Figure 23 in the procedures. The Band object encloses/defines the objects that will move.

4. Screenshot of the visualization showing the magnitude of the generator’s magnetic fields, at a time step of the students’ choice.
   - The result should look similar to the image below. If the students chose a different time step, the rotor will have rotated farther.

![Magnetic Fields](image2.png)
5. Screenshot and interpretation of the visualization showing the magnetic field vectors.
   - The result should look similar to the image below, again depending on the time step. The students may also have chosen different options for the vectors, such as changing the arrow’s size, adding vector tails, and so forth. The magnetic field vectors should be directed outward (i.e., toward the stator) from the north magnet, and inward to the south magnet. The stator teeth opposite to a permanent magnet should be magnetized to align with that magnet’s field. The vectors on the symmetry planes should match, i.e., the vectors going outward on one symmetry plane should go into the other symmetry plane. The overall vector field should circulate between the north and south ends of each magnet, zero divergence of $B$.

![Image of magnetic field vectors](image.png)

6. Screenshots of the numerical meshes produced by Maxwell in the Transient solution mode. There should be one screenshot that focuses on the magnets’ faces, another that focuses on the rotor’s teeth, and a few different views of the mesh across the entire model. Interpret the variations in these meshes; for example, explain in terms of the underlying electromagnetics why the mesh needs to be finer in some areas.
   - The image of the rotor’s teeth should look similar to Figure 26 in the procedures. Examples of the other mesh images are included below. The mesh is finer in areas where the magnetic field is changing rapidly and when where the object’s surface is curved rather than straight.

![Image of numerical meshes](mesh.png)
7. Screenshot of the plot showing the magnetic flux through the Phase A coil and the resulting EMF induced across that coil as a function of time. Description of the mathematical relationship between the magnetic flux and the induced EMF, and a discussion of whether the plot demonstrates that relationship.

- The EMF induced across a coil is proportional to the change in the magnetic flux passing through the coil. In the plot, when the magnetic flux is increasing or decreasing linearly, the EMF is constant. A faster change (steeper slope) in the magnetic flux produces a greater EMF magnitude. Zero change in the magnetic flux would result in zero EMF.
Session III – Refining the Air-X Simulation

Summary of Specific Information Requested for the Lab Report

From the Ansoft/Ansys Maxwell 3D Software:

1. Screenshot of the plot showing the magnetic flux through and the induced EMF across the Phase A and Phase B coils when the time step is 0.5 ms. Comparison between this plot, the plot generated in Session II with a step of 1.0 ms, and the plots shown in Figure 27 of the procedures which show time steps of 0.2 and 0.1 ms.
   ○ In the Session II plot, the magnetic flux trace looks like a triangle wave while the induced voltage looks like a square wave. As the time step is refined, the magnetic flux trace begins to look more like a sine wave with narrow peaks, or perhaps a smoothed triangle wave, while the induced voltage looks more like a smoothed square wave with ripple.

2. Obtain screenshots of objects’ meshes after 5 adaptive passes. There should be one screenshot focusing on the curved side of the magnets, one screenshot focusing on the side of the rotor teeth facing the magnets, and a couple screenshots showing the combined coils, stator, rotor, and magnets. Discuss how these meshes differ from those obtained in the previous session.
   ○ The major difference in the meshes involves further refinement of the magnet and rotor teeth sides that are facing the gap, and refinements extending from the magnets into the rotor.
3. Obtain a screenshot of the plot of the magnetic flux through and EMF induced across the Phase A coil as a function of time, when the refined mesh is used and the time step is 0.5 ms. Compare this result to the one obtained in the previous section, where the time step was 0.5 ms but the mesh was not as refined.

- The differences between this plot and the one obtained with the coarser mesh are not that significant. The finer mesh makes a more noticeable, though still not tremendous, difference when the time step is 0.1 ms, as demonstrated by Figures 27b and 28 in the procedures.
4. Save a screenshot of your magnets’ altered coordinate systems, as well as a screenshot of the resulting magnetic flux through and voltage induced across the Phase A coil after the magnets’ coordinate systems have been altered. Compare this plot to those obtained previously.

   - The screenshot of the altered coordinate systems should look similar to Figure 29 in the procedures. The new coordinate systems primarily affected the ripple in the induced EMF. The strong fields at the magnets’ sharp edges are likely a cause of these ripples but are difficult to correct – not worth the lab time and student frustration.

   ![Graph of magnetic flux and induced voltage](image)

5. List several parameters that you could change in the Air-X model or the simulation settings, along with your predictions of the effects that each of these changes would have on the final result. Try one of these changes, and obtain and interpret a screenshot of the resulting simulation’s output. Compare these and the earlier results to the actual Air-X measurements.

   - There are many possible answers to this question, of course. Feel free to send us any interesting responses that you receive!

*Additional Concept and Design Questions:*

1. Why do you think that the Air-X manufacturers took special care to smooth sharp edges in the magnets and stator slots?

   - As seen in some of the previous visualizations, the magnetic fields become focused / strengthened at a sharp point, distorting the intended field.