Individual Analytical Analysis

CWC Gen Team

Northern Arizona University

Christian Brown

ME 476C

April 25, 2025

Introduction:

The CWC Gen Team is tasked with designing and manufacturing a custom small-scale generator. This will be used by the NAU CWC (Collegiate Wind Competition) Team in future competitions, aiming to reduce their time and resources spent on the generator. These resources can be applied to the turbine and housing they will need to make.

This analysis focuses on the optimal number of magnets and slots for the custom generator the CWC Gen Team is making. Two different generators were tested to help understand the impact of the number of slots and magnets. These generators are named MAD JENNY and Melon Motor. I was tasked with creating MAD JENNY in Maxwell and running simulations on it. The optimization included Ansys Maxwell CAD and simulations to see the most optimal 3-phase output from the different combinations. Further equations applied to all combinations within a spreadsheet were found and reviewed, validating the different simulations made and helping compare some of the more optimal magnet and slot combinations. The spreadsheet also helps remove many combinations from our considerations due to the meaning of the equations and their results.

Assumptions:

A primary assumption was that the dimensions of the MAD JENNY generator CAD are accurate to the actual dimensions. MAD JENNY was never taken apart, so the specific dimensions were never found, merely approximated. This assumption drives the CAD and simulations of MAD JENNY in Ansys Maxwell.

Maxwell Simulations:

Ansys Maxwell was utilized for this analysis. Within Maxwell, the magnetic flux generated shows the 3-phase behavior of the generator. When the slots and magnets are not properly ratioed, the 3-phase activity gets disturbed, becoming suboptimal. Figure 1 below shows the CAD of the generator named MAD JENNY that we used for testing. On the outside are the magnets in silver, the green interior is the silicon steel stator, and the red, blue, and yellow represent the 3-phase coils made of copper.

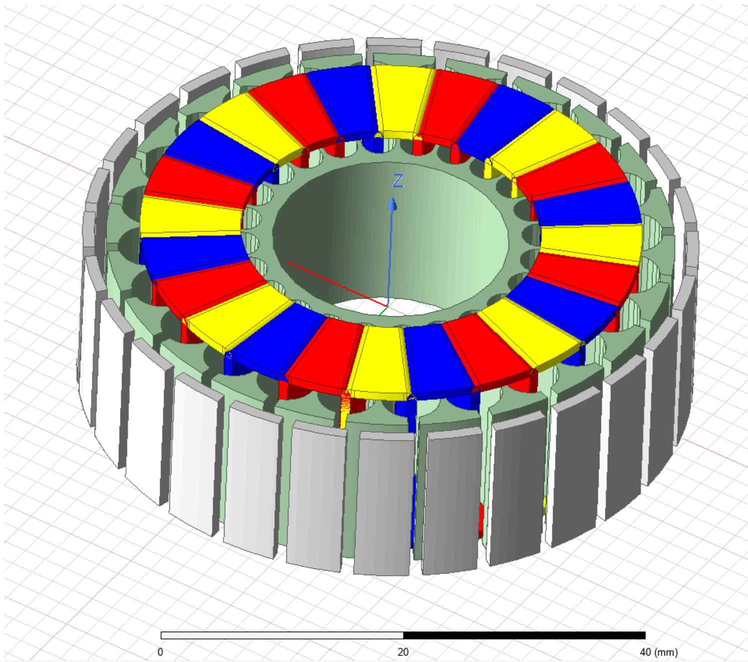

Figure 1: MAD JENNY Ansys Maxwell CAD

The MAD JENNY was analyzed in Maxwell with a transient magnetic analysis simulation. This allowed the magnets to interact with the stator and the coils, producing magnetic flux. This magnetic flux was graphed to visualize the 3-phase activity of the generator. Figure 2 below shows the optimal 3-phase distribution with 28 magnets and 24 slots, where each winding peaks at a symmetrically offset time. The combination of 28 magnets and 24 slots is the default ratio of MAD JENNY and was changed later on to observe the change in the 3-phase distribution. This peak in the flux also lines up with when the cogging torque peaks. So having the peaks evenly distributed lowers the cogging torque of the generator and makes it more efficient by working at lower wind speeds.

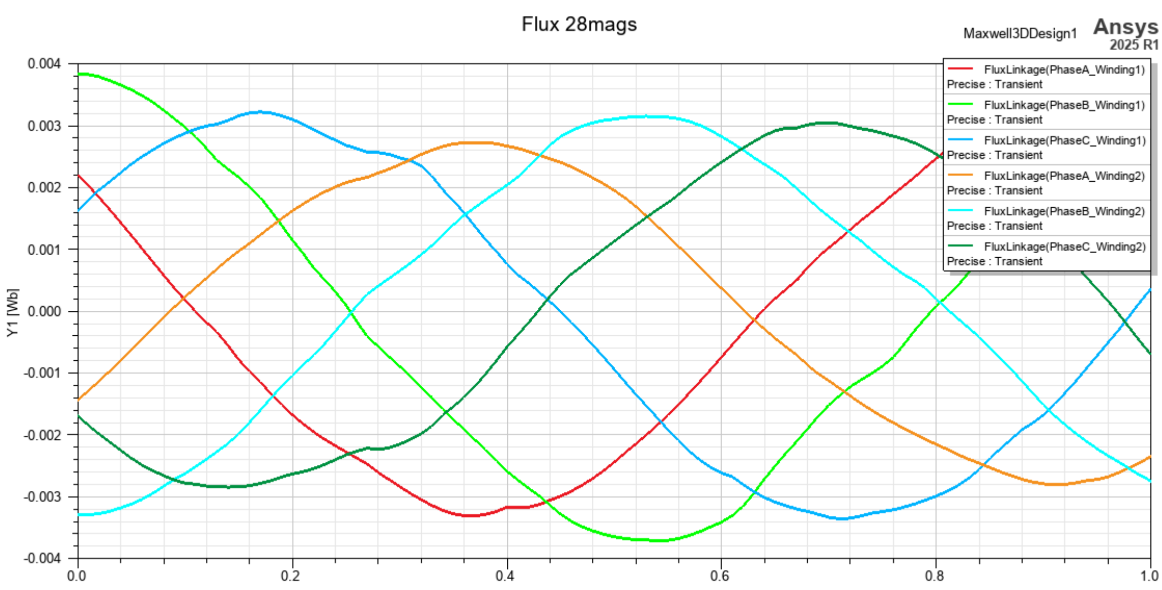

Figure 2: Flux Graph of 28 Magnets and 24 Slots

Figure 3 below shows the flux graph when the magnets were changed from 28 to 32. The number of magnets were changed rather than the slots because of how they are defined in Maxwell, making the magnets easier to change than the stator and the coils. The even distribution observed earlier is lost, with only a few windings being optimally spaced while others overlap.

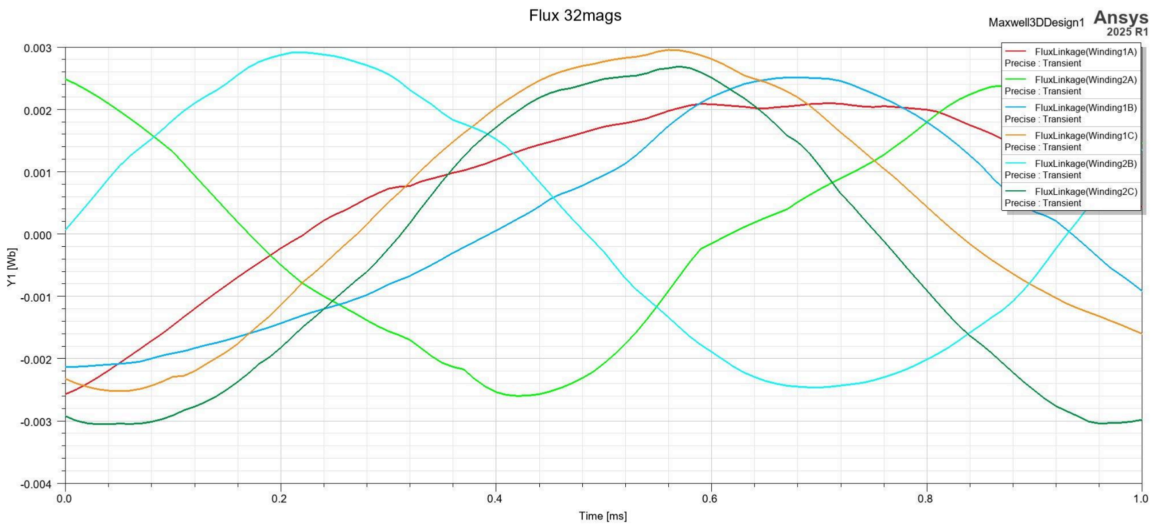

Figure 3: Flux Graph of 32 Magnets and 24 Slots

Shown below is Figure 4 where the number of magnets were changed again from 32 to 36. This is the worst case scenario for a magnet to slot ratio because multiple peaks occur at the same time, meaning the cogging torque would make this version of the generator inoperable. These graphs give valuable insight into how the ratio of slots to magnets affects the output and efficiency of the generator. This helps the design process by being able to dive deeper into the ratio of the slots and magnets and find the most optimal ones for our design specifications.

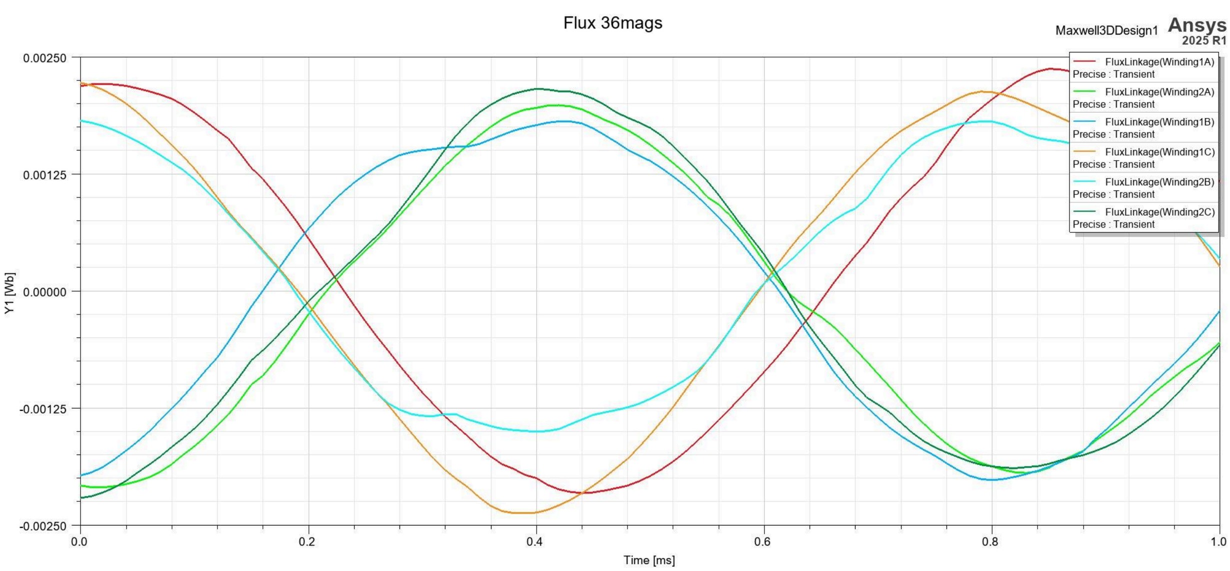

Figure 4: Flux Graph of 36 Magnets and 24 Slots

Slot and Magnet Ratio Analysis:

A resource was found giving a spreadsheet of the different combinations of magnets and slots, and the different parameters to calculate with the below equations, and the meanings of the results [1]. This helped our design by being able to easily observe the more optimal combinations and the combinations that would never work for a generator. The information found from the Maxwell simulations were cross referenced with the information from the spreadsheet and were observed to be the same. The process of the calculations are as follows:

$$q = \frac{N_s}{N_{ph} \cdot N_m} \tag{1}$$

Starting with Equation 1, q is the fraction of the slots per pole per phase of the generator. A q less than one denotes a concentrated winding generator, which is part of the 3-phase design.

$$z = \frac{N_s}{\gcd(N_s, N_m \cdot N_{ph})} \tag{2}$$

Equation 2 finds z, the number of coils in a pole unit, dividing the number of slots by the greatest common divisor of the slots, poles, and phases.

$$k_{mn} = \frac{\sin(\frac{1}{2} n\sigma)}{z \sin(\frac{n\sigma}{2z})} \tag{3}$$

Equation 3 then n and theta, the winding space harmonic order and 60 degree spread angle respectively, to find the distribution factor of the fractional slot windings.

$$\gamma_s = \frac{\pi \cdot N_m}{N_s} = \frac{\pi}{q \cdot N_{ph}} \tag{4}$$

Equation 4 finds the slot pitch angle based on the number of magnets and the number of slots.

$$\varepsilon = \pi - \gamma_s \tag{5}$$

Equation 5 uses the slot pitch angle to find the coil span angle of the generator.

$$k_{en} = \cos(\frac{1}{2} n\varepsilon) \tag{6}$$

Equation 6 then calculates the coil span factor, where the closer to one you are, the better.

$$k_{wn} = k_{mn} k_{en} \tag{7}$$

These equations help define the bounds of what generators are actually feasible and efficient versus those that would be impossible to make work. Any combination of magnets and slots that had a q factor greater than 0.5, less than 0.25, were unbalanced, or had no symmetry based on the equations above were removed from the possible combinations. The cogging factor, found in the denominator of the z factor, is the greatest common denominator between the number of slots and magnets. The higher this number the better for a generator because it reduces the cogging torque and makes the peaks of the torque more even. The removal cases of q, unbalanced, and symmetry and the different cogging frequencies are shown below in Table 1.

Table 1: Multiple Cogging Frequencies

Cogging frequency Ns	Nm 2	4	6	8	10	12	14	16	18	20	22	24	26	28
3	NoSym	NoSym	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25
6	q > 0.5	12	UnBal	24	q < 0.25	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25
9	q > 0.5	q > 0.5	18	NoSym	NoSym	36	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25	q < 0.25	q < 0.25	q < 0.25
12	q > 0.5	q > 0.5	UnBal	24	60	UnBal	84	48	UnBal	q < 0.25	q < 0.25	UnBal	q < 0.25	q < 0.25
15	q > 0.5	q > 0.5	UnBal	q > 0.5	30	UnBal	NoSym	NoSym	UnBal	60	q < 0.25	UnBal	q < 0.25	q < 0.25
18	q > 0.5	q > 0.5	q > 0.5	q > 0.5	q > 0.5	36	126	144	UnBal	180	198	72	q < 0.25	q < 0.25
21	q > 0.5	q > 0.5	UnBal	q > 0.5	q > 0.5	UnBal	42	NoSym	UnBal	NoSym	NoSym	UnBal	NoSym	84
24	q > 0.5	q > 0.5	UnBal	q > 0.5	q > 0.5	UnBal	q > 0.5	48	UnBal	120	264	UnBal	312	168

Based on Table 1 above, MAD JENNY has a cogging factor of 168 with 28 magnets and 24 slots while the second generator we tested, Melon Motor, has a cogging factor of 84 with 14 magnets and 12 slots. While MAD JENNY's combination seems more appealing based on the cogging factor. Size and overall losses play a factor in the concept generation. The more slots fitted into a small stator, the more likely the flux will jump between the teeth, reducing the efficiency of the motor. Due to this and the previously calculated factors, the Melon Motor's magnet and slot combination is the most promising for a small scale generator.

Results:

This analysis on the ratio of magnets and slots helped set the foundation for the final design of the generator. Everything is structured around the stator, which is why the number of slots drives the rest of the generator's design. This maintains the 3-phase power generated and the small scale design of the generator. The 28 magnets and 24 slots combination of the MAD JENNY was found to be an optimal combination, but considering the size of the generator and need for greater efficiency, it was not chosen for the final design. With 14 magnets and 12 slots, the cogging frequency is optimal for the size and the smaller number of each will have less overall losses. These parameters best fit the task of creating a small scale generator for the CWC.

References:

[1] R. Parsons, “Things in Motion: Selecting the best pole and slot combination for a BLDC (PMSM) motor with concentrated windings,” Things in Motion, Jan. 27, 2019. https://things-in-motion.blogspot.com/2019/01/selecting-best-pole-and-slot.html