Final Project

Due in Two Installments (as specified on Canvas):
- First installment: Submit requested number of poles and slots
- Second installment: Submit complete project

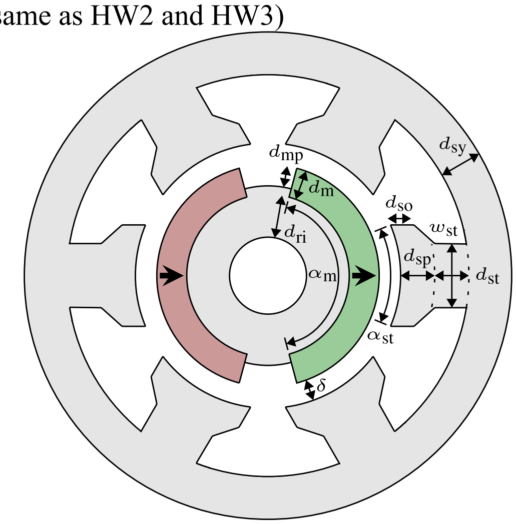
Description:
After successfully completing ME8287, your employer has promoted you to be the company's electric machine designer. On your first day of work in your new position, you are asked to complete the magnetic design for a new electric machine that the company is developing for the wastewater aeration equipment market. You are told that the design should have a rated speed of 10,000 RPM, have a rated power of 50 kW, have an electric frequency under 600 Hz, have three phases, use surface mounted permanent magnets on the rotor, and use forced air cooling. You need to determine the number of slots, poles, the winding layout, and various dimensions of the machine. Your objectives are to minimize the design cost, losses, and torque ripple. Customers will only buy your design if it has an efficiency over 90% and a torque ripple less than 50% (and your manager is hoping that with the new skills you learned in ME8287 that you can create a design with even better performance).

To do this, you will create a modified version of `evaluateDesign` and the necessary supporting functions to link this to MATLAB's multiobjective optimization algorithm, and then run an optimization.

Machine Optimization Problem:
Design specification:
- Rated power: 50 kw
- Rated speed: 10,000 RPM
- Frequency: < 600 Hz

Constants and Materials:
- Conductor current density: $5 \frac{\mathrm{A_{rms}}}{\mathrm{mm^2}}$
- Magnets: NdFeB (N40 grade) https://www.arnoldmagnetics.com/wp-content/uploads/2017/11/N40-151021.pdf
- Steel: M19, 29 Gauge
- Wire: 18 AWG wire
- Slot fill factor: $\mathrm{k_{cu}}$: determine based on the type of winding you select

Geometry parameterization: (same as HW2 and HW3)



Free variables: (your optimization algorithm chooses these)

- $d_m,\ \delta,\ \alpha_{st},\ d_{sy},\ d_{st},\ w_{st}$

Dependent and fixed variables

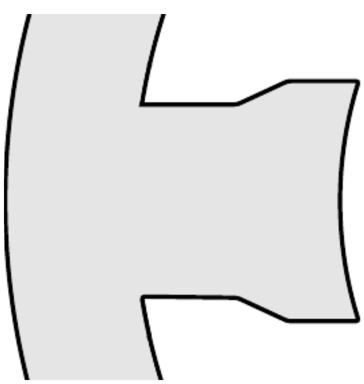
- $d_{mp} = d_m$
- $d_{so} = 2$ mm
- $d_{sp} = 4$ mm
- $\alpha_m = \frac{180°}{p}$, where p is the number of pole-pairs of the rotor.
- Stator outer radius $r_s = 180$ mm
- $d_{ri} = r_{si} - \delta - d_m$ (only iron resides inside the magnets), where $r_{si} = r_s - d_{sy} - d_{st} - d_{sp}$
- Number of turns in a coil z_Q: determine from available slot area (using method from Lecture 20) and copper fill factor
- Active length of motor l: to be determined through FEA analysis.

Allowable free variable range:

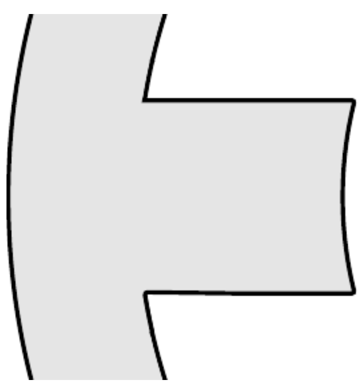
- 0.25 mm < d_m < 5mm
- 1mm < δ < 5mm
- 5mm < d_{sy} < 50mm
- 5mm < d_{st} < 100mm
- 5mm < w_{st} < 100mm
- Determine appropriate range for: α_{st}

Constraints

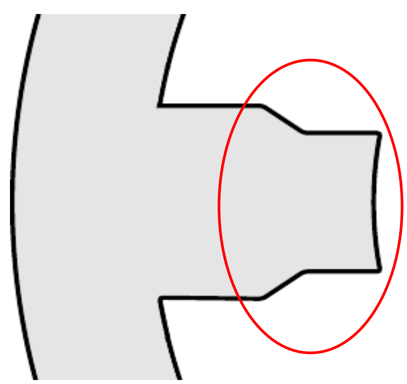
- Surface speed of the rotor $v_{\text{tip}} < 175$ [m/s]
- $\hat{A}_{\text{rms}} < 80\,\frac{\text{kA}_{\text{rms}}}{\text{m}}$ (constrain electric loading to a range that allows for air cooling)
- Check that tooth tip is thick enough (I am providing you with a function that checks this)
- Ensure that the tooth tip is not narrower than the tooth, see image below:



Acceptable tooth tip shape



Acceptable tooth tip shape



Unacceptable: you need to implement a constraint to prevent this.

Objectives

- Maximize efficiency. Model losses (magnet, iron, and winding loss) in the same manner that we used in HW3 and use the following material properties
  - Hysteresis loss coefficient, $c_h = 0.0186 \left[\frac{\mathrm{W}}{\mathrm{kgT^2Hz}}\right]$
  - Eddy current loss coefficient, $c_e = 6.887 \times 10^{-5} \left[\frac{\mathrm{W}}{\mathrm{kgT^2Hz^2}}\right]$
  - Conductivity of copper = $5.77 \times 10^7 \left[\frac{\mathrm{S}}{\mathrm{m}}\right]$
  - Conductivity of selected magnets = $5.55 \times 10^5 \left[\frac{\mathrm{S}}{\mathrm{m}}\right]$
- Minimize torque ripple
- Minimize the following material costs (rotor and stator steel, rotor magnets, stator copper), use the following prices for M19 steel, magnets, and copper
  - M19 steel: $14.03 \times 10^3 \left[\frac{\$}{\mathrm{m^3}}\right]$
  - Copper: $0.06 \left[\frac{\$}{\mathrm{m}}\right]$ of AWG 18 magnet wire
  - Magnets: $708.5 \times 10^3 \left[\frac{\$}{\mathrm{m^3}}\right]$

Assignment:

1. (5 pts) Propose a number of slots and poles that you wish to use in your design which satisfies the electric frequency and symmetry requirements. **Submit this in Canvas as your first deliverable** in the form of a ranked list of 3 slot / pole combinations you are interested in. I will confirm/assign you a combination of slots and poles to use for the project. **Once your combination of slots and poles is confirmed, you must use these values for the rest of your project.** If for some reason you feel that you need to change values, please contact me for permission first. <u>**Projects completed with an unauthorized slot-pole combination will not receive credit.**</u>

2. (11 pts) Perform a winding layout. Make this a double layer winding. Provide a winding schematic for your design that shows the connections of phase u. Select an appropriate winding fill factor for your winding: k_{cu}. Write an expression for α_w in terms of the mechanical rotor angle that should be used to create the maximum torque per ampere of current if the winding currents are given by $I_u = \hat{I}\cos\alpha_w$, $I_v = \hat{I}\cos\left(\alpha_w - \frac{2\pi}{3}\right)$, $I_w = \hat{I}\cos\left(\alpha_w - \frac{4\pi}{3}\right)$. Assume that slot 1 is aligned with $\alpha = 0°$.

3. (9 pts) Finish the incomplete components of "Dependent and fixed variables," "Allowable free variable range," and "Constraints." Do this by providing the following expressions:
   a. Number of turns in a coil z_Q
   b. Determine appropriate range for: α_{st}
   c. Constraint equation to ensure acceptable tooth tip shape. *Hint:* This should be in terms of free variables w_{st} and α_{st} and may include other free and dependent variables.

4. (10 pts) Create an expression for active material cost (rotor and stator steel, rotor magnets, stator copper) in terms of the free and dependent variables that you will use to evaluate this objective. For the copper, please determine the length of magnet wire based on the same expression for length that we used for loss calculations.

5. (25 pts) Perform an initial analytic design of your motor to determine a set of values for the free variables that satisfy the allowable variable range and the constraint. Indicate the following information:
    a. Selected magnetic loading, electric loading, and rotor volume
    b. Number of turns in a coil
    c. The maximum field in the stator teeth
    d. The maximum field in the stator yoke
    e. All dimensions of the machine cross-section (free variables and the dependent variables)

    Note: to receive full credit, you must assume reasonable values for parts a, c, and d.

6. (Extra Credit: 10 pts) Modify `evaluateDesign` from HW3 by having it determine the required axial length to achieve a specified rated torque. Do this by performing the complete FEMM analysis of your machine with an axial length of 1mm, extract the field and torque values at each rotor location (just like you did in HW3, but now the length is 1mm), and then calculate the length required to obtain the rated torque. Use this newly calculated length for the loss calculations. The function should have the following function signature (the only differences are `ratedTorque` in Nm and the returned `length` in mm):

    `function [designEval, `***`length`***`] = evaluateDesign(materials, dimensions, p, winding, settings, `***`ratedTorque`***`)`

    I am providing you with an `evaluateDesign.p` *file that has already implemented this which you can use in your optimization. You will receive extra credit if you create your own working* `evaluateDesign.m` *function.*

7. (5 pts) <u>Create a MATLAB function</u> `evaluateConstraints` that will be called by MATLAB's `gamultiobj`. This function is responsible for evaluating the design constraints. In addition to the constraints that I have indicated above, I am providing you with a MATLAB function `checkToothTip` which will indicate whether your free variables will yield valid tooth-tip geometry. The function returns 0 if the geometry is valid and 1 if the geometry is invalid. Use this function inside `evaluateConstraints` to constrain the optimization to valid geometry.

8. (5 pts) <u>Create a MATLAB function</u> `evaluateObjectives` that will be called by MATLAB's `gamultiobj`. This function will receive the optimization algorithm's free variables as its arguments, formulate the arguments for `evaluateDesign` (calculate the dependent variables), call `evaluateDesign`, and then convert the returned values of `designEval` into the objectives that this function will return.

    This function will implement a lot of the functionality of `testDesign1.m` from Homework 3. To determine the appropriate `settings.steps` value, use your analytic design from step 5 and evaluate the iron and magnet losses when the number of steps is swept over a range of even integers from 10 to 30. <u>Create a plot</u> where the y axis is the total iron and magnet losses and the x axis is the value of `steps` used. <u>Explain your choice</u> for `lowestHarmonic` and `steps` in two sentences or less.

    Hint: because `gamultiobj` will still call `evaluateObjectives` even if designs fail `evaluateConstraints`, I recommend that you implement the following functionality in the `evaluateObjectives` function:

1. Call `evaluateConstraints`—if the function indicates that the design violates a constraint, set all objectives to `inf` and return.
2. If the design does not violate constraints, proceed to call `evaluateDesign`.

9. (10 pts) Analysis of initial design
   a. Use your MATLAB functions to evaluate the objectives of your initial design from question 5. Provide these values.
   b. Use FEMM to audit your assumptions for maximum field in the stator teeth, stator yoke, and magnetic loading from question 5. Compare FEMM's calculations to the values you have assumed and in three sentences or less explain likely causes for any differences between your assumed values and the actual values. *Hint:* in ALE 21, I gave you example code for calculating magnetic loading of a FEMM model.

10. (5 pts) Create a MATLAB script called `optimizeMotor.m` that uses `gamultiobj` to optimize your motor design. Use a population size of at least 50. Determine appropriate values for `settings.lowestHarmonic` and `settings.steps`.

11. Run your optimization to find a set of designs that meet your customer's requirements. Run your optimization for however many generations is takes to find a set of suitable designs to meet your customer's requirements (I recommend trying 50 or more generations).

    Hint 1: If you allow `gamultiobj` to use parallel processing (recommended), `evaluateDesign` will be called in parallel by MATLAB's worker threads. Since FEMM requires the model file to be saved to the hard drive, you need to have `evaluateDesign` use a unique file name for each worker thread (so they don't write over each other and cause your optimization to crash). I recommend using the following approach to come up with a file name (example code is on Canvas and the `evaluateDesign.p` file I am providing you already implements this):

```
threadID = get(getCurrentTask(),'ID');
if(isempty(threadID))
    filename = ['testDesign.fem'];
else
    filename = [num2str(threadID),'.fem'];
end
mi_saveas(filename);
```

    Hint 2: This optimization is challenging because it takes several minutes to run `evaluateDesign`. In ALE 21, you learned how to set the initial population of your algorithm. This will allow you to "resume" an optimization (sets the initial population of a new optimization run). This is optional to implement, but highly recommended.

    Hint 3: Consider creating an initial population of designs that are similar to your analytic design to more quickly converge to set of suitable designs.

    Hint 4: Based on your initial design from problem 5, you may decide to impose more stringent restrictions on the free variable range. This can help you converge to a suitable design more rapidly (but be careful! If you are too restrictive, you will prevent your optimization algorithm from finding suitable designs). If you do further restrict the free variables, provide your updated restrictions in your final submission report.

12. (15 pts) Create a document analyzing your final generation of candidate designs. This should be a typed document with the following plots/information.

    a. Create a 3D plot of your objectives. X axis: efficiency, Y axis: torque ripple, Z axis: cost
    b. Create a 2D plot of your objectives. X axis: efficiency, Y axis: torque ripple, Marker color: cost
    c. Create a table that compares the following designs. Each column of the table should correspond to one of the designs listed below. The rows of the table should consist of each of the free variables, each of the objectives, the magnetic loading (calculated using an FFT from a FEMM solve), and the electric loading. This table needs to be professionally formatted and use appropriate column/row labels and units.
        1. “Lowest Cost Design” –The lowest cost design that meets the customer’s requirements (efficiency and torque ripple)
        2. “Most Efficient Design” –The most efficient design that meets the torque ripple requirements
        3. “Lowest Ripple Design”—The lowest ripple design that meets the efficiency requirements
        4. “Recommended Design”— Pick one design that you think will impress your manager the most (best compromise of all objectives).
    d. For the design you recommended in part C, provide an image of the machine’s cross-section (this can be a screenshot from FEMM or you can export the DXF file and render it in higher quality with a CAD tool). In three sentences, explain to your manager why you have selected this design.
    e. You are trying to convince your company that using optimization techniques will allow the company to create more competitive motors than using analytic design techniques alone. Write a brief paragraph (five sentences or less) explaining the merits of using optimization in the machine design process by comparing the performance of your optimal designs with the analytic design you created in question 5.

<u>Deliverable:</u>

- A single PDF report document that contains answers to all questions, contains all required plots, and the required table. The document should be professionally formatted and clearly indicate which question each answer, plot, and table correspond to. Your answers to questions 1 – 4 can be a hand drawn provided that they are easily readable and are inserted in the report.
- Your MATLAB code in a single zip file. This should have everything I need to run your optimization. If your code does not run, you will not receive credit for questions that depend on the code. I will be testing your functions `evaluateDesign.m` (for extra credit), `evaluateObjectives.m`, `evaluateConstraints.m`, and `optimizeMotor.m` as part of the grading.