Model-based Generation of Scaling Laws for Radial-Gap Permanent Magnet Motors

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ABSTRACT

Oak Ridge National Laboratory's (ORNL) computer code PMM_IDT (Permanent Magnet Motor Interactive Design Tool) was used to study the sensitivity to changes in design parameters at constant power output and scaling laws for similar designs with different rated power outputs. The base design used was a radial-gap motor with 30 kW of net output characteristic of the PNGV "Series" vehicles. Sensitivity parameters studied were active length, magnet and air gap thicknesses, and number of magnets. Power output variation approaches considered were active length, stator external diameter, and rotor external diameter. The impact on efficiency, cost, weight, specific power, cooling requirements, drive current and voltage requirements, and demagnetization margins are presented. Common constraints in this study are: Hollow rotor, trapezoidal back emf - 212 V maximum - and double layer winding leading to an even number of turns per slot

INTRODUCTION

Codes used for evaluation of candidate technologies for electric vehicles and hybrids rely on scaling algorithms to generate performance, weight, and cost data for their target motor from known data for similar motors. ORNL has developed the radial-gap permanent magnet design computer code PMM_IDT under the auspices of the U.S. Department of Energy's Office of Advanced Automotive Technologies.

PMM_IDT mostly implements the design formulations found in references 1 and 2. With this code a 30 kW motor was designed as a reference to study the sensitivity to selected parameters and to net power outputs from 15 kW to 45 kW. This was accomplished by means of a driver computer program that called PMM_IDT repeatedly as a subroutine. This driver program was written specifically to generate the results documented in this paper.

REFERENCE PERMANENT MAGNET (PM) MOTOR

The reference PM-motor was chosen to be in the target range for the "Series" PNGV concept. Its main characteristics are:

Net Output Power: 30 kW (continuous with a current density of 6.3 A/mm^2);
Nominal speed: 3333.3 rpm (corresponding to a 500 Hz electrical frequency);
Number of Phases: 3 (2 active at a time. Trapezoidal back emf);
Number of magnets: 18 (4 mm thick NdFeB [grade 27]);
Number of stator slots: 54;
Air Gap thickness 1 mm;
Stator's Outside Diameter: 9 inches;
Rotor's Outer Diameter: 6.25 inches (hollow rotor);
Length of active part: 2.25 inches; and
Stator material: 0.019 inch NonOriented Silicon Steel.

This reference PM-motor, according to the code PMM_IDT, will look as shown in Schematic # 1 and will be characterized by:

Motor Efficiency: 96.3%(at nominal conditions. Without Drive System losses);
Phase Current: 86.3 A;

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Terminal Voltage: 360.7 V (between the terminals of two active phases);
Fundamental_Electrical_Frequency: 500 Hz;
Number of turns per slot: 10;
Rotor Inertia: 43.1 lb in^2;
Weight of active components: 33 pounds (excluding bearings and housing);
Cost: $451 (based on the following $/lb prices: NdFeB: 40.00, Cu: 1.85, Stator_Fe:1.20, Rotor_Fe: 0.80).

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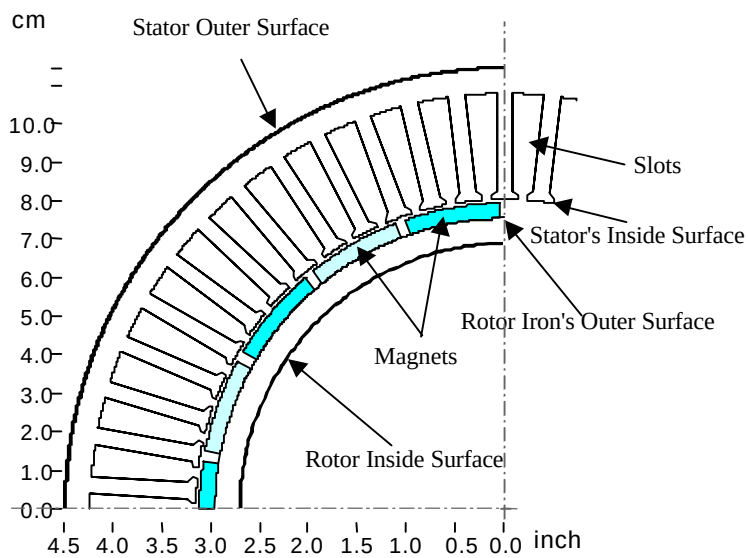

Schematic # 1
Cross Section of the Reference 30 kW Radial Gap Permanent Magnet Motor

PMM_IDT was subsequently run with the same choice of inputs except for selected parameters that were scaled from 50% below to 50% above their base values, in 5% steps. The results obtained are summarized in the sections below. Note that since neither the number of turns nor the number of wires per turn can be fractional and since, because of double layering, the number of turns must be even, the scaling curves are not necessarily monotonic.

The set of figures generated are included at the end of the paper. Each figure represents a case and consists of a collection of graphs with the X-axis labeled with numbers from 0.5 to 1.5. These numbers refer to multiplier used for the reference value of the parameter being changed in the particular case.

The actual value of the input parameter changed is shown in the top left graph (and top right graph, when two of different dimension are changed). Input points are marked by hollow round (and square) icons. The rest of the graphs are computed outputs.

The "Efficiency" graphs show, in per cent units, efficiency accounting for ohmic, magnetic, stray, friction, and windage losses.

The values in the graphs of "Current Density" can be used to determine the kind of cooling needed by the stator's copper windings. Typically, current densities above 6 A/mm^2 require other cooling than forced air.

The values in the graphs of "Cooling Requirements" can be used to dimension the overall cooling system for the motor. The "High" value shown in these graphs corresponds to the case in which all waste heat is assumed to leave the motor through the outside cylindrical portion of the stator. The "Low" curves correspond to the case in which the interior cylindrical surface of the stator and the two annular surfaces on its sides are added as heat transfer areas.

In all cases, the "Terminal Voltage" and the "Back EMF" (actually twice this value for display scaling reasons) are plotted in the same graph. The terminal voltage and current shown in the graphs are demands that the electronic drive system must supply. In all cases the voltage must be trapezoidal. In all cases, except # 3, the electrical frequency must be the same as the reference, i.e., 500 Hz. In case # 3, in which the number of poles changes, the frequency varies from 222.2 Hz for 8 magnets, to 722.2 Hz for 26 magnets.

The "Weights" graphs show the amounts of magnet, copper, stator iron and rotor iron in the motors The total weight, sum of the above, is also shown except when its presence obscures the rest. Logarithmic scale is shown in order to emphasize relative changes in weight.

Whenever the "Specific Power" or "Current Density" graphs are not shown it is because their change is negligible and instead the graph of a more significant parameter is shown.

SENSITIVITY OF REFERENCE MOTOR TO DESIGN CHOICES

The reference 30 kW motor was redesigned by varying the active core length, the thickness of the PM and air-gap, and the number of magnets, one at a time, while maintaining the rest of input parameters unchanged.

Sensitivity to Active Length

Figure 1 corresponds to case #1, which studies the effect of varying the lengths of the stator core and rotor of the 30 kW motor.

For higher efficiency, the optimal length of the motor is in the 0.9 to 1.2 region. The "Cost" and "Specific Power" graphs favor the shorter motor versions at the expense of higher "Current Density" and "Cooling Requirements" and lower "Demagnetization Margin."

We have defined the demagnetization margin as:

$$\text{Demag Margin} = 1 - \frac{\Phi sar}{\Phi m}$$

where,

Φsar is the stator's reaction magnetic flux density, and

Φm is the mean magnetic flux in the PM.

The stator's reaction magnetic flux and the main magnetic flux are assumed to superimpose linearly, i.e., add and subtract symmetrically across each magnet.

Note that when the demagnetization line for the PM material is of constant slope with no knee, the inverse of unity minus the demagnetization margin is the ratio of the demagnetization current to the rated current. For instance, Demag Margin = {0.9, 0.8, and 0.5} imply that currents {10, 5, and 2} times the present value of phase current will cause permanent demagnetization.

Sensitivity to PM and Air-Gap Thickness

Figure 2 corresponds to case #2, which studies the effect of varying the allocation of the motor's 5 mm space between the stator's inside radius and the rotor's iron outside radius, between the PM and the air gap. That is, the thickness of the air gap is varied from 50% to 150% of the reference value while the thickness of the PMs varies in the opposite direction so that their sum remains equal to 5 mm. This essentially tends to keep the stator-armature reaction's magnetic flux constant. As the PM's thickness decreases and the air-gap increases, though, the PM's flux density decreases and, as a result, the demagnetization margin decreases with magnet thickness.

The graphs show that efficiency, current density, total weight, and cooling requirements do not vary significantly. The amount of copper needed increases as much as the reduction in weight of the irons and magnets with decreasing magnet. The higher cost of the magnetic material makes the overall cost to decrease as the magnet thickness is reduced. Thus, the "Cost" graph favors the thinner magnets at the expense of lower "Demagnetization Margin."

Sensitivity to the Number of Magnets (i.e., Poles)

Figure 3 corresponds to case #3, which studies the effect of varying the motor's number of magnets, i.e., the number of poles. Note that the number of magnets must be even. In addition the required electrical frequency, for the terminal voltages and resulting phase currents shown in Fig. 3, varies in direct linear relation to the number of magnets (from 222.2 Hz for 8 magnets to 722.2 Hz for 26 magnets.)

As the number of magnets increases the demagnetization margin increases while current density and, most significantly, the cost, decrease. This is due to the reductions in back iron requirements in both the stator and rotor. The amount of copper increases, efficiency is slightly affected and the overall weight decreases causing the specific power to increase with the number of magnets.

Note that the weight of magnetic material does not change. This is because the spacing between magnets is not a fixed quantity here since it is set to be a fixed fraction (10%) of the magnets pitch, i.e., the magnet pitch to pole pitch ratio is 0.90.

SCALING OF REFERENCE MOTOR TO $\pm$50 % OUTPUT POWER

Cases #4, #5, and #6 study three approaches to scale the power output of the motor in the 15 kW to 45 kW range. To this end, PMM_IDT was run with only two changes from the 30 kW reference: the desired motor's

$Ds(k=1) = Ds_o = 9$ inch is the reference value.

Thus, Ds(0.5) = 7.7 inch and Ds(1.5) = 10.1 inch.

In this case, the cost of the motor, in the 15 kW to 45 kW range, varies almost linearly with power as the stator's outside diameter increases, at a slope of 11 $/kW. The cost in dollars per unit of power output decreases as power output increases. In this range, it goes from 19$/kW for 15 kW to 13$/kW for 45 kW. Efficiency increases slightly with power output while the demagnetization margin decreases substantially and the motor's specific power remains constant.

<u>15 kW to 45 kW Changing the Rotor's Outside Diameter</u>

Figure 6 corresponds to case #6, which studies the approach of varying the rotor iron's outside diameter in relation to the scaling of the motor's output. This was done by varying the annular area between the outer iron surfaces of stator and rotor in the same proportion as the power scaling, i.e., from 0.5 to 1.5, with the stator's outer diameter unchanged. The rotor's outside diameter for each power scaling factor was computed as follows:

$$\mathrm{Dri}(k) = \sqrt{\mathrm{Ds}_o^{\,2} - (\mathrm{Ds}_o^{\,2} - \mathrm{Dri}_o^{\,2}) * k}\ ,$$

where

Ds_o, Dri_o, and k are as above, and

$Dri(k=1) = Dri_o = 6.25$ in is the reference value.

Accordingly, Dri(0.5) = 7.7 inch and Dri(1.5) = 4.3 inch.

In this case, the cost of the motor varies with power as the rotor's outside diameter decreases. In the 15 kW to 36 kW range, it varies almost linearly at a slope of 8.6 $/kW. In the 36 kW to 45 kW range the cost remains almost constant. The demagnetization margin decreases substantially as the power increases though. The cost in dollars per unit of power output decreases with power output. In this range, it goes from 22 $/kW for 15 kW, to 11 $/kW for 45 kW.

Efficiency peaks at about 36 kW with power output while the motor's specific power remains constant.

CONCLUSIONS

The sensitivity studies performed in cases 1, 2, and 3 indicate that the 30 kW reference motor is at a good compromise design point with regard to length, magnet thickness, and number of magnets. It is significant that as the number of magnets increases the demagnetization margin and specific power increase while the current density and cost decrease.

The power scaling study shows that for higher than the reference output, the approach of reducing the rotor iron's outside diameter is most economical. The associated penalty is a reduction in demagnetization margin which must be carefully assessed. For lower than the reference output power, decreasing the length is most desirable in cost and in all accounts except for weight.

CONTACT

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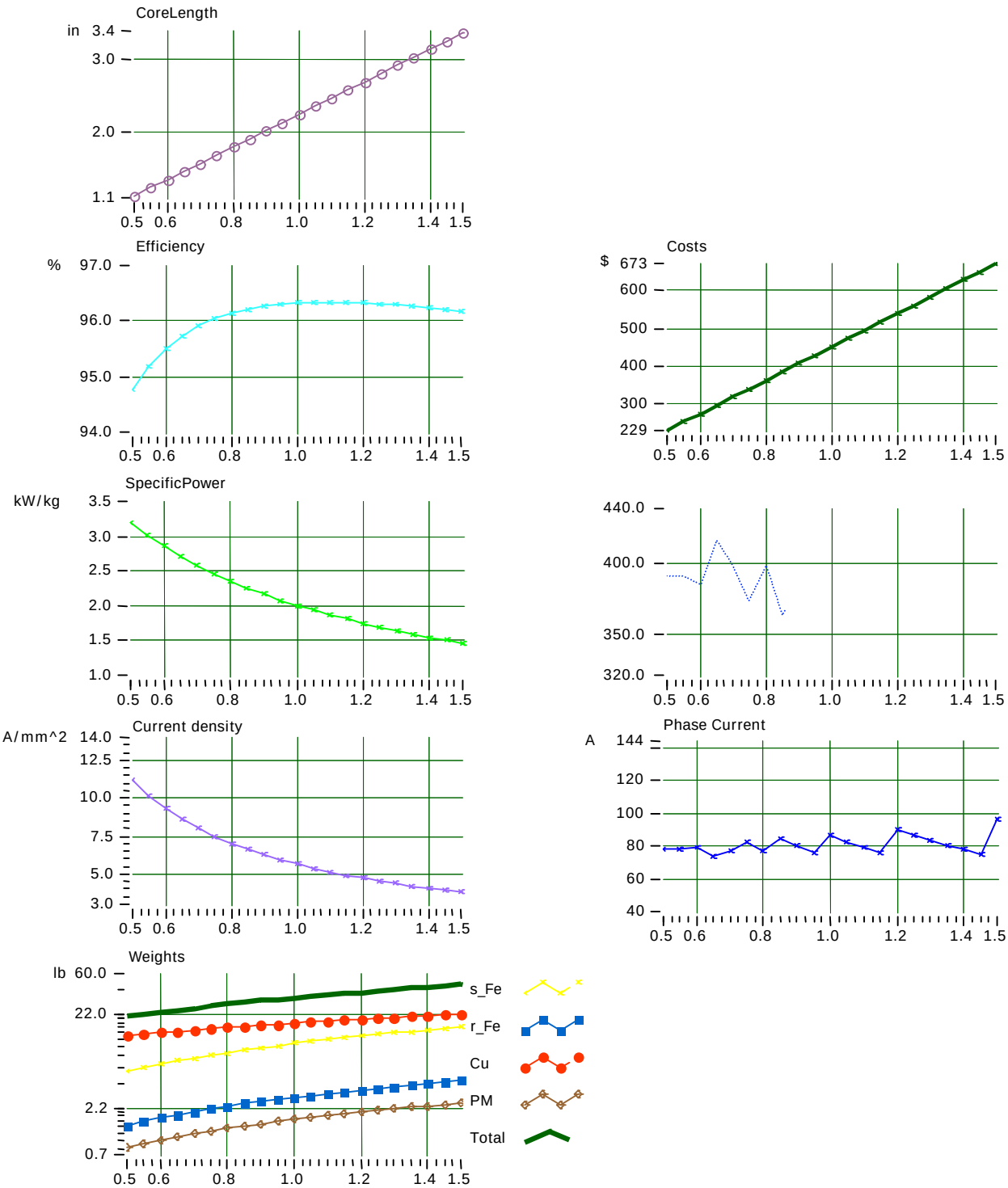
2. J. R. Hendershot Jr. and Tje Miller, "Design of Permanent-Magnet Motors." Magna Physics Publishing and Claredon Press Oxford, 1994.

FIGURES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2.0
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95.0
94.0
Costs
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500
400
300
229
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Phase Current
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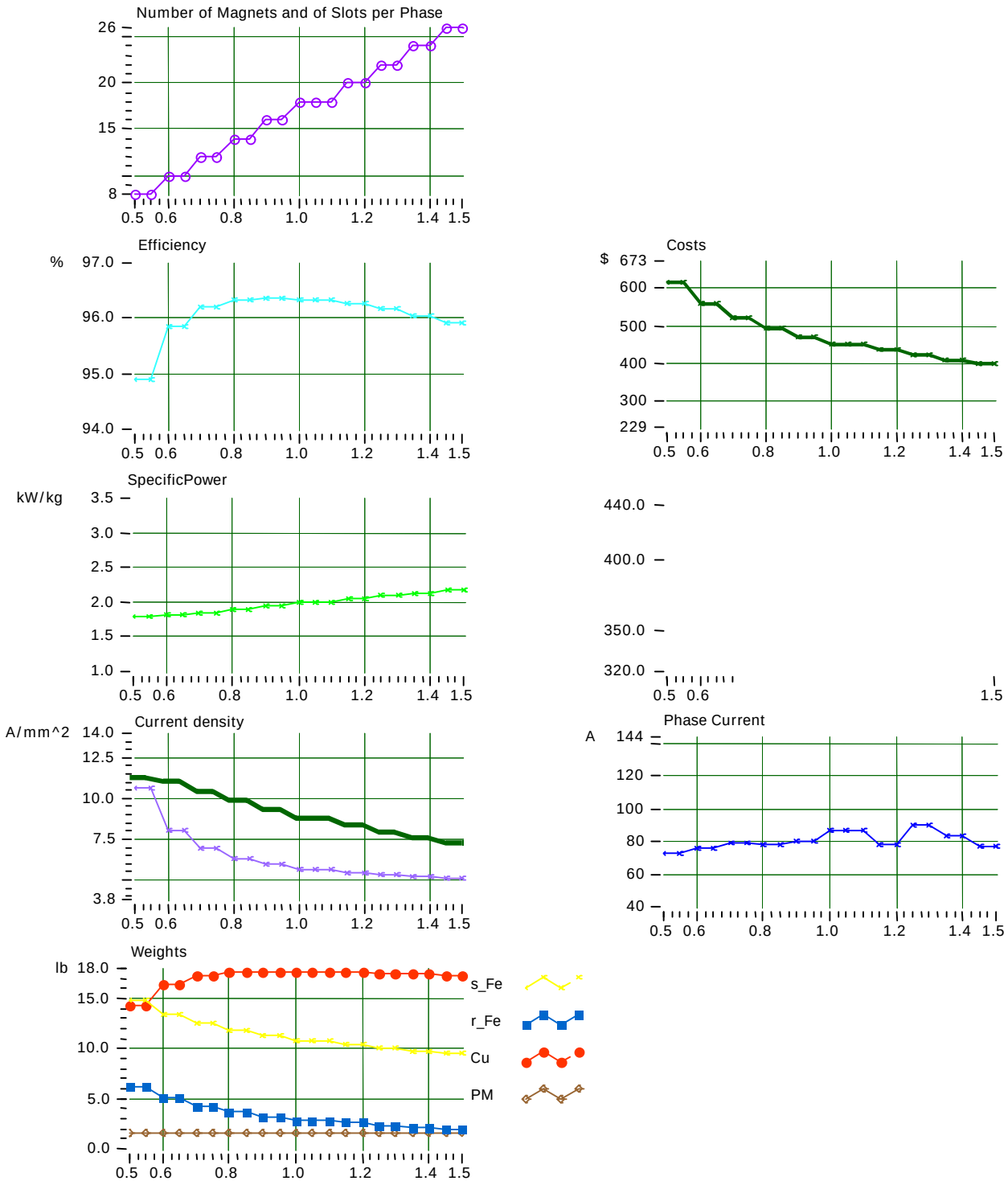
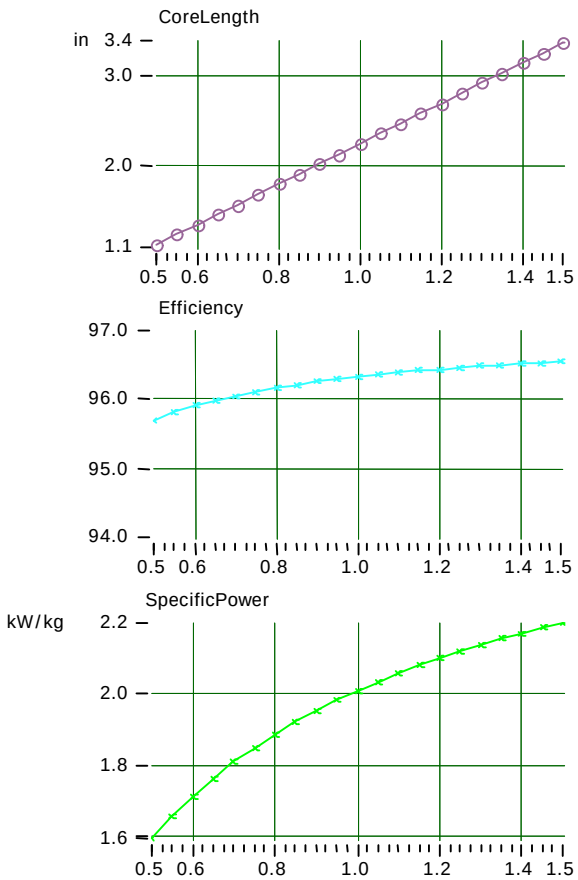


Figure 3
Case #3: 30 kW motor's number of magnets varies, as even integers, from 50% to 150% of the reference value of 18.



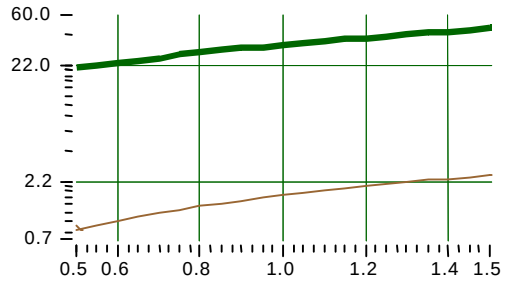
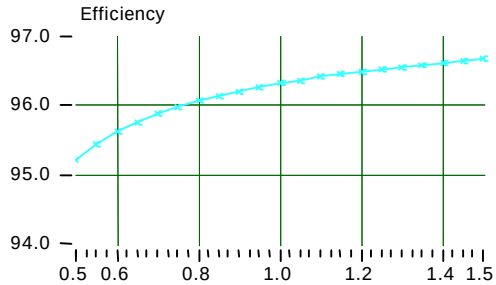


Figure 4
Case #4: Scaling in the range 15 kW to 45 kW.
Motor power output and length vary from 50% to 150% of their 30 kw and 2.25 inch reference values.
Note, current density and demagnetization margin are not shown because they do not change significantly.



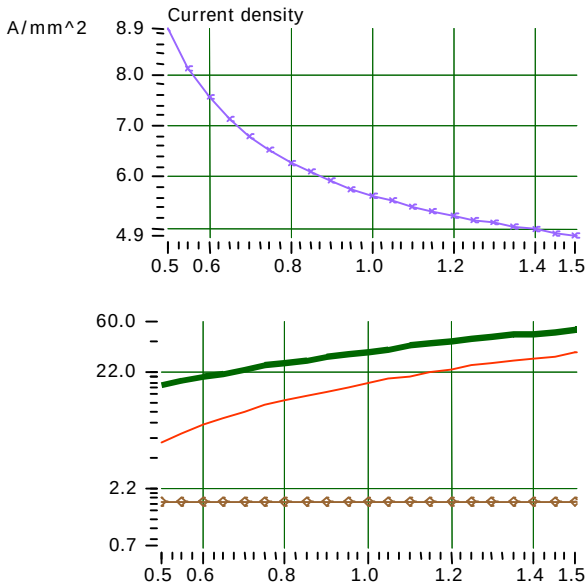


Figure 5
Case #5: Scaling in the range 15 kW to 45 kW.
Motor power output varies from 50% to 150% of the 30 kW reference value.
Simultaneously, the stator's outside diameter varies from 7.7 inch to 10.1 inch in proportion to the reference motor's annular area between the outer iron surfaces of stator and rotor.
Note, specific power is not shown because it does not change significantly.

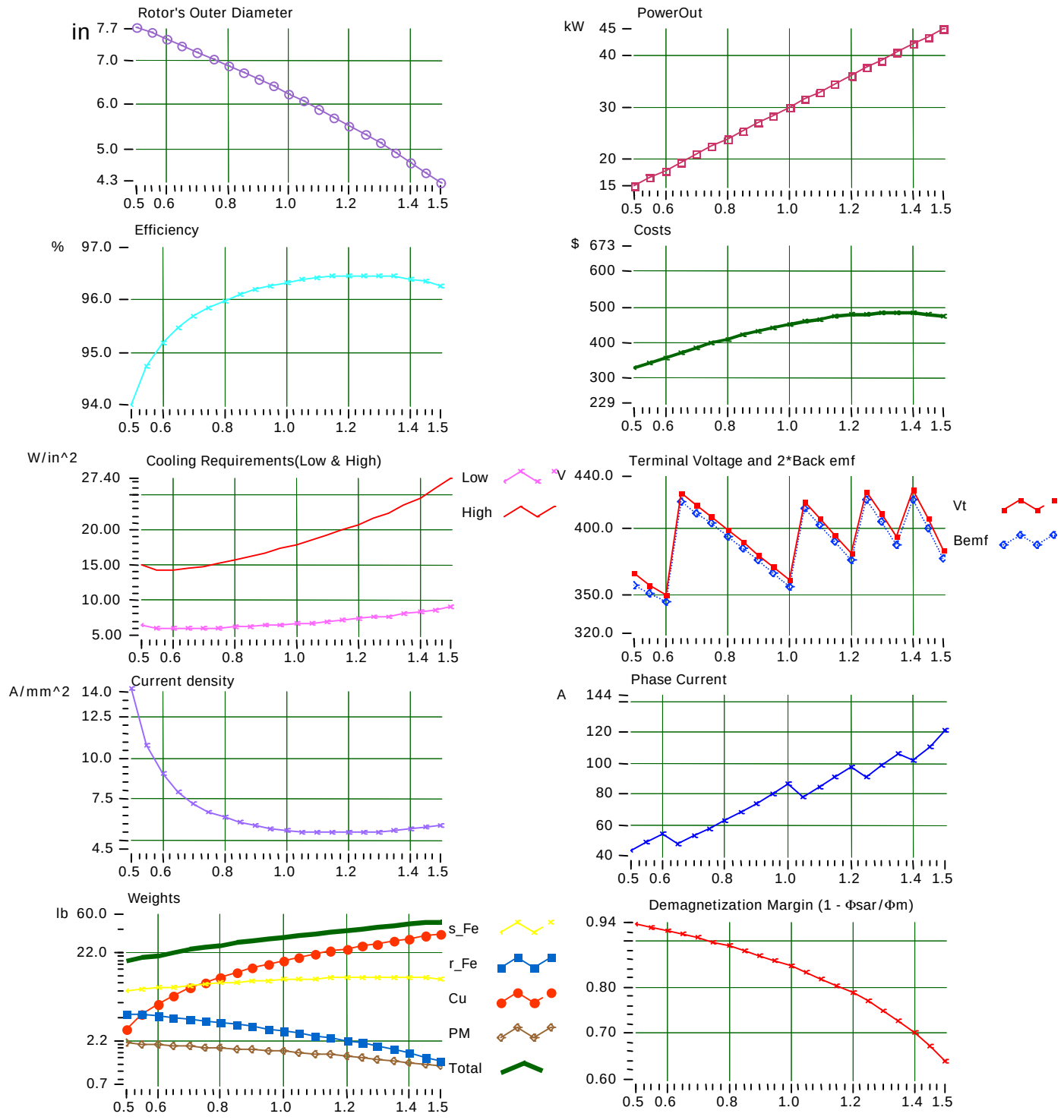


Figure 6
Case #6: Scaling in the range 15 kW to 45 kW
Motor power output varies 50% to 150% of its 30 kW reference value.
Simultaneously, the rotor's iron outside diameter varies from 7.7 inch to 4.3 inch in proportion to the reference motor's annular area between the outer iron surfaces of stator and rotor.
Note, specific power not shown because it does not change significantly.