ASM INNOVATIVE PROJECT

AIM
To calculate Rotating Losses in a Surface Mount Permanent Magnet Motor using several Finite Element Analysis runs as well as plot the curves of the variation of each type of loss with speed and represent the power loss density on a heat map.

SOFTWARES USED

1) **FEMM (Finite Element Method Magnetics)** is a suite of programs for solving low frequency electromagnetic problems on two-dimensional planar and axisymmetric domains. The program currently addresses linear/nonlinear magnetostatic problems, linear/nonlinear time harmonic magnetic problems, linear electrostatic problems, and steady-state heat flow problems
2) **MATLAB** (an abbreviation of "matrix laboratory") is a proprietary multi-paradigm programming language and numeric computing environment developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages.
3) **OctaveFEMM** - To aid in the use of FEMM from Matlab, a toolbox called OctaveFEMM is available. This toolbox implements Matlab commands that subsume the functionality of Lua using equivalent Matlab commands, in a similar way to the fashion that MathFEMM works with Mathematica. Using the toolbox, all details of the ActiveX interface are taken care of in a way that is completely transparent to the user.

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Motor Construction

The present example uses a 3/8 pitch winding with 16 magnets and 18 stator slots, shown in the figure below. Although the stator teeth are straight, the motor has very low cogging torque (~1% per unit) and very low harmonic distortion of the back EMF waveform (~1% THD). This motor could be used in precision direct-drive servo applications where precise control over the motor is required.

The magnet material is N42UH with a nominal coercivity of Hc = 1,007,000 A/m and a relative permeability of 1.0277. The electrical conductivity of the magnet material is 0.556*106 S/m.The core material is DI-MAX M-19 non-oriented silicon steel laminations

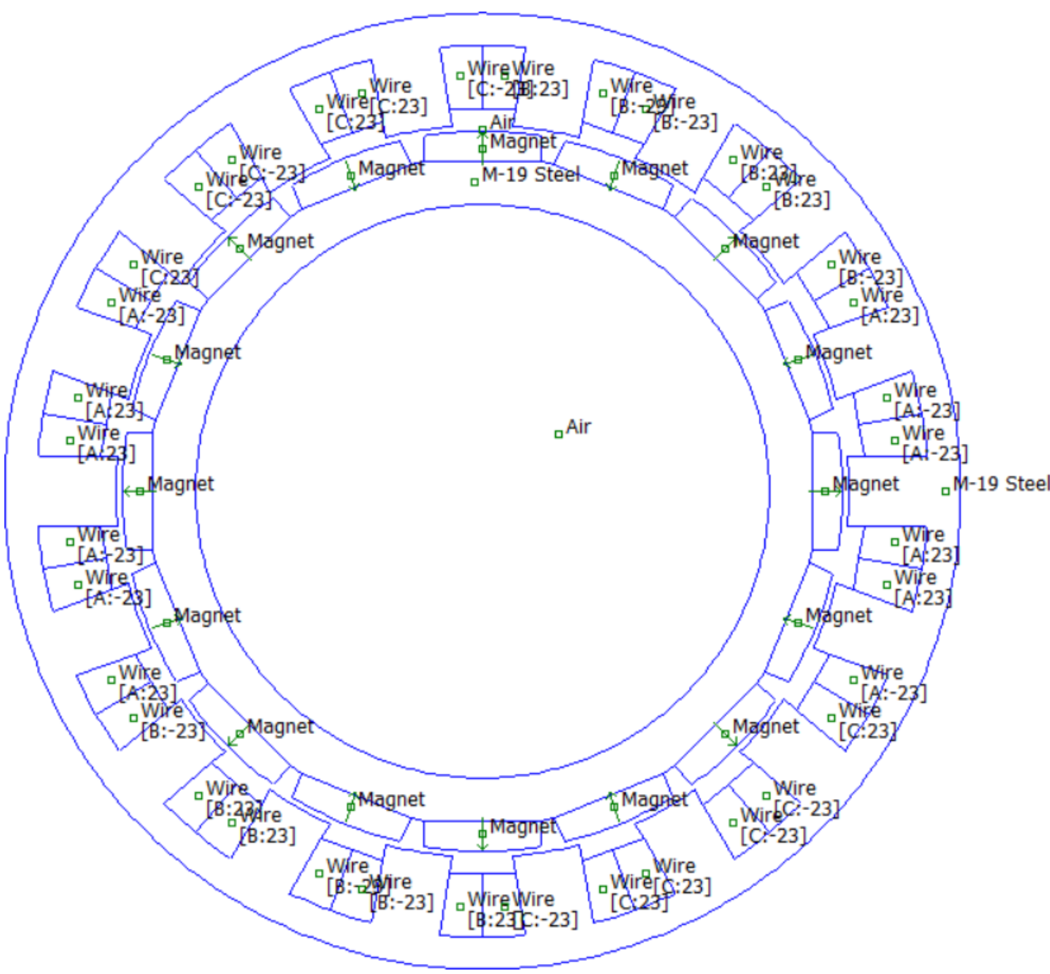

Figure 1: Motor with 3/8 pitch.

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Core Loss Data

Material property data is required as a basis for core loss calculations. A grade of silicon core iron that is both high quality and commonly available is M-19. Loss data for M-19 is shown below in Figure 2 for a 29-gauge sheet (0.014" thick).

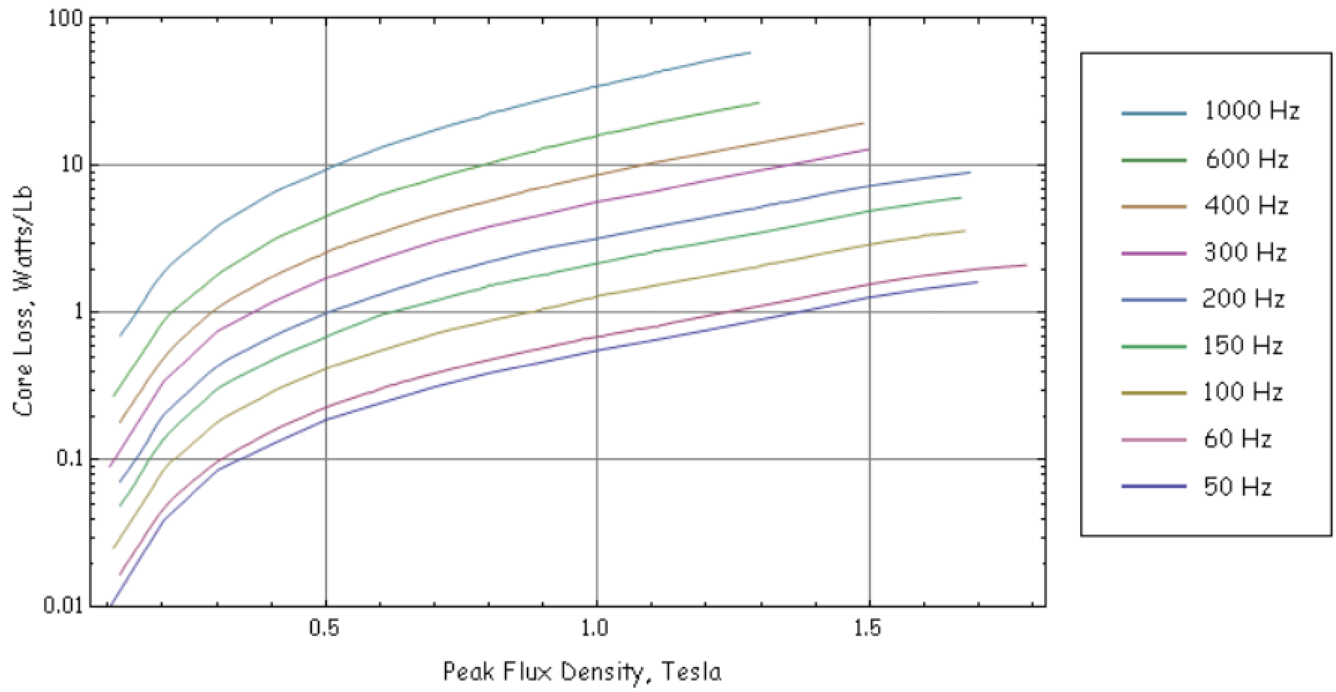

Figure 2: Core loss curves of 29-gauge sheet.

For the purposes of loss computation, it is useful to have a simple form that approximately captures the entire range of curves. A "traditional" way to do this is to assume that the core loss can be broken into a part due to hysteresis, which varies linearly with frequency, and a part due to eddy currents, which varies with the square of frequency:

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$$P_{core} = P_h + P_e = C_h \omega B^2 + C_e \omega^2 B^2 \qquad (1)$$

where Ph and Pe are hysteresis loss and eddy current loss, respectively. Parameters Ch and Ce are hysteresis and eddy current loss coefficients that are regressed from the core loss data. The B in the formula is the amplitude of the flux density (i.e. the peak value).The simple form of (1) is employed here because a curve fit to this form yields reasonable accuracy over the range of application in the problem under consideration.

A reasonable fit to the data for 29-gauge M-19 from 50Hz to 600 Hz is:

$C_h = 0.00844$ Watt/(lb*Tesla2*Hz)

$C_e = 31.2 \times 10^{-6}$ Watt/(lb*Tesla2*Hz2)

For the purposes of finite element calculations, however, we are interested in loss per unit volume, not loss per unit weight. The density of M-19 is:

$\rho = 7.70$ gm/cm3

If the density is used to convert between loss per unit weight and loss per unit volume, the loss is:

$C_h = 143$ Watt/(m3*Tesla2*Hz)

$C_e = 0.530$ Watt/(m3*Tesla2*Hz2)

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Loss Calculation

- To collect and analyze the requisite flux density vs. time information, a (heavily commented) Matlab script was created (script mySPMLossScript.m that operates on model my_SPM_motor.fem).
- The script performs a series of finite element runs, incrementing the rotor position and stator currents with each successive run and collecting the required data on the magnetic fields in rotor, stator, magnets, and coils.
- To keep track of which loss mechanism applies to each section of the model, different regions of the model are assigned to specific groups. The script assumes the region grouping listed in the table below.
- During the first run of the series, the script performs some additional bookkeeping that is needed to locate the points at which the magnetic field is to be evaluated during subsequent iterations of the script. The location of the centroid and the size of each element contained in a laminated region is recorded for later use.

Region	Group
Air	0
Stator Core	1
Windings	2
Rotor Core	10
Magnets	11...26

Table 1: Grouping of model regions for loss calculation.

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- As the rotor's position is changed, the finite element mesh changes. The element centroids from the initial finite element mesh are fixed points in the lamination geometry at which the field is evaluated in each incremental analysis, regardless of remeshing.
- The flux density is then evaluated at every stored element centroid for every rotor position, essentially building up a history of flux density versus time for each element in the laminated regions. Some extra care is required for points located in the rotor.
- The initial centroid locations need to be rotated through the same angle as the rotor so that the rotor field is always evaluated at the same points on the rotor from run to run.
- The resulting field evaluations also need to be rotated so that the field for points on the rotor is always represented in the same rotor-fixed reference frame.
- Care must also be taken to evaluate the performance over a suitably broad range of angles. In particular, concentrated windings like the one considered in this example can have significant sub-harmonics of significant amplitude, and a big enough angle must be considered to capture the effects of the winding sub-harmonics on rotor losses.
- For example, the winding factor for various harmonics in the selected 3/8 winding is shown below in Table 2. For this winding, there is significant content on the 2nd harmonic.
- To properly account for all induced currents in the magnets, the example machine must therefore be evaluated over 180 of rotor motion to expose the rotor magnets to the complete stator winding waveform.

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EE-3/P1

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Harmonic	Winding Factor
1	0
2	0.0606617
3	0
4	0.13985
5	0
6	0
7	0
8	0.945214
9	0
10	0.945214
11	0
12	0
13	0
14	0.13985
15	0
16	0.0606617
17	0
18	0
19	0
20	0.0606617
21	0

Table 2: Winding Factor vs. Harmonic for a 3/8 winding with 18 slots and 16 magnets.

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- Once finite element runs have been performed over a suitably large arc, Matlab's built-in Fast Fourier Transform (fft) function is used to turn what is essentially a time series of flux densities at each element centroid into amplitudes of various harmonics of flux density, as required by (6) for the evaluation of losses.
- The contributions from all harmonics for all elements are then added up to get the total core and proximity effect losses. FFTs of the vector potential in the magnet are also used to compute the loss at each harmonic.

Loss Results

Running the core loss script with a phase current amplitude of 2A positioned in-phase entirely aligned with the machine's Iq axis, the script produces the following loss results at the 4000 RPM base speed:

- rotor speed = 4000 RPM
- mechanical power = 62.2952 W
- rotor core loss = 0.0574995 W
- stator core loss = 3.40587 W
- prox loss = 0.0585815 W
- i^2 R loss = 4.37018 W
- magnet loss = 1.38116 W
- total electromagnetic losses = 9.27329 W

The losses computed by the script over a wide range of speeds is shown in the graph below. Only one set of finite element runs is needed to infer the results for all speeds.

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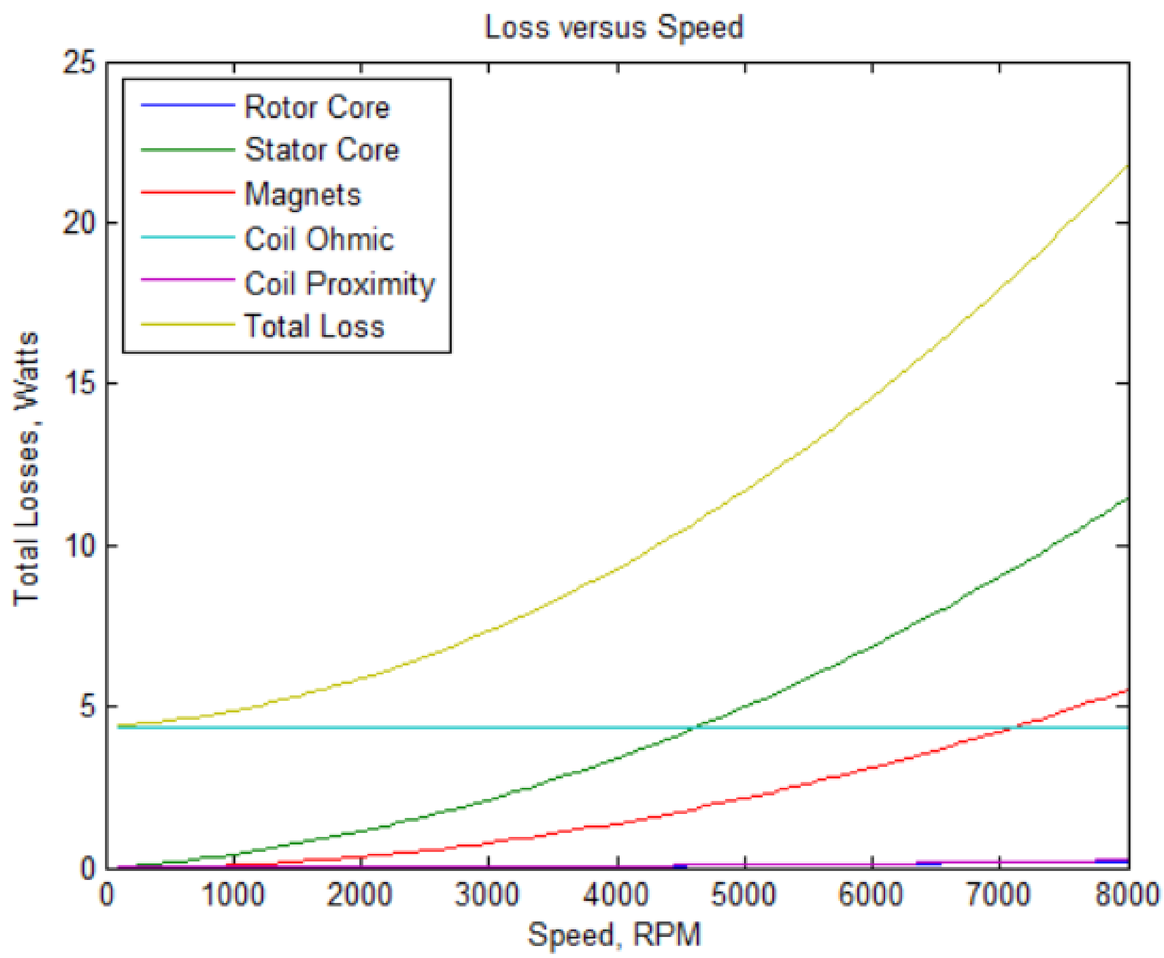

Figure 3: Plot of loss components versus speed for a 2A motor current.

- The power loss density can be plotted out into a heating map of the motor, as shown in Figure 4. White color represents high losses; low/no loss is represented by a dark color.
- This analysis shows that although the magnets are a relatively small portion of the loss, the loss density in the magnets is the highest of anywhere in the motor. In the stator, the highest losses are in the pole tips, though the losses are fairly uniform throughout the stator.
- A small amount of proximity effect loss is in evidence on the surface of the coils nearest to the air gap.

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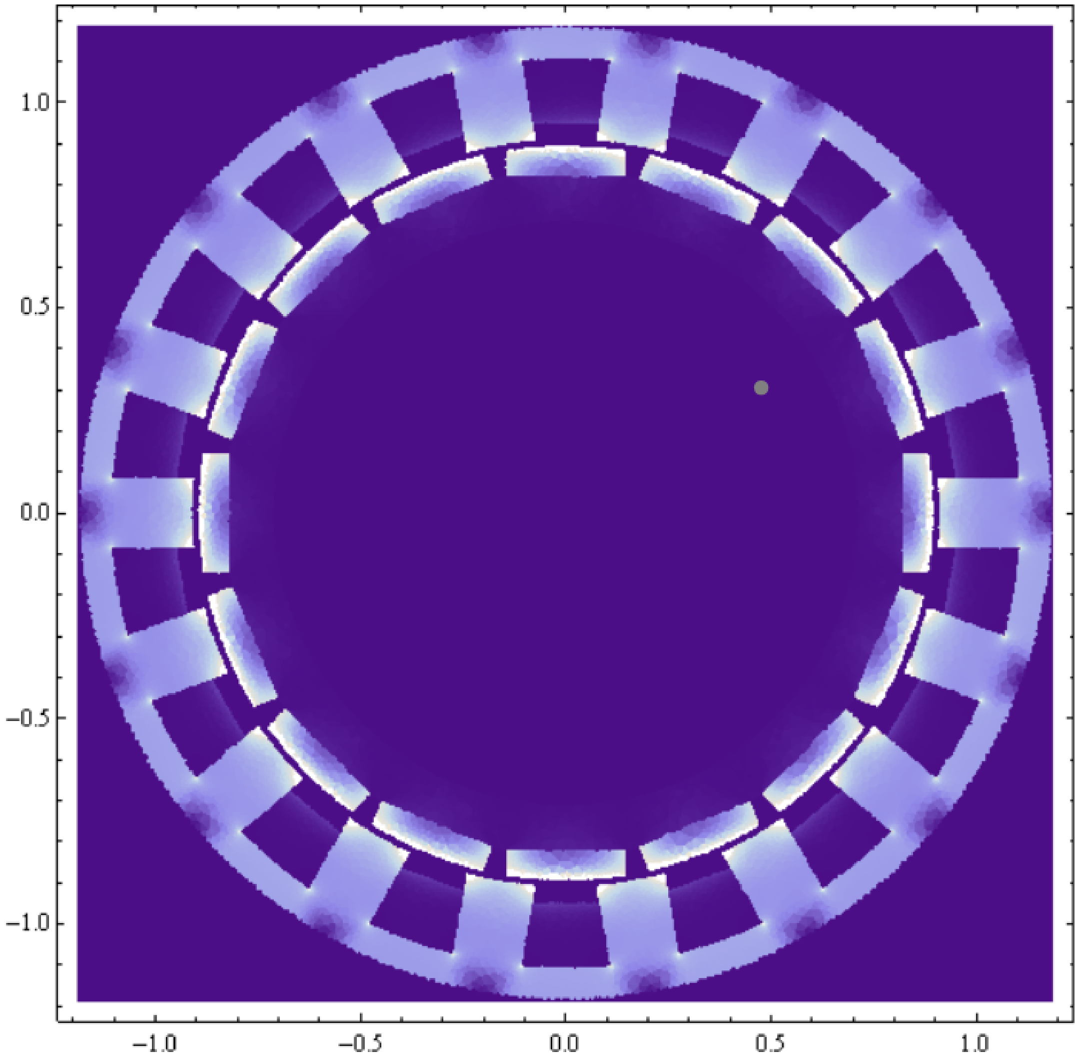

Figure 4: Plot of loss power density due to eddy currents and hysteresis throughout the motor at 4000RPM.

CONCLUSIONS

An example has been presented in which FEMM is used to compute the core, magnet, winding losses of a permanent magnet motor under load. A more complete analysis could also consider windage and bearing losses. A more complete thermal analysis of the motor would also help to determine the actual operating temperature of the machine, which influences the ohmic losses in the windings and the flux sourced by the permanent magnets.

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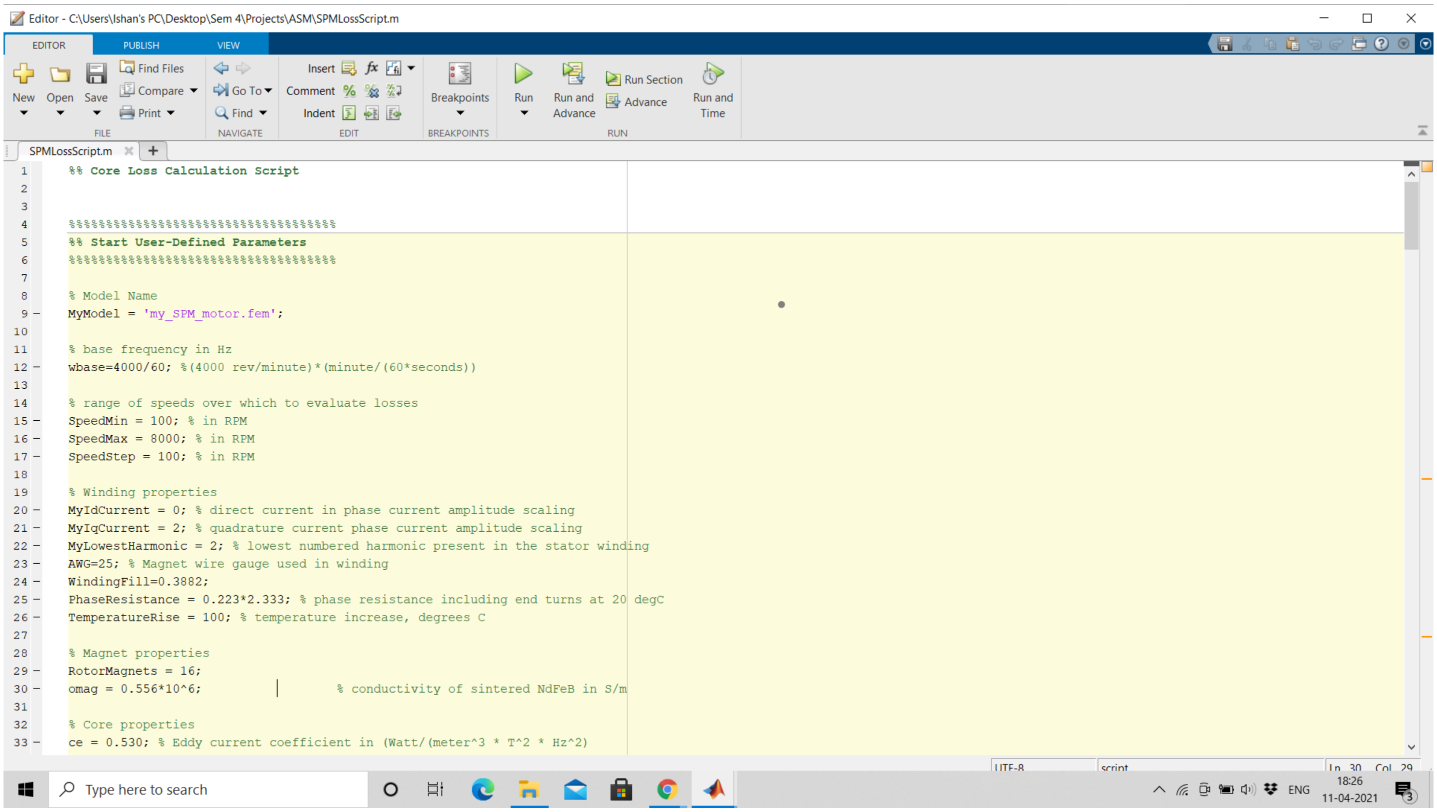
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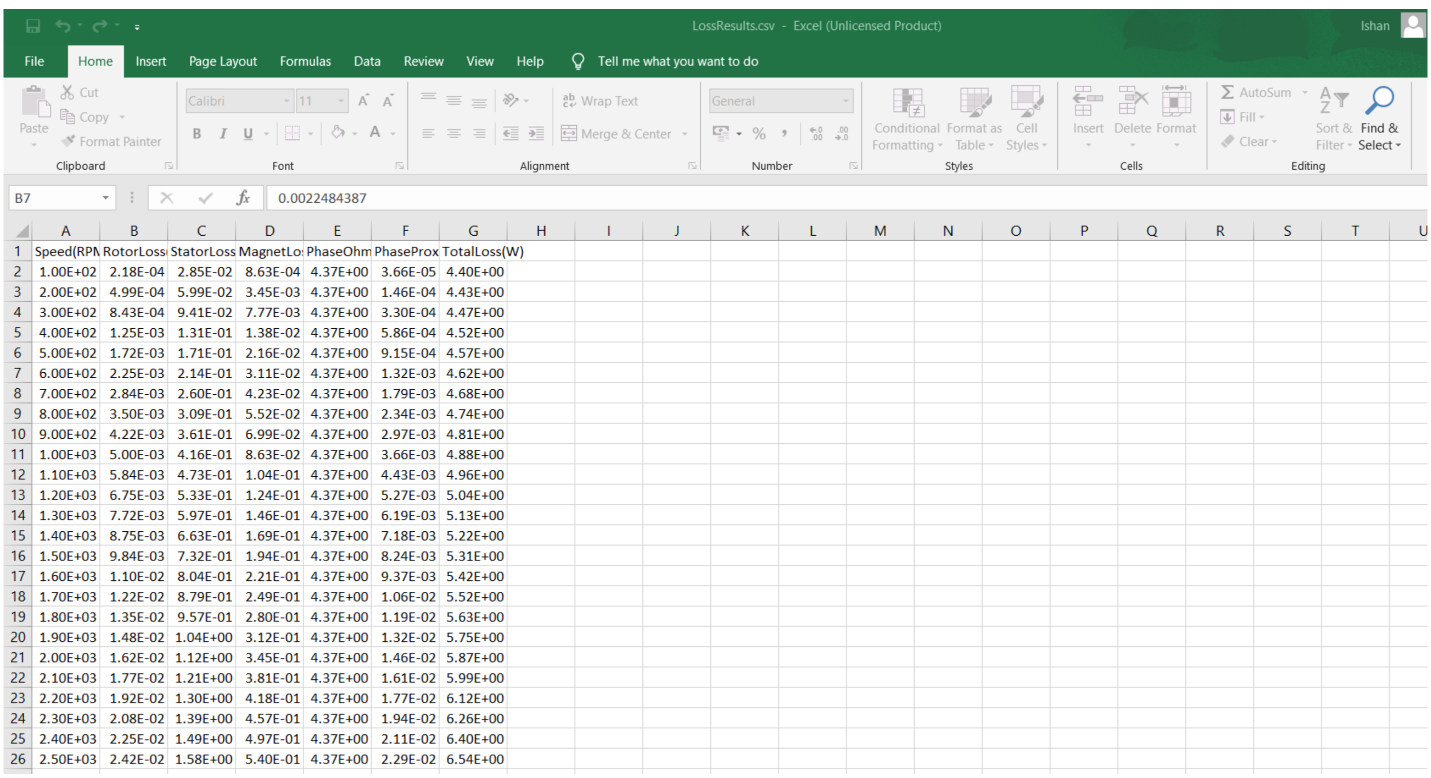
SPMLossScript.m

```
%% Core Loss Calculation Script


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Start User-Defined Parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Model Name
MyModel = 'my_SPM_motor.fem';

% base frequency in Hz
wbase=4000/60; %(4000 rev/minute)*(minute/(60*seconds))

% range of speeds over which to evaluate losses
SpeedMin = 100; % in RPM
SpeedMax = 8000; % in RPM
SpeedStep = 100; % in RPM

% Winding properties
MyIdCurrent = 0; % direct current in phase current amplitude scaling
MyIqCurrent = 2; % quadrature current phase current amplitude scaling
MyLowestHarmonic = 2; % lowest numbered harmonic present in the stator winding
AWG=25; % Magnet wire gauge used in winding
WindingFill=0.3882;
PhaseResistance = 0.223*2.333; % phase resistance including end turns at 20 degC
TemperatureRise = 100; % temperature increase, degrees C

% Magnet properties
RotorMagnets = 16;
omag = 0.556*10^6;          % conductivity of sintered NdFeB in S/m

% Core properties
ce = 0.530; % Eddy current coefficient in (Watt/(meter^3 * T^2 * Hz^2)
```


LossResults.csv - Excel (Unlicensed Product)

B7 | 0.0022484387

	A	B	C	D	E	F	G
1	Speed(RPN	RotorLoss	StatorLoss	MagnetLo:	PhaseOhm	PhaseProx	TotalLoss(W)
2	1.00E+02	2.18E-04	2.85E-02	8.63E-04	4.37E+00	3.66E-05	4.40E+00
3	2.00E+02	4.99E-04	5.99E-02	3.45E-03	4.37E+00	1.46E-04	4.43E+00
4	3.00E+02	8.43E-04	9.41E-02	7.77E-03	4.37E+00	3.30E-04	4.47E+00
5	4.00E+02	1.25E-03	1.31E-01	1.38E-02	4.37E+00	5.86E-04	4.52E+00
6	5.00E+02	1.72E-03	1.71E-01	2.16E-02	4.37E+00	9.15E-04	4.57E+00
7	6.00E+02	2.25E-03	2.14E-01	3.11E-02	4.37E+00	1.32E-03	4.62E+00
8	7.00E+02	2.84E-03	2.60E-01	4.23E-02	4.37E+00	1.79E-03	4.68E+00
9	8.00E+02	3.50E-03	3.09E-01	5.52E-02	4.37E+00	2.34E-03	4.74E+00
10	9.00E+02	4.22E-03	3.61E-01	6.99E-02	4.37E+00	2.97E-03	4.81E+00
11	1.00E+03	5.00E-03	4.16E-01	8.63E-02	4.37E+00	3.66E-03	4.88E+00
12	1.10E+03	5.84E-03	4.73E-01	1.04E-01	4.37E+00	4.43E-03	4.96E+00
13	1.20E+03	6.75E-03	5.33E-01	1.24E-01	4.37E+00	5.27E-03	5.04E+00
14	1.30E+03	7.72E-03	5.97E-01	1.46E-01	4.37E+00	6.19E-03	5.13E+00
15	1.40E+03	8.75E-03	6.63E-01	1.69E-01	4.37E+00	7.18E-03	5.22E+00
16	1.50E+03	9.84E-03	7.32E-01	1.94E-01	4.37E+00	8.24E-03	5.31E+00
17	1.60E+03	1.10E-02	8.04E-01	2.21E-01	4.37E+00	9.37E-03	5.42E+00
18	1.70E+03	1.22E-02	8.79E-01	2.49E-01	4.37E+00	1.06E-02	5.52E+00
19	1.80E+03	1.35E-02	9.57E-01	2.80E-01	4.37E+00	1.19E-02	5.63E+00
20	1.90E+03	1.48E-02	1.04E+00	3.12E-01	4.37E+00	1.32E-02	5.75E+00
21	2.00E+03	1.62E-02	1.12E+00	3.45E-01	4.37E+00	1.46E-02	5.87E+00
22	2.10E+03	1.77E-02	1.21E+00	3.81E-01	4.37E+00	1.61E-02	5.99E+00
23	2.20E+03	1.92E-02	1.30E+00	4.18E-01	4.37E+00	1.77E-02	6.12E+00
24	2.30E+03	2.08E-02	1.39E+00	4.57E-01	4.37E+00	1.94E-02	6.26E+00
25	2.40E+03	2.25E-02	1.49E+00	4.97E-01	4.37E+00	2.11E-02	6.40E+00
26	2.50E+03	2.42E-02	1.58E+00	5.40E-01	4.37E+00	2.29E-02	6.54E+00

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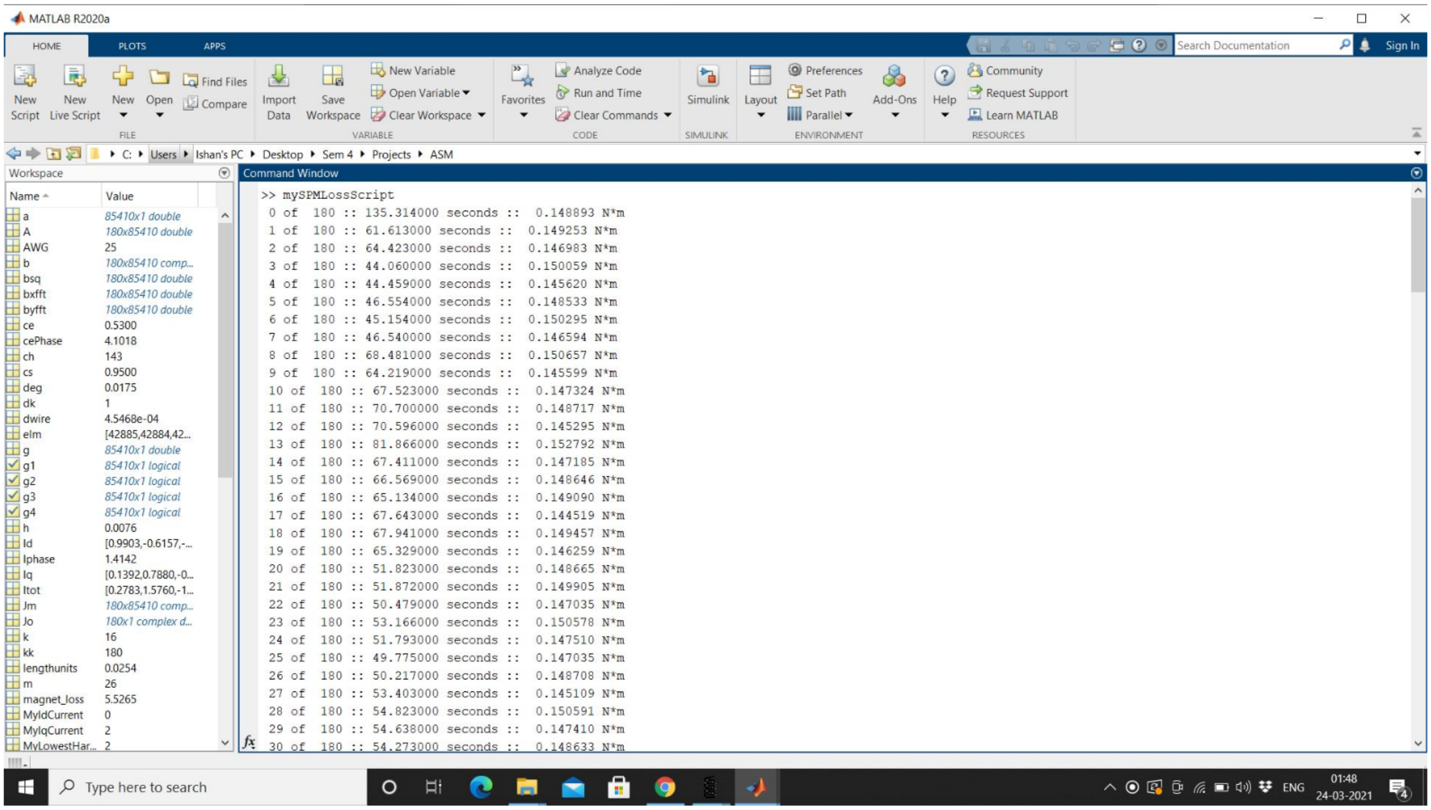

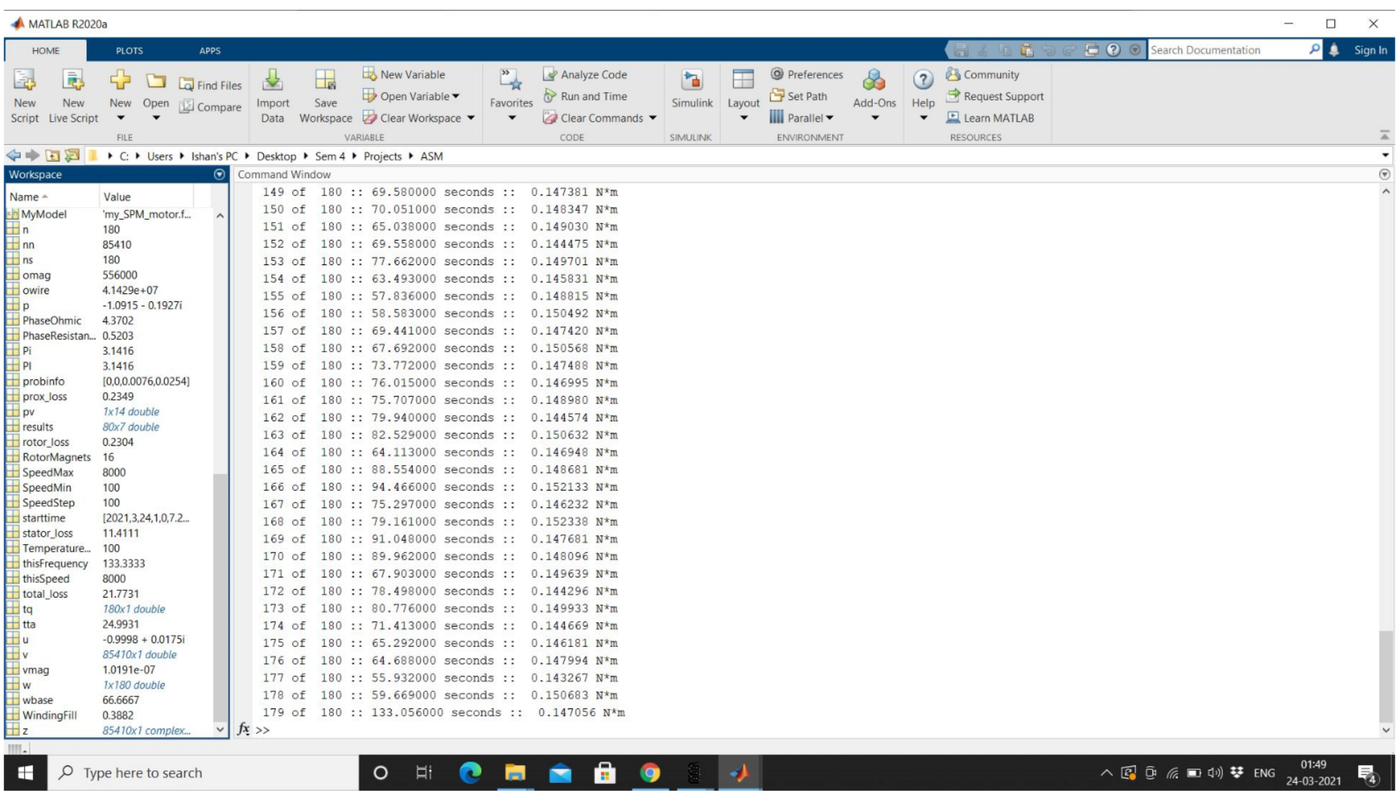

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References

[1] F. Libert, J. Soulard, "Investigation on pole-slot combinations for permanent-magnet machines with concentrated windings", KTH Report, 2004.

[2] E. Dlala, "Comparison of models for estimating magnetic core losses in electrical machines using the finite-element method," IEEE Transactions on Magnetics, 45(2):716-725, Feb. 2009.

[3] H. Trabelsi, A. Mansouri, and M. Gmiden, "On the no-load iron losses calculations of a SMPM using VPM and transient finite element analysis," International Journal of Sciences and Techniques of Automatic Control & Computer Engineering, 2(1):470-483, July 2008.

[4] R. L. Stoll, "The analysis of eddy currents," Oxford University Press, 1974.

[5] D. M. Ionel et al. "On the variation with flux and frequency of the core loss coefficients in electrical machines," IEEE Transactions on Industry Applications, 42(3):658-667 May/June 2006. (http://eprints.gla.ac.uk/3438/)

[6] D.C. Meeker, "An improved continuum skin and proximity effect model for hexagonally packed wires," Journal of Computational and Applied Mathematics, 236(18):4635-4644, Dec. 2012. http://dx.doi.org/10.1016/j.cam.2012.04.009

[7] D. Ishak, Z. Q. Zhu, and D. Howe, "Eddy-current loss in the rotor magnets of permanent-magnet brushless machines having a fractional number of slots per pole," IEEE Transactions on Magnetics, 41(9):2462-2469, Sept. 2005.

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