

Aerospace Power & Electronics Workshop
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***Performance Prediction for a Permanent Magnet
Two-Pole Synchronous Machine for a Flywheel
Energy Storage System***

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Outline

- ***Background***
- ***Flywheel System Description***
- ***Machine Characteristics***
- ***Requirements of Space Flywheel System Machine***
- ***Machine modeling***
- ***Modeling Tools***
- ***Quantify Rotor Loss***
- ***Quantify Ripple Torque***
- ***Concluding Observations***

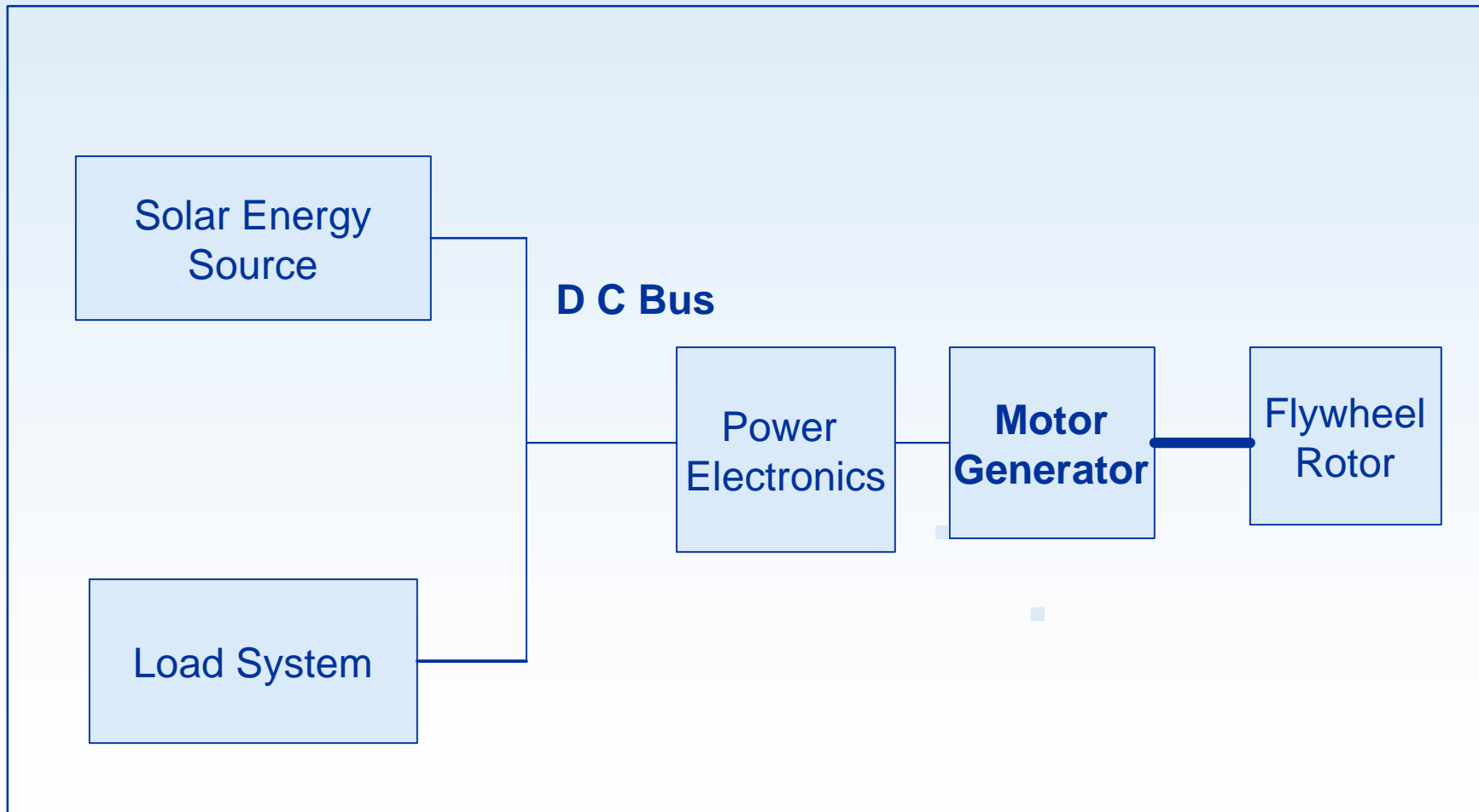
Background

- ***Flywheel Principle is well known***
 - ***Energy Storage proportional of Inertia Constant and Omega²***
- ***Used extensively for Guidance, Navigation, & Control of Space Crafts***
 - ***Energy exchange among flywheels used to change Space Craft Attitude***
- ***Proposed as a 'battery replacement' for Space Station***
 - ***Longer life than batteries***
 - ***Much greater Depth of Discharge***
- ***Energy Storage function can be combined with GN&C***
 - ***Integrated Power & Attitude Control System (IPACS)***
 - ***Storage requirements for GN&C only a fraction of 'battery function'***
 - ***Independent control of two functions needed***

The Flywheel Energy Storage System

- ***Excess energy available during insolation is stored in the Flywheel (charging)***
- ***Flywheel supplies stored energy to load during eclipse (discharging)***
- ***Electrical machine mechanically coupled to flywheel shaft effects energy transfer***
- ***Electrical Machine works as motor (charging) or generator (discharging)***
 - ***During charge, motor speed increases***
 - ***Rate of Charge is controlled to match the power electronics rating***
 - ***During discharge, generator speed decreases***
 - ***Rate of Discharge controlled to maintain constant D C Bus Voltage***
- ***Controller needed to operate the machine***

Flywheel System Schematic



Machine Characteristics

- ***Permanent Magnet Synchronous Machine selected for Flywheel***
 - ***Magnets mounted on the Rotor***
 - ***No Field circuit (No Copper Losses)***
 - ***Back EMF directly proportional to speed***
 - » ***No independent Voltage Control possible***
 - ***Rotor mounted on Flywheel shaft***
 - ***Flywheel absorbs heat from rotor core losses***
 - ***Possible Degradation of the flywheel composite material***
 - ***Magnetic Bearings used for higher efficiency at 60 kRPM***
 - ***Able to dissipate rotor losses by Radiation only***
 - ***Rotor operates in near vacuum***

Requirements of Space F/W System Machine

- ***Low Rotor Losses***
 - ***Will Enhance Mission Life***
 - ***Lower Life Cycle Cost***
- ***Space Harmonics in the air gap flux induce rotor losses***
 - ***Caused by***
 - ***Time Harmonics of Stator Excitation***
 - ***Discrete stator winding distribution***
 - ***Slot Harmonics***
 - ***Trade-off studies with laminated rotor iron and/or the magnets***
 - ***Need to accurately compute rotor iron losses during Design Process***
 - ***Need complete information on Magnetic Materials***
- ***Validation of rotor losses***
 - ***How to measure rotor losses? (Temperature Rise!!)***

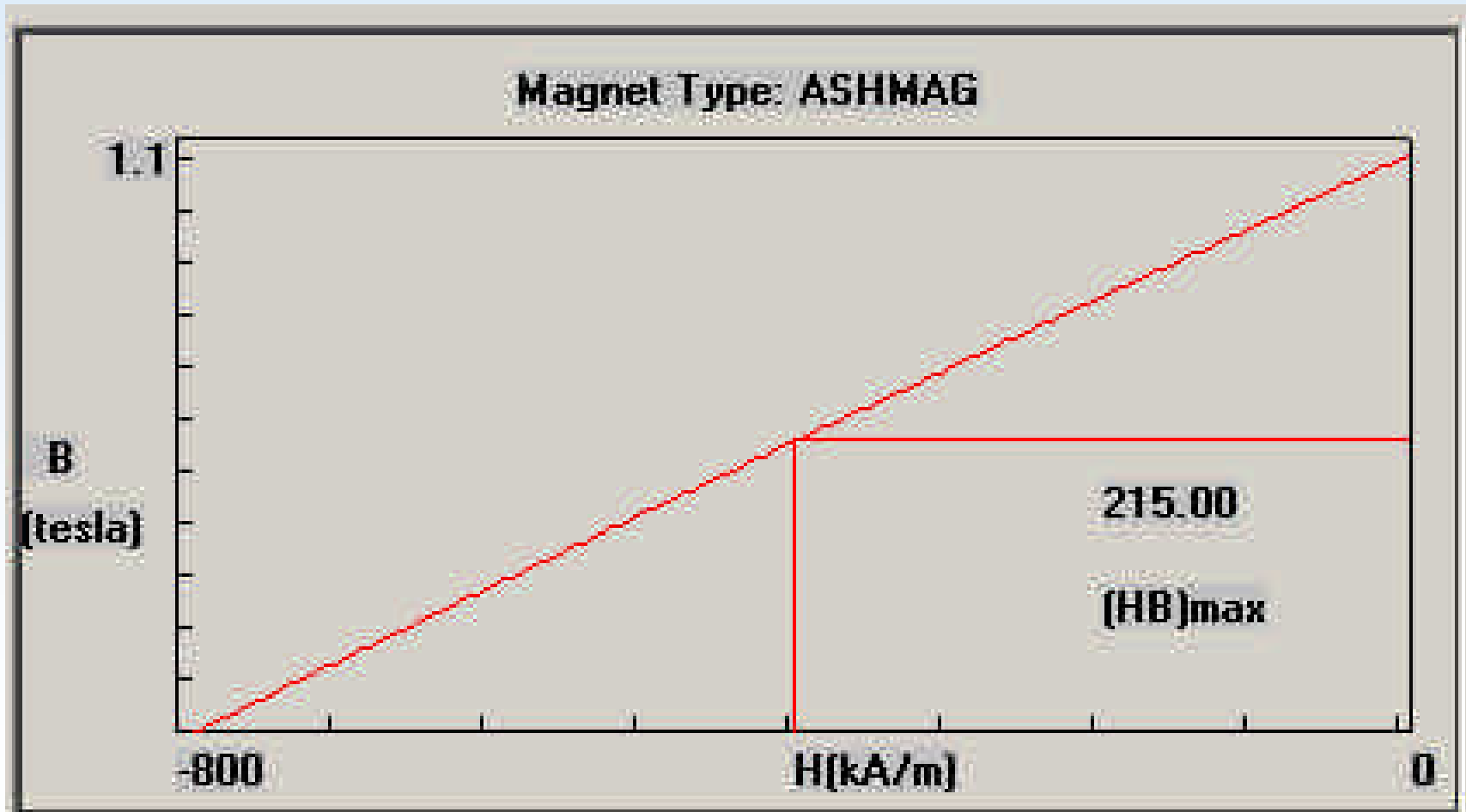
Requirements (continued)

- ***Low Torque Ripple***
 - ***Ripple tends to excite Space Craft modes***
 - ***Interaction with GN&C system***
 - ***Reduction of Mission life***
 - ***Design will estimate value of Torque ripple***
 - ***Testing needed for validation***
- ***Torque Ripple caused by***
 - ***Non-Sinusoidal winding distribution***
 - ***Ripple reduction difficult due to the small number of slots***
 - ***Non-Sinusoidal excitation of stator winding***
 - ***The Power Electronics output must have adequate filtering to reduce excitation harmonics***
 - ***Non-Skewed Slots (Cogging)***

Machine Modeling

- ***Use an existing machine with incomplete information***
 - ***Basic Input Parameters available***
 - ***Power, Voltage Rating, RPM***
 - ***Stator, Rotor Overall Dimensions***
 - ***Stator Number of Slots***
 - ***Pole Face Shape***
 - ***Stator back iron lamination thickness***
 - ***Permanent magnet Characteristics (B_r , H_c , Max Energy Density)***
 - ***Straight Line model generated using B_r and H_c***
 - » ***Max Energy Density within 10% of given value***

Permanent Magnet Characteristics



Modeling (continued)

- ***Needed information not available***
 - ***Winding Details***
 - ***Type, Distribution, Wire size, Number of Turns in a coil, Number of parallel paths***
 - ***Stator back iron material characteristics***
 - ***Stacking Factor***
 - ***Rotor back iron material characteristics***
 - ***Specified only as 'soft iron' hub***
 - ***Assumed as not laminated***
- ***Information generated from Testing***
 - ***Flux distribution from Pole Faces (in air)***
 - ***Will identify magnet field orientation***
 - ***Voltage wave form***
 - ***Spectral Analysis yields harmonic content***

Modeling Software Employed

- ***Basic Machine Design***
 - ***Performed using RMxpert from Ansoft Corp.***
 - ***Designs a machine by iterating on a minimum set of input data, applying laws of Physics***
 - ***When complete input information not available –***
 - ***Provides for a large selection of magnetic materials***
 - ***Permits different options in Winding Types, Slot Shapes, Magnet arrangement, Pole face shape***
 - ***Provides ‘slot skewing’ option to study cogging torque***
 - ***Provides for automated slot shape and winding data determination***
 - ***Suggests possible reason why solution not converged***
 - ***New solution could be attempted with modified input***

RMxpert Input Data 1

Adjustable-Speed Permanent-Magnet Synchronous Motor Design

General | Stator1 | Stator2 | Rotor Pole

Rated Output Power (kW):

Rated Voltage (V):

Number of Poles:

Frequency (Hz):

Friction Loss (W):

Trigger Pulse Width:

Transistor Drop (V):

Diode Drop (V):

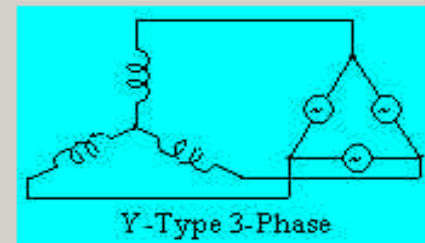
Operating Temperature:

Rotor Position

Inner

Outer

Circuit Type



Source Type

DC PWM Sine Wave

Change to Frequency Domain

RMxpert Input Data 2

Adjustable-Speed Permanent-Magnet Synchronous Motor Design

General Stator1 Stator2 Rotor Pole

Outer Diameter (inch): 3.05

Inner Diameter (inch): 1.607

Number of Slots: 12

Skew Width: 0

Slot Dimensions (inch):

Auto Design Hs0 0.0414

Hs1 0.03819

Hs2 0

Bs0 0.10436

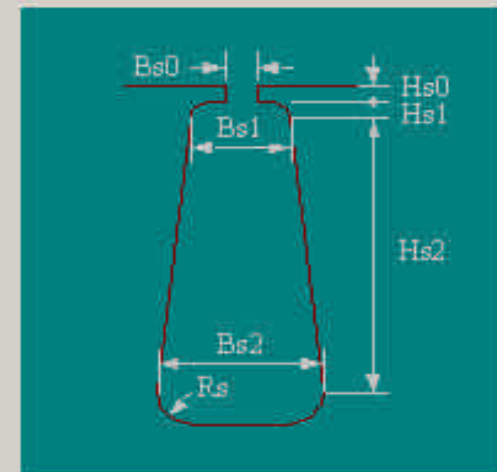
Bs1 0

Bs2 0

Rs 0

Slot Type

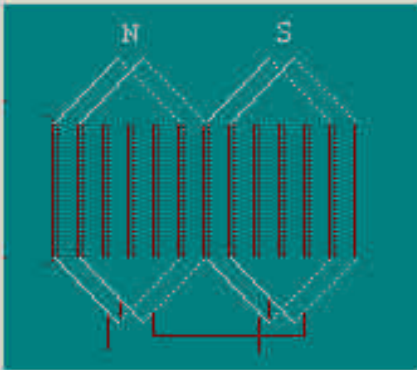
1 2 3 4



Input Tooth Width (inch): 0

RMxpert Input Data 3

Adjustable-Speed Permanent-Magnet Synchronous Motor Design

General	Stator1	Stator2	Rotor Pole
Length of Stator (inch):	<input type="text" value="1.45"/>		
Stacking Factor:	<input type="text" value="0.95"/>		
Steel Type:	<input type="text" value="HP76F"/>		
Slot Insulation (inch):	<input type="text" value="0.0005"/>		
End Adjustment (inch):	<input type="text" value="0"/>		
Parallel Branches:	<input type="text" value="1"/>		
Conductors per Slot:	<input type="text" value="6"/>		
Coil Pitch:	<input type="text" value="6"/>		
Wires per Conductor:	<input type="text" value="0"/>		
Wire Wrap (inch):	<input type="text" value="0"/>		
Wire Diameter (inch):	<input type="text" value="0"/>		
Winding Type:			
<input type="text" value="10"/> <input type="text" value="11"/> <input type="text" value="12"/> <input type="text" value="20"/> <input type="text" value="21"/> <input type="text" value="22"/>			
			
Gauge:			<input type="text" value="AUTO"/>

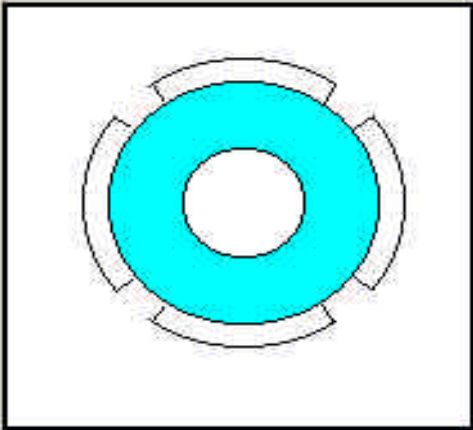
RMxpert Input Data 4

Adjustable-Speed Permanent-Magnet Synchronous Motor Design

General	Stator1	Stator2	Rotor Pole
Air Gap (inch):			<input type="text" value="0.0885"/>
Inner Diameter (inch):			<input type="text" value="0.6"/>
Length of Rotor (inch):			<input type="text" value="1.7"/>
Stacking Factor:			<input type="text" value="1"/>
Steel Type:			<input type="text" value="HP76F"/>
Pole Arc Offset (inch):			<input type="text" value="0"/>
Rib (inch):			<input type="text" value="0"/>
Pole Embrace:			<input type="text" value="0.9"/>
Magnet Type:			<input type="text" value="XG240/46"/>
Magnet Thickness (inch):			<input type="text" value="0.235"/>
Magnet Width (inch):			<input type="text" value="0"/>

Rotor Type

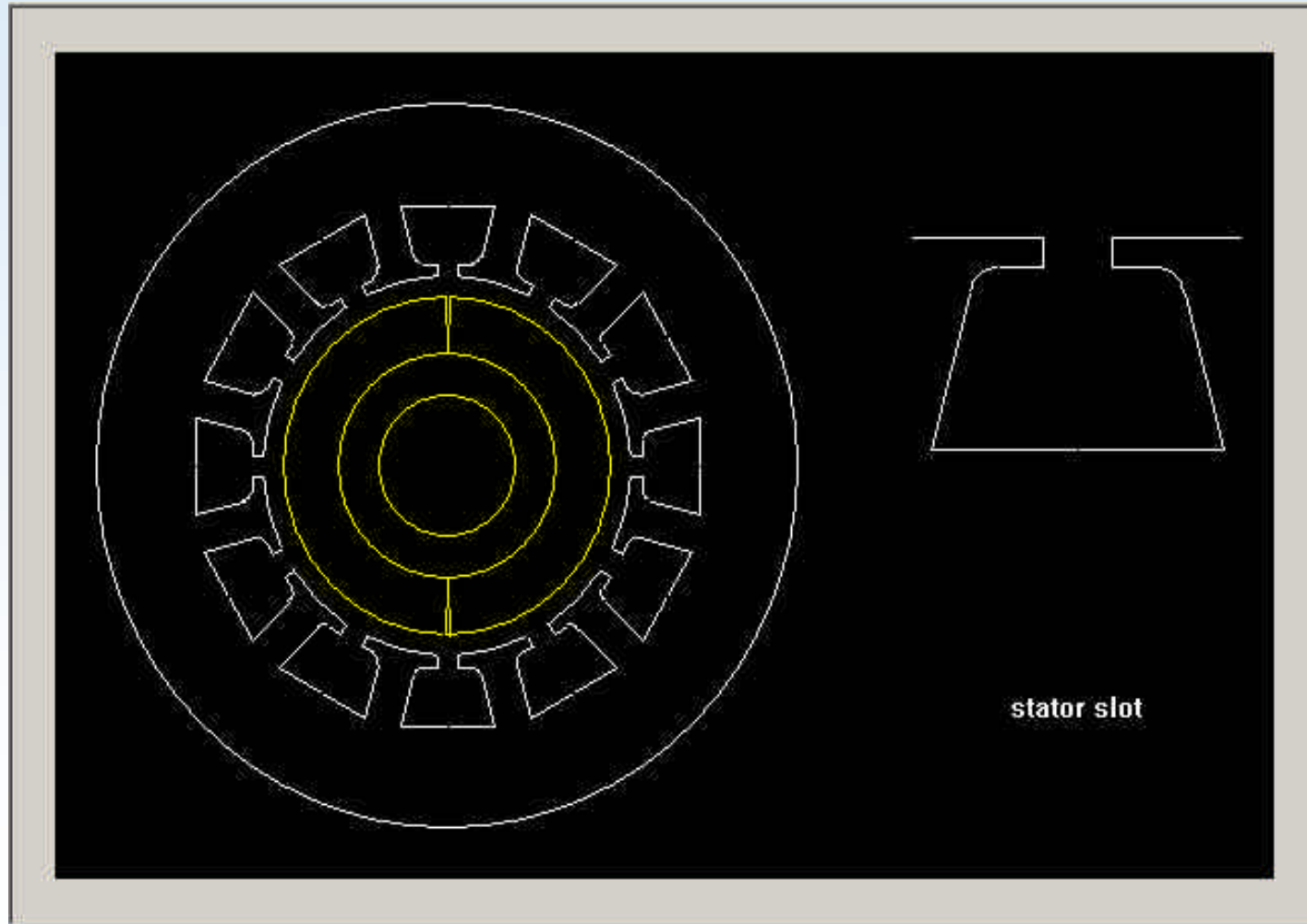
1 2 3 4 5



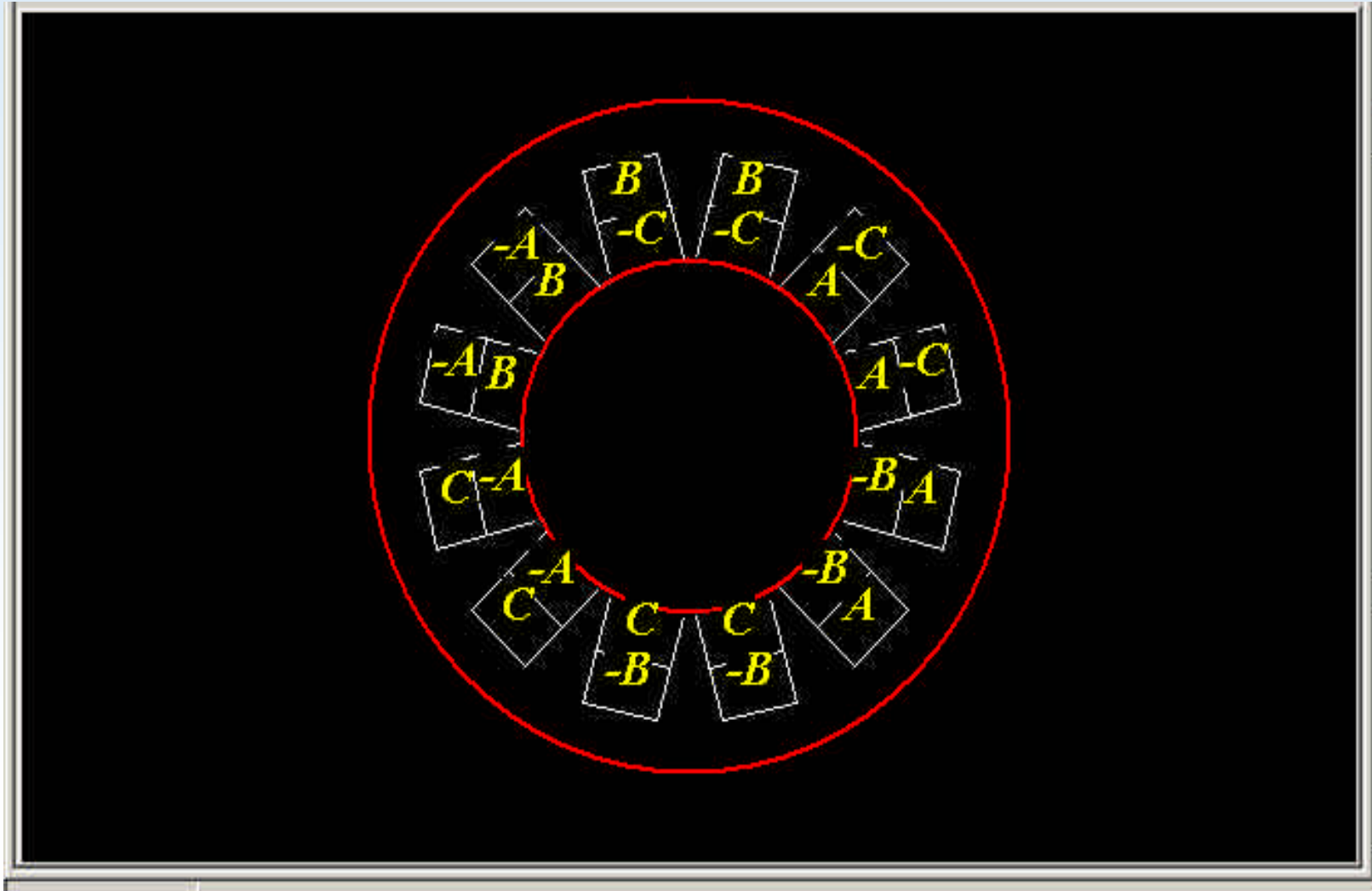
RMxpert (continued)

- ***Design Output data provides***
 - ***Shape of Lamination and pole faces***
 - ***Winding Distribution in stator slots***
 - ***Complete Design data (including input) and calculated operating conditions, losses, and efficiency***
 - ***Perusal of solved operating conditions to decide if further refinement needed***
 - ***Rotor Loss not explicitly identified***
 - ***Plots of voltage, current, flux over one cycle***
 - ***Permits FFT analysis to estimate harmonic content***
 - ***Prepares Geometrical Layout for Finite Element Analysis***
 - ***Permits Transfer of data file to FEA software***
 - ***Permits Transfer of data file to SIMPLORER (circuit analysis)***

Lamination View



Winding Layout



Design Data Sample

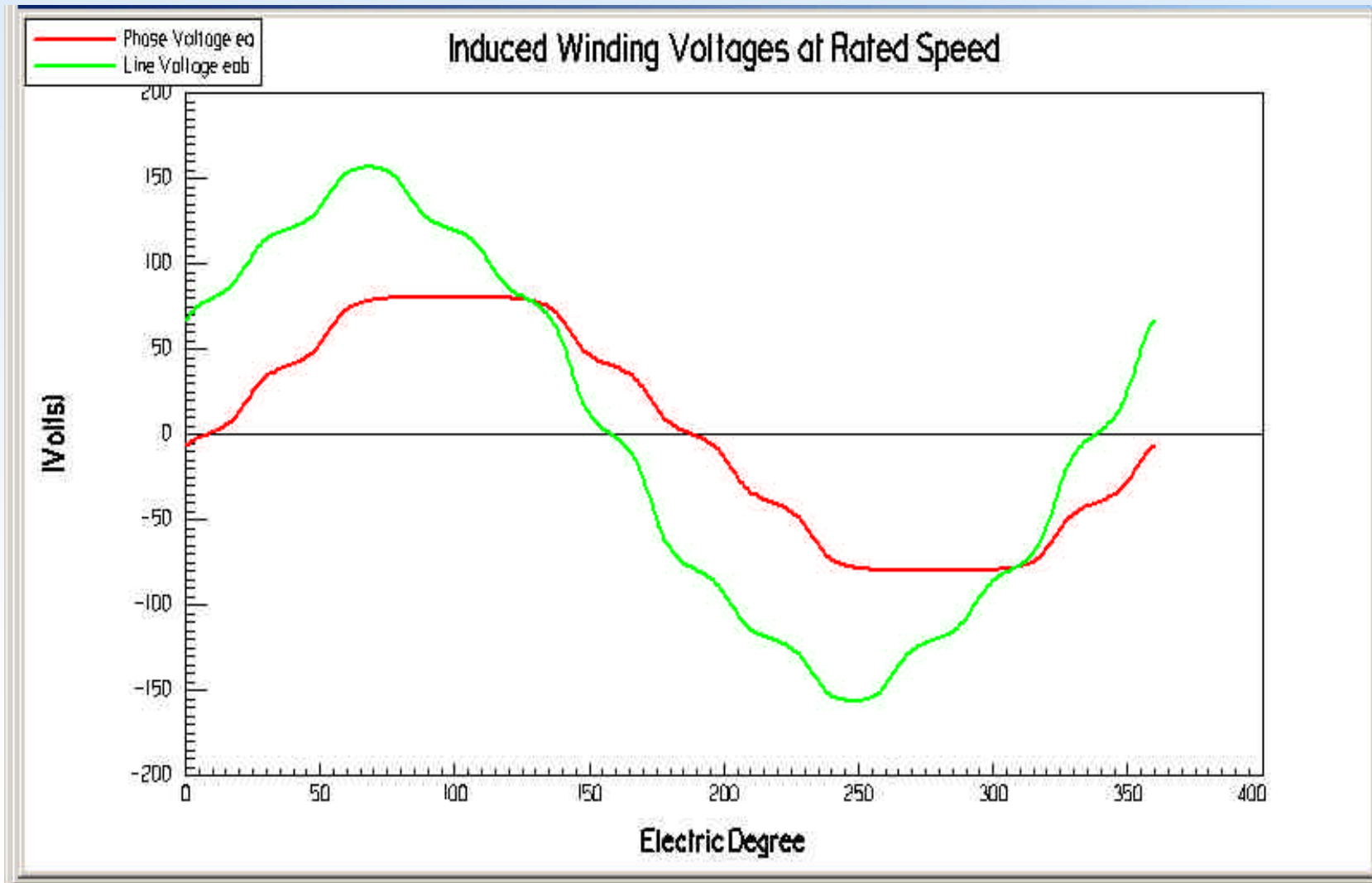
FULL-LOAD DATA

Maximum Line Induced Voltage (V):	156.506
Root-Mean-Square Line Current (A):	45.1114
Root-Mean-Square Phase Current (A):	45.1114
Armature Thermal Load (A^2/mm^3):	115.056
Specific Electric Loading (A/mm):	7.94747
Armature Current Density (A/mm^2):	14.477
Friction and Wind Loss (W):	0
Iron-Core Loss (W):	230.171
Armature Copper Loss (W):	117.915
Total Loss (W):	348.086
Output Power (W):	3001.27
Input Power (W):	3349.36
Efficiency (%)	89.6074
Synchronous Speed (rpm):	60000
Rated Torque (N.m):	0.477667
Torque Angle (degree):	8.20624
Maximum Output Power (W):	22361.2

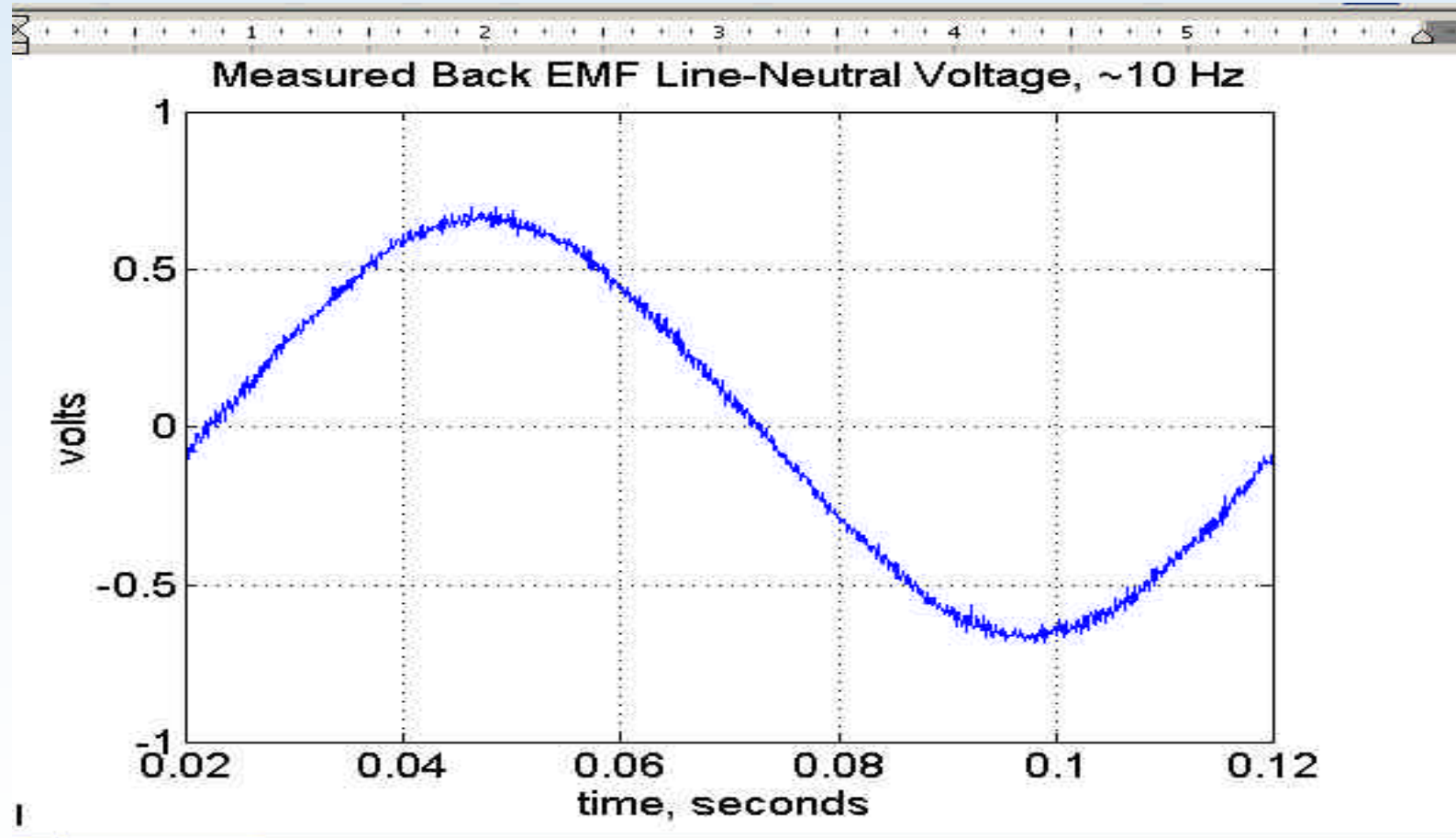
WINDING ARRANGEMENT

The 3-phase, 2-layer winding can be arranged in 12 slots as below:

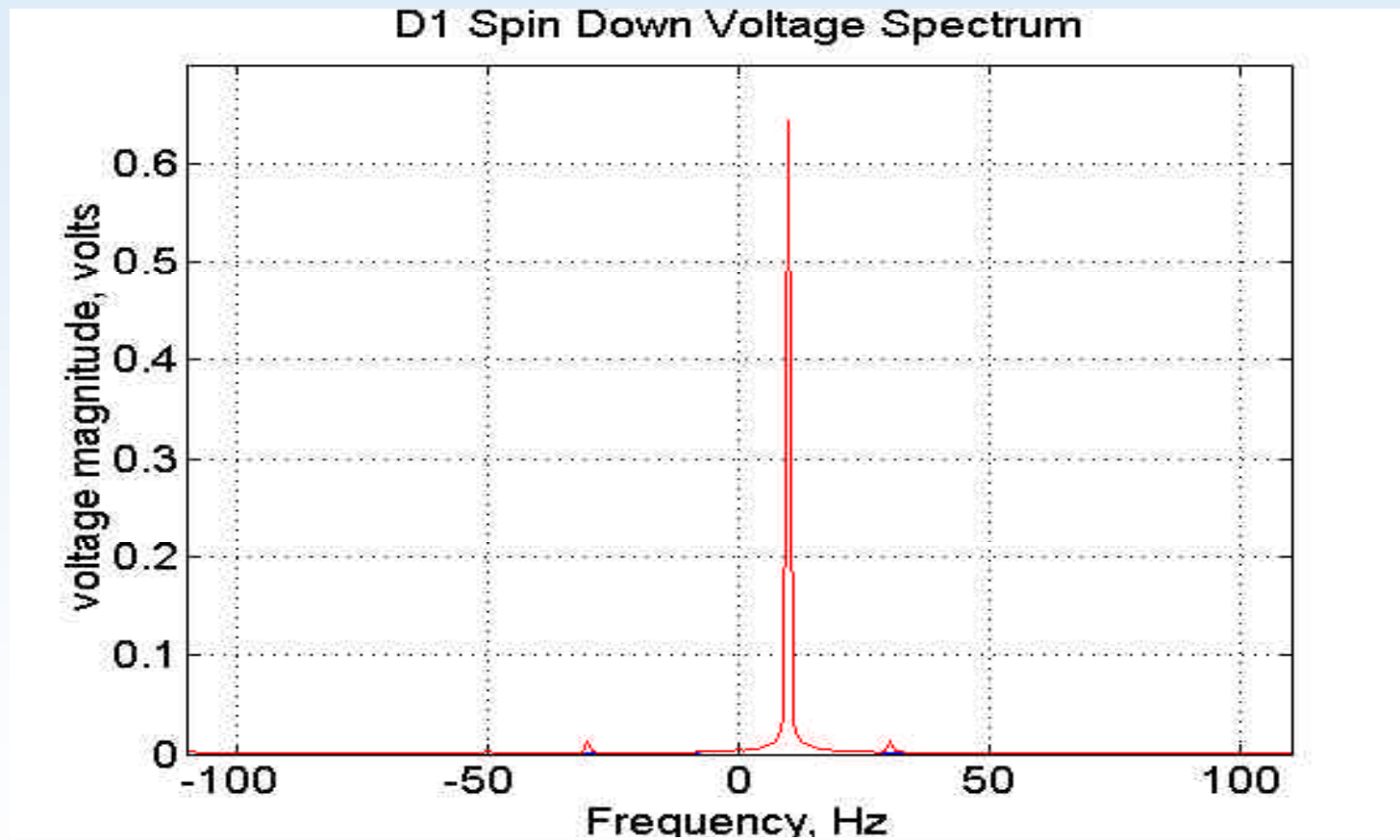
2 pole motor Back EMF at 1000 Hz



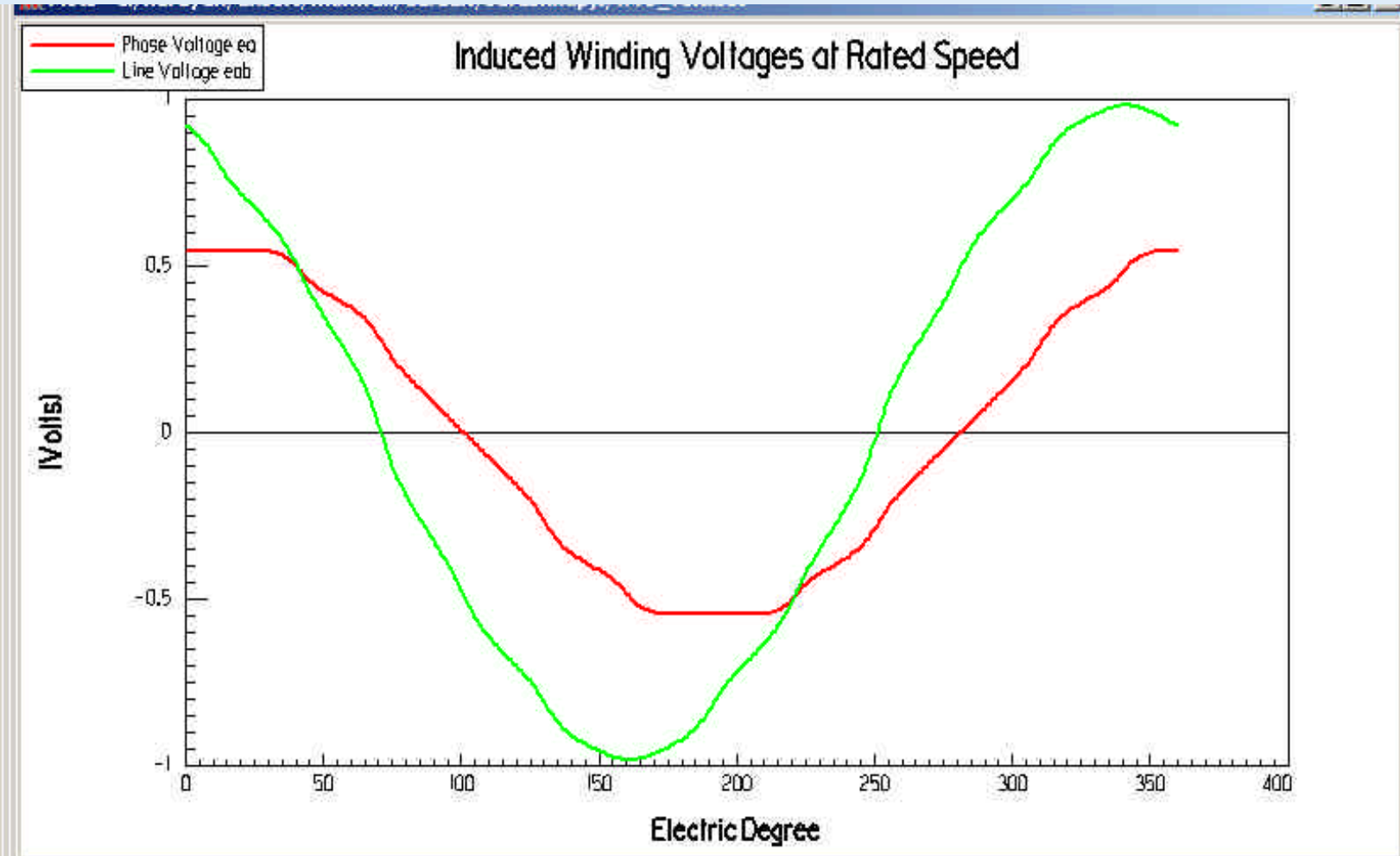
2 Pole L-N Back EMF at 10 Hz (measured)



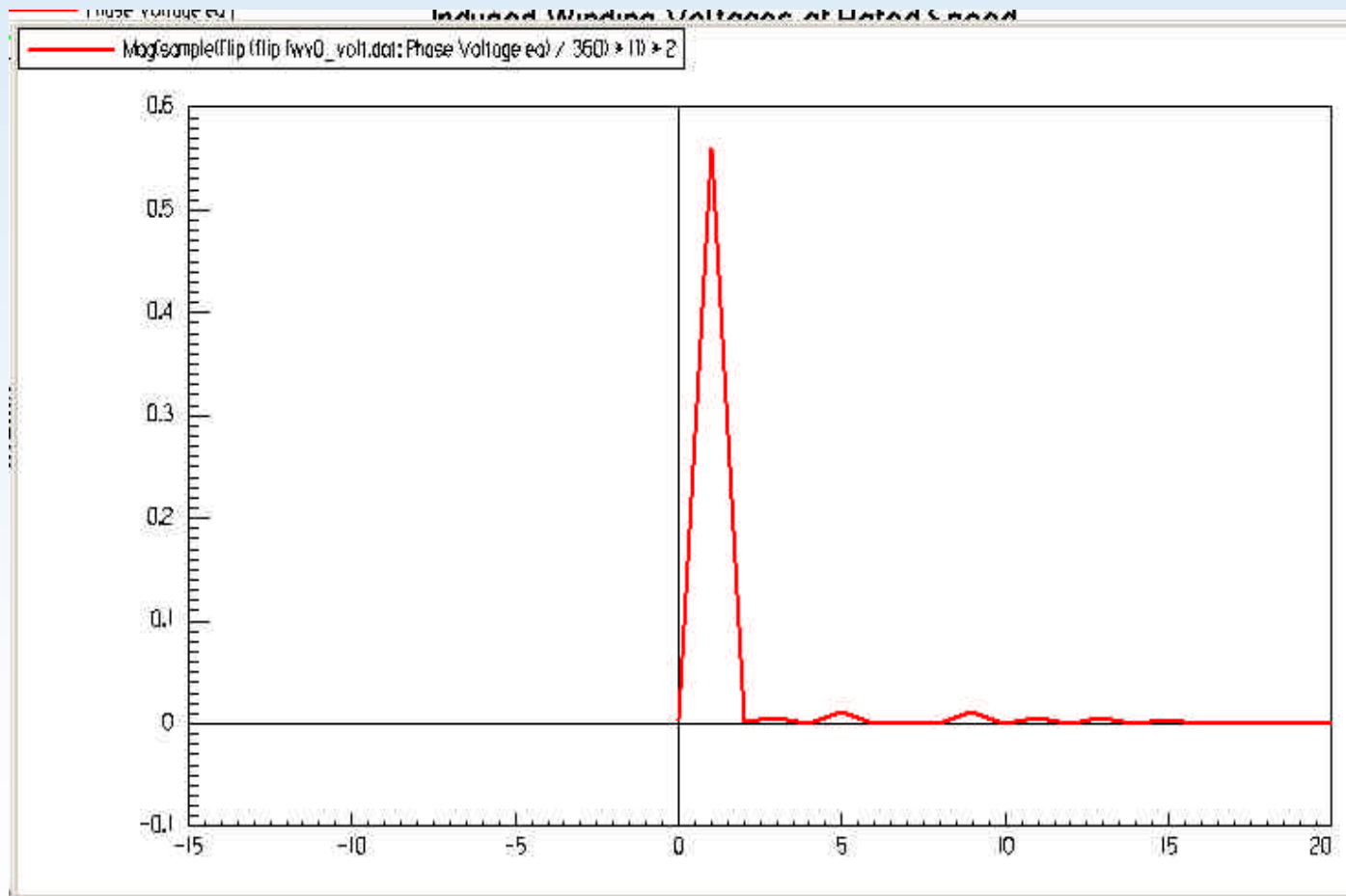
2 Pole Motor Measured Spectral Data



2 Pole Motor Back EMF at 10 Hz



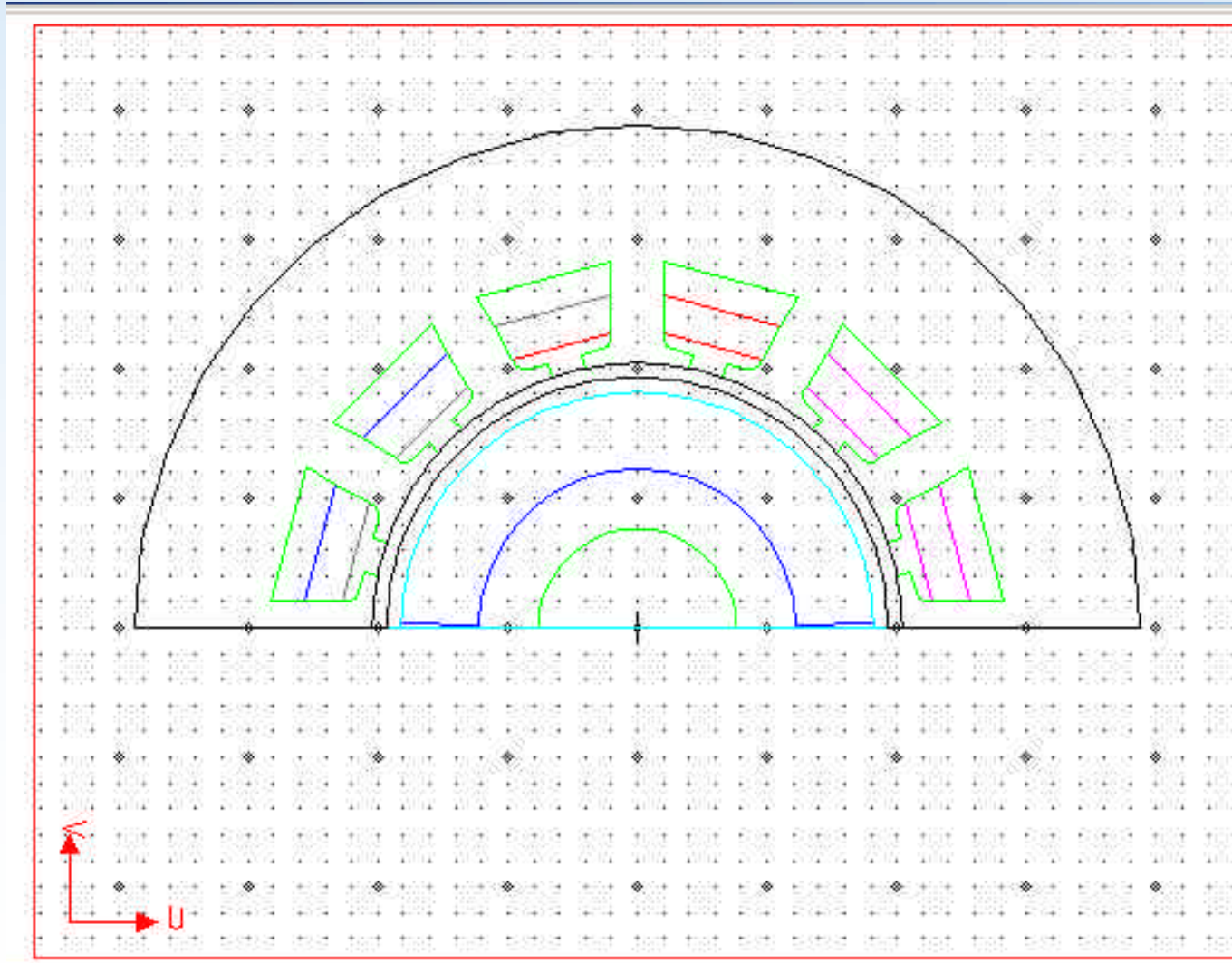
Model L-N 10 Hz Spectral Analysis



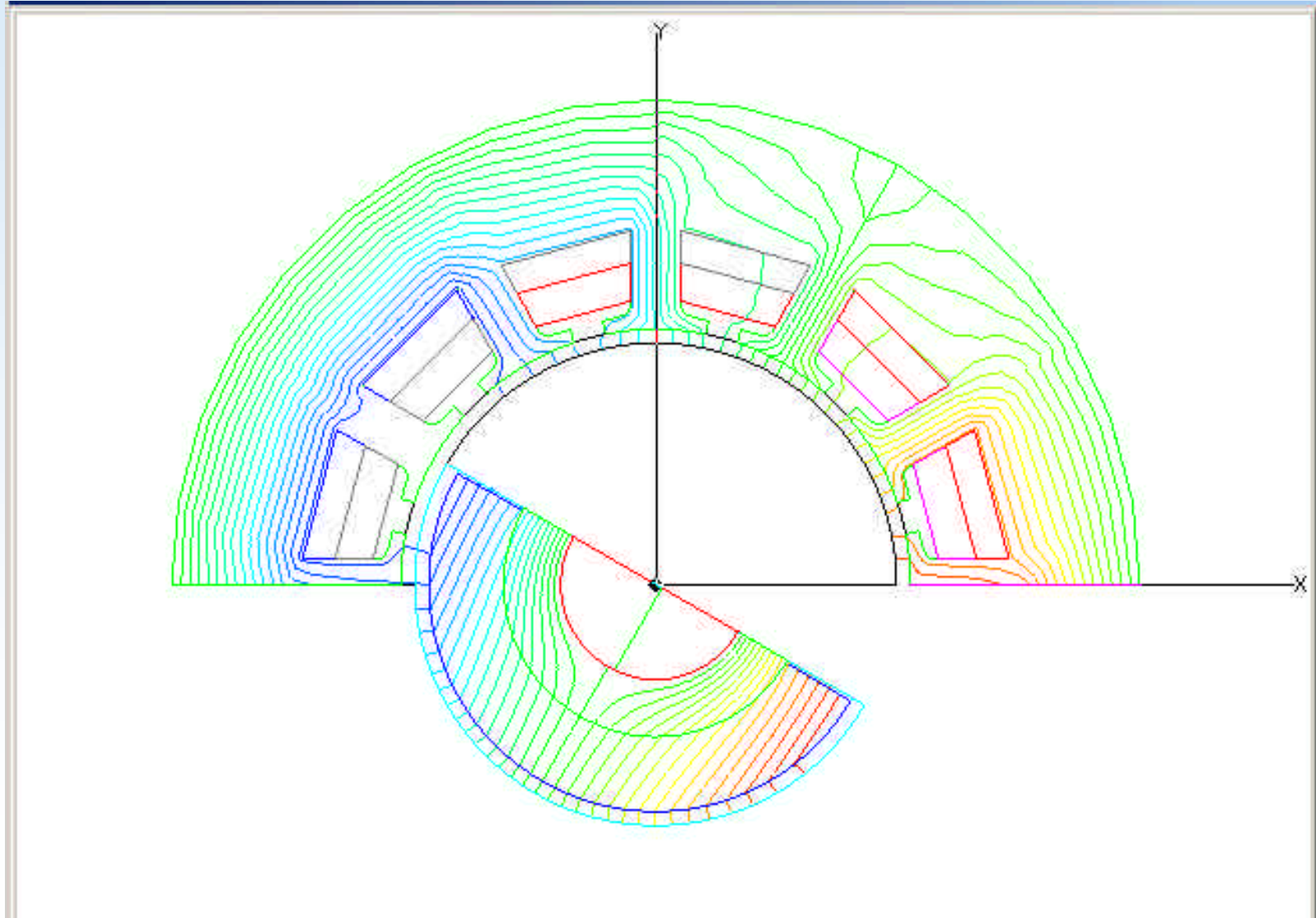
Modeling Software (continued)

- ***Finite Element Analysis of designed machine***
 - ***Performed using Maxwell 2D from Ansoft Corp.***
 - ***Permits core loss calculation under 'Transient' mode***
 - ***Performs 2 dimensional FEA of electro-magnetic flux distribution***
 - ***Geometry of the model imported from RMxpert***
 - ***Provides for a large selection of materials plus user supplied data can be inputted***
 - ***Core (iron) loss can be computed for different objects (stator iron, rotor iron, etc)***
 - ***Machine windings can be excited with appropriate time varying voltages/currents***
 - ***Yields outputs of various quantities as time functions***
 - ***Yields distribution of B, H in the geometry of the machine***

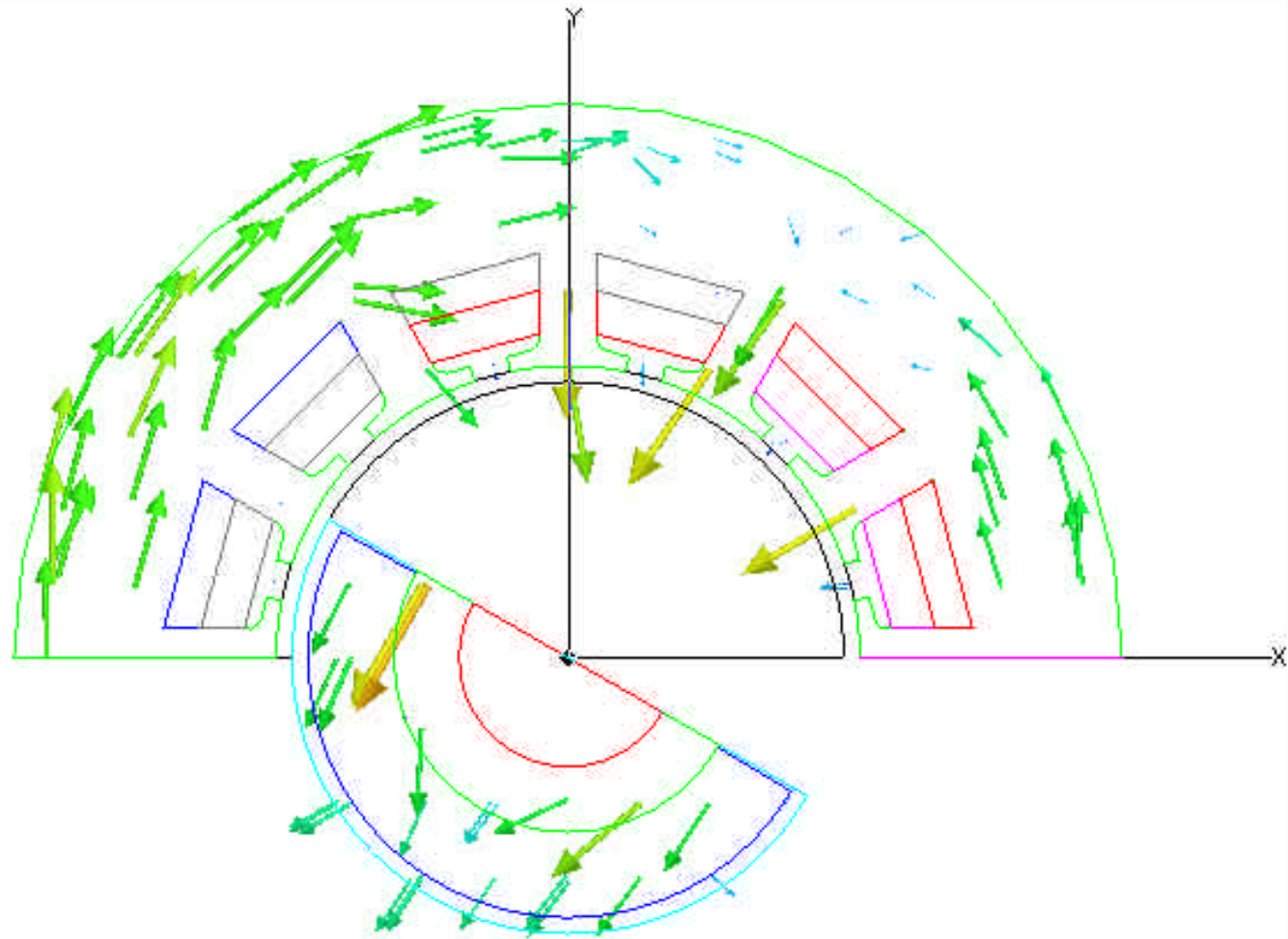
Model Geometry



2 Pole Motor B Magnitude Plot (flux lines)



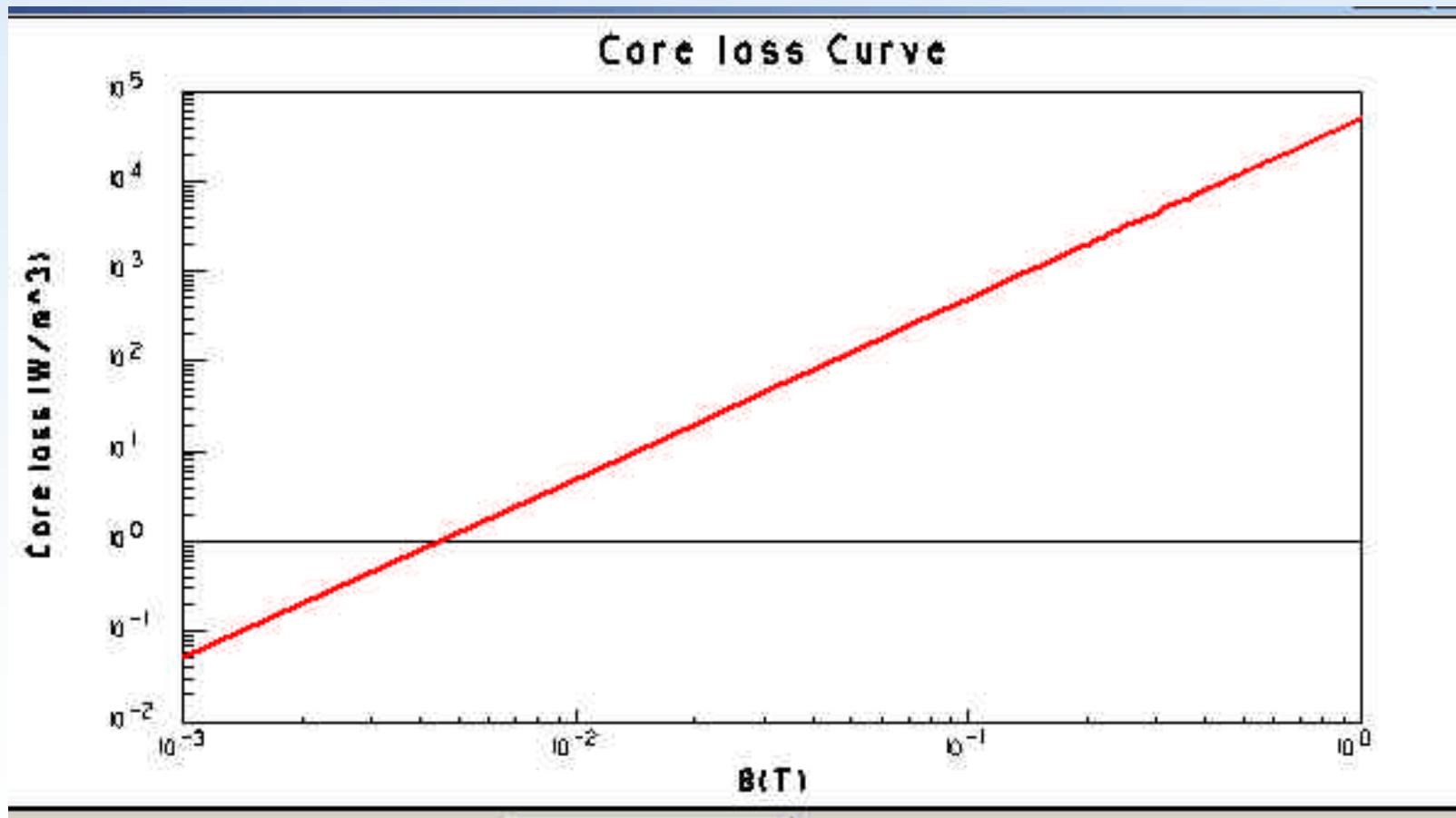
2 Pole Motor B Vector Plot



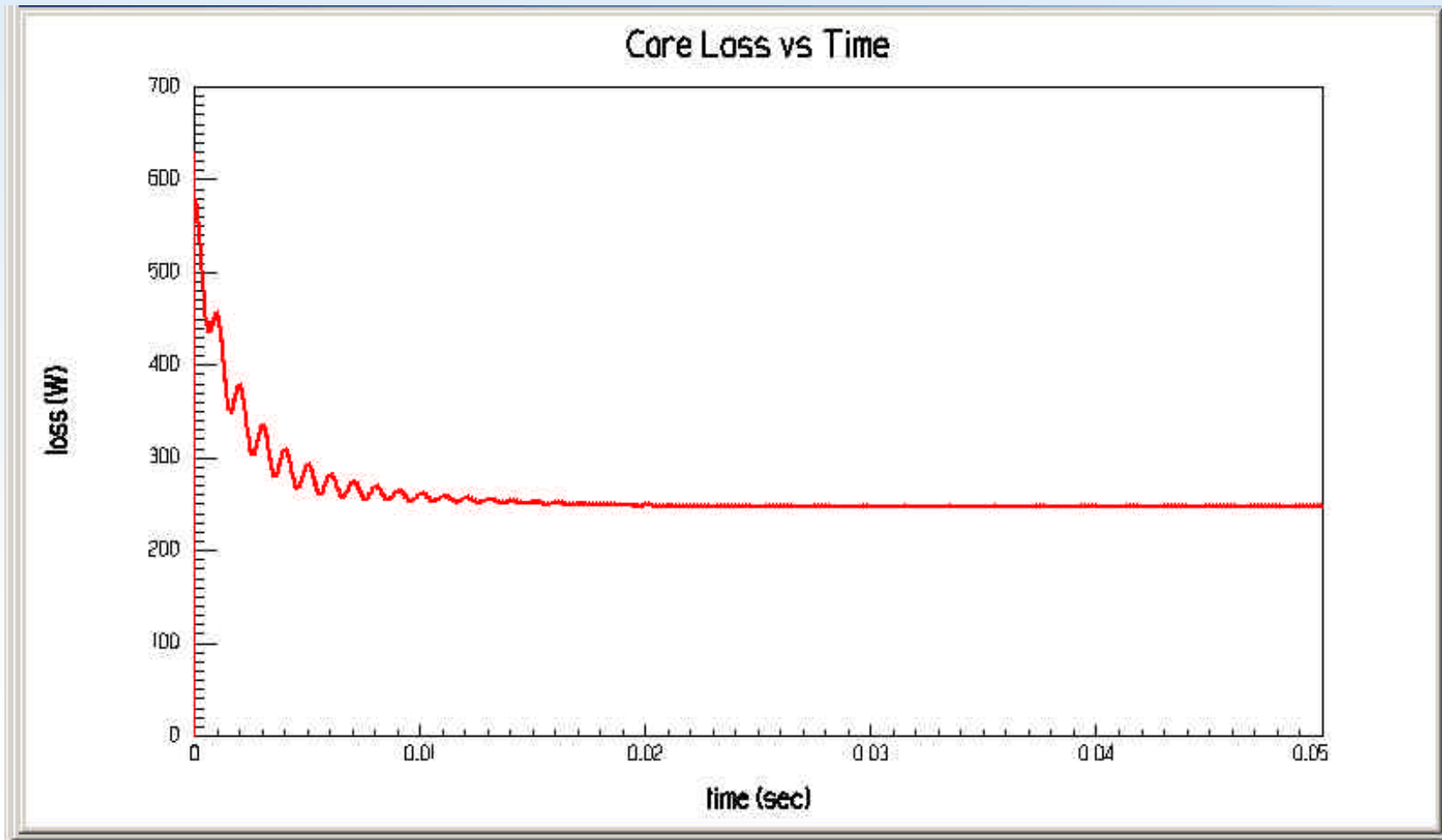
Quantify Rotor Loss

- ***Rotor Loss estimate needed for flywheel FEM to calculate Temperature rise of rotor***
 - ***Loss characteristics of materials needed in RMxpert***
 - ***Watts/Kg at given Flux Density, Reference Frequency***
 - ***Material conductivity and lamination thickness***
 - ***Multipliers (Ke, Kh, ..) calculated to compute eddy current and hysteresis losses as function of flux density and frequency (Total loss is sum of the two types)***
 - ***Used in Maxwell 2D to compute core loss***
- ***Core Losses are due to only time varying magnetic flux***
 - ***In PM Synchronous Machine the rotor flux has a predominant constant value with a small time varying value superimposed***
 - ***In the FEA software only varying component is used to compute core loss***

Core Loss Curve (for given data)



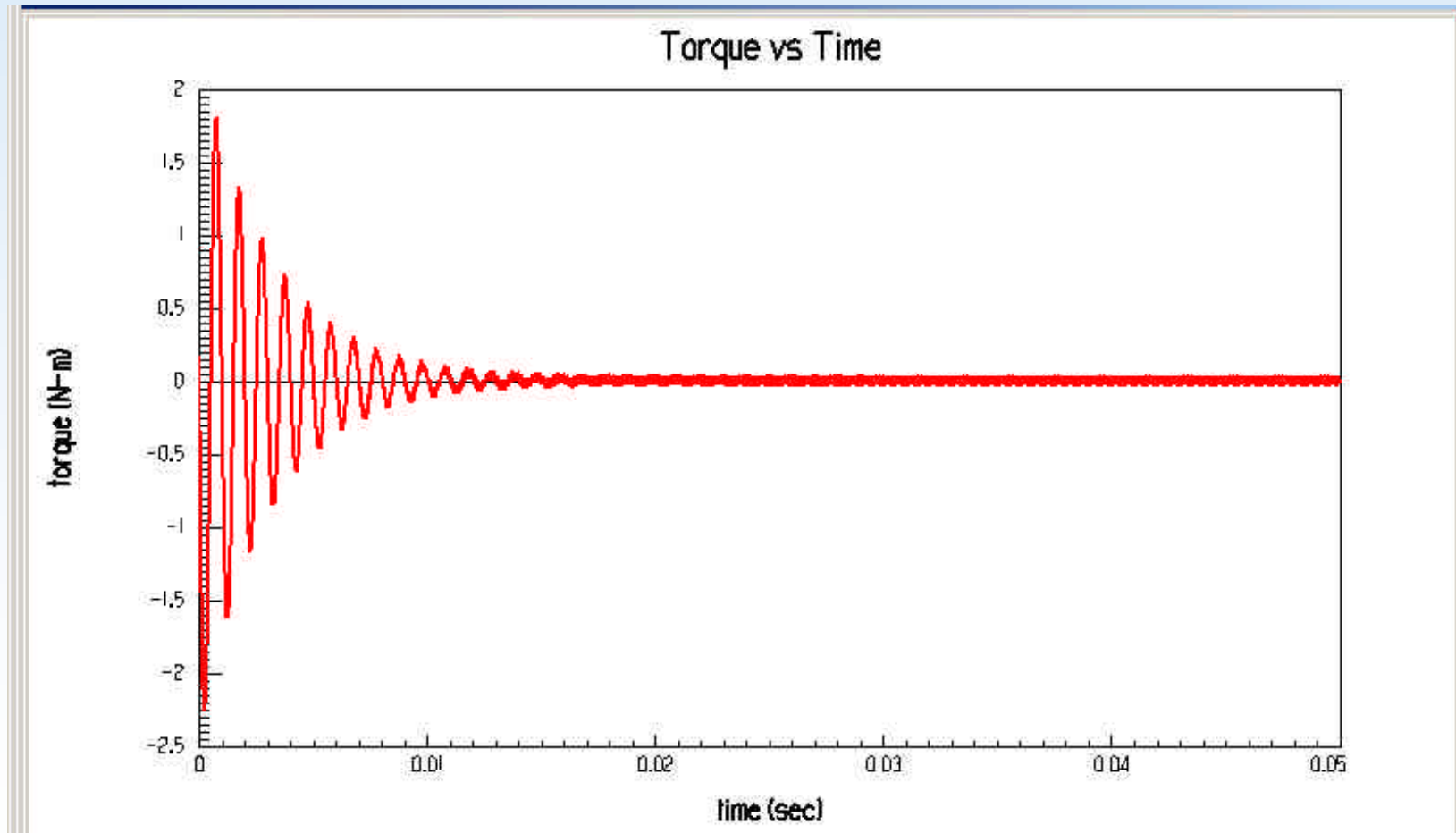
Sample Rotor Core Loss



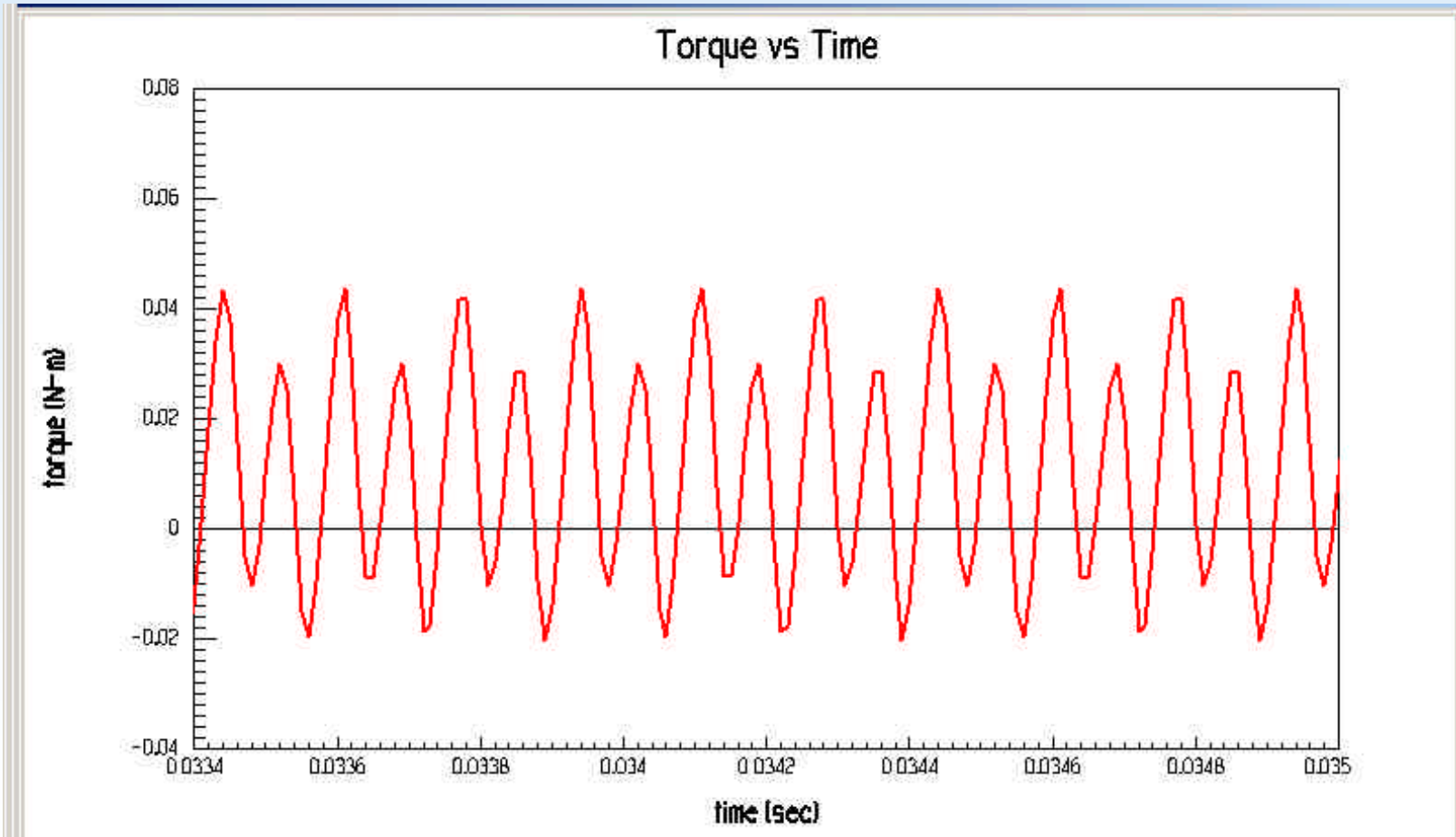
Quantify Torque Ripple

- ***RMxpert provides for slot skewing***
 - ***Not tested since the existing machine had none***
- ***Motor Torque vs Time plot can be analyzed to estimate Ripple Torque***
 - ***Calculate ripple mode frequencies and amplitudes***
- ***Similar procedure can be followed with respect to data from the test machine***
 - ***Comparison of the respective ripple data quantities provides validation for Torque Ripple estimation***

Sample Motor Torque



Torque Ripple



Concluding Observations

- ***Performance Prediction of an electrical machine requires a detailed design of the machine***
- ***RMxpert is a good software design tool as the first step***
 - ***Yields a fast design based on some basic input design data***
 - ***Provides for filling gaps in input data information***
 - ***Facilitates further FEA***
- ***Maxwell 2D permits FEA in 'Transient' mode***
 - ***Yields important Electrical and Mechanical Quantities as Time varying functions***
 - ***Permits Rotor Loss and Torque Ripple estimation***
- ***Modeling (design) an existing machine is difficult when winding and magnetic characteristic information not available***