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STABILITY ANALYSIS – PART 11
3-Day Workshop on Motor, Inverter, Hardware, and Firmware Design Techniques for Permanent Magnet Brushless Motors – A System Approach
April 22-24, 2025

FINITE ELEMENT ANALYSIS – PART 12
3-Day Workshop on Motor, Inverter, Hardware, and Firmware Design Techniques for Permanent Magnet Brushless Motors – A System Approach
April 22-24, 2025

FINITE ELEMENT ANALYSIS USING FEMM – PART 13
3-Day Workshop on Motor, Inverter, Hardware, and Firmware Design Techniques for Permanent Magnet Brushless Motors – A System Approach
April 22-24, 2025

Day Three Topics

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SYSTEM STABILITY

CURRENT CONTROL LOOP

- Current Control Loop Analysis:
 - Single Phase is considered;
 - Open Loop transfer function is plotted;
 - Open loop transfer function with Kp is plotted;
 - Open loop transfer function with Type 2 amplifier is plotted;
 - Closed Loop analysis carried out
 - with Kp=640 and switching frequency of 5kHz;
 - with type 1 amplifier
 - with type 2 amplifier

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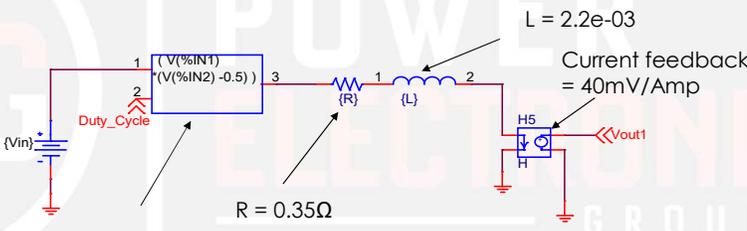


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SYSTEM STABILITY

SINGLE PHASE TRANSFER FUNCTION

➤ Single Phase Transfer Function is shown below:



$V_o = 36 \cdot (d - 0.5)$

We do not need to consider backemf for transfer function analysis

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SYSTEM STABILITY

SINGLE PHASE TRANSFER FUNCTION WITH KP=640

Open Loop Transfer Function = V_{out1}/V_{in2}

Open Loop Transfer Function with $K_p = 640 = V_{out3}/V_{in2}$

Based on technique proposed by Christophe Basso

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SYSTEM STABILITY

SINGLE PHASE TRANSFER FUNCTION

Open Loop Transfer Function = V_{out1}/V_{in2}

Magnitude

Phase

Cross over frequency = 100Hz
Phase is -75 degrees

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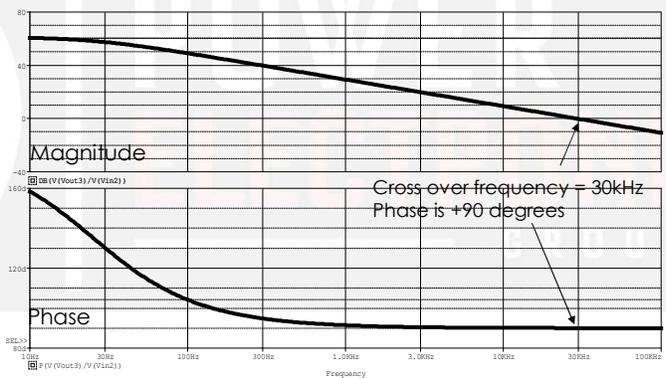


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SYSTEM STABILITY

SINGLE PHASE TRANSFER FUNCTION

Open Loop Transfer Function = V_{out3}/V_{in2}



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SYSTEM STABILITY

CURRENT CONTROL LOOP

- Conclusion:
 - $K_p = 640$ greatly improved system bandwidth from 100Hz to 30kHz;
 - Low frequency gain is also increased from 12 to 60;
 - It seems $K_p = 60$ alone is sufficient to stabilize the system.

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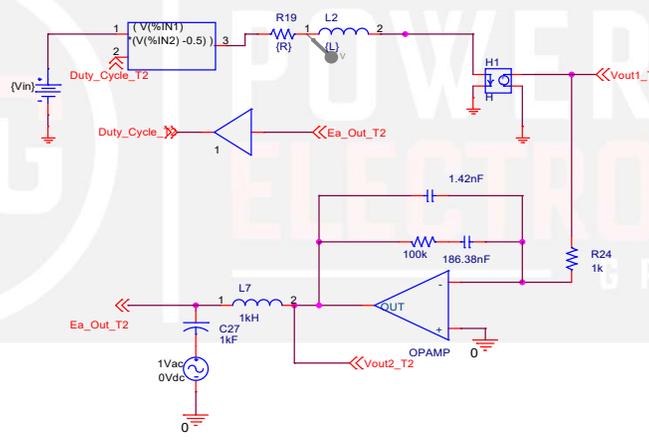
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SYSTEM STABILITY

SINGLE PHASE TRANSFER FUNCTION WITH TYPE 2 AMPLIFIER



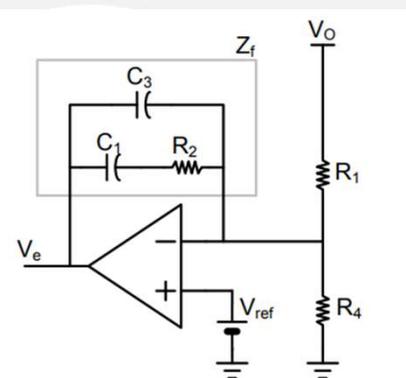
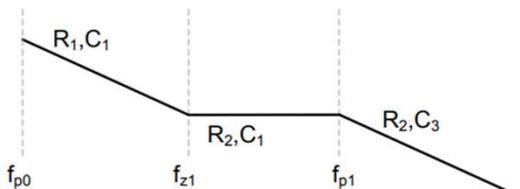
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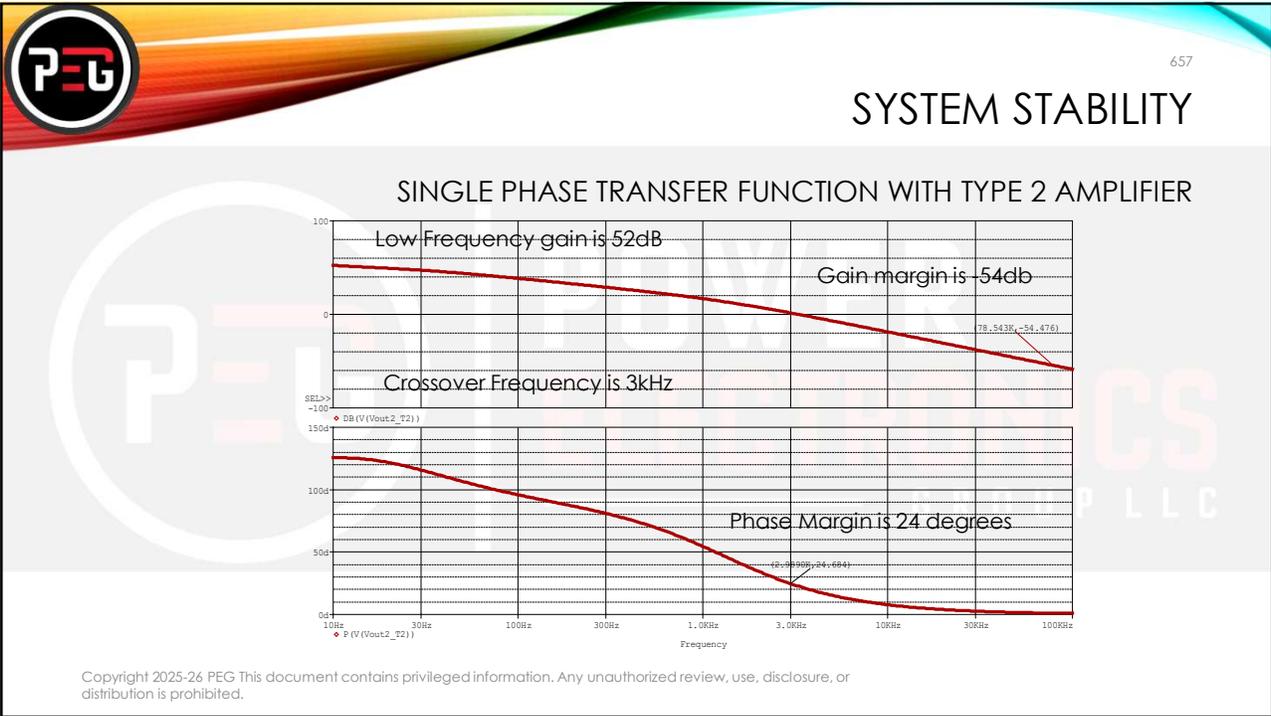
TYPE 2 AMPLIFIER

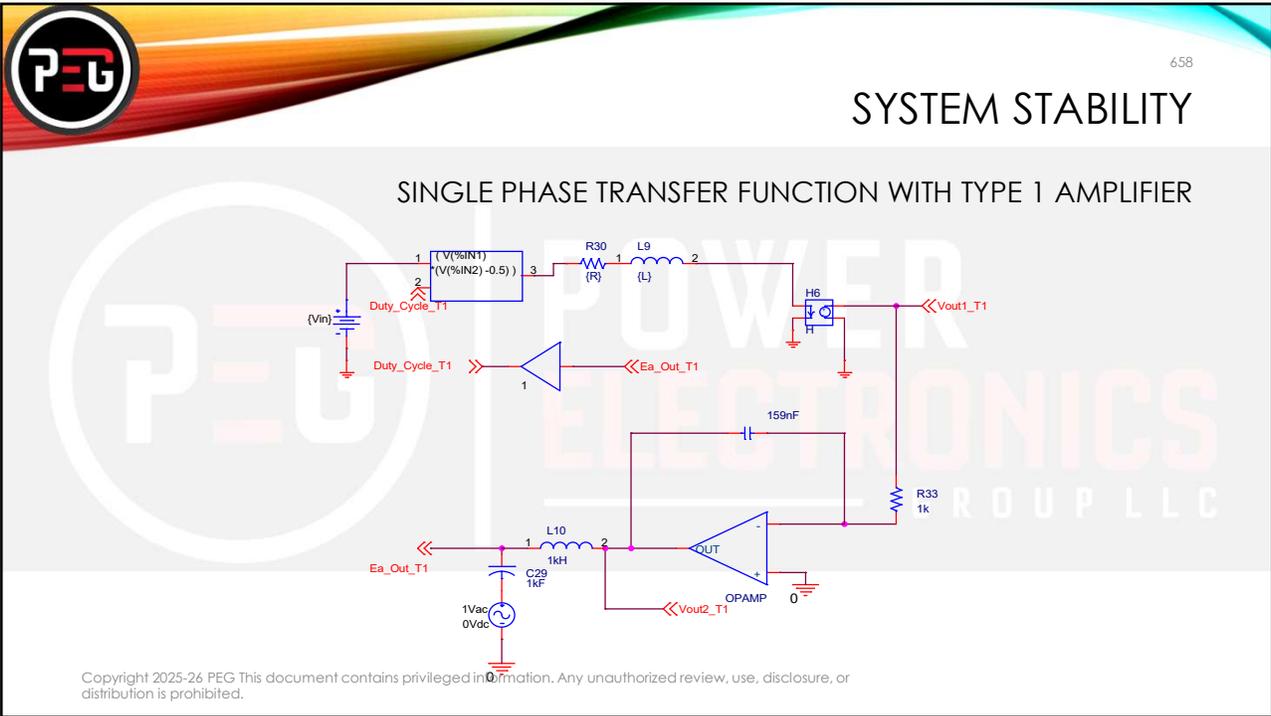
$$H(s) = \frac{1 + C_1 R_2 s}{(C_3 + C_1) R_1 s + R_1 C_1 C_3 R_2 s^2}$$

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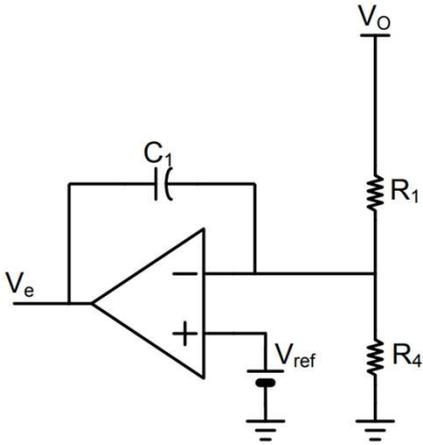


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TYPE 1 AMPLIFIER



$$H(s) = \frac{V_e(s)}{V_o(s)} = -\frac{1}{sC_1R_1}$$

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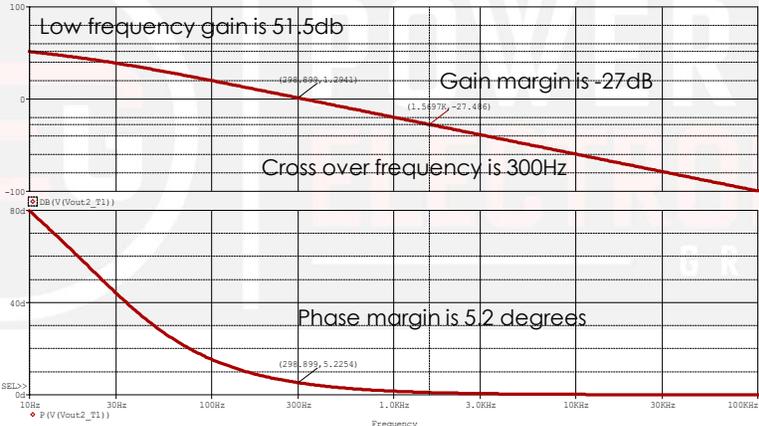
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SYSTEM STABILITY

SINGLE PHASE TRANSFER FUNCTION WITH TYPE 1 AMPLIFIER



Low frequency gain is 51.5db

Gain margin is -27dB

Cross over frequency is 300Hz

Phase margin is 5.2 degrees

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SYSTEM STABILITY

CURRENT CONTROL LOOP

- Conclusion:
 - Type 2 amplifier increases the bandwidth to 3kHz;
 - Type 1 amplifier increases the bandwidth to 300Hz;
 - Type 1 amplifier compensation is barely stable;
 - $K_p = 640$ beats out the type 1 and type 2 compensation.

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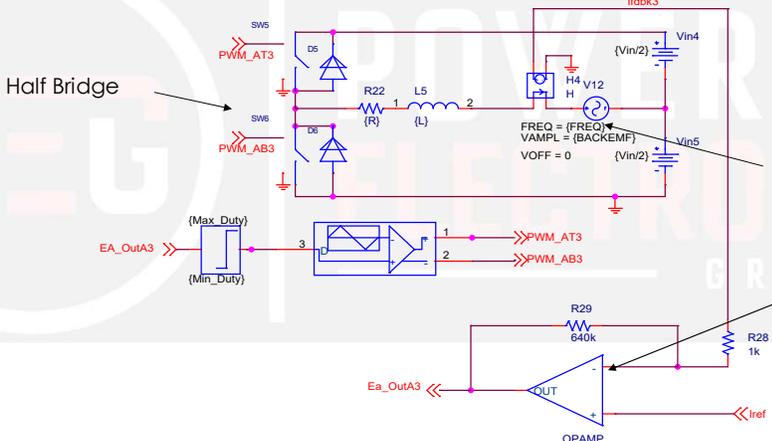
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SYSTEM STABILITY

CLOSE LOOP TIME DOMAIN ANALYSIS



Half Bridge

Motor BackEMF 53mV/rpm

$K_p = 640$

OPAMP

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SYSTEM STABILITY

CLOSE LOOP TIME DOMAIN ANALYSIS

Half Bridge

Motor BackEMF 53mV/rpm

Type 1

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SYSTEM STABILITY

CLOSE LOOP TIME DOMAIN ANALYSIS

Half Bridge

Motor BackEMF 53mV/rpm

Type 2

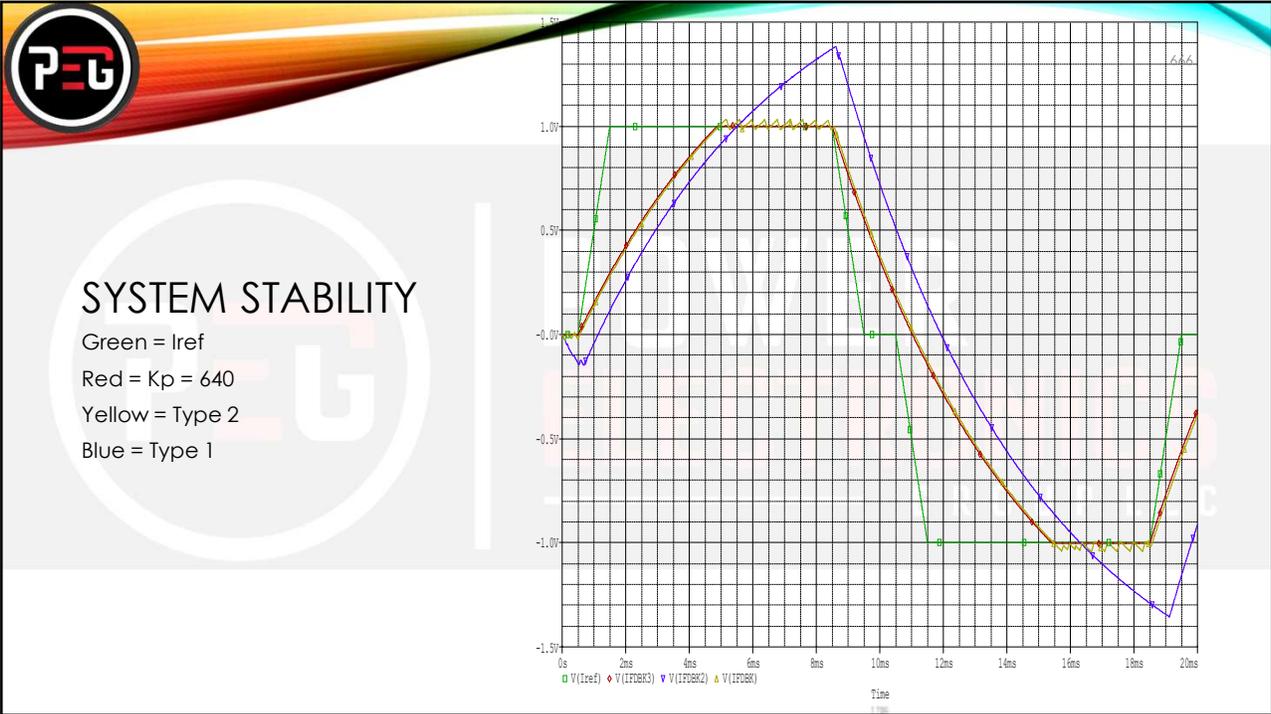
Trapezoidal Iref

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SYSTEM STABILITY

CURRENT CONTROL LOOP

- Conclusion:
 - $K_p = 640$ has the best transient response with no current ripple even at 5kHz switching;
 - Type 2 response is OK;
 - Type 1 response is not acceptable;
 - Trapezoidal current is difficult to follow at higher frequencies;

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SYSTEM STABILITY

CONCLUDING REMARKS

- System is inherently stable;
- Simple K_p compensator is sufficient;
- Even 5kHz switching is sufficient;

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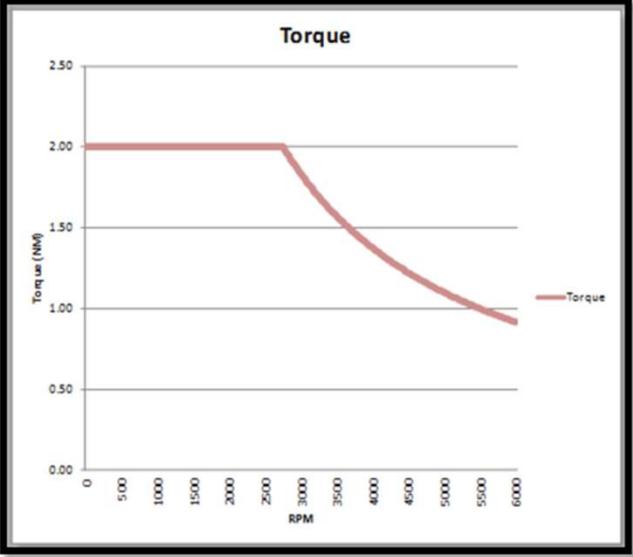


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DUAL MOTOR DRIVE SYSTEM

Torque Speed Curve Provided by the Customer



RPM	Torque (Nm)
0	2.00
500	2.00
1000	2.00
1500	2.00
2000	2.00
2500	2.00
3000	1.80
3500	1.50
4000	1.30
4500	1.15
5000	1.05
5500	1.00
6000	0.95

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DUAL MOTOR DRIVE SYSTEM

Base Speed:	2,750 RPM	2.00 NM
Maximum RPM:	6,000 RPM	0.92 NM
Power:	575 Watts	
Voltage:	24 V _{DC}	
Controller Current: Per Channel	30 A _{rms} - Continuous	
	40 A _{rms} - Peak (10 Seconds)	
Motor Diameter:	90 mm MAX	
Motor Length:	110 mm MAX	

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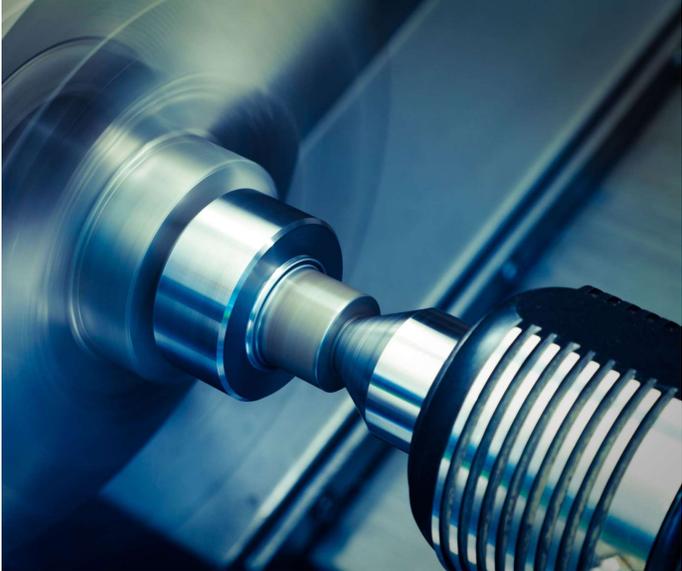
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ANALYSIS TO BE DONE

Torque per unit volume
 Stator Diameter = 83mm
 Rotor Diameter = 0.4 to 0.6 (33.2mm to 49.8mm)
 Optimum Design
 Max Torque and Efficiency.



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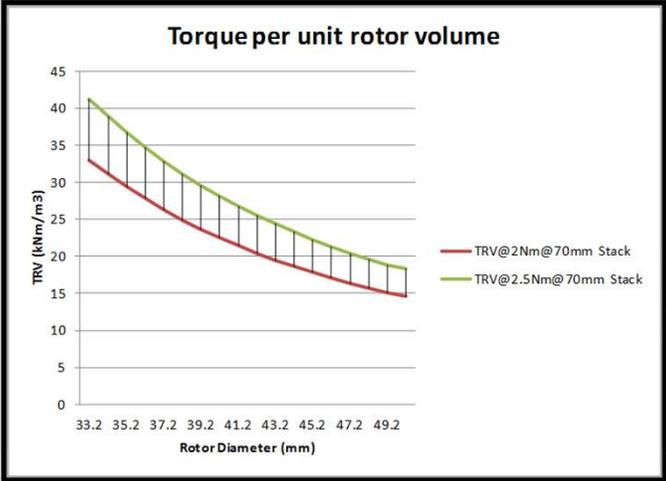
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TORQUE PER UNIT VOLUME



Torque per unit rotor volume



Rotor Diameter (mm)	TRV@2Nm@70mm Stack (kNm/m ³)	TRV@2.5Nm@70mm Stack (kNm/m ³)
33.2	33.0	41.0
35.2	28.0	36.0
37.2	24.0	32.0
39.2	21.0	29.0
41.2	18.5	26.5
43.2	16.5	24.5
45.2	15.0	22.5
47.2	14.0	21.0
49.2	13.5	20.0

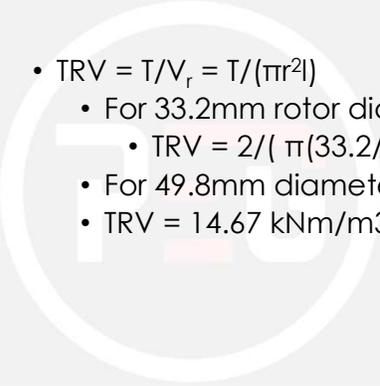
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TORQUE PER UNIT VOLUME

- $TRV = T/V_r = T/(\pi r^2 l)$
 - For 33.2mm rotor diameter,
 - $TRV = 2/(\pi(33.2/2)^2 \cdot 70) = 33 \text{ kNm/m}^3$
 - For 49.8mm diameter
 - $TRV = 14.67 \text{ kNm/m}^3$



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TORQUE PRODUCTION

$$T_e = \frac{3}{2} \cdot (D \cdot L) \cdot (B_m \cdot \sin\beta) \cdot (N_s \cdot I_m) \cdot \sin\delta$$

Where as

- D** = Air Gap Diameter or Inner Stator Diameter or Bore Diameter, m;
- L** = Stack Length, m;
- B_m** = Operating Magnet Flux Density, T;
- β** = Magnet Arc Angle in Electrical Degrees;
- N_s** = Number of Turns per Phase;
- I_m** = Peak Phase Current;
- δ** = Control Angle between magnet flux and stator current;

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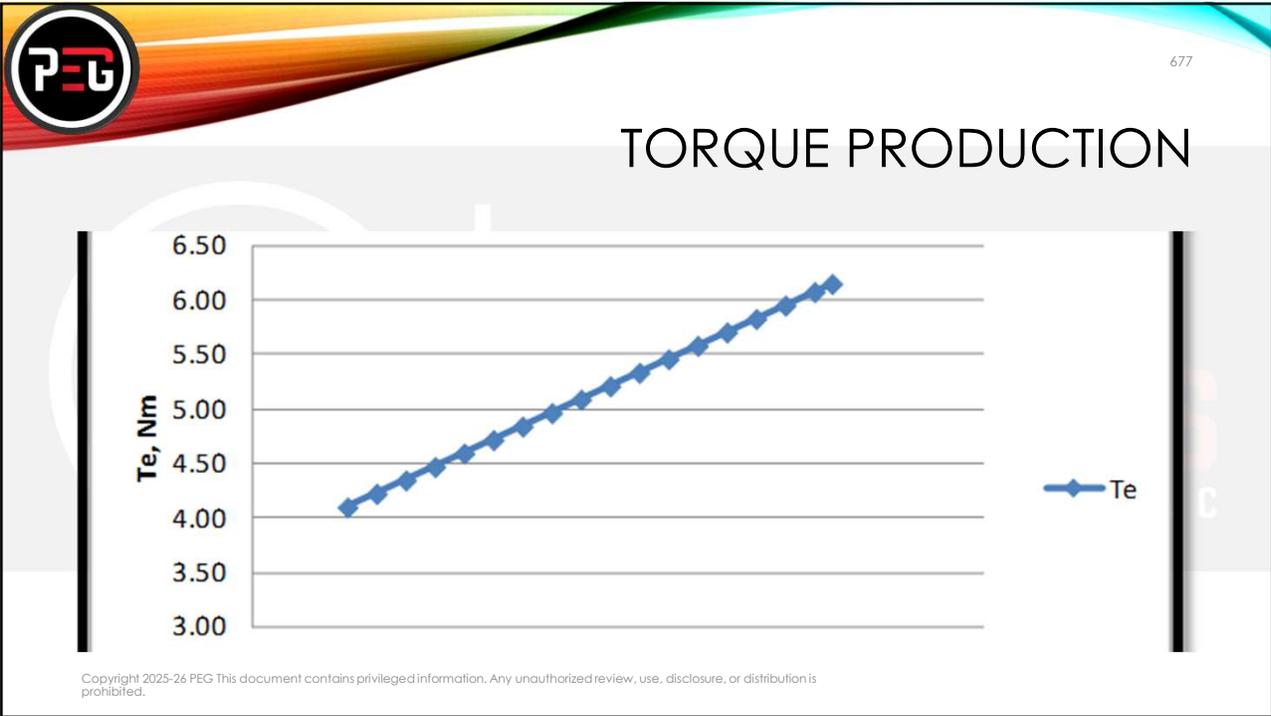
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TORQUE PRODUCTION

- D = 45mm,
- L = 70mm,
- B_m = 1T,
- β = 90 degrees,
- N_s = 21 Turns,
- I_m = 56A, and
- δ = 90 degrees
- Te = 5.6Nm

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DESIGNS TO BE CONSIDERED

Rotor Architectures

- Surface Mount Magnets;
- IPM Motor with Lateral Magnets;
- IPM Motor with Angled Barriers;
- IPM Motor with V-Magnets;
- IPM Motor with Spoked Magnets;

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SLOT-POLE ARCHITECTURES

6-pole, 9-Slot IPM	8-pole, 24-slot IPM	4-pole, 18-slot SPM
8-pole, 12-slot IPM	10-pole, 18-slot SPM	10-pole, 18-slot IPM
10-pole, 12-slot IPM	8-pole, 18-slot SPM	8-pole, 18-slot IPM
4-pole, 6-slot SPM	6-pole, 18-slot SPM	6-pole, 18-slot IPM
8-pole, 6-slot SPM	8-pole, 9-slot SPM	4-pole, 18-slot IPM
8-pole, 6-slot IPM	8-pole, 9-slot IPM	Etc.

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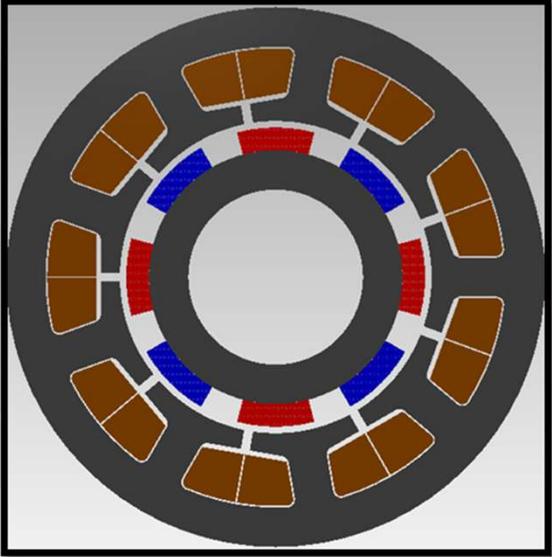
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SURFACE MOUNT ARCHITECTURE

6mm Tooth Width



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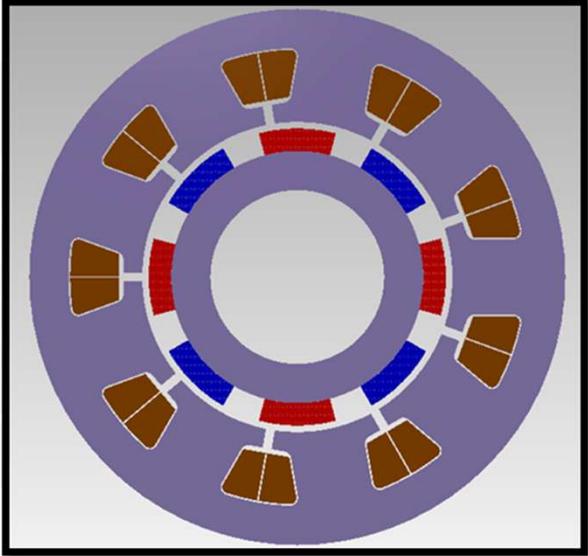
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SURFACE MOUNT MAGNET

11.6mm Tooth Width



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DESIGN COMPARISONS

	Design A	Design B
Stator OD (mm)	83	
Rotor OD (mm)	46	
Air Gap (mm)	1	
Magnet Angle (degrees)	30	
Magnet Thickness (mm)	3.49	
Phase Resistance(Ohms)	0.03095	0.0211
Nph	21	
Tooth Width (mm)	11.6	6
Rotor Core Mass (kg)	0.337	
Rotor Magnet Mass (kg)	0.163	
Stator Core Mass(kg)	1.5	1.28
Stator Winding Mass (kg)	0.274	0.449
Magnet Type	Neodymium Iron Boron 40/23	
Lamination Material	M19, 29 Gauge	

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DESIGN COMPARISONS

Torque is reduced by 10% while the resistance has been reduced by 46% by change in tooth width.



Torque
Peak Current=56 A, Advance angle=0°, Rotor speed=100%

Torque (N.m)

Rotor angle (°)

Source phase angle (°)

infolytic corporation

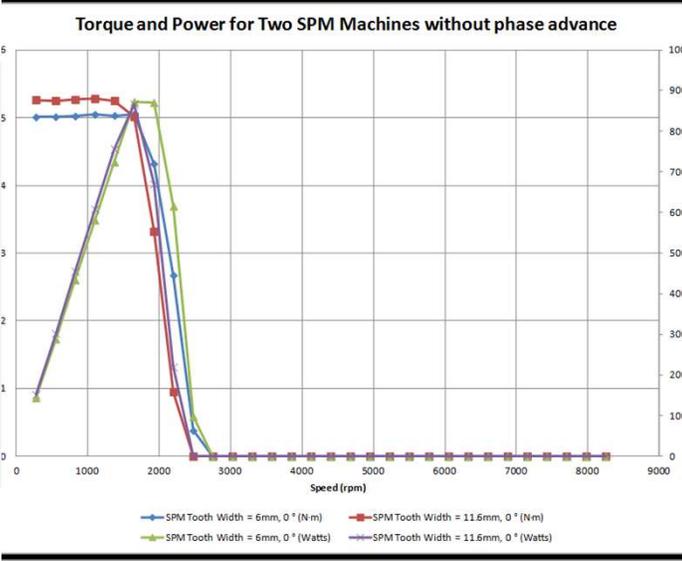
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TORQUE AND POWER COMPARISONS

Without Phase Advance



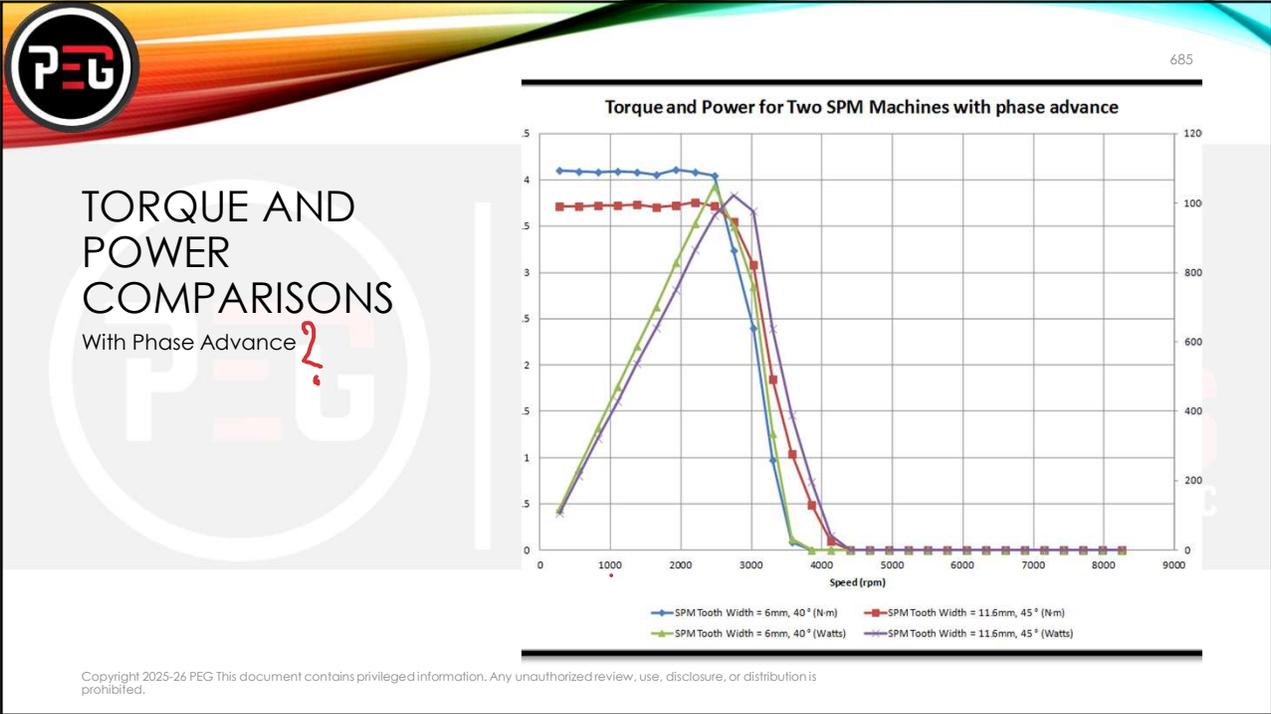
Torque and Power for Two SPM Machines without phase advance

Speed (rpm)

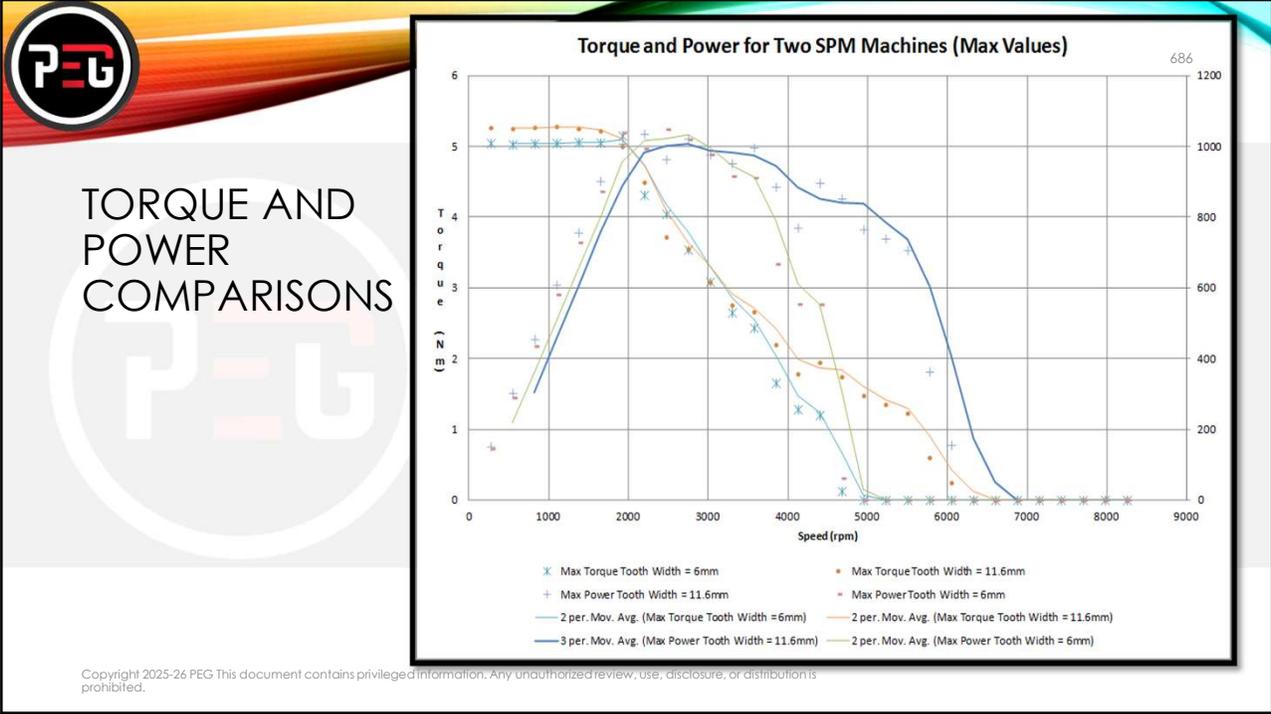
—●— SPM Tooth Width = 6mm, 0° (N.m)
 —■— SPM Tooth Width = 11.6mm, 0° (N.m)
—▲— SPM Tooth Width = 6mm, 0° (Watts)
 —◆— SPM Tooth Width = 11.6mm, 0° (Watts)

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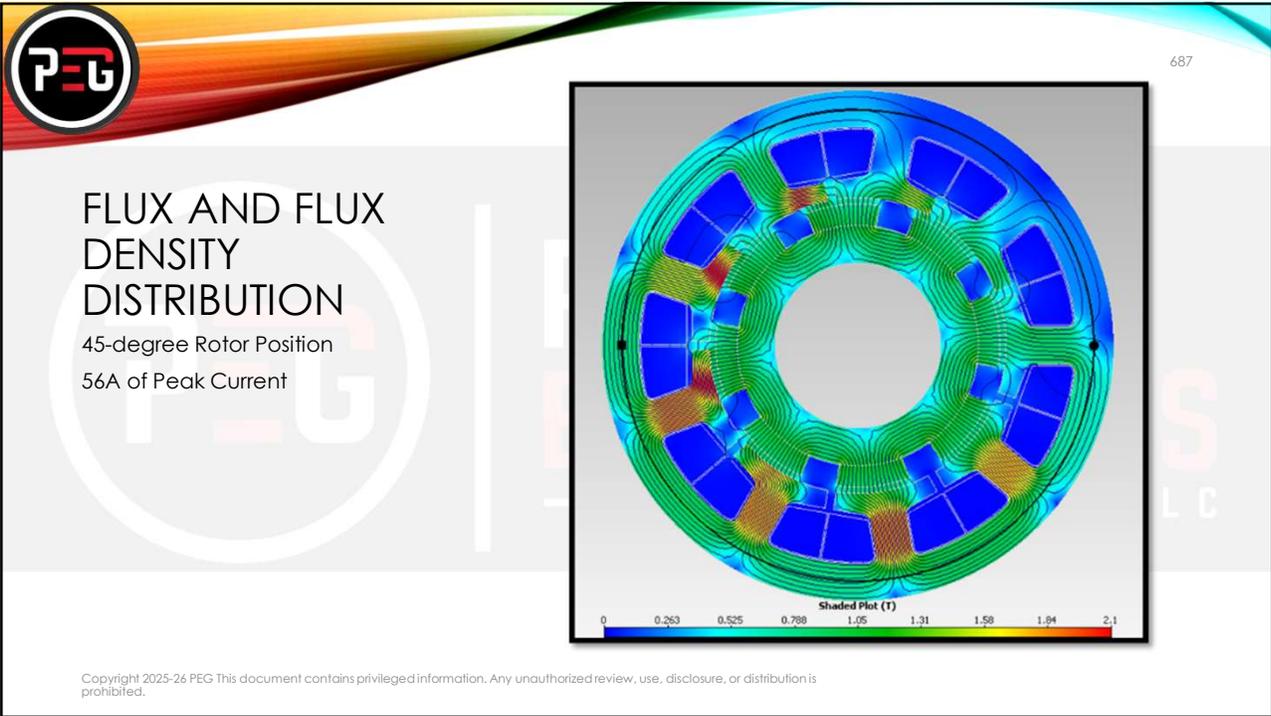
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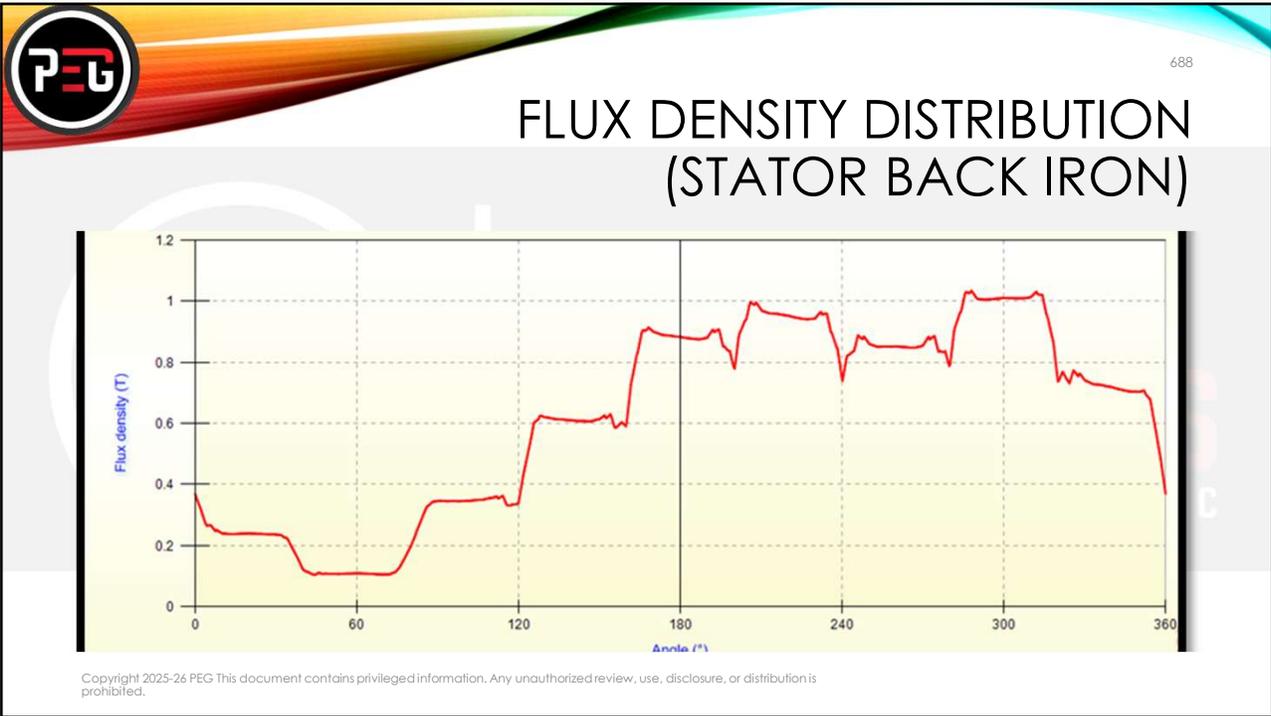
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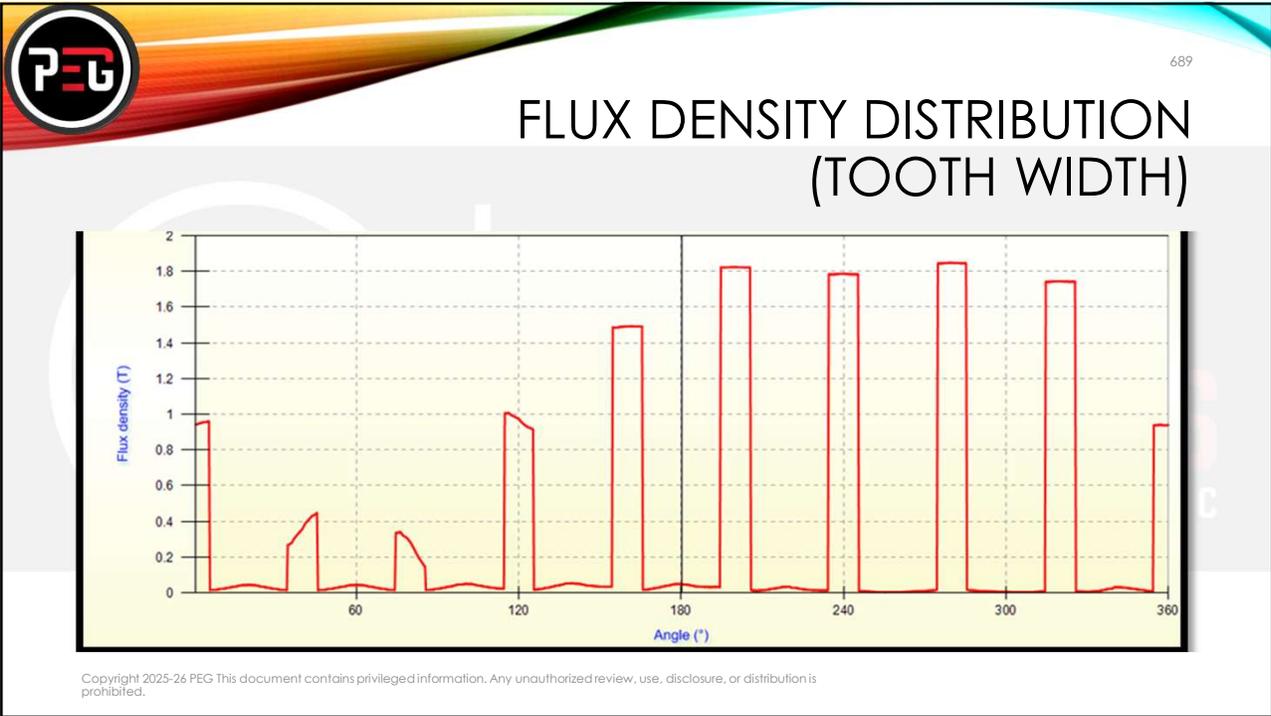
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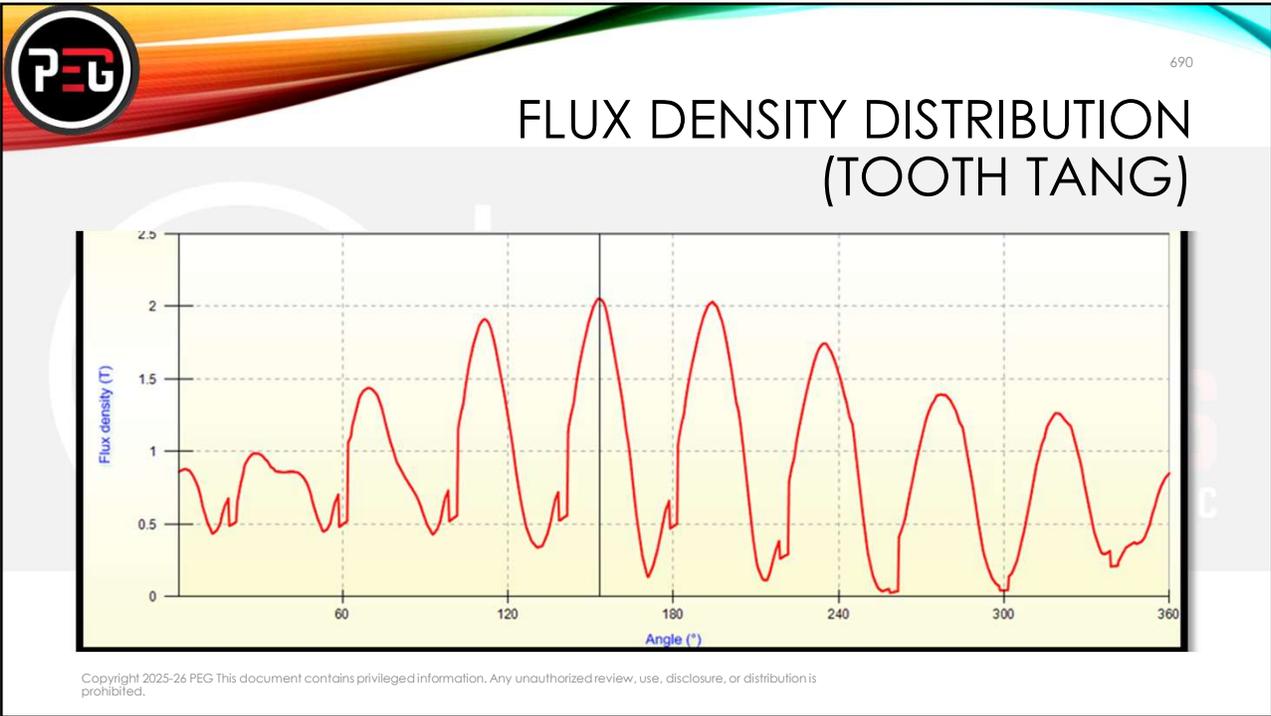
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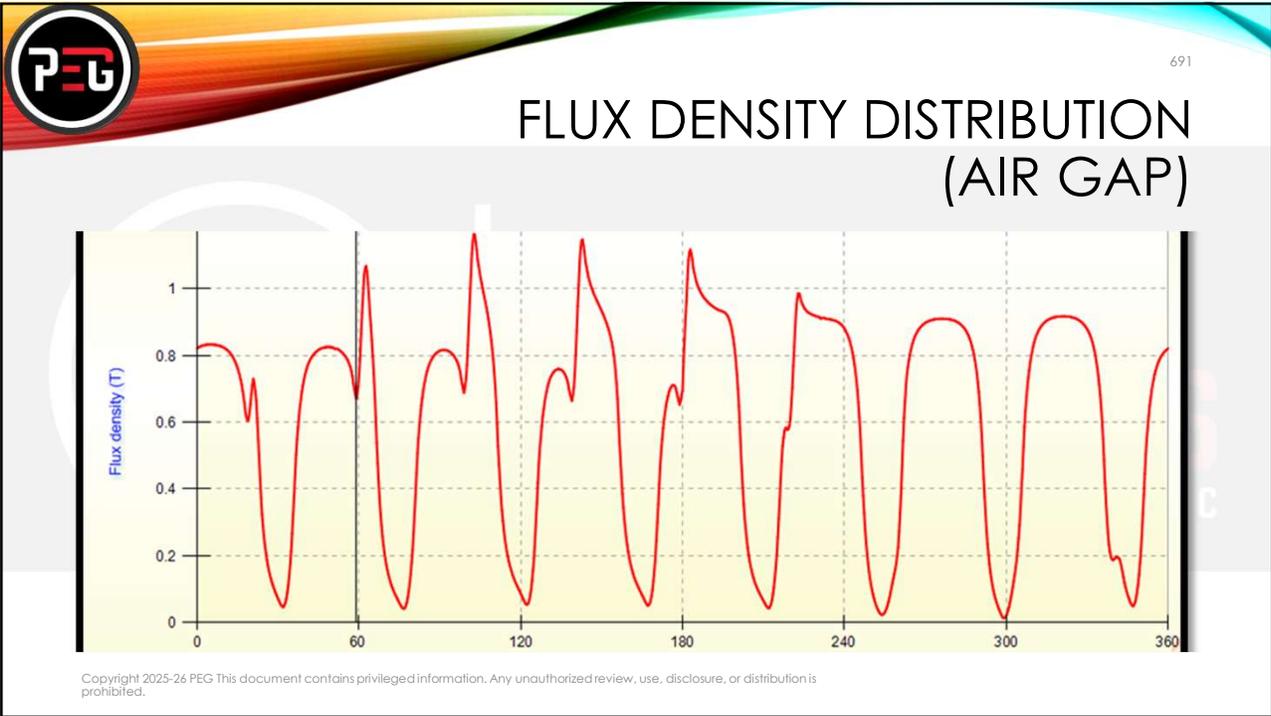
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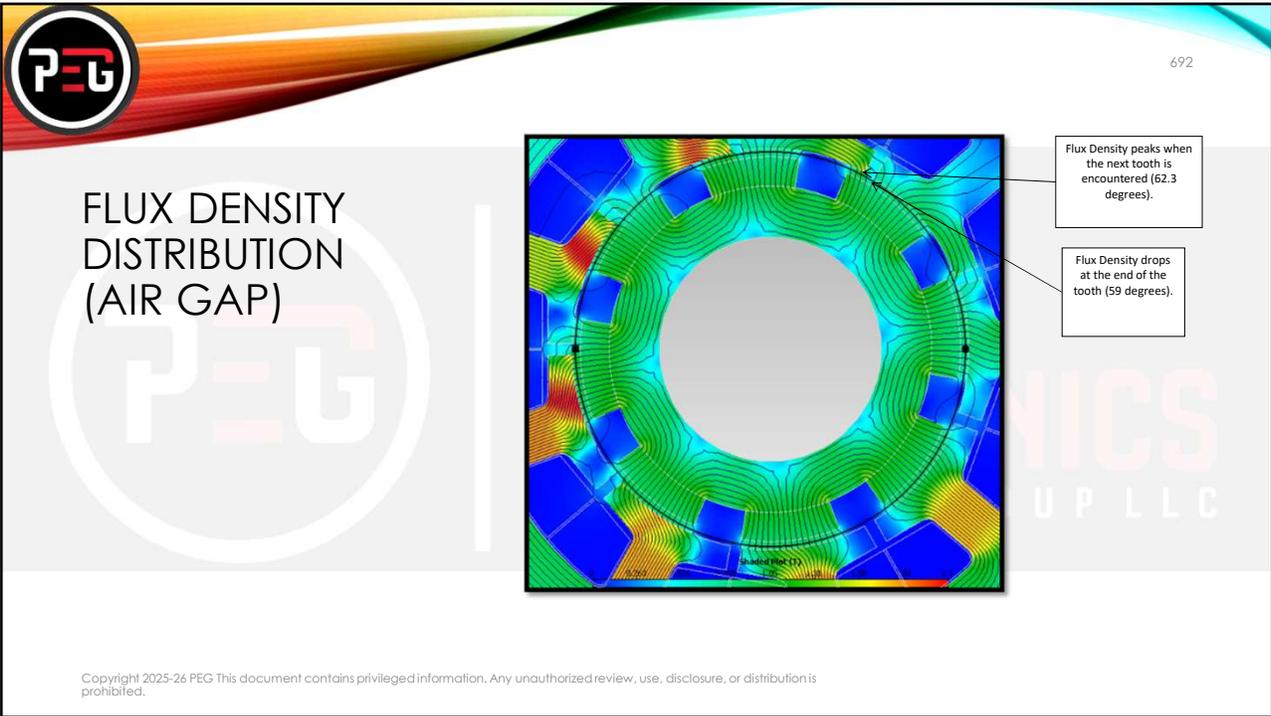
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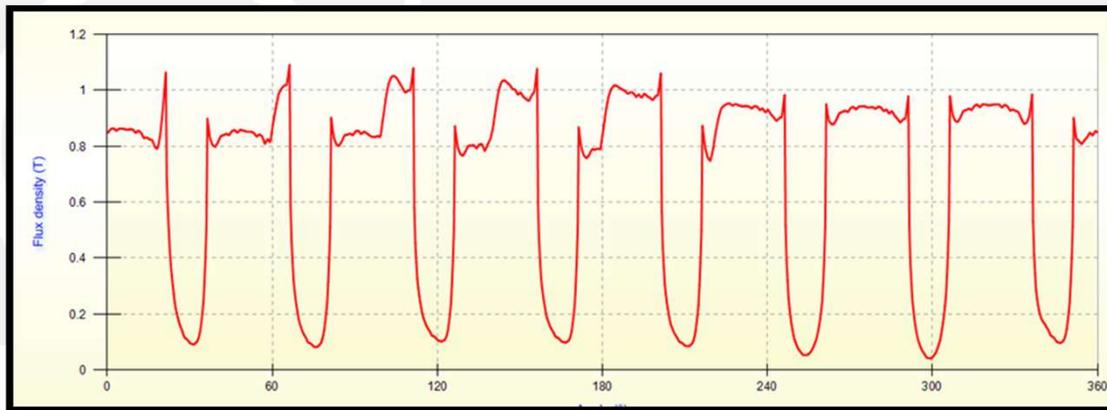


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FLUX DENSITY DISTRIBUTION (MAGNETS)



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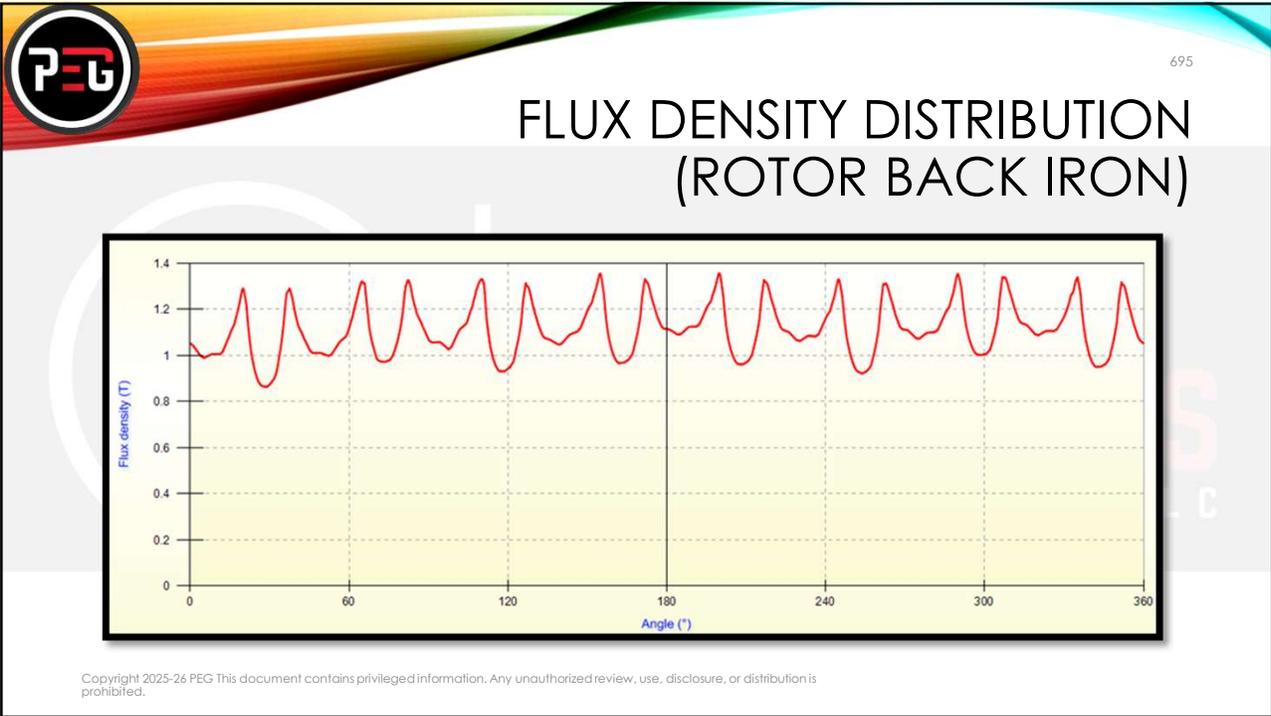
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FLUX DENSITY DISTRIBUTION (CENTER OF THE MAGNETS)

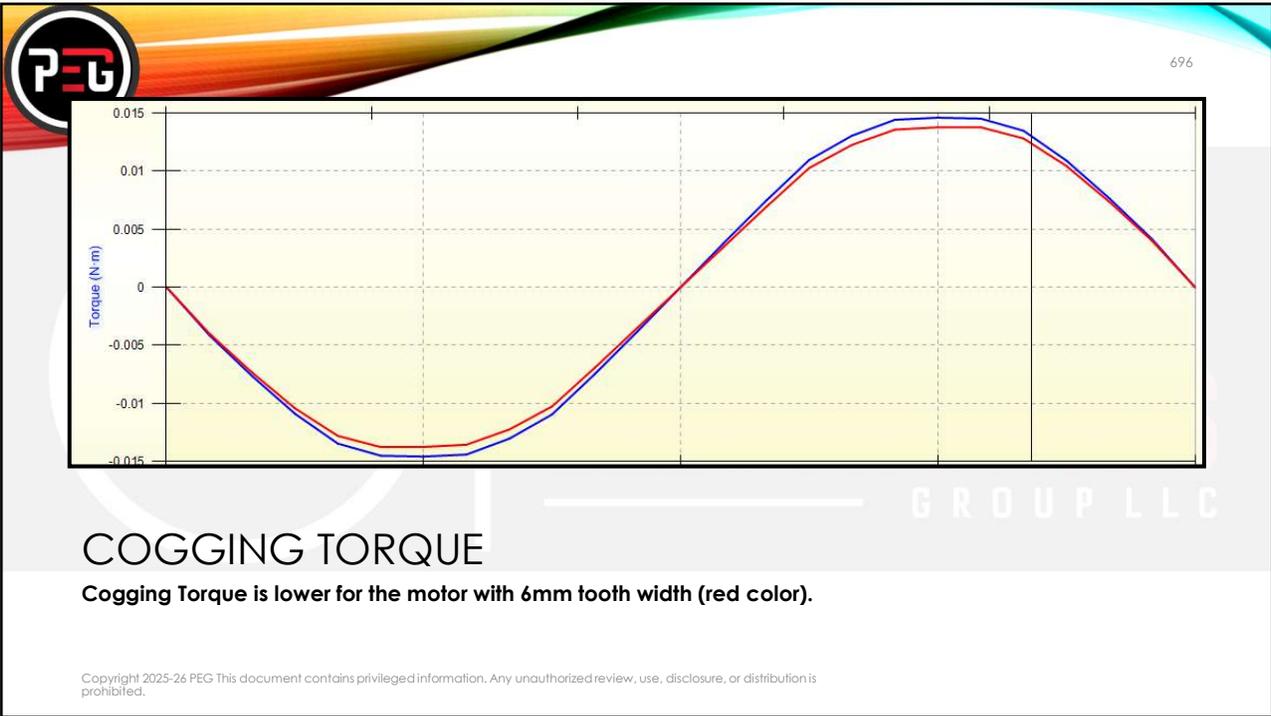


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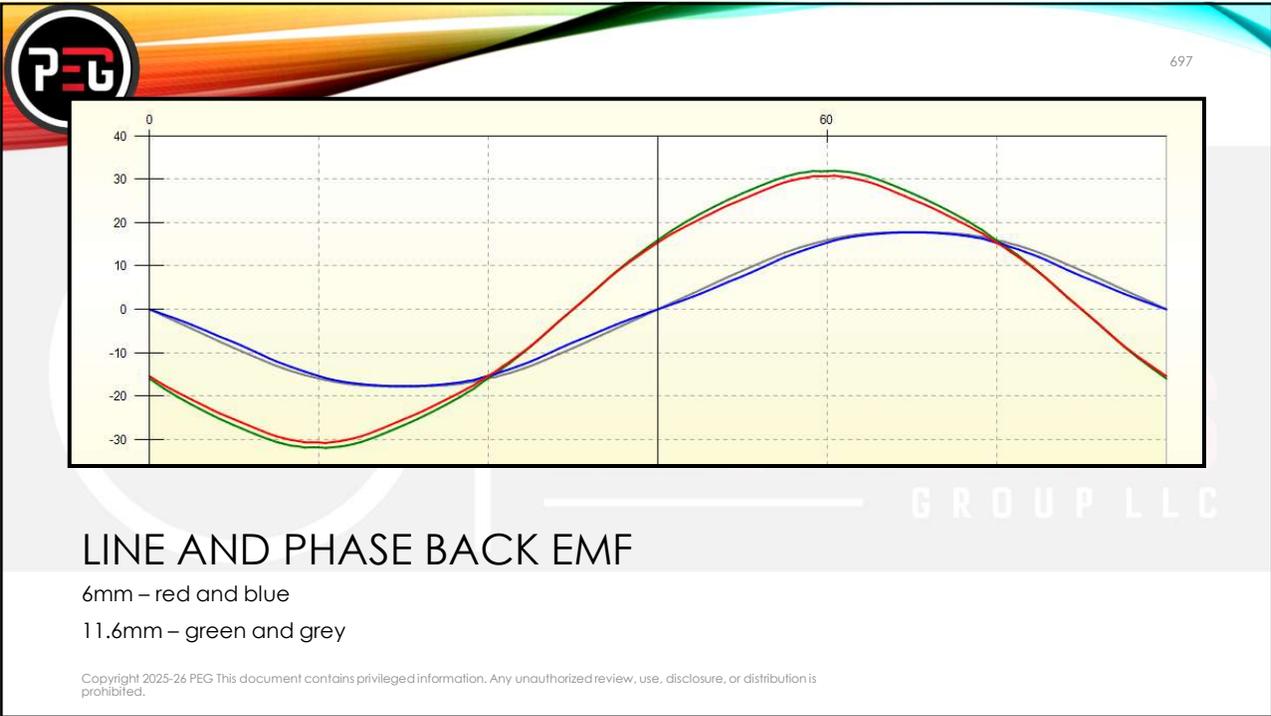
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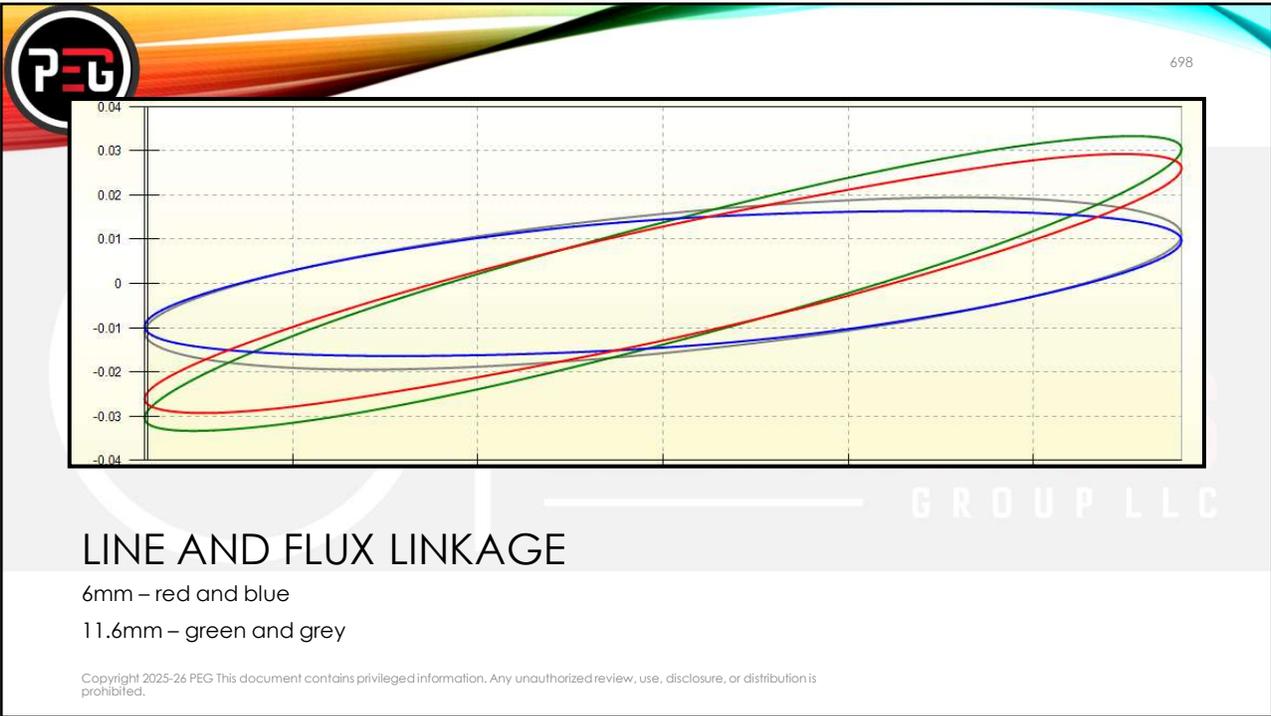
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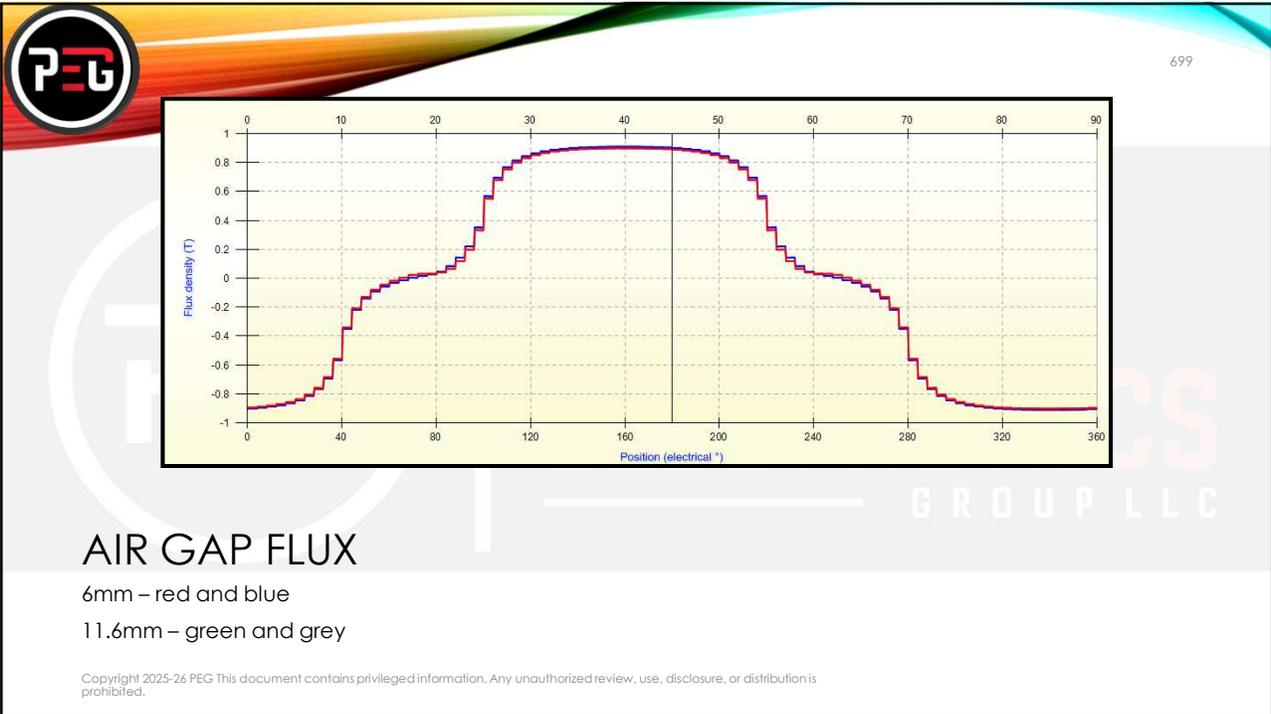
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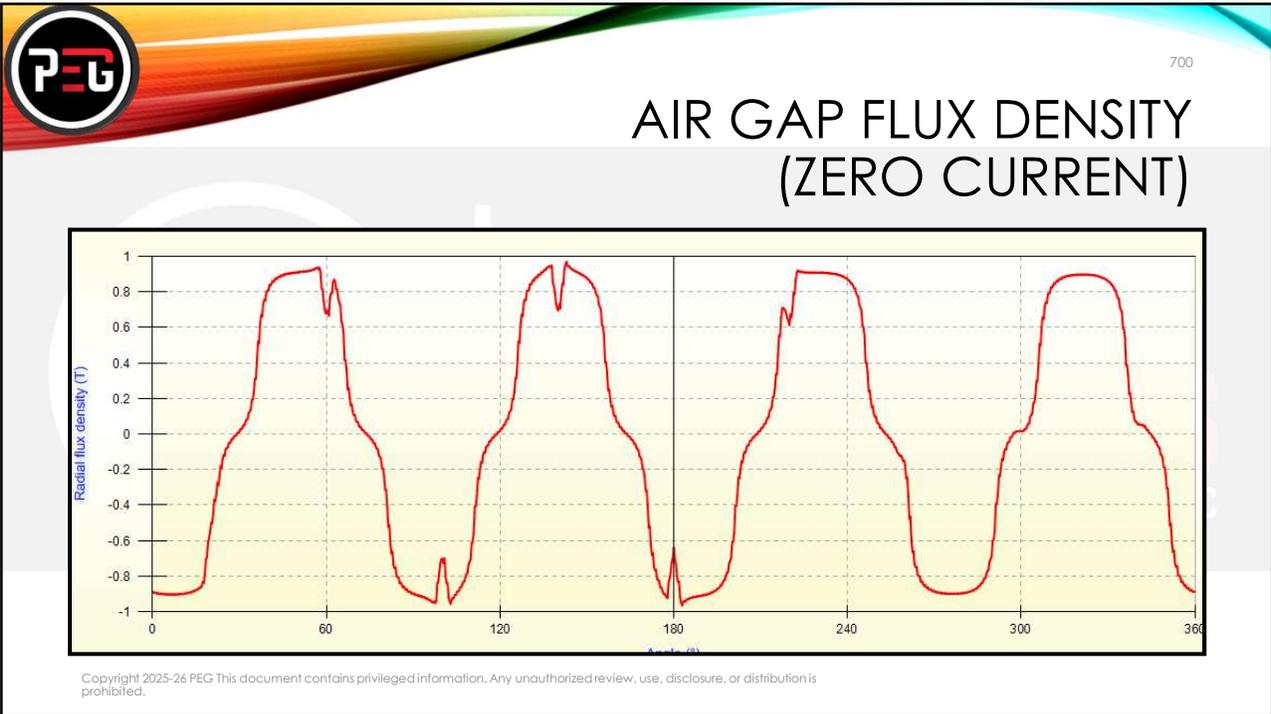
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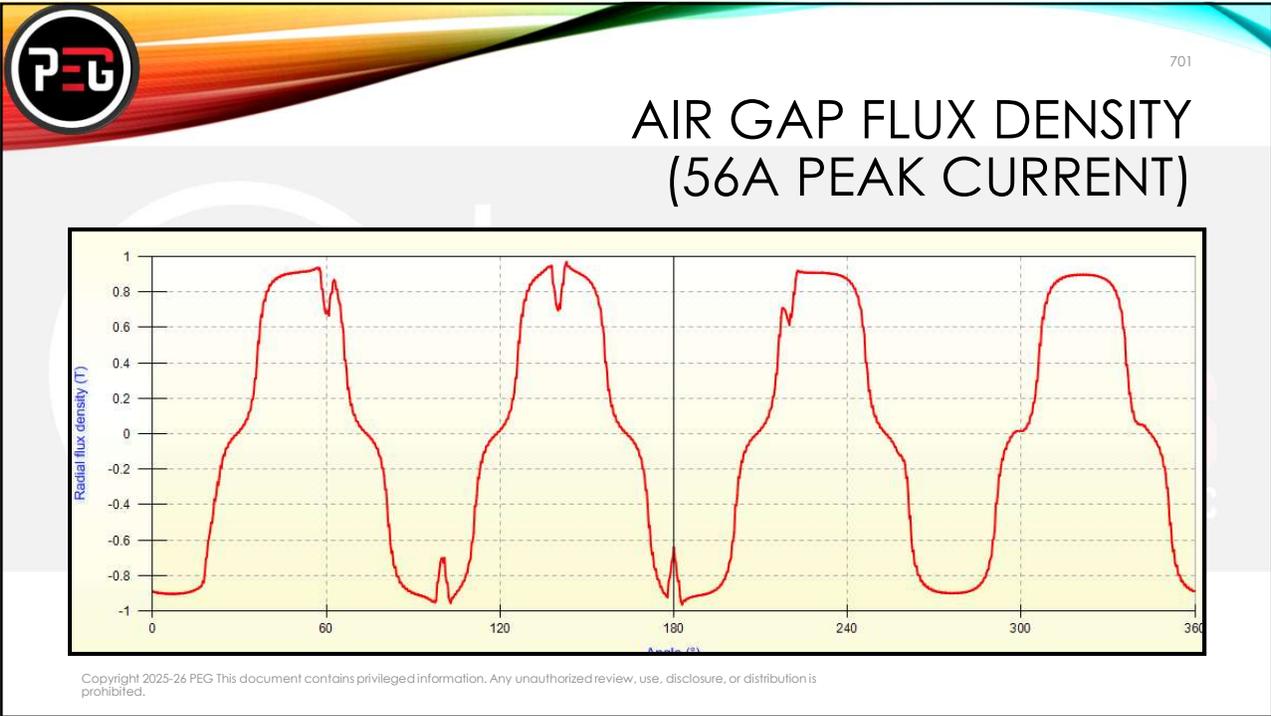
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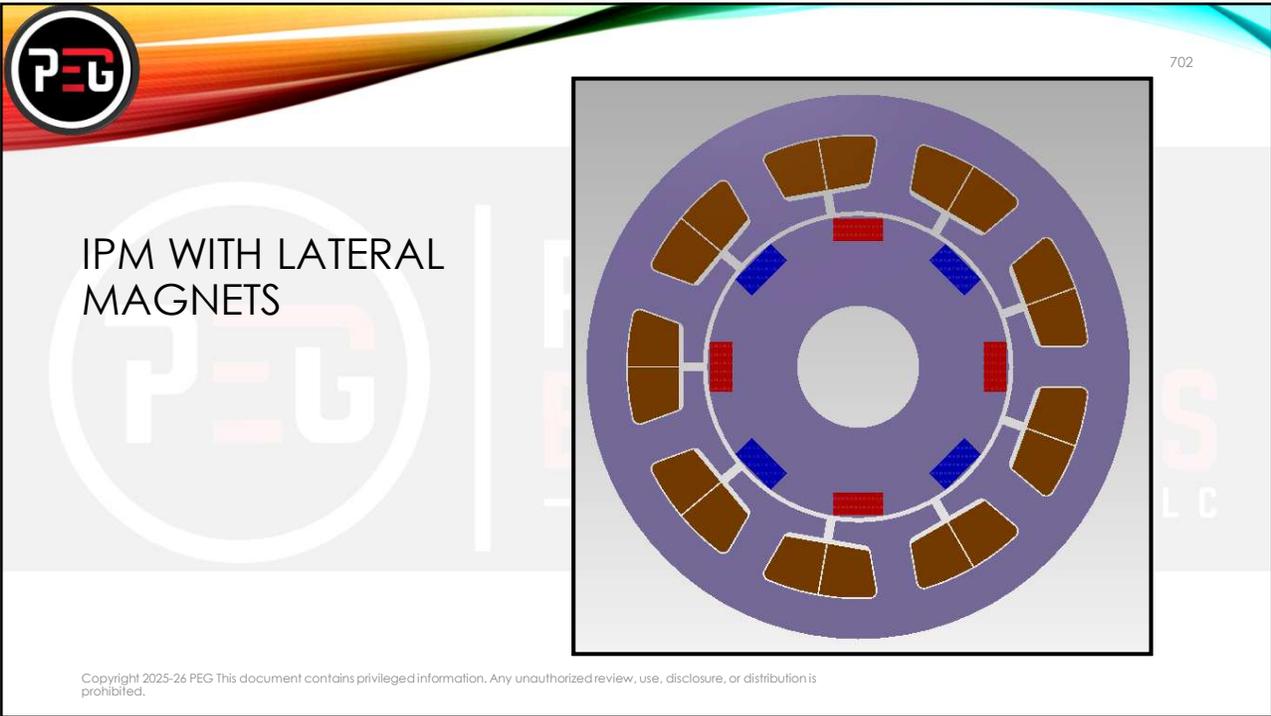
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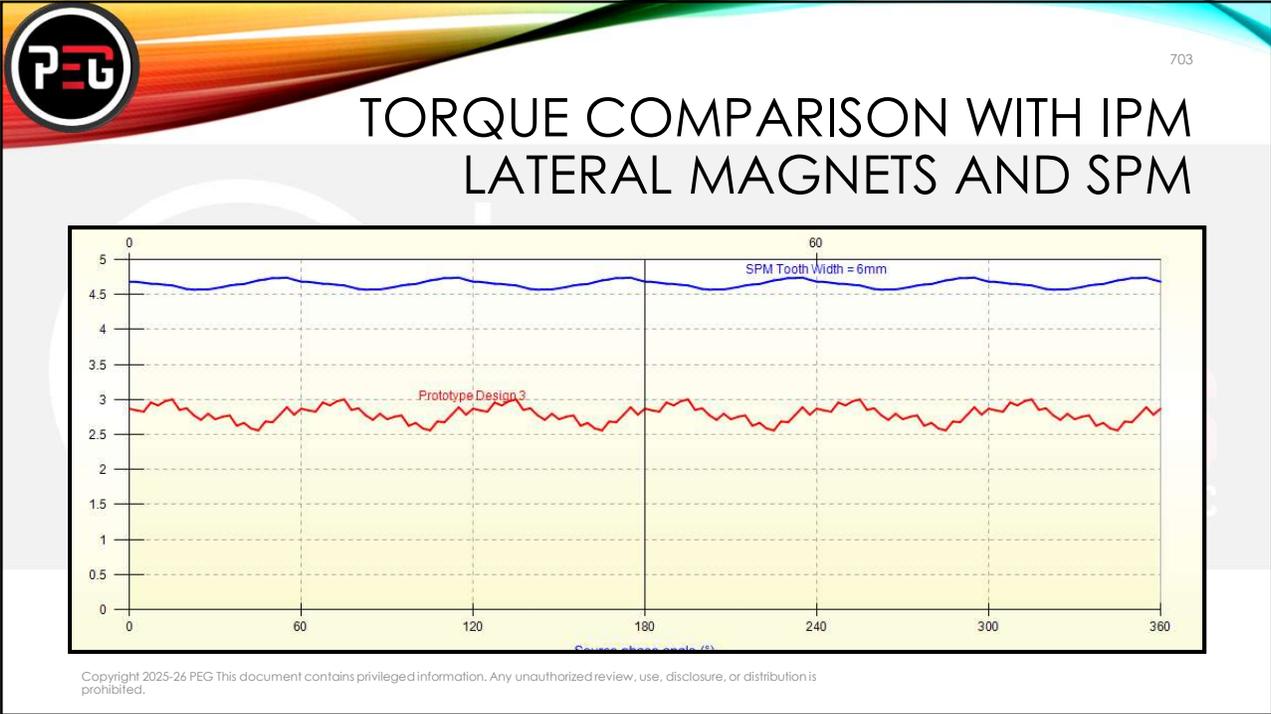
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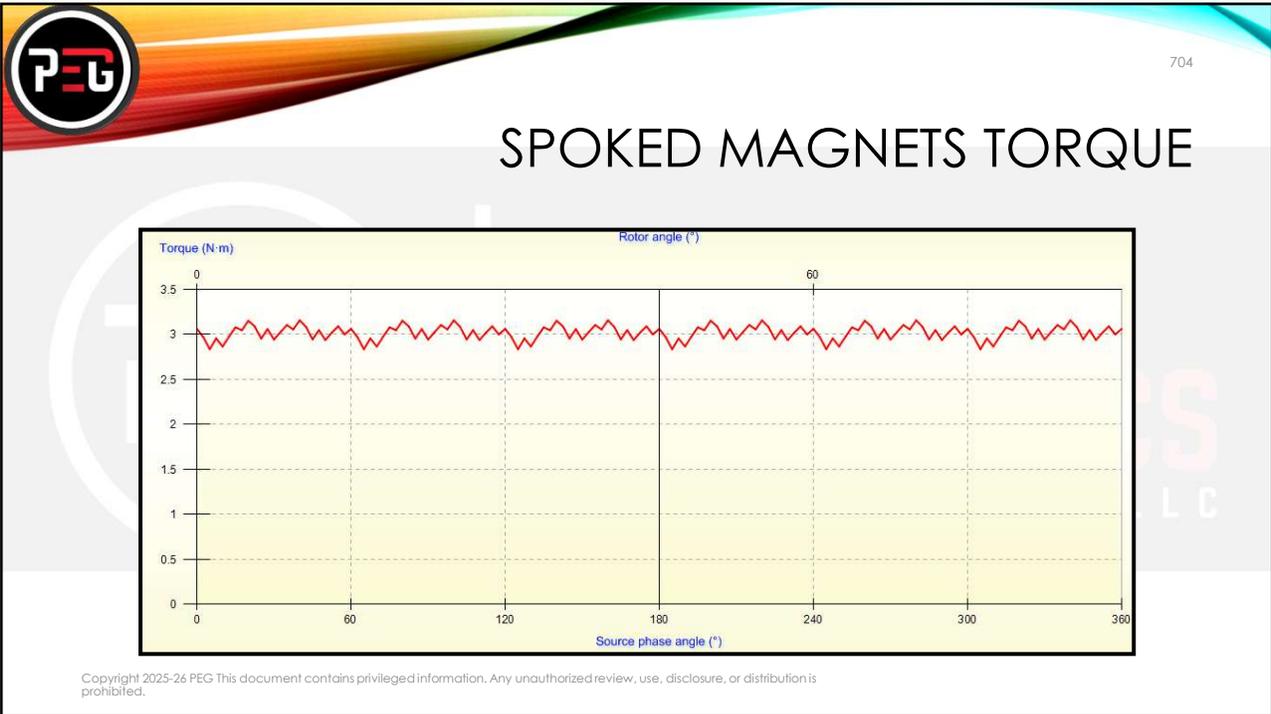
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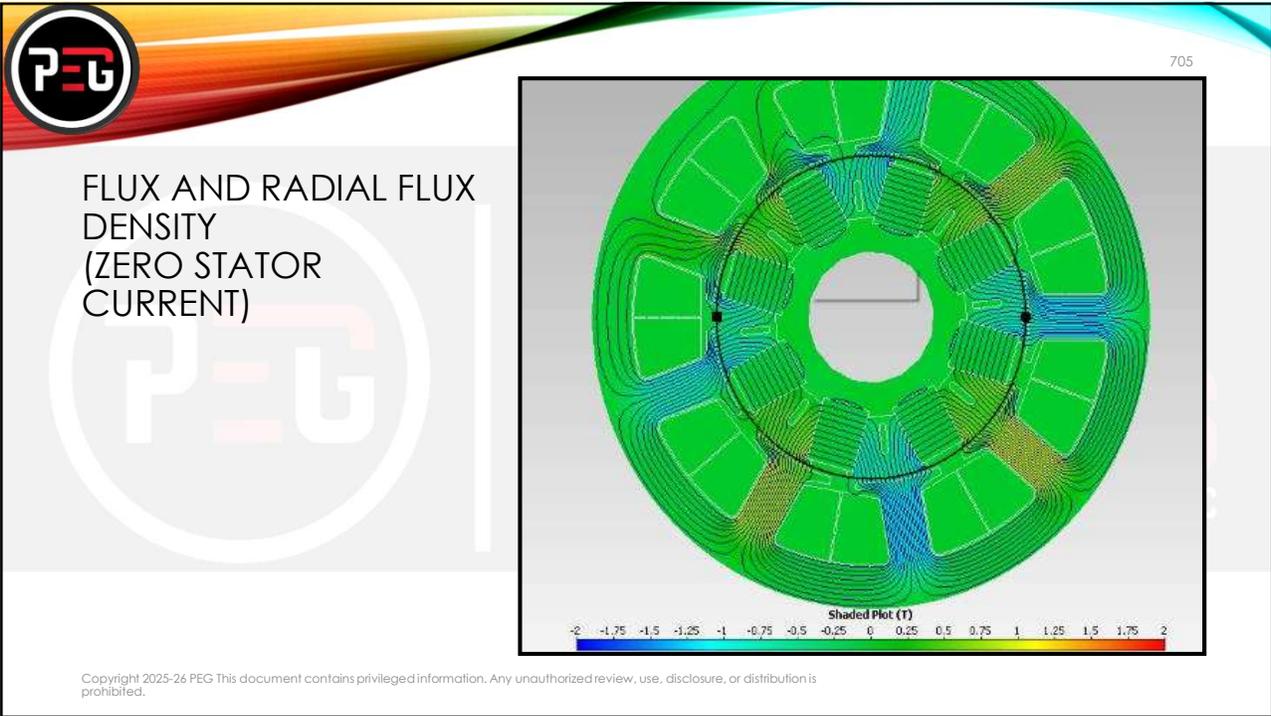
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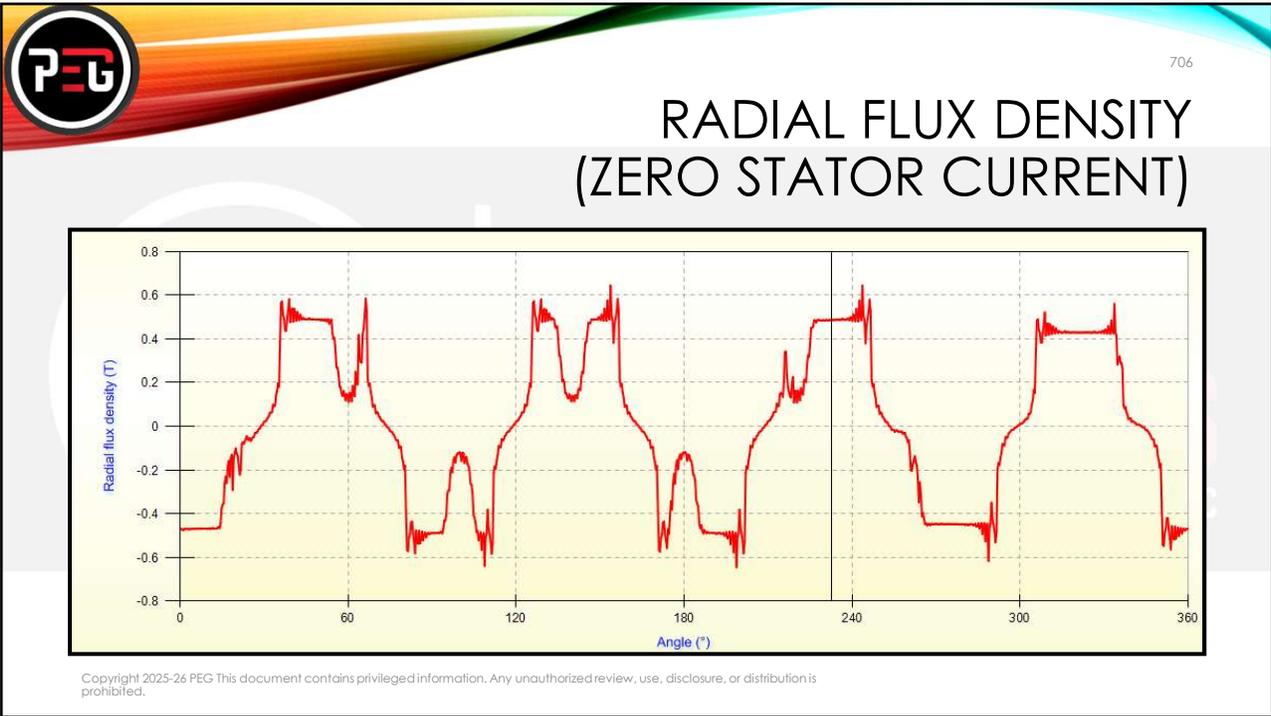
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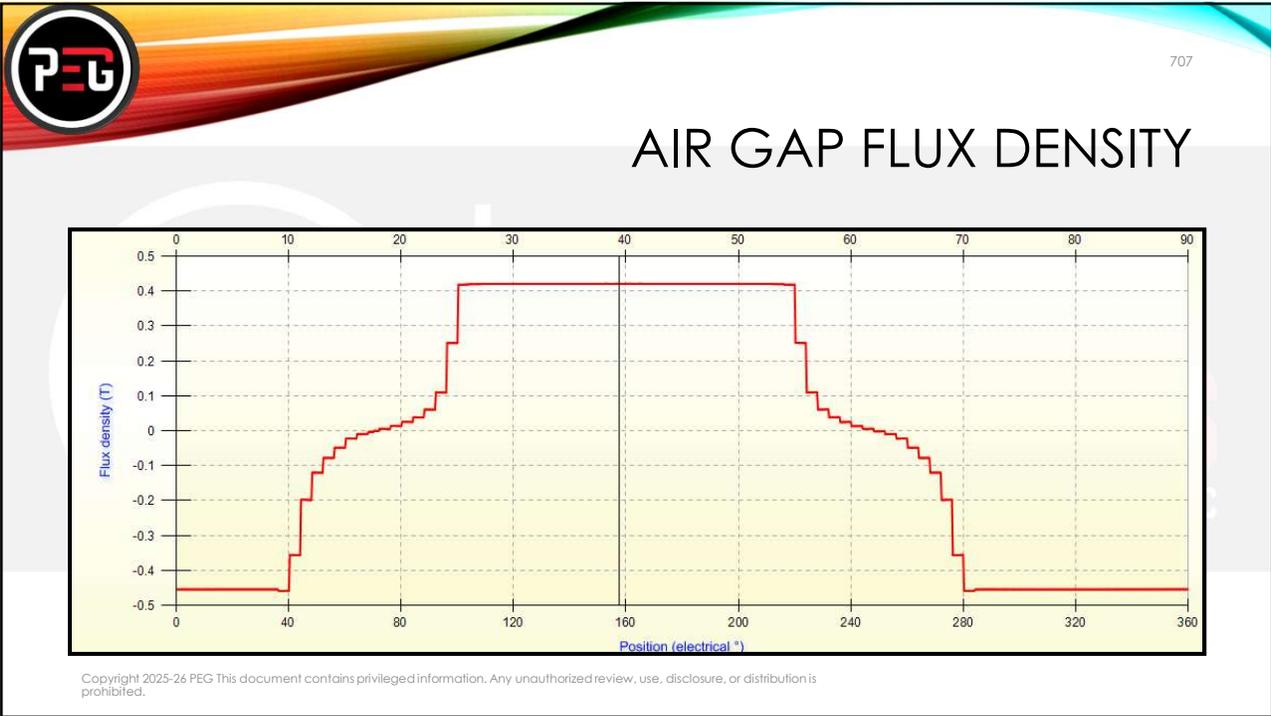
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FINITE ELEMENT ANALYSIS

IPM with Spoked Magnets (Ferrite)

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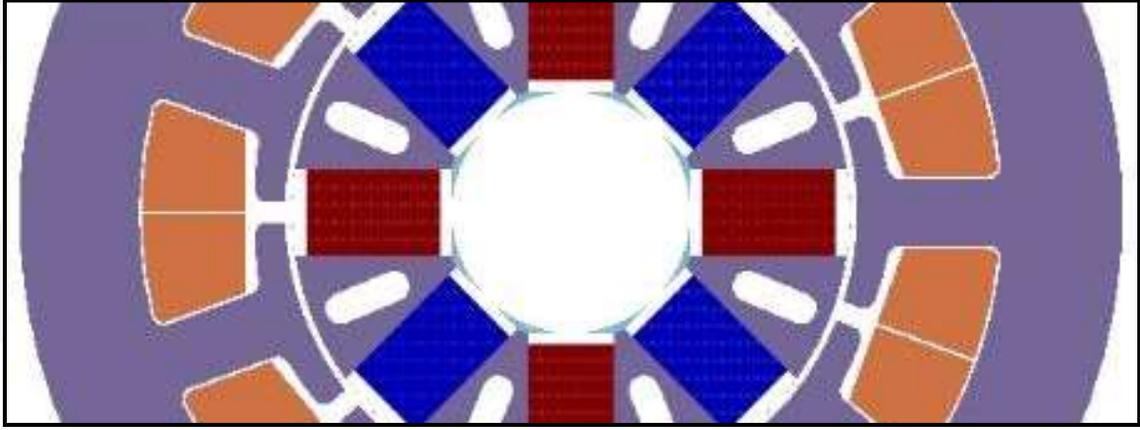
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IPM WITH SPOKED MAGNETS



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THREE DESIGNS (GENERAL DIMENSIONS)

General Dimensions	Design A	Design B	Design C
Outside Diameter (mm)	83	83	83
Air Gap Thickness (mm)	0.5	0.5	0.5
Stack Length (mm) ?	70	70	70
Number of Poles	8	8	8
Number of Slots	9	9	9
Rotor Diameter (mm)	42.1	42.1	46
Inner Diameter (mm)	18	18	18

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THREE DESIGNS (STATOR DIMENSIONS)

Stator Dimensions	Design A	Design B	Design C
Outside Diameter (mm)	83	83	83
Inner Diameter (mm)	43.1	43.1	47
Slot Area (mm ²)	125	117	149
Tooth Width (mm)	5	6	5.25
Tooth Tang Depth (mm)	2.25	3	1.05
Tooth Gap Width (mm)	1.5	2.5	2.5
Back Iron Depth (mm)	9	8.5	7
Number of Turns	8		

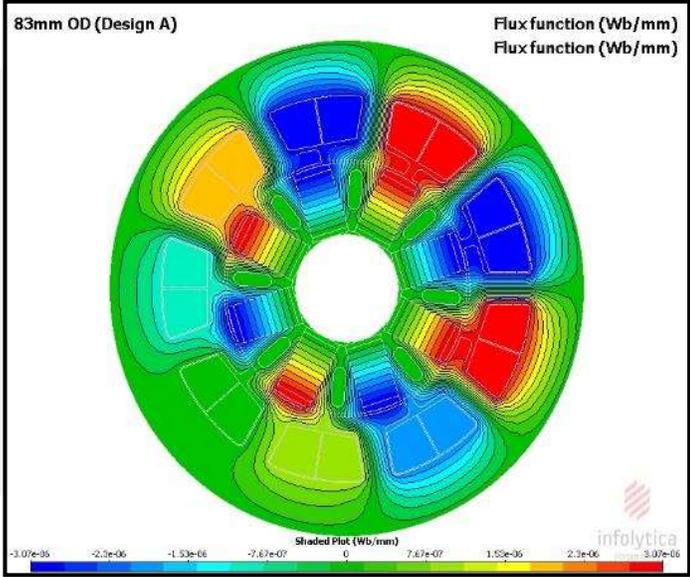
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FLUX DISTRIBUTION AT ZERO DEGREES



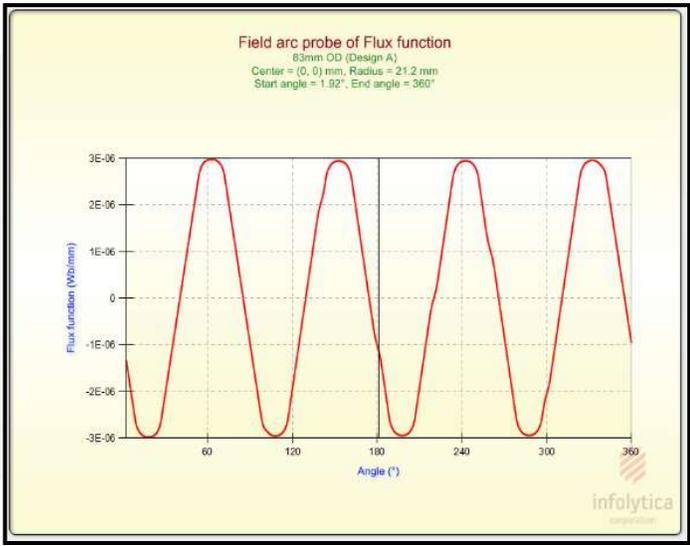
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FLUX AT AIR GAP



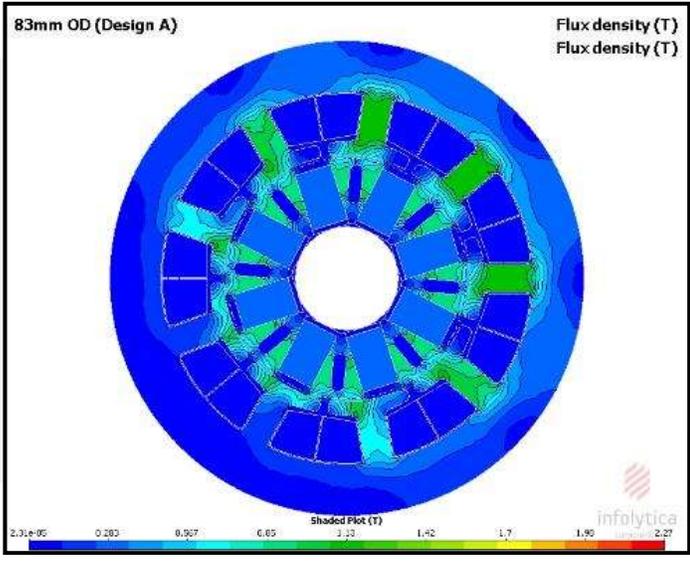
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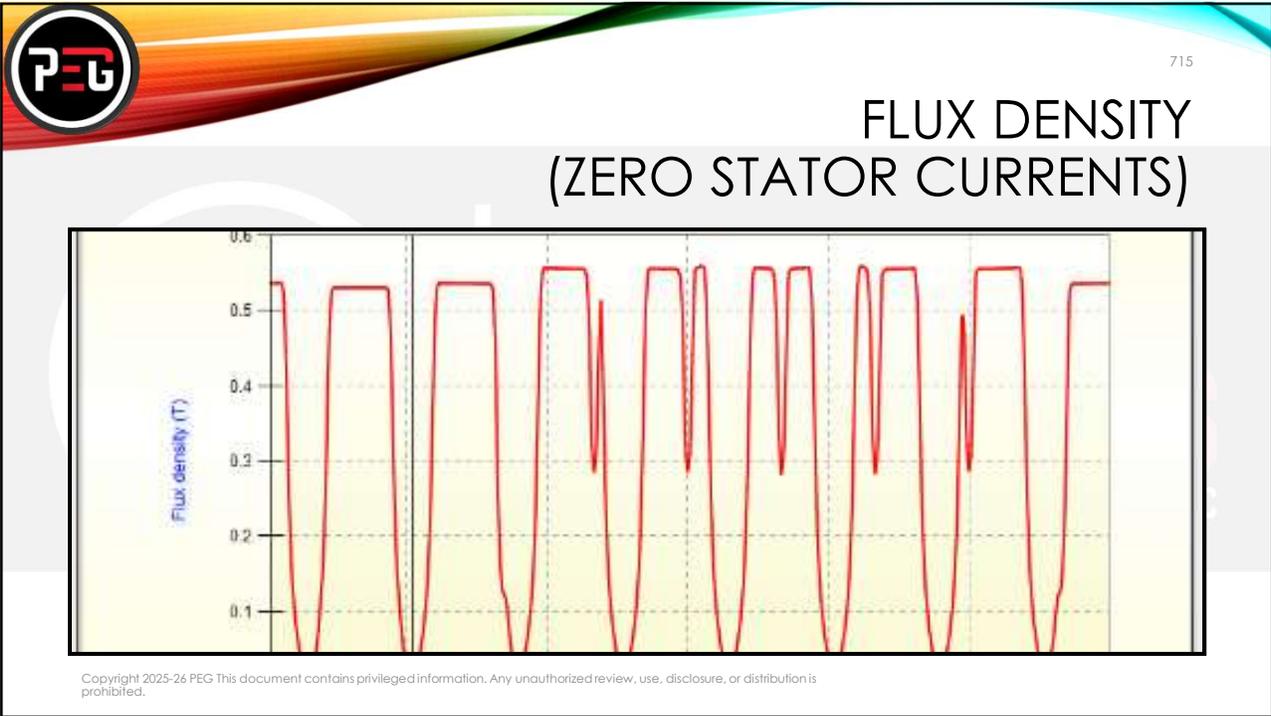
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FLUX DENSITY DISTRIBUTION (ZERO STATOR CURRENT)

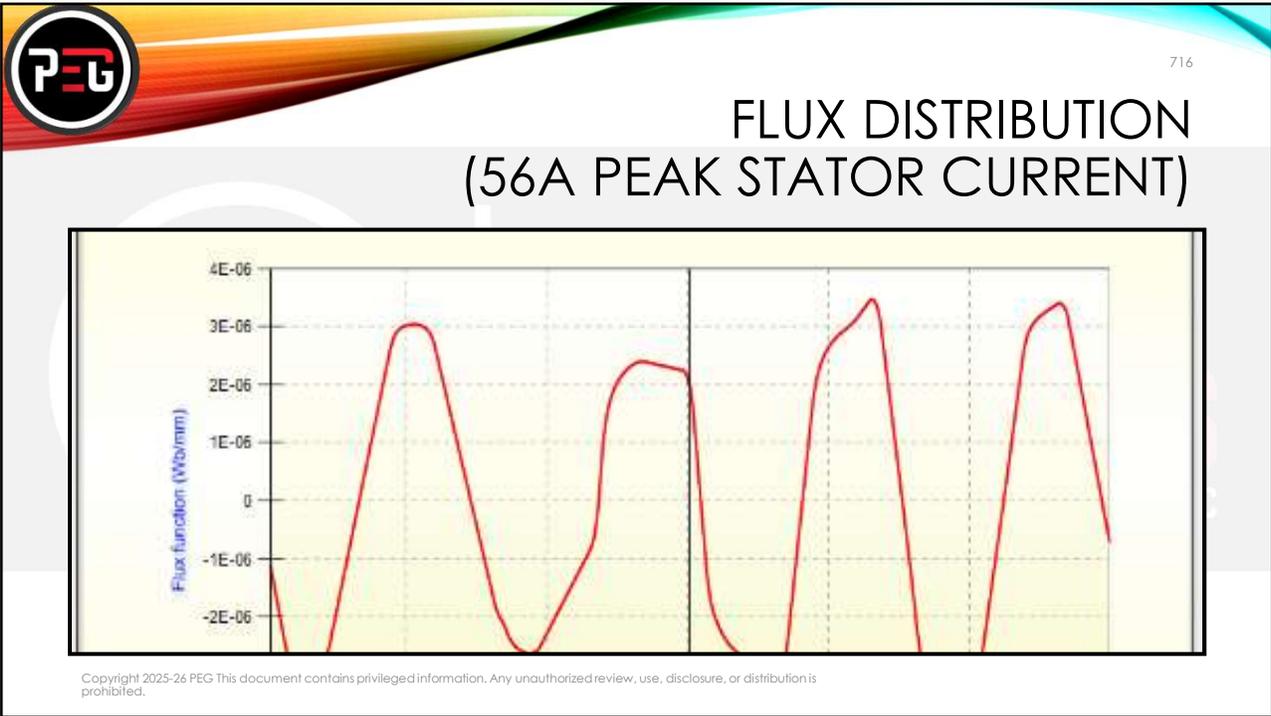


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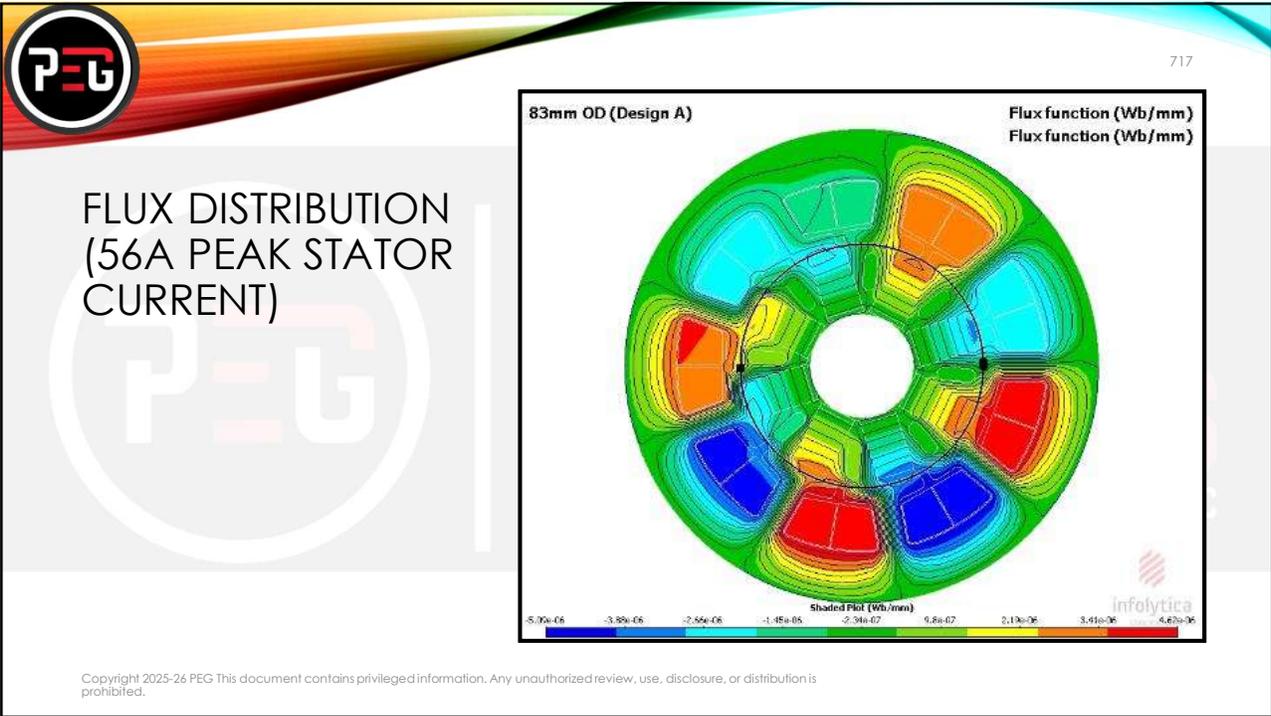
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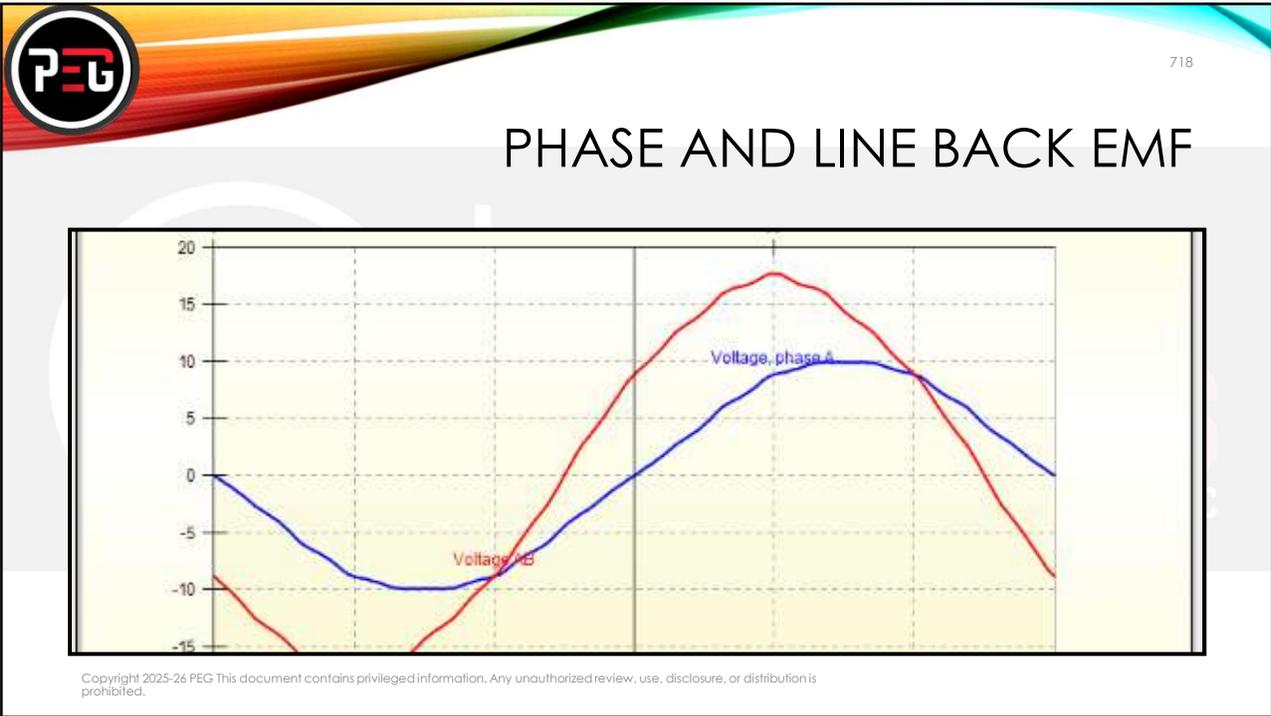
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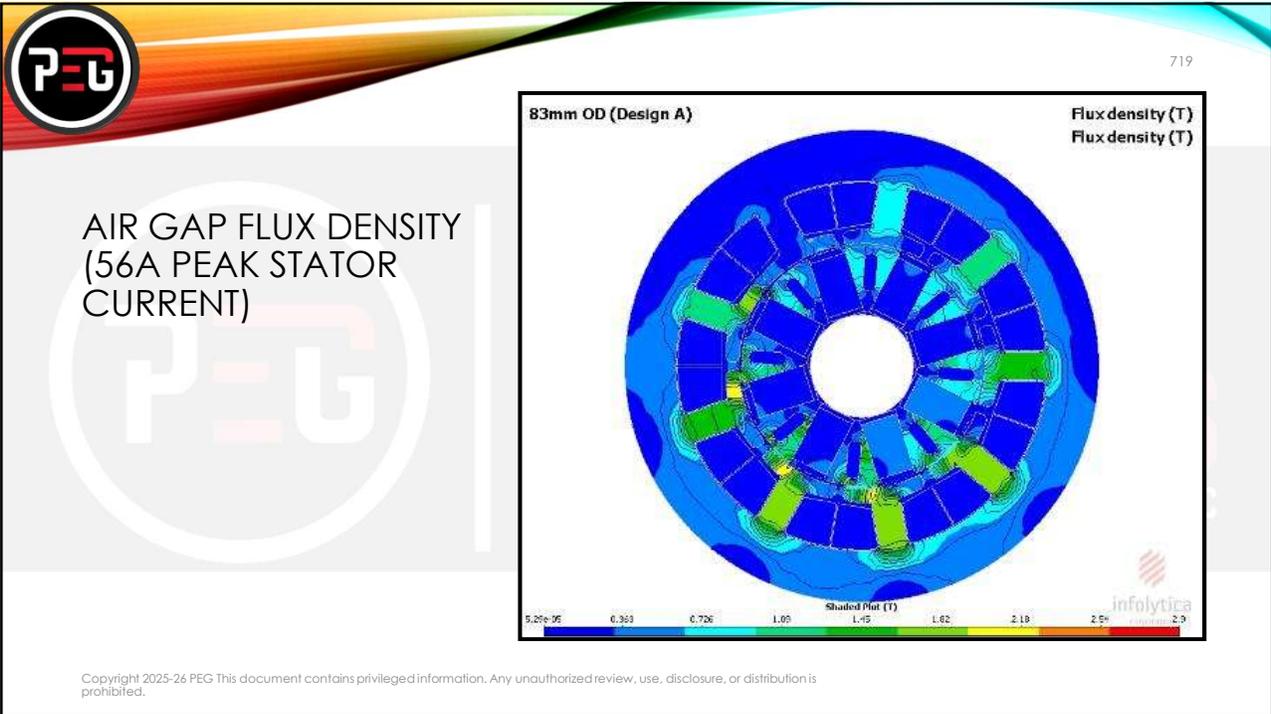
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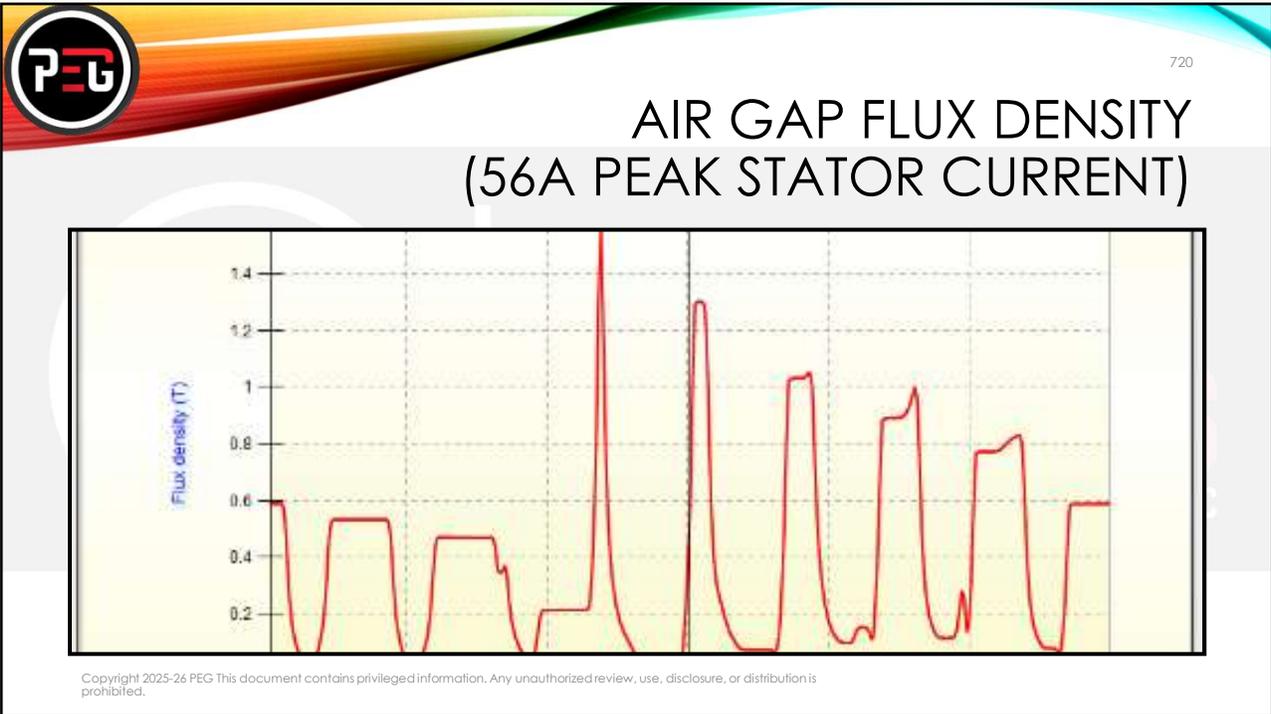
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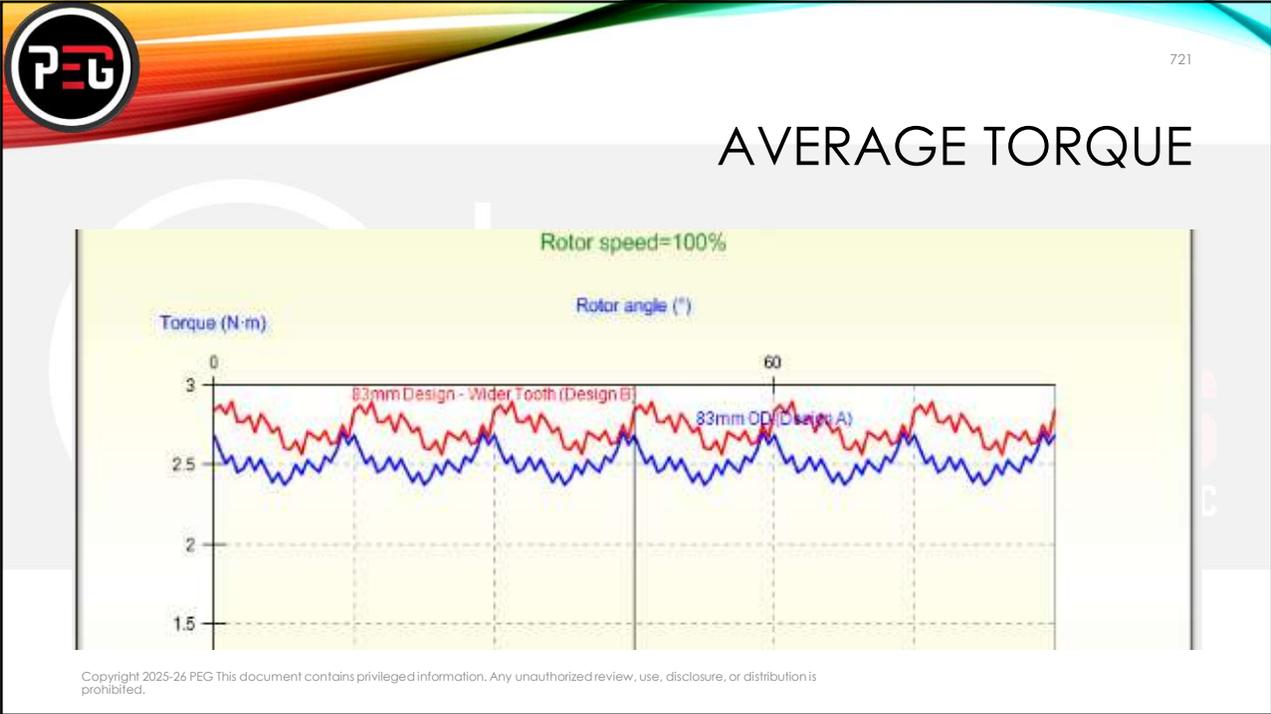
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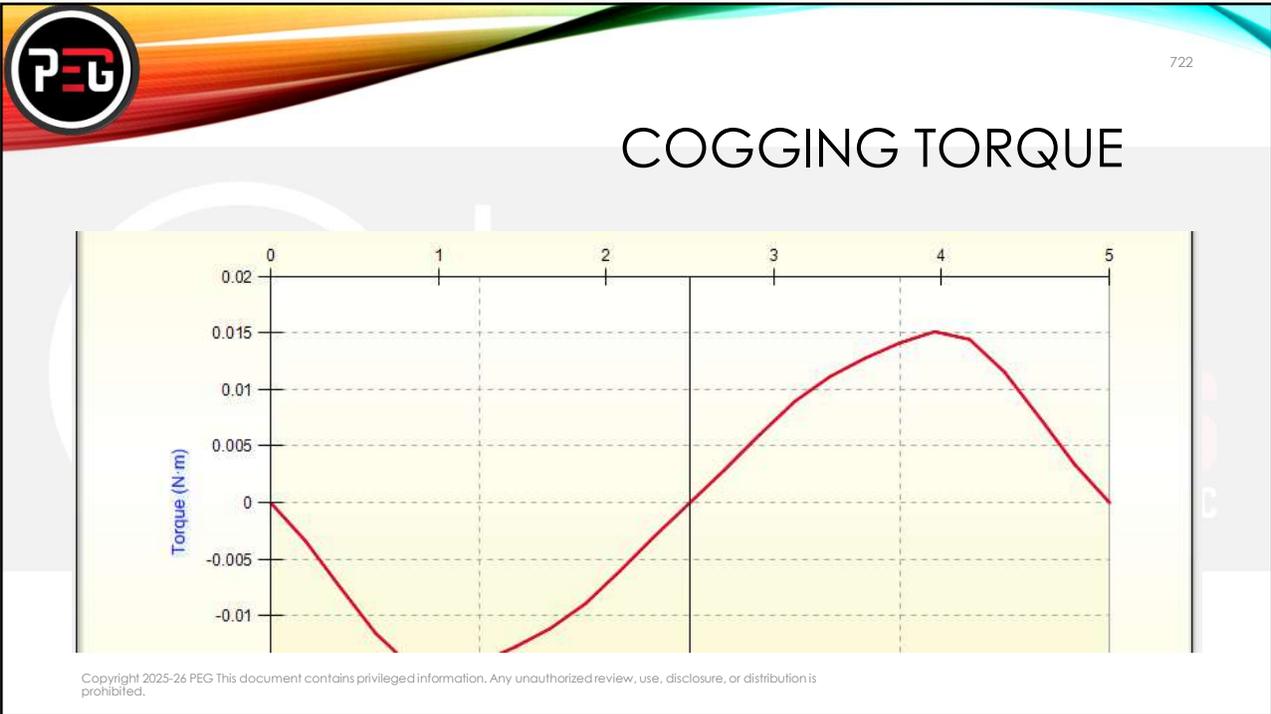
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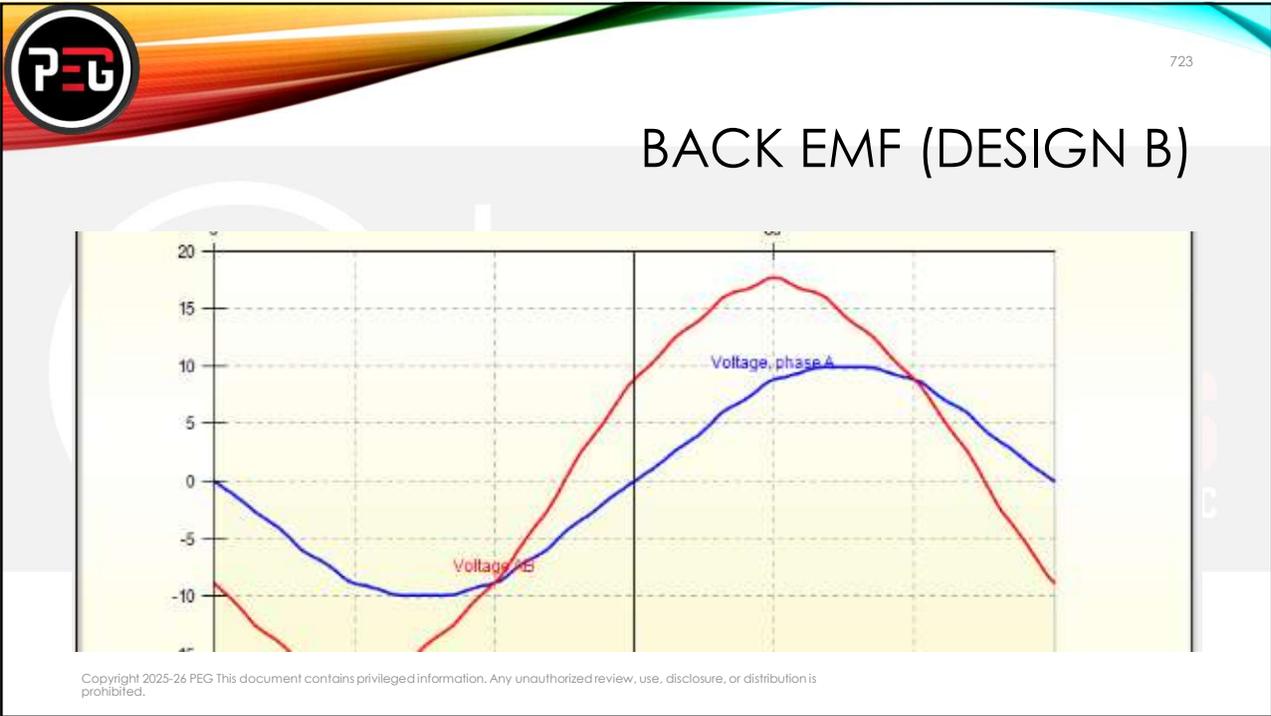
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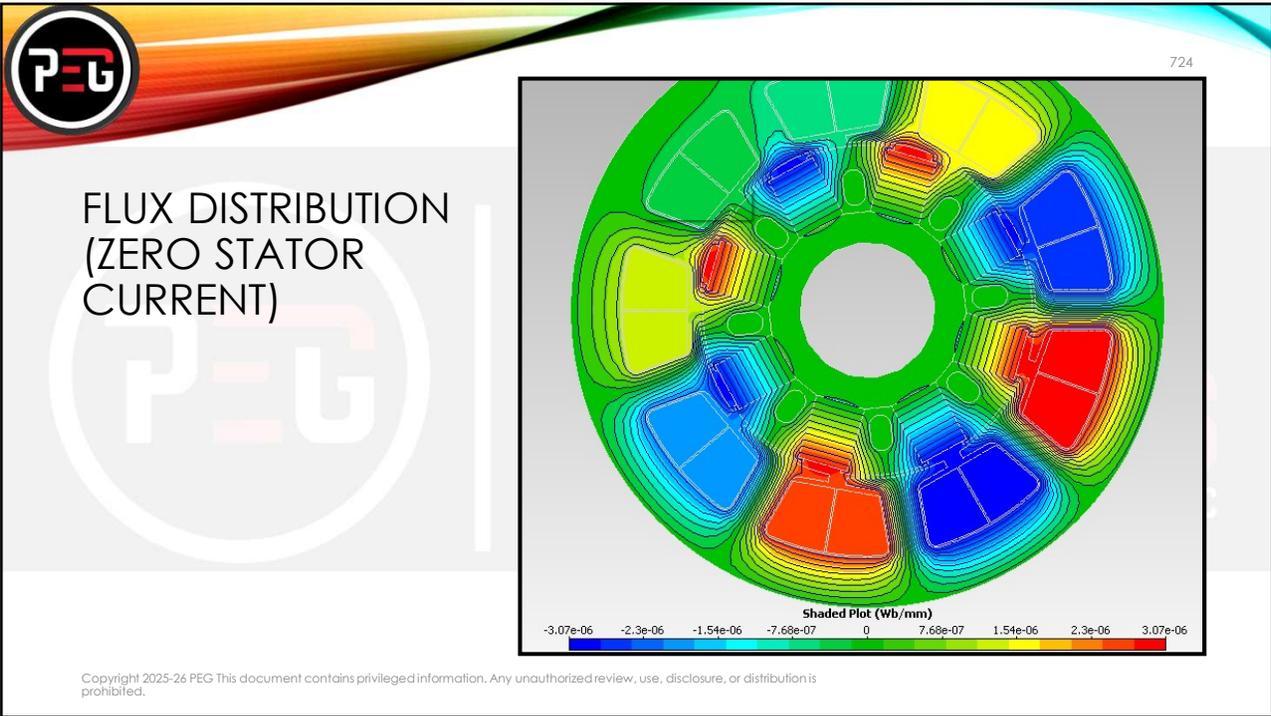
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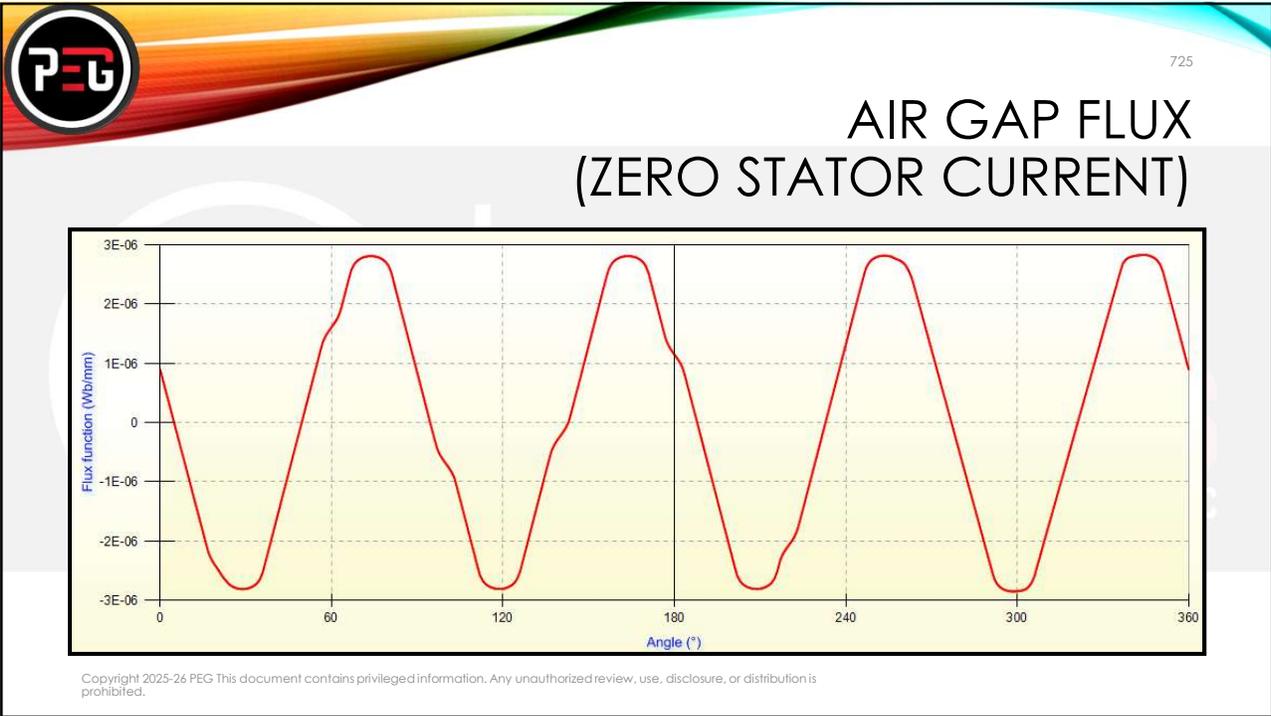
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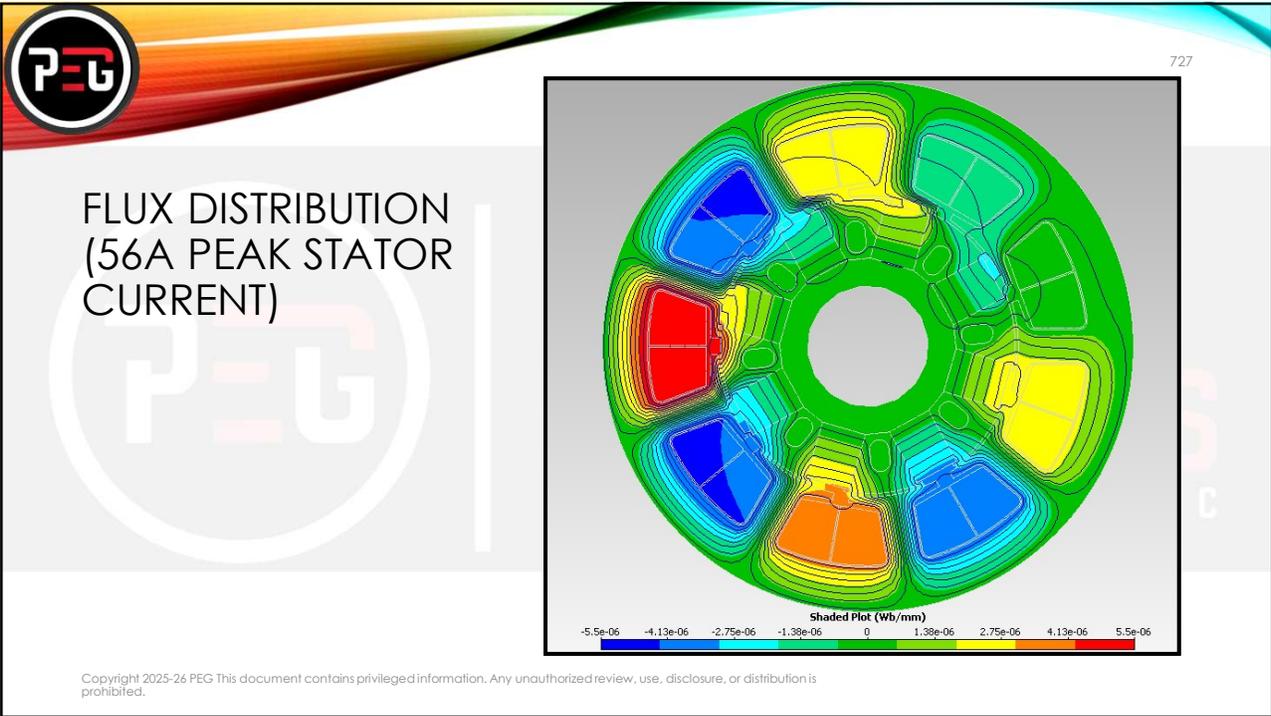
FINITE ELEMENT ANALYSIS

Design C analysis

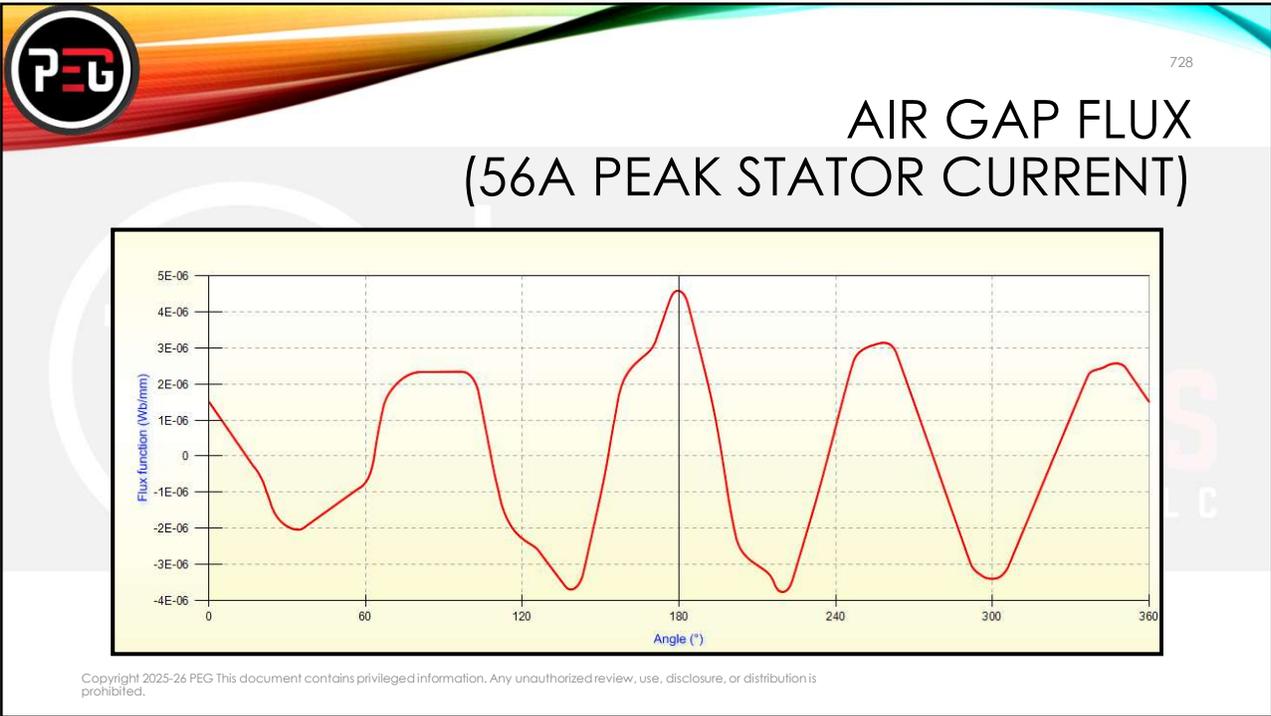
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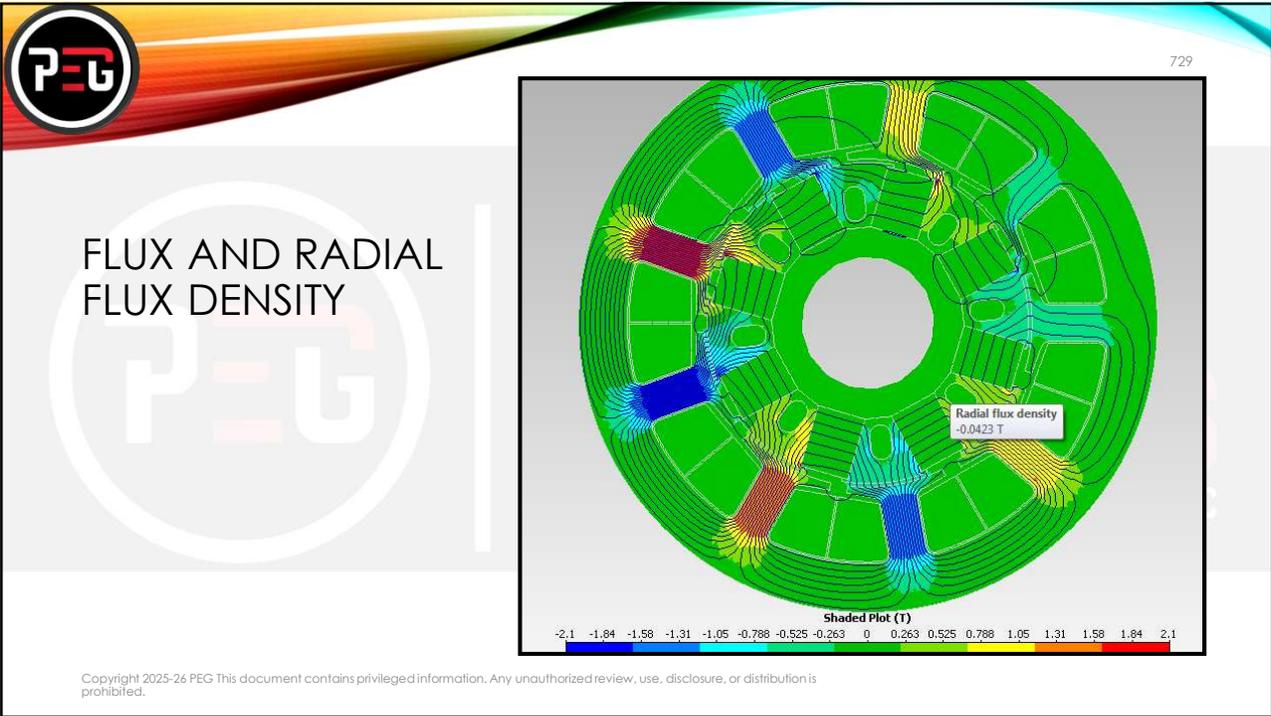
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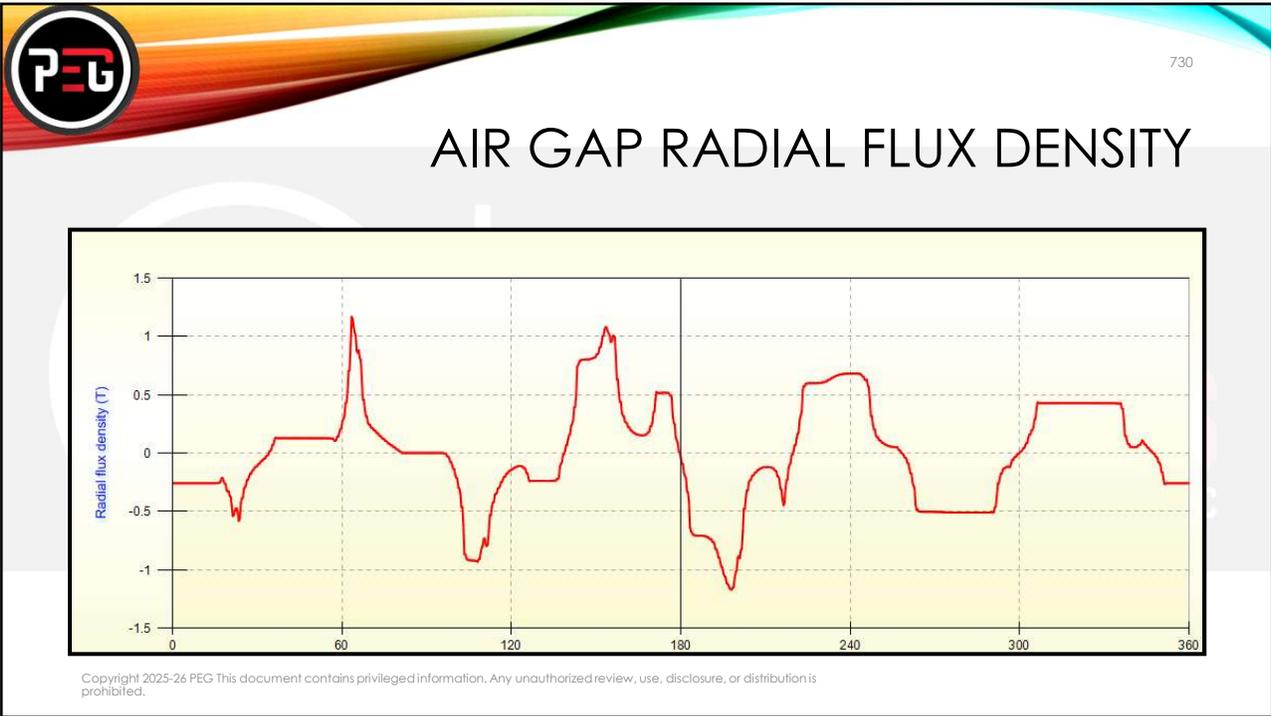
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FINITE ELEMENT ANALYSIS

IPM with Spoked Magnets (NdFeB)
(Design D)

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COGGING TORQUE



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BACK EMF



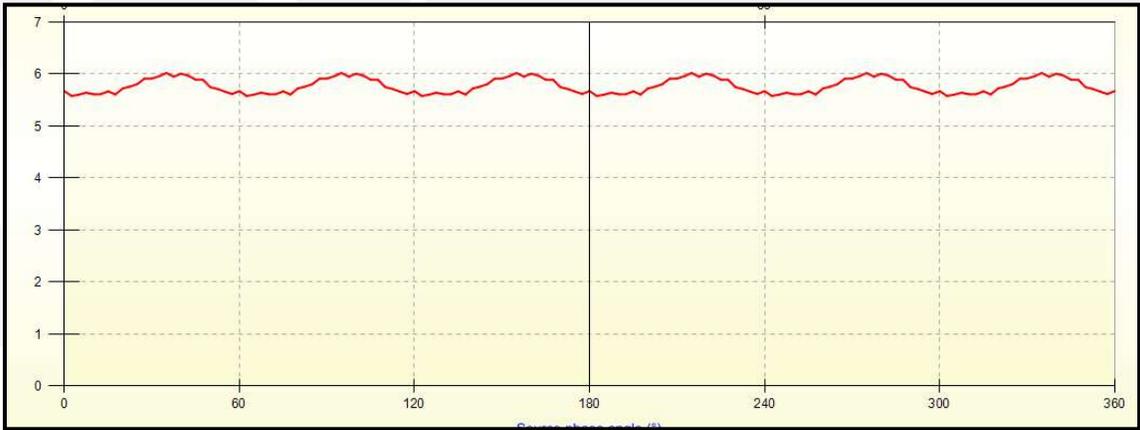
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TORQUE (60A PEAK PHASE CURRENT)



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TORQUE V/S PEAK CURRENT

Peak Current	Average Torque with 8T/pole	Comments
60	5.75	Slight Saturation
50	4.95	Linear
40	4.05	Linear
30	3.1	Linear
20	2.1	Linear
10	1	Linear

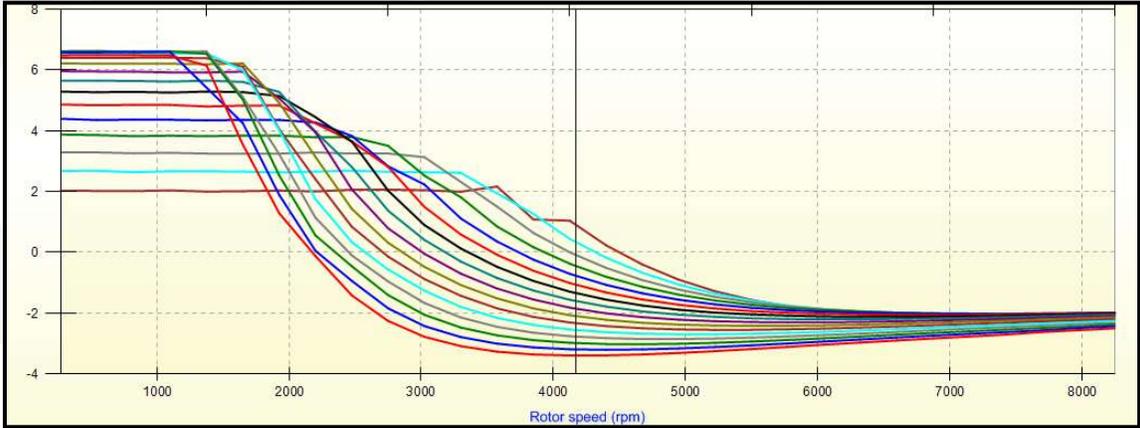
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TORQUE V/S SPEED



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PWM ANALYSIS

	1	2	3
Rotor Speed (rpm)	138	825	1512
Rotor Speed (% of rated)	5	30	55
Torque (N·m)	6.05	6.02	5.23
Magnet torque (N·m)	6.06	6.03	5.25
Reluctance torque (N·m)	-0.00965	-0.0103	-0.0206
Input power (kW)	0.255	0.681	0.949
Output power (kW)	0.0871	0.52	0.829

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PWM ANALYSIS

	1	2	3
Efficiency (%)	34.2	76.4	87.4
RMS voltage (V)	11.3	16.2	19.4
RMS current (A)	39.4	39.2	34.2
RMS back EMF (V)	1.28	7.69	14.1
Power factor	0.328	0.617	0.82
Supply current (A)	10.6	28.4	39.5
Maximum supply current (A)	58.8	58.7	50.4

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PWM ANALYSIS

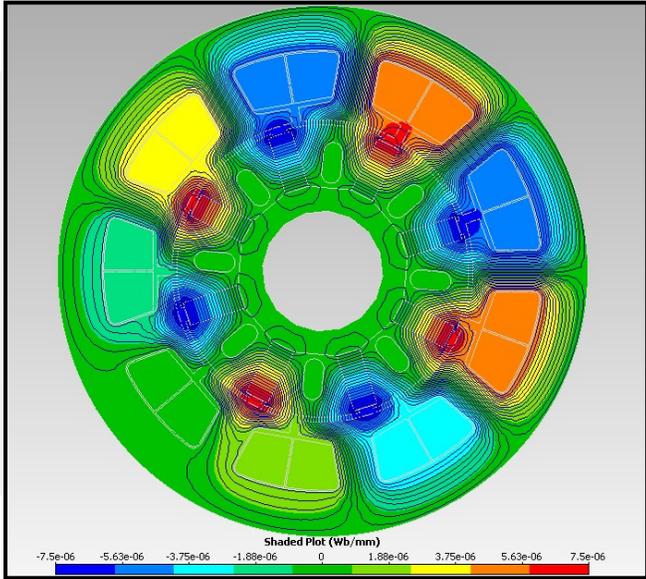
	1	2	3
Loss - Total (kW)	0.168	0.159	0.119
Loss - Winding (kW)	0.129	0.128	0.0976
Loss - Bridge (kW)	0.0382	0.0309	0.0212
Torque per unit volume (N·m/mm ³)	5.28E-05	5.26E-05	4.57E-05
Airgap stress (N/mm ²)	0.0264	0.0263	0.0228
Advance angle (°)	0	0	0
Rotor speed (rpm)	138	825	1512

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FLUX (ZERO CURRENT)

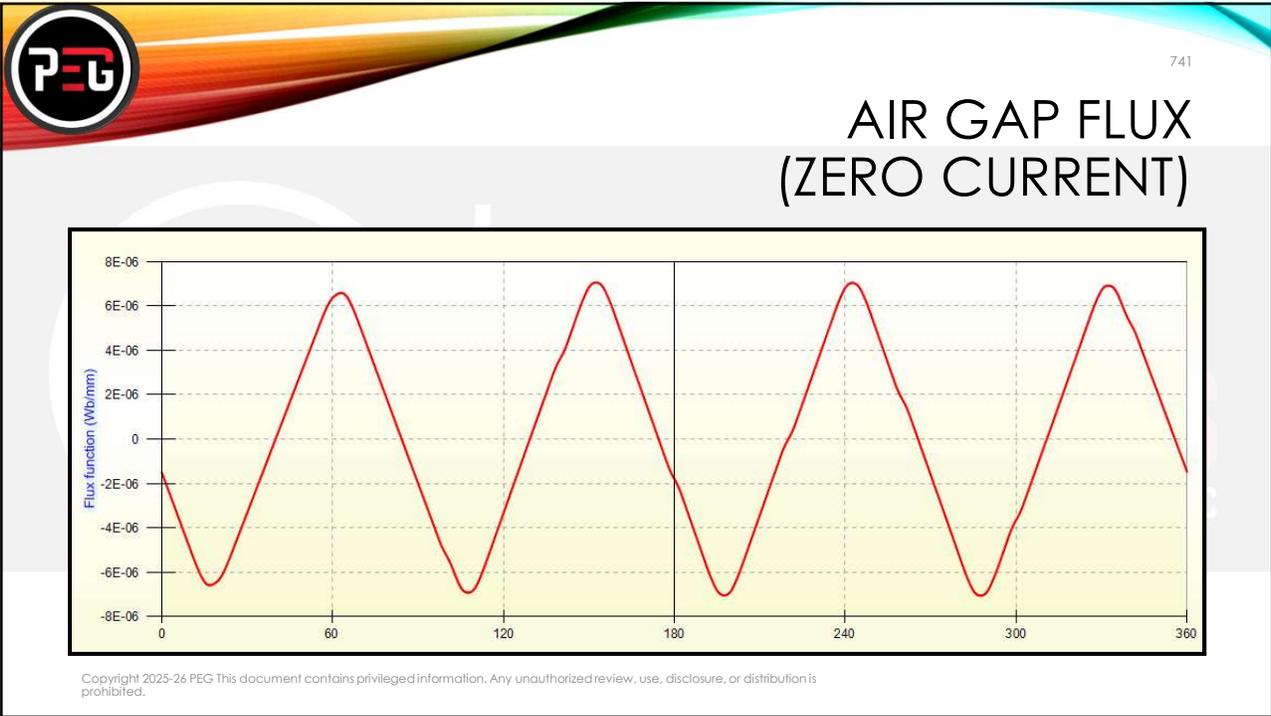


Shaded Plot (Wb/mm)

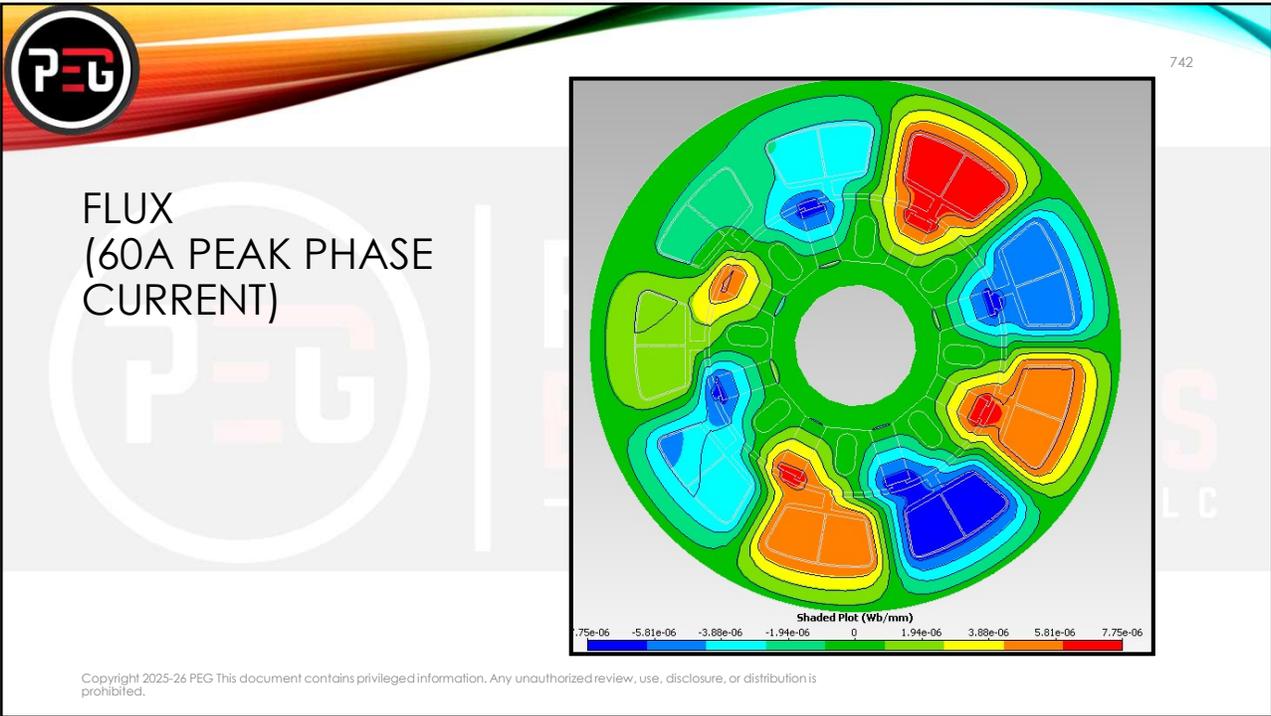
-7.5e-06 -5.63e-06 -3.75e-06 -1.88e-06 0 1.88e-06 3.75e-06 5.63e-06 7.5e-06

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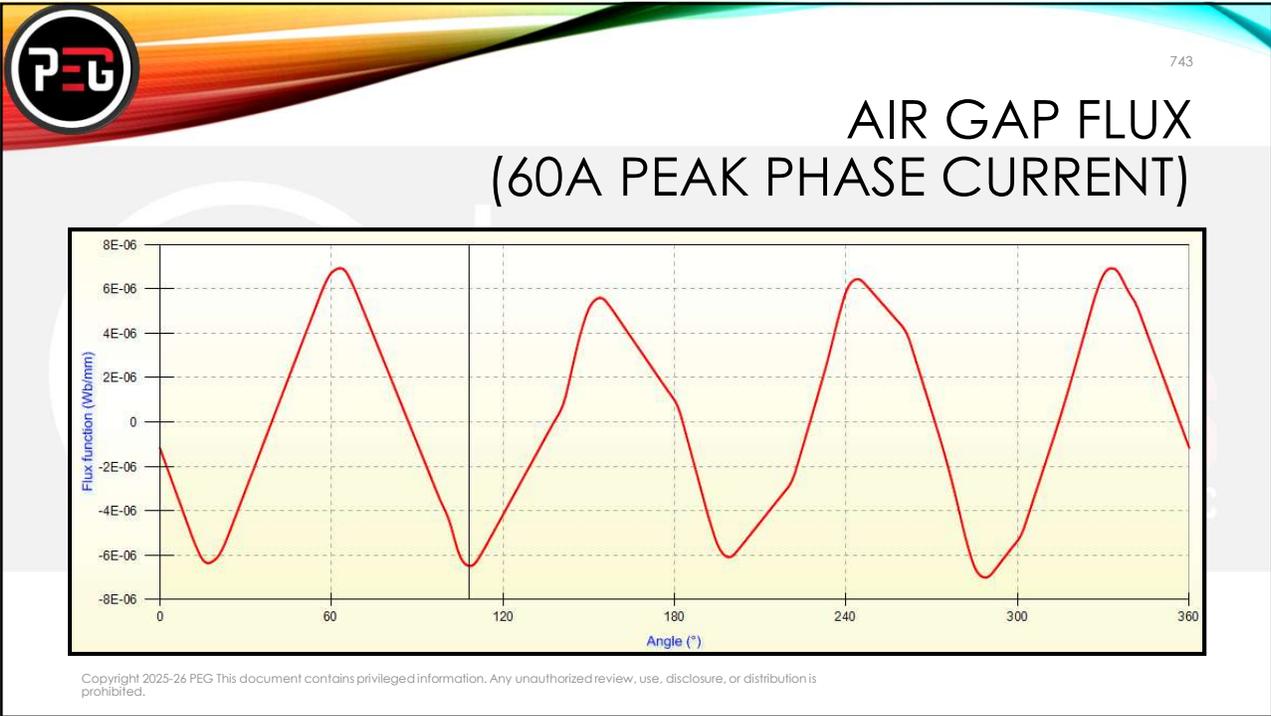
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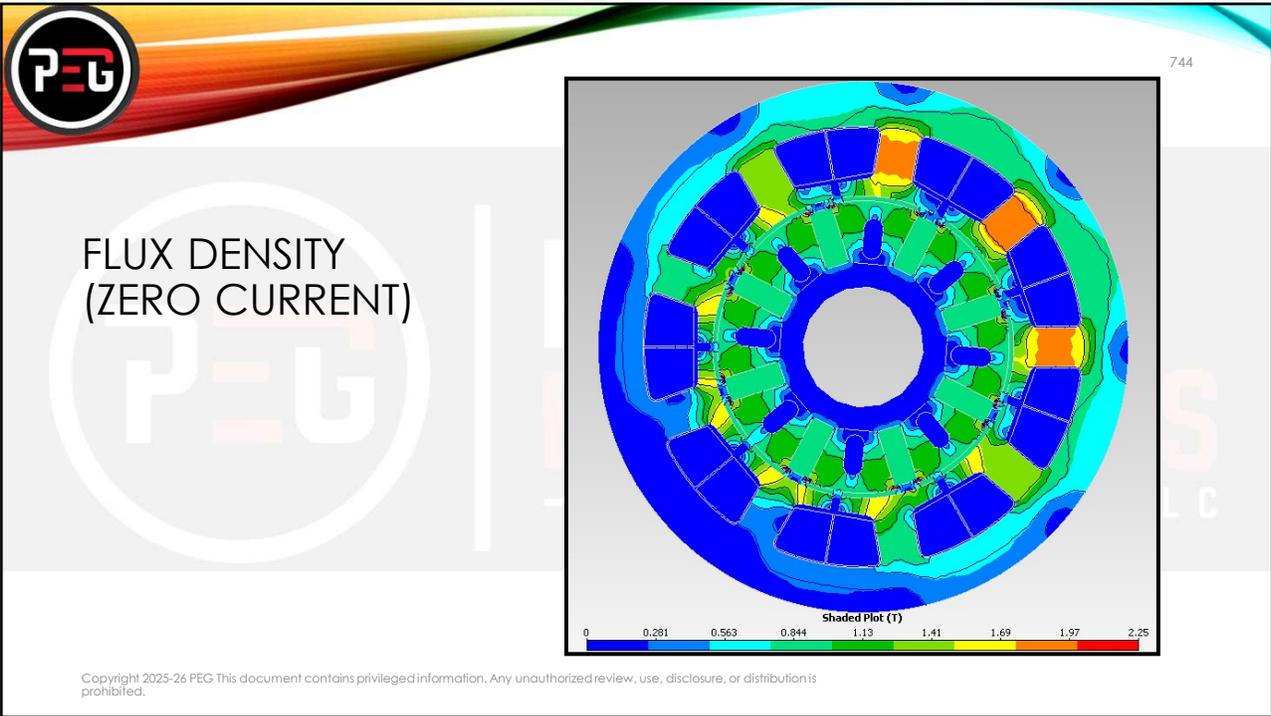
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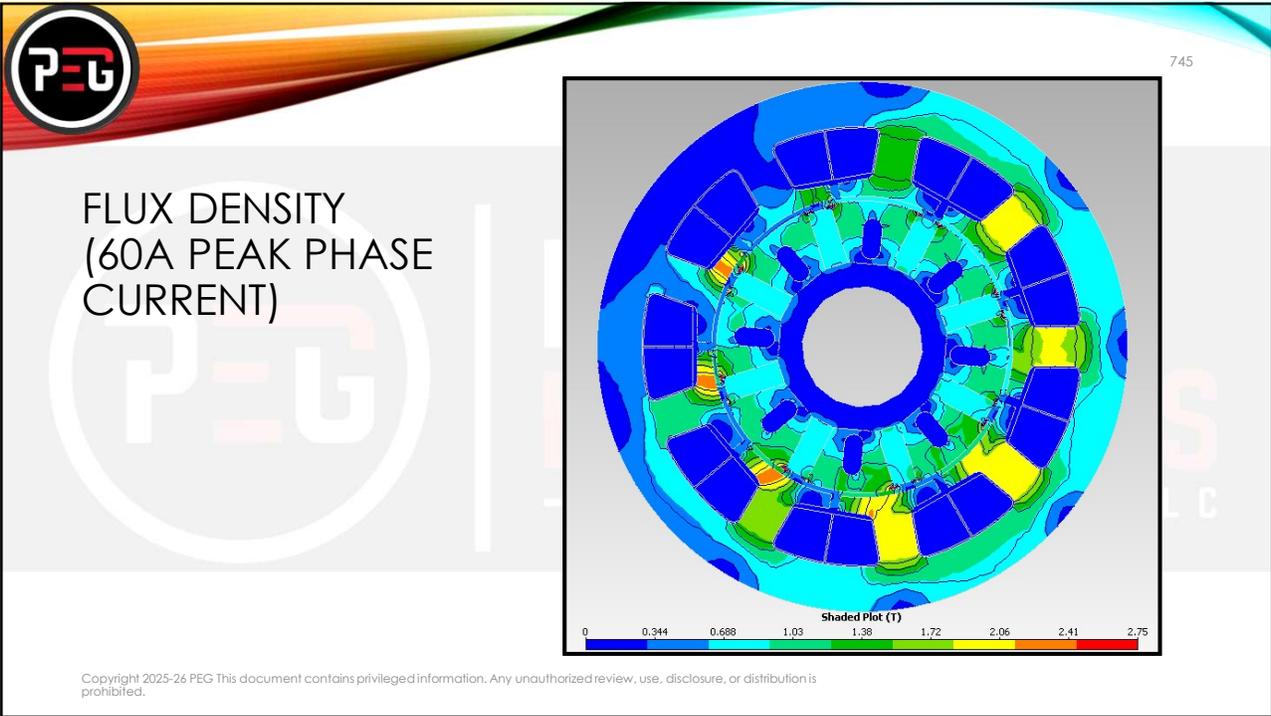
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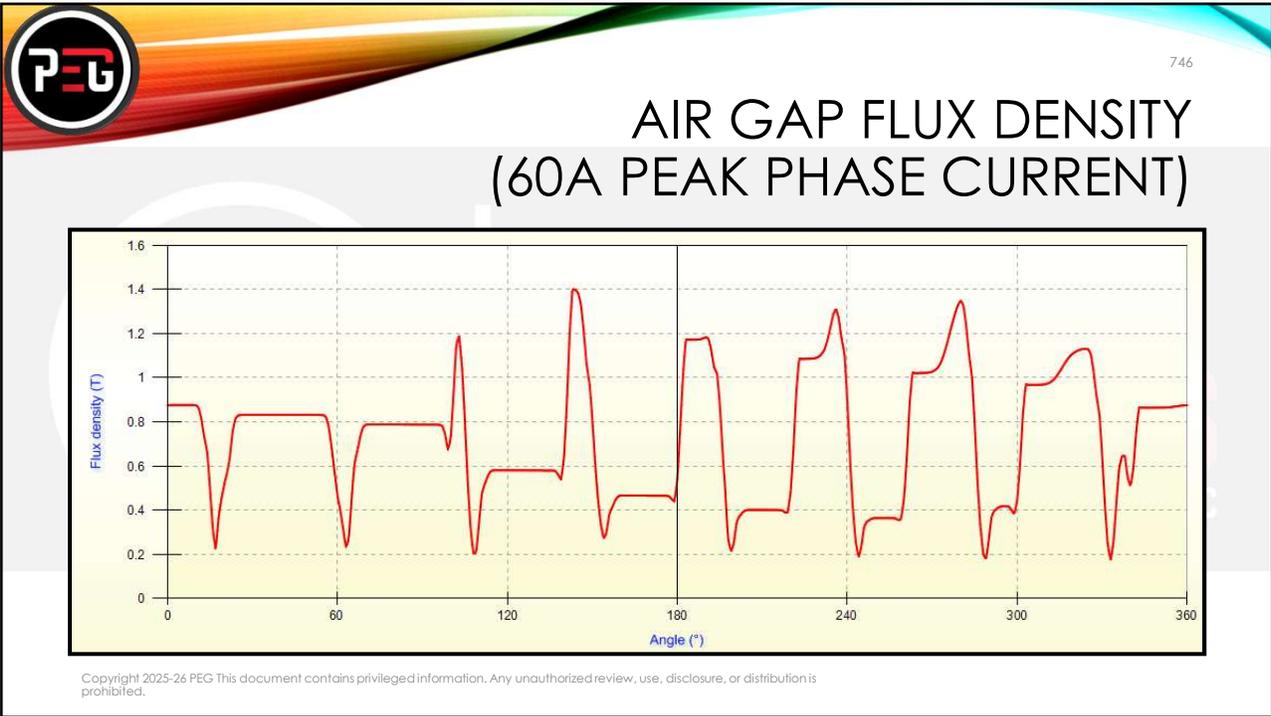
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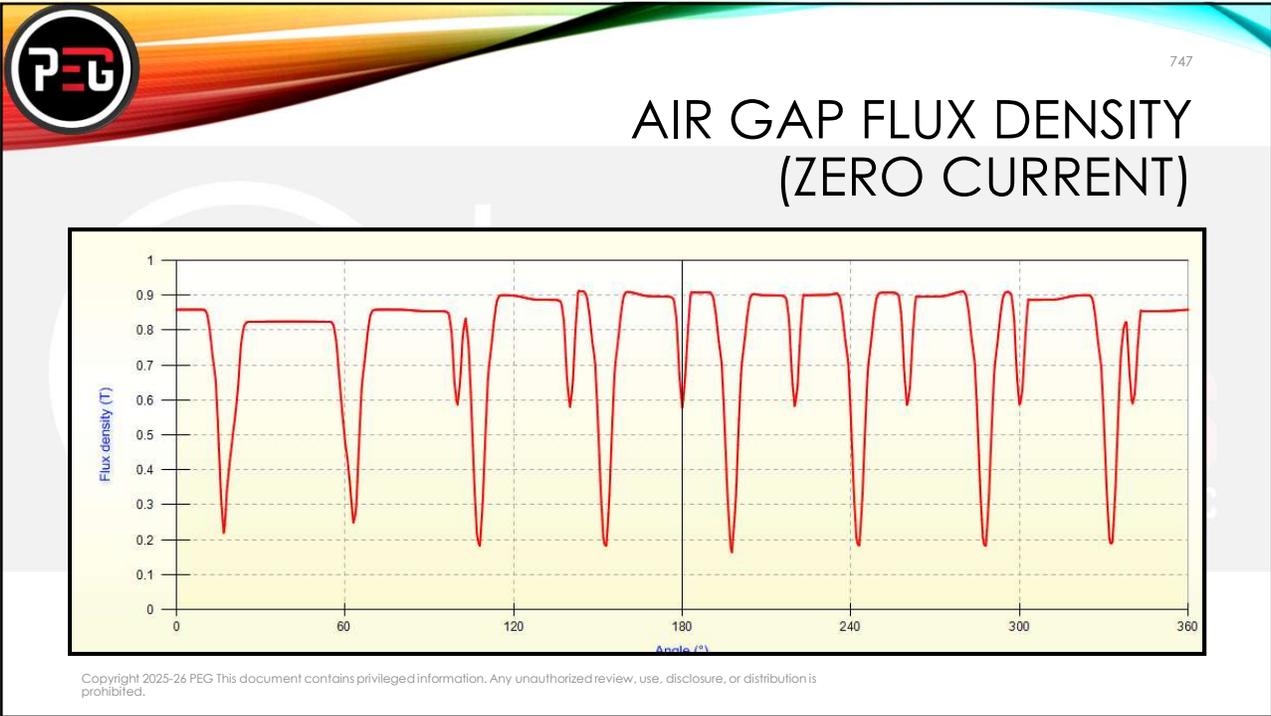
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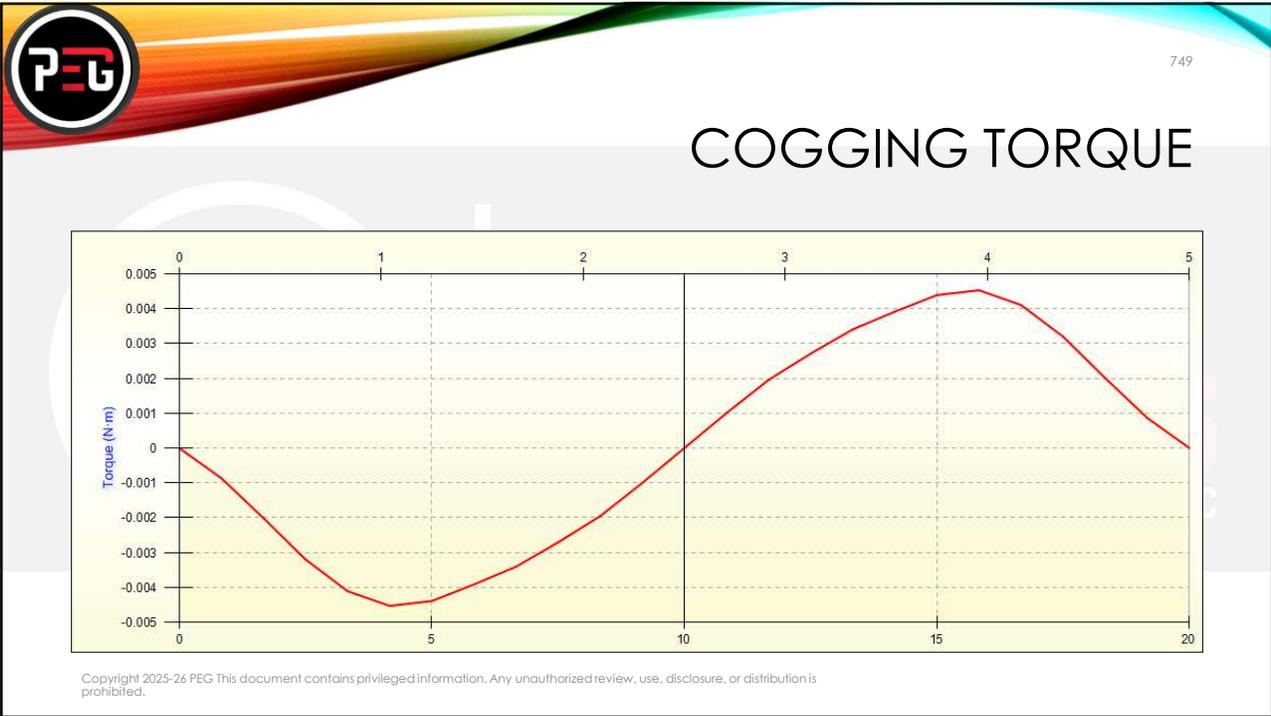
FINITE ELEMENT ANALYSIS

IPM with Spoked Magnets (Ferrite)
(Design D)

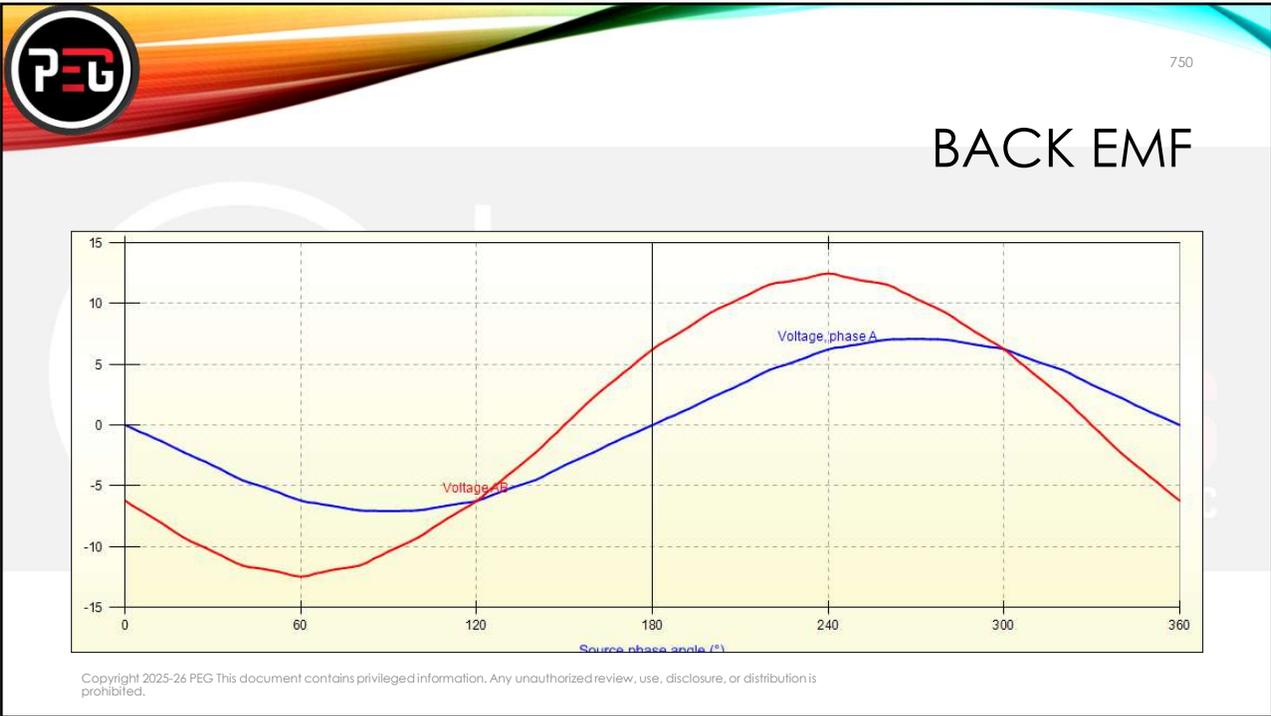
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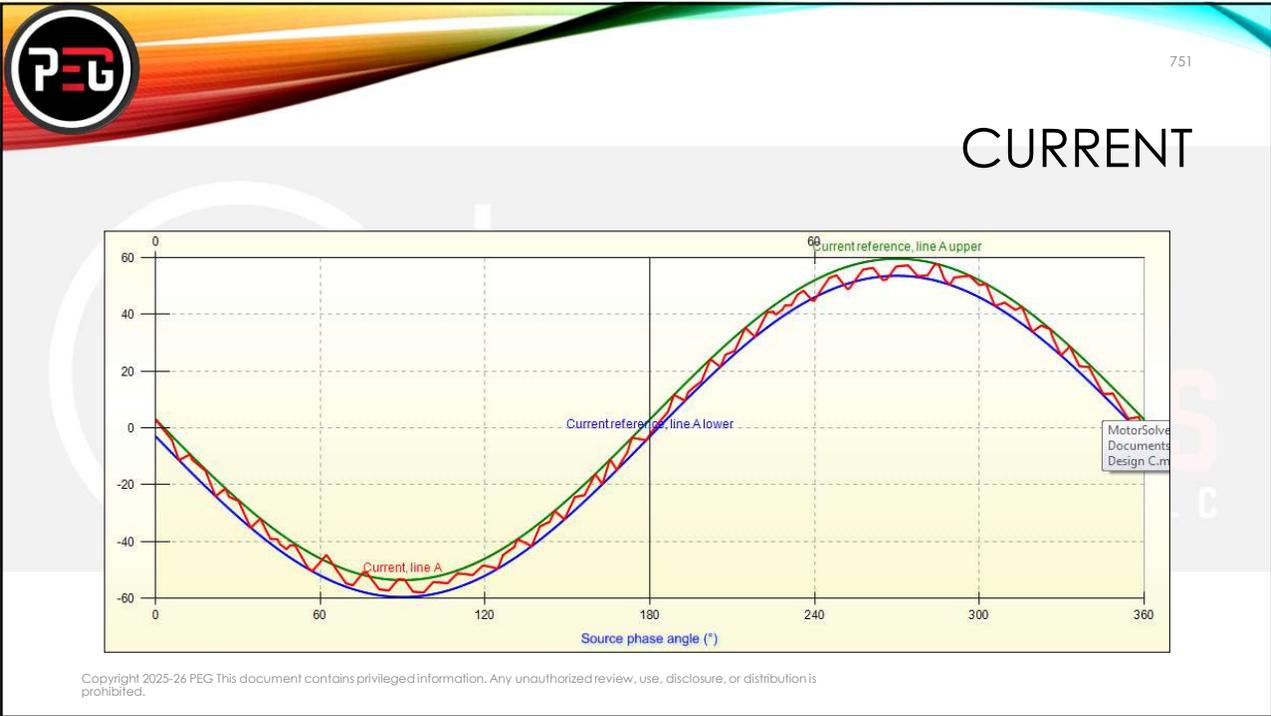
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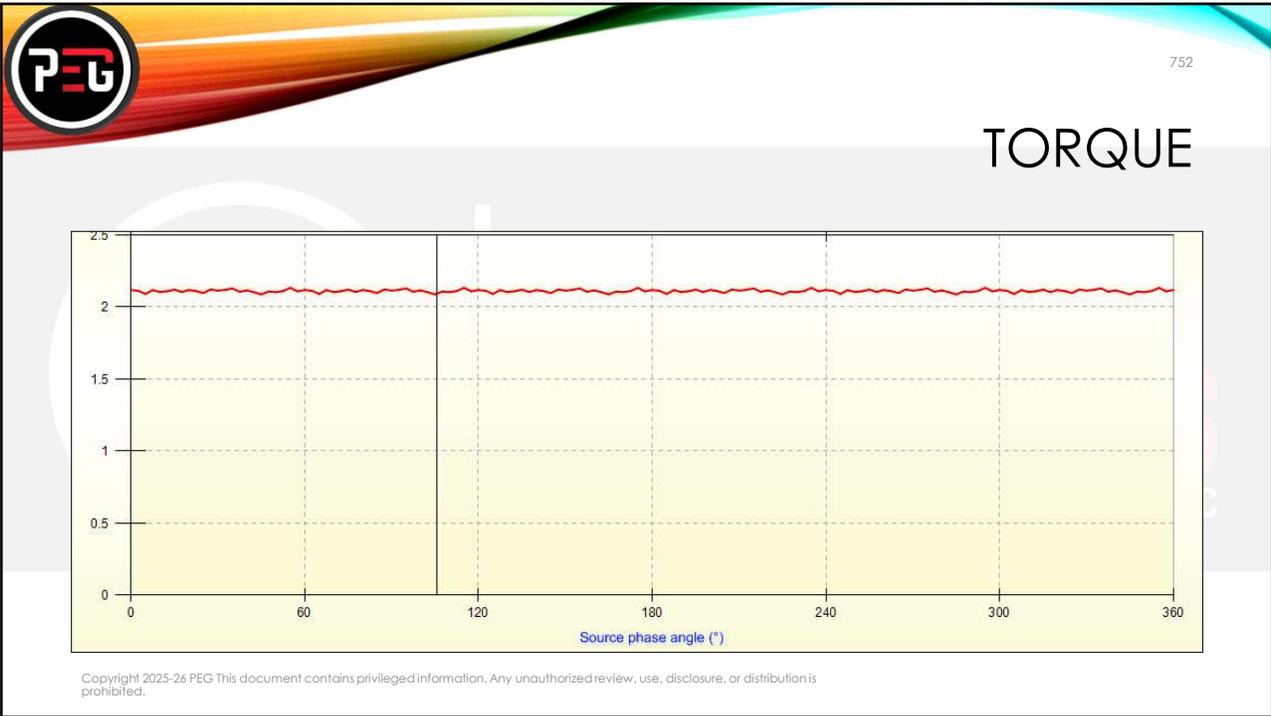
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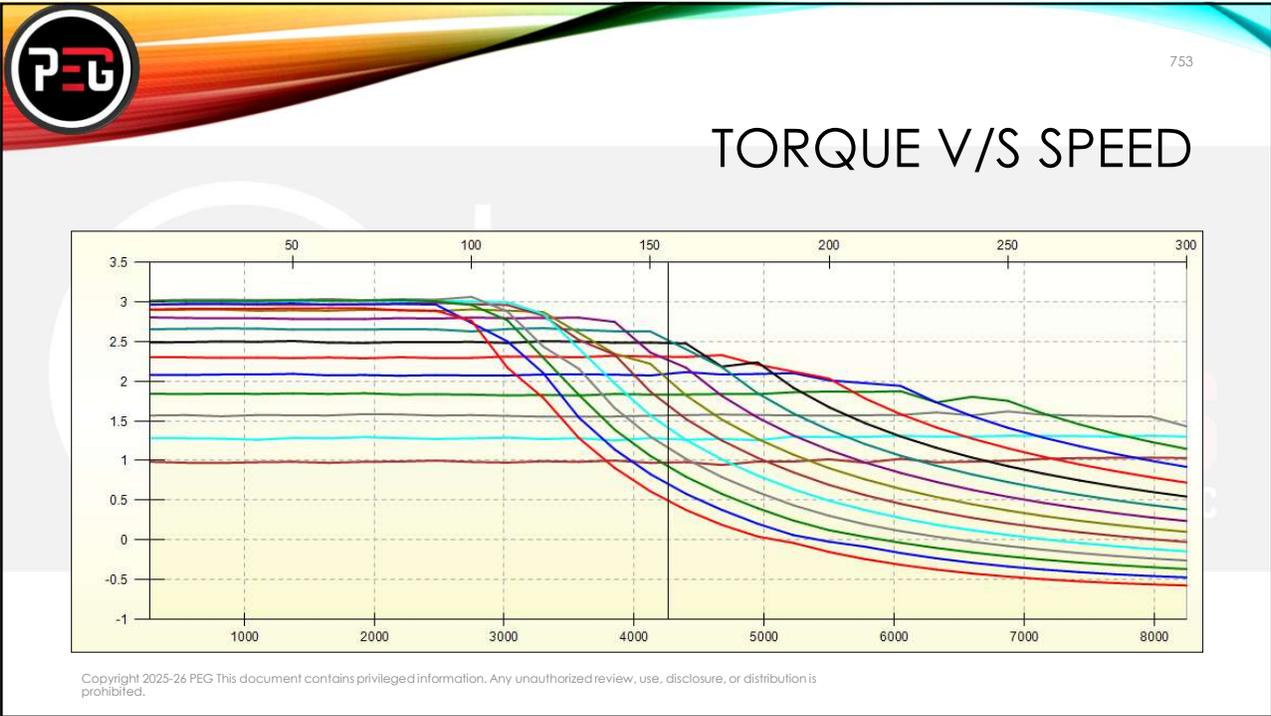
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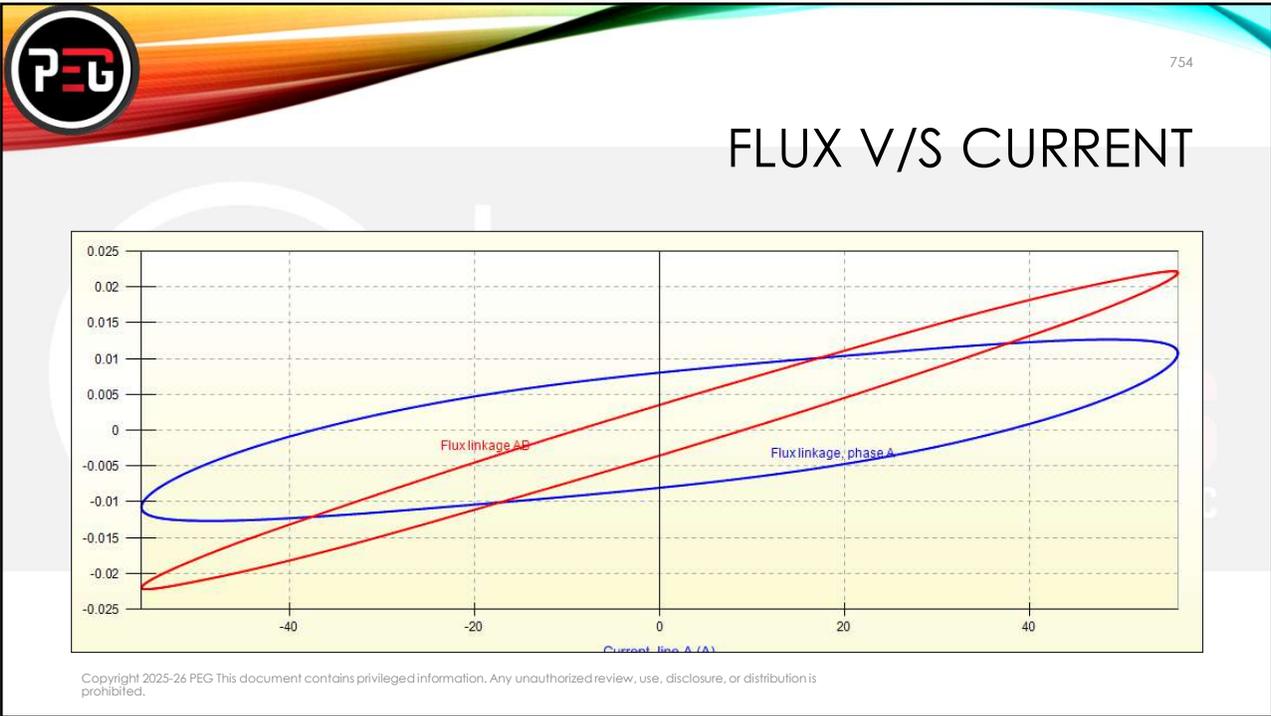
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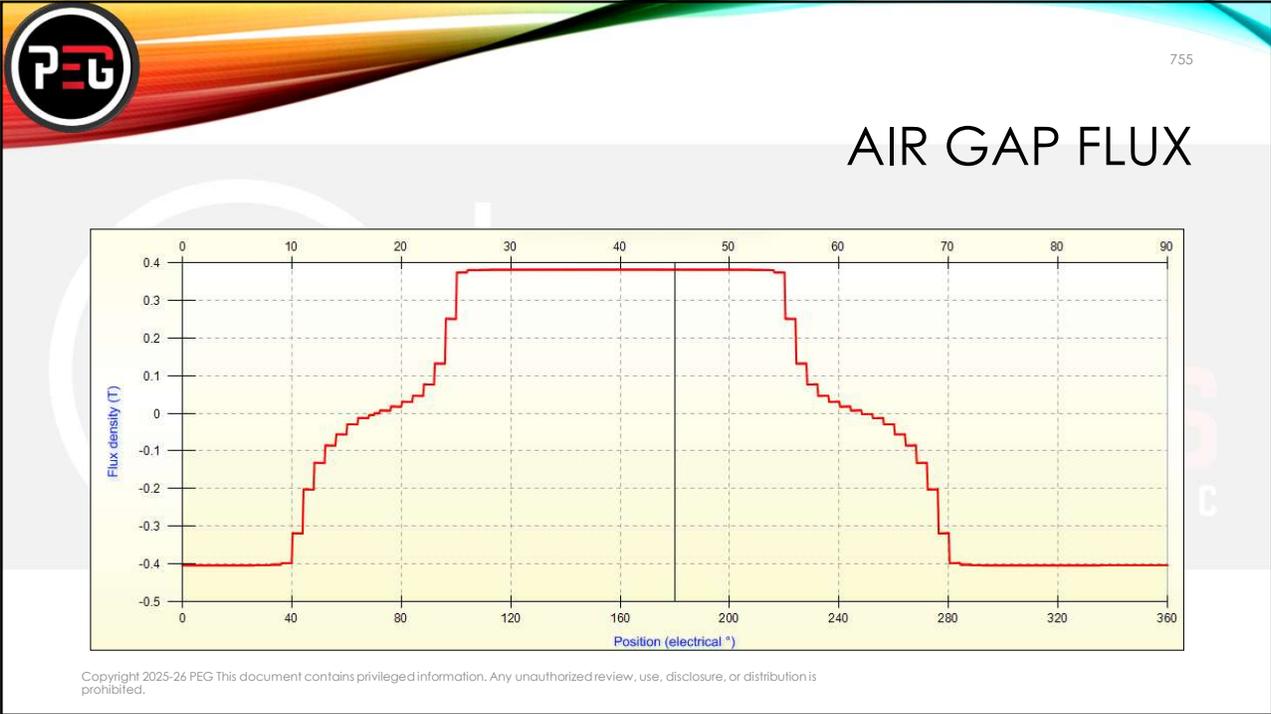
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MOTION ANALYSIS @ 2000RPM

Torque (N·m)	2.71
Input power (kW)	0.681
Output power (kW)	0.568
Efficiency (%)	83.4
RMS voltage (V)	14.1
RMS current (A)	42.4
RMS current density - Winding (A/mm ²)	9.42
Power factor	0.65

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MOTION ANALYSIS @ 2000RPM

Torque per unit volume (N·m/mm ³)	2.36E-05
Airgap stress (N/mm ²)	0.0118
Loss - Total (kW)	0.113
Loss - Winding (kW)	0.107
Loss - Rotor coils (kW)	0
Loss - Stator back iron hysteresis (kW)	0.00134
Loss - Stator back iron eddy current (kW)	0.0003

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MOTION ANALYSIS @ 2000RPM

Loss - Stator teeth hysteresis (kW)	0.00288
Loss - Stator teeth eddy current (kW)	0.000775
Loss - Rotor back iron hysteresis (kW)	0.000308
Loss - Rotor back iron eddy current (kW)	0.000124

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MOTION ANALYSIS @ 4000RPM

Torque (N·m)	2.7
Input power (kW)	1.25
Output power (kW)	1.13
Efficiency (%)	90.2
RMS voltage (V)	27.3
RMS current (A)	42.4
RMS current density - Winding (A/mm ²)	9.42
Power factor	0.618

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MOTION ANALYSIS @ 4000RPM

Torque per unit volume (N·m/mm ³)	2.36E-05
Airgap stress (N/mm ²)	0.0118
Loss - Total (kW)	0.123
Loss - Winding (kW)	0.107
Loss - Rotor coils (kW)	0
Loss - Stator back iron hysteresis (kW)	0.00308
Loss - Stator back iron eddy current (kW)	0.0012

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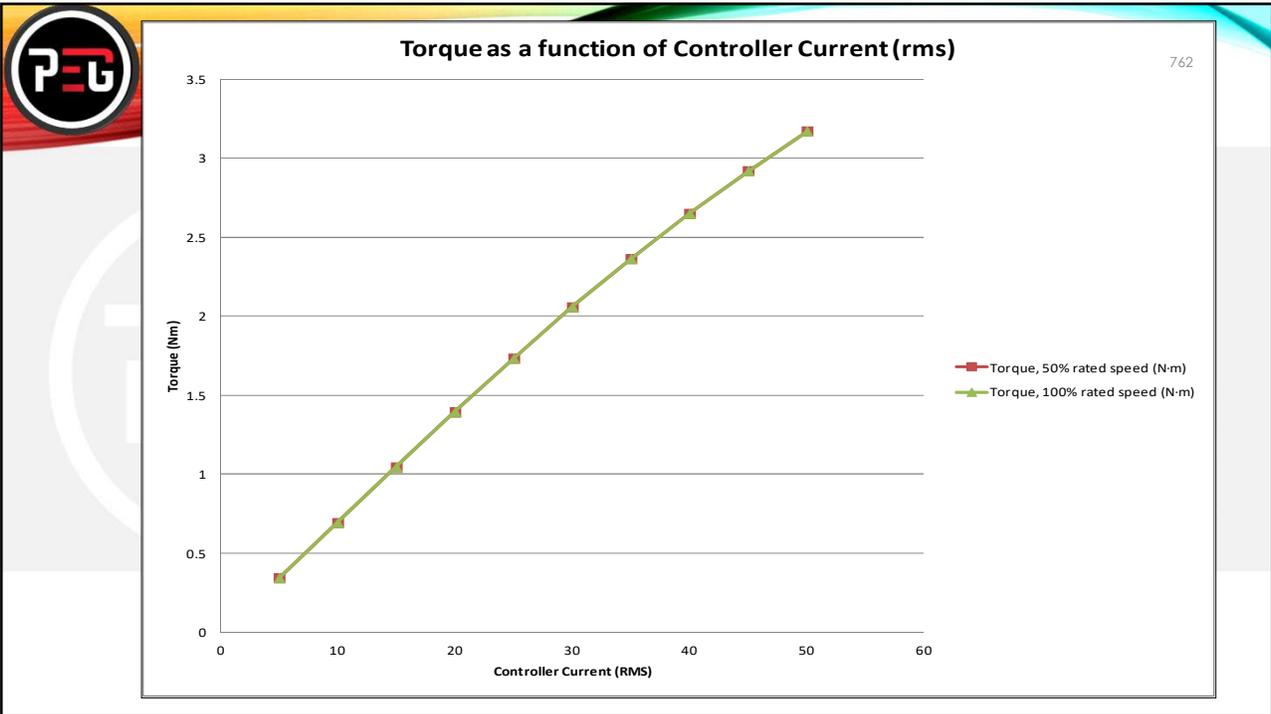
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MOTION ANALYSIS @ 4000RPM

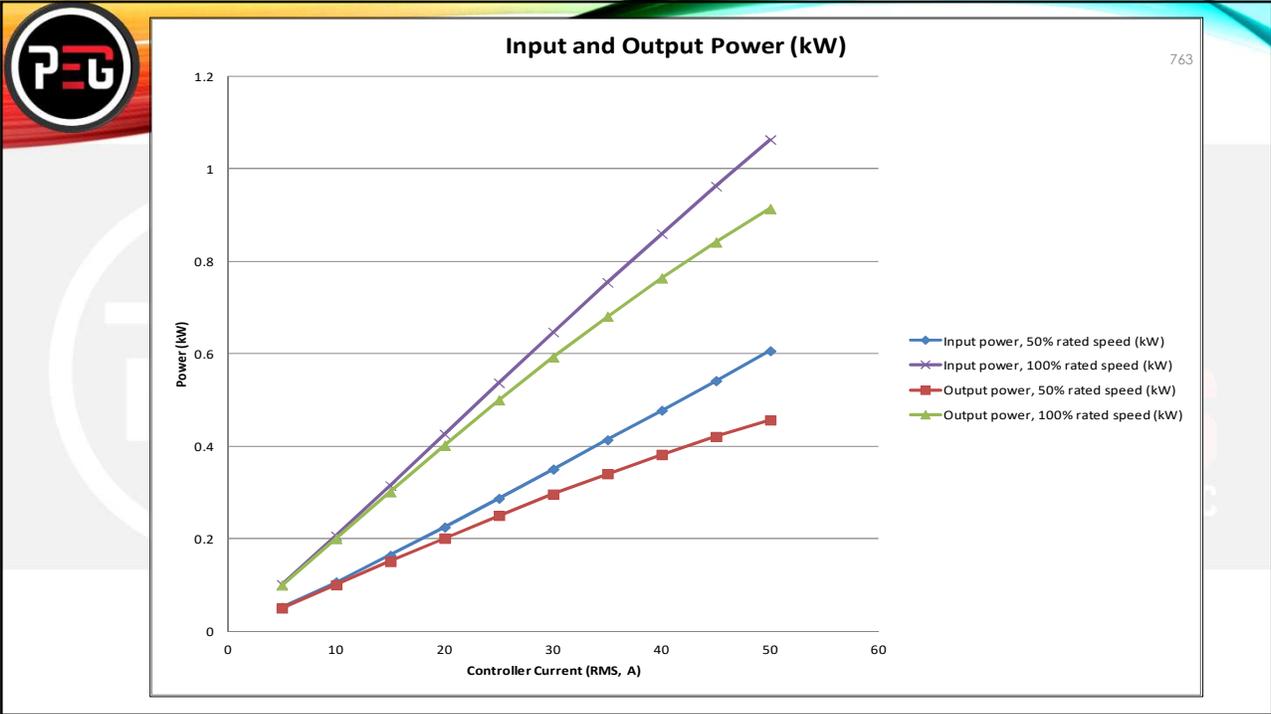
Loss - Stator teeth hysteresis (kW)	0.00661
Loss - Stator teeth eddy current (kW)	0.0031
Loss - Rotor back iron hysteresis (kW)	0.000706
Loss - Rotor back iron eddy current (kW)	0.000494

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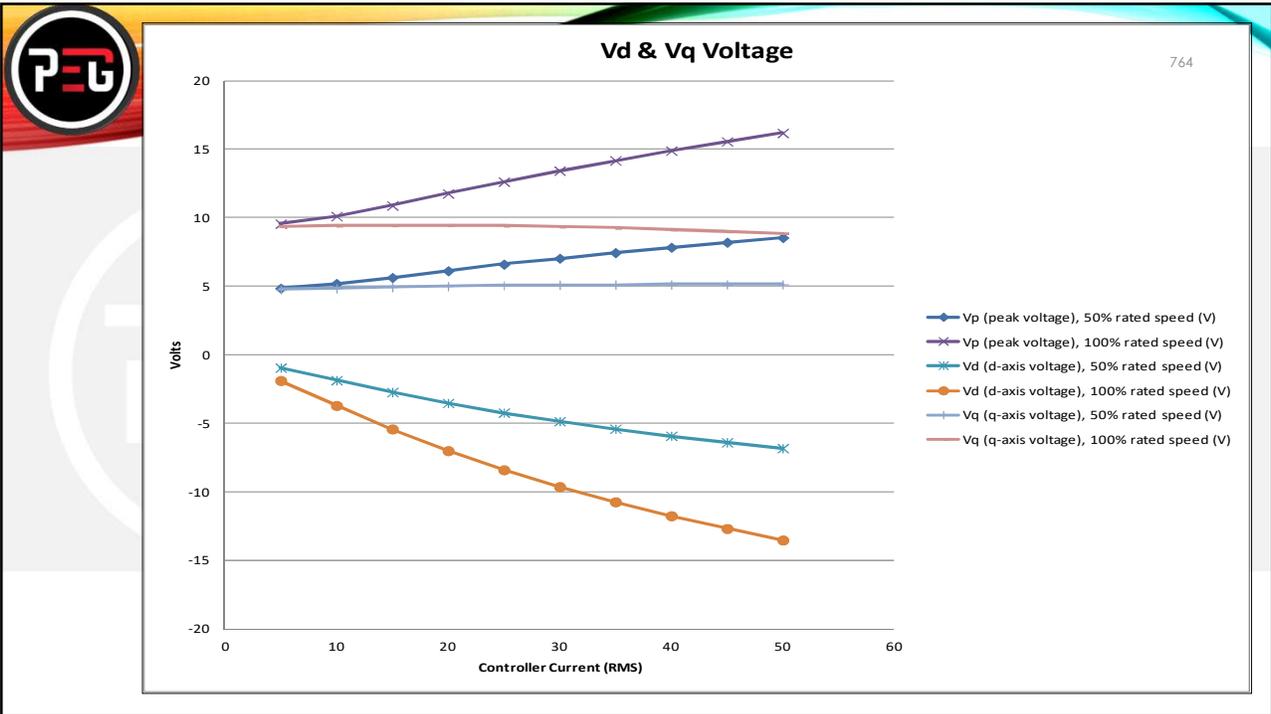
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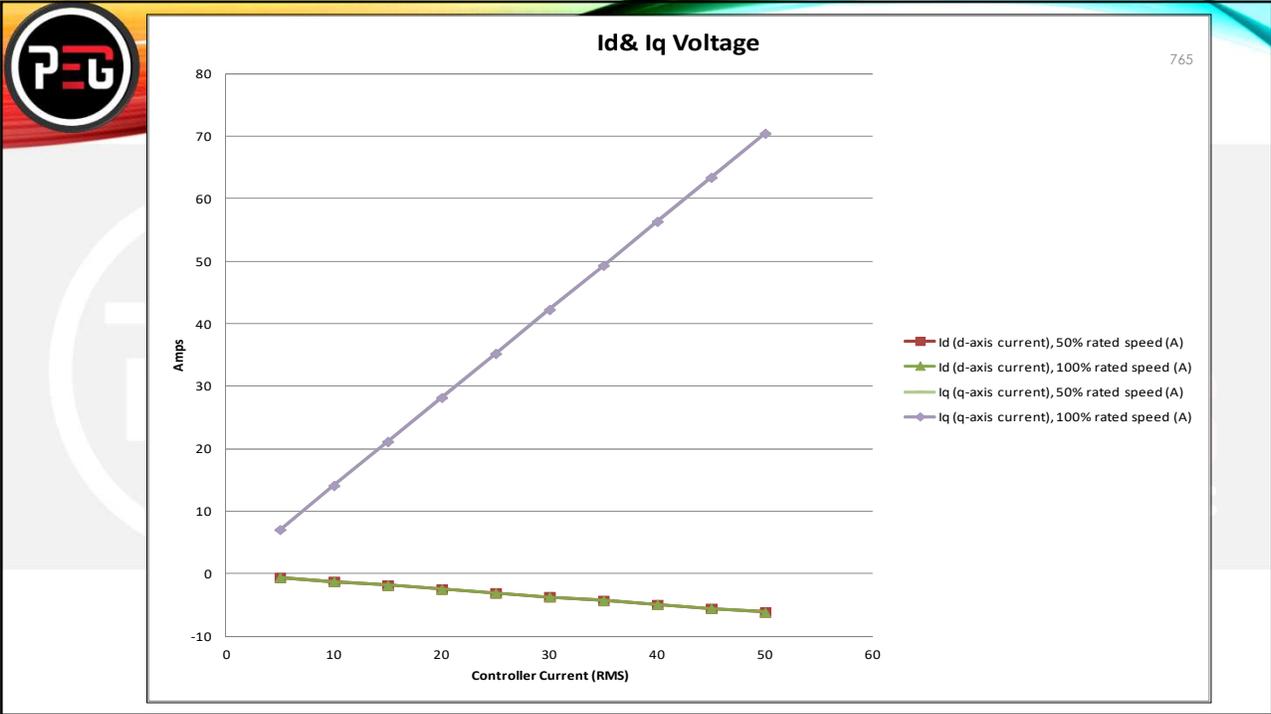
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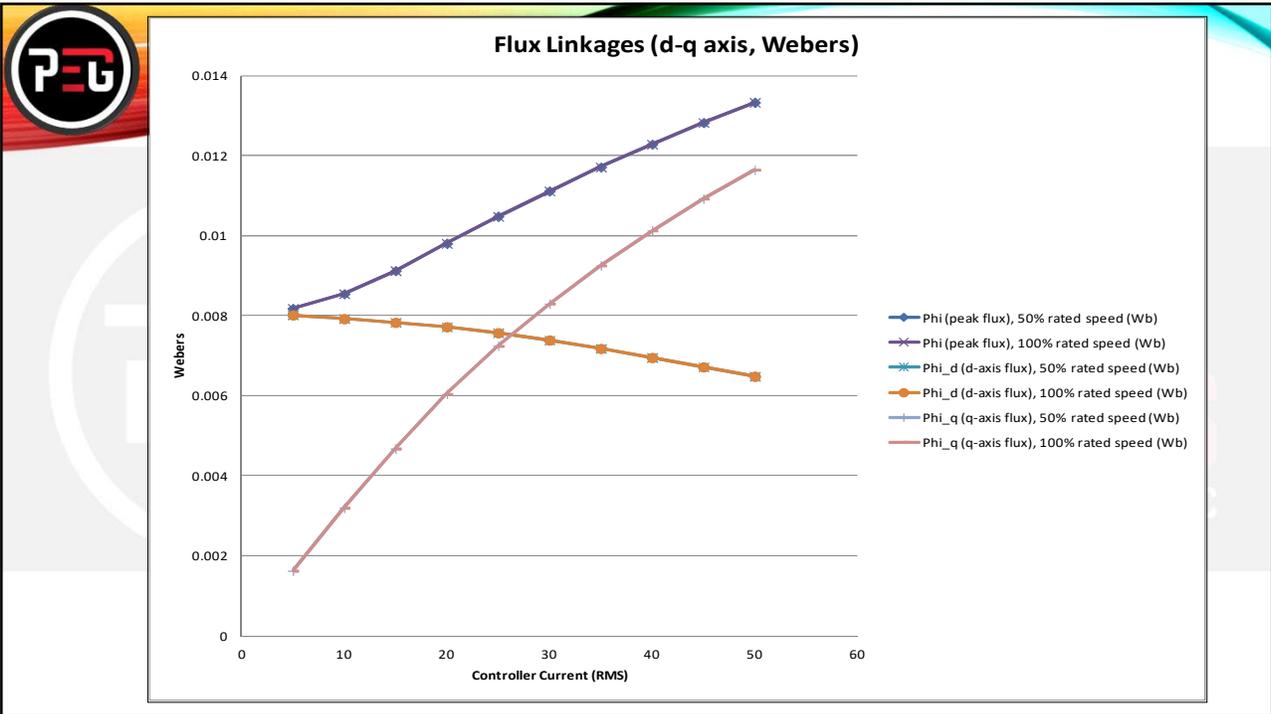
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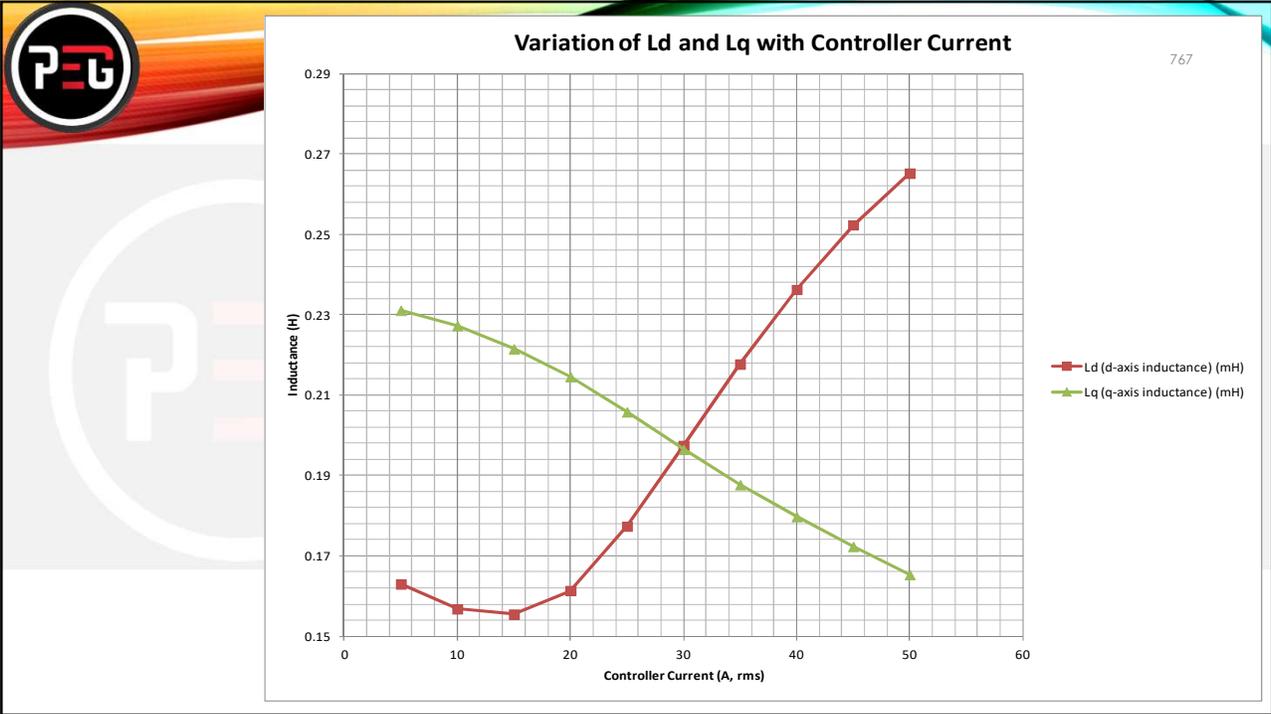
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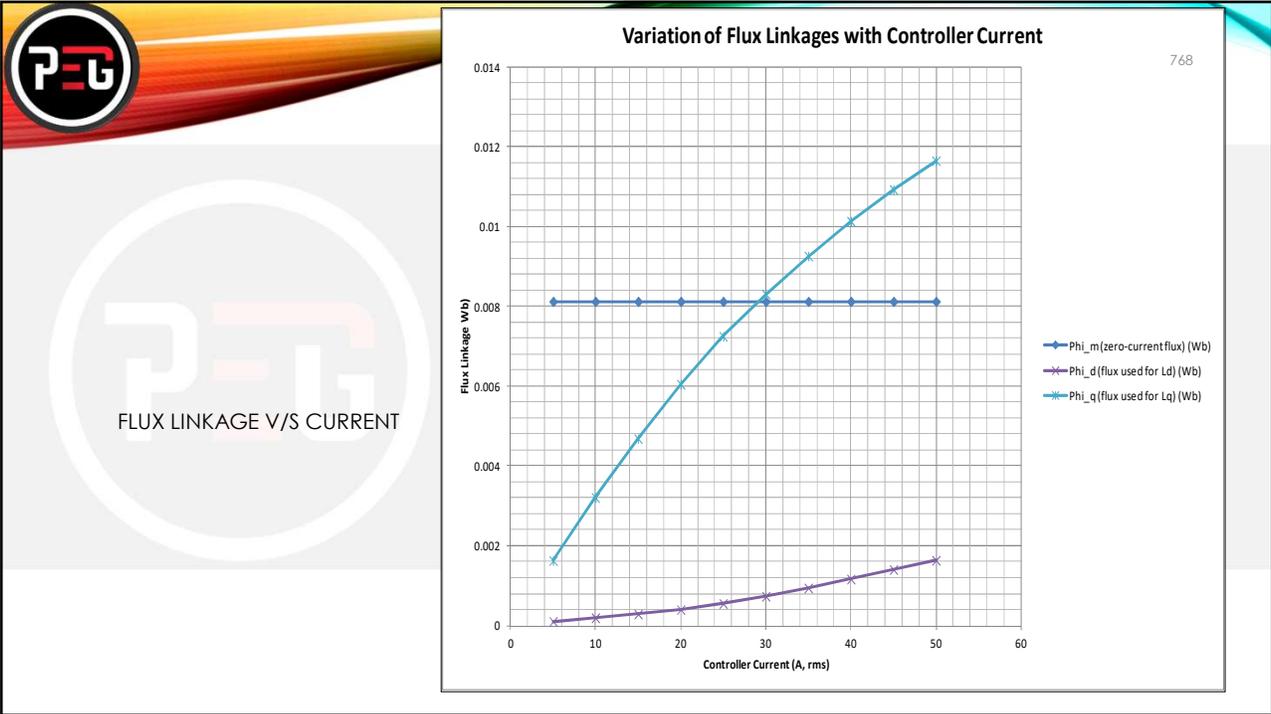
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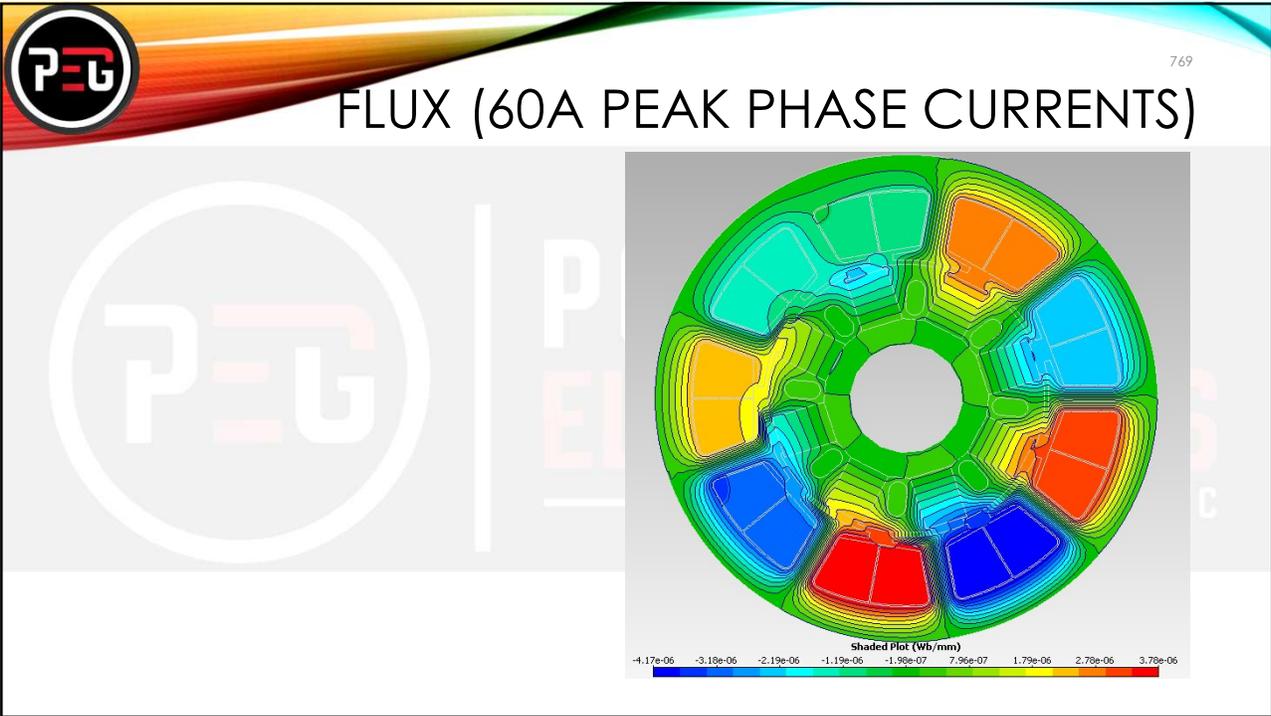
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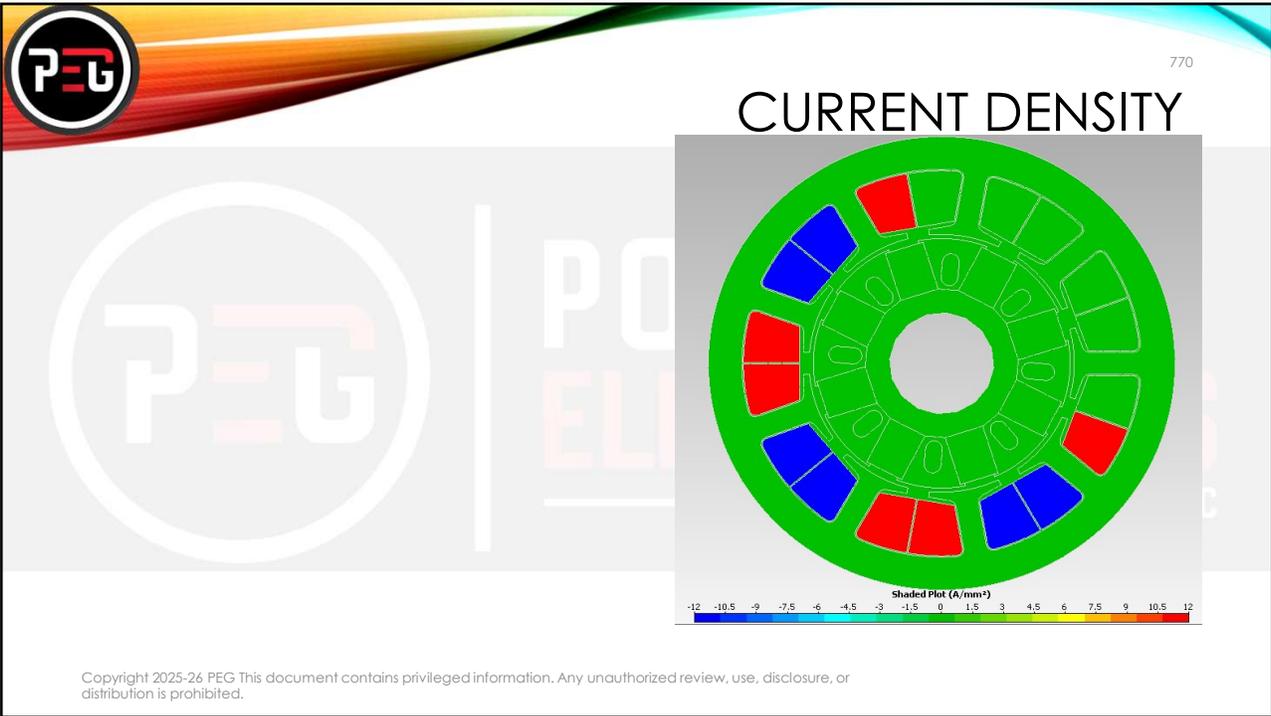
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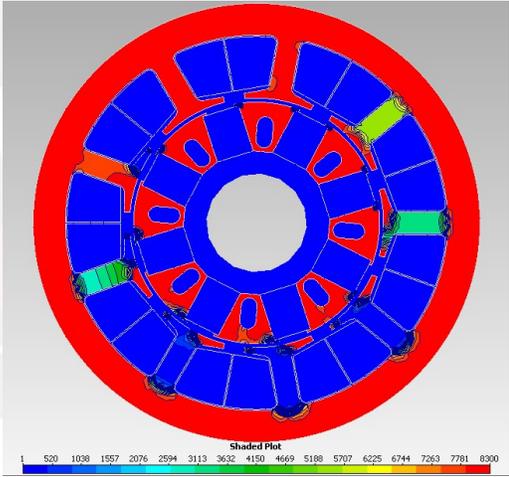
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RELATIVE PERMEABILITY



Shaded Plot

1 520 1038 1557 2076 2594 3113 3632 4150 4669 5188 5707 6225 6744 7263 7781 8300

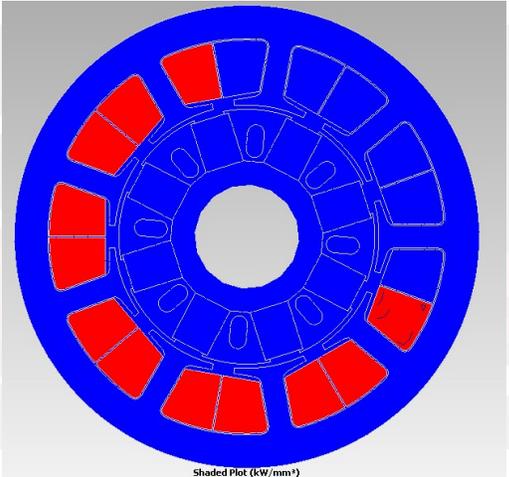
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WINDING LOSS



Shaded Plot (kW/mm²)

0 1.31e-07 2.61e-07 3.92e-07 5.22e-07 6.53e-07 7.83e-07 9.14e-07 1.04e-06

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DEMAGNETIZATION PREDICTION

Shaded Plot

0 0.125 0.25 0.375 0.5 0.625 0.75 0.875 1

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DEMAGNETIZATION PROXIMITY

Shaded Plot (T)

-0.433 -0.368 -0.303 -0.237 -0.172 -0.107 -0.0418 0.0234 0.0866

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FINITE ELEMENT ANALYSIS USING FEMM – PART 13

3-Day Workshop on Motor, Inverter, Hardware, and Firmware Design Techniques for Permanent Magnet Brushless Motors – A System Approach
April 22 – 24, 2025

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WHAT IS FEMM ?

- Finite Element Method Magnetics;
- Developed by David Meeker;
- Software used for Magnetic analysis of Motor Drives;
- Solves problems by interactive shell & Mesh generation;
- Results can be extracted using graphical flux density plots;

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INTRODUCTION

- Solving 2D planar and axis-symmetric problems in low frequency magnetic and electrostatics;
- An interactive shell encompassing graphical pre- and post-processing; a mesh generator; and various solvers;
- Magneto-Static Problem;
- Electro-Static Problem;
- The Heat Flow Problem;
- Current Flow Problem;

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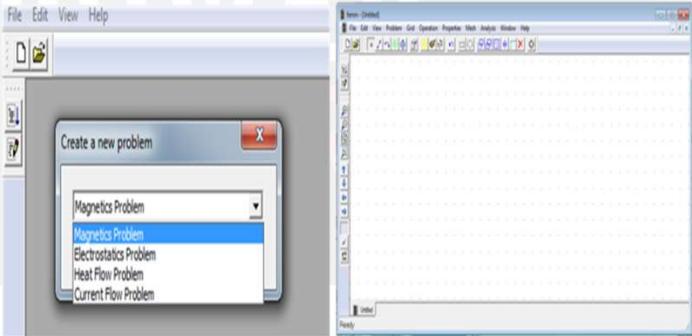
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PROBLEM SELECTION :

- Select the problem type;
- Go for magnetic problem;



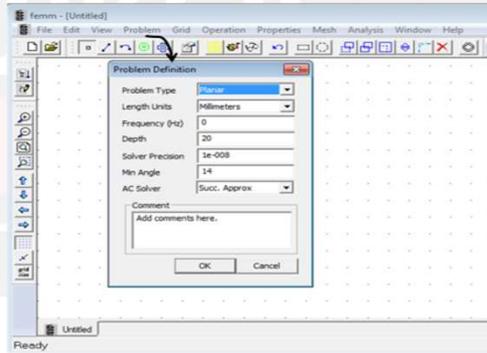
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PROBLEM DEFINITION:

- Defining problem to solve;
- Here stack length and planar model is optimized;

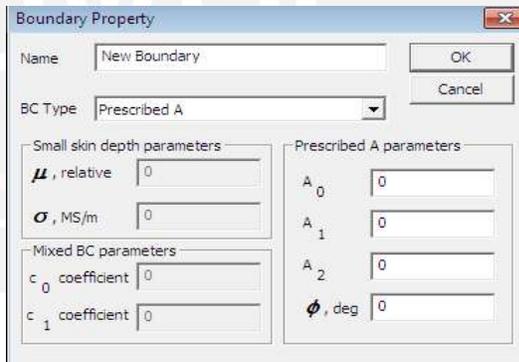


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BOUNDARY PROPERTY:

- Defining the boundary to problem;
- Boundary is defined for obtaining a unique solution;



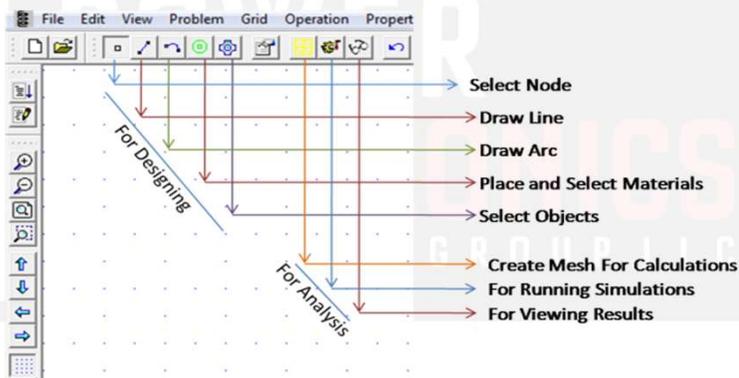
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WORKSPACE TOOLBAR:

- Usage of the toolbar;



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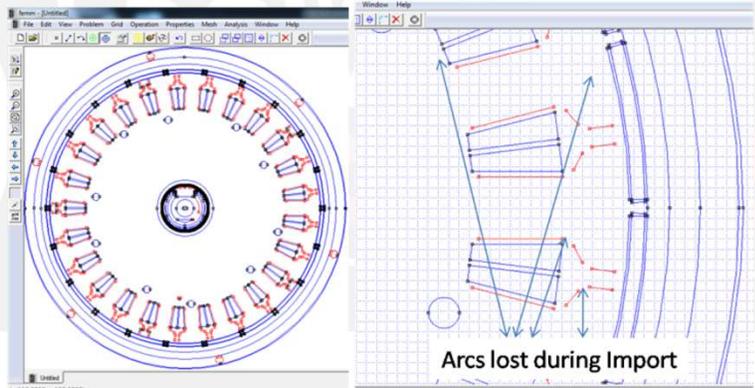
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IMPORTING CAD(DXF):

- Model import and critical things to see at import time;



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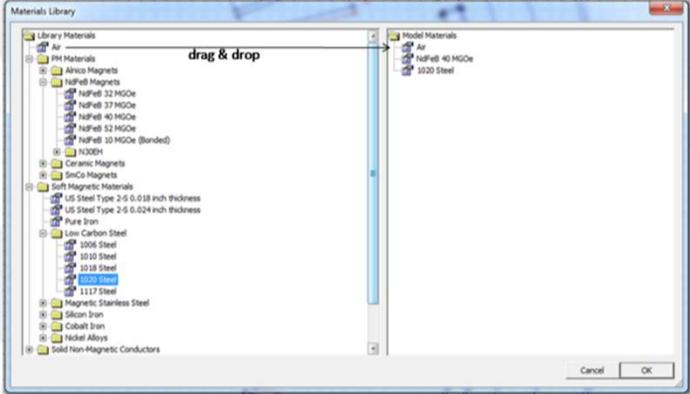
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CONFIGURE MATERIALS

- Material selection for designing;



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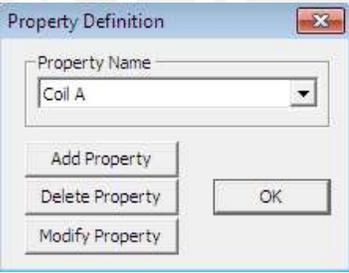
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CIRCUIT ASSIGNMENT:

- Select circuit property from toolbar and define coils and phases;
- Defining the circuit property;



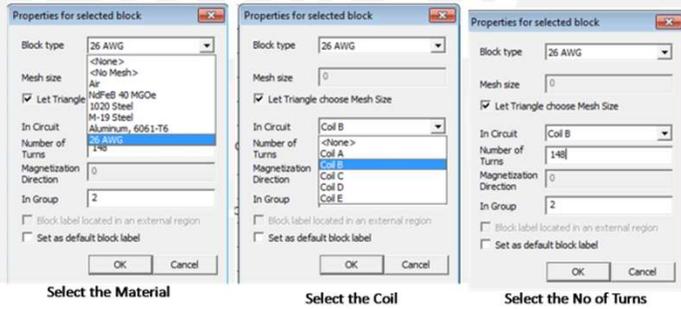
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CIRCUIT ASSIGNMENT:

- Placing of circuit material and type of gauge we use;

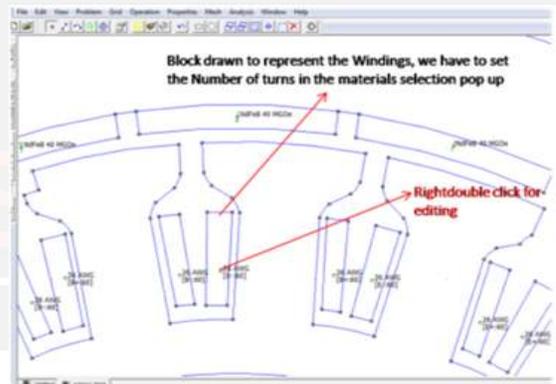


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WINDING INITIALIZE:

- Defining the winding material;

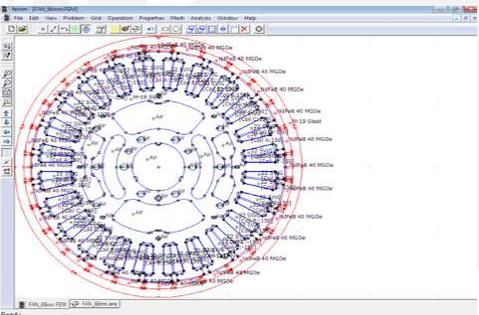
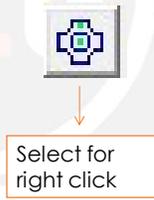


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GROUPING:

- Stationary type under single group;
- Rotating parts under a single group;
- Select & right click over Dxf;

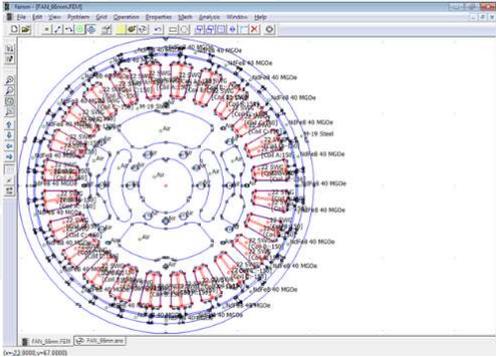
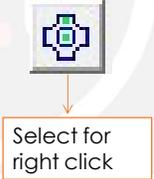


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GROUP FOR RESISTIVE LOSSES

- All the stator windings must be selected under one group;



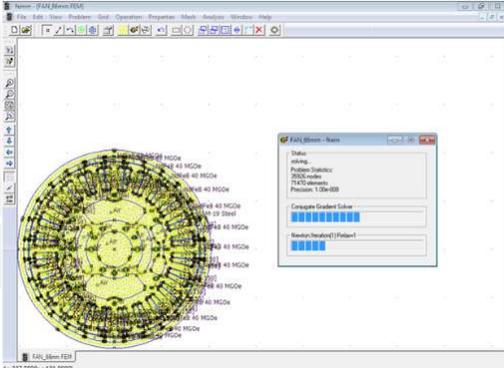
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MESH ANALYSIS:

- It will generate no of nodes through mesh synthesis;





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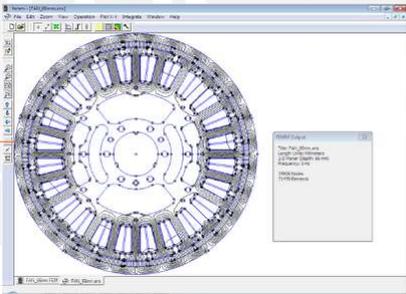
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RESULT WINDOW:

- Result of femm with out flux density(B) plot.
- Effective flux distribution analysis;
- For different Magnetic angle;

Flux distribution can be made on stator reference Frame.



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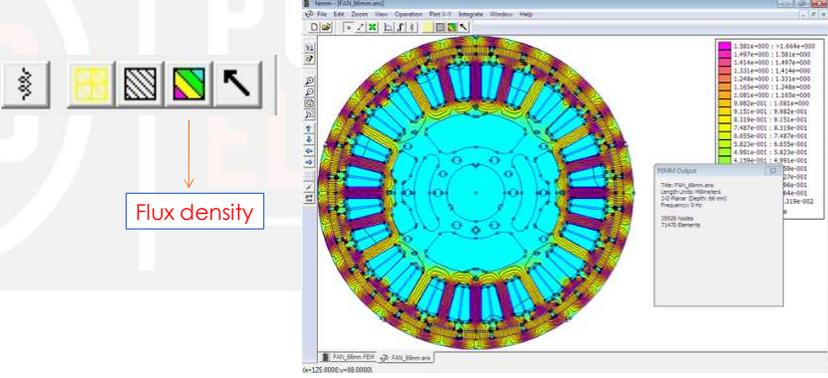
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GRAPHICAL FLUX DENSITY PLOTS;

- With flux density plot with FEMM output window ;



Flux density

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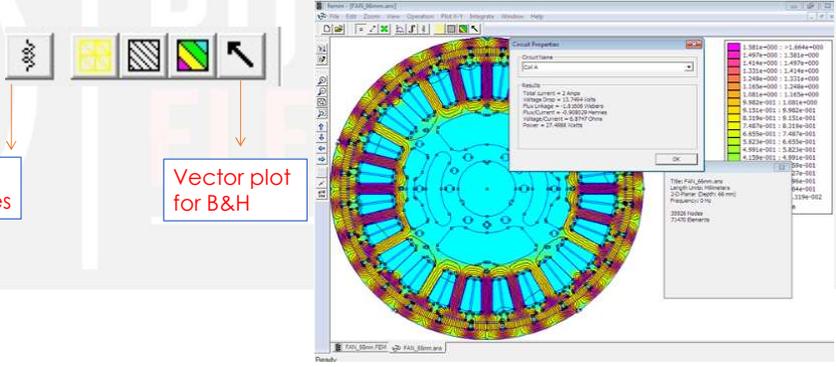
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RESISTANCE AND FLUX CALCULATION:

- Resistance calculated from the toolbar by selecting the tool;



Circuit properties

Vector plot for B&H

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WHY MATLAB INTEGRATION:

- FEMM has built in functions and Macros that can be used in MATLAB for Data analysis & Data extraction;
- Simulation can be automated using MATLAB;
- To use this macros, we have to add the FEMM folder path to the MATLAB execution path;
- Once the path has been added, we can access the FEMM functions through MATLAB;

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MATLAB PROCESS

- The basic Idea is to get the Torque and Flux values at different currents and different angles;
- If we do it without MATLAB every time we have to change currents manually, Run the simulations and record the data;
- But if we automate the process through MATLAB, then every thing can be done just by running the MATLAB code;
- All the observations can be easily recorded in the text files;
- These files can then be used for the analysis of the data and the results;

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FEM FILE LOCATION:

- Copy .FEM file to the location here & create the renamed folder here (C.Drive/Users/My PC/mydocuments/Matlab/);
- Save Matlab command, .m file to above location;
- Open MATLAB run .m file;
- Add FEMM matlab code to execution path;
- Input, Phase current, speed values;

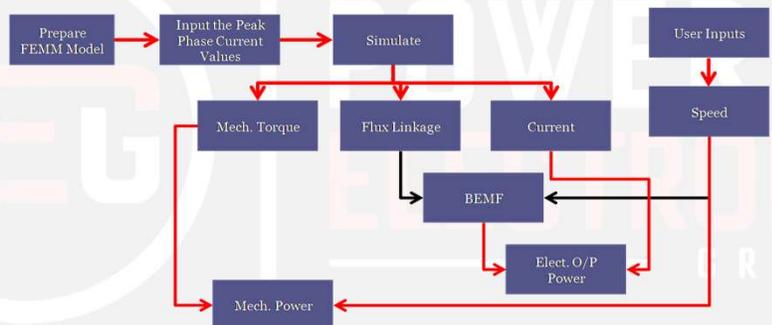
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MATLAB DATA EXECUTION PROCESS



```

    graph TD
      A[Prepare FEMM Model] --> B[Input the Peak Phase Current Values]
      B --> C[Simulate]
      C --> D[Mech. Torque]
      C --> E[Flux Linkage]
      C --> F[Current]
      G[User Inputs] --> H[Speed]
      H --> I[BEMF]
      E --> I
      I --> J[Elect. O/P Power]
      J --> K[Mech. Power]
      D --> K
  
```

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MAT LAB INTEGRATION:

- “pathtool” command is used in command window;

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SETTING MATLAB EXECUTION PATH;

- Select femm folder from C-drive to path and save it;

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MATLAB SCRIPT:

- “Openfemm” command is used to call femm from Mat lab;
- Individual function commands are used to call each function for accessing femm specific tasks;
- All the instructions are executed sequentially;
- Results are extracted in same pattern and stored in .txt files;

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MAT LAB SCRIPT EXAMPLES:

- open document ('specify the FEMM file name here');
- mi_modifycircprop ('COIL X', 1, Phase current value);
- mi_analyze(1);
- mi_loadsolution;
- mo_showdensityplot();
- mo_groupselectblock(1);
- Torque = mo_blockintegral();

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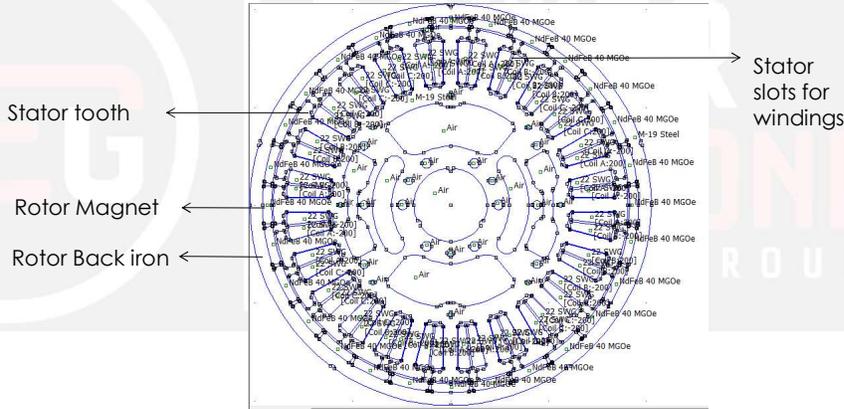
SIMULATION PROCESS;

- Create the directory in Matalb folder path;
- Extracted results from Matalb are stored in .txt files;
- Flux information for different phase current;
- Torque at different magnetic angle;
- Torque versus phase current relationship;
- Magnetic saturation;

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DXF MODEL IN FEMM (22MM STACK LENGTH)



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MECHANICAL DIMENSIONS

Sl.No	Parameters	Dimensions
1	Inner diameter	366-mm
2	Outer diameter	410-mm
3	Air Gap	2-mm
4	Rotor Location	Exterior
5	Rotor Type	SM with radial Magnet
6	Number of Poles	28
7	Number of slots	24
8	Magnet Thickness	9-mm
9	Back iron depth	31.2-mm
10	Inner Diameter	180-mm
11	Outer Diameter	362-mm

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TORQUE AND FLUX DENSITY FOR 22MM:

- Mean torque generated is 90 Nm for 5A phase current.

Sl.NO	Phase current in Amperes	Torque in N-M Average	Flux Density in Tesla	Resistive Losses in Watts
01	1	16.18	1.48T	4.583
02	2	32.95	1.48 – 1.50T	18.33
03	3	48.86	1.58T	41.24
04	4	68.11	1.60 – 1.65T	73.3
05	5	89.3	1.65T	114.57
06	8	133.99	1.8T	293.32
07	10	161.98	1.84T	458.31

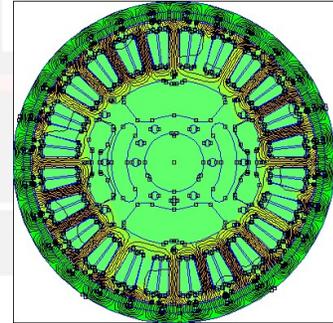
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SIMULATION EXAMPLES(22MM):

- Graphical flux density for 5A phase current;
- Flux density is 1.65T;
- No magnetic saturation is observed;



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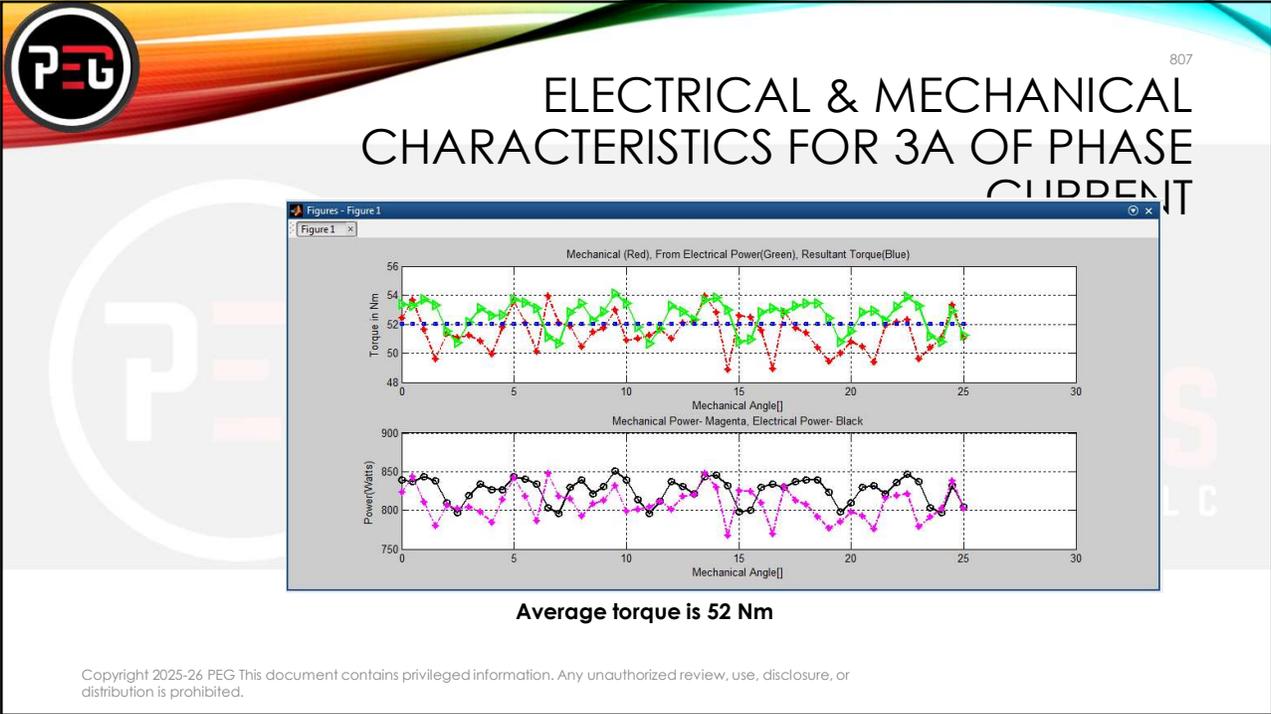
COMPARISON RESULTS:

- Comparison of torque & phase current;
- Phase current & Resistive losses;

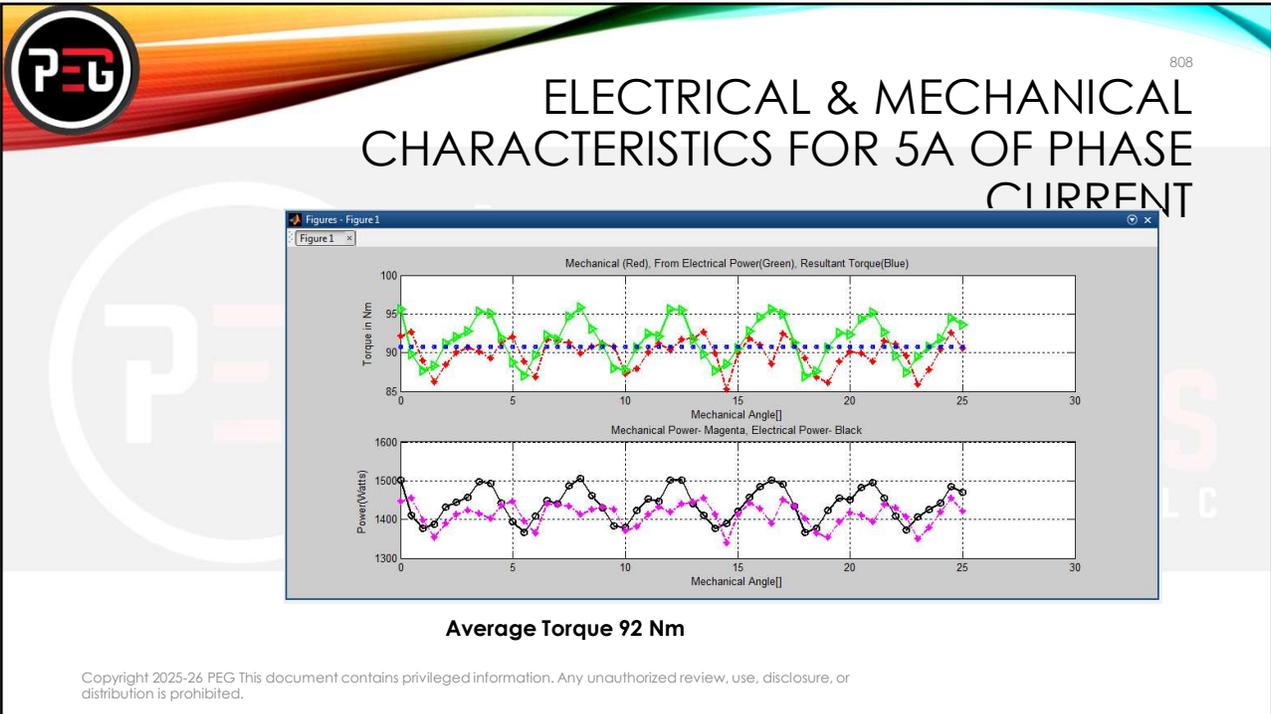
FEMM Simulation Results with Matlab							
Sl_No/Phase current	Torque (N-m)				Resistive losses(Watts)		
	12mm	22mm	39mm	66mm	12mm	22mm	39mm
1 1 Amp	9.65	16.18	26.81	32.87	2.49	4.583	8.124
2 2 Amp	18.43	32.95	58.41	71.91	9.99	18.33	32.49
3 3 Amp	28.26	48.86	89.76	112.61	22.49	41.24	73.121
4 4 Amp	37.88	68.11	120.74	154.45	39.99	73.3	129.92
5 5 Amp	49.38	89.3	151.22	191.29	62.49	114.57	203.11
6 8 Amp	73.6	133.19	235.45	305.8	159.9	293.32	519.97
7 10 Amp	88.4	161.98	282.78	375.84	249.99	458.31	812.46

Note: Motor speed is set to 200-RPM while Integrating with FEMM & Matlab.
 Rotor back iron: M-19 steel
 Winding material: 22 SWG
 Magnets: NdFeB40
 Stator core: M-19 steel

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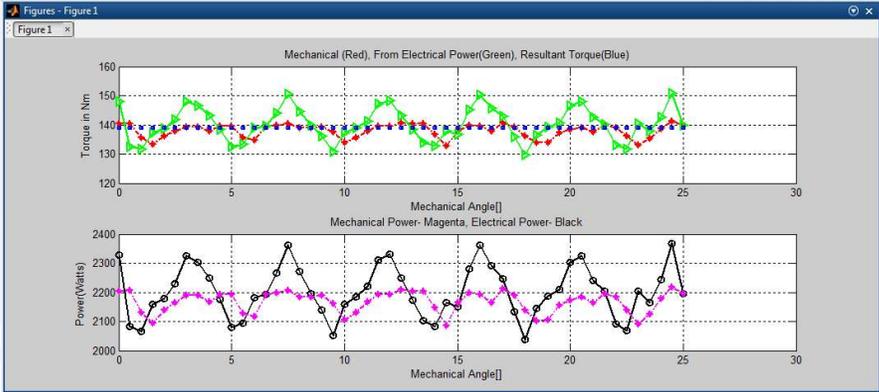


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ELECTRICAL & MECHANICAL CHARACTERISTICS FOR 8A OF PHASE CURRENT



Average torque 140 Nm

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