ESTIMATING MOTOR PARAMETERS

Part 4

AGENDA

- Assumptions;
- Modeling of PMSM motor;
- Estimate actual motor parameters;
- Example;

ASSUMPTIONS

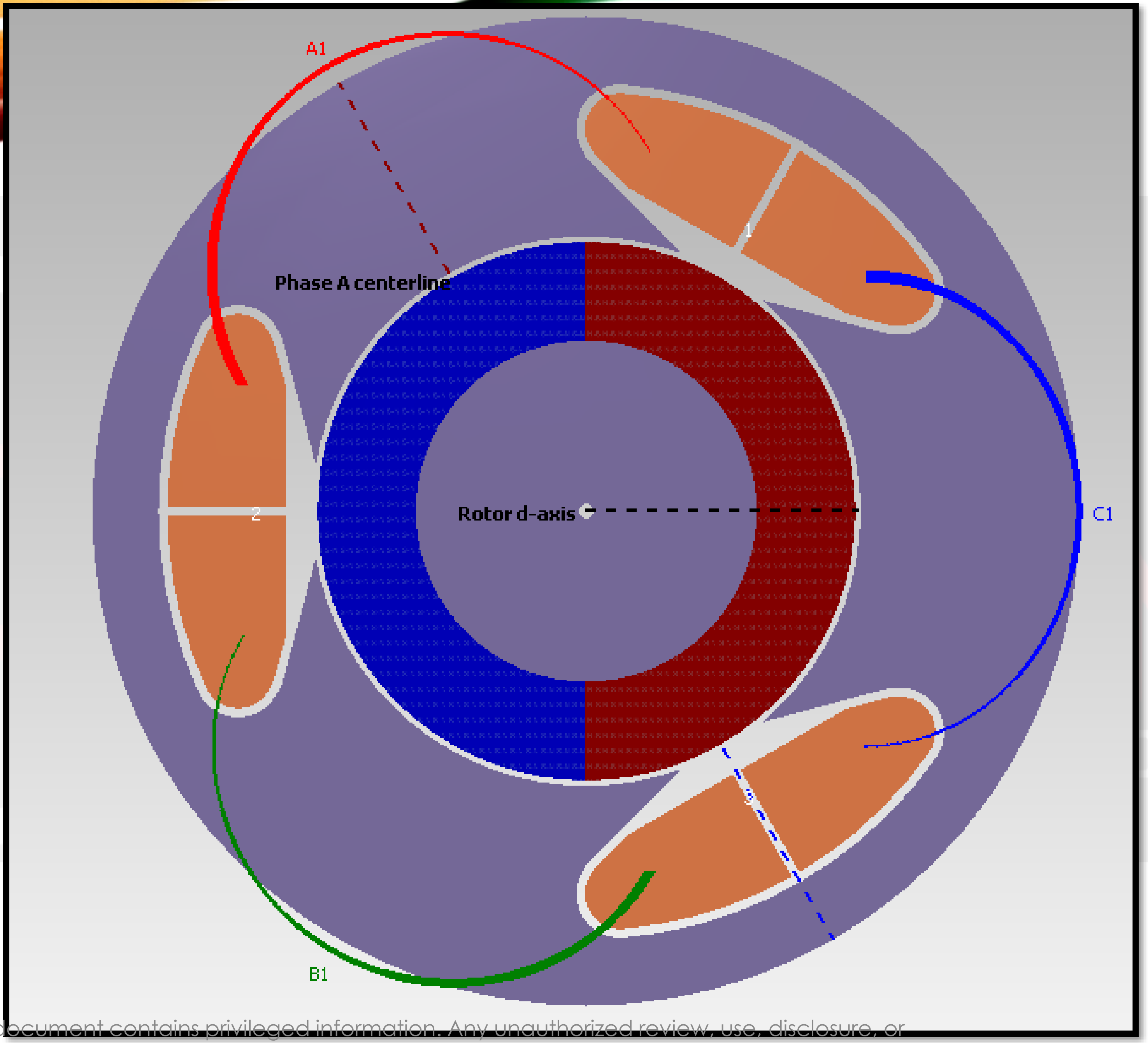
- Stator windings produce sinusoidal MMF;
- Space harmonics in the air-gaps are neglected;
- Air-gap reluctance have a constant & sinusoidally varying component;

ASSUMPTIONS

- Balanced 3-phase supply voltage;
- Eddy currents & Hysteresis effects neglected;

MODELING OF PMSM MOTOR

- Stator reference axis for phase-A is chosen in the direction of maximum MMF when a positive phase A current is maximum;
- Stator self inductances are maximum when rotor q-axis is aligned with the particular phase;
- Mutual inductances are maximum when rotor q-axis is midway between two phases;


A1
Phase A centerline
Rotor d-axis
C1
B1

MODELING OF PMSM MOTOR

Self Inductance — Leakage Inductance — Magnet Interaction

$$L_{aa} = L_{s0} + L_{s1} + L_x \cos(2\theta)$$
$$L_{bb} = L_{s0} + L_{s1} + L_x \cos(2\theta + 120)$$
$$L_{cc} = L_{s0} + L_{s1} + L_x \cos(2\theta - 120)$$
$$L_{ab} = (-1/2)L_{s0} + L_x \cos(2\theta - 120)$$
$$L_{bc} = (-1/2)L_{s0} + L_x \cos(2\theta)$$
$$L_{ca} = (-1/2)L_{s0} + L_x \cos(2\theta + 120)$$

2θ is the terms introduced due to saliency

When q-axis is aligned with the particular phase, self-inductance is maximum.

When q-axis is midway between phases, mutual-inductance is maximum.

MODELING OF PMSM MOTOR

$$V_a = R_s I_a + p\lambda_a$$
$$V_b = R_s I_b + p\lambda_b$$
$$V_c = R_s I_c + p\lambda_c$$

MODELING OF PMSM MOTOR

$$\lambda_a = L_{aa} I_a + L_{ab} I_b + L_{ac} I_c + \lambda_{ma}$$

$$\lambda_b = L_{ba} I_a + L_{bb} I_b + L_{bc} I_c + \lambda_{mb}$$

$$\lambda_c = L_{ca} I_a + L_{cb} I_b + L_{cc} I_c + \lambda_{mc}$$

MODELING OF PMSM MOTOR

$$\lambda_{ma} = \lambda_m \cos(\theta)$$
$$\lambda_{mb} = \lambda_m \cos(\theta - 120)$$
$$\lambda_{mc} = \lambda_m \cos(\theta + 120)$$

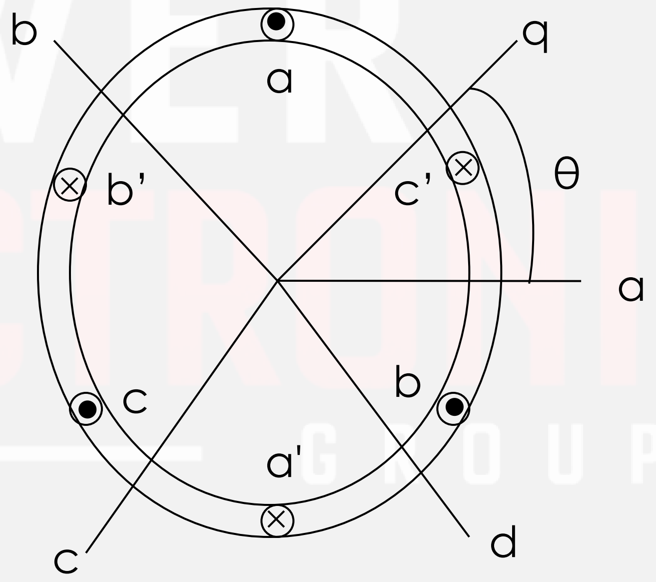
MODELING OF PMSM MOTOR

Park's transformation

$$\begin{bmatrix} S_q \\ S_d \\ S_0 \end{bmatrix} = (2/3)\begin{bmatrix} \cos(\theta) & \cos(\theta-120) & \cos(\theta+120) \\ \sin(\theta) & \sin(\theta-120) & \sin(\theta+120) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} . \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix}$$

Anti-Park's transformation

$$\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos(\theta-120) & \sin(\theta-120) & 1 \\ \cos(\theta+120) & \sin(\theta+120) & 1 \end{bmatrix} . \begin{bmatrix} S_q \\ S_d \\ S_0 \end{bmatrix}$$



Beware of θ

MODELING OF PMSM MOTOR

$$V_q = R_s I_q + p\lambda_q + \omega\lambda_d$$

$$V_d = R_s I_d + p\lambda_d - \omega\lambda_q$$

Why this is –ve?

MODELING OF PMSM MOTOR

$$\lambda_q = L_q I_q$$

$$\lambda_d = L_d I_d + \lambda_m$$

Synchronous inductances are effective inductances seen by phase winding during balanced operation.

MODELING OF PMSM MOTOR

$$L_q = (3/2)(L_{s0} + L_x) + L_{s1}$$

$$L_d = (3/2)(L_{s0} - L_x) + L_{s1}$$

- L_{s0}: Average Value
- L_x: Position Dependent Component
- L_{s1}: Leakage Inductance

MODELING OF PMSM MOTOR

$$V_q = (R_s + L_q p) I_q + \omega L_d I_d + \omega \lambda_m$$

$$V_d = (R_s + L_d p) I_d - \omega L_q I_q$$

MODELING OF PMSM MOTOR

- Synchronous inductances are effective inductances under balanced conditions;

$$P_i = (3/2)\{V_q I_q + V_d I_d\}$$

$$P_o = (3/2)\{\omega\lambda_d I_q - \omega\lambda_q I_d\}$$

$$T = \boxed{(3/2).(P/2)\{\lambda_m I_q} + \boxed{(L_d - L_q) I_d I_q\}}$$

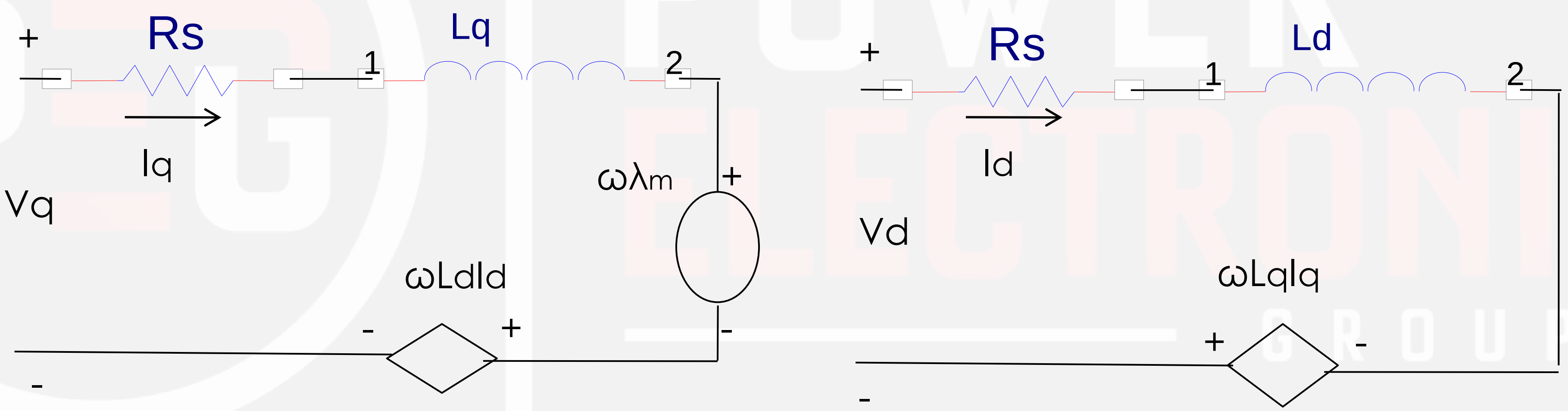
Mutual reaction Torque

Reluctance Torque

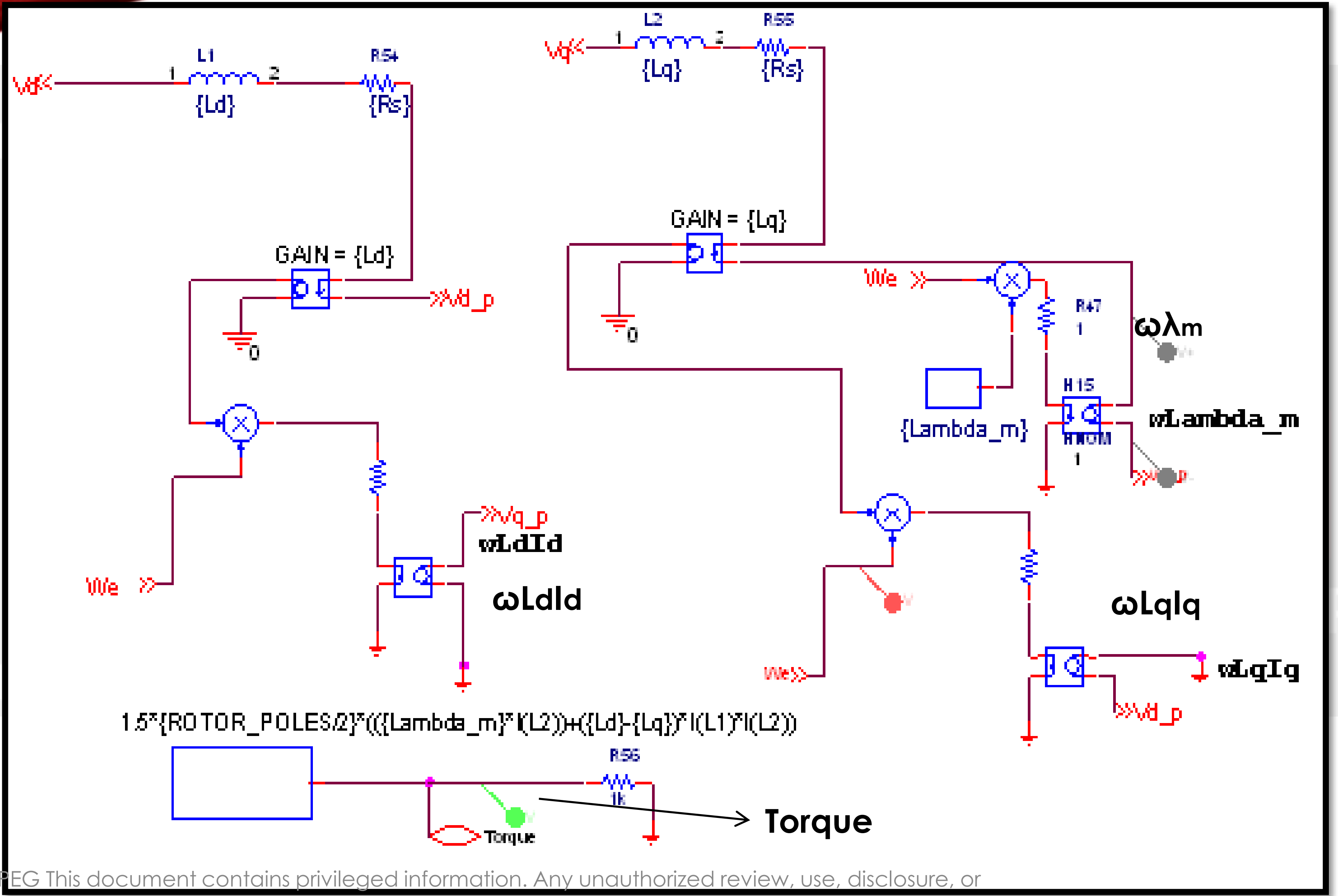
Lq>Ld, Hence Id must be –ve to produce torque

MODELING OF PMSM MOTOR

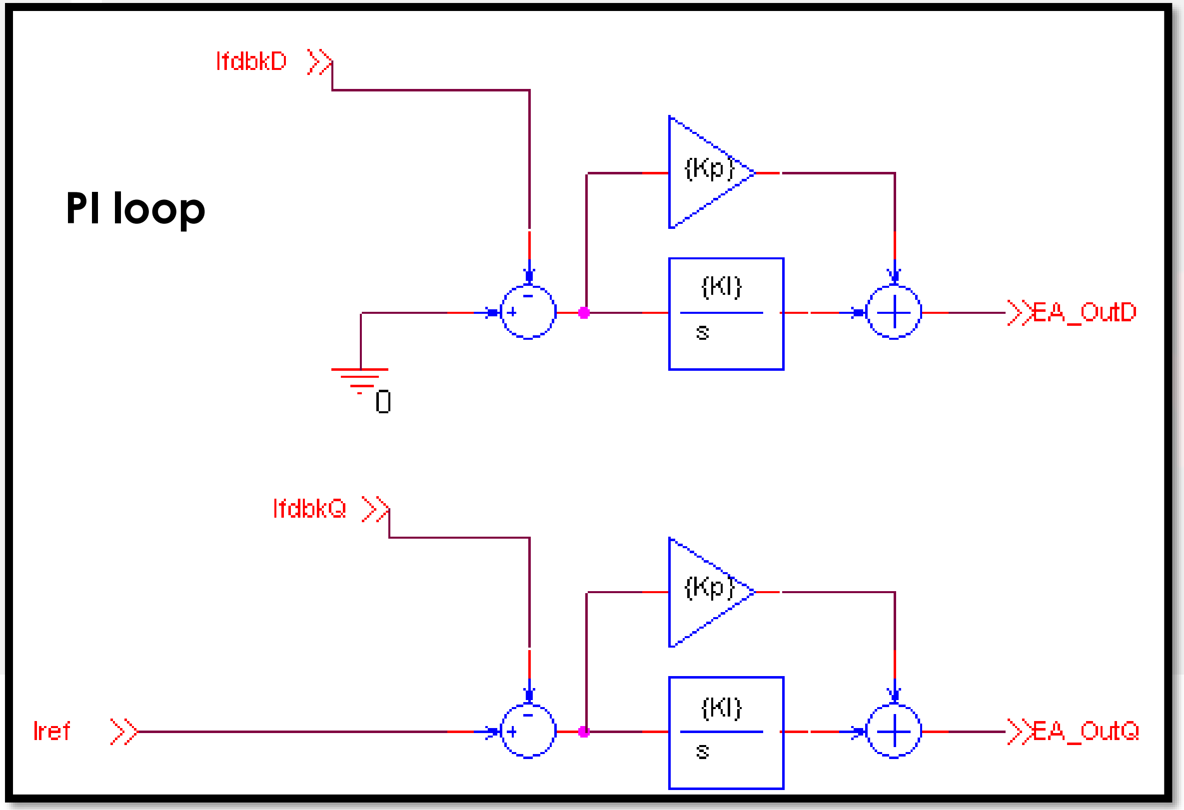
- Equivalent circuit of PMSM:



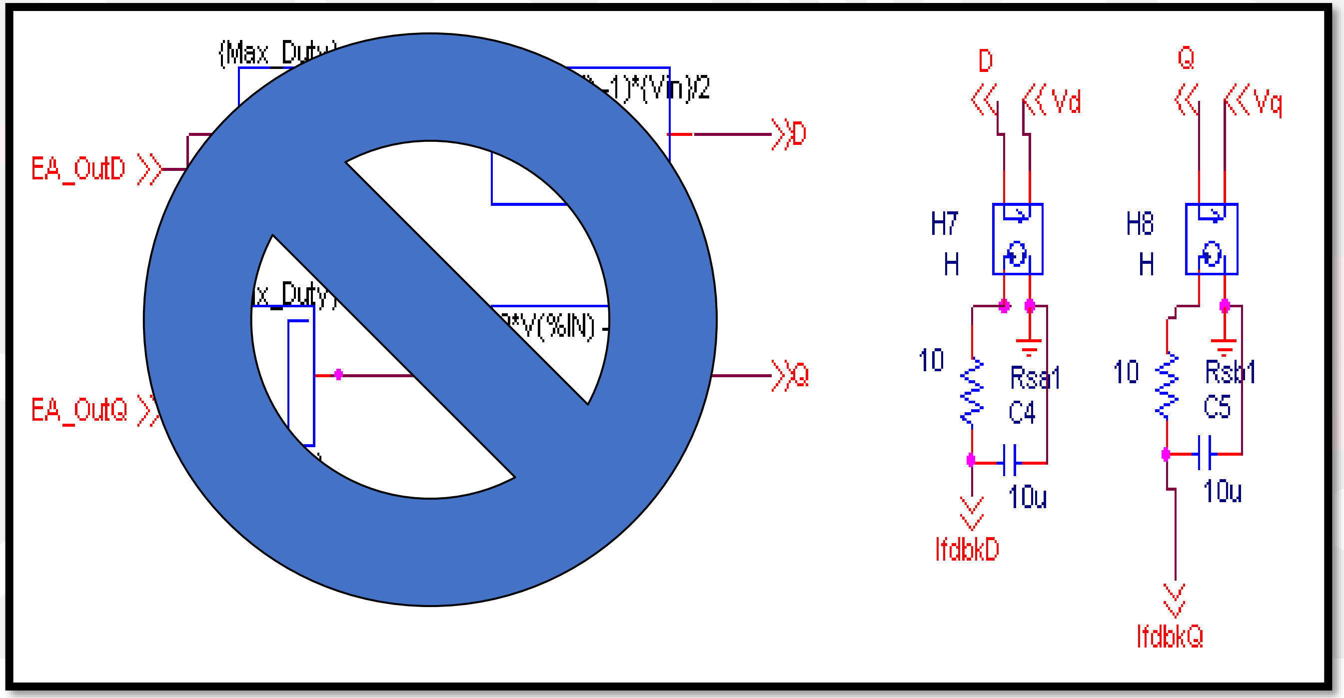
MODELING OF PMSM MOTOR



MODELING OF PMSM MOTOR

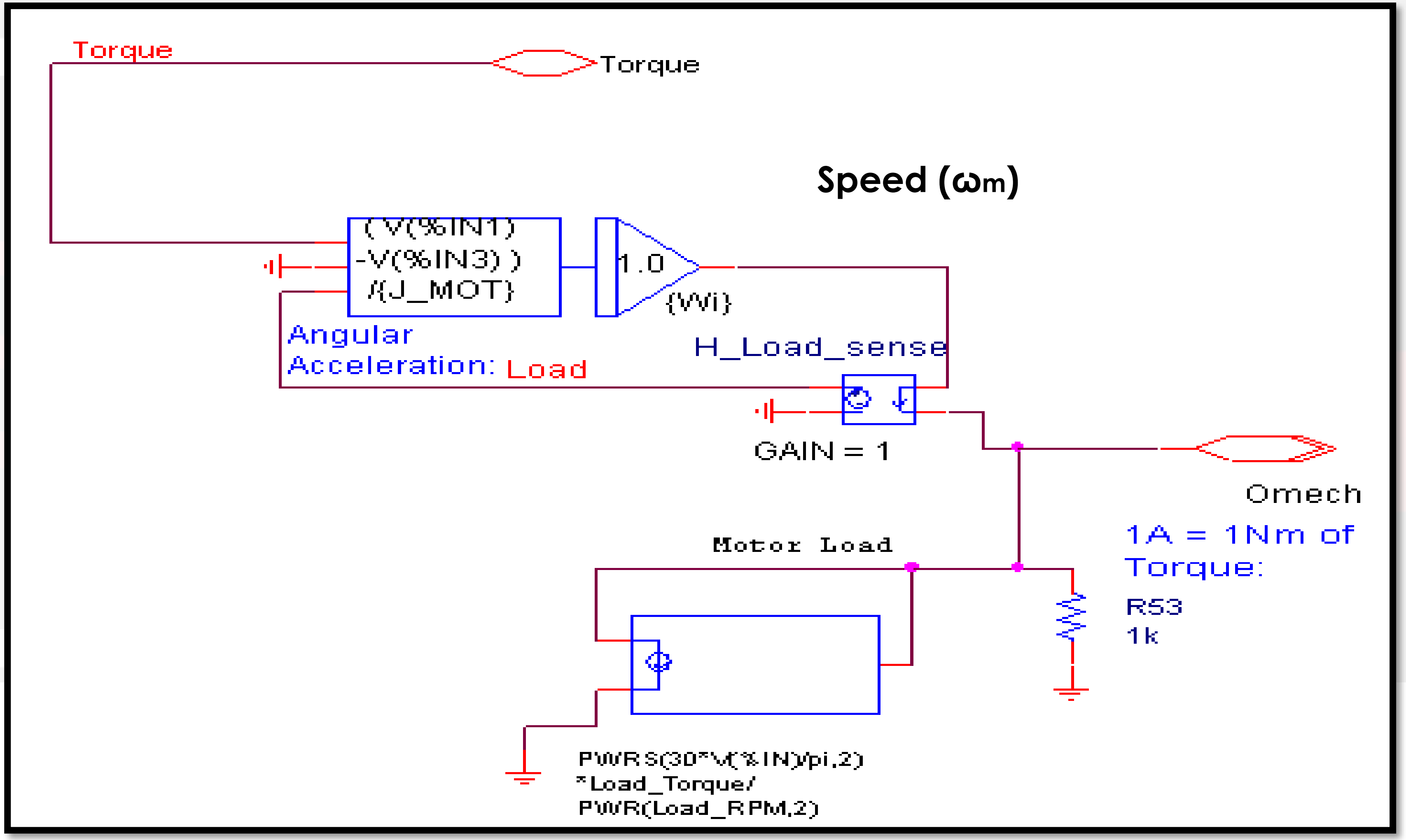


MODELING OF PMSM MOTOR

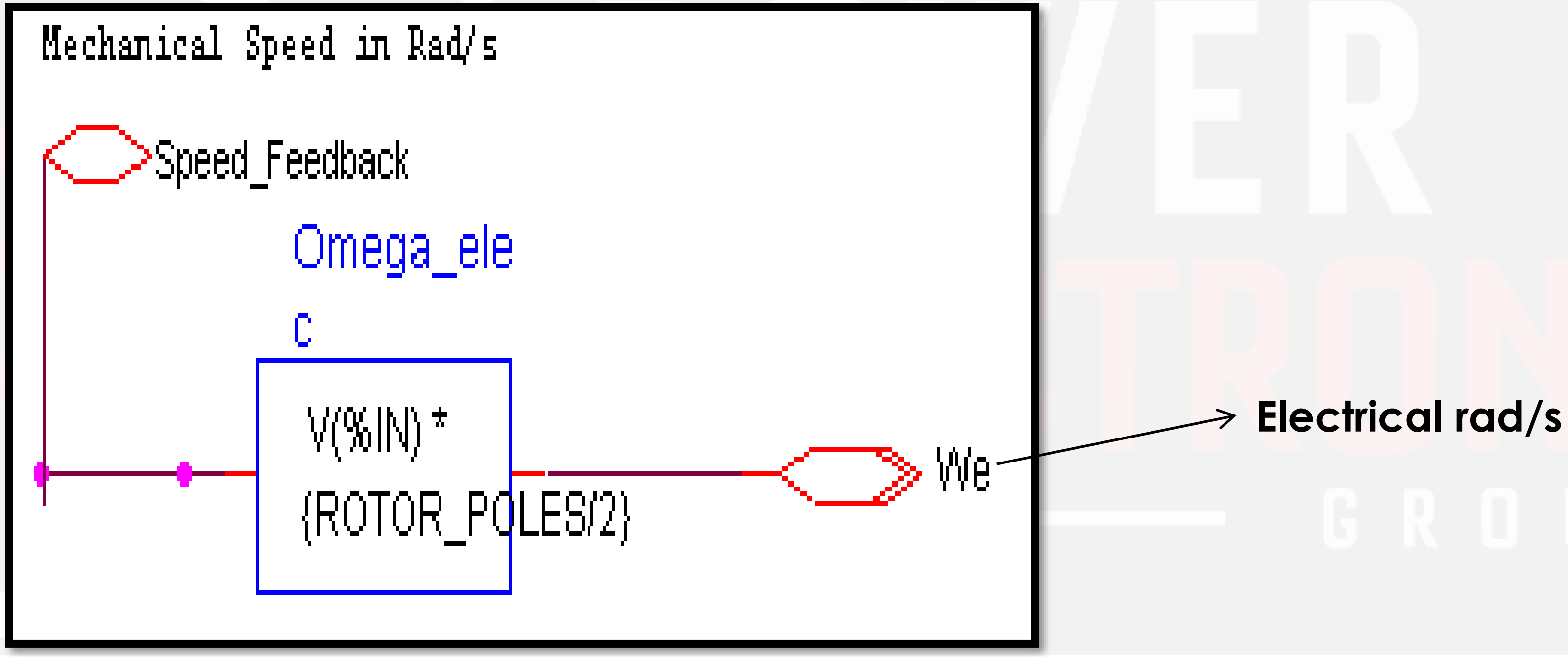


Large signal model of Half bridge inverter

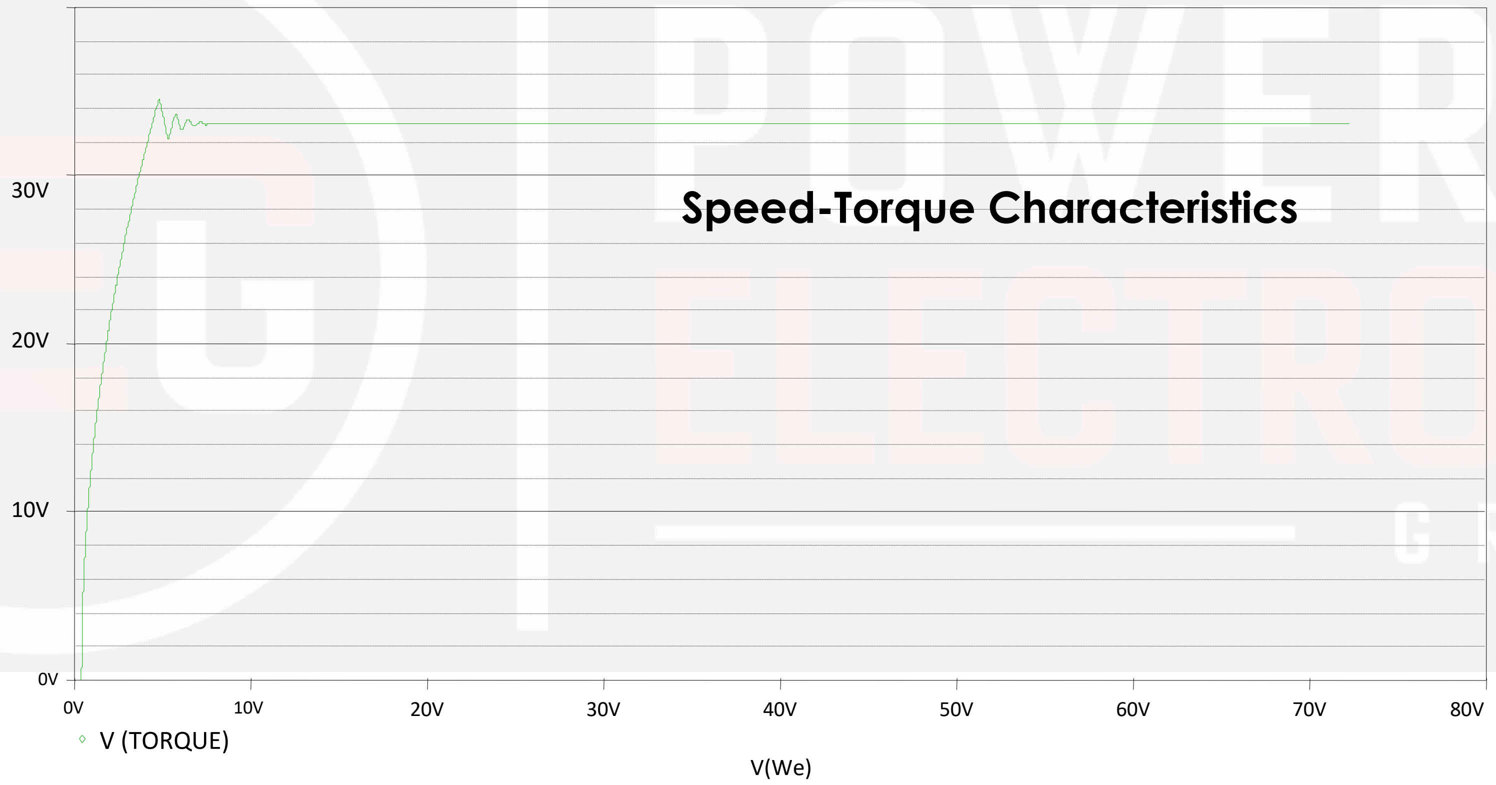
MODELING OF PMSM MOTOR



MODELING OF PMSM MOTOR

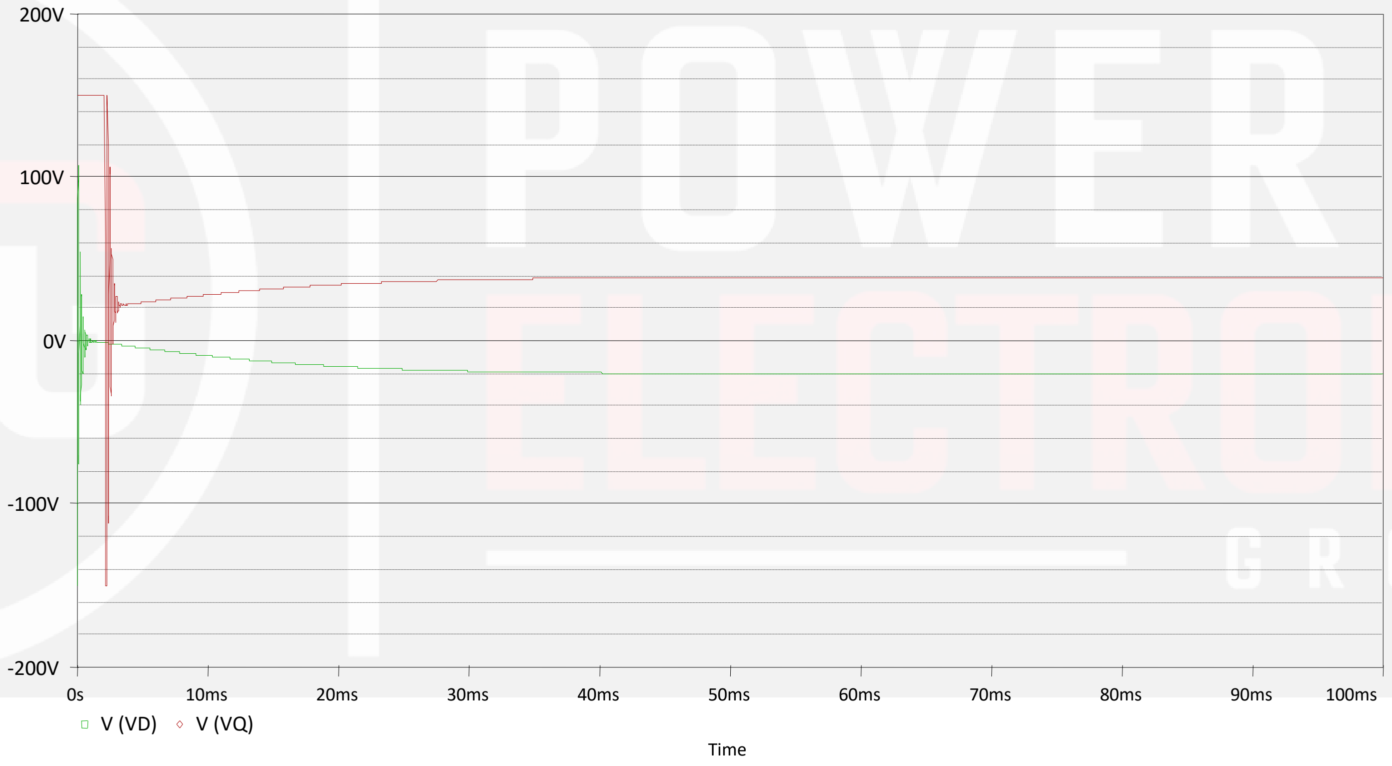


SIMULATION RESULTS

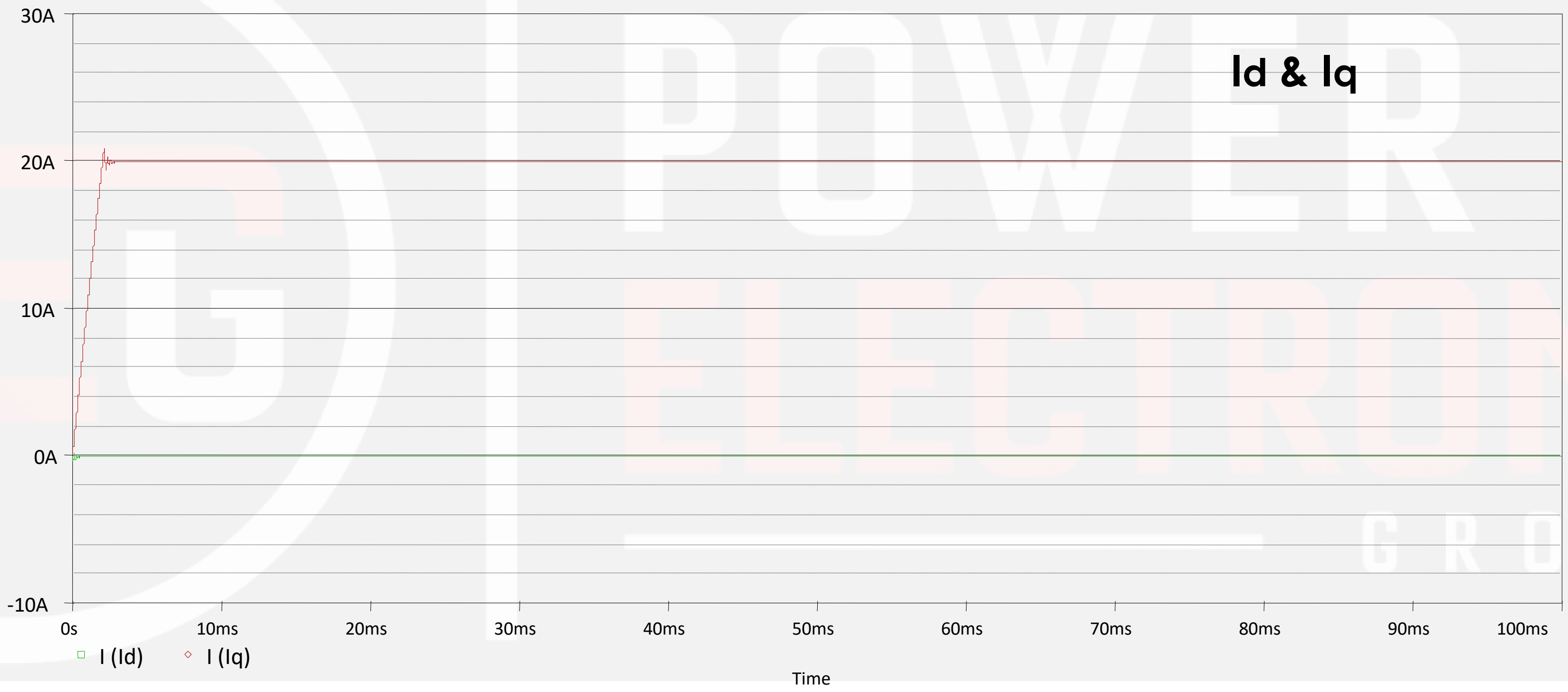


SIMULATION RESULTS

Vd & Vq



SIMULATION RESULTS



MODELING OF PMSM MOTOR

$$|V_s| = \sqrt{V_q^{\ 2} + V_d^2}$$

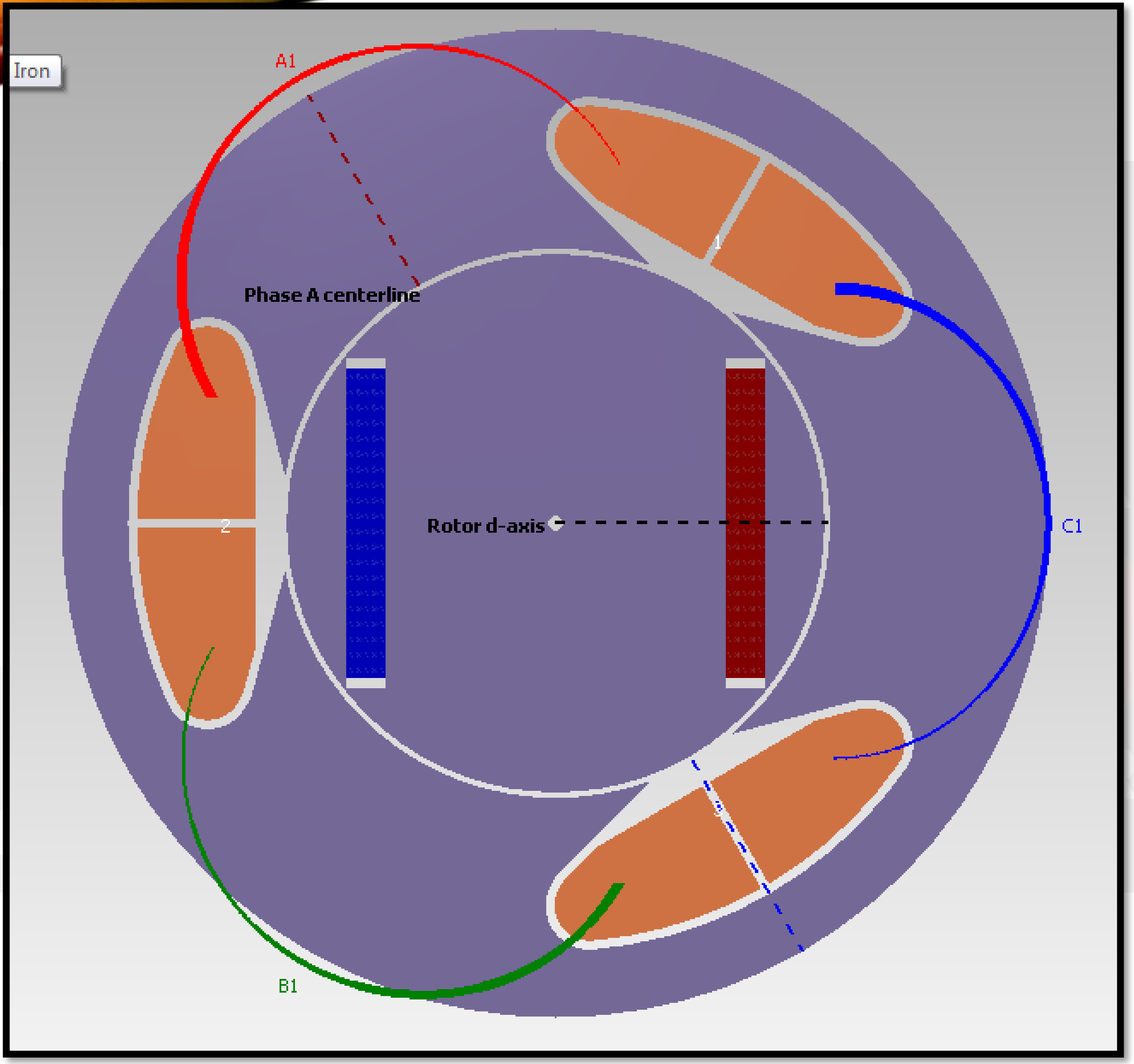
$$|I_s| = \sqrt{I_q^{\ 2} + I_d^2}$$

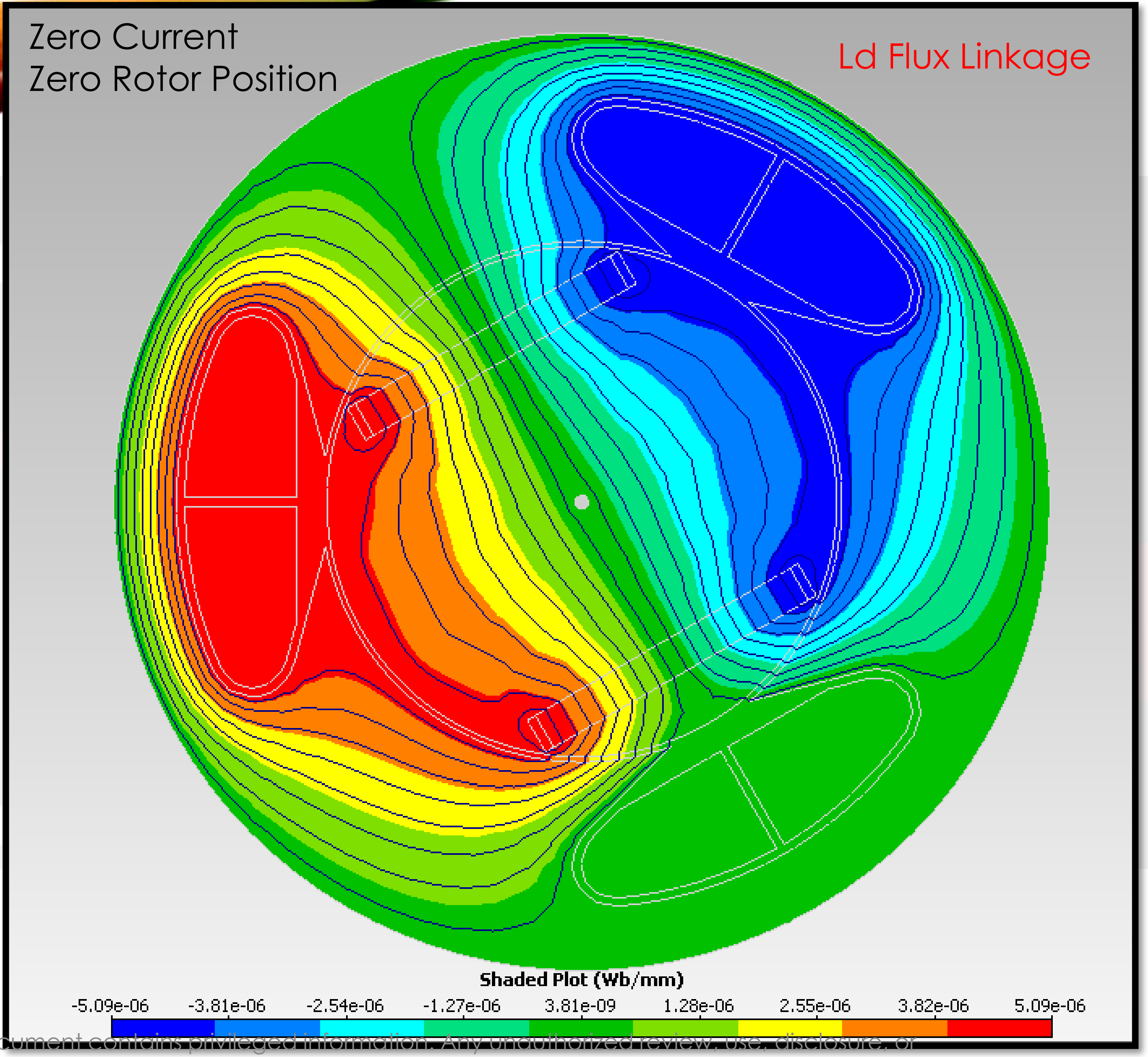
$$I_q = I_s \cos(\theta_m)$$

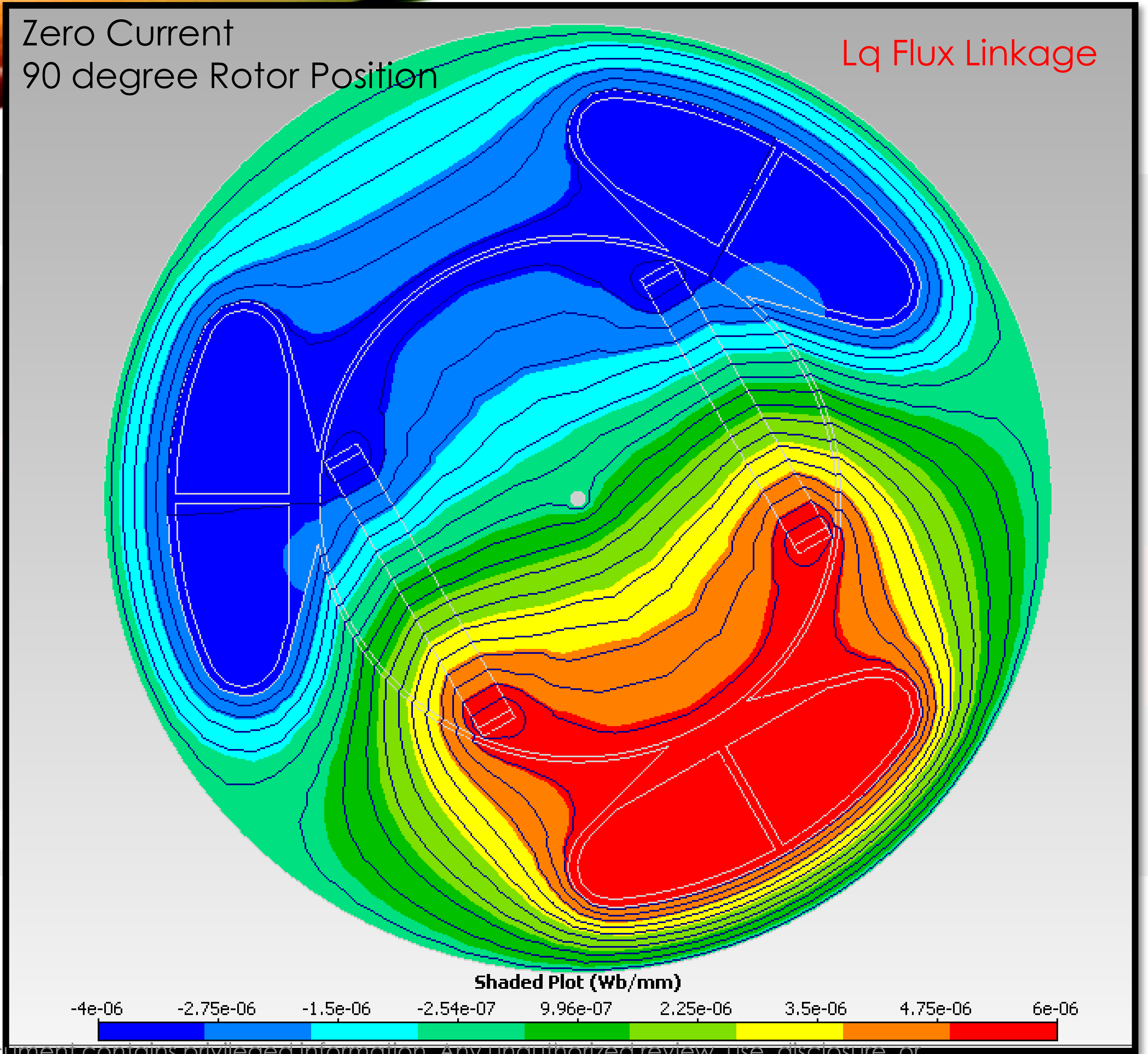
$$I_d = -I_s \sin(\theta_m)$$

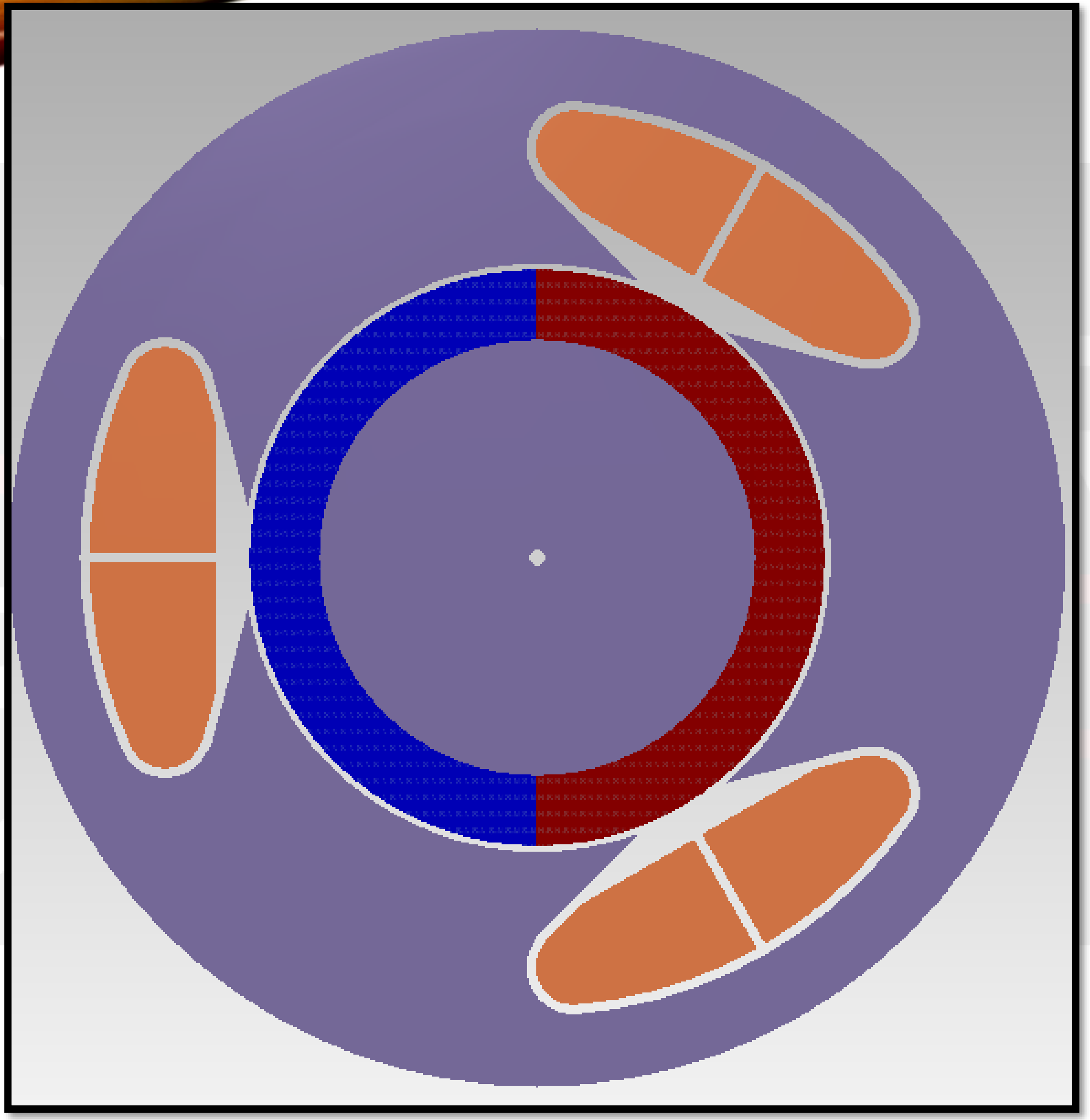
$$T = (3/2).(P/2)\{\lambda_m I_s \cos(\theta_m) + 0.5(L_d - L_q) I_s^{\ 2} \sin(2\theta_m)\}$$

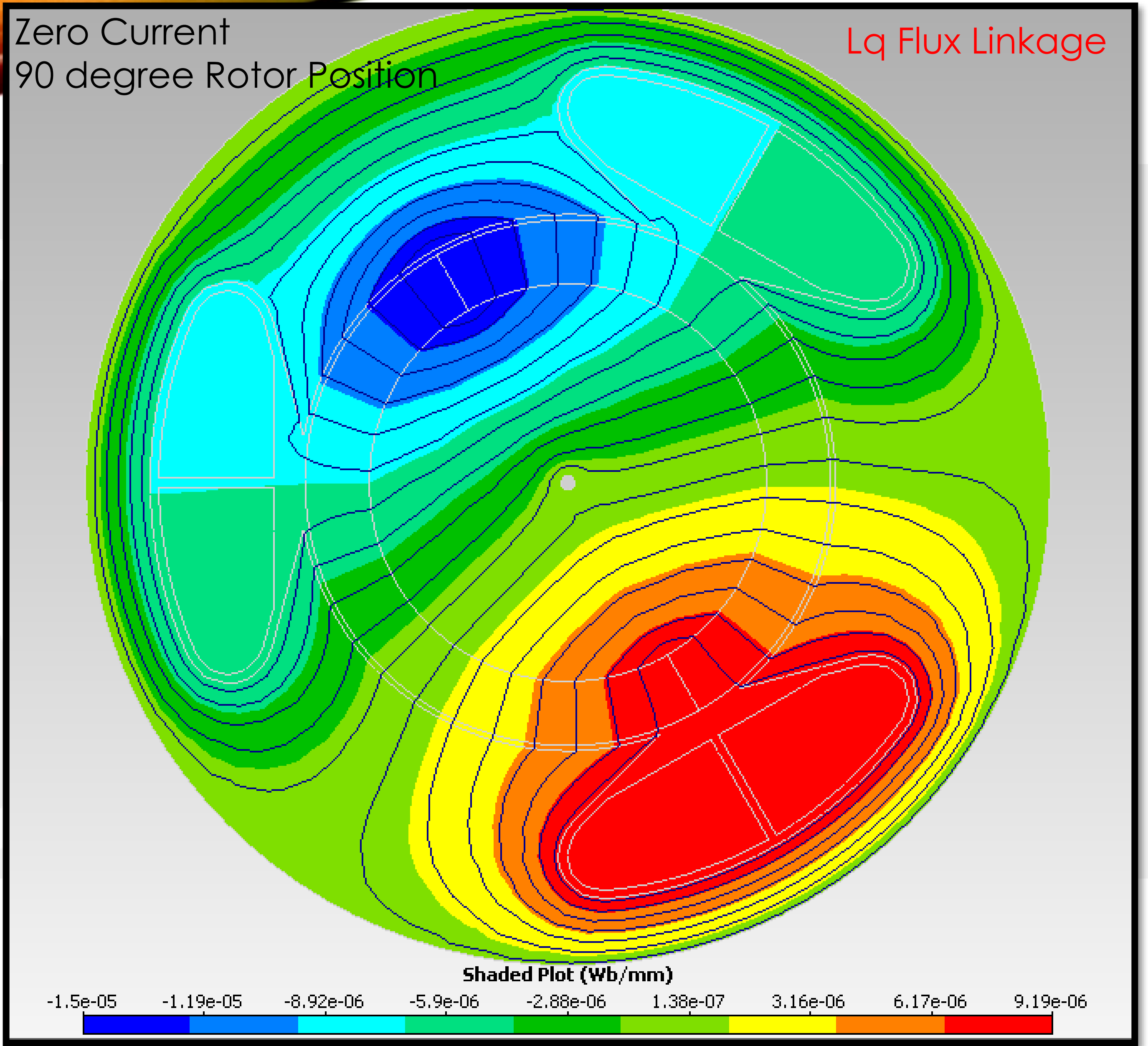
$$T = (3/2)(P/2)(\lambda_m I_s \cos(\theta_m))$$


Iron
A1
Phase A centerline
Rotor d-axis
C1
B1
1
2
3

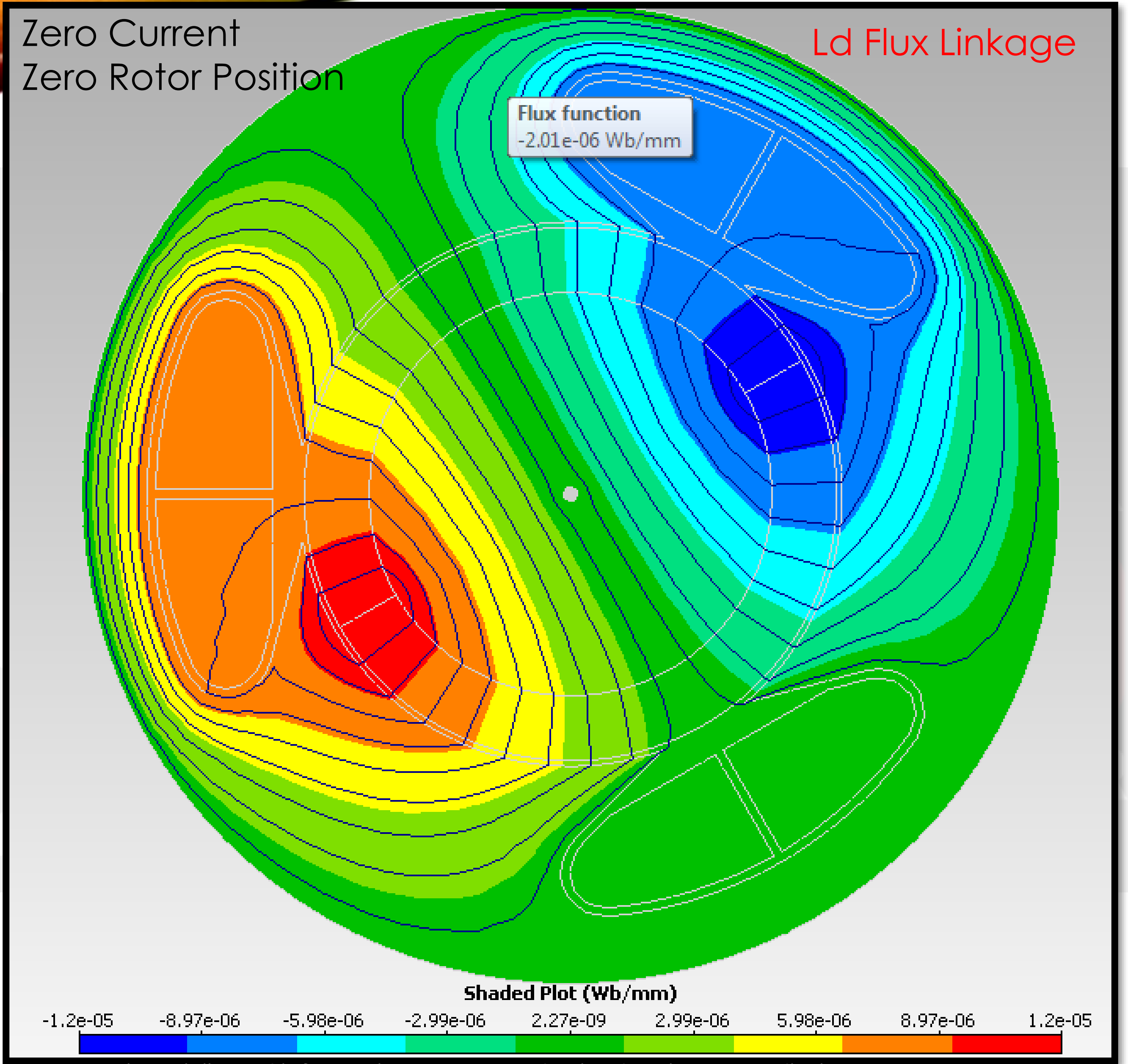

Zero Current
Zero Rotor Position
Ld Flux Linkage
Shaded Plot (Wb/mm)
-5.09e-06
-3.81e-06
-2.54e-06
-1.27e-06
3.81e-09
1.28e-06
2.55e-06
3.82e-06
5.09e-06

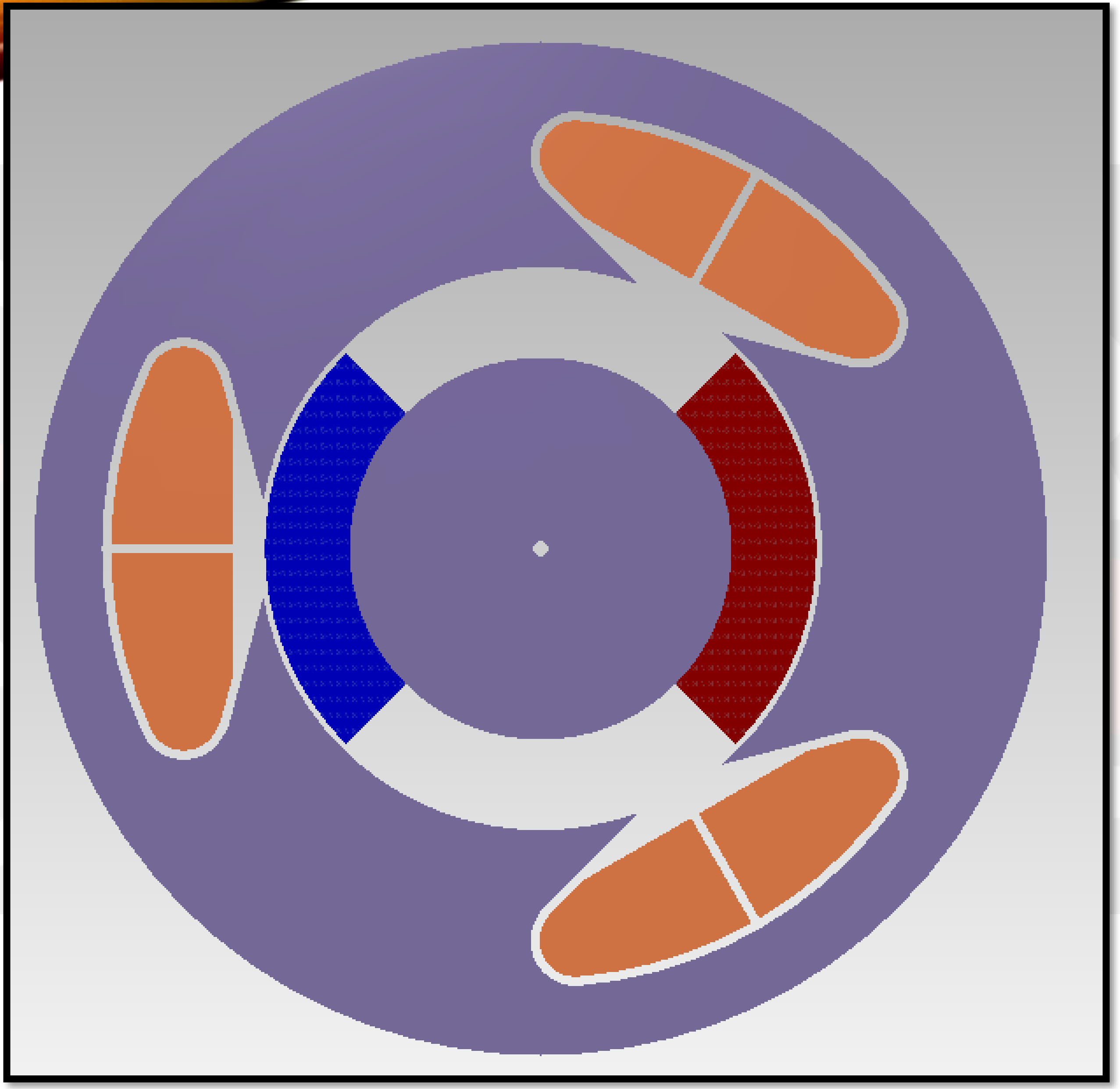

Zero Current
90 degree Rotor Position
Lq Flux Linkage
Shaded Plot (Wb/mm)
-4e-06
-2.75e-06
-1.5e-06
-2.54e-07
9.96e-07
2.25e-06
3.5e-06
4.75e-06
6e-06

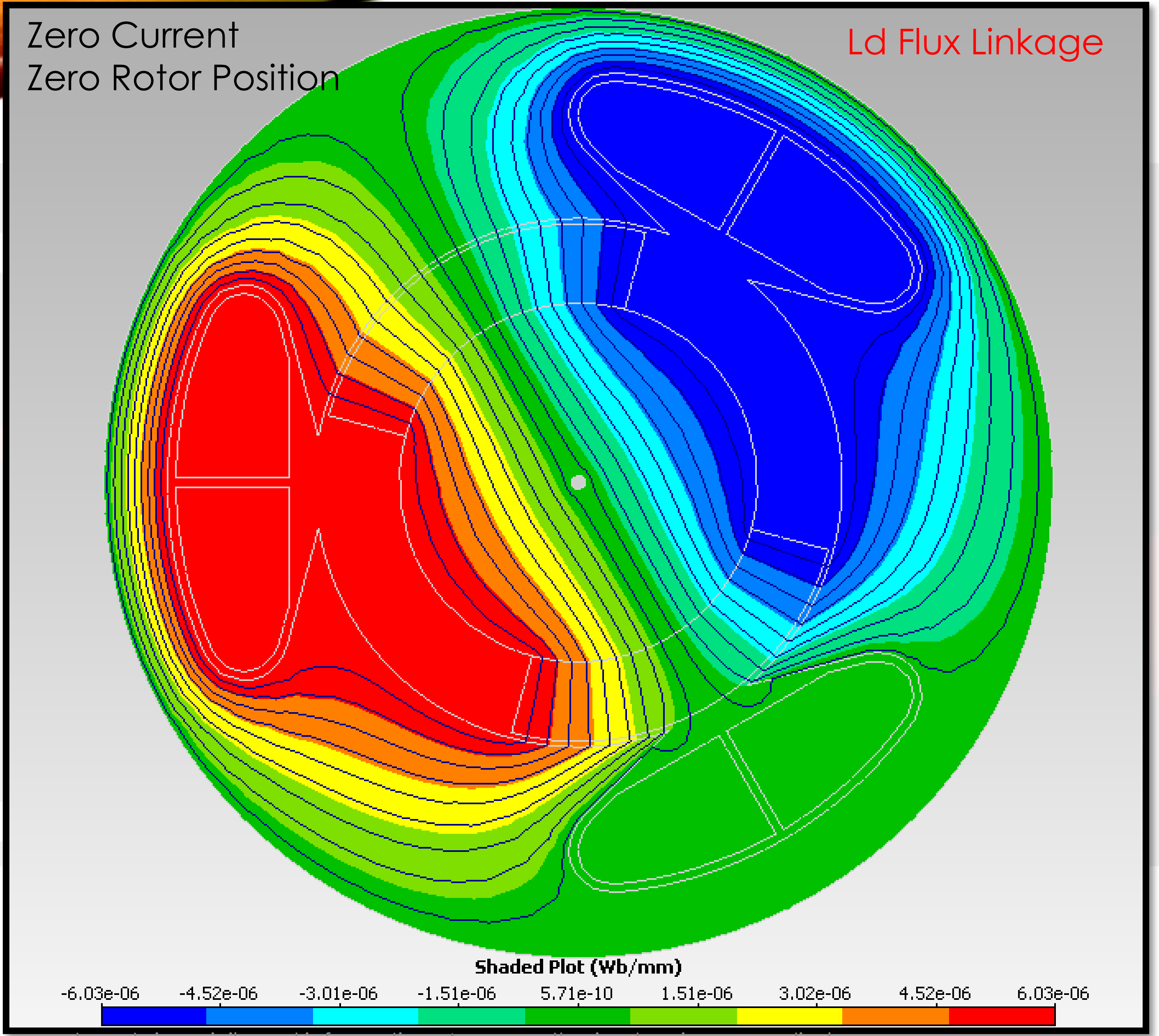


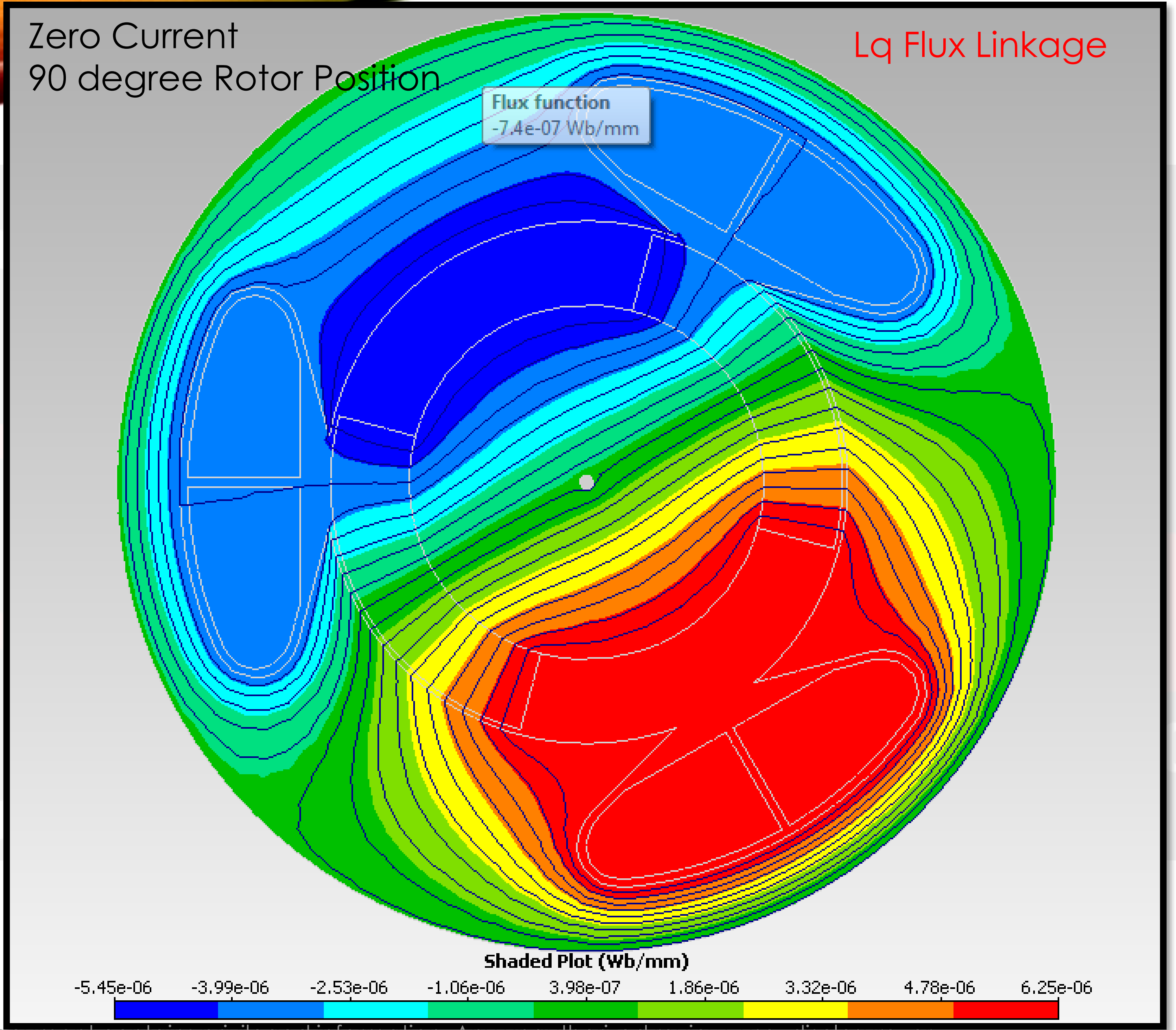


Zero Current
90 degree Rotor Position
Lq Flux Linkage
Shaded Plot (Wb/mm)
-1.5e-05
-1.19e-05
-8.92e-06
-5.9e-06
-2.88e-06
1.38e-07
3.16e-06
6.17e-06
9.19e-06


Zero Current
Zero Rotor Position
Ld Flux Linkage
Flux function
-2.01e-06 Wb/mm
Shaded Plot (Wb/mm)
-1.2e-05
-8.97e-06
-5.98e-06
-2.99e-06
2.27e-09
2.99e-06
5.98e-06
8.97e-06
1.2e-05




Zero Current
Zero Rotor Position
Ld Flux Linkage
Shaded Plot (Wb/mm)
-6.03e-06
-4.52e-06
-3.01e-06
-1.51e-06
5.71e-10
1.51e-06
3.02e-06
4.52e-06
6.03e-06


Zero Current
90 degree Rotor Position
Lq Flux Linkage
Flux function
-7.4e-07 Wb/mm
Shaded Plot (Wb/mm)
-5.45e-06
-3.99e-06
-2.53e-06
-1.06e-06
3.98e-07
1.86e-06
3.32e-06
4.78e-06
6.25e-06

LUMPED PARAMETER ANALYSIS

Zero Rotor Position + 45 degree phase advance			
	SPM - 180 degree Magnet Span	SPM - 90 degree magnet span	IPM - Laterial Magnets
Ld (d-axis inductance) (mH)	0.102	0.089	0.429
Lq (q-axis inductance) (mH)	0.103	0.0867	**0.929**
L average (mH)	0.102	0.0879	0.679
Phi_m (zero-current flux) (Wb)	0.0114	0.00853	0.00617
Phi_d (flux used for Ld) (Wb)	0.000508	0.000445	0.00214
Phi_q (flux used for Lq) (Wb)	0.000517	0.000434	0.00464

ESTIMATION OF PARAMETERS

- Resistance:
- Line to line R is measured with an RLC meter;
- Half the value gives R/phase;
- Neglecting skin effect R is given by:

$$R_t = R_0(K + T_t)/(K + T_0)$$

  - Where Ro is the resistance measured at To;
  - Rt is the value at different temperature;
  - K=243.5 constant of the material (copper);

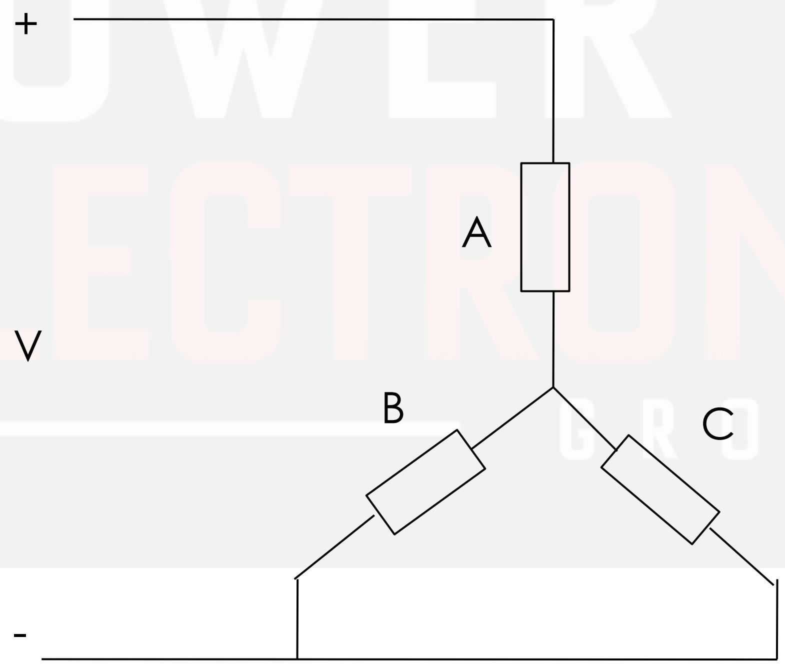
ESTIMATION OF PARAMETERS

- Synchronous Inductances Ld & Lq:

$$V = \{(3/2)R_s + (3/2)L_q p\}I_q$$

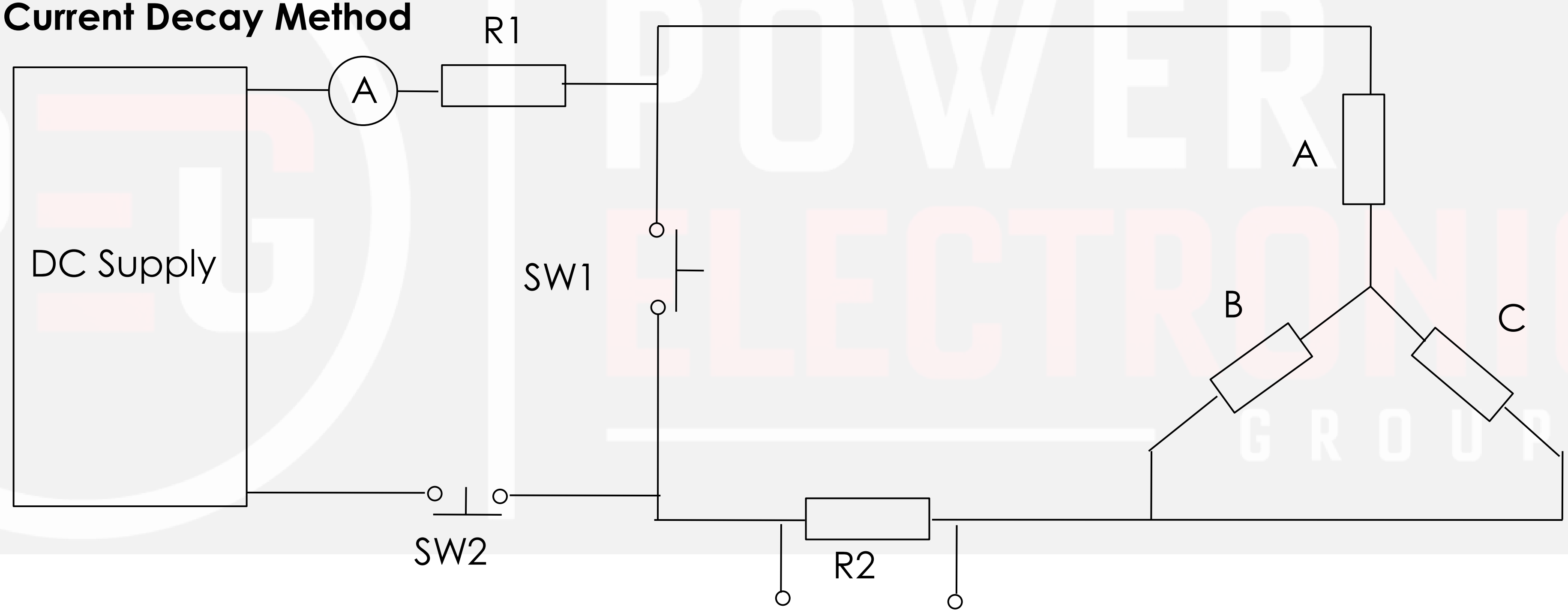
$$L_q = (2/3)L(\theta = 0^o)$$

$$L_d = (2/3)L(\theta = 90^o)$$



ESTIMATION OF PARAMETERS

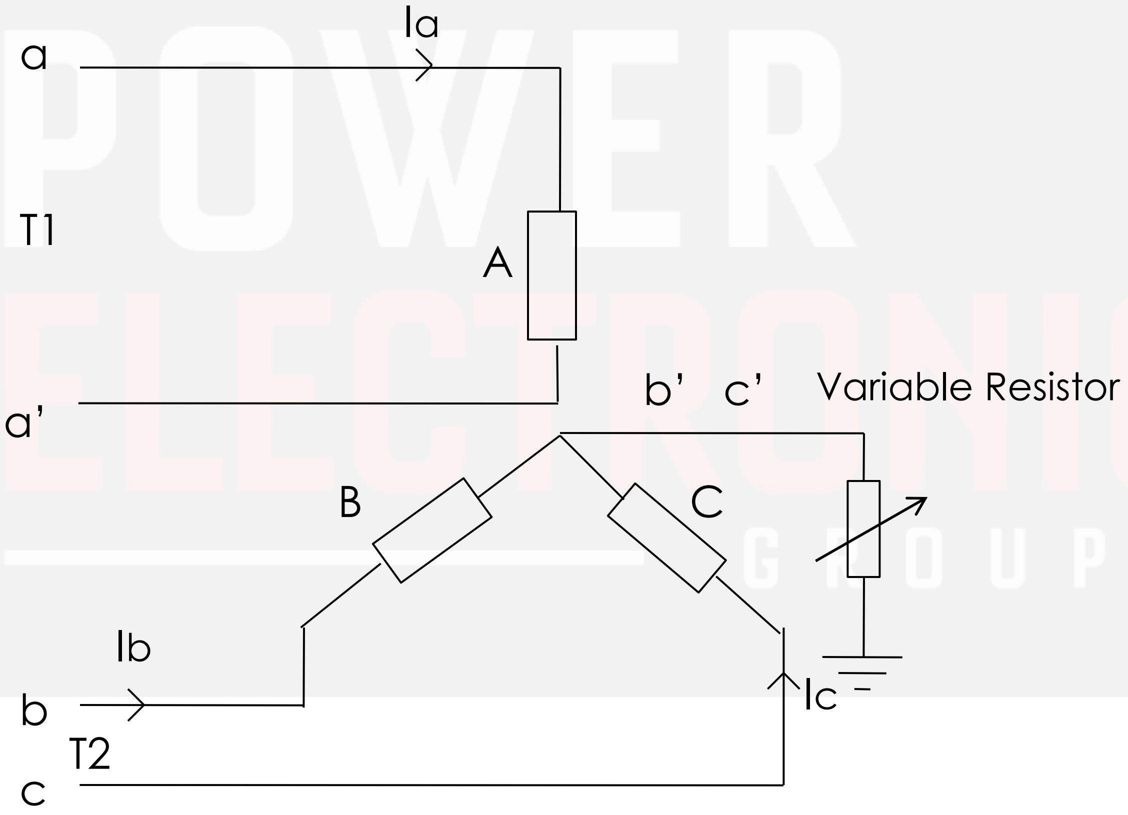
Current Decay Method



ESTIMATION OF PARAMETERS

Circuit for general Inductance Measurement

Lock the rotor, keep the currents balanced and measure inductance for various values of current and position. Position is simulated by different current magnitudes.



ESTIMATION OF PARAMETERS

- Permanent magnet flux linkage;

$$\lambda_m = \sqrt{(2/3)}.V_{nl} / \omega$$

- Where $\omega = \omega_m (P/2)$;
- BEMF const $K_e = V_{nl}/\omega$;
- Maintaining orthogonal at stand still λ_m can be found as: $\lambda_m = (2/3).(2/P)T / I_s$
- Where I_s is peak current value;

ESTIMATION OF PARAMETERS

- Let L_{q0}, L_{d0} & λ_{m0} be the values in the linear region;
- In linear region $|I_q| < |I_0|$;
- But at high currents $|I_q| > |I_0|$;
- L_q is subjected to saturation;
- L_d & λ_m are subjected to armature reactions;
- At high currents Frolich's formula can be used for calculating L_d, L_q & λ_m;

ESTIMATION OF PARAMETERS

- Frolich's formula:

$$L_q(I) = L_{q0}(a + I_0)/(a + |I_q|)$$

$$L_d(I) = L_{d0}(b + I_0)/(b + |I_q|)$$

$$\lambda_m(I) = \lambda_{m0}(b + I_0)/(b + |I_q|)$$

ESTIMATE

- P=6;
- $R_{l\text{-}l}$=1.9Ω at 25 degrees celsius;
- V_{nl}=106.8V at 1000rpm;
- Orthogonal Torque=17.6Nm at 10A rms & 31Nm at 20A rms;
- L(0)=21.15mH up to 10A rms & 16.08mH at 20A rms;
- L(90)=12.20mH up to 10A rms & 10.73mH at 20A;

HINT

- L_d=8.13mH;
- L_q=14.1mH;
- λ_m=0.2765 Wb-T;
- R_s=0.95Ω;

Calculate a and b