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MASTER THE ART OF MOTOR, INVERTER, HARDWARE & FIRMWARE DESIGN

Online Workshop | April 22-24, 2025

POWER ELECTRONICS GROUP LLC

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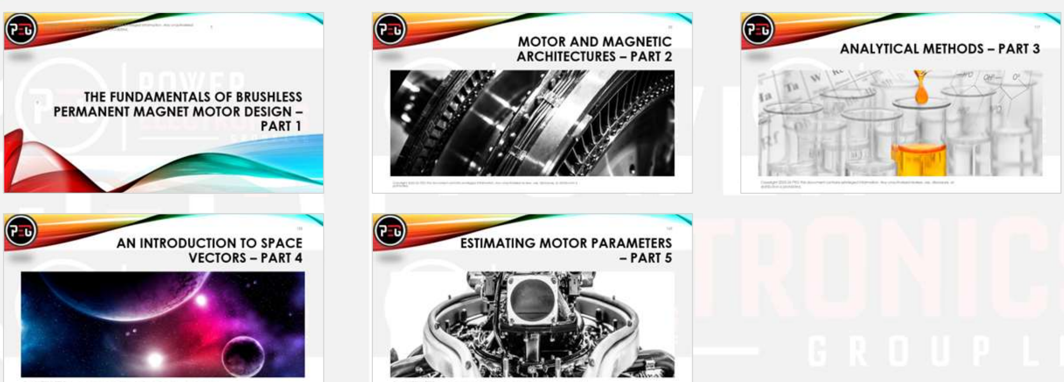

Day One Topics

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3
MECHANICAL CONSIDERATIONS – PART 6
Drive
Motor
Coupling
Machine
Flow of Power
THERMAL ANALYSIS – PART 7
POWER STAGE DESIGN – PART 8
MOTOR CONTROL PROBLEMS AND SOLUTIONS – PART 9
FIRMWARE DEVELOPMENT – PART 10
Day Two Topics
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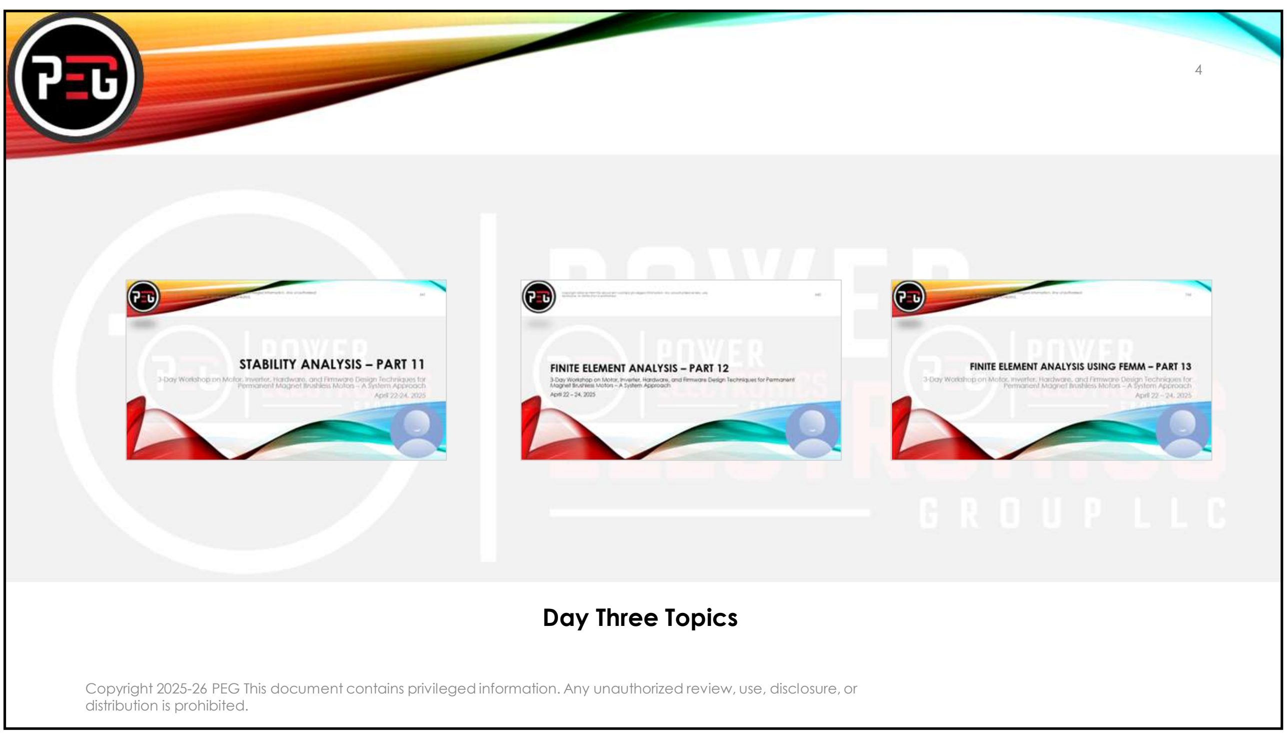
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STABILITY ANALYSIS – PART 11
FINITE ELEMENT ANALYSIS – PART 12
FINITE ELEMENT ANALYSIS USING FEMM – PART 13
Day Three Topics
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THE FUNDAMENTALS OF BRUSHLESS PERMANENT MAGNET MOTOR DESIGN – PART 1

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WHY DOES THE MOTOR TURN?

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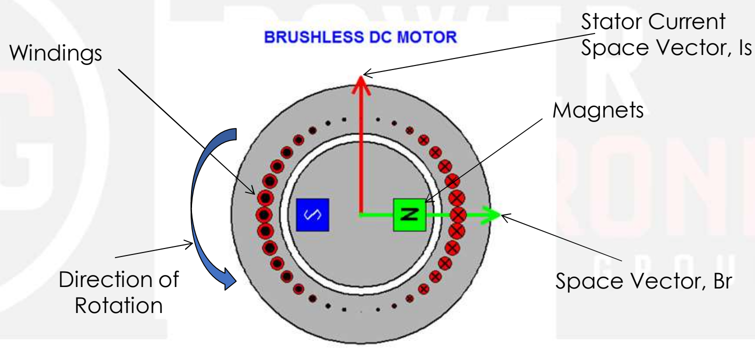
WHY DOES THE MOTOR ROTATE?



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QUESTIONS

- How is the current distributed?
- What are the two vectors?
- Which vector is leading and what is the significance of that?
- How can you physically create this space relationship?

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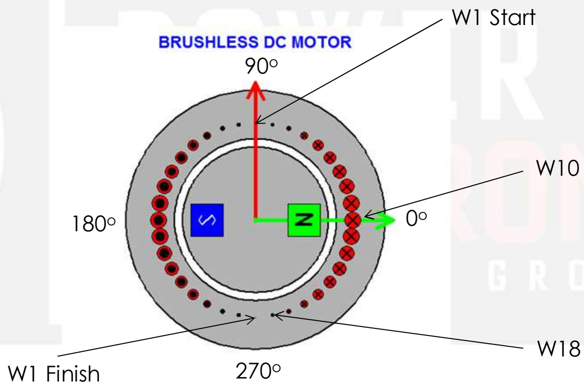
LET US ANALYZE

Beware of 0°

North Follows the Max Current



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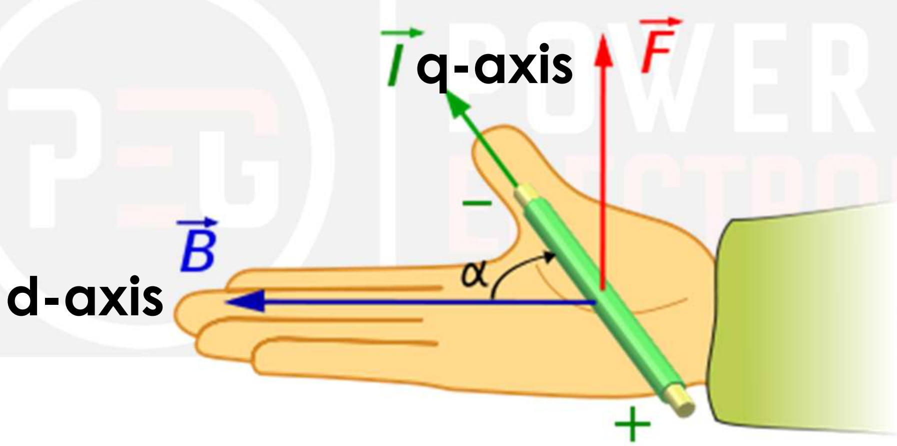
THE CONCEPT OF D-Q AXIS



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THE BASICS

- A **magnetic field** can be described using lines of flux;
- Such lines form closed loops;
- Such lines do not cross;
- Such lines when parallel repel one another.

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THE BASICS

- Magnetic fields have north and south poles;
- A current carrying conductor lying in a magnetic field experiences a force;

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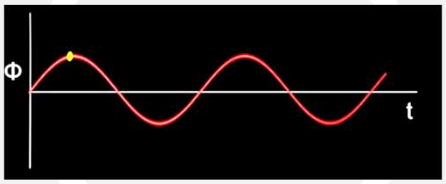
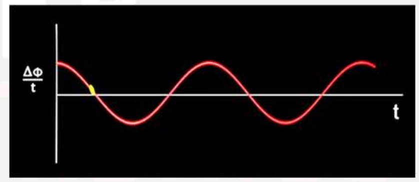
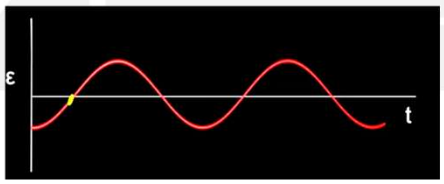
THE BASICS

- Varying magnetic flux linking a circuit induces an EMF (**Faraday's Law**);
- Induced EMF opposes the change of flux (**Lenz's Law**).



$$\mathcal{E} = -N \frac{\Delta \phi}{\Delta t}$$





Reference: Faradays Law in 3 minutes by PhysicsHigh https://youtu.be/npls3sQP7xk?si=RhtRnF6vx1DMww-l

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IMPORTANT FORMULAE

- Force F = BIL;
- Flux Φ = BA;
- Flux Density B = Φ/A;
- EMF = Blu, u is the rate of change;
- EMF = -dΦ/dt;
- EMF = -dNΦ/dt;

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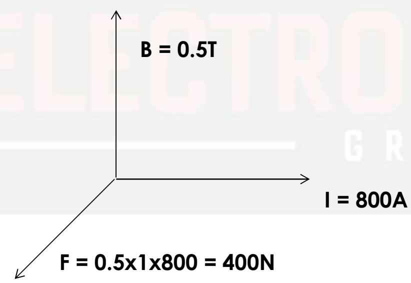
THE BASICS

- Force on a Current Carrying Conductor, 1m in length



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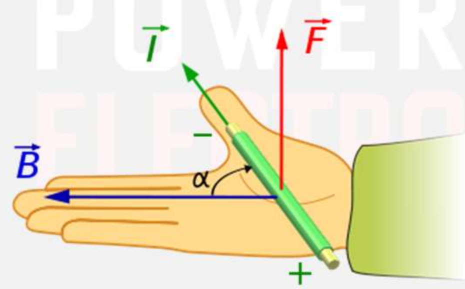
FORCE ON A CURRENT CARRYING WIRE

- F = ILXB



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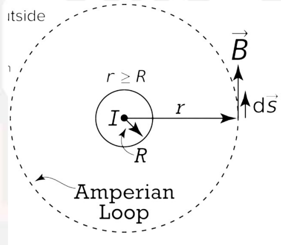
AMPERE'S LAW

➢Line integral of a magnetic field in a closed path equals net current enclosed;

$$\oint B.dl = \mu_0 \sum I_{enclosed}$$

$$\oint_c H.dl = \oint_s J.ds$$

$$H_c l_c = Ni$$



$$\Rightarrow B \oint ds = B(2\pi r) = \mu_0 I \Rightarrow B = \frac{\mu_0 I}{2\pi r}$$

Reference: Ampère's Law, YouTube, uploaded by Flipping Physics
https://youtu.be/gVr_CFlIY2A?si=eUFQsPtjZZObt0jR

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AMPERE'S LAW

- Where B-magnetic flux density in Tesla;
- H- magnetic field strength in AT/m;
- N- Number of turns;
- *i*- Current flowing in the path in Amperes;
- l_c- length of the path through which current flows in meter;
- J-current density in A/m2;
- Small incremental length-dl and area-ds;

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KEY DIFFERENCE SUMMARY (B VS. H)

Concept	Flux Density (B)	Field Intensity (H)
Represents	Magnetic field **effect**	Magnetic field **cause**
Depends on	Field intensity **and** material	Only on current/magnetic sources
Units	Tesla (T)	Amperes per meter (A/m)
Formula	B=μH	H=B/μ
Affected by material	Yes (Via Permeability)	No (intrinsic to the field source)

FUNDAMENTALS OF MAGNETIC CIRCUITS

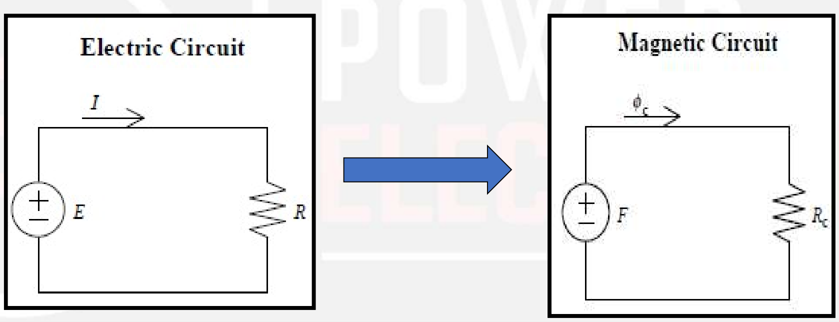
- Magnetic flux in the cross section of a core is given as: $\phi_c = B_c A_c$
- Where Φ is the flux in the core;
- Magnetic Flux density is defined as: $B = \mu H$
- Where μ is the permeability given by: $\mu = \mu_0 \mu_r$
- The flux can be also expressed as:

$$\phi = \mu H.A = \frac{\mu.Ni.A}{l} = \frac{Ni}{R}$$

FUNDAMENTALS OF MAGNETIC CIRCUITS

- Where R is the reluctance given by: $R = \dfrac{l}{\mu A}$
- Ni is defined as MMF denoted as ‘F’;
- Flux can also be written as: $\phi = \dfrac{F}{R}$
- Magnetic circuits are analogous to electric circuits;

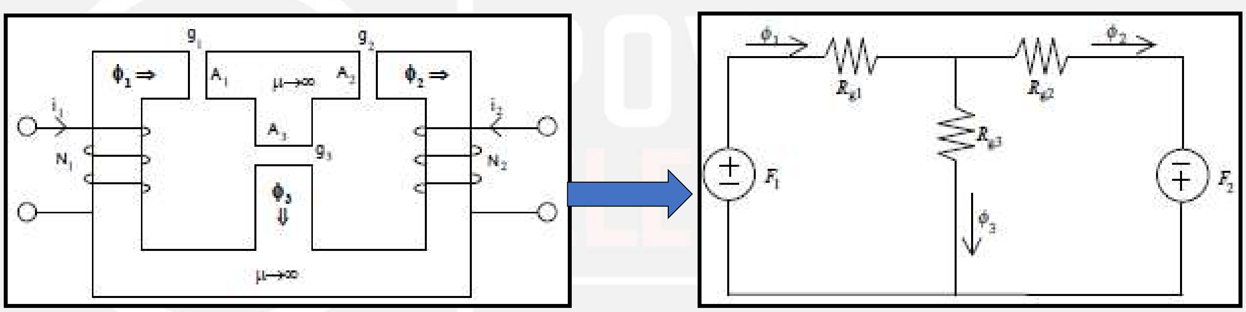
FUNDAMENTALS OF MAGNETIC CIRCUITS



FUNDAMENTALS OF MAGNETIC CIRCUITS

Electrical Circuit	Magnetic Circuit
V=IR	F=ΦR
R=l/(σA)	R=l/(μA)
R=1/G, G→ Conductance	R=1/P, P →Permeance
∑V=∑IR (KVL)	∑F=∑ΦR (KVL)
∑I=0 (KCL)	∑Φ=0

FUNDAMENTALS OF MAGNETIC CIRCUITS



FUNDAMENTALS OF MAGNETIC CIRCUITS

- Flux linkage (**Total Flux in a Coil**) is defined as: **λ=NΦ**;
- Magnetic flux linkages of 2 coils is given by:

$$\lambda_1 = \lambda_{11} + \lambda_{12}$$
$$\lambda_2 = \lambda_{21} + \lambda_{22}$$

- First subscript indicates coil of flux linkage;
- Second subscript indicates coil which is carrying current;
- Inductance is defined as: L=(NΦ/I)=(λ/I);

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FUNDAMENTALS OF MAGNETIC CIRCUITS

- Self & Mutual inductances are defined as:
- Self inductance of j coil when j=k;
- Mutual inductance of j & k coil when j not equal to k;

$$L_{jk} = \frac{\lambda_{jk}}{i_k}$$

$$\lambda_1 = L_{11} i_1 + L_{12} i_2$$
$$\lambda_2 = L_{21} i_1 + L_{22} i_2$$

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WHAT IS INDUCTANCE?

- Defines the Geometry of the Magnetic Circuit
- $L = \mu.N^2.A/l$
- (Geometric Parameters Define Inductance)

Can this formula be significant in determining stator level inductance, Ld and Lq?

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WHAT IS RELUCTANCE?

- Another parameter which defines the geometry of a magnetic circuit;
- $R = l/(\mu.A)$;
- $L = N^2/R$;
- Inductance is inversely proportional to Reluctance.

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QUESTION

- **If I have a magnet placed in a magnetic circuit that also includes an air gap —**
- **and I assume there's no flux leakage or fringing —**
- **will the magnetic flux density stay the same throughout the whole path, including through the magnet, the core, and the air gap?**

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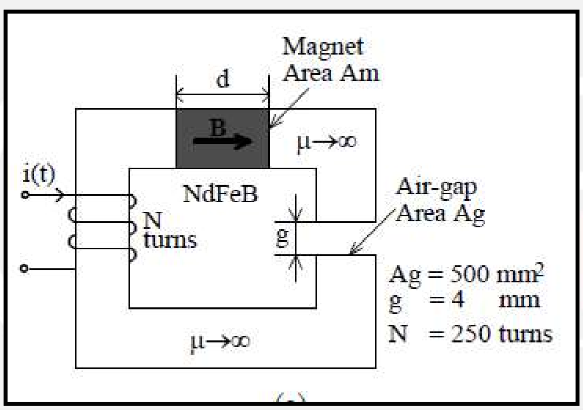
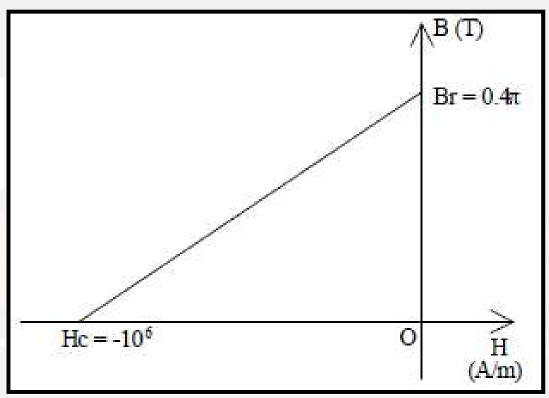
CALCULATE





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A SAMPLE PROBLEM

- B_g = 0.5 + 0.25.Sin(wt);
- 0.5T created by the magnet;
- 0.25T created by the current;
- Find d and i.

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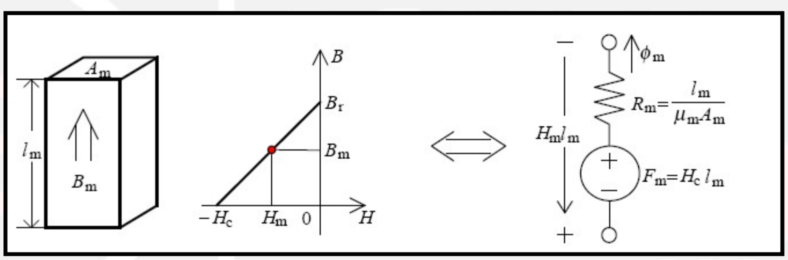
A PERMANENT MAGNET



$$B_m = \frac{B_r}{H_c}\left(H_m + H_c\right) = \mu_m\left(H_m + H_c\right)$$

$$H_m l_m = \left(\frac{B_m}{\mu_m} - H_c\right) l_m = \frac{l_m}{\mu_m A_m}\phi_m - H_c l_m = R_m \phi_m - F_m$$

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BASIC DESIGN CONSIDERATIONS IN MOTOR DESIGN

Dynamic Modeling of BLDC Motors

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BASIC DESIGN CONSIDERATIONS

- Torque Output;
- Weight;
- Size;
- Power Output;
- Noise.

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DESIGN CONSTRAINTS

- Specifications
  - Bus Voltage;
  - Rated Speed;
  - Rated Torque

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DESIGN CONSTRAINTS

- Number of Phases;
- Number of Poles;
- Number of Slots;
- Air Gap Thickness;
- Motor Aspect Ratio;
- Maximum Outer Diameter;
- Maximum Length.

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DESIGN CONSTRAINTS

- Rotor Parameters
  - Rotor Location;
  - Rotor Type;
  - Rotor Temperature;
  - Rotor Magnet Material.

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DESIGN CONSTRAINTS

- Stator Parameters
  - Stator Type;
  - Stator Temperature;
  - Stator Coil Material;

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DESIGN CONSTRAINTS

- Sizing Parameters
  - Torque per Unit Volume (TRV);
  - Rated Current Density;
  - Fill Factor;
  - Rotor Stator Diameter Ratio;
  - Stator Flux Density;
  - Back-EMF limit;
  - Magnet air gap ratio;
  - Magnet Coverage.

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DESIGN CONSTRAINTS

- Controller
  - Size;
  - Current;
  - Location;
  - Control Methods.

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DESIGN CONSTRAINTS

- Mechanical Interfaces
  - Geared or Gearless;
  - Mechanical or Electromagnetic Brake Interface;
  - Very Low Cogging Torque.

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DESIGN CONSTRAINTS

- Manufacturing Considerations
  - Winding Method & Design;
  - Lamination Method & Design;
  - Magnet Method & Design;
  - Shaft Method & Design;
  - Metal Housing + Cover Method & Design;
  - Thermal Limitations.

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EXAMPLE

- Specifications
  - Bus Voltage = 24V;
  - Rated Speed = 155 rpm;
  - Rated Torque = 22Nm.

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EXAMPLE

- Number of Phases = 3;
- Number of Poles = 28;
- Number of Slots = 24;
- Air Gap Thickness = 1mm;
- Motor Aspect Ratio = 0.1;
- Maximum Outer Diameter = 200mm;
- Maximum Length = 20mm.

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EXAMPLE

- Rotor Parameters
  - Rotor Location = External;
  - Rotor Type = Surface Mount w/ Radial Magnets;
  - Rotor Temperature = 50 deg. C Max;
  - Rotor Magnet Material = NdFeB 36MGOe.

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EXAMPLE

- Stator Parameters
  - Stator Type = Square;
  - Stator Temperature = 100 deg. C;
  - Stator Coil Material = Copper;

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EXAMPLE

- Sizing Parameters
  - Torque per Unit Volume = DNC (Do Not Care);
  - Rated Current Density = DNC;
  - Fill Factor = 40% Minimum;
  - Rotor Stator Diameter Ratio = 0.65;
  - Stator Flux Density = 1.2T Max;
  - Back-EMF limit = 0.9 Max;
  - Magnet air gap ratio = 3.5;
  - Magnet Coverage = 0.95.

EXAMPLE

- Controller
  - Size = Small;
  - Current = 50A peak;
  - Location = Internal;
  - Control Methods = FOC+SVM.

EXAMPLE

- Mechanical Interfaces
  - Gearless;
  - Brake = None;
  - Very Low Cogging Torque.

DESIGN CONSTRAINTS

- Manufacturing Considerations
  - Winding Type, Method & Design;
  - Lamination Type, Method & Design;
  - Magnet Type, Method & Design;
  - Shaft Type, Method & Design;
  - Metal Housing + Cover Type, Method & Design;
  - Thermal Limitations.

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END PRODUCT

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MOTOR AND MAGNETIC ARCHITECTURES – PART 2

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MOTOR ARCHITECTURES

- Radial
- Axial
- Transverse
- Halbach Array

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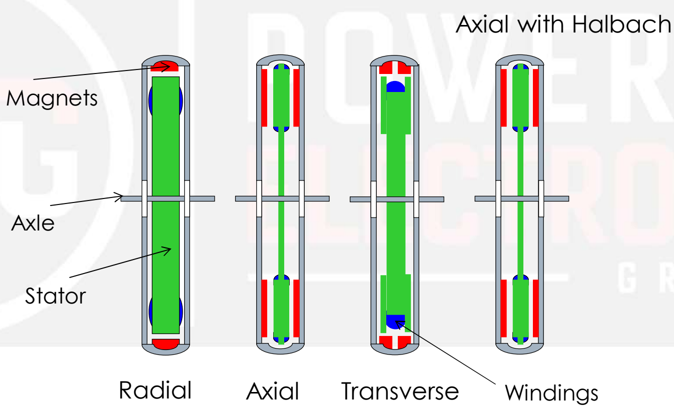
MOTOR ARCHITECTURES (OUTER ROTOR - GEARLESS)



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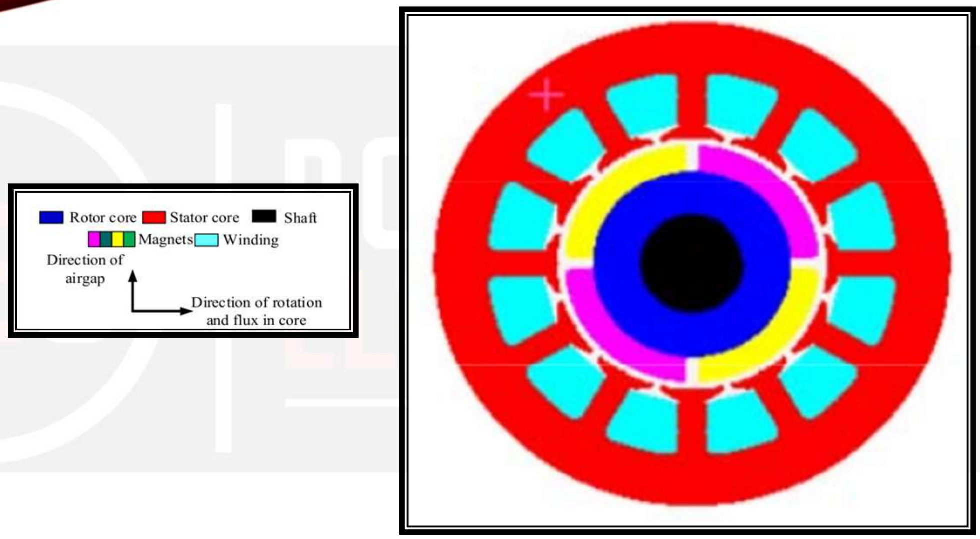
RADIAL FLUX MOTOR



Reference: Ballestín-Bernad, V.; Artal-Sevil, J.S.; Domínguez-Navarro, J.A. A Review of Transverse Flux Machines Topologies and Design. Energies 2021, 14, 7173. https://doi.org/10.3390/en14217173

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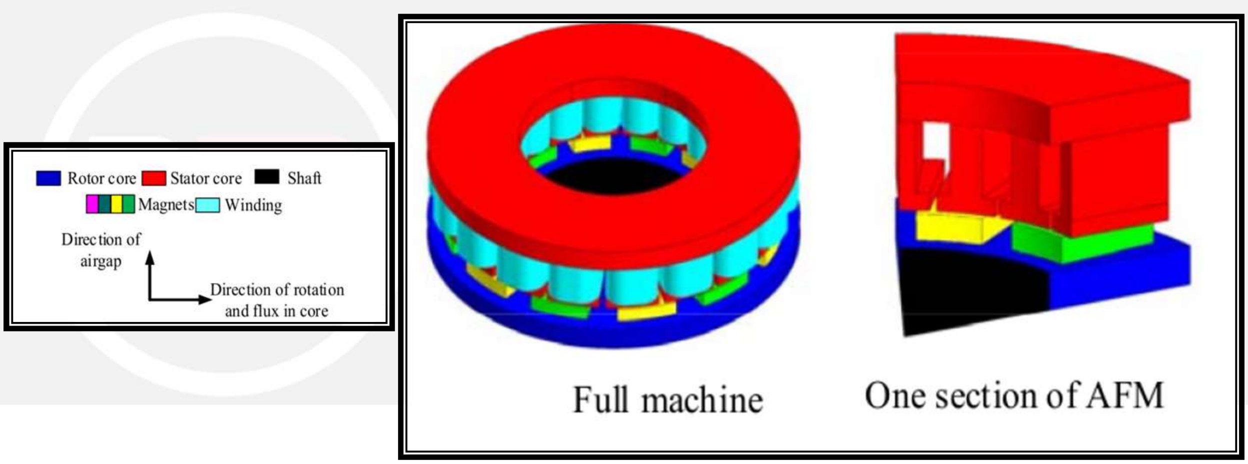
AXIAL FLUX MOTOR



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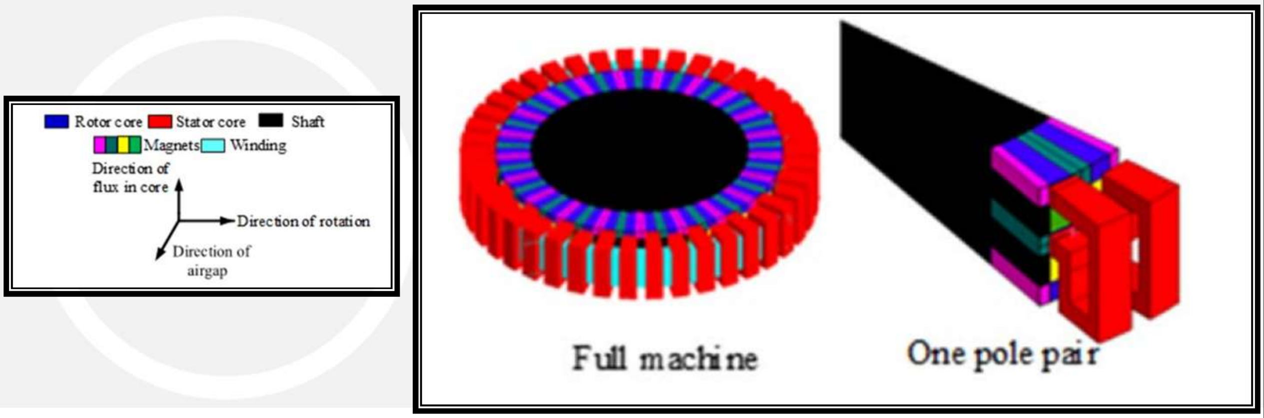
TRANSVERSE FLUX WITH RADIAL GAP



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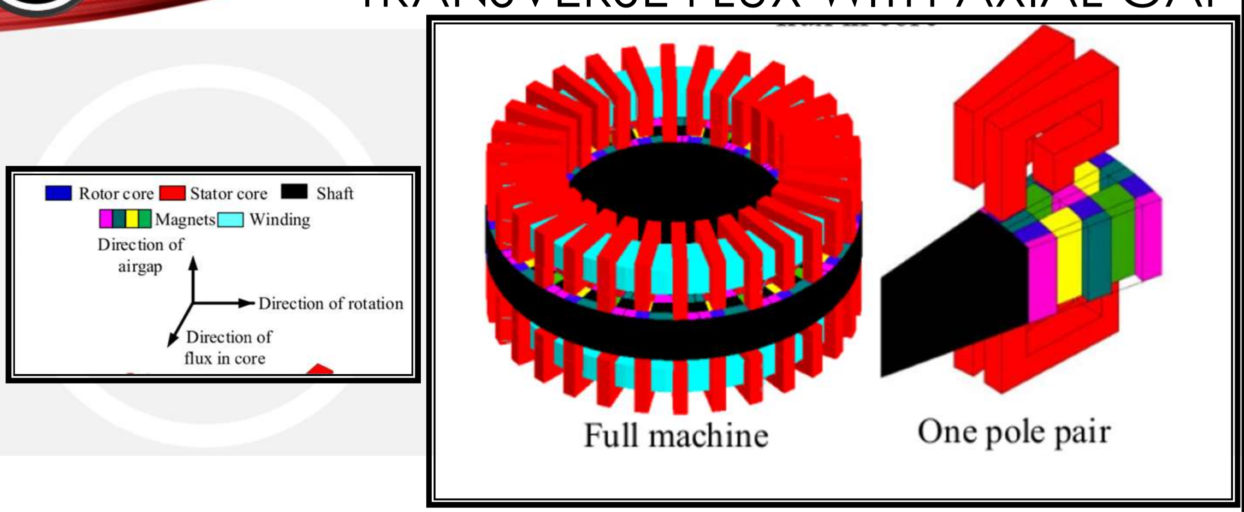
TRANSVERSE FLUX WITH AXIAL GAP



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RADIAL FLUX

- 2D Magnetic Structure;
- Largely used in the industry;

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AXIAL FLUX

- 3-D magnetic structure;
- Lamination manufacturing is tricky;
- AFMs can outperform RFMs under a set of narrow conditions;
- Number of poles must be high;
- Axial length must be short;

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TRANSVERSE FLUX

- 3D magnetic structure;
- Jury is out on the effectiveness;
- Perfect for SMC application;
- Limited research in the industry.

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HALBACH ARRAY

- Emerging Interest;
- Exciting possibilities with precise arrangement of magnets and magnetization direction;
- Demonstrated utility for very high speed applications.

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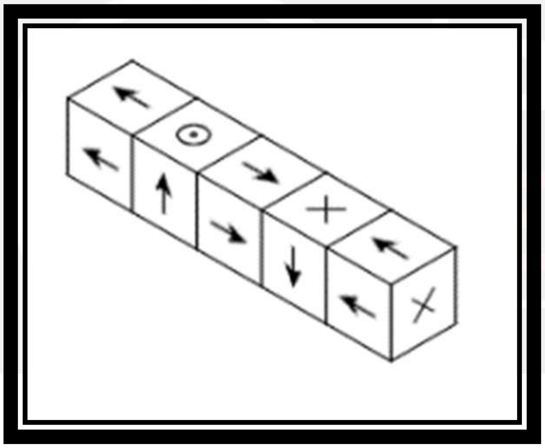
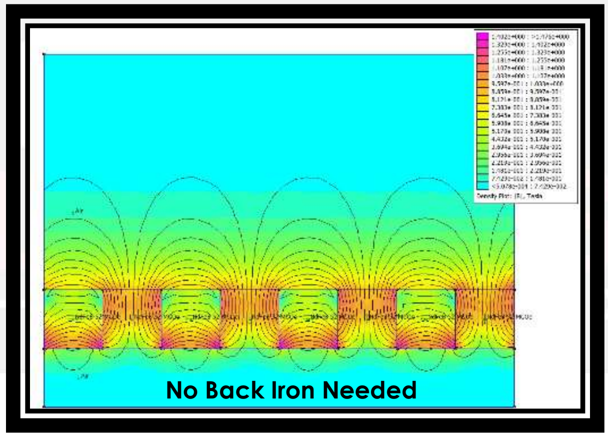
HALBACH ARRAY





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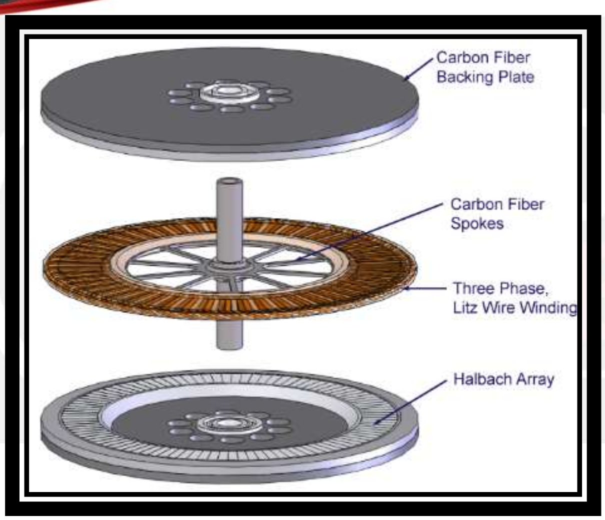
HALBACH ARRAY



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VARIOUS MOTOR ARCHITECTURES

Architecture	Flux Direction	Key Feature	Application Focus	Pros	Cons
Radial Flux Motor (RFM)	Radial	Common, mature design	General industry, EVs, fans	Mature, good performance, easier to manufacture	Limited cooling, longer motor for high torque
Axial Flux Motor (AFM)	Axial	Compact, high torque density	eBikes, aerospace, EVs	High torque density, better cooling, compact	Manufacturing complexity, tight tolerances
Transverse Flux Motor (TFM)	Transverse	High torque, modular	Direct-drive, robotics	Very high torque density, direct-drive suitability	Complex design, higher losses
Flux Switching PM Motor (FSPM)	Radial/Switching	Robust rotor, stator magnets	EVs, high-reliability systems	High reliability, robust rotor	High core losses, complex flux paths
Hybrid Excitation PM Motor	Radial	PM + wound field	Automotive, field-weakening	Wide speed range, tunable field	Added complexity, heavier
Linear Permanent Magnet Motor	Linear	Straight-line motion	Automation, maglev	No conversion loss, precise motion	Costly, niche applications

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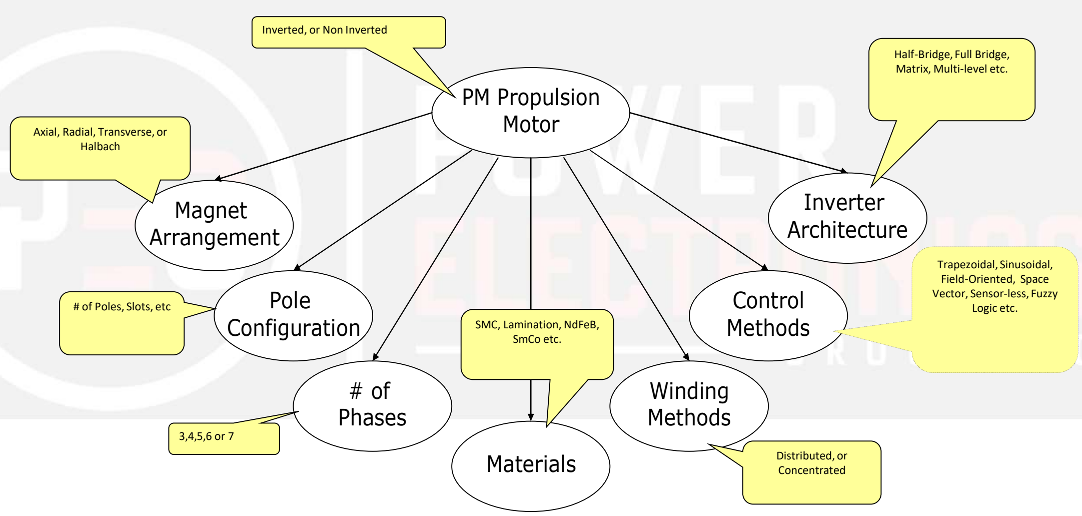
CURRENT STATE OF THE ART



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INVERTER ARCHITECTURES

Architecture	Voltage Levels	Complexity	Common Use
2-Level VSI	2	Low	General motor drives, EVs
3-Level NPC	3	Medium	High-power industrial applications
Multilevel (MLI)	5+	High	HVDC, wind/solar farms
Matrix	AC-AC	High	Aerospace, compact systems
CSI	2	Medium	Constant torque applications
Z-Source / qZSI	Variable	Medium	Solar inverters, EVs
Dual Inverter	2x2-Level	High	Aerospace, EVs
Multiphase Inverter	N-Phase	High	Fault-tolerant, high-performance

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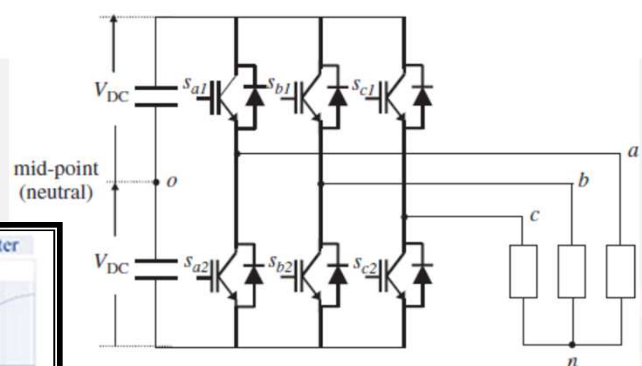
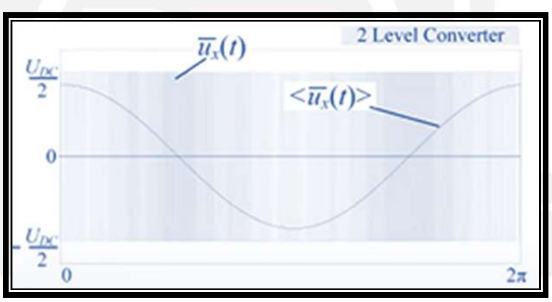
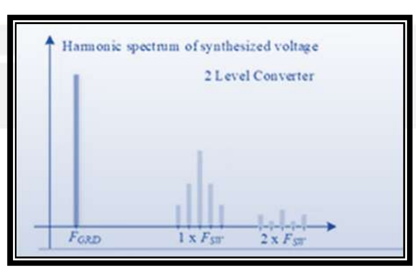
2-LEVEL INVERTER







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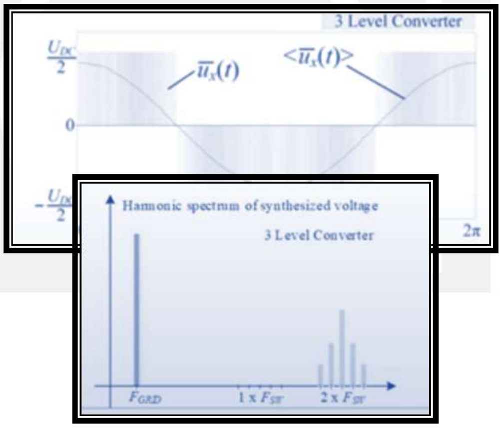
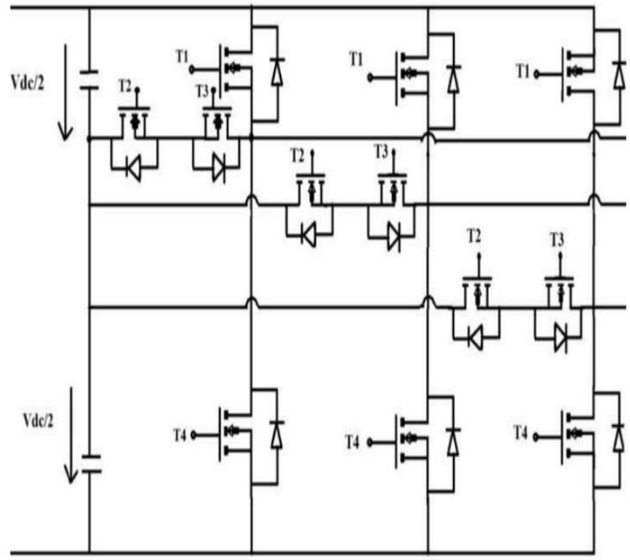
3-LEVEL NPC

T-Type Inverter





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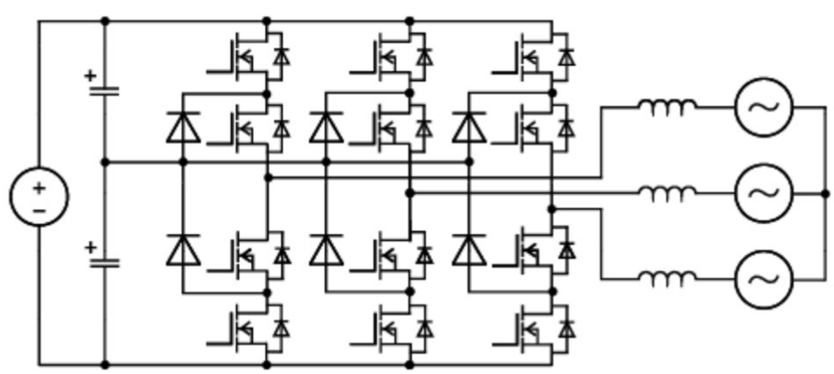
3-LEVEL NPC

I-Type Inverter



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3 VS. 5 VS. 7

- Advantages:
  - 5 Phase can help reduce motor size;
  - 5 and 7 phases can help reduce inverter size.
- Disadvantages:
  - Controller Complexity

WINDING METHODS

- Fractional Slot Concentrated Winding
  - High Power Density;
  - High Efficiency;
  - Short End Turns;
  - High Slot Fill Factor;
  - Low Cogging Torque;
  - Flux Weakening Capability;
  - Fault Tolerance.

OPTIMIZATION

- N_s = Number of stator slots
- N_m = Number of magnets
- N_{spp} = Ns/Nm/Nph = Number of slots per pole per phase
- R_{ro} = Rotor outside radius
- R_{so} = Stator outside radius
- R_{ro}/R_{so} = Radius Ratio
- K_m = Motor constant = N.m/√W
- α_{*sk} = Skew Factor
- n_{cog} = Cogging factor

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K_M INCREASED FROM 0.82 TO 1.28

N_s	N_m	N_{spp}	R_{ro}/R_{so}	K_m	α^*_{sk}	n_{cog}
15	8	0.625	0.6	0.82	0.125	15
18	10	0.6	0.6	0.94	0.2	9
21	8	0.875	0.6	1.01	0.125	21
30	8	1.25	0.6	1.02	0.25	15
27	8	1.125	0.6	1.05	0.125	27
18	8	0.75	0.6	1.06	0.25	9
33	8	1.375	0.6	1.06	0.125	33
36	8	1.5	0.6	1.07	0.5	9
24	8	1	0.6	1.1	1	3
15	10	0.5	0.6	1.1	0.5	3
12	10	0.4	0.6	1.19	0.2	6
9	10	0.3	0.6	1.28	0.1	9

Constant

74

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K_M INCREASED FROM 1.12 TO 1.39

N_s	N_m	N_{spp}	R_{ro}/R_{so}	K_m	α^*_{sk}	n_{cog}
36	10	1.2	0.62	1.12	0.2	18
24	10	0.8	0.62	1.13	0.2	12
18	12	0.5	0.62	1.15	0.5	3
33	10	1.1	0.62	1.16	0.1	33
30	10	1	0.62	1.21	1	3
27	12	0.75	0.62	1.23	0.5	9
15	14	0.35714	0.62	1.35	0.071429	15
12	14	0.28571	0.62	1.39	0.14286	6

Constant

75

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K_M INCREASED FROM 0.95 TO 1.49

N_s	N_m	N_{spp}	R_{ro}/R_{so}	K_m	α^*_{sk}	n_{cog}
27	14	0.64286	0.64	0.95	0.071429	27
36	20	0.6	0.64	1.01	0.2	9
24	14	0.57143	0.64	1.02	0.14286	12
30	14	0.71429	0.64	1.25	0.14286	15
21	16	0.4375	0.64	1.25	0.0625	21
36	16	0.75	0.64	1.29	0.25	9
18	16	0.375	0.64	1.34	0.125	9
24	20	0.4	0.64	1.37	0.2	6
15	16	0.3125	0.64	1.42	0.0625	15
18	20	0.3	0.64	1.49	0.1	9

Constant

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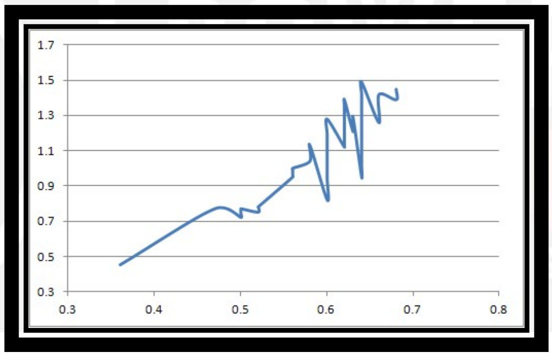
K_M VS. R_{RO}/R_{SO}



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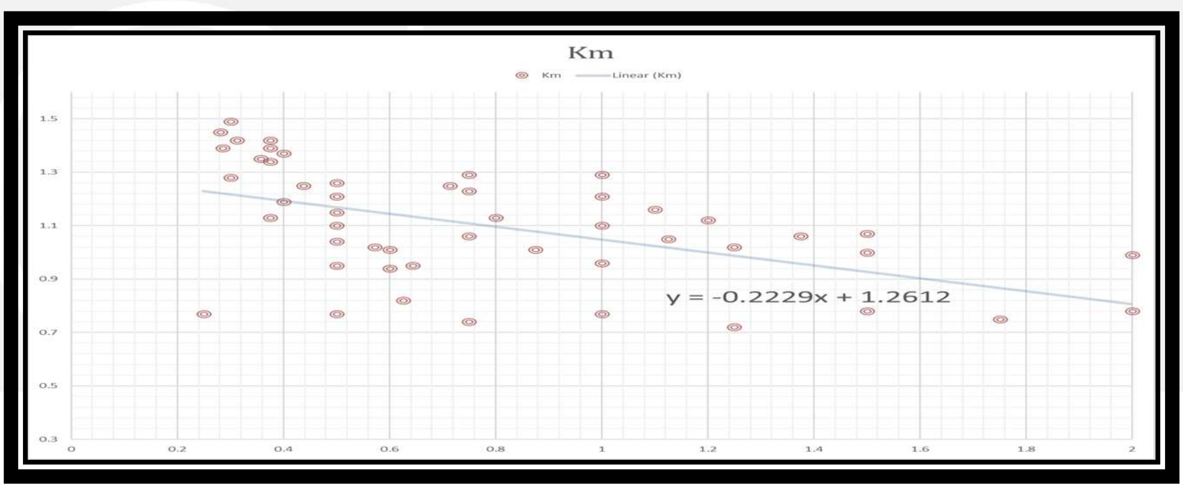
K_M VS. N_{SPP}



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TAKE AWAYS

- Small Tweaks can make a big difference in Motor performance;
- One must engage in the Optimization effort diligently and judiciously;
- One must have a well thought out design of experiments.

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MAGNETIC ARCHITECTURES

Brushless PM Motor Design Workshop with System Focus

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ARCHITECTURES

- Rotor Architectures (Interior)
- Rotor Architectures (Exterior)
- Stator Architectures (Interior)
- Stator Architectures (Exterior)

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ROTOR ARCHITECTURES (INTERIOR)

- **Surface Mount Magnets**
  - Radial magnets;
  - Two radial magnets per pole;
  - Three radial magnets per pole;
  - Four radial magnets per pole;
  - Parallel magnets.

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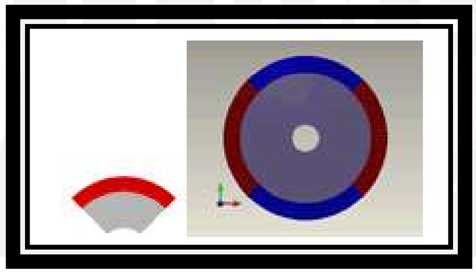
ROTOR ARCHITECTURES (INTERIOR)

- **Surface mounted with radial magnets**



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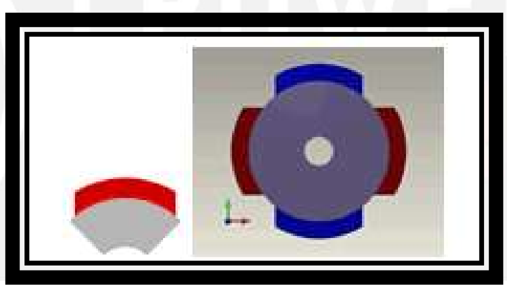
ROTOR ARCHITECTURES (INTERIOR)

- **Surface mounted with parallel magnets**



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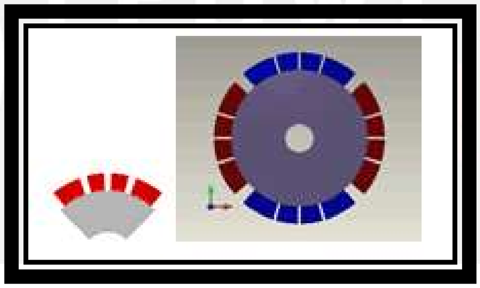
ROTOR ARCHITECTURES (INTERIOR)

- **Surface mounted with four radial magnets per pole**



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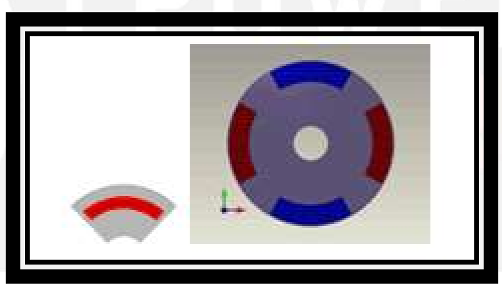
ROTOR ARCHITECTURES (INTERIOR)

- **Inset radial magnets**



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ROTOR ARCHITECTURES (INTERIOR)

- **Spoke Magnets**
  - Embedded Magnets;
  - Non-Embedded Magnets.

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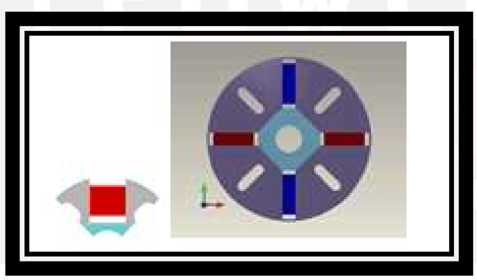
ROTOR ARCHITECTURES (INTERIOR)

- **Spoke with embedded magnets**



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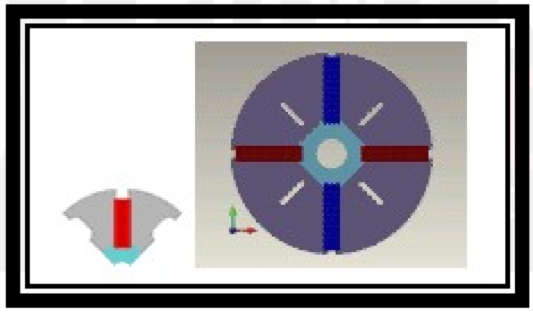
ROTOR ARCHITECTURES (INTERIOR)

- **Spoke with non embedded magnets**



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ROTOR ARCHITECTURES (INTERIOR)

- **Bread-loaf Magnets**
  - Non-Embedded Magnets (NEMs);
  - Two NEMs per pole;
  - Four NEMs per pole;
  - Six NEMs per pole;
  - Eight NEMs per pole;
  - Ten NEMs per pole;
  - Twelve NEMs per pole;
  - Sixteen NEMs per pole.

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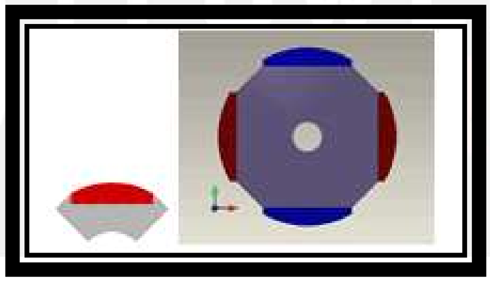
ROTOR ARCHITECTURES (INTERIOR)

- **Bread- loaf with non-embedded magnets**



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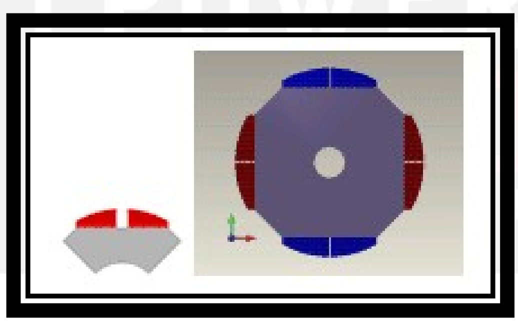
ROTOR ARCHITECTURES (INTERIOR)

- Bread-loaf with two non-embedded magnets per pole



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ROTOR ARCHITECTURES (INTERIOR)

- **IPM**
  - Lateral Magnets;
  - Curved Magnets;
  - Inset Lateral Magnets;
  - Angled Barrier;
  - Angled Barrier (2 Layers);
  - Angled Barrier (3 Layers);
  - Angled Barrier (4 Layers);
  - V-Shaped Barrier (2 Layers);
  - Variable Orientation Magnets;
  - Embedded Variable Orientation Magnets.

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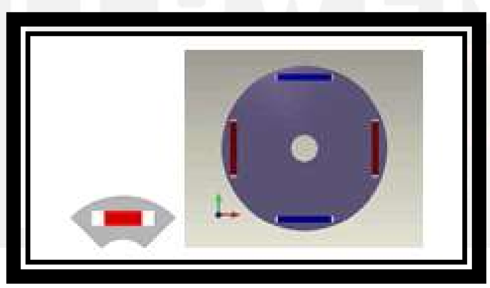
ROTOR ARCHITECTURES (INTERIOR)

- **IPM with lateral magnets**



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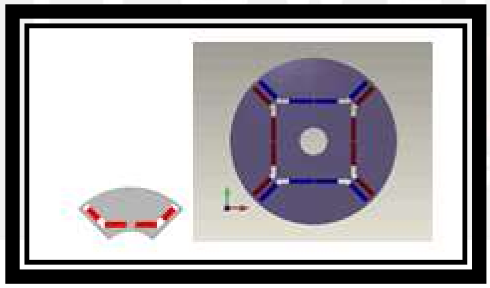
ROTOR ARCHITECTURES (INTERIOR)

- **IPM with angled barrier**



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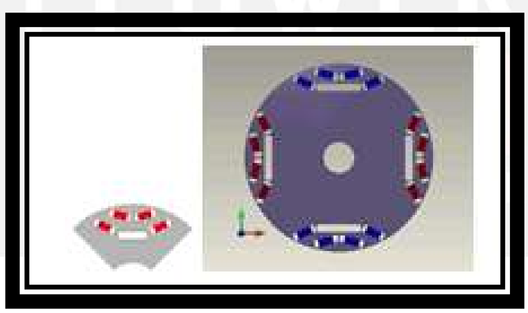
ROTOR ARCHITECTURES (INTERIOR)

- **IPM with V-shaped barrier (2 layers)**



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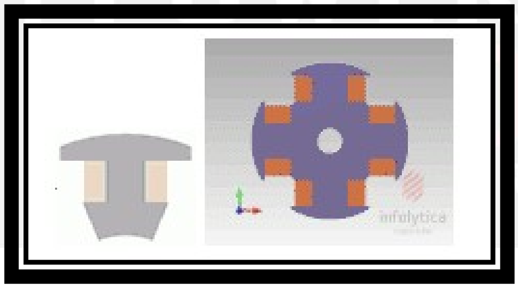
ROTOR ARCHITECTURES (INTERIOR)

- **Wound square type**



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ROTOR ARCHITECTURES (EXTERIOR)

- **Surface Mount**
  - Radial Magnets;
  - Two Radial Magnets per pole;
  - Three Radial Magnets per pole;
  - Four Radial Magnets per pole;
  - Parallel Magnets.
- **Wound square**

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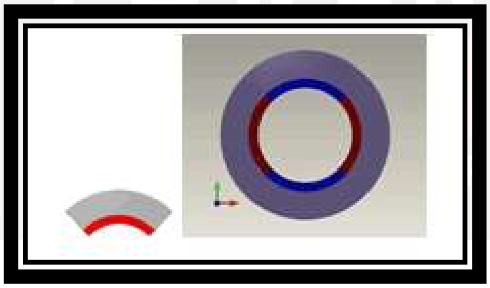
ROTOR ARCHITECTURES (EXTERIOR)

- Surface mounted with radial magnets



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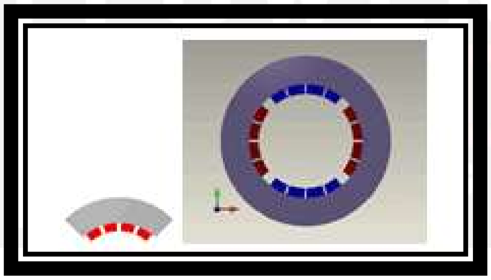
ROTOR ARCHITECTURES (EXTERIOR)

- Surface mounted with 4 radial magnets per pole



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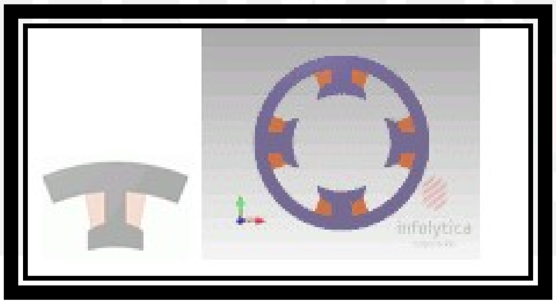
ROTOR ARCHITECTURES (EXTERIOR)

- **Wound square**



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STATOR ARCHITECTURES (EXTERIOR)

- Square;
- Square with curved tangs;
- Round;
- Parallel tooth;
- General square;
- General round.

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STATOR ARCHITECTURES (EXTERIOR)

- Parallel square;
- Parallel round;
- Parallel;
- Slotless.

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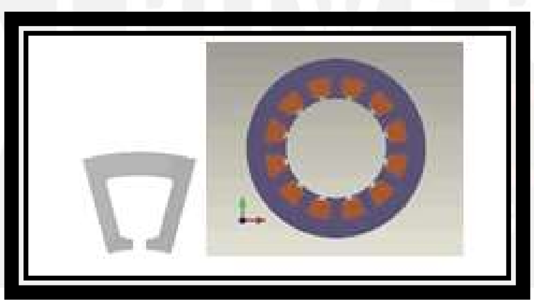
STATOR ARCHITECTURES (EXTERIOR)

- **Square**



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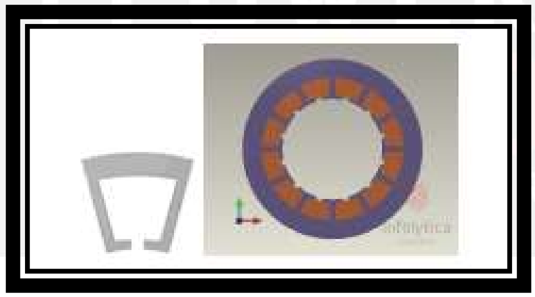
STATOR ARCHITECTURES (EXTERIOR)

- **Square with curved tangs**



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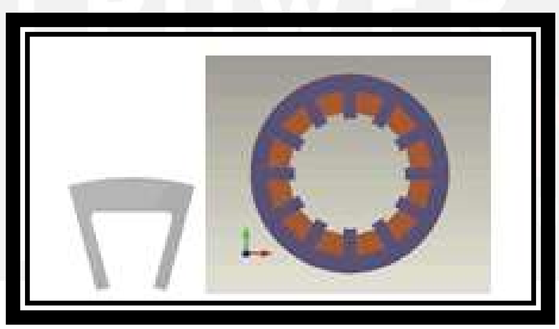
STATOR ARCHITECTURES (EXTERIOR)

- **Parallel tooth**



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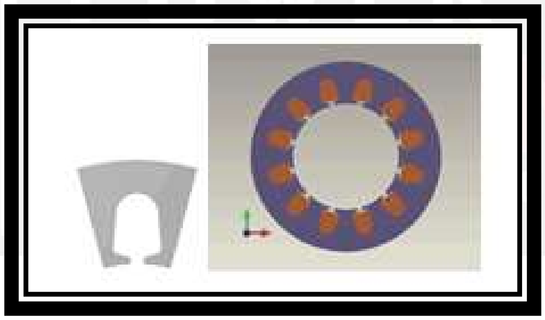
STATOR ARCHITECTURES (EXTERIOR)

- **General round**



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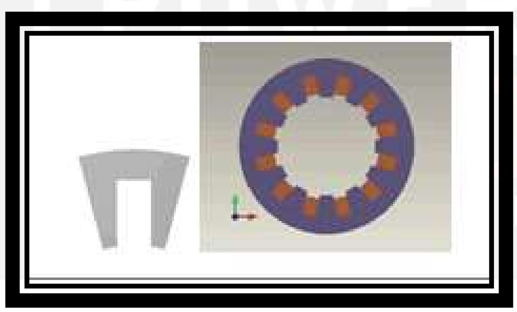
STATOR ARCHITECTURES (EXTERIOR)

- **Parallel**



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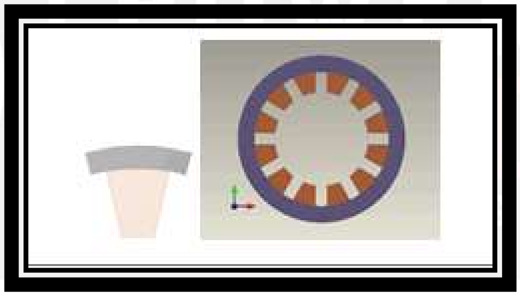
STATOR ARCHITECTURES (EXTERIOR)

- **Slotless**



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STATOR ARCHITECTURES (INTERIOR)

- Square;
- Square with cylindrical tange;
- Round;
- Parallel tooth;
- General square.

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STATOR ARCHITECTURES (INTERIOR)

- General round;
- Parallel round;
- Parallel;
- Slotless.

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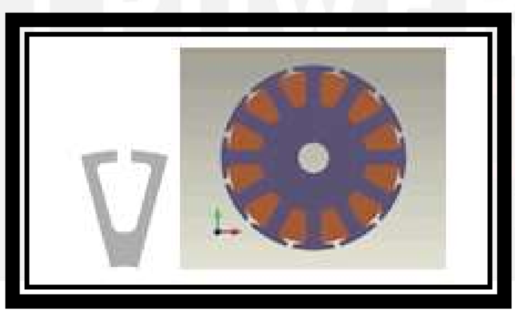
STATOR ARCHITECTURES (INTERIOR)

- **Square**



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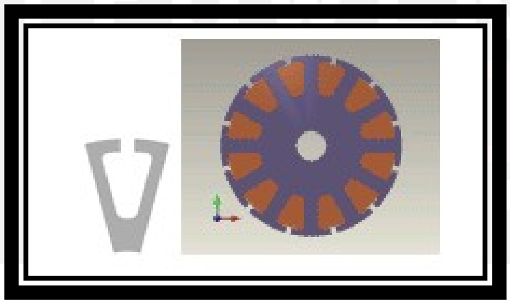
STATOR ARCHITECTURES (INTERIOR)

- **Square with cylindrical tangs**



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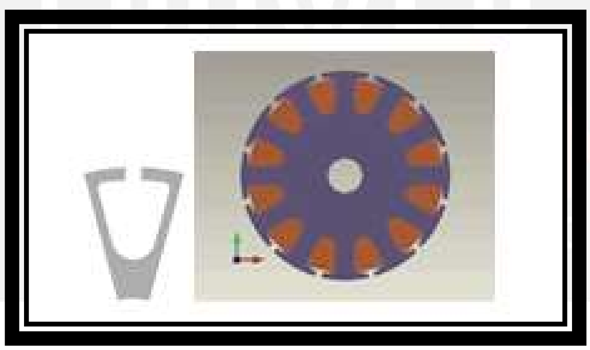
STATOR ARCHITECTURES (INTERIOR)

- **Round**



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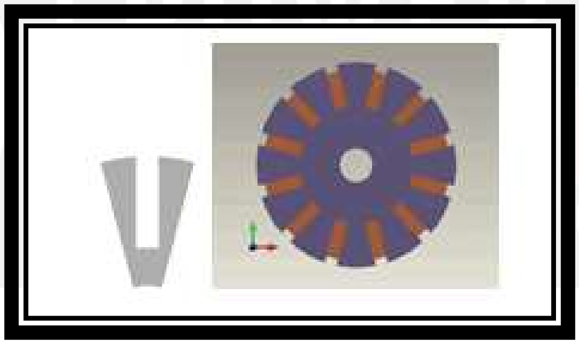
STATOR ARCHITECTURES (INTERIOR)

- **Parallel**



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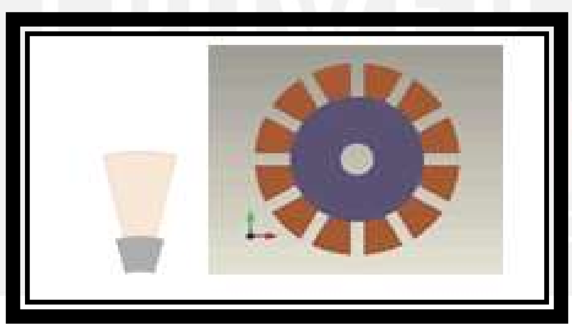
STATOR ARCHITECTURES (INTERIOR)

- **Slotless**



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ANALYTICAL METHODS – PART 3

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AGENDA

- Magnetic Circuit Concepts;
  - Air Gap Modeling;
  - Slot Modeling;
- Magnetic Materials
  - Core Loss;
  - Permanent Magnet Magnetic Circuit Model

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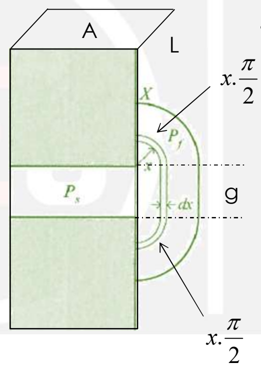
AIR GAP MODELING



- The calculation of the air gap permeance using approximation utilizes the fact that permeances add in parallel just as electrical conductances do.

$$P_f = \sum \frac{\mu_o dA}{l} = \sum \frac{\mu_o L dx}{l}$$

Contribution

$$P_f = \int_0^X \frac{\mu_o L}{g+\pi x} dx = \frac{\mu_o L}{\pi} \ln\left(1+\frac{\pi X}{g}\right)$$

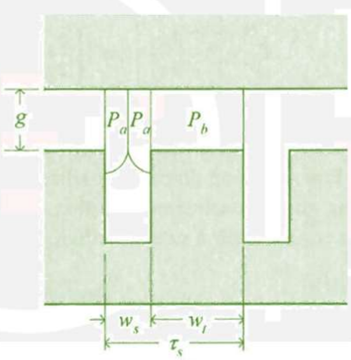
AIR GAP MODELING

- As we move further from the air gap the contribution of differential permeances decreases.
- The exact value chosen are not that critical.
- As X increases beyond about 10g, there is little change in the total air gap permeance.

AIR GAP MODELING

- Discuss its implications with respect to the motor design.
  - Thin Stack Designs
  - Stack Height vs. Air Gap

SLOT MODELING



W_s = Slot Width
W_t = Tooth Width
T_s = Slot Pitch

- Crude approximation
  - Ignore the flux crossing the gap over the slot

$$P_g = \mu_0 (A - A_s)/g$$

  - $A_s = w_s L$
  - Not accurate

SLOT MODELING

- Accurate Methods to determine air gap permeance
  - The flux crossing the gap over the slot travels a further distance before reaching the highly permeable material across the gap

$$P_g = \mu_0 . \frac{A}{g_e} \qquad g_e = k_c . g$$

  - K_c> 1 is an air gap length correction factor and is known as Carter's coefficient

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SLOT MODELING

- Conformal Mapping Technique
  - Carter was able to determine an analytic magnetic field solution
  - Analytical expressions for Carter's coefficient

$$K_{c1} = \left[1 - \frac{1}{\frac{\tau_s}{w_s}\left(5\frac{g}{w_s} + 1\right)}\right]^{-1}$$

$$K_{c2} = \left[1 - \frac{2w_s}{\pi\tau_s}\left\{\tan^{-1}\left(\frac{w_s}{2g}\right) - \frac{g}{w_s}\ln\left[1 + \frac{1}{4}\left(\frac{w_s}{g}\right)^2\right]\right\}\right]^{-1}$$

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SLOT MODELING

- Air gap permeance calculation utilizes the circular arc, straight line modeling
  - The permeance of the air gap over one slot pitch τ_s

$$P_g = 2P_a + P_b = \mu_o L\left[\frac{w_t}{g} + \frac{4}{\pi}\ln\left(1+\frac{\pi w_s}{4g}\right)\right]$$

$$K_{c3} = \left[1 - \frac{w_s}{\tau_s} + \frac{4g}{\pi\tau_s}\ln\left(1+\frac{\pi w_s}{4g}\right)\right]^{-1}$$

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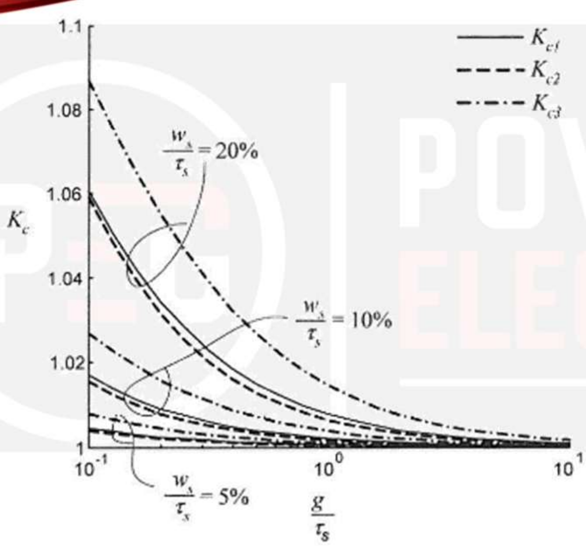
SLOT MODELING



- K_{c3} dictates a larger correction factor than either of the historical Carter's coefficient expressions

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SLOT MODELING

- The correction factor **increases** as the slot percentage w_s/τ_s increases (Slot Width Increases).
- Correction factor **decreases** as the relative gap length g/τ_s increases (Air Gap Increases).
- **Smaller slot openings and larger air gap lengths** require less correction because the influence of the longer flux path length in the slot area is decreased.

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SLOT MODELING

- The presence of a permanent magnet across the air gap from the slotted structure changes the computation of Carter's coefficient.
- The air gap length g must be replaced by $g+l_m/\mu_R$

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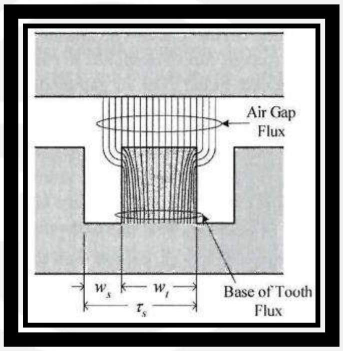
SLOT MODELING



- The presence of slots squeezes the air gap flux into a cross-sectional area $(1-w_s/\tau_s)$ times smaller than the cross-sectional area of the entire air gap over one slot pitch.
- The average flux density $B=\phi/A$ at the base of the teeth is greater by a factor of $\mathbf{(1-w_s/\tau_s)^{-1}}$

SLOT MODELING EXAMPLE

- Average flux density crossing the air gap is 1.0 T
- Slot fraction, $\alpha_s= w_s/\tau_s$ is 0.5
- The average flux density in the base of the teeth is 2.0 T.
- Since this flux density level is sufficient to saturate most magnetic materials, there is an upper limit to the achievable air gap flux density in a motor.

WHAT IS AN AIR GAP LENGTH CORRECTION FACTOR?

- Discuss its implications with respect to the motor design
  - Consider Small Air Gap (<0.5mm)
    - Discuss Manufacturing Implications;
    - Discuss Performance Implications.
  - Consider Small Slot Width
    - Repeat the above exercise

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MAGNETIC MATERIAL ANALYSIS

- Assumptions
  - Magnetic field direction;
  - Flux path lengths;
  - Flux uniformity over cross-sectional areas.

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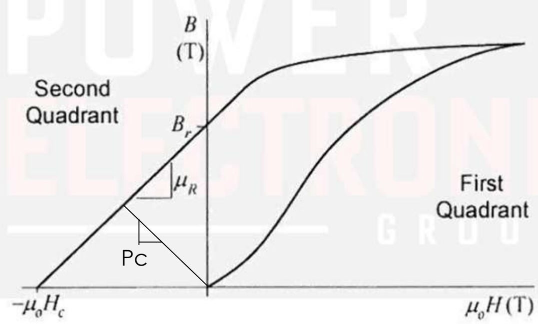
PERMANENT MAGNETS

- Permanent magnets are magnetic materials with **large hysteresis loops**
  - Alnico
  - Ferrite (ceramic)
  - Somarium-cobalt
  - Neodymium-iron boron (NdFeB)
- Ferrite types are the most popular because they are inexpensive.
- NdFeB magnets are more popular in higher performance applications because they are much cheaper than somarium cobalt

PERMANENT MAGNETS

- The remanence is the maximum flux density that the magnet can produce by itself

1. Which quadrant is significant for motor design?
2. What is the significance of the first quadrant?



PERMANENT MAGNETS

- At B=0, the magnitude of the field intensity across the magnet is equal to the negative of the coercivity or coercive force, denoted H_c because H_c is stated as a positive value on permanent magnet specifications.
- The magnitude of the slope of a line drawn from a point on the curve to the origin is known as the permeance coefficient, denoted Pc.
- Pc=0 is operation at the coercivity B=0, H= -Hc, and Pc=infinity is operation at the remanence B=Br, H=0.

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PERMANENT MAGNETS

- Permanent magnet materials such as samarium-cobalt and NdFeB materials have straight demagnetization curves throughout the second quadrant at room temperature
- The slope of the straight line demagnetization curve in the second quadrant is equal to μ_R, where μ_R is the **relative recoil permeability** of the material.

Do Magnets store energy? Why is this energy not dissipated like in a battery?

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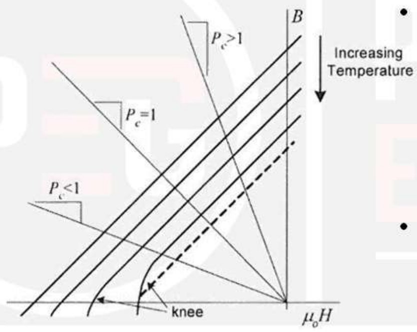
PERMANENT MAGNETS



- At higher temperatures, the demagnetization curve shrinks toward the origin, the flux available from the magnet drops, reducing the performance of the magnet.
- This performance degradation is reversible as the demagnetization curve returns to its former shape as temperature drops

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PERMANENT MAGNETS

- The maximum energy product (BH)max of a magnet is the maximum product of the flux density and field intensity along the magnet demagnetization curve.
- Even though this product has units of energy, it is not actual stored magnet energy, but rather it is a qualitative measure of a magnet's performance capability in a magnetic circuit.
- By convention, (BH)max is usually specified in the English units of millions of Gauss – Oersteds (MG-Oe).
- 1MG-Oe=7.958 kJ/m^3

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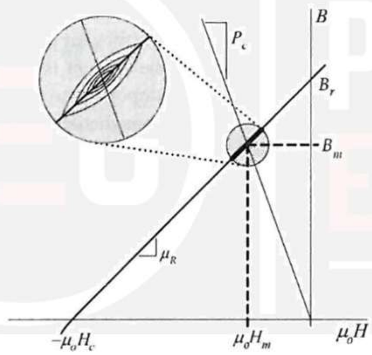
PM MAGNETIC CIRCUIT MODEL



- When motor windings are energized, the operating point dynamically varies following minor hysteresis loops about the static operating point

PM CIRCUIT MODEL

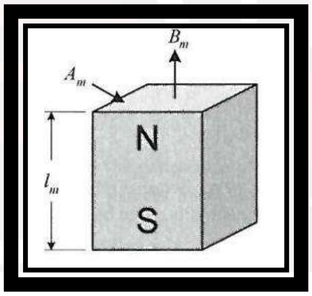
- **Loops:** These loops are thin and have a slope essentially equal to that of the demagnetization characteristic.
- **Trajectory:** The trajectory closely follows the straight line demagnetization characteristic

$$B_m = B_r + \mu_R \mu_o H_m$$

- **Demagnetization:** If the external magnetic field opposes that developed by the magnet and drives the operating point into the third quadrant past the coercivity, it is possible to irreversibly demagnetize the magnet if a knee in the characteristic is encountered.

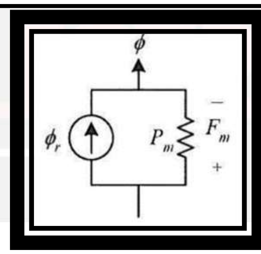
PM MAGNETIC CIRCUIT MODEL

Rectangular magnet



Flux leaving the magnet is

$$\phi = B_m A_m = B_r A_m + \mu_R \mu_o A_m H_m$$



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PM MAGNETIC CIRCUIT MODEL

$$\phi = \phi_r + P_m F_m$$

$$\phi_r = B_r A_m$$

$$P_m = \frac{\mu_R \mu_o A_m}{l_m}$$

- Uniform Magnetization: It is important to recognize that this model assumes that the physical magnet is uniformly magnetized over its cross section and is magnetized in its preferred direction of magnetization

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PM CIRCUIT MODEL

- **Uniformity:** During magnetization the same amount of flux magnetizes each differential length.
- **Br:** The achieved remanence decreases linearly with increasing radius because the same flux over a increasing area gives a smaller flux density.

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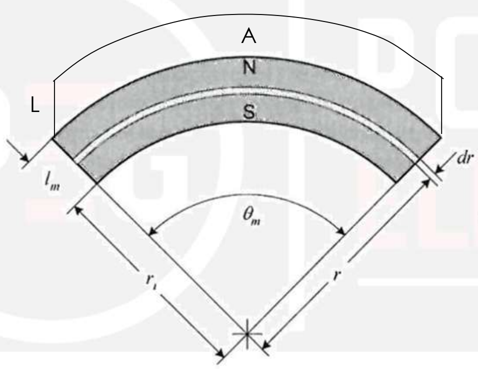
PM MAGNETIC CIRCUIT MODEL



$$dR = \frac{dl}{\mu A} = \frac{dr}{\mu r \theta_m L}$$

- Because reluctances add in series just as resistors do, the net reluctance of the magnet is given by the sum, i.e., integral, of each differential reluctance

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PM MAGNETIC CIRCUIT MODEL

$$R_m = \int_{r_i}^{r_i+l_m} dR = \int_{r_i}^{r_i+l_m} \frac{1}{\mu_R \mu_o L \theta_m r} dr = \frac{\ln\left(1+{l_m}/{r_i}\right)}{\mu_R \mu_o L \theta_m}$$

$$P_m = \frac{\mu_R \mu_o L \theta_m}{\ln\left(1+{l_m}/{r_i}\right)}$$

$$P_m = \frac{\mu_R \mu_o L \theta_m r_i}{l_m}$$

- Which is equivalent to the permeance of a rectangular block having width $\Theta_m r_i$ and length l_m. That is, the magnet appears to have a constant width given by the arc width at r_i

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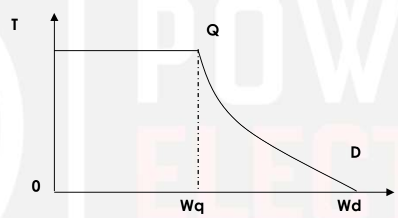
TWO PHASE MOTOR EQUATIONS



$$\text{At Wq,}\ I_d = 0; I_q = I_c; V_q = E_{qo}; V_d = -X_{so} I_c$$

$$\text{At Wd,}\quad I = I_d = -I_c = \frac{V_c - xE_{qo}}{xX_{so}}$$

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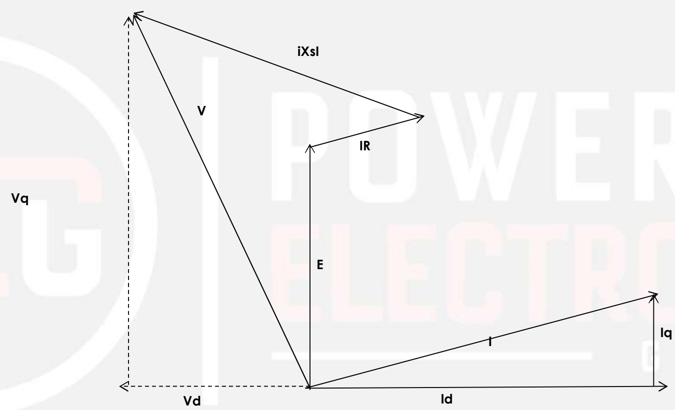
DESIGN



$$V = E + (R + jX_s)I$$

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DESIGN

At Wq,

$$I_d = 0$$

$$I_q = I_c$$

$$V_q = E_{q0}$$

$$V_d = -X_{so} I_c$$

$$I = jI_q = jI_c$$

$$V_c^2 = E_{q0}^2 + X_{so}^2 I_c^2$$

$$I_c = \sqrt{\frac{V_c^2 - E_{qo}^2}{X_{so}^2}}$$

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DESIGN

At Wd,

$$I = I_d = -I_c = \frac{V_c - xE_{q0}}{xX_{so}}$$

$$x = \frac{W_d}{W_q}$$

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DESIGN

For a given speed N, rpm

$$w_e = \frac{2.\pi.N}{60}.p$$

$$E_o = \lambda.w_e$$

$$X_q = w_e.L_q$$

$$X_d = w_e.L_d$$

Field Weakening Equation

$$I_d = \frac{-\lambda L_d + \sqrt{\lambda^2 L_d^2 + \left(L_q^2 - L_d^2\right) - \left(\lambda^2 - \left(\frac{V_{ph}}{w_e}\right)^2 + I_{cmax}^2 L_q^2\right)}}{L_d^2 - L_q^2}$$

$$\lambda = \frac{Nd\varphi}{dt} = L\frac{di}{dt}$$

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DESIGN

$$I_q = \sqrt{I_{cmax}^{\ \ 2} - I_d^{\ 2}}$$

$$I_{cmax}^{\ \ 2} = I_d^{\ 2} + I^2_{\ q}$$

$$T_{rel} = \text{m.p.}\left(L_d - L_q\right).I_d.I_q$$

$$T_{syn} = m.p.\lambda.I_q$$

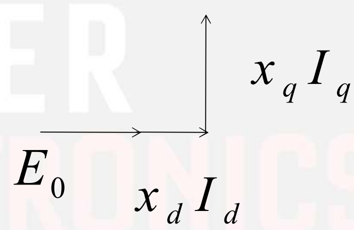
DESIGN

$$T_{em} = T_{syn} + T_{rel}$$

$$V_{c,rms} = \sqrt{\left(X_q I_q\right)^2 + \left(E_0 + X_d I_d\right)^2}$$

$$I_{c,rms} = \sqrt{I_d^{\ 2} + I^2_{\ q}}$$

$$\gamma = \tan^{-1}\frac{I_d}{I_q}$$



PERFORMANCE

At Base Speed

$I_d, I_{q,} V_{d,} V_q$ etc

$$I_d = -I_c \sin(\theta)$$

$$I_q = I_c \cos(\theta)$$

$$V_d = R_{ph} I_d - w_e L_{ph} I_q$$

$$V_q = R_{ph} I_q + w_e L_{ph} I_d + \frac{w_e}{p} \frac{K_w N_{ph} B_g D_r L_{stk}}{\sqrt{2}}$$

$$\delta = \tan^{-1}\left(\frac{V_d}{V_q}\right)$$

PERFORMANCE

$$V_{ph} = \sqrt{V_d^{\,2} + V_q^{\,2}}$$

$$I^2R = m.I_c^{\,2} R_{ph}$$

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AN INTRODUCTION TO SPACE VECTORS – PART 4

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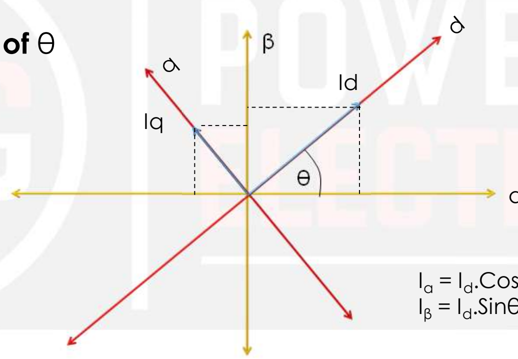
SPACE VECTOR FUNDAMENTALS

Beware of θ



$I_\alpha = I_d.\text{Cos}\theta - I_q.\text{Sin}\theta$
$I_\beta = I_d.\text{Sin}\theta + I_q.\text{Cos}\theta$

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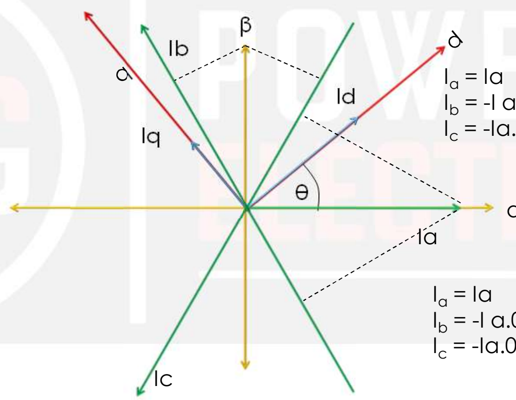
SPACE VECTOR FUNDAMENTALS



$I_{\alpha} = I\alpha$
$I_{b} = -I\,\alpha.Cos60+I\beta.Cos30$
$I_{c} = -I\alpha.Cos60-I\beta.Cos30$

$I_{\alpha} = I\alpha$
$I_{b} = -I\,\alpha.0.5+I\beta.0.87$
$I_{c} = -I\alpha.0.5-I\beta.0.87$

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SPACE VECTOR EQUATIONS

$I_{\alpha} = I_{d}.Cos\theta-I_{q}.Sin\theta$
$I_{\beta} = I_{d}.Sin\theta+I_{q}.Cos\theta$

$I_{a} = I\alpha$
$I_{b} = -I\,\alpha.0.5+I\beta.0.87$
$I_{c} = -I\alpha.0.87-I\beta.0.5$

$I_{a} = I_{d}.Cos\theta-I_{q}.Sin\theta$
$I_{b} = -(I_{d}.Cos\theta-I_{q}.Sin\theta).0.5+(I_{d}.Sin\theta+I_{q}.Cos\theta).0.87$
$I_{c} = -(I_{d}.Cos\theta-I_{q}.Sin\theta).0.5-(I_{d}.Sin\theta+I_{q}.Cos\theta).0.87$

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SPACE VECTOR EQUATIONS

$$\begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} = \begin{bmatrix} Sin\theta & Cos\theta \\ Sin(\theta - \frac{2.\pi}{3}) & Cos(\theta - \frac{2.\pi}{3}) \\ Sin(\theta + \frac{2.\pi}{3}) & Cos(\theta + \frac{2.\pi}{3}) \end{bmatrix} . \begin{bmatrix} Id \\ Iq \end{bmatrix}$$

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SPACE VECTOR EQUATIONS

Beware of θ

$$\begin{bmatrix} Id \\ Iq \end{bmatrix} = \frac{2}{3} \begin{bmatrix} Sin\theta & Sin(\theta - \frac{2\pi}{3}) & Sin(\theta + \frac{2\pi}{3}) \\ Cos\theta & Cos(\theta - \frac{2\pi}{3}) & Cos(\theta + \frac{2\pi}{3}) \end{bmatrix} . \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix}$$

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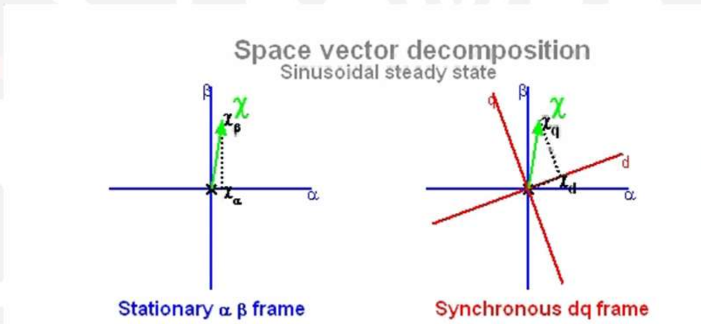
SINUSOIDAL STEADY STATE



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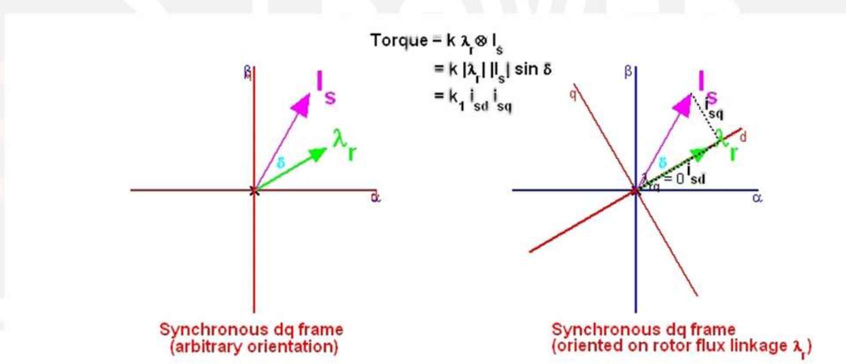
SPACE VECTORS



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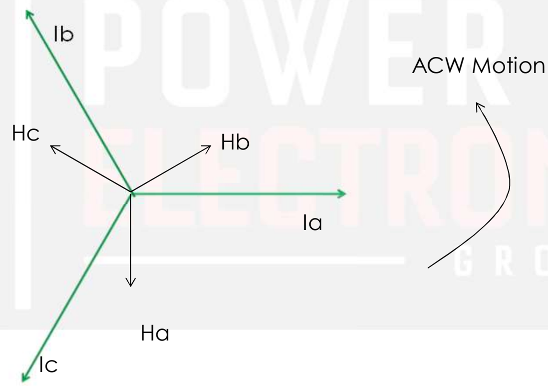
SPACE VECTOR FUNDAMENTALS

Set up the equations such that Iq must lead Id



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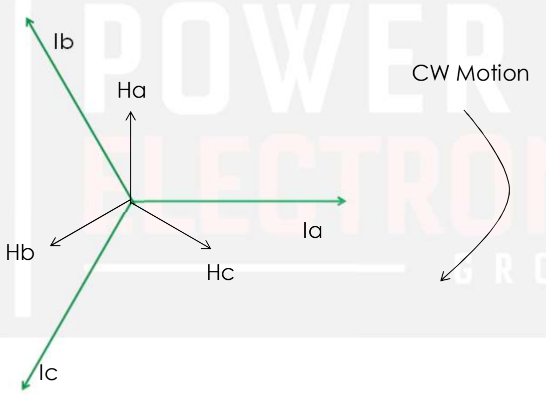
SPACE VECTOR FUNDAMENTALS

Set up the equations such that Iq must lead Id



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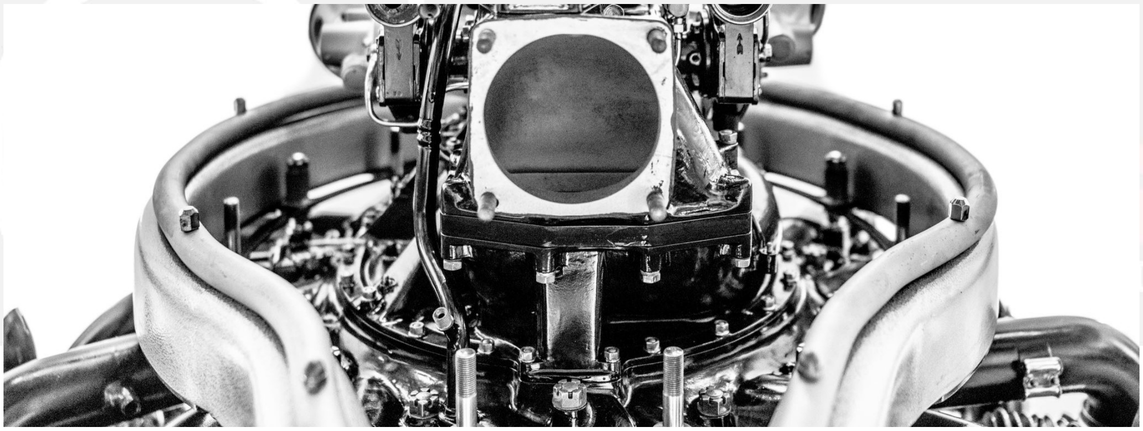
ESTIMATING MOTOR PARAMETERS – PART 5



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AGENDA

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

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ASSUMPTIONS

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

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ASSUMPTIONS

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

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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;

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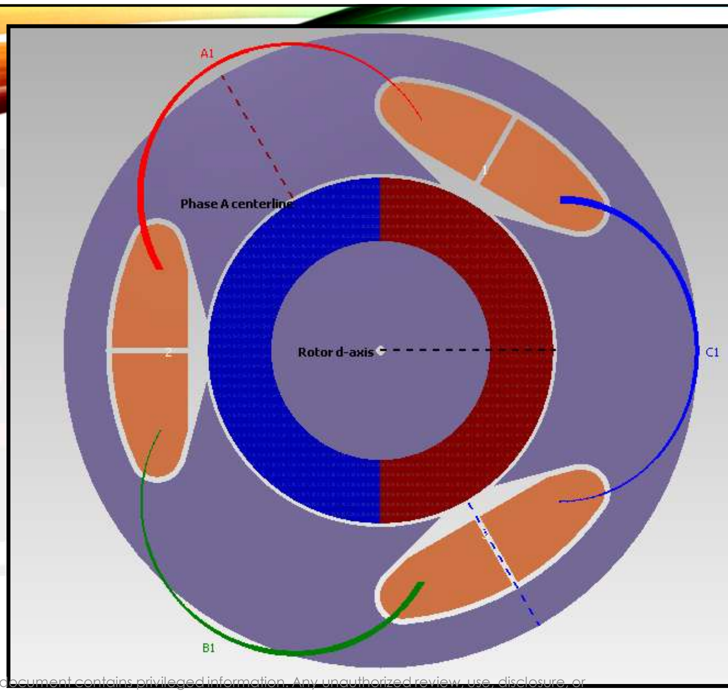

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MODELING OF PMSM MOTOR

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.

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MODELING OF PMSM MOTOR

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

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MODELING OF PMSM MOTOR

$$\lambda_a = L_{aa}I_a + L_{ab}I_b + L_{ac}I_c + \lambda_{ma}$$
$$\lambda_b = L_{ba}I_a + L_{bb}I_b + L_{bc}I_c + \lambda_{mb}$$
$$\lambda_c = L_{ca}I_a + L_{cb}I_b + L_{cc}I_c + \lambda_{mc}$$

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MODELING OF PMSM MOTOR

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

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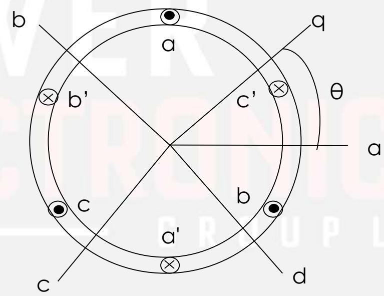
MODELING OF PMSM MOTOR

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

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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?

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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.

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MODELING OF PMSM MOTOR

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

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

Average Value (L_{s0})

Position Dependent Component (L_x)

Leakage Inductance (L_{s1})

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MODELING OF PMSM MOTOR

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

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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

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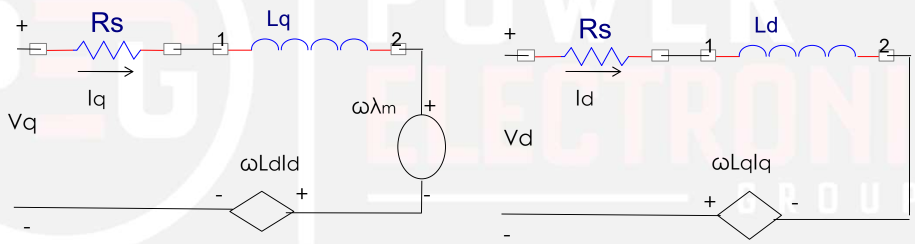
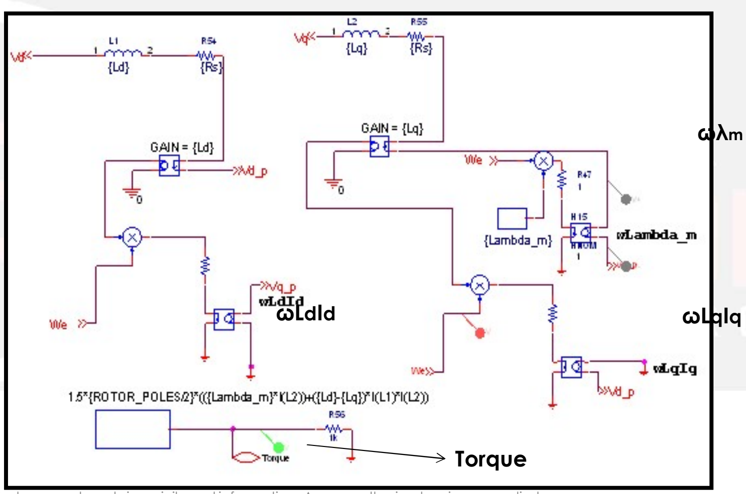
MODELING OF PMSM MOTOR

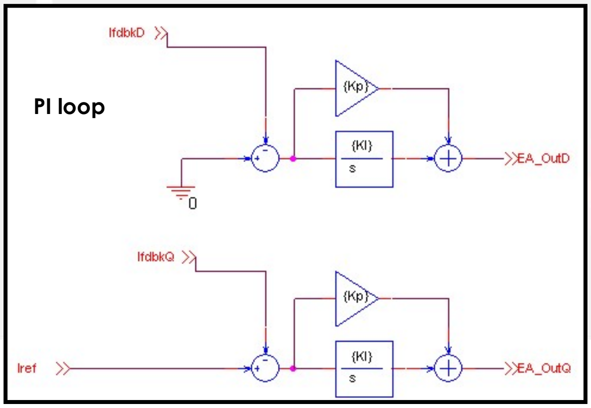
- Equivalent circuit of PMSM:



MODELING OF PMSM MOTOR



MODELING OF PMSM MOTOR



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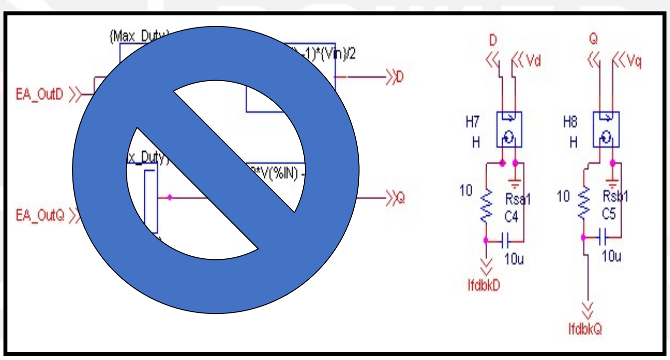
MODELING OF PMSM MOTOR



Large signal model of Half bridge inverter

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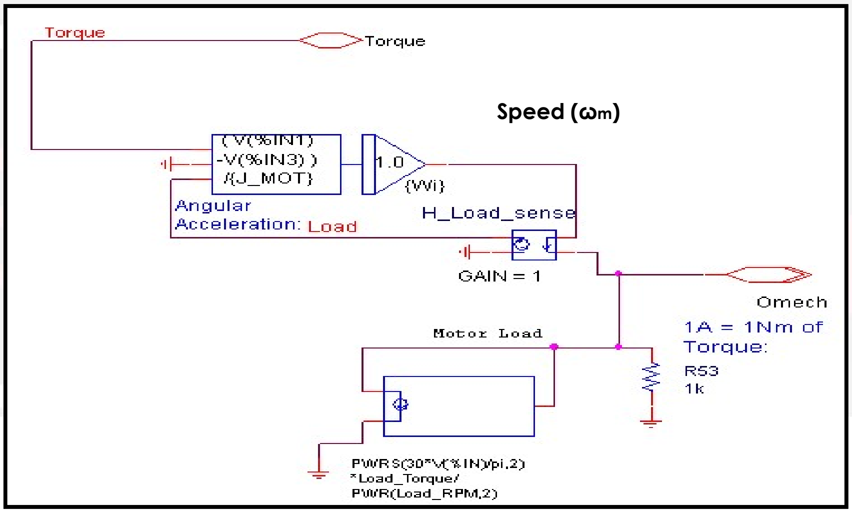
MODELING OF PMSM MOTOR



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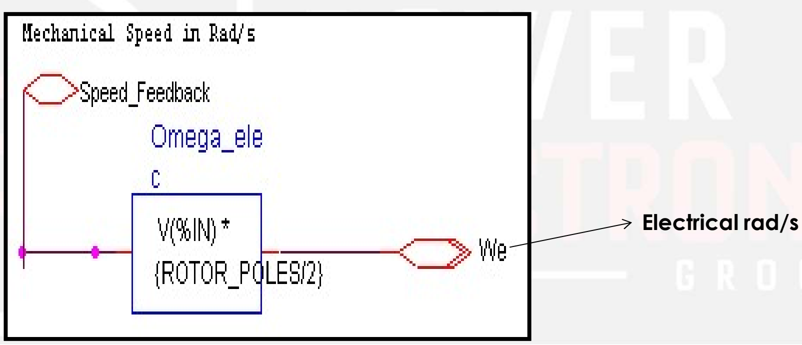
MODELING OF PMSM MOTOR



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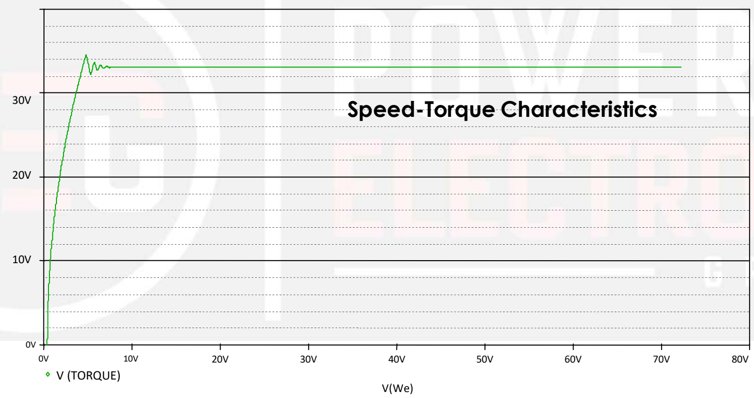
SIMULATION RESULTS



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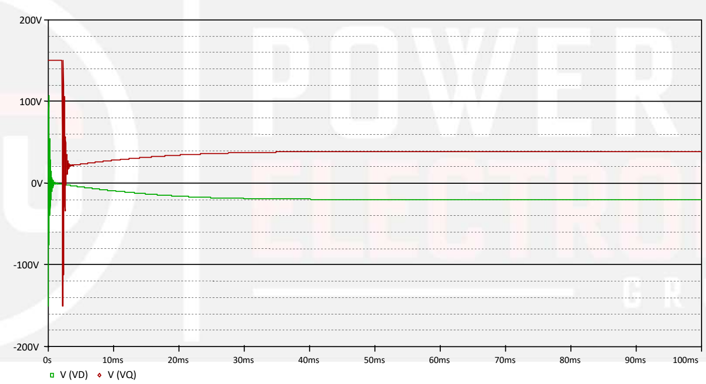
SIMULATION RESULTS

Vd & Vq



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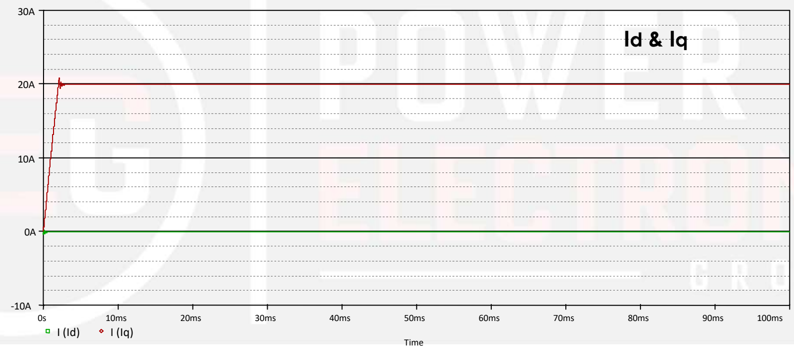
SIMULATION RESULTS



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MODELING OF PMSM MOTOR

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

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

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

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

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

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

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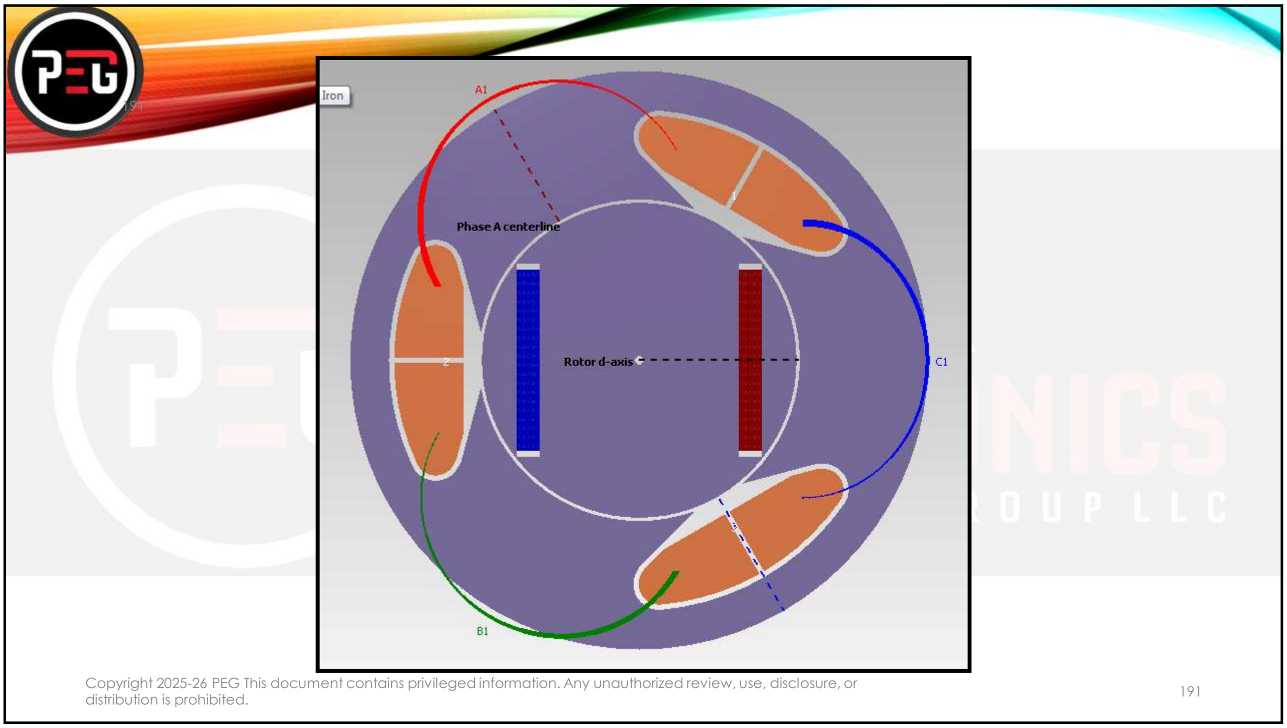
Iron
A1
Phase A centerline
Rotor d-axis
C1
B1
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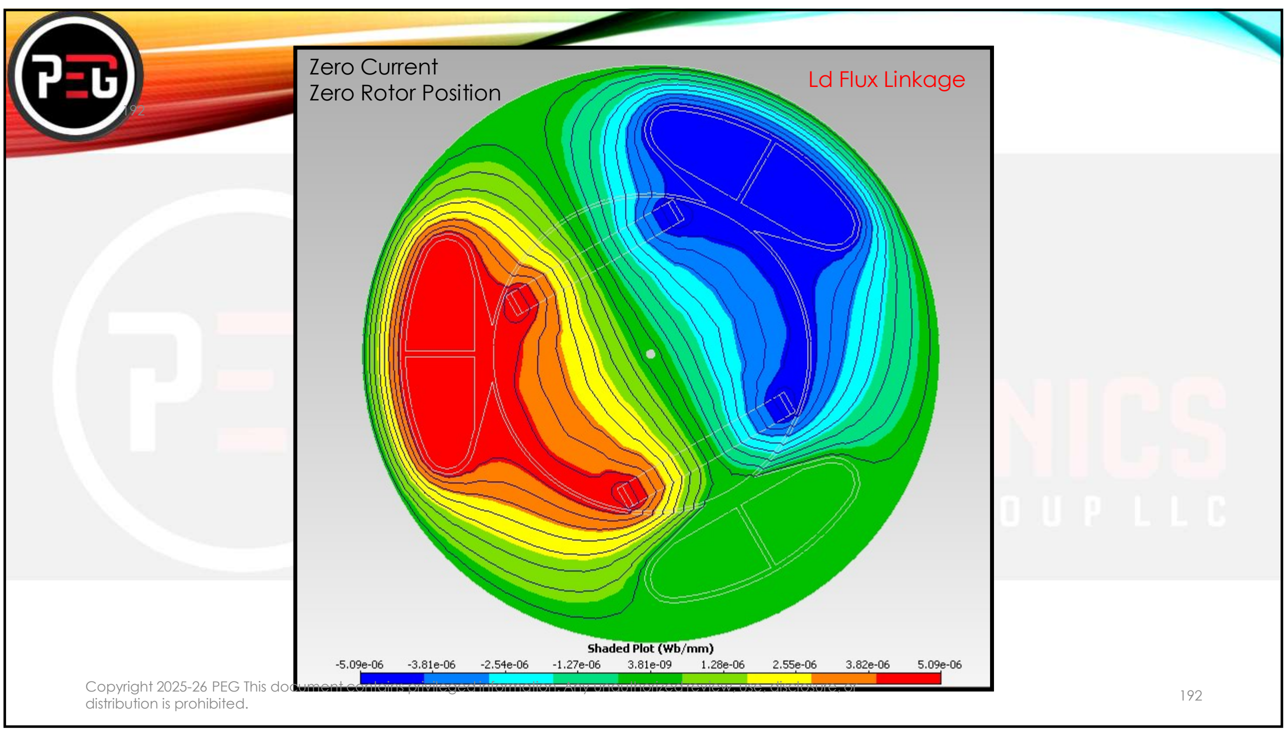
Zero Current
Zero Rotor Position
Ld Flux Linkage
Shaded Plot (Wb/mm)
-5.09e-06 -3.81e-06 -2.54e-06 -1.27e-06 3.81e-09 1.28e-06 2.55e-06 3.82e-06 5.09e-06
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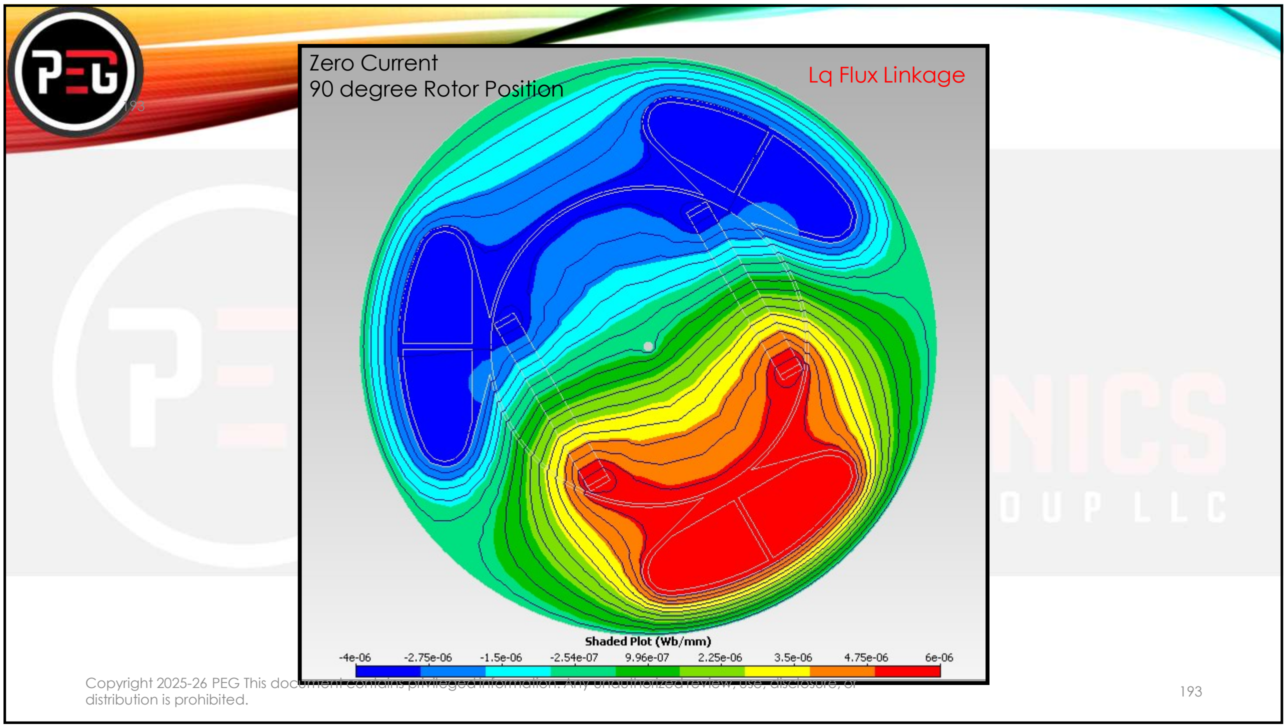
Zero Current
90 degree Rotor Position
Lq Flux Linkage
Shaded Plot (Wb/mm)
-4e-06 -2.75e-06 -1.5e-06 -2.54e-07 9.96e-07 2.25e-06 3.5e-06 4.75e-06 6e-06
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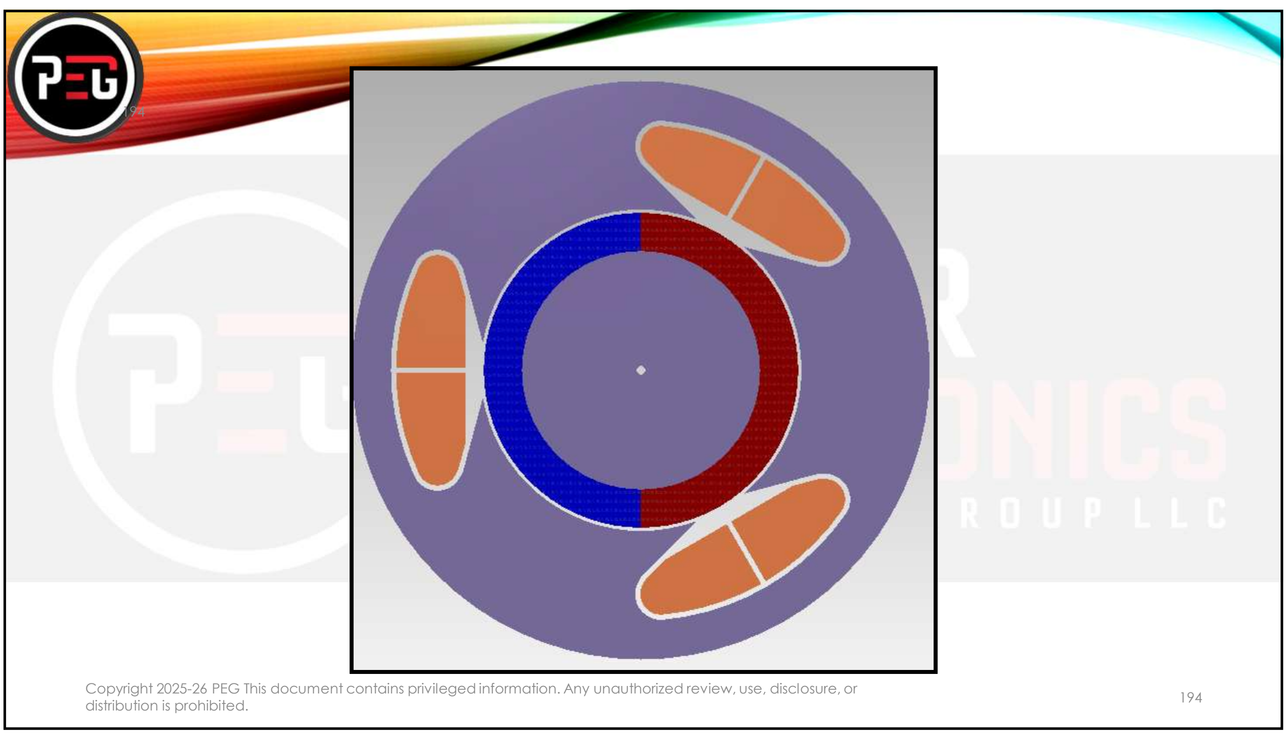
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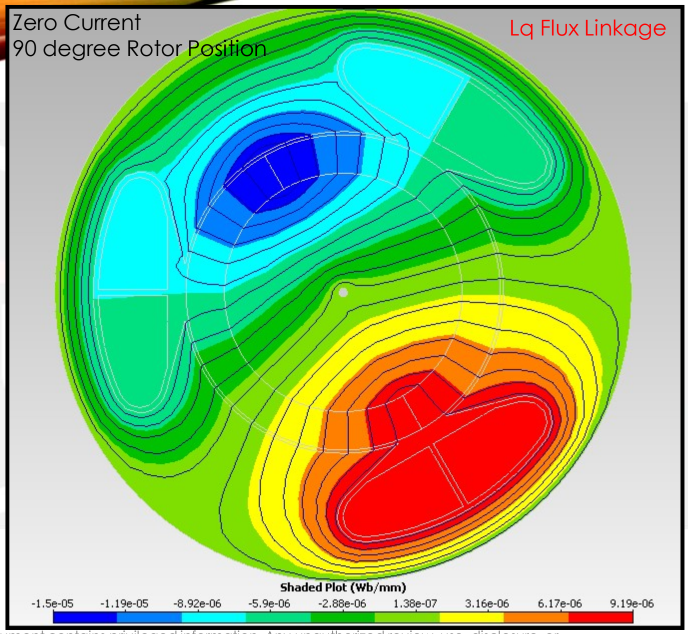

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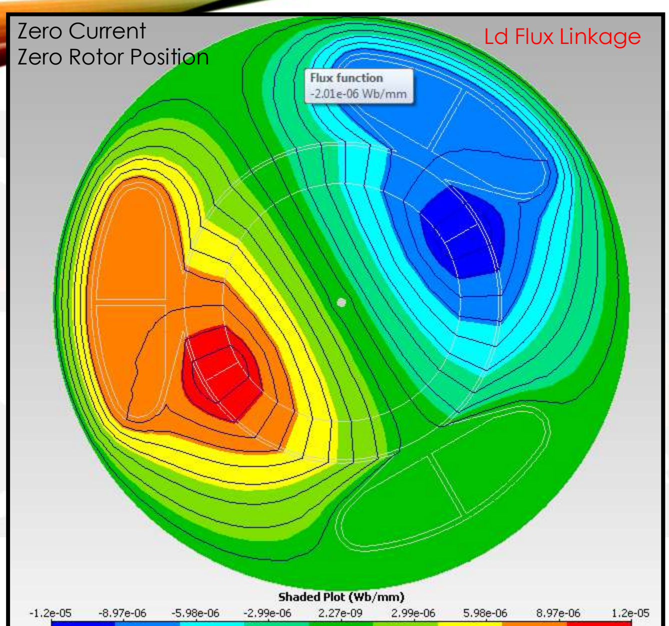

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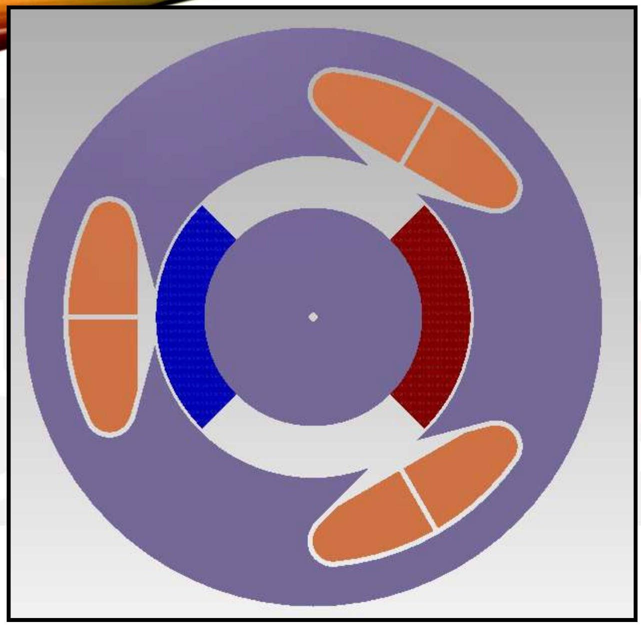

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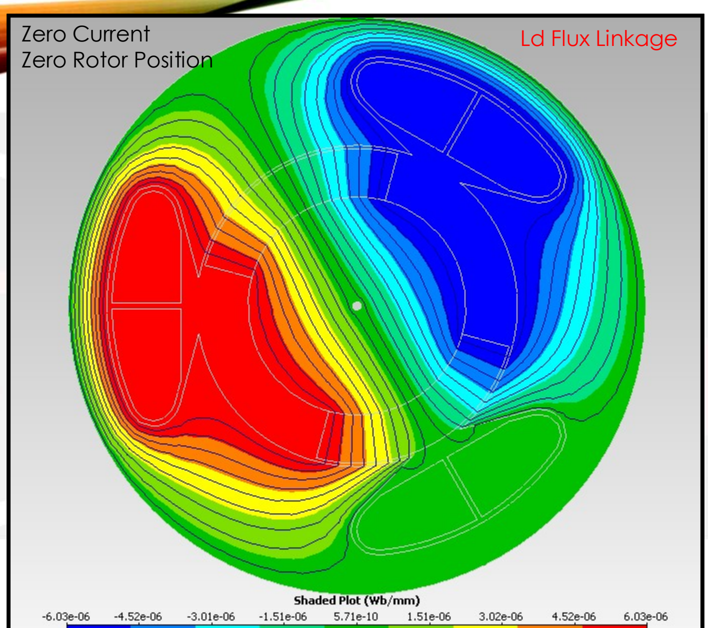
Zero Current
Zero Rotor Position
Ld Flux Linkage
Shaded Plot (Wb/mm)
-6.03e-06
-4.52e-06
-3.01e-06
-1.51e-06
5.71e-10
1.51e-06
3.02e-06
4.52e-06
6.03e-06

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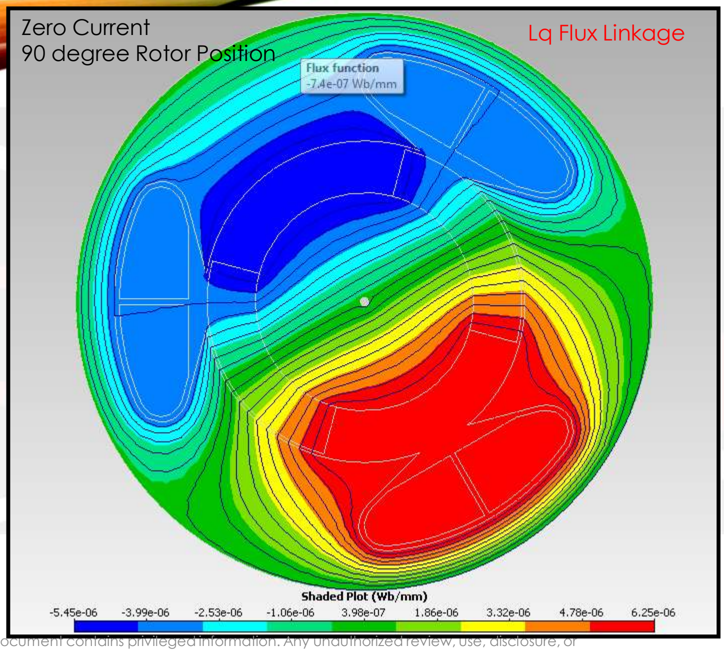

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LUMPED PARAMETER ANALYSIS

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

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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:

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

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

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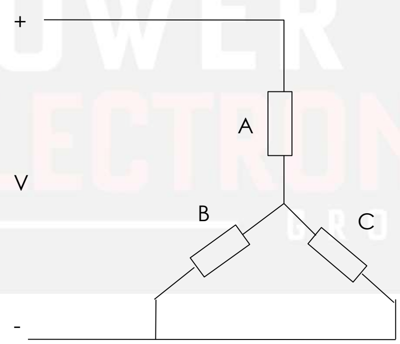
ESTIMATION OF PARAMETERS

- Synchronous Inductances L_d & L_q:

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

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

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



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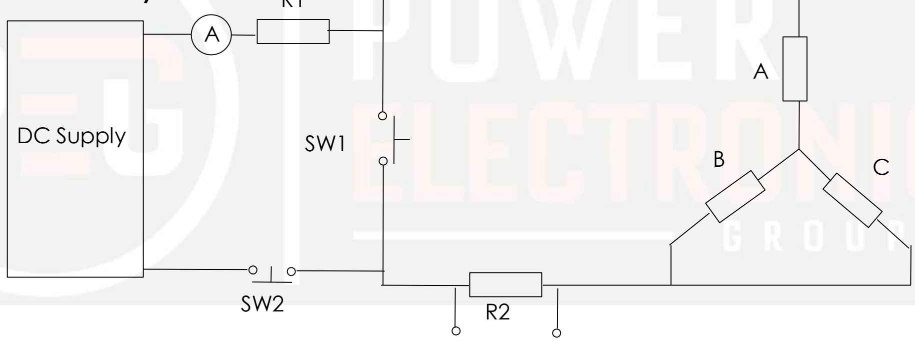
ESTIMATION OF PARAMETERS

Current Decay Method



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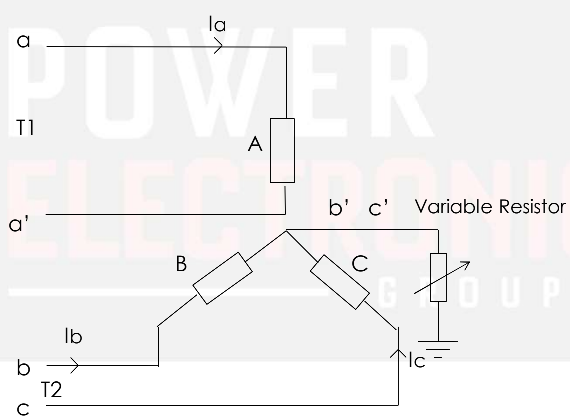
ESTIMATION OF PARAMETERS

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.



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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;

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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;

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ESTIMATION OF PARAMETERS

- Frolich's formula:

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

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

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

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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;

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HINT

- Ld=8.13mH;
- Lq=14.1mH;
- λm=0.2765 Wb-T;
- Rs=0.95Ω;

Calculate a and b

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