The Fundamentals of Brushless Permanent Magnet Motor Design – Part 1

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THE FUNDAMENTALS OF BRUSHLESS PERMANENT MAGNET MOTOR DESIGN – PART 1

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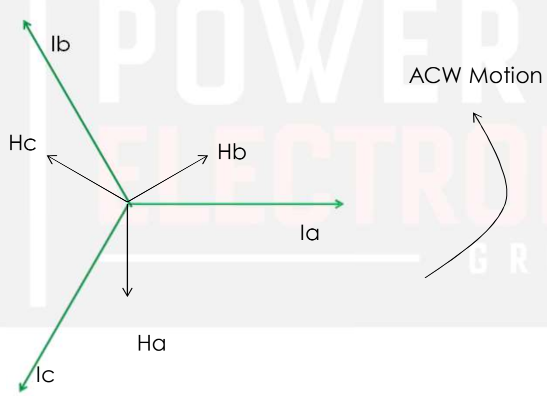
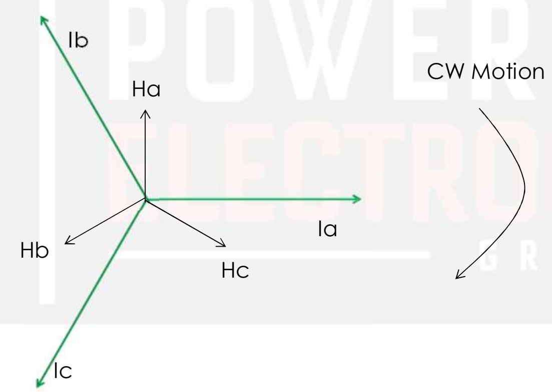
VECTOR DIAGRAM - ACW



VECTOR DIAGRAM - CW



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THE BASICS OF ELECTROMAGNETISM

Dynamic Modeling of BLDC Motors

DYNAMIC MODELING OF BLDC MOTORS

- The Basics of Electromagnetism
- Why does the motor turn?
- Space Vector Fundamentals

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.

THE BASICS

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

THE BASICS

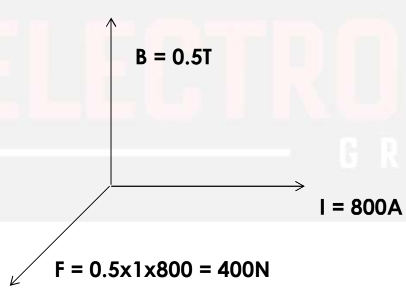
- Varying magnetic flux linking a circuit induces an EMF (**Faraday's Law**);
- Induced EMF opposes the change of flux (**Lenz's Law**).

IMPORTANT FORMULAE

- F = Bll;
- Flux Φ = BA;
- Flux Density B = Φ/A;
- EMF = Blu;
- EMF = dΦ/dt;
- EMF = dNΦ/dt;

THE BASICS

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



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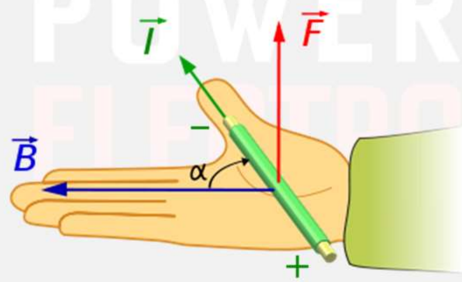
FORCE ON A CURRENT CARRYING WIRE

- $F = I\ell XB$



AMPERE'S LAW

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

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

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

$$H_c l_c = Ni$$

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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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FUNDAMENTALS OF MAGNETIC CIRCUITS

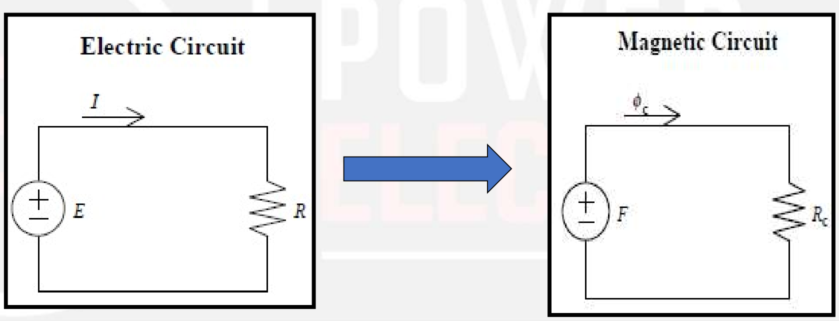
- Magnetic flux in the cross section of a core is given as: $\phi_c = B_c A_c$
- Where Φ is the flux in the core;
- Magnetic Flux density is defined as: $B = \mu H$
- Where μ is the permeability given by: $\mu = \mu_0 \mu_r$
- The flux can be also expressed as:

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

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;

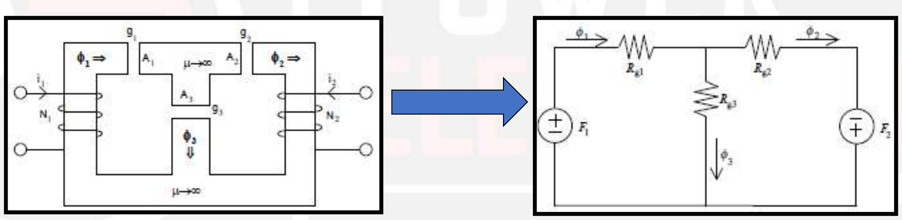
FUNDAMENTALS OF MAGNETIC CIRCUITS



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 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);

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;

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

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

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?

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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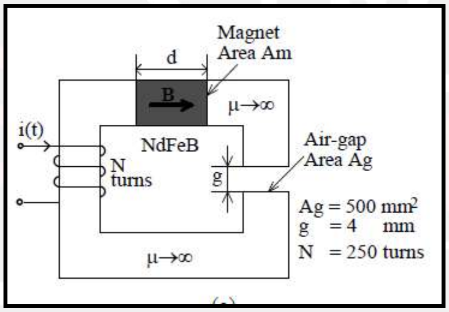
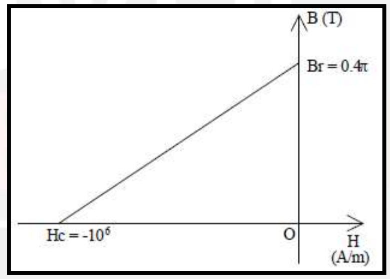
CALCULATE





A SAMPLE PROBLEM

- Bg = 0.5 + 0.25.Sinwt;
- 0.5T created by the magnet;
- 0.25T created by the current;
- Find d and i.

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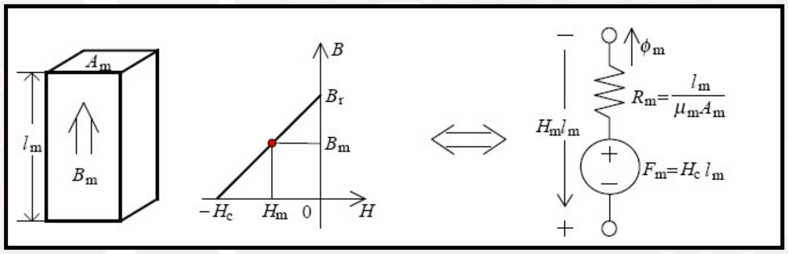
A PERMANENT MAGNET



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

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

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BASIC DESIGN CONSIDERATIONS

Dynamic Modeling of BLDC Motors

BASIC DESIGN CONSIDERATIONS

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

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;
  - Rated Current Density;
  - Fill Factor;
  - 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.

DESIGN CONSTRAINTS

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

EXAMPLE

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

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.

EXAMPLE

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

EXAMPLE

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

EXAMPLE

- Sizing Parameters
  - Torque per Unit Volume = DNC (Do Not Care);
  - Rated Current Density = DNC;
  - Fill Factor = 40% Minimum;
  - 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

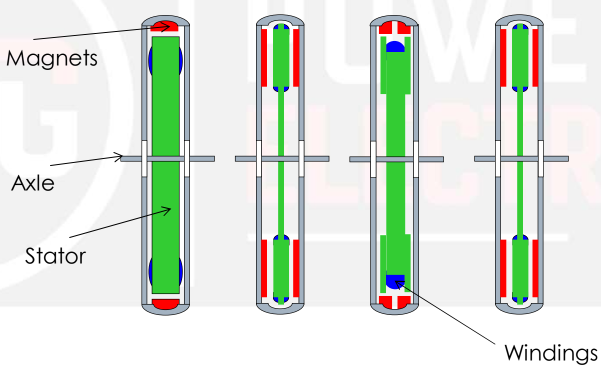
- Manufacturing Considerations
  - Winding Type, Method & Design;
  - Lamination Type, Method & Design;
  - Magnet Type, Method & Design;
  - Shaft Type, Method & Design;
  - Metal Housing + Cover Type, Method & Design;
  - Thermal Limitations.

MOTOR AND MAGNETIC ARCHITECTURES

MOTOR ARCHITECTURES

- Radial
- Axial
- Transverse
- Halbach Array

MOTOR ARCHITECTURES (OUTER ROTOR - GEARLESS)



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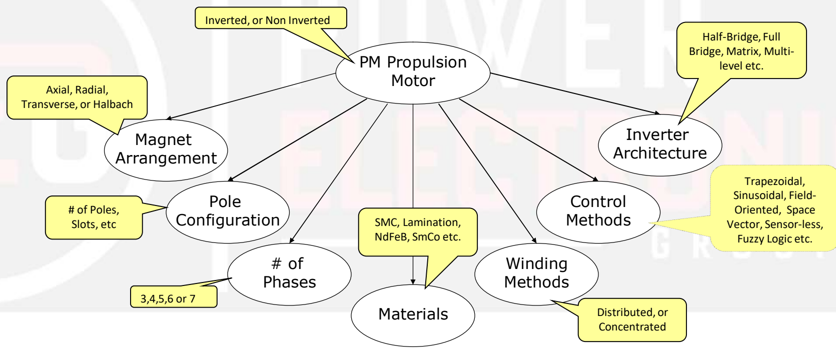
CURRENT STATE OF THE ART



RADIAL FLUX

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

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;

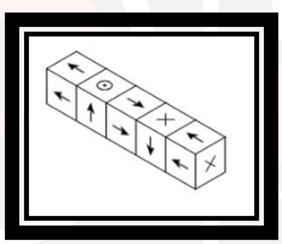
TRANSVERSE FLUX

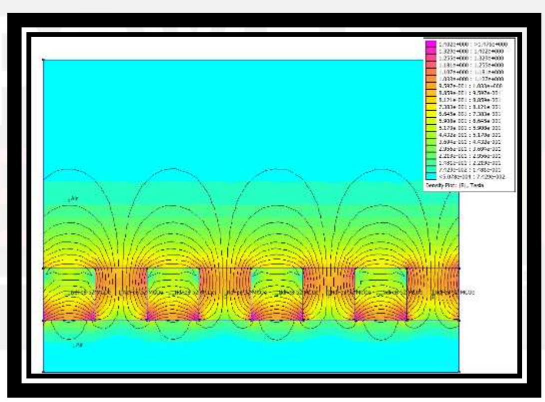
- 3D magnetic structure;
- Jury is out on the effectiveness;
- Perfect for SMC application;
- Limited research in the industry.

HALBACH ARRAY

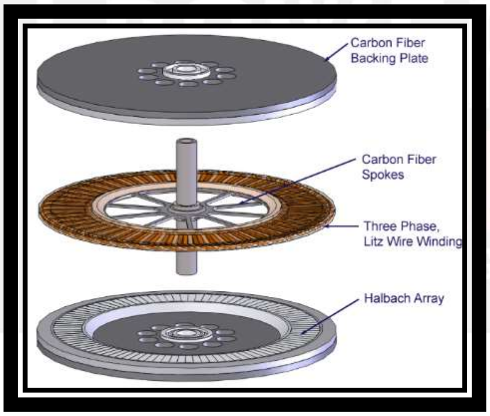
- Emerging Interest;
- Exciting possibilities with precise arrangement of magnets and magnetization direction;
- Demonstrated utility for very high speed applications.

HALBACH ARRAY





HALBACH ARRAY



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
- a_{*sk} = Skew Factor
- n_{cog} = Cogging factor

K_M INCREASED FROM 0.82 TO 1.28

Ns	Nm	Nspp	Rro/Rso	Km	α*sk	ncog
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

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K_M INCREASED FROM 1.12 TO 1.39

Ns	Nm	Nspp	Rro/Rso	Km	α*sk	ncog
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

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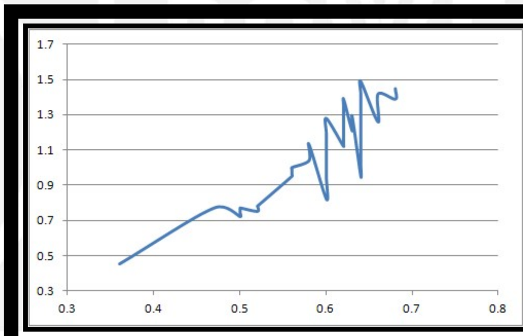
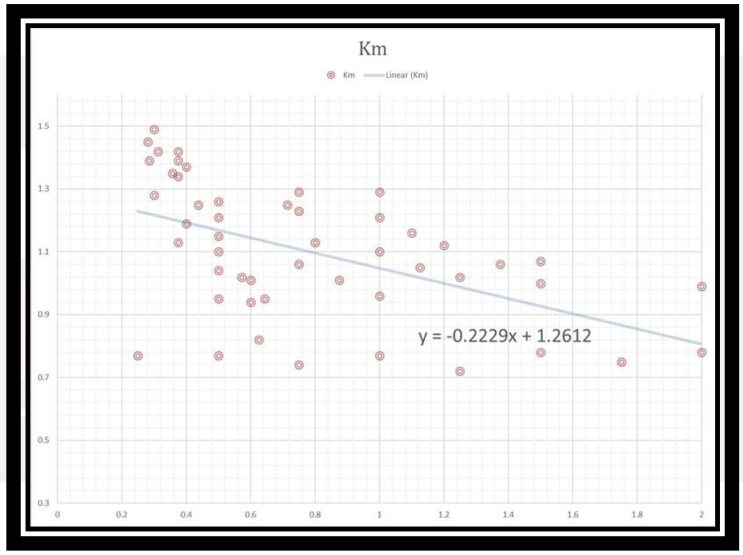
K_M VS. R_{RO}/R_{SO}





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.