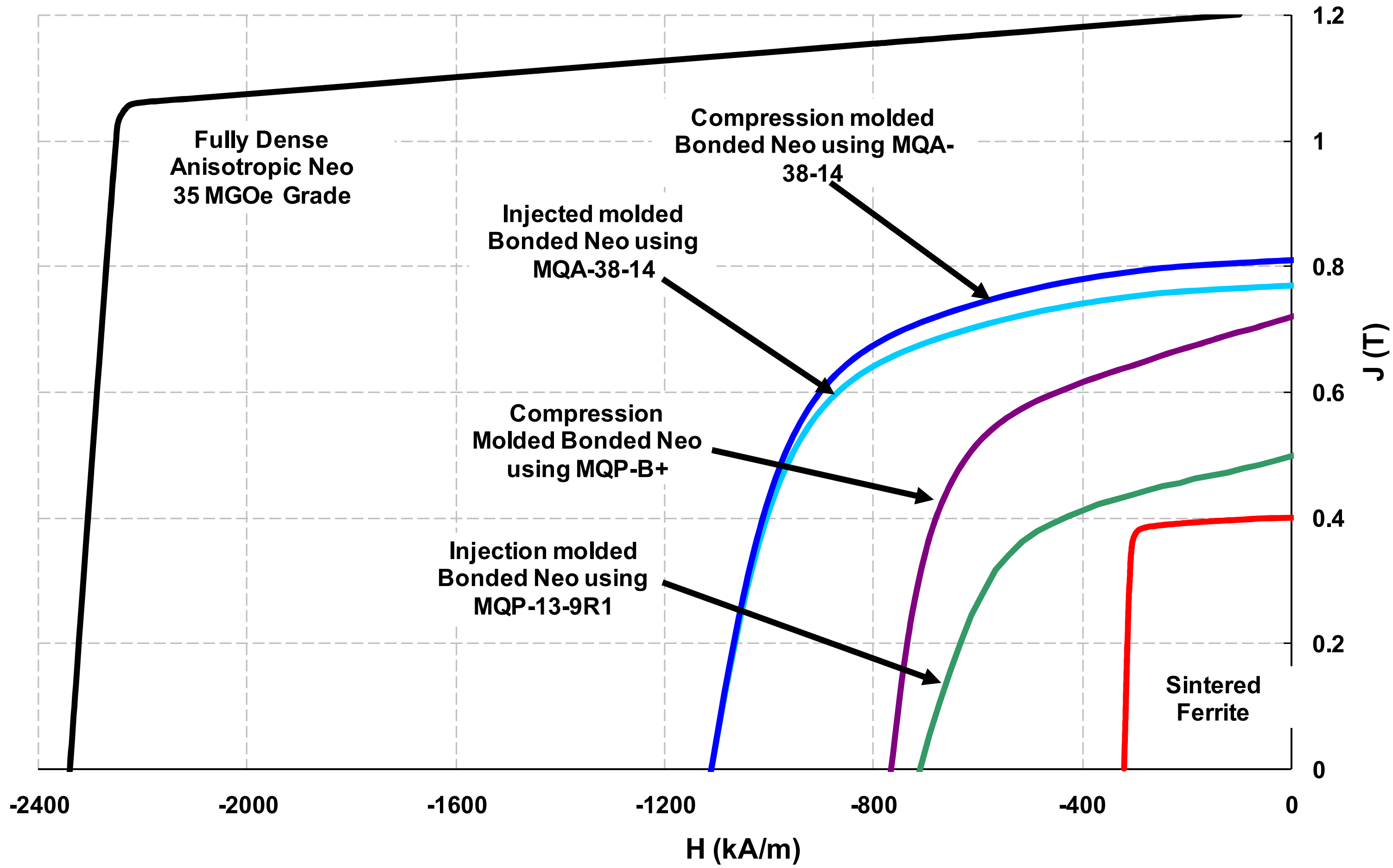
Noise and Vibration in PM Motors – Sources and Remedies

A typical Rubber Ferrite Magnet

Iso / Anisotropic	Remanence		Coercive Force		Intrinsic Coercive Force		Max. Energy Product	
	Br		Hcb		Hcj		(BH)max	
	mT	Gs	kA/m	Oe	kA/m	Oe	KJ/m3	MGOe
Iso	165+/-10	1,650+/-100	108+/-8	1,350+/-100	132+/-8	1,650+/-100	5.2+/-0.4	0.65+/-0.05
Iso	170+/-10	1,700+/-100	112+/-8	1,400+/-100	136+/-8	1,700+/-100	5.6+/-0.4	0.70+/-0.05
Aniso	220+/-5	2,200+/-50	136+/-8	1,700+/-100	160+/-8	2,000+/-100	8.0+/-0.4	1.00+/-0.05
Aniso	245+/-5	2,450+/-50	140+/-8	1,750+/-100	148+/-8	1,850+/-100	11.2+/-0.4	1.40+/-0.05
Aniso	247.5+/-2.5	2,475+/-25	168+/-8	2,100+/-100	224+/-8	2,800+/-100	12.0+/-0.4	1.50+/-0.05

Property Range for Bonded Neo Magnets



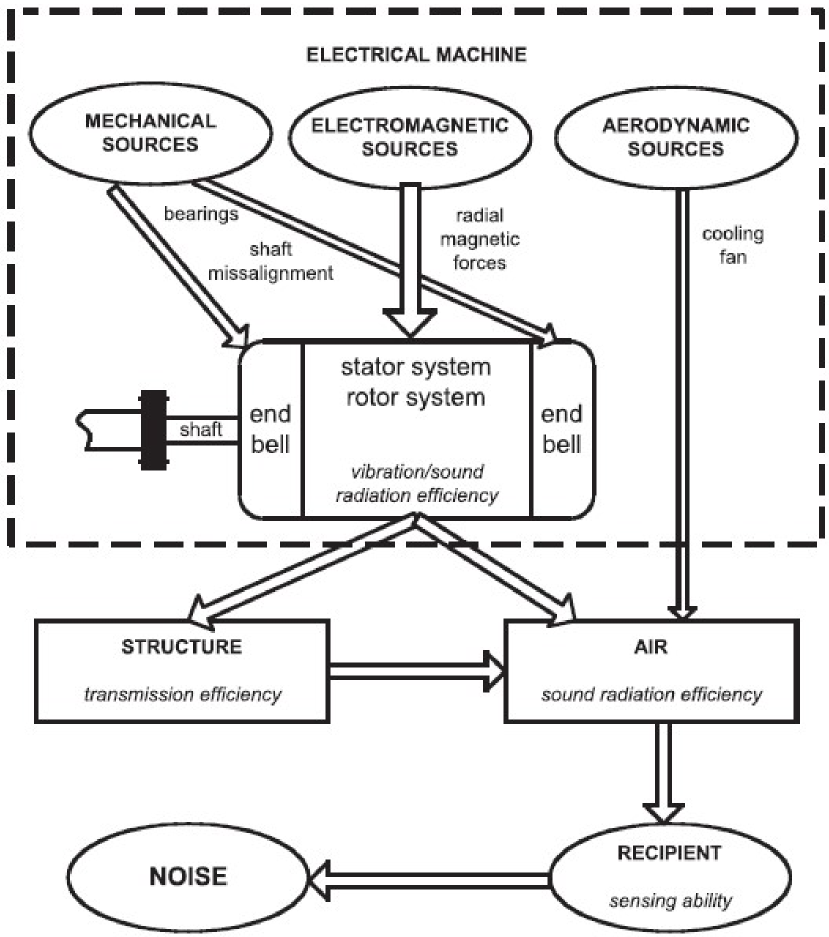
Salient Features of Bonded Neo Magnets

- Net Shape Pressing
  - 1mm wall thickness in rings (less for injection molded rings); no extra magnet material due to process limitations
  - No material yield loss during processing; $/kg magnet cost is relatively constant with respect to size
- Non Conductive
  - No temperature rise or efficiency loss due to eddy currents in high frequency applications
- Tailored Magnetization in isotropic MQP
  - Allows for any orientation in the same magnet design

Overview
Salient Features of Bonded Neo Magnets

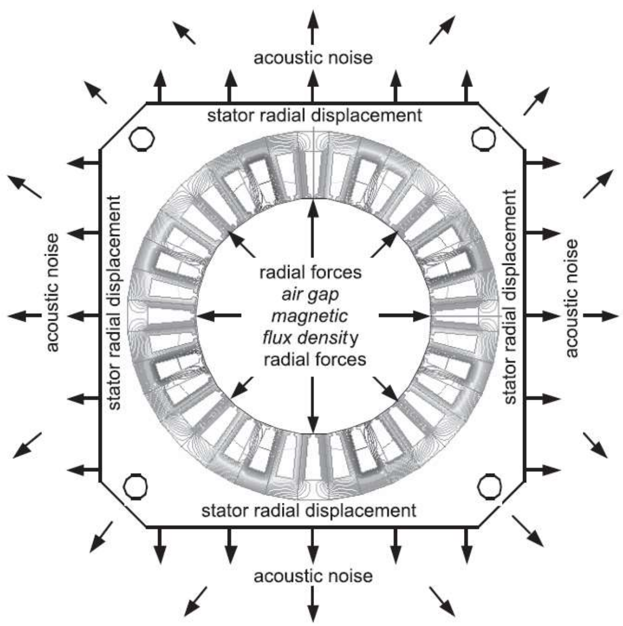
- Stronger than Rubber and Sintered Ferrite
  - Can achieve the same performance in a much smaller motor
- More practical than sintered neo in smaller applications
  - Automotive accessory motors due to process limitations of sintered neo

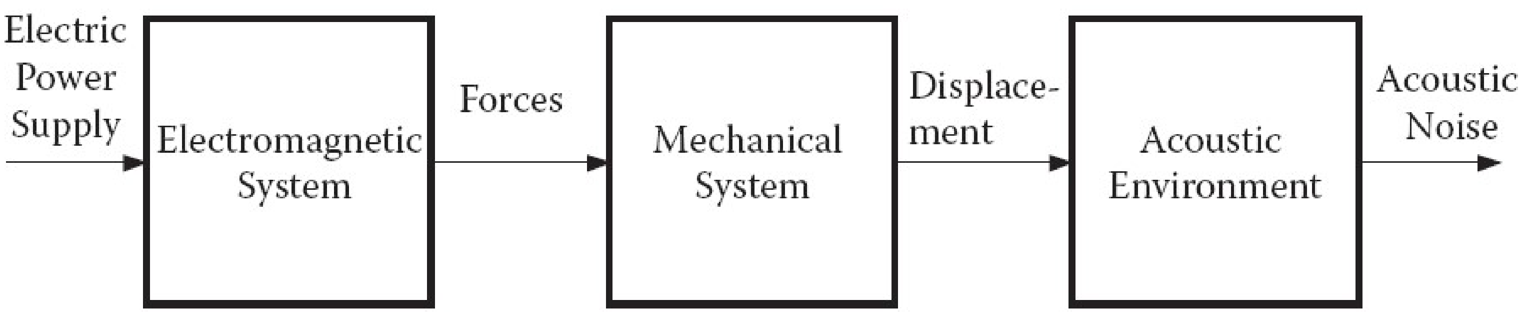
Noise Generation and Transmission in Electrical Machine



Various Sources of Noise Generation in Electric Motors

Generation of Vibration and Noise





Multiphysics system representing noise and vibration generation

Sources of Noise in Electrical Machines - Mechanical

- Sources of Noise

1. Mechanical
2. Electromagnetic
3. Aerodynamic

- Mechanical Sources of Noise
  - Angular and Parallel shaft misalignment
  - Dynamically unbalance rotor
  - Loose stator stack
  - Bearing

Sources of Noise in Electrical Machines - Mechanical

- Angular and parallel shaft misalignment
  - Shaft misalignment produces a mechanical vibration with the frequency,

$$f_s = 2n_m,\ n_m \text{ is the shaft speed in rev/sec}$$

- Dynamically unbalanced rotor
  - Rotor unbalanced, bent shaft, eccentricity, rubbing parts etc. produces a vibrating frequency of once per revolution or multiple of the no. of revolution per cycle.

$$f_s = kn_m,\ n_m \text{ is the shaft speed in rev/sec and } k = 1, 2, 3\,...$$

- Loose stator stack
  - Loose stator lamination results in to the following vibration frequency with the frequency side bands of 1000 Hz.

$$f_{lam} = 2f,\ f \text{ is the line frequency}$$

Sources of Noise in Electrical Machines - Mechanical

- Stator stack related noise can be reduced by impregnation (Encapsulation) of the stator stack.
- Bearing Noise
- Roller Bearing
  - Rolling bearing generates mechanical impulses when the rolling element passes the defective groove, causing small radial movement of the rotor.
  - The frequency at which the defect in the outer race causes an impulse when the ball or the roller passes the defective are of the race,

$$f_{or} = \frac{N_b}{2} n_m \left(1 - \frac{d_b}{D}\cos\alpha\right) \quad \text{or } f_{or} = 0.4 N_b n_m \text{ , where } n_m = \text{shaft speed in rev/sec}$$

$D =$ pitch diameter, $N_b =$ No. of rolling elements (balls), $d_b =$ Ball diameter and

$\alpha =$ Contact angle of the rolling element

Sources of Noise in Electrical Machines - Mechanical

- The frequency at which the defect in the outer race causes an impulse when the ball or the roller passes the defective are of the race,

$$f_{ir} = \frac{N_b}{2} n_m \left(1 + \frac{d_b}{D} \cos\alpha\right) \quad \text{or} \quad f_{ir} = 0.6 N_b n_m$$

- The ball spin frequency,

$$f_{bs} = \frac{D}{2d_b} n_m \left(1 - \left(\frac{d_b}{D}\right)^2 \cos^2\alpha\right)$$

- The cage fault frequency

$$f_{cf} = \frac{1}{2} n_m \left(1 + \frac{d_b}{D} \cos\alpha\right)$$

Sources of Noise in Electrical Machines - Mechanical

- Irregularities in the ball cage produces,

$$f_{bc} = n_m \left(\frac{d_i}{d_i + d_o} \right), \text{where } \mathrm{d_i} \text{ and } \mathrm{d_o} = \text{Diameter of inner and outer contact surface}$$

- Irregular shape of balls when turning about their own axis,

$$f_{re} = n_m \frac{d_i d_o}{d_r \left(d_i + d_o \right)}$$

- Variation of bearing stiffness results into,

$$f_{st} = N_b k n_m \frac{d_i}{d_i + d_o}, k = 1, 2, 3....$$

Sources of Noise in Electrical Machines - Electromagnetic

- Electromagnetic Sources of Noise
  - Phase unbalanced
  - Slot opening
  - Input current waveform distortion
  - Magnetic saturation
  - Magnetostrictive expansion of core laminations
  - Unbalanced Magnetic Pull
    - Static and dynamic eccentricity error produces unbalanced magnetic pull resulting in to bending of shaft
    - Reduces the mechanical stiffness of the shaft and first critical speed of the rotor due to increased magnetic pull

Sources of Noise in Electrical Machines - Electromagnetic

- Unbalanced force due to diametrically asymmetric disposition of the stator slots and coils – Proper selection of slot/pole combination no. will help in reducing the unbalanced magnetic pull

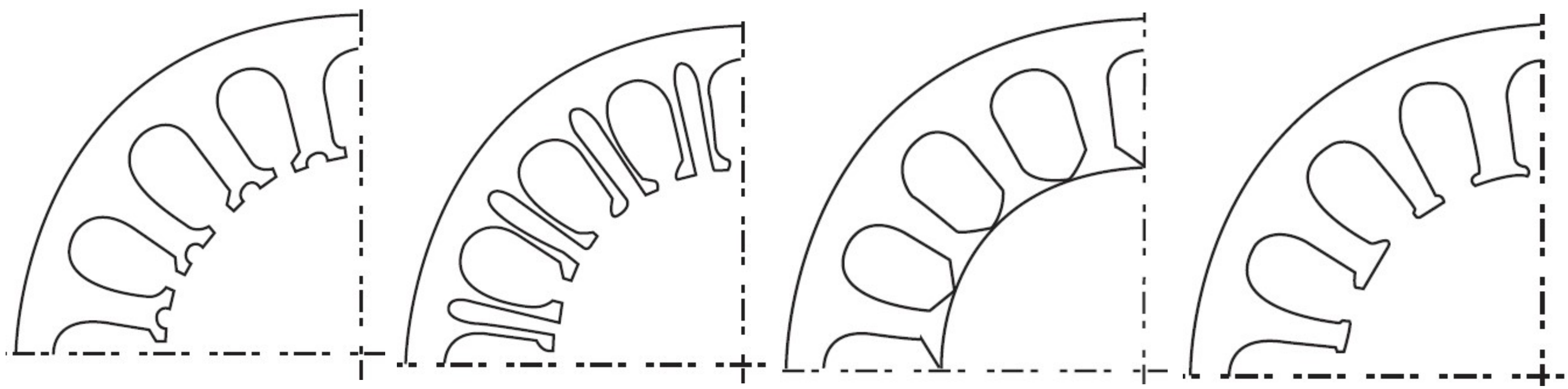
- Torque Pulsation
  - Cogging torque
  - Distrortion of the sinusoidal or trapezoidal distribution of the magnetic flux density in the airgap – Commutation torque ripple
  - The difference between the airgap permeances in the magnetic d and q-axis – Reluctance torque.
  - Current ripple resulting from the causes like PWM
  - Phase current commutation

Reduction of the Cogging Torque

- Slotless winding
  - No slot and teeth on the stator- No change in the airgap permeance – No cogging torque
  - Increase effective airgap of the motor – More PM material to achieve the same airgap flux density as of the slotted machine
- Skewing stator slots
  - Reduction in the effective back-emf of the motor
  - Less effective in case of the rotor eccentricity
  - Manufacturing difficulty with the windings when automated winding machines are used

Reduction of Cogging Torque

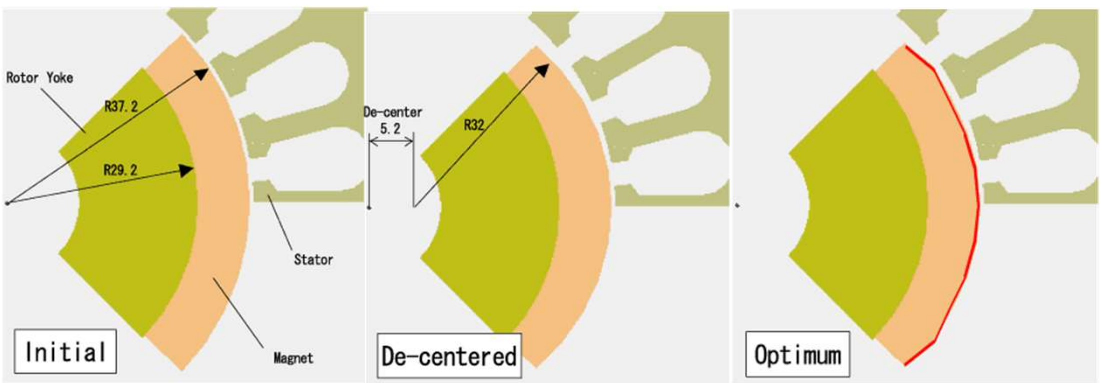
- Shaping of the stator slots
  - Bifurcated slots
  - Empty (Dummy) slots
  - Closed slots
  - Teeth with different width of active surface



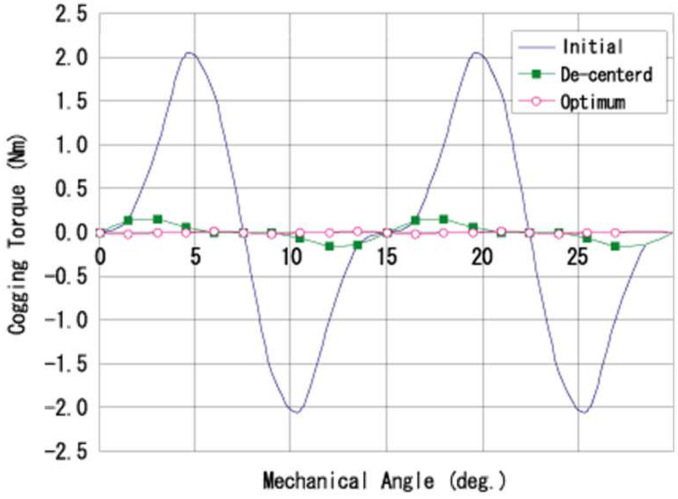
Different shapes of stator slots for cogging torque reduction

Reduction of Cogging Torque – Shaping of Magnet

- Shaping of PM
  - Magnet thickness lower at the edges compared to central part – cogging and commutation torque ripple both reduces
  - Magnet may required a polygonal cross section of the core
  - Decentered PMs with bifurcated stator slot can help in reducing the cogging torque without much sacrifice of back-emf



Shaping of permanent magnet for cogging torque reduction

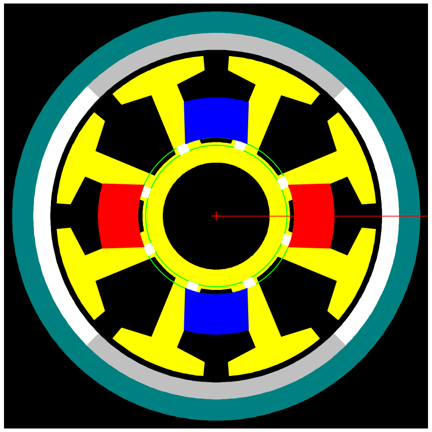


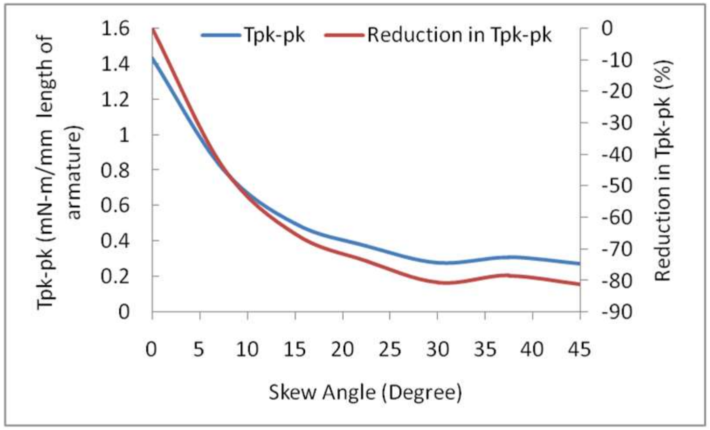
Reduction of Cogging Torque - Magnetic Asymmetry

- Magnetic circuit asymmetry
  - Shifting each pole by a fraction of the pole pitch with respect to the symmetrical position, or designing different size of north and south poles for the magnet of the same pole pair
  - Increases the order of Fourier harmonics that appears in cogging torque decomposition
  - Selective cogging torque harmonic can be eliminated
  - Additional torque ripple due to the shifting of the emf waveform

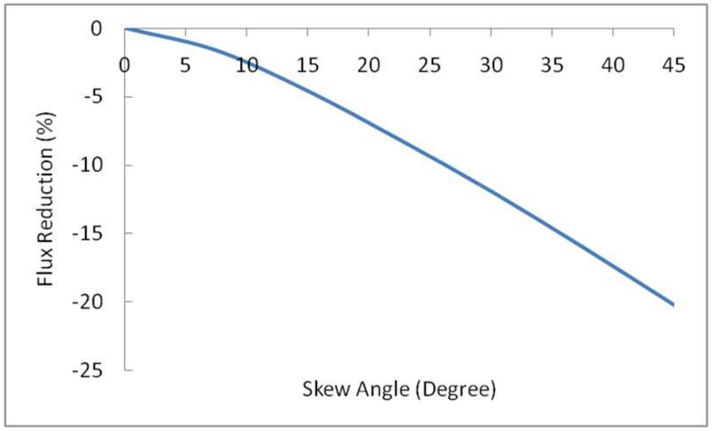
Reduction of Cogging Torque – Skewing

- Skewing of Magnet / Magnetization Profile
  - Fabrication of twisted magnet for smaller rotor diameters and smaller no. of poles is difficult
  - Bread loaf shaped PMs with edges cut at a slant are equivalent to skewed PMs.





Effect of skew angle on peak to peak cogging torque



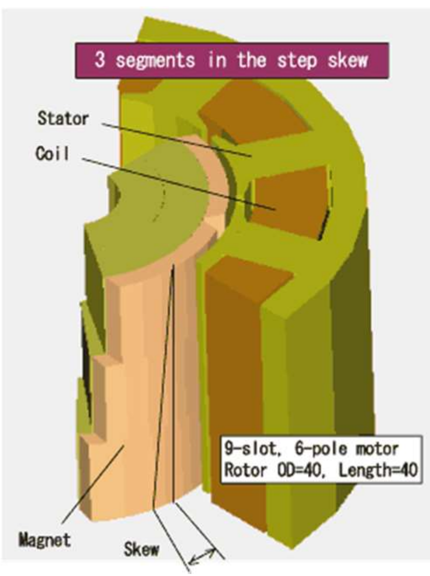
Effect of skew angle on airgap flux

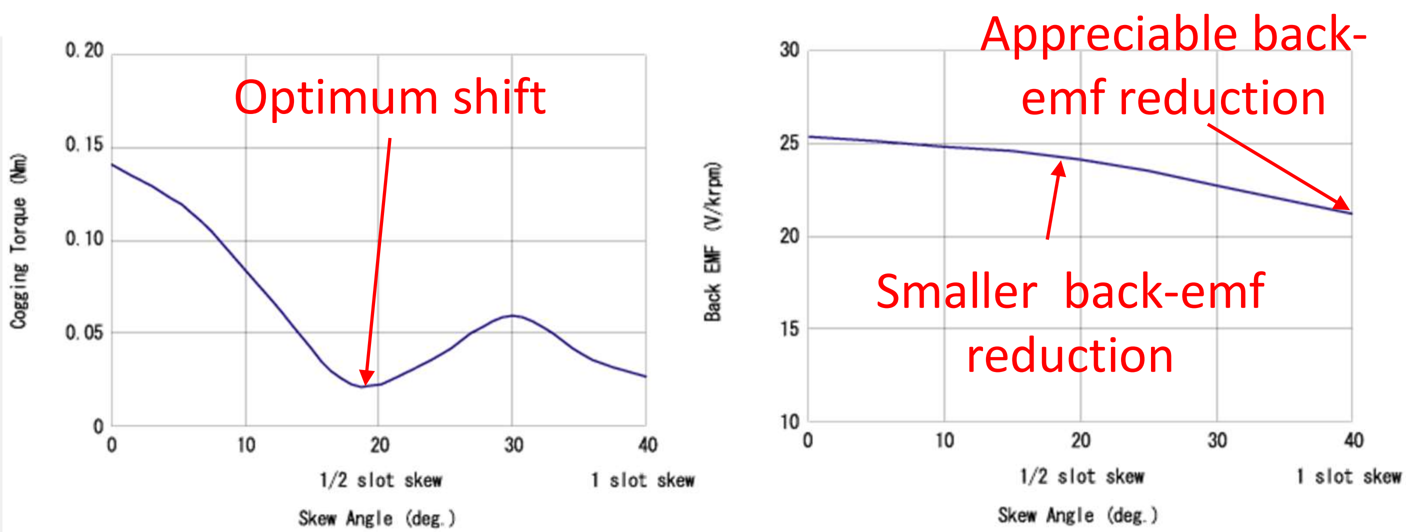
Reduction of Cogging Torque – Skewing

- Optimum angle of skew helps in reducing the peak to peak cogging torque without much reduction in airgap flux.
- Skewing introduces the phase angles between the radial magnetic forces at different axial positions and hence reduces the average radial force, vibration and noise.
- The amplitude of the radial force and radial displacement is proportional to the skew factor.

Reduction of Cogging Torque – Segmented PM

- Shifting of PM segments
  - Axial segment of the magnets.
  - A stepped skew instead of continuous one
  - Segments are shifted from each other by equal or unequal distance to achieve desired net skew angle.





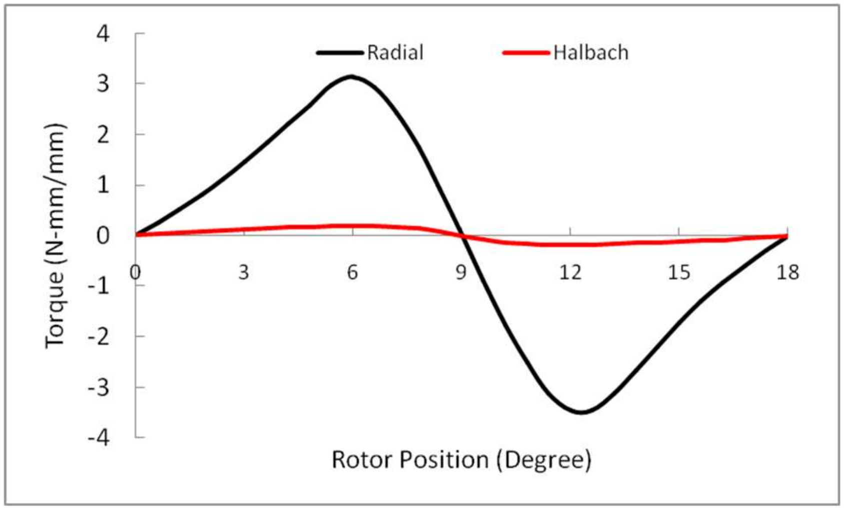
Effect of shifting of PM segments on the cogging torque and back-emf

Reduction of Cogging Torque – PM Width and Magnetization

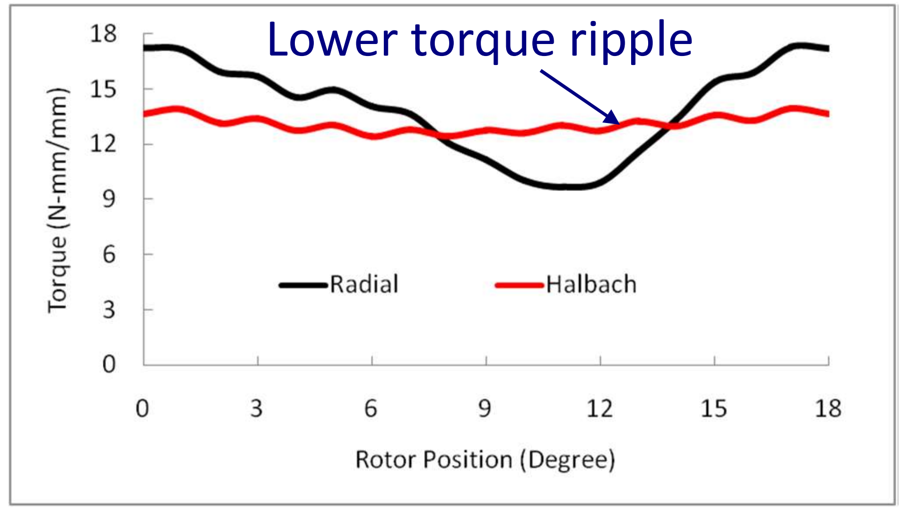
- Selection of PM width
  - Proper selection of PM width with respect to the stator slot pitch helps in reducing the cogging torque.
  - To reduce cogging torque wider pole shoe than the multiple of slot pitch is required.
- Magnetization of PMs
  - The possible choice of type of magnetization profiles are,

    Radial, Parallel and Halbach
  - Halbach magnetization may help in reducing the cogging torque
  - Halbach magnetization is very useful for servo application and slotless motors
  - Halbach magnetization is useful with thick magnets

Effect of Magnetization on the Cogging and Developed Torque



Cogging torque of a power tool motor for radial and Halbach magnetized magnets

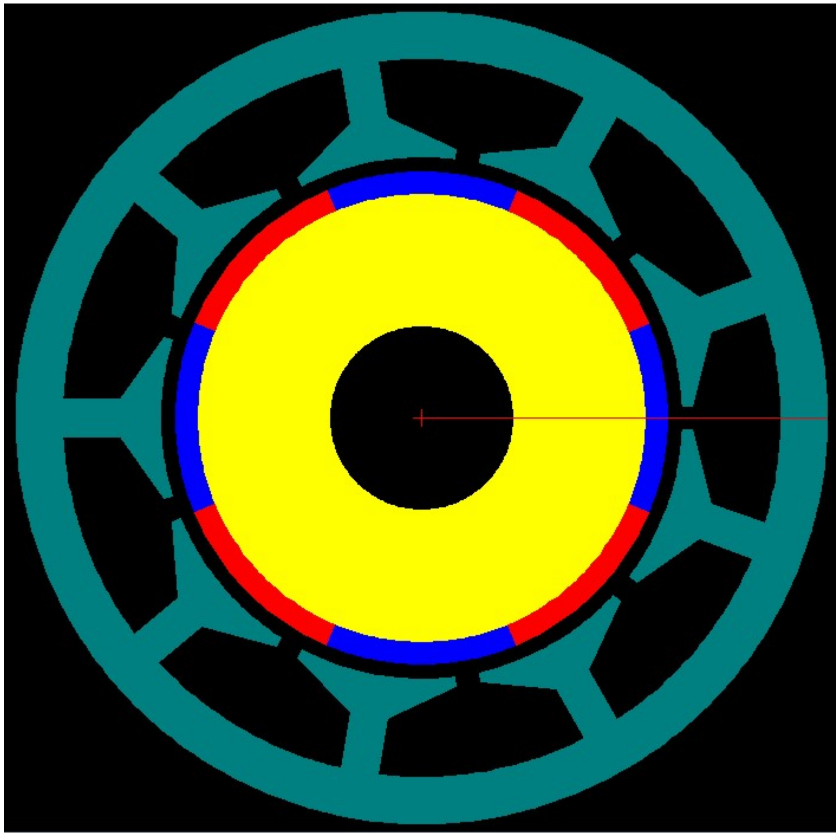


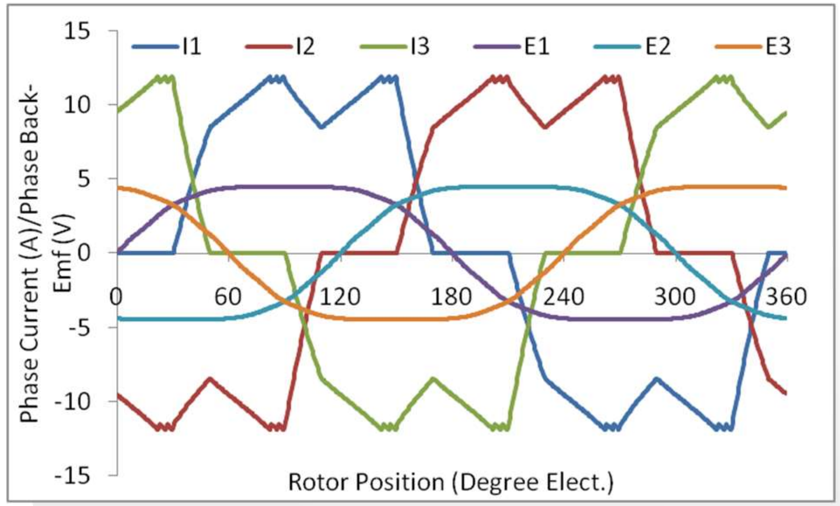
Developed torque of a power tool motor for radial and Halbach magnetized magnets

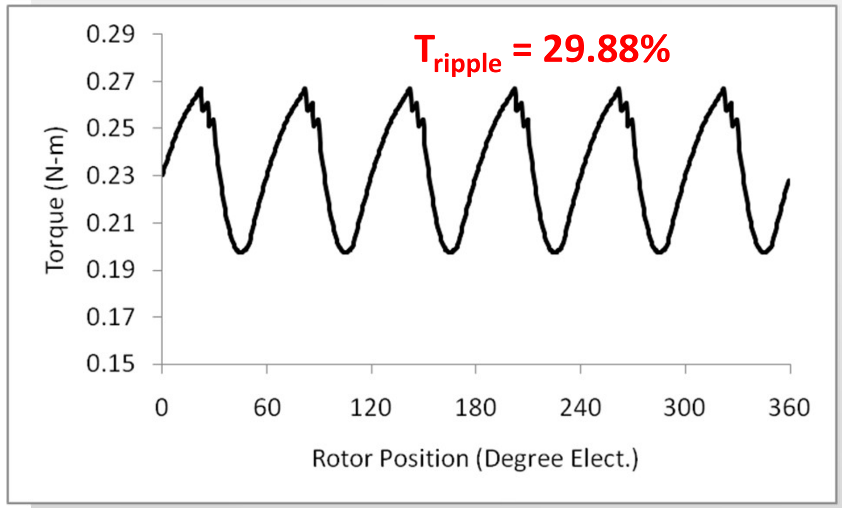
Magnetization	Radial	Halbach
T_{max} (N-mm/mm)	3.13	0.19
T_{min} (N-mm/mm)	-3.45	-0.18
T_{pk-pk} (N-mm/mm)	**6.58**	**0.37**
ΔT_{pk-pk} (%)	**-**	**-94.38**

Magnet	Radial	Halbach
$T_{average}$ (N-mm/mm)	14.04	13.12
T_{ripple} (%)	54.22	11.74
$\Delta T_{average}$ (%)	**-**	**-6.55**
ΔT_{ripple} (%)	**-**	**-78.35**

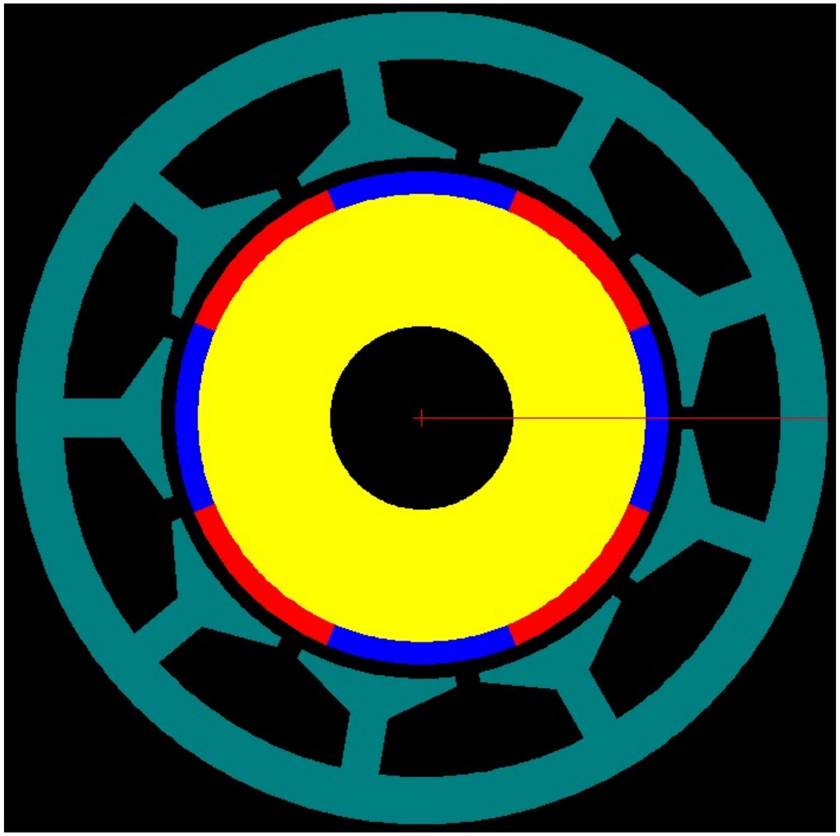
Reduction of Cogging Torque – Effect of Magnetization Profile

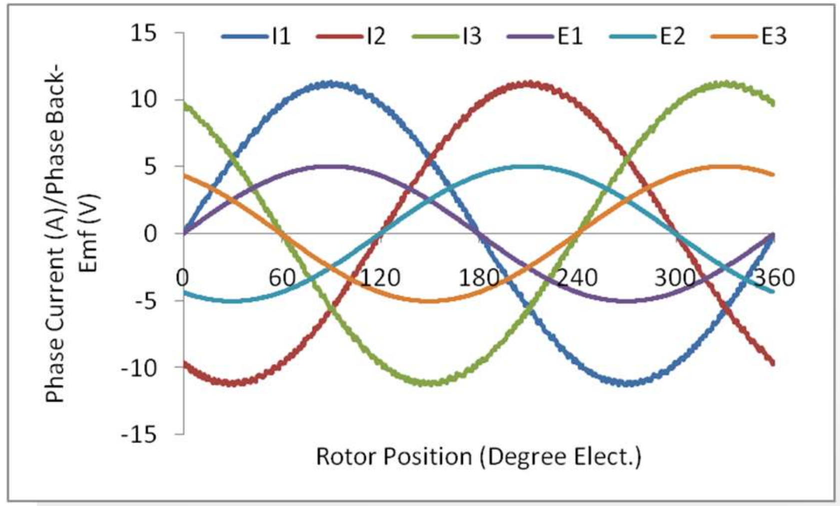


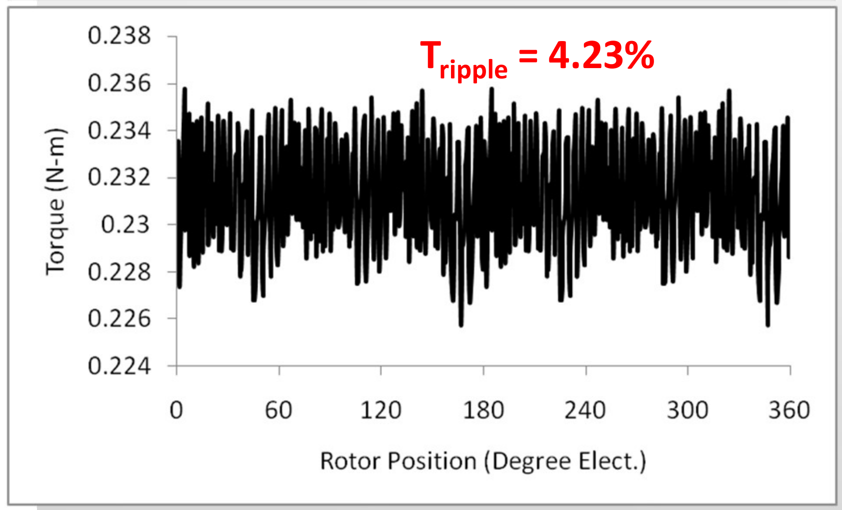




Reduction of Cogging Torque-Effect of Magnetization Profile







Reduction of Cogging Torque – No. of Slot/Pole Selection

- Selection of Slot/Pole Combination
  - Higher vibration when the frequency of radial vibration force coincides with the natural frequency of the stator mechanical structure having the same order of vibration mode.
  - When the vibration mode order associated with dominant radial exciting force is high, noise and vibration is lower due to higher mechanical stiffness.
  - Higher smallest common multiple between the slot no. and the pole no. results in lower cogging torque
  - Cogging torque increase with the increase in the largest common factor between the slot no. and pole no.
  - Even no. of slots eliminates the unbalanced magnetic pull.
  - Fractional slot machines exhibits lower cogging torque.

Reduction of Cogging Torque- No. of Slot/Pole Selection

- For integral slot machine, i.e.

$$q = \frac{N_s}{(2p)m} = Integer$$

  - Dominant vibrating mode order = 2*P*

- For double layer winding with

$$2p = N_s \pm 2$$

  - The lowest order of radial force harmonic = 2

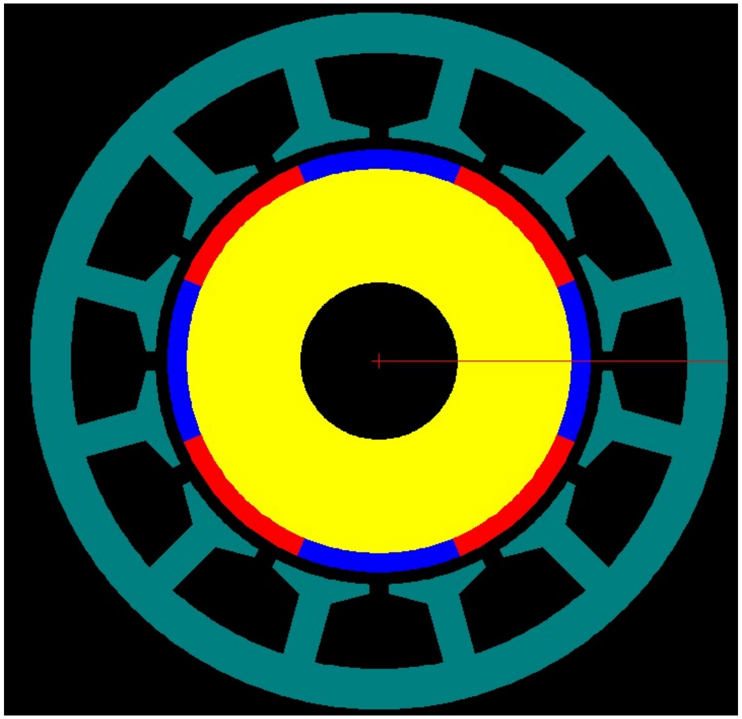
- For single layer winding with

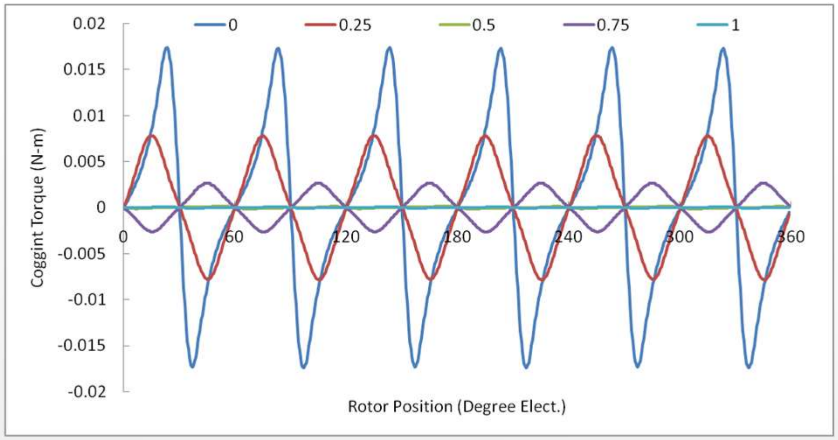
$$2p = N_s \pm 2 \text{ and } \frac{N_s}{t} = Even, \text{ where } t = GCD(N_s, 2p)$$

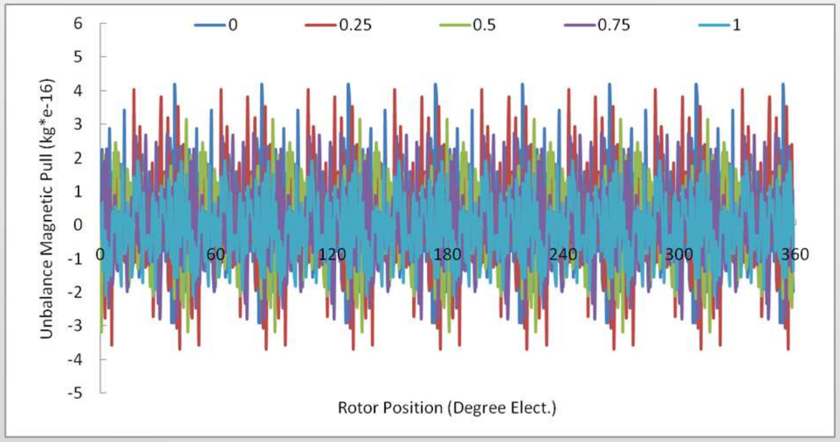
  - The lowest order of radial force harmonic = 2

  - $2p = N_s \pm 2 \text{ and } \frac{N_s}{t} = Odd, \text{ where } t = GCD(N_s, 2p)$

Effect of Slot/Pole Combination on Noise and Vibration

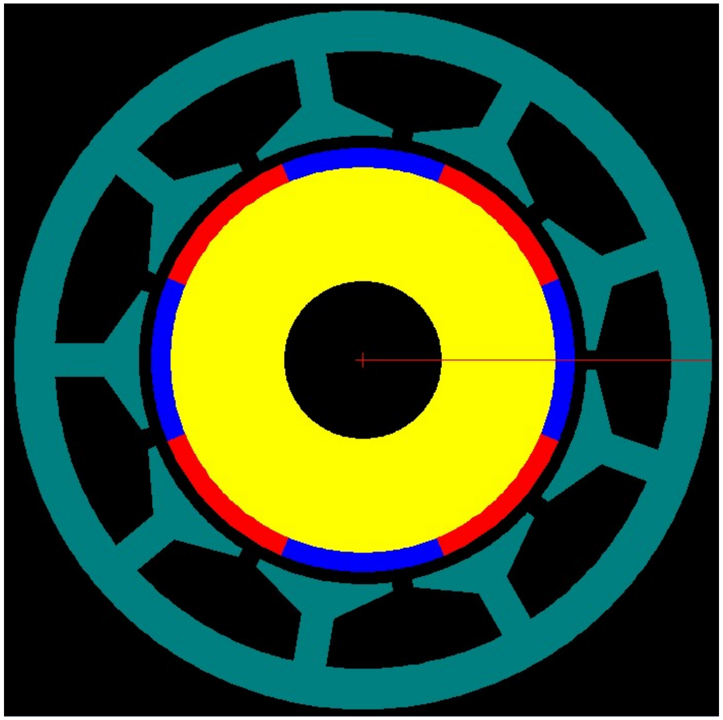


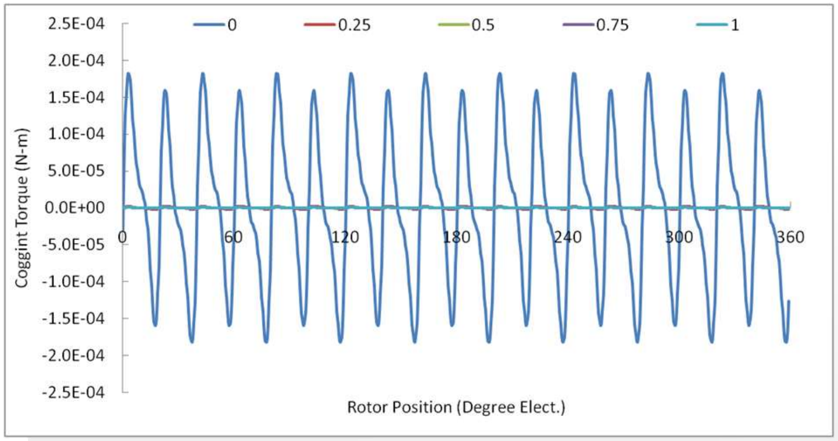


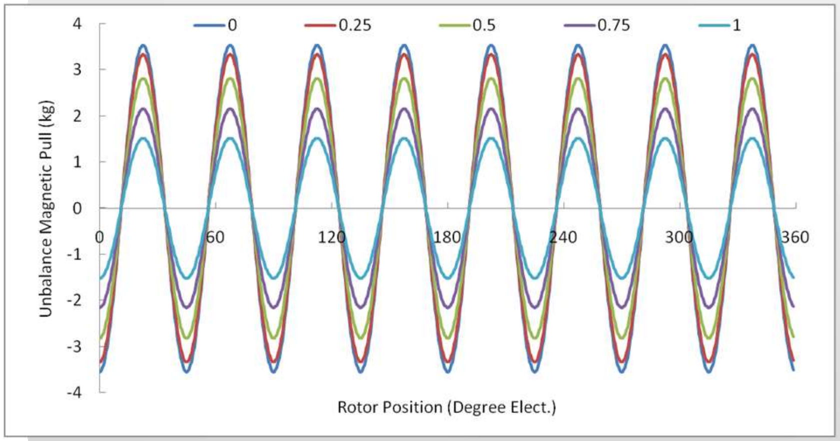


- High Cogging – Skewing is needed
- Negligible UMP

Effect of Slot/Pole Combination on Noise and Vibration







- Low Cogging
- High UMP

Sources of Noise in Brushed PM DC Motor & Remedies

- Cogging torque
- Mechanical Resonance
- Interaction between the armature excitation and the case with the magnets
  - Various coils are energized by current or by magnetic coupling through the mutual inductance, the magnetic field produced by the coil attracts/repels the magnets in the case. Energy is transferred from the armature to steel case.
- Commutation
  - Commutation affects the current harmonics because the mutual coupling from the commutating coils transfer energy from the wave form in those coils to other coils and because of the sudden switching of coils in the armature circuits.

Sources of Noise in Brushed PM DC Motor & Remedies

- Harmonics from the commutating coil's current are getting transferred to the other coils due to mutual coupling.
- Lower mutual harmonics helps in reducing the harmonics in the commutating currents and hence noise and vibration.
- Positing of the coil in a slot results in to different self inductance.
- Variation in the self inductance of both commutating and noncommutating coils produces fluctuation in the armature current.
- Higher brush widths increases the commutating coil current and arcing duration.

Sources of Noise in Brushed PM DC Motor & Remedies

- Optimal brush shifting will help in reducing the DC commutation arcing.

- Proper selection of slot depth and width will help in controlling the effective inductance.
  - Deep and narrow slot - Higher effective inductance
  - Shallow and wide slot - Lower effective inductance

Sources of Noise in Brushed PM DC Motor & Remedies

- Reduction of the airgap magnetic flux density
  - The magnitude of the radial force pressure is proportional to the stator and rotor amplitude of the magnetic flux density (MFD) waves.
  - MFD can be reduced by (1) Increasing the active airgap, (2) Keeping the same phase back-emf increase the no. of stator turns and/or extend the length of the stator stack.
- Reduction in the pulsating noise
  - Use of dynamically balanced rotor
  - Minimizing of the magnet permenace variation in stator and rotor cores.

Sources of Noise in Brushed PM DC Motor & Remedies

- Reduction of sound radiation efficiency
  - Reduction in the ratio of frame length to frame diameter results in to lower noise.
- Reduction of the dynamic vibration of the machine surface
  - Increase in stator core thickness results in to higher stiffness and lower noise.
  - Sealing the gap between the stator core and frame with varnish or epoxy resin or inserting shear damping rings in the motor yoke
  - Increase the exciting force order by proper selection of the slot/pole combination

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