CHAPTER 4

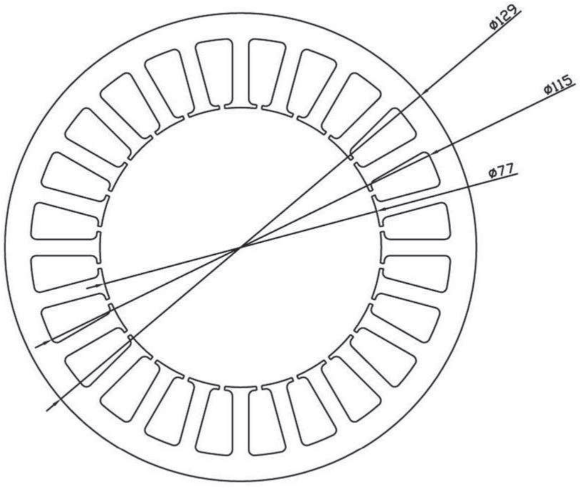
DESIGN OF INTEGRAL SLOT AND FRACTIONAL SLOT BRUSHLESS DC MOTOR

4.1 INTRODUCTION

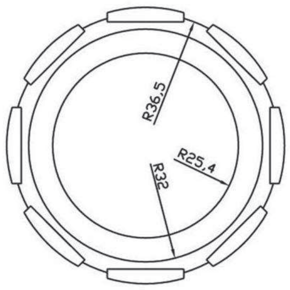
This chapter deals with the design of 24 slots 8 poles, 48 slots 16 poles and 60 slots 16 poles brushless dc motor configurations. Preliminary design is carried out with 24 slots and 8 poles motor configuration. The permeance coefficient is worked out for the designed magnetic circuit and magnet operating point is found in the magnet demagnetization characteristics. The number of conductors for the required torque output is then calculated. The major problem encountered while fabricating the 24 slots and 8 poles motor is listed. The new design configuration with 48 slots 16 poles and 60 slots 16 poles are worked out. The quadruplex armature winding pattern and triplex Hall sensor assembly pattern is given.

4.2 24 SLOTS 8 POLES CONFIGURATION

The permanent magnet brushless dc motor has three phase star connected winding. The quadruplex winding redundancy requires four three phase windings in four quadrants of the motor. The rotor assembly should have minimum of two poles per quadrant and hence 8 poles and 16 poles are the possible options for the proposed motor. 12 poles rotor configuration is not suitable for this requirement and hence 8 poles configuration is selected initially for the preliminary design. From the volume apportionment of stator assembly and rotor assembly the integral slot configuration of six slots per quadrant, total of 24 slots for four quadrants is selected such that slots per pole per phase is one. The 8 poles and 24 slots configuration is selected based on the width to length ratio of the magnet, reduced leakage flux, lower frequency (low core loss), sufficient back iron thickness and slot area. The magnetic circuit calculations are worked out for preliminary design configuration. In order to maximize the magnetic loading rare earth Samarium Cobalt 25 MGOe (SmCo5) magnet is selected for the specified maximum temperature of operation. The tooth width, back iron thickness and slot opening are calculated based on the magnetic flux density value and validated with the finite element analysis. Figure 4.1 shows the stator core lamination and magnet rotor assembly.



Stator Lamination



Rotor ring and Magnet assembly

Figure 4.1 24 slots 8 poles stator-rotor configuration

The dimensions are selected such that the maximum flux density is 1.5 Tesla in the tooth and 1.2 Tesla in the back iron. M19 29 gage silicon steel material is used instead of commercially available M45, 26 gage for the stator magnetic core in order to reduce the core losses. The stator stack is skewed for one slot pitch (15 degree mechanical) to reduce the cogging torque. Skewing the stator slots reduces the total developed torque by skew factor. The magnet width is selected such that the contribution to the cogging torque by the magnet is lower. The magnet radial thickness for producing required flux is apportioned from the rotor assembly.

For the apportioned radial magnet thickness of 4mm, magnet width of 21mm and airgap length of 0.5mm, the permeance coefficient (PC) is calculated.

$$PC = \frac{l_m}{gC_\phi} = 9.7$$

C_ϕ = flux concentration factor

The operating flux density of the magnet is found from the magnet demagnetizing characteristics curve of 25MGOe Samarium Cobalt magnet shown in Figure 4.2. The intersection of permeance coefficient line with the magnet demagnetization curve gives the operating point. The operating flux density is 0.65 Tesla for this permeance coefficient and used for further design calculations.

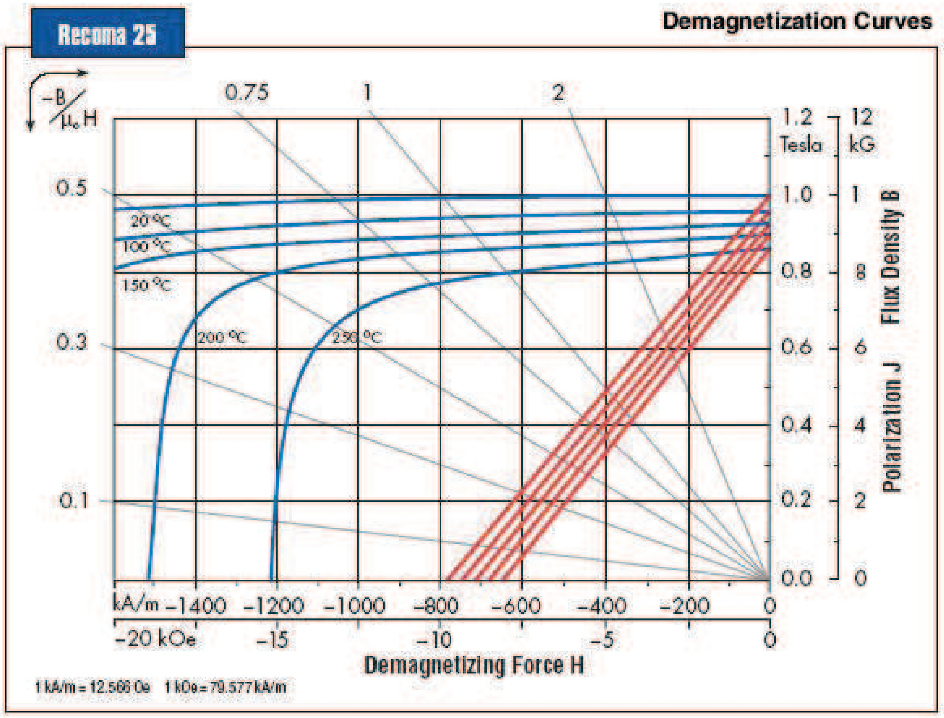


Figure 4.2 Demagnetization curve of 25 MGOe Samarium Cobalt magnet

Magnet properties

(BH) max : 25 MGOe

Br : 1 Tesla

Hcb : 775 KA/m

Intrinsic Coercivity Hcj : 2400 KA/m

Relative Permeability : 1.02

Density : 8.4 g/cm³

Temp co-eff of Br, α (23-150°C) : -0.050%K

Tempco-eff of Hcj, β(23-150°C) : -0.200%K

Max operating temp : 250 °C

4.2.1 24 Slots 8 Poles: Magnetic Circuit Details

Number of slots : 24
Number of poles : 8
Number of phases : 3
Slots per pole per phase : 1
Number of slots per pole : 3
Pole pitch for diameter 76.0mm, : 29.84
Magnet Width, mm : 21
Magnet thickness, mm : 4.0
Airgap length, mm : 0.5
Permeance coefficient : 9.7
Airgap area per pole, mm^2 : 1090
Airgap flux density (max), Tesla : 0.7
Back iron thickness, mm : 7
Tooth width, mm : 4.5
Stator back iron radius, mm : 57.5
Slot bottom width, mm : 10.45
Slot width inside shoe, mm : 6.345
Total slot depth, mm : 19
Useful slot depth, mm : 16.5
Shoe depth, mm : 2.5
Slot area, mm^2 : 137
Lamination thickness, mm : 0.35
Lamination ID/OD, mm : 77/129
Stator stack length (max), mm : 43

4.2.2 24 Slots 8 Poles: Back-EMF and Number of Conductors

The airgap diameter and length of the motor is apportioned from the given dimensions. The electrical loading requirement for specified torque output is calculated with the airgap flux density of 0.65 Tesla found from magnet characteristics and for the given current of 12.4 Ampere.

Torque constant, K_t = 0.645 Nm/A
Back-EMF constant, K_b = 0.645 V/(rad/sec)
No-load speed = 1000 rpm
Supply voltage = 75 V

The back-EMF, E is found from the back-EMF constant

$$E = K_b \text{ x (rad/sec)} = 67.5 \text{ V}$$

Number of conductors required to generate the back-EMF is worked out from the basic relation, $Z = \frac{E}{BL\pi Dn_s}$

Surface velocity, v = 3.979 m/s

No. of conductors for generating the back-EMF is 151 per slot.

4.2.3 24 Slots 8 Poles: Armature Winding Pattern Per Quadrant

From the magnetic circuit details the following parameters are derived for finding the winding pattern for the quadruplex redundancy.

No. of slots per quadrant = 6
No. of poles per quadrant = 2
No. of slots per pole = 3

Three phase star connected winding, Single coil per phase

Number of turns per coil = 151

Symmetry in all four quadrants

Figure 4.3 shows the winding pattern for three phase star connected winding per quadrant. Similar winding pattern is repeated for the remaining three quadrants of the motor. All quadrant windings are physically and electrically separated from each other to form four independent motors.

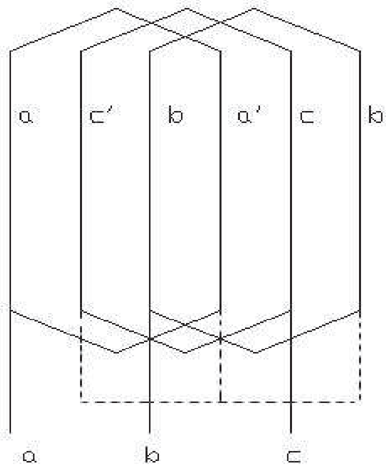


Figure 4.3 Winding diagram (one quadrant) for 24 slots configuration

4.2.4 Selection of Copper Wire and Armature Resistance

The size of the copper wire is selected based on the load cycle of the motor operation. For the given periodic and intermittent duty cycle, the equivalent RMS current is 3.3 A (Continuous rating)

The 23 SWG copper wire of diameter 0.61mm, cross sectional area of 0.292 mm^2 is selected for the current density of 11.3 A/mm^2

Diameter of the wire (insulated) = 0.686 mm

Area of the wire = 0.369 mm^2

Total coil area = 151 * 0.369 mm^2.

= 55.719 mm^2

Slot area available for conductors = 137 mm^2

Slot packing factor = 0.4

Mean length of the coil =160 mm

Total length of the coil = 48.32 m (line to line)

Table 4.1 Resistance calculation for 24 slots 8 poles configuration

Parameters	23SWG
Bare conductor diameter, mm	0.610
Bare conductor area, mm²	0.292
Current density, A/mm²	11.3
Conductor diameter with medium insulation covering	0.686
Conductor area with medium insulation covering	0.369
Total coil (151 cond) area, mm²	55.719
Slot area available, mm²	137
Conductor packing factor	0.4
Mean length of turn, mm	160
Length of wire, m	48.32
Resistance, Ω	2.85 Ω

The standard resistance of 23 SWG copper wire per 1000m at 20° C is 59.02Ω.

For 48.32 meters, the resistance is 2.85 Ω (Specification: 2.5 Ω ± 10%).

The analytical calculation of electrical loading and magnetic loading for 24 slots and 8 poles motor configuration is validated and the armature winding details are verified. The fabrication of the electrical sheet lamination, winding, stacking and coil forming fixtures are initiated. The individual coils are machine wound using the winding fixture for the required number of turns. Figure 4.4 shows the three coils for three phase winding per quadrant. The number of turns per coil is 151. Figure 4.5 shows the coils inserted in the magnetic core assembled in the winding fixture. Figure 4.6 shows the quadruplex armature stator with four three phase winding but with reduced number of turns in the slot.

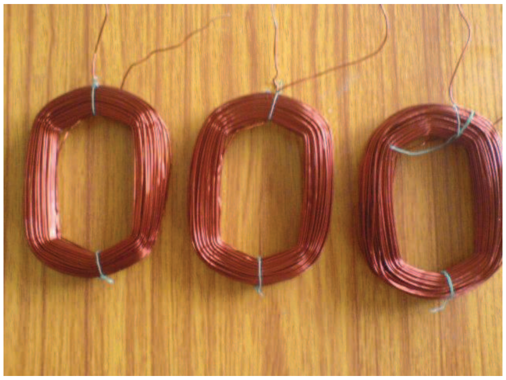


Figure 4.4 Machine wound coils for 24 slots 8 poles configuration

Figure 4.5 24 slots 8 poles armature winding with large overhang

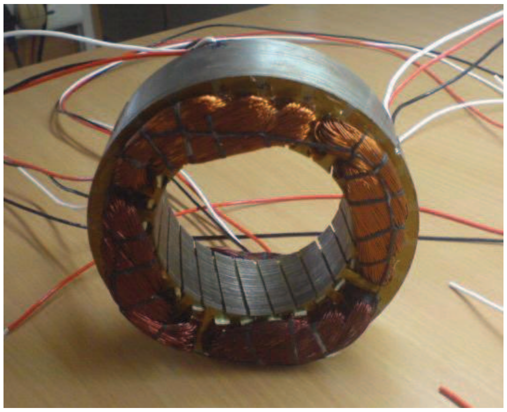


Figure 4.6 24 slots 8 poles configuration with reduced no. of turns

4.2.5 Limitations in 24 Slots 8 Poles Configuration

Three major setbacks observed while winding the armature coils in 24 slots and 8 poles motor configuration which is selected initially for the prototype model. Firstly, the slot area was insufficient to accommodate the calculated number of turns for 25MGOe magnet flux even though the packing factor is less than 0.4. Secondly, the overhang thickness was more than the specified limit due to insertion difficulty of the last phase coil. Thirdly, the torque variation was more due to single coil per phase. These limitations are overcome by distributing the conductors over periphery of the armature volume. This is accomplished by increasing the number of slots to 48 and corresponding poles to 16. 60 slots 16 poles motor configuration is also designed to study the performance output comparison.

4.3 48 SLOTS 16 POLES CONFIGURATION

In order to limit the overhang thickness with in the required dimension the number of conductors per slot should be reduced. This is achieved by distributing the conductors in the armature by increasing the number of poles to 16 and number of slots to 48. To reduce the line to line resistance value the total number of turns per phase is reduced. To get the required torque with the reduced turns the magnetic loading is increased. The airgap flux density is increased by increasing the radial thickness of the magnet and energy product from 25 MGOe to 28 MGOe. The distribution of the armature conductors is also studied for the 60 slots 16 poles motor (fractional slot) configuration possible for this quadruplex redundancy magnetic circuit. Table 4.2 shows the magnetic circuit for both the motor configurations design comparison. The permanent magnet rotor assembly is kept common for both the motors. In order to reduce the cogging torque, the proposed skew for 48 slots stator is one slot pitch since it is an integral slot configuration and half slot pitch skew for 60 slots configuration.

Table 4.2 Magnetic circuit comparison of 48 slots and 60 slots motor

Parameters	48 slots, 16 poles	60 slots, 16 poles
Pole pitch, mm	14.92	14.92
Magnet width, mm	**11**	**11**
Slot Skew angle in deg	7.5	3
Tooth width, mm	**3**	**2.4**
Back iron thickness, mm	**6**	**4.8**

The 48 slots stator has integral slots per pole and 60 slots stator has fractional slots per pole and these two armature windings for quadruplex redundancy are worked out. The Figure 4.7 shows the lamination drawing for 48 slots stator and Figure 4.8 shows the lamination drawing for 60 slots stator.

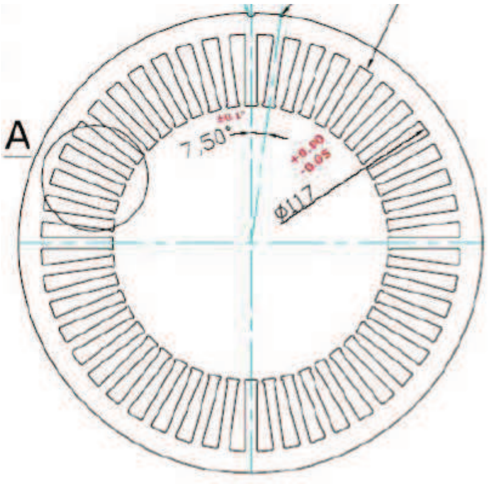


Figure 4.7 48 slots lamination drawing

The tooth width and back iron thickness are fixed based on the analytical calculation and finite element analysis. M19 29 gage silicon steel lamination material is used for the stator magnetic core. The dimensions are selected such that the maximum flux density in the tooth is around 1.5 Tesla and in back iron 1.2 Tesla. The slot pitch for 48 slots stator is 7.5 degree mechanical and for 60 slots stator is 6 degree mechanical. The fractional slot configuration itself reduces the cogging torque. Half slot pitch skew of 3 degree is recommended for 60 slots configuration since skewing reduces the torque output.

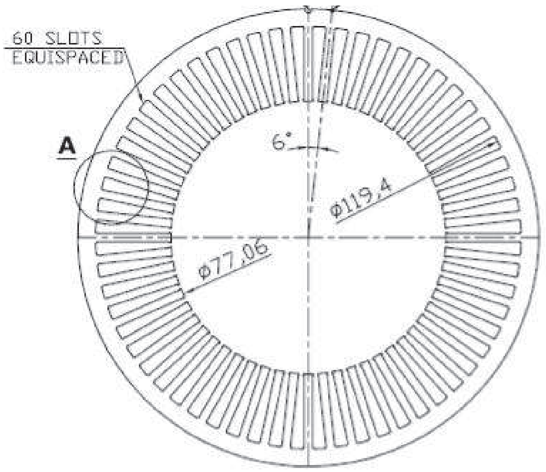


Figure 4.8 60 slots lamination drawing

4.3.1 48 Slots 16 Poles: Magnet Operating Point

In 16 poles rotor assembly configuration the magnetic loading is increased by increasing the magnet radial thickness to 5.5mm from 4.0mm. The magnet energy product is increased to 28 MGOe from 25 MGOe considered for 8 poles motor configuration. The 11mm magnet width is fixed to reduce the cogging torque. The flux concentration factor is worked out for the airgap diameter and magnet fraction. The permeance coefficient for this volume of the magnet with 0.5mm physical airgap length is then calculated to find the operating point of the magnet.

$$\text{Permeance coefficient} = \frac{l_m}{gC_\phi} = 15$$

The operating flux density for the selected magnet dimensions is found from Samarium Cobalt 28 MGOe magnet demagnetization characteristics shown on Figure 4.9. For the calculated permeance coefficient of 15, the operating flux density of the magnet is found to be greater than 0.8 Tesla. The airgap flux density of 0.75 Tesla is taken to calculate the electrical loading requirement to generate the desired torque output. The 16 poles rotor configuration is shown in Figure 4.10 and the actual rotor assembly where permanent magnets housed on the magnetic return ring is shown in Figure 4.11.

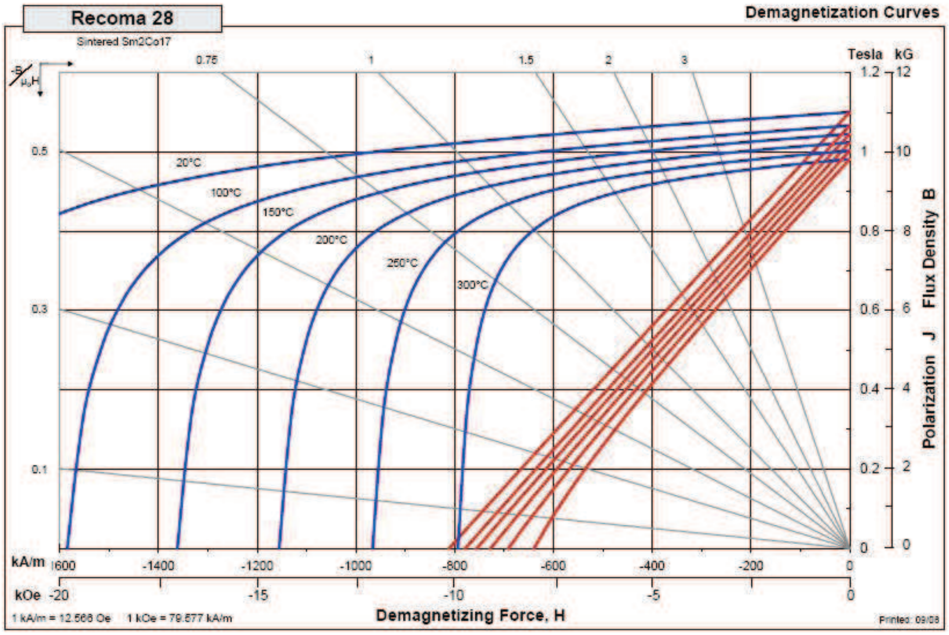


Figure 4.9 Demagnetization curve of 28 MGOe Samarium Cobalt magnet

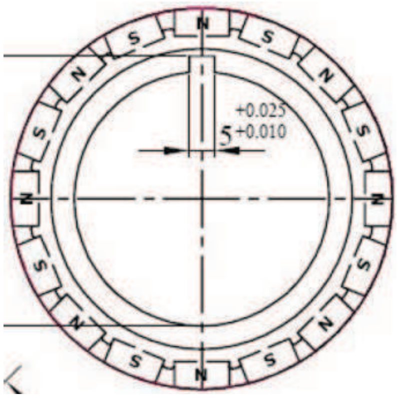


Figure 4.10 16 poles rotor assembly configuration

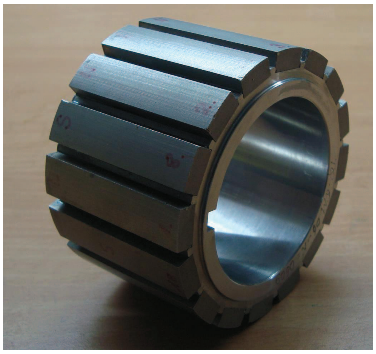


Figure 4.11 16 poles permanent magnet rotor

4.3.2 48 Slots 16 Poles: Back-EMF and Number of Turns

The airgap flux density of 0.75 Tesla is used to calculate the electrical loading required for specified torque generation.

Torque constant, K_t = 0.645 Nm/A
Back-EMF constant, K_b = 0.645 V/(rad/sec)
No-load speed = 1000 rpm
Supply voltage = 75 V

The back-EMF, E is found from the back-EMF constant, E = 67.5 V

Number of conductors required to generate the back-EMF is worked out from the basic relation, $E = BLv$

Surface velocity v = 3.979 m/s

Number of conductors required for this back-EMF is 64 conductors per slot.

4.3.3 48 Slots 16 Poles: Quadruplex Winding Details

Two layer, four coils per phase, totally twelve coils are machine wound and interconnected for three phase star connected winding. The winding pattern and coil interconnections per quadrant are as shown in the

Figure 4.12. Each quadrant has four pole armature winding with three output leads and the star point. 23 SWG copper wire is used for winding the coil to carry continuous RMS current of 3.3 A for a current density of 11.3 A/mm². The three phase coils are distributed and interconnected with star point in 12 slots such that each quadrant behaves as a separate motor. The winding pattern is similar to all other three quadrants. Figure 4.13 shows the quadruplex winding armature stator assembly of 48 slots configuration.

Total number of slots = 48
Total number of poles = 16
No of slots per quadrant = 12
No. of poles per quadrant = 4
Three phase coils per quadrant
Four coils per phase
Double layer winding
No. of turns per coil = 32

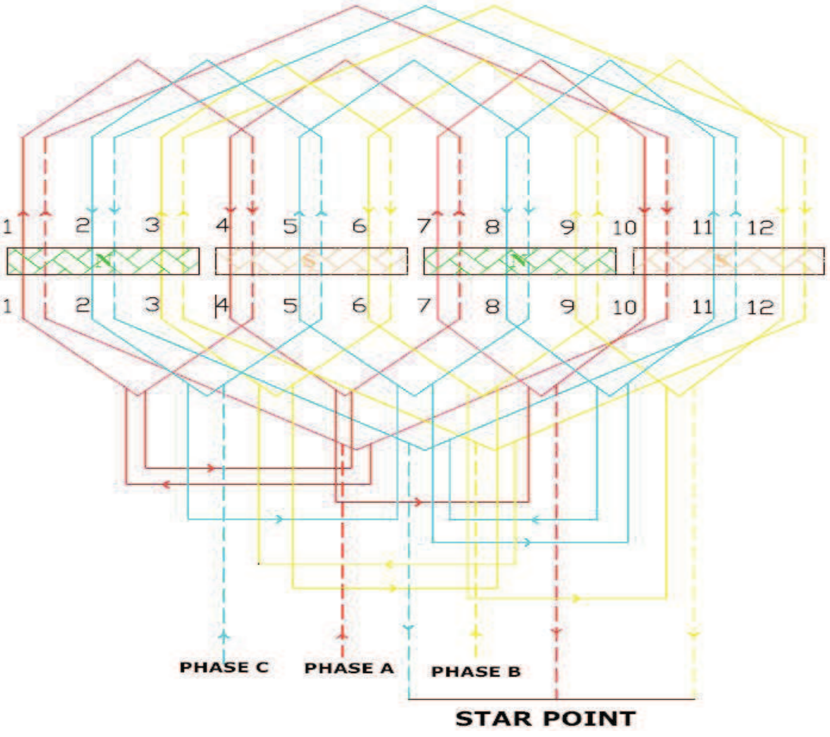


Figure 4.12 48 slots 16 poles one quadrant quadruplex winding pattern

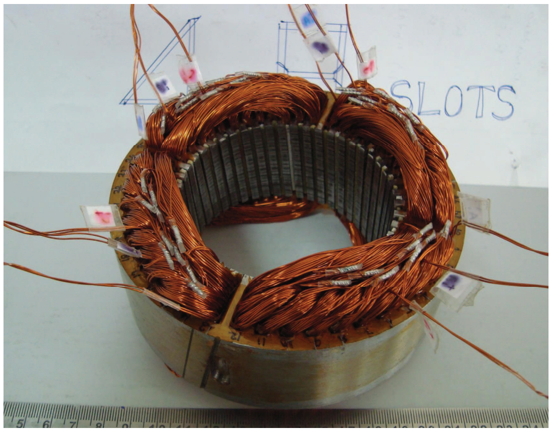


Figure 4.13 48 slots quadruplex winding armature stator

Three phase star connected coils are wound for all the four quadrants. There are two types of coil sizes, twelve coils with slot pitch of 1-4 and three coils with slot pitch of 1-10. Each individual quadrant has three phase winding and three armature leads such that each behaves as a separate motor leading to a quadruplex redundancy. The armature stator meets the resistance and inductance specification.

The 48 slots 16 poles motor fabrication is carried out using the design details. The motor configuration is tested for frequency response characteristics at motor level, actuator level and system level of the mechanism. The test details are presented in the chapter 6. In order to improve the system response, the 60 slots 16 poles (fractional slot) configuration is developed.

4.4 60 SLOTS 16 POLES CONFIGURATION

The 16 poles rotor assembly configuration is fixed in order to reduce the overhang thickness. For fractional slot stator assembly, 60 slots configuration is selected such that there are fifteen slots per quadrant for four permanent magnet poles. The magnetic circuit is simulated in the finite element based electromagnetic software to determine the tooth width, back iron thickness and slot opening. Fractional slot configuration itself reduces the cogging torque to a lower value. Half slot pitch skew is suggested to reduce the cogging torque further. The airgap length and permanent magnet rotor assembly is same as 48 slot configuration.

4.4.1 60 Slots 16 Poles: Quadruplex Winding Details

Keeping the stator assembly and rotor assembly apportioned volume same as that of 48 slots motor configuration, the number of conductors per slot for 60 slots configuration is worked out for the airgap flux density of 0.75 Tesla. For the given back-EMF constant and speed, the number of conductors per slot is 52. For 15 slots per quadrant, 15 coils are used for the three phase star connected winding. Figure 4.14 shows the quadruplex winding pattern for the 60 slots configuration. Double layer technique is adopted for the machine wound coils. 23 SWG copper wire is used for winding the coil to carry continuous RMS current of 3.3 A for a current density of 11.3 A/mm². The three phase coils are distributed and interconnected with star point in 15 slots such that each quadrant behaves as a separate motor. The winding pattern is similar to all other three quadrants.

Total number of slots = 60
Total number of poles = 16
No. of slots per quadrant = 15
No. of poles per quadrant = 4
No. of slots per pole = 3.75
No. of turns per slot = 52
Copper wire = 23 SWG
Double layer winding
No. of turns per coil = 26
Three phase star connected winding in all four quadrants

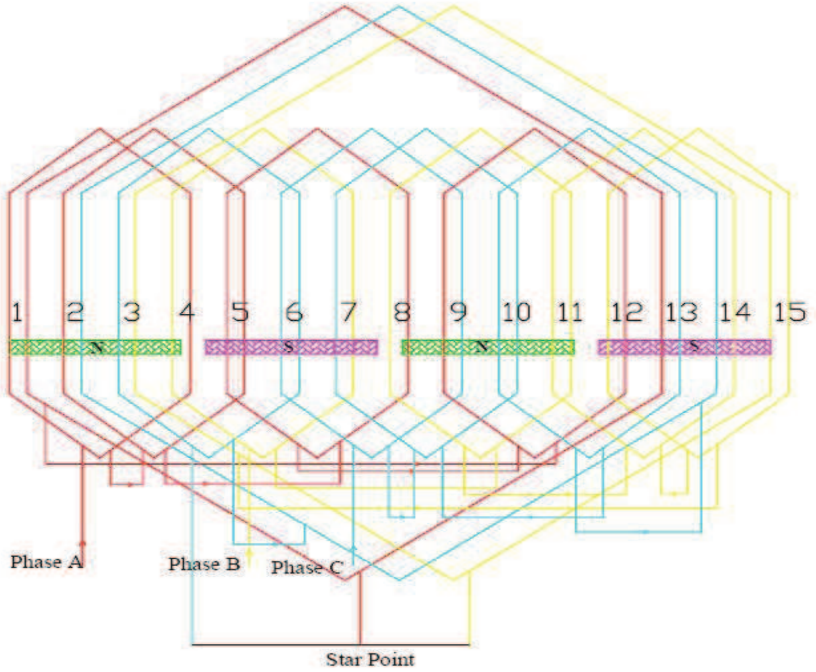


Figure 4.14 60 slots 16 poles one quadrant quadruplex winding pattern

Figure 4.15 shows the armature stator assembly of 60 slots stator configuration. The figure shows four groups of coils in four quadrants physically isolated form each other. Three phase armature leads are taken out for all the four quadrant windings. The three phase star connected-one quadrant winding and 16 pole permanent magnet rotor assembly perform as a separate bldc motor.

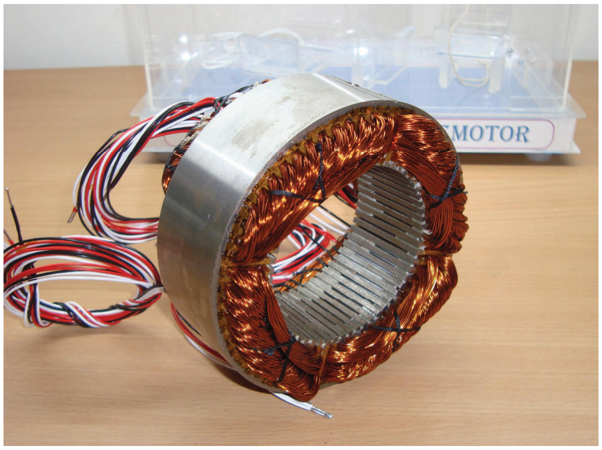


Figure 4.15 60 slots quadruplex winding armature stator

4.5 TRIPLEX REDUNDANCY HALL SENSOR ASSEMBLY

The brushless dc motor requires rotor position signal to commutate the armature windings. The rotor position can be obtained directly from a resolver or sensing device such as Hall sensors. The indirect method of obtaining the rotor position is by measuring the back-EMF of the winding. Here six step trapezoidal commutation drive electronics is used to run the motor. Latching type Hall effect sensors are used to sense the rotor position and feedback for commutation logic. Three Hall sensors are required to commutate the three phase winding. The quadruplex winding redundancy permanent magnet brushless dc motor for the electromechanical actuator requires triplex sensor redundancy for reliability. Three sets of three Hall sensors are required for triplex redundancy. The details of the lead position are given in the interface drawing. Figure 4.16 shows the layout of Hall sensors in the strip. The Hall sensor ring is aligned for equal speed in both directions and adhesively fixed with the armature stator assembly.

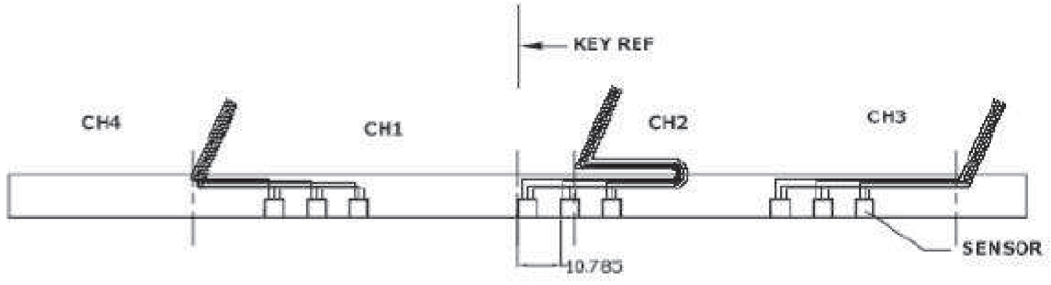


Figure 4.16 Triplex redundancy Hall sensor assembly

Each set of Hall sensor assembly can drive each quadrant motor individually or all four quadrants together. The reliability of the Hall sensors are ensured with this three sets of sensors.

4.6 SUMMARY

The preliminary design of the motor is carried out with 8 poles permanent magnet rotor and 24 slots armature stator having quadruplex redundancy winding in the armature. The magnetic loading and electrical loading are worked out for the above configuration. The copper wire size is selected based on the current density and the resistance requirement. The quadruplex winding pattern for the 24 slots and 8 poles structure is provided. The laminations are wire-cut and stacked for the armature magnetic core. Only two-third of the calculated winding turns is inserted into the designed slot area because of winding difficulty. This is due to overhang coil length limitations for mechanical interface. To overcome the problem of overhang thickness for single coil per phase in 24 slots stator, distribution of phase coils is considered. Hence 48 slots 16 poles and 60 slots 16 poles configurations are worked out. The magnet energy product is increased to 28 MGOe to get the required torque output. The corresponding electrical loading, magnetic circuit details and armature winding patterns for both the integral slot and fractional slot configurations are given. Triplex redundancy Hall sensor assembly is designed for the quadruplex redundancy armature winding.