CHAPTER 3

QUADRUPLEX WINDING REDUNDANCY BRUSHLESS DC MOTOR

3.1 INTRODUCTION

This chapter presents the design of new quadruplex winding redundancy permanent magnet brushless dc motor. The design is carried out based on the requirement specification and interface drawing of the motor for electromechanical actuator application in aerospace mechanism. The new quadruplex winding technique for reliability requirement is introduced. List of major components for the stator assembly and rotor assembly is provided. The motor volume is apportioned from the given overall dimensional constraint. Assuming the value of airgap flux density, the number of conductors for back-EMF and torque requirement is calculated.

3.2 DESIGN CONSIDERATION

Before designing the motor for required specification, the fundamental design issues are considered. The size of the motor to produce the desired torque for radial flux motors stated as

\[ T = KD^2L \]  \hspace{1cm} (3.1)

Where,  
T is torque in Nm
K is a motor constant
D is the airgap diameter, m
L is the stack length, m
Torque is linearly proportional to length

Torque is proportional to diameter squared

The ability to produce force increases linearly with diameter ($\pi D$) and force produces torque which is proportional to radius (D/2).

### 3.2.1 Motor Diameter

Mechanical power output is directly proportional to torque whereas the torque is proportional to square of the diameter as given in 3.1. A motor having larger diameter generates more mechanical power which states the motor diameter should be maximized. There are constraints that limit the diameter of the motor. The important constraint in this application is space limitation and interface with the mechanism. The mass and inertia of the motor also plays a major role in operation of the motor in space mechanism requiring maximum torque to inertia ratio. The torque to inertia ratio of a motor decreases as the square of the diameter. The diameter of the motor should be selected based on the above constraints.

Alternate equation for the development of torque in a motor is given by

$$T = PB_g IL(D/2)$$  \hspace{1cm} (3.2)

where $P =$ No. of poles, $B_g =$ Airgap flux density.

In order to increase the power output for a fixed diameter motor the electrical loading and magnetic loading shall be increased.

### 3.2.2 Active Motor Length

The torque developed by the motor is directly proportional to the active length of the motor. But by increasing the length, the mass and volume
of the motor get increased. Also the resistance of the winding depends on the core length and hence the resistive loss increases as longer copper wire is required for more active length. Therefore, increasing the motor active length does not improve the efficiency of the motor.

3.2.3 Ampere-Turn

Ampere turn is the product of number of turns and the winding current. The winding inductance increases square of the number of turns. High inductance affects the motor electrical time constant. The winding resistance is proportional to resistive loss. Increase in number of turns increases the resistive loss. But increase in number of turns reduces the winding current for the required torque and hence copper loss is reduced as it is proportional to square of the current. If the conductor size is constant, the cross sectional area increases as turns increases. The increase in slot area increases the mass of the stator core which affect the power density and increase in slot current increases the armature reaction field. This increases the core loss in the magnets and decreases the airgap flux density due to stator core saturation.

3.2.4 Airgap Flux Density

In permanent magnet brushless dc motor the magnetic loading is maximized to get the required torque output and this requires high energy permanent magnet material. The airgap flux density will increase by increasing the permeance coefficient of the magnetic circuit. High permeance coefficient implies larger magnet length and shorter effective airgap length. Decreasing the effective airgap length increases the cogging torque. And hence for a high magnetic loading the volume of the magnet material and its
energy product should be high and ferromagnetic material is required to concentrate the flux. The saturation in the stator core teeth also limits the improvement in the airgap flux density.

### 3.2.5 Number of Poles

The selection of pole numbers depends on the airgap diameter. Increasing the number of poles in a fixed area decreases the magnet width to accommodate the additional magnets. With this the magnet leakage flux increases which reduces the flux density in the airgap. Increasing the number of poles increases the rotational frequency of the motor. The core loss depends on the rotational frequency of the motor. The hysteresis loss is directly proportional to frequency and eddy current loss is directly proportional to square of the frequency. The increase in rotational frequency increases the core loss in the motor which decreases the efficiency. The advantage of more poles is that the overhang length will be reduced and which reduces the end winding resistance and inductance. The back iron thickness gets reduced by increasing the number of poles. In a high performance brushless dc motor the design goal is to improve the tradeoff between the electrical loading and magnetic loading by finding a method to increase one in manner that does not diminish the other.

### 3.3 MAGNETIC CIRCUIT DETAILS

Brushless permanent magnet motor operation relies on the conversion of energy from electrical to magnetic to mechanical and magnetic energy which depends on spatial distribution of flux in the motor plays a central role in the production of torque. A simple geometry of the magnetic field can be found analytically to determine the magnetic field distribution in
the motor. The direction of magnetic field is assumed for the preliminary design of the motor (Duane C. Hanselman 1994).

The stator and rotor structure of brushless dc motor is shown in Figure 3.1 and 3.2. The magnetic circuit model of one flux loop shown in Figure 3.3 composed of one half of the two magnets and associated stator and rotor back iron. The magnetic field due to winding current is not considered. By considering $R_r$ and $R_s$ to be negligible with respect to $R_g$ and $R_{ml}$, the magnetic circuit can be simplified as shown in Figure 3.4.

Figure 3.1 Bldc motor stator-rotor structure

Figure 3.2 Permanent magnet and magnetic material structure
Figure 3.3 Magnetic circuit model of the structure

- $R_r$ = Rotor back iron reluctance
- $R_s$ = Stator back iron reluctance
- $2R_s$ = Reluctance of the one half of airgap with compensation for slotting
- $\Phi_r/2$ = Flux source of one half of the magnet
- $2R_m$ = Reluctance of one half of the magnet
- $\Phi_g/2$ = Airgap flux flowing through one half of the airgap cross section area
- $R_{ml}$ = Reluctance modeling the flux leakage from magnet to magnet

Figure 3.4 Simplified magnetic circuit
The airgap permeance describes the net permeance seen by the magnet flux that enters the stator. This flux emanates from cross sectional area is given by

\[ A_g = \tau_p L \frac{1 + \alpha_m}{2} \]  

(3.3)

the airgap permeance. \( P_g \) is

\[ P_g = \frac{\mu_o \tau_p L (1 + \alpha_m)}{2 g_e} \]  

(3.4)

\( g_e \) = Effective airgap length,

\[ g_e = \left( g + \frac{l_m}{\mu_r} \right) k_c \]  

(3.5)

\( \tau_p \) = Magnet pole pitch

\( \alpha_m \) = Magnet fraction

\( k_c \) = Carter coefficient

\( l_m \) = Magnet radial thickness

\( g \) = Physical airgap length

The airgap flux with the above equations

\[ \Phi_g = \frac{l}{1 + \mu_r k_c k_{ml} / PC} \Phi_r \]  

(3.6)

PC = Permeance coefficient

\( k_{ml} \) = Magnet leakage factor
The flux concentration factor, 
\[ C_{\phi_b} = \frac{A_m}{A_g} \]  

(3.7)

The airgap flux density, 
\[ B_g = \frac{C_{\phi_b}}{1 + \mu_r k_c k_{ml}/PC} B_r \]  

(3.8)

\[ B_r = \text{Remanence flux} \]

### 3.4 DESIGN APPROACH

The design approach starts with basic motor geometrical constraints. The volume for stator assembly and rotor assembly is apportioned from the given overall dimensional specification of the motor. The motor stack length and airgap diameter are fixed based on the designer experience. Once the motor volume is fixed, the magnetic loading for the torque production is calculated. The magnetic circuit details determining the number of poles and slots are worked out. The permeance coefficient and magnet operating point is found for the magnetic circuit. The size, shape and energy product of the magnet are determined to maximize the magnetic loading. Once the magnetic loading is calculated to carry maximum flux in the given magnetic circuit, the electrical loading is worked out. The current required to generate the required motor output torque is then determined. Given the desired back-EMF at rated speed, the number of conductors for generating the back-EMF is calculated. The phase inductance and winding resistance are computed from the winding information.

The proposed work describes the design and development of brushless dc motor having four independent winding in its armature assembly as per the specification requirement of motor for electromechanical actuator application. The design of armature stator assembly, permanent magnet rotor assembly and Hall sensor assembly are worked out. Armature design is a quadruplex three phase star connected winding separately housed in four
quadrants of the armature stator providing physical and electrical isolation of each quadrant winding for reliability and redundancy. The permanent magnet rotor assembly is designed conforming to the quadruplex armature in which each quadrant of the armature and the magnet rotor performs independently as a separate brushless dc motor. The Hall sensor assembly is a triplex redundancy separate assembly housed in the stator core to sense the rotor position for six step commutation logic.

3.5 SPECIFICATION REQUIREMENT OF THE MOTOR

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<td>2. Winding</td>
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<td>3. Position sensor</td>
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<td>4. Commutation scheme</td>
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<td>5. Stall torque</td>
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<td>6. No-load speed</td>
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<td>9. Back-EMF constant</td>
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<td>10. Winding resistance</td>
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<td>11. Winding inductance</td>
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<td>12. Rotor inertia</td>
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<td>13. Cogging torque</td>
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<td>14. Ripple Torque</td>
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<td>Drive electronics</td>
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3.5.1 Interface Drawing

Figure 3.5 Interface drawing of the motor
## 3.6 SPECIFICATION DERIVED

### Table 3.2 Design goal

<table>
<thead>
<tr>
<th><strong>Motor</strong></th>
<th>Frameless BLDC motor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Supply Voltage</strong></td>
<td>75 V, DC</td>
</tr>
<tr>
<td><strong>Three phase winding in each quadrant</strong></td>
<td>Star connection</td>
</tr>
<tr>
<td><strong>Current per quadrant</strong></td>
<td>12.4 A</td>
</tr>
<tr>
<td><strong>Current for four quadrants</strong></td>
<td>12.4 * 4 = 49.6 A</td>
</tr>
<tr>
<td><strong>Load cycle</strong></td>
<td>As per sketch</td>
</tr>
<tr>
<td><strong>Hall sensors for six sequence commutation</strong></td>
<td>Triplex redundancy</td>
</tr>
<tr>
<td><strong>Overall dimensions</strong></td>
<td>As per interface drawing</td>
</tr>
<tr>
<td><strong>Stator outer diameter, (max)</strong></td>
<td>129 mm</td>
</tr>
<tr>
<td><strong>Rotor inner diameter, (min)</strong></td>
<td>50.8 mm</td>
</tr>
<tr>
<td><strong>Rotor inertia</strong></td>
<td>8.8e-4 Kg m²</td>
</tr>
<tr>
<td><strong>Overall stator length (max)</strong></td>
<td>69mm</td>
</tr>
<tr>
<td><strong>Overall rotor length (max)</strong></td>
<td>49mm</td>
</tr>
<tr>
<td><strong>Armature stack length</strong></td>
<td>43mm</td>
</tr>
<tr>
<td><strong>Winding overhang inner diameter</strong></td>
<td>77.47mm</td>
</tr>
<tr>
<td><strong>Operational temperature</strong></td>
<td>80°C</td>
</tr>
<tr>
<td><strong>Maximum torque per quadrant</strong></td>
<td>8 Nm (Nominal)</td>
</tr>
<tr>
<td><strong>Total torque: (8Nm * 4 quadrant)</strong></td>
<td>32 Nm (Nominal)</td>
</tr>
<tr>
<td><strong>No-load speed@ 75 V, DC</strong></td>
<td>1000 rpm</td>
</tr>
<tr>
<td><strong>Line to line Winding resistance</strong></td>
<td>2.4 ohms ± 10 %</td>
</tr>
<tr>
<td><strong>Line to line Winding inductance</strong></td>
<td>10.2mH ± 30 %</td>
</tr>
</tbody>
</table>

Three sets of Hall sensor signal output for redundancy.
Independent four quadrant winding design for winding isolation and redundancy.
3.7 LIST OF MAJOR ELEMENTS

(1) Permanent magnet rotor assembly
   - Rotor back iron ring
   - Permanent magnets
   - Potting compound

(2) Armature stator assembly
   - Electrical lamination sheet
   - Slot insulation
   - Copper wire
   - Lead wires
   - Solder wire, lead
   - Flux
   - Heat shrinkable sleeves
   - Epoxy bonding resin
   - Potting compound
   - Hall effect sensors and PCB

(3) Tools and fixtures
   - Lamination stacking fixture
   - Coil winding fixture
   - Stack holding fixture during winding
   - Overhang forming fixture
   - Armature potting fixture
   - Rotor magnet assembly fixture
   - Stator-rotor assembly fixture
   - Testing fixture
3.8 MAGNETIC CIRCUIT PHYSICAL DIMENSIONS

Based on the design input and output requirements and the given overall dimensions two-third of the annular volume is apportioned for stator assembly and one-third to the magnet rotor assembly since high coercive magnets is used for the rotor design. This apportionment meets the winding overhang inner diameter needed and the inner diameter of the stator stack is taken as 77mm for magnetic circuit calculations.

The following input dimensions are worked out from the given volume constraints. The magnetic circuit details are calculated with the following dimensions.

- Stator outer diameter: 129mm
- Stator inner diameter: 77mm
- Stack length: 43mm
- Physical airgap length: 0.5mm
- Rotor outer diameter: 76.0mm
- Rotor inner diameter: 50.8mm

The torque motor diameter and length is specified and fixed. The torque output of the motor which is the product of electrical loading and magnetic loading is found by calculating the work done per revolution ($W_r$).

$$W_r = (\text{Total magnetic loading}) \times (\text{Total electrical loading})$$

Electrical loading = $IZ$

Magnetic loading = $P\Phi$

Where
- $I$ = Winding current in Ampere
- $Z$ = No. of conductors
- $P$ = No. of poles
\[ W_r = (P\Phi)(IZ) \quad (3.9) \]
\[ 2\pi T = \pi^2 D^2 LB_g q \quad (3.10) \]

where \( B_g \) = Airgap flux density in Tesla
\( q \) = Ampere conductors
\( T \) = Torque in Nm

Torque developed by the motor is given by
\[ T = \frac{\pi}{2} D^2 LB_g q \quad (3.11) \]

The magnetic loading is provided by high energy rare earth permanent magnets in the rotor assembly. The radial thickness of the magnet is apportioned from the rotor return ring. The undesired cogging torque in the motor is also depends on magnet width. The magnet width is selected such that it reduces the cogging torque. The volume of the magnet is worked out and the magnet permeance coefficient is calculated. The magnet operating point is found from the high energy magnet demagnetization curve. Assuming the airgap flux density over the pole arc and with the values of \( D \) and \( L \), the needed Ampere conductors to develop the required torque is found out using the above relation. Once the total magnetic loading and total electrical loading are worked out, the number of poles and slots are selected. The aim of the proposed work is to select slot-pole combination based on the following constraints.

1. Number of slots for quadruplex winding redundancy
2. Number of poles conforming to the stator quadruplex redundancy
3. To keep the cogging torque minimum.
4. To reduce the core losses
3.9 QUADRUPLEX WINDING REDUNDANCY TECHNIQUE

This thesis focus on the design of brushless dc motor with quadruplex redundant three phase star connected winding in the armature stator for reliability requirement of electromechanical actuator. The present application requirement needs four independent motors operation in single magnetic core for functional redundancy of the actuator system. A new winding method is adopted in stator assembly to isolate four quadrant windings electrically and physically from each other for quadruplex winding redundancy.

The torque motor requirement of quadruplex winding isolation puts constraint in selecting the number of poles in steps of two. Twelve poles are suitable for the apportioned airgap diameter but the quadruplex winding isolation is not possible with three poles per quadrant. Hence eight poles or sixteen poles are the possible options for this configuration. In this work the eight poles and twenty four slots configuration is selected initially and the analytical calculations are carried out to find the magnetic loading and electrical loading. Flux density in the airgap is ensured in the finite element
analysis. The magnetic circuit details are validated with the analysis result. Based on the design simulation the fabrication of the motor is carried out. For the eight poles twenty four slots configuration, each quadrant has six slots for three phase winding and the slots per pole per phase is one for eight poles rotor. Three coils are used to wound for three phase winding of a quadrant. The 23 SWG copper wire is selected for the assumed current density around 10 A/mm² for the given duty cycle. The slot space factor is around 0.4 for the calculated number of turns in the slot for the required torque. While winding the armature coils only two-third of the designed turns were able to put into the slots due to overhang length limitation constraint for mechanical interface with the mechanism. Also the line to line resistance value meets the requirement specification with this two-third calculated turns. To overcome the overhang problem two motor configurations, 48 slots stator and 60 slots stator with common 16 poles rotor, are designed. To reduce the number of conductors the magnetic loading is increased by increasing the magnet volume and changing energy product of the magnets from 25 MGOe to 28 MGOe. The magnetic circuit is iterated to the increased magnetic loading. The analytical design is validated with finite element analysis software and magnetic circuit details are plotted for comparison. Based on the simulation results the above two proto type motors (Integral slot and Fractional slot) are developed. Both the motor are experimentally tested and the results are tabulated for comparison of all the four quadrants performance output.

### 3.10 COGGING TORQUE

The major disadvantage of brushless dc motor is production of undesired cogging torque and ripple torque. Cogging torque is due to interaction between the rotor permanent magnets and the tooth of the stator. It is generated by the interaction of airgap flux and stator reluctance variation in the airgap. The rotor tends to align to the stator teeth even without winding
excitation. This cogging torque superimposed on the desired output torque causes vibration and acoustic noise in the motor while running. Techniques to reduce cogging torque play a prominent role in motor design.

Cogging torque is given by

\[
T_{cog} = \frac{1}{2} \phi_s^2 \frac{dR_s}{d\theta}
\]  

(3.13)

Where \( \phi_s \) is the airgap flux and \( R_s \) is the airgap reluctance.

In this design stator slots are skewed to reduce cogging torque by making \( \frac{dR_s}{d\theta} \) near zero value over angular rotation of the torque. Skewing can be done either for magnet or to the slots. Skewing the magnet increases the magnet cost. Skewing the slots increases the ohmic loss because the increased slot length requires long wire. Both integral slot pitch and fractional slot pitch configurations are considered for the stator assembly design. The stator slots are skewed for one slot pitch for integral slot configuration and half slot pitch for fractional slot configuration. The cogging torque reduction technique in rotor assembly is also adopted. The pole pitch is selected such that the pole slot combination reduces the cogging torque. The demerit of skewing the stator slots is, it reduces the developed torque by skew factor as the effective Ampere-turn under the pole pitch is reduced. Limiting the magnet width to reduce the cogging torque lowers the magnetic loading.

The magnitude of the cogging torque for the torque motor configuration with and without skewing is evaluated using finite element analysis tool. However it is possible to meet the cogging torque specification by introducing one slot pitch skew for the integral slot and half slot pitch for fractional slots.
### 3.11 LOAD CYCLE

The load cycle per quadrant of the motor for ball screw actuator mechanism is given in Figure 3.7. The peak load current is 12.4 Ampere and no-load current is 1.5 Ampere per quadrant.

- **Load cycle**: 1225 seconds
- **Peak load duration**: 25 seconds
- **No-load duration**: 1200 seconds

For the given periodic and intermittent duty cycle, the equivalent RMS current producing the same loss is calculated for the selection of copper conductor diameter for the armature winding.

\[ I = \text{3.3 A (Continuous RMS current)} \]

The gage of the copper wire is selected based on the current density and resistance per phase requirement. Normally class C insulation with current density in the range of 10 A/mm² to 15 A/mm² is suggested for space grade application. For the current density around 11 A/mm² for continuous...
operation, 23 SWG copper wire with bare conductor diameter of 0.61mm and
cross sectional area of 0.292 mm² is selected. Total mean length of the copper
wire is calculated to find the line to line winding resistance. The number of
conductors per coil is calculated from back-EMF constant and speed of
rotation. The slot space factor is ensured for winding the coils in the slot
comfortably and within the overhang limitation for interfacing the armature
with the mechanism.

3.12 PERMANENT MAGNET MAGNETIC CIRCUIT

The different types of permanent magnet material available are
Alnico, Ferrite, Samarium Cobalt (SmCo) and Neodymium Iron Boron
(NdFeB). At room temperature NdFeB has the highest energy product of all
commercially available magnets. The high remanence and coercivity permit
marked reductions in motor size for the same output compared with motors
using Ferrite (ceramic) magnets. For the magnetic circuit consisting of
permanent magnet, high permeable ferromagnetic material and airgap, the
operating point of the magnet is calculated with the following equations.

By Guass’s law the flux density in the magnet and airgap are
related by

\[ B_m A_m = B_g A_g \]  
(3.14)

\[ \frac{B_m}{H_m} = -\mu_0 \frac{A_m g}{A_g l_m} \]  
(3.15)

\[ B_m H_m = \frac{B_g H_g A_g g}{A_m l_m} \]  
(3.16)

\[ B_m H_m = \frac{2W_g}{V_m} \]  
(3.17)
where \( B_m \) = Magnet flux density
\( A_m \) = Magnet area
\( B_g \) = Airgap flux density
\( A_g \) = Airgap area
\( g \) = Airgap length
\( l_m \) = Magnet thickness
\( H_m \) = Field density of the magnet
\( W_g \) = Magnetic energy stored in the airgap
\( V_m \) = Volume of the magnet

### 3.13 BACK-EMF AND NUMBER OF CONDUCTORS

From the given requirement specification, the following values are taken.

Torque constant, \( K_t = 0.645 \text{ Nm/A} \)

Back-EMF constant, \( K_b = 0.645 \text{ V/(rad/sec)} \)

No-load speed \( = 1000 \text{ rpm} \)

Supply voltage \( = 75 \text{ V} \)

The back-EMF, \( E \) is found from the back-EMF constant,

\[
E = K_b \times \text{rad/sec} = 67.5 \text{ V}
\]

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

Surface velocity, \( v = \pi Dn_s \text{ m/s} \)

No. of conductors for generating the torque for six step commutation is found from the following relation.
\[ Z = \frac{E}{BL\pi Dn_s} \]  

(3.18)

where \( n_s \) is revolution per second

The calculated number of turns is distributed in the stator volume depending upon the pole-slot combination.

3.14 SUMMARY

The requirement specification of the electrical motor for the electromechanical actuator in the space mechanism is given. The performance and geometrical input data are derived from the specification for the design of the advanced motor. The mechanical and electrical interface drawing for the motor in the actuator mechanism is provided. The approach for the design of the motor is explained briefly. The insight of new quadruplex winding redundancy technique is investigated. The continuous RMS current for selection of copper wire is worked out for the given operation load cycle. The main dimensions are worked out from the given volume constraint. The major considerations for the design of the motor are also listed. The effect of cogging torque on the performance of the motor and the method to limit the cogging torque is also studied.