# Design and Development of High Torque, Compact and Energy Saver IPMSM Motor for Hydraulic Applications

Case Study

**Rupalee S. Ambekar**
Bharati Vidyapeeth (Deemed to be University) College of Engineering, Pune
Faculty of Engineering, Department of Electrical Engineering
Pune-Satara Road, Pune-411043, INDIA
pawar.roopali@gmail.com

***Abstract*** *– The Permanent Magnet Synchronous Motor (PMSM) is widely used for various applications. It is the highly efficient motor as there are no field copper losses. The electrical energy is supplied to the motor through generator and the generator size depends upon the motor output. The efficiency of motor is the factor which will affect the size of the generator. This paper contributes the research work for the design of 35 kW, 440 V, 1000 rpm, 8 pole Synchronous Motor with Interior mounted Permanent Magnets (IPMSM) for the Hydraulic application. The designed IPMSM motor has efficiency of 98 % and can be used in place of 3-phase Induction Motor for the hydraulic application. The simulation is done in Ansys RMxprt fulfilling the required characteristics of Hydraulic application.*

***Keywords****: ansys software, energy saver, generator size, IPMSM, optimum design, RMxprt, skewing*

## 1. INTRODUCTION

An effective and efficient design methodology of Permanent Magnet Synchronous Motor (PMSM) is possible by dividing the rotor design into Induction Motor (IM) and PMSM design. The proposed design approach can then be validated by comparing the calculated results with the simulation results [1]. The design parameters of PMSM for required applications are core diameter, core length, number of poles & conductors, types of slots and materials [2]. The demagnetizing effect on limiting the ampere conductors per meter weakens the flux and use of Permanent Magnets (PM) makes the PMSM costlier. But, PMSM is widely used due the high efficiency and reliability [3]. Short end connections in Interior Permanent Magnet (IPM) machines makes its construction simple and also improves the performance [4].The starting torque and efficiency are the important factors for the optimum design of rotor [5]and in this study IPMSM machine is analyzed for different speed ranges and observed that the efficiency, torque and torque angle varies with the speed. Change in rotor geometry improves the efficiency of Line Start Permanent Magnet Motor (LSPMM) and increases the air gap flux [6, 7]. The performance and the main dimensions of the machine depend upon the type of magnetic material [8]. The PMSM performance can be improved by major considerations of stator and rotor structure and the development would avoid the importation [9]. The motor performance and the geometry can also be improved by using different stator configurations, magnet shape and rotor structure [10, 11]. The proposed IPMSM is analyzed by changing the stator outside diameter from 400 mm to 420 mm, selecting bridge type rotor construction. The motor performance and geometry are optimized with changed no-load and full load parameters. The distribution of magnetic field in PM motor scan be estimated by analytical approach [12]. Differential evolution algorithm with stator and rotor performance and geometric parameters issued to develop the software which will optimize the machine design using Finite Element Analysis [13]. Magnetization and the air gap between the magnets and the inter-poles influence the magnetic flux density and the counter emf [14]. The estimated values of EMF, Inductance and magnetic circuit by conventional calculations are validated with FEM analysis and experimental results [15]. It is found that the design of the Permanent Magnet Synchronous Generator can be optimized and verified by FEM analysis. The performance of the permanent magnet machines can be improved with different rotor geometry and can also be cost effective with ferrite magnet [16]. On comparison with different rotor geometry having same magnet volume, the rotor geometry with radial and circumferential magnetized magnet gives high flux density in air gap [17]. The air gap flux, flux linkages and hence the back emf may deviates from the analytical results due to the inaccuracies in manufacturing [18].

**Table 1.** Proposed Solutions as per Literature Review

| Sr. No. | Analysis Type | Advantages | Disadvantages |
|---|---|---|---|
| 1 | Limiting the ampere conductors per meter | It is widely used due the high efficiency and reliability [3] | Weakens the flux and use of Permanent Magnets (PM) makes the PMSM costlier [3] |
| 2 | Short end connections in Interior Permanent Magnet (IPM) machines | makes its construction simple and also improves the performance [4] | The air gap flux, flux linkages and hence the back emf may deviates from the analytical results due to the inaccuracies in manufacturing [4] |
| 3 | Change in rotor geometry | improves the efficiency of Line Start Permanent Magnet Motor (LSPMM) and increases the air gap flux [6, 7] | The air gap flux, flux linkages and hence the back emf may deviates from the analytical results due to the inaccuracies in manufacturing [18] |
| 4 | type of magnetic material | It affects the performance and the main dimensions of the machines [8] | The air gap flux, flux linkages and hence the back emf may deviates from the analytical results due to the inaccuracies in manufacturing |
| 5 | Use of different stator configurations, magnet shape and rotor structure | The motor performance and the geometry can be improved [10, 11] | The air gap flux, flux linkages and hence the back emf may deviates from the analytical results due to the inaccuracies in manufacturing |
| 6 | Magnetization and the air gap between the magnets and the inter-poles | influences the magnetic flux density and the counter emf [14] | The air gap flux, flux linkages and hence the back emf may deviates from the analytical results due to the inaccuracies in manufacturing |
| 7 | Different rotor geometry | Improves the performance of the permanent magnet machines and can also be cost effective with ferrite magnet [16] | The air gap flux, flux linkages and hence the back emf may deviates from the analytical results due to the inaccuracies in manufacturing |

The objective of this work is to design and develop the high torque, compact and energy saver Interior Permanent Magnet Synchronous Motor(IPMSM)for hydraulic application. To analyze and compare the results obtained by RMxprt with the calculated results. The design is then validated with the features of the machine and the requirements of the application.

The fundamentals of rotating machines, design calculations of AC and DC machines and the design software Ansys (RMxprt) are the basic requirements of this study.

The interior permanent magnet synchronous motor is recommended for Hydraulic application based on its advantages. It is proposed in place of the existing induction motor of 40 kW, 415 V, 69 A with a power factor of 0.86 and full load efficiency of 94 %. The required full load torque for the 1500 rpm speed and 40 kW power rating is 255 Nm and the input to the motor is the 100 kVA generator output. The induction motor frame size is 225 M (Medium) with a stator Outer Diameter (OD) of 400 mm. The proposed IPMSM is made compact by reducing the stack length, using the Interior mounted permanent magnets with the same stator outer diameter (OD). The proposed machine is analyzed for different speed ranges from 500 rpm to 2500 rpm as per the operating characteristics of axial hydraulic pump. It is analyzed for different voltages as 220 V, 440 V, 690 V, for different stator OD as 410 mm, 420 mm and also analyzed with different power rating as 30 kW, 32.5kW, 35kW, 37.5kW and 40kW. Finally, the optimum design is achieved which is compact and energy saver as it will reduce the generator size.

## 2. STATEMENT OF THE EXISTING SYSTEM

The existing motor is 40 kW, 415 V, 50 Hz, 69 Amp., 3-phase Induction motor with power factor of 0.86 and full load efficiency of 94 %. The full load torque is 255 Nm as per the given speed and power rating. The generator of 100 kVA is used to give supply to the motor.

As per the operating characteristics of Pump Model 4046 the power consumption at 1450 rpm and at maximum pressure and displacement is 32 kW, Maximum torque on the shaft is 350 Nm, Maximum permissible load on drive shaft is 1500 N and speed rating is 500 to 2500 rpm. For safety, power rating should be taken as 35 kW and generator size required is as per Table 2 for different power factor of generator by calculations.

Pump Model 4046 is a variable displacement axial piston pump which can operate at high pressure with low noise level and suitable for hydraulic oils having lubricating characteristics. The length of the stroke of the pumping piston affects the actual displacement and the position of the swashing plate determines the length of the stroke.

The pump supply voltage is 220 V AC with a tolerance of ± 10 % and frequency is 50 Hz as per the insulation class 'H' and connector protection degree of IP 65.

**Table 2.** Generator kVA for 35 kW motor output with different Power Factor (PF)

| Motor Output. Power (kW) | Motor Efficiency | Motor Input Pin | Generator Input | Generator PF | Generator kVA |
|---|---|---|---|---|---|
| 35 | 0.98 | 35.71 | 39.572 | 0.8 | 49.465 |
| | | | | 0.75 | 52.763 |
| | | | | 0.7 | 56.532 |
| | | | | 0.65 | 60.880 |
| | | | | 0.6 | 65.954 |

The 40 kW IPMSM can also run with the 62.5 kVA generator if power factor of the generator is good. The generator size required is as per Table 3 with different power factor of generator by calculations.

**Table 3.** Generator KVA for 40 kW motor output with different Power Factor (PF)

| Motor Output. Power (kW) | Motor Efficiency | Motor Input Pin | Generator Input | Generator PF | Generator kVA |
|---|---|---|---|---|---|
| 40 | 0.98 | 40.816 | 45.225 | 0.8 | 56.532 |
| | | | | 0.75 | 60.301 |
| | | | | 0.7 | 64.608 |
| | | | | 0.65 | 69.578 |
| | | | | 0.6 | 75.376 |

Motor Efficiency = 98 % and Assumed: Drive Efficiency = 95 % Generator Efficiency = 95 %

The best suitable motor for the same application of lifting is PMSM which have the advantages over Induction motor as of higher efficiency, higher power density, higher torque density and better dynamic performance.

## 3. DESIGN ANALYSIS

The design analysis is verified with different parameters as follows:

1) As per the pump details, the speed range is 500 rpm to 2500 rpm, so the same machine is analyzed for different speed ranges and observed that there are changes in frequency, frictional losses, no load line current, no load input power and all full load parameters such as line voltage increases, line current decreases, thermal and electric loading decreases, frictional and iron losses increases, copper losses decreases which decreases the total loss. Efficiency increases up to speed of 1500 rpm and afterwards decreases with further increase in speed. Torque and torque angle decrease with increase in speed as shown in Figure 1.

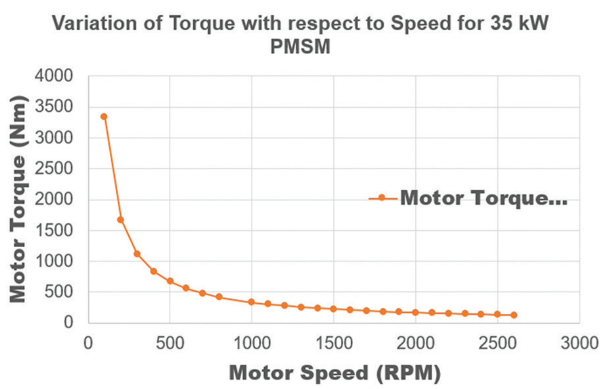


**Fig. 1.** Variation of Torque with speed

2) If the power rating is changed from 35 kW to 55 kW then there is change in torque as shown in Figure 2 for 1500 rpm IPMSM and Figure 3 for the speed range of 500 rpm to 2500 rpm.

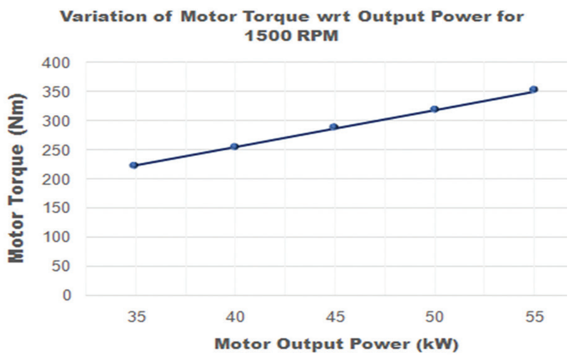


**Fig. 2.** Variation of torque w. r. t. output power for 1500rpm IPMSM

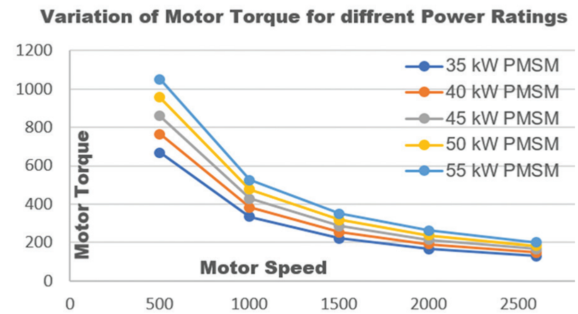


**Fig. 3.** Variation of motor torque for different power ratings

3) The same machine with a power rating ranges from 35 kW to 55 kW is analyzed for different voltage ratings as 690 V, 440 V, 220 V and observed the changes in i) no. of conductors per slot: it is doubled ii) no. of wires per conductors: reduced by half with increase in voltage iii) Steady state parameters: reactive inductances reduced with the increase in voltage, armature phase resistance increases with increase in voltage. iv) No load line current, no load input power. v) Full load parameters. It is presented in Figure 4.

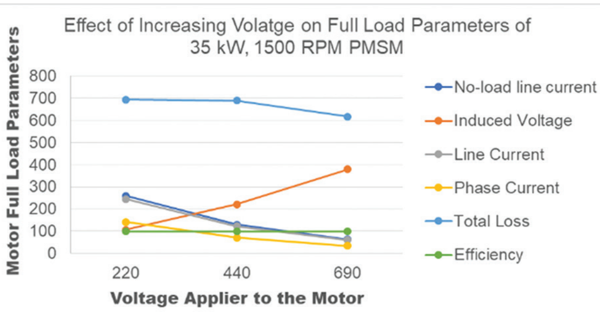


**Fig.4.** Effect of Stator voltage on full load parameters of 35 kW, 1500 rpm IPMSM

To attain the requirement of 350 Nm torque and speed of 1500 rpm, the power rating is 55 kW and power rating can be reduced by reducing the speed.

4) The effect of stator outside diameter is also analyzed by changing the diameter from 400 mm to 420 mm. The no-load and full load parameters changed with large deviation from 400 mm to 410 mm but from 410 mm to 420 mm the slight deviation is observed as shown in Figure 5.

The best suitable motor for the same application of lifting is IPMSM which have the advantages over Induction motor as of higher efficiency, higher power density, higher torque density and better dynamic performance.

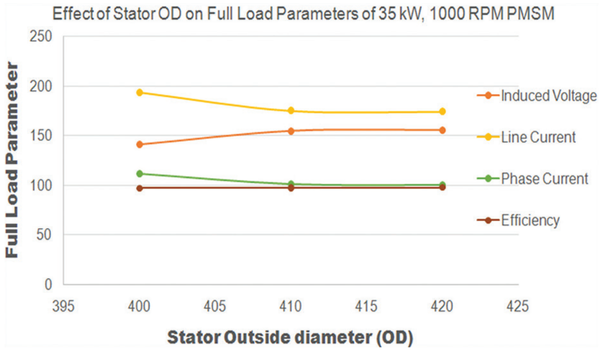


**Fig. 5.** Effect of Stator OD on full load parameters of 35 kW, 1000 rpm IPMSM

## 4. FINANCIAL IMPLICATIONS

The proposed IPMSM motor with better performance, high power per unit volume will make the generator compact and hence there would be saving in fuel consumption and electricity bill.

**Justification:**
For Diesel Generator:
Energy and fuel consumption Calculations

Electrical Energy and oil fuel cost associated to 67 kVA generator for existing 3-phase Induction Motor is as follows:

For 67 kVA generator the generator active power with power factor of 0.8 is 54 kW. The total energy consumption, total fuel consumption and electricity bill per month is estimated as shown in Table 4 and 5 respectively for 54 kW& 40 kW generator input.

**Table 4.** Generator Energy Consumption

| Generator input (kW) | Hours/day | Energy Consumption (kWH) | Liter/kWH |
|---|---|---|---|
| 54 | 10 | 540 | 0.4 |
| 40 | 10 | 400 | 0.4 |

If the machine power rating is changed to 35 kW then the energy consumption, total fuel consumption and electricity bill per month for generator input as 40 kW is estimated as shown in Table 4 and 5.

Hence the generator rating is reduced to 50 kVA which reduces the operating cost.

**Table 5.** Total Consumption of fuel and electricity bill

| Total Consumption of fuel (Liter) | Cost of Fuel/ Liter (Rs.) | Electricity Bill/ Day (Rs.) | Electricity Bill/ Month (Rs.) |
|---|---|---|---|
| 216 | 67 | 14, 472/- | 4,34,160/- |
| 160 | 67 | 10,720/- | 3,21,600/- |

## 5. PROPOSED SYSTEM

### 5.1 DESIGN CONSIDERATIONS

#### a) SPECIFICATION OF INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR

The Interior Permanent Magnet Synchronous Motor is compact in size, the installation and maintenance of permanent magnet is easy and it improves the system efficiency. The selected machine has the following specification:

Type of Operation: Motor
Type of Mechanical Load: Constant Power
Output Power(kW): 35
Applied Voltage (V): 440
Number of Poles, p: 8
Speed (RPM): 1000
Frequency (Hz): 66.67
Loss due to Friction (W): 18
Rotor location: Inner
In service Temperature (°C): 75

The total loss and no-load line current of the proposed IPMSM get reduced with the increase in voltage. Hence the 440 V rating is selected and optimized design is achieved with the 440 V voltage rating. The performance of the motor is improved and cost of the motor is therefore reduced.

The proposed design specification of the motor then helps to decide the stator and rotor main dimensions.

#### b) STATOR CONSTRUCTION

Design calculations are carried out with given rating of the motor and some assumptions. The following are the stator core dimensions and type of the core material.

Stator Slots Number: 48
Stator OD (mm): 400
Stator ID (mm): 270
Stator Core Length (mm): 90
Stator Core Stacking Factor: 0.95
Steel Type: M19_24G
Designed Wedge Thickness (mm): 5.11966
Parallel Branches: 1
Conductors per Slot: 10
Skew Width (Number of Slots): 2

With these stator core data, the following results have been obtained:

| | |
|---|---|
| Top Tooth Width (mm): | 6.59375 |
| Bottom Tooth Width (mm): | 5.83885 |
| Average Coil Pitch: | 6 |
| Number of Wires per Conductor: | 99 |
| Wire Diameter (mm): | 0.724 |
| Stator Slot Fill Factor (%): | 70.3924 |
| Coil Half-Turn Length (mm): | 257.529 |
| Wire Resistivity (ohm.mm^2/m): | 0.0217 |

Figure 6 presents the stator with semi-enclosed slots.

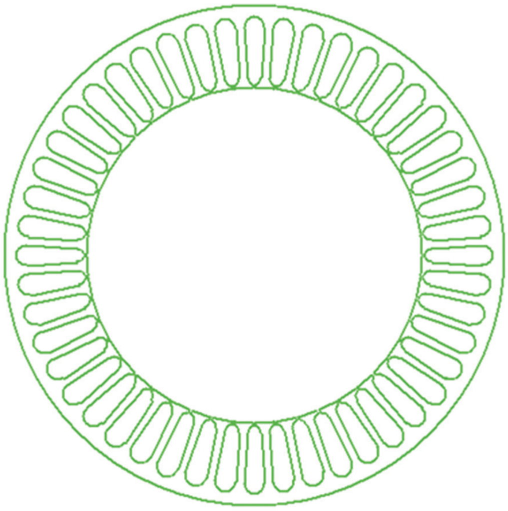

**Fig. 6.** Stator with semi-enclosed slot

**WINDING ARRANGEMENT**

The 3-phase, 2-layer winding can be arranged in 6 slots as below and shown in Figure 7.

| | |
|---|---|
| Angle per slot (elec. degrees): | 30 |
| Phase-A axis (elec. degrees): | 105 |
| First slot center (elec. degrees): | 0 |

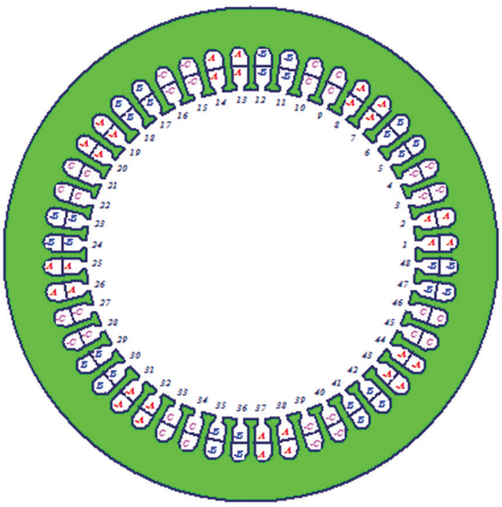

**Fig. 7.** Stator Winding Layout

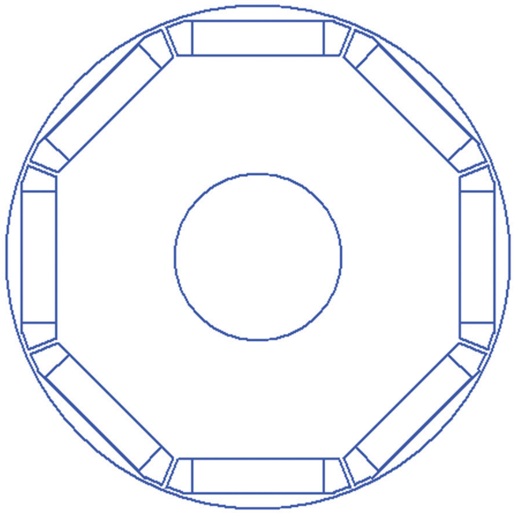

**Fig. 8.** Bridge Type Magnet Rotor

**c) ROTOR CONSTRUCTION**

On the basis of stator core dimensions, it is possible to estimate the rotor core dimensions &to decide the type of rotor magnet structure. Estimated rotor core dimensions and type of core material, magnet material are as follows:

| | |
|---|---|
| Air Gap (mm): | 0.5 |
| ID (mm): | 90 |
| Length (mm): | 90 |
| Iron Core Stacking Factor: | 0.95 |
| Steel Type: | M19_24G |
| Bridge (mm): | 2 |
| Rib (mm): | 3 |
| Pole Embrace (Mechanical): | 0.8 |
| Pole Embrace (Electrical): | 0.748 |
| Max. Magnet Thickness (mm): | 18 |
| Magnet Width (mm): | 70 |
| Magnet Type: | NdFe35 |

**a) MATERIAL CONSUMPTION**

With the stator and rotorcore data, the material consumption is calculated and the results are as follows:

| | |
|---|---|
| Copper Weight of Armature (kg): | 44.83 |
| Weight of Permanent Magnet (kg): | 6.71 |
| Weight of Armature Core Steel (kg): | 20.09 |
| Weight of Rotor Core Steel (kg): | 24.71 |
| Total Net Weight (kg): | 96.35 |
| Consumption of Armature Core Steel (kg): | 68.778 |
| Consumption of Rotor Core Steel (kg): | 37.449 |

The total net weight and size of the motor depends upon the volume of the motor. The volume is estimated by main dimensions of the motor. The main dimensions are stator bore diameter and stator core length.

### b) STEADY STATE PARAMETERS

The steady state parameters have been calculated after optimizing the design. The steady state parameters are d & q axis inductances, leakage inductance and armature phase resistance.

| | |
|---|---|
| Stator Winding Factor: | 0.965926 |
| D-Axis Reactive Inductance Lad | (H):0.00103 |
| Q-Axis Reactive Inductance Laq | (H):0.01383 |
| D-Axis Inductance L1+Lad (H): | 0.002065 |
| Q-Axis Inductance L1+Laq (H): | 0.014898 |
| Armature Leakage Inductance L1 (H): | 0.00103342 |
| Slot Leakage Inductance Ls1 (H): | 0.00048239 |
| End Leakage Inductance Le1 (H): | 0.00015713 |
| Harmonic Leakage Inductance Ld1 (H): | 0.000393896 |
| Zero-Sequence Inductance L0 (H): | 0.00103342 |
| Armature Phase Resistance R1 (H): | 0.0219383 |
| Armature Phase Resistance at 20$^0$C (ohm): | 0.0180461 |

### c) NO LOAD DATA

The performance of the motor is based upon the no load line current, no load input power and cogging torque. These no-load parameters are affected by the magnetic flux density and Ampere Turns (ATs).

| | |
|---|---|
| Stator-Teeth Flux Density (Tesla): | 2.04552 |
| Stator-Yoke Flux Density (Tesla): | 2.19373 |
| Rotor-Yoke Flux Density (Tesla): | 0.295285 |
| Air-Gap Flux Density (Tesla): | 0.633033 |
| Magnet Flux Density (Tesla): | 0.775206 |
| | |
| Stator-Teeth By-Pass Factor: | 0.0654571 |
| Stator-Yoke By-Pass Factor: | 0.0496894 |
| Rotor-Yoke By-Pass Factor: | 7.79752e-06 |
| | |
| Stator-Teeth Ampere Turns (A.T): | 2011.23 |
| Stator-Yoke Ampere Turns (A.T): | 3657.92 |
| Rotor-Yoke Ampere Turns (A.T): | 0.924299 |
| Air-Gap Ampere Turns (A.T): | 263.784 |
| Magnet Ampere Turns (A.T): | -5923.41 |
| | |
| Leakage-Flux Factor: | 1.08676 |
| Correction Factor for Magnetic Circuit Length of Stator Yoke: | 0.26853 |
| Correction Factor for Magnetic Circuit Length of Rotor Yoke: | 0.753369 |
| | |
| No-Load Line Current (A): | 194.217 |
| No-Load Input Power (W): | 871.026 |
| Cogging Torque (Nm): | 1.47273e-12 |

The no load line current is minimum and cogging torque is minimized by skewing the stator slots. The flux density in air gap is maximum and it is as per the choice.

### d) FULL LOAD DATA

| | |
|---|---|
| Maximum Line Induced Voltage (V): | 140.448 |
| Root-Mean-Square Line Current (A): | 189.108 |
| Root-Mean-Square Phase Current (A): | 109.285 |
| Armature Thermal Load (A2 /mm3): | 165.821 |
| Specific Electric Loading (A/mm): | 61.8416 |
| Armature Current Density (A/mm2): | 2.68138 |
| Frictional and Windage Loss (W): | 18 |
| Iron-Core Loss (W): | 195.697 |
| Armature Copper Loss (W): | 786.03 |
| Total Loss (W): | 999.727 |
| Output Power (W): | 34875 |
| Input Power (W): | 35874.7 |
| Efficiency (%): | 97.2133 |
| Synchronous Speed (rpm): | 1000 |
| Rated Torque (Nm): | 333.031 |
| Torque Angle (degree): | 76.8727 |

The proposed IPMSM on full load gives the satisfactory results as shown above. The full load torque and the output power is as per the requirements and the efficiency is improved by different ways as discussed in section 3 of design analysis.

### e) PERFORMANCE ANALYSIS

The design is optimized and the results are obtained for the different core diameter and length, tooth and slot dimensions and rotor geometry.

**Table 6.** IPMSM Optimized Design Sheet

| Specification | Value |
|---|---|
| Operation Type: | Motor |
| Mechanical Load Type | Constant Power |
| Power Output (kW) | 35 |
| Voltage (V) | 440 |
| Number of Poles | 8 |
| Speed (rpm) | 1300 |
| Stator slots No. | 48 |
| OD of Stator (mm) | 380 |
| ID of Stator (mm) | 250 |
| Length of Stator Core (mm) | 90 |
| No. of Conductors per slot | 10 |
| ID of Rotor (mm) | 90 |
| Rotor Structure Type | Bridge |
| Type of Magnet | NdFe 35 |
| Line Current on No-Load (A) | 142.065 |
| Input Power on No-Load (W) | 797.553 |
| No-Load Air Gap Flux Density (Tesla) | 0.761 |

| Specification | Value |
|---|---|
| Cogging Torque | 2.1148e-12 |
| Line Voltage (V) | 208.986 |
| RMS Line Current (A) | 133.703 |
| RMS Phase Current (A) | 77.7342 |
| Armature Thermal Load (A2/mm3) | 136.465 |
| Specific Electric Loading (A/mm) | 47.5067 |
| Total Loss (W) | 815.153 |
| Power Output (W) | 34840.1 |
| Power Input (W) | 35655.2 |
| Efficiency (%) | 97.71 |
| Synchronous Speed (rpm) | 1300 |
| Rated Torque (Nm) | 255.922 |
| Torque Angle (degree) | 70.2798 |

The cogging torque is reduced by skewing the stator slots. The curve shown in Fig. 9 and indicates the zero-cogging torque for different air gap positions. Here the stator slots are skewed by two slots so that the cogging torque is reduced to zero value.

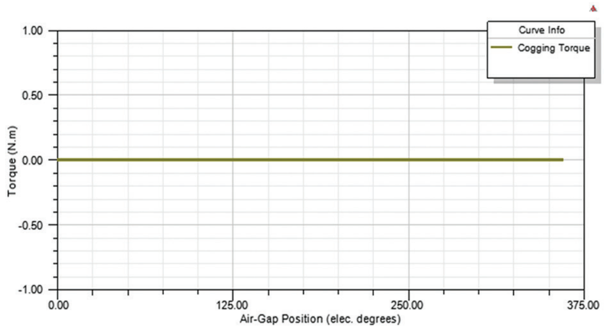


**Fig. 9.** Cogging Torque

The skewing of the stator slots by two slots optimized the $B_{gmax}$ as shown in Fig. 10.

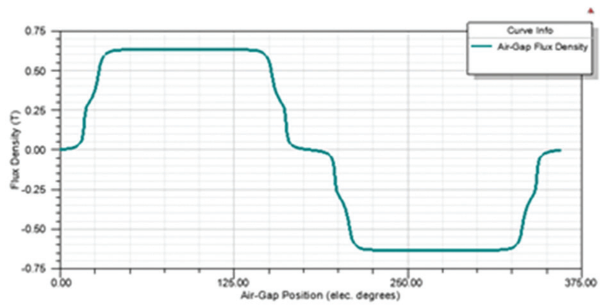


**Fig. 10.** Flux Density in Air gap

The sinusoidal nature of the phase currents and line currents as presented in Fig. 11 indicates the normal working of the motor on full load.

The skewing of the stator slots also improves the phase voltage as shown in Fig. 12 which is sinusoidal in nature.

The stability of the system depends upon the power torque angle characteristics of the motor. The curve shown in Fig. 13 indicates the satisfactory operation on the motor.

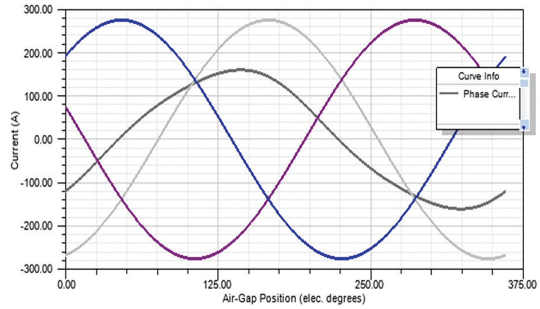


**Fig. 11.** Phase and line Currents

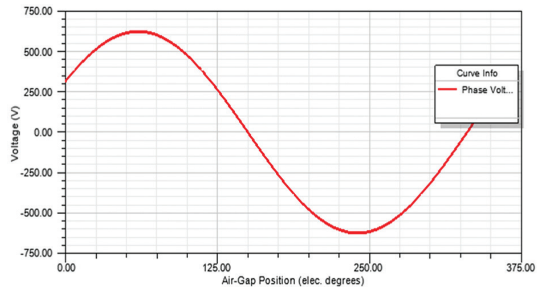


**Fig.12.** Phase Voltage

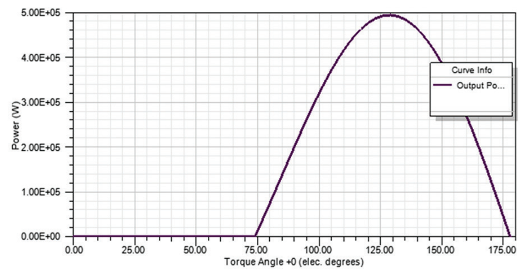


**Fig. 13.** Output Power and Torque Angle Characteristics

The curve of induced phase voltage with respect to the air gap positions is shown in Fig. 14 and indicates the better performance of the motor as the induced phase voltage is almost sinusoidal in nature.

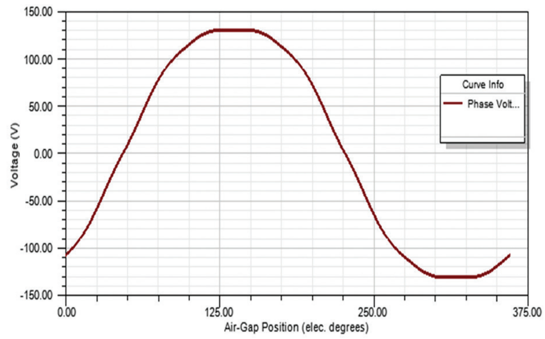


**Fig. 14.** Induced phase voltage at rated speed with respect to the air gap

## 6. COMPARISON OF PERFORMANCE

The performance of the IPMSM machine can be compared with the 3-Phase Induction motor for the same power rating but to the higher side of 55 kW. The data of the 3-phase induction motor is available and the PMSM is analyzed for the same rating using RMxprt.

**Table 7.** Comparison of Performance

| Parameters | 3-Phase Induction Motor | PMSM |
|---|---|---|
| Power Rating (kW) | 55 | 55 |
| Full Load Current (Amp) | 110 | 63 |
| Speed (RPM) | 1500 | 1500 |
| Losses (Copper) (W) | 2500 | 282.153 |
| Losses (Total) (W) | 3760 | 713.935 |
| %Efficiency | 93.6 | 98.71 |
| Frame Size | 225 M | 225 M |
| Stack Length (mm) | Not exactly Known, but it could be large in length | 110 mm |

The performance of both the machines can be compared on the basis of the different losses in the motor. The following table shows the percentage of the losses due to the motor components.

**Table 8.** Comparison of Losses

| 3-Phase Induction Motor | | PMSM | |
|---|---|---|---|
| Motor Component Loss | Total Loss % | Motor Component Loss | Total Loss % |
| Stator copper Losses, $I^2 R_1$ | 37% | Armature copper Losses, $I^2 R_1$ | 39% |
| Rotor copper Losses, $I^2 R_2$ | 18% | Rotor copper Losses, $I^2 R_2$ | 00% |
| Magnetic Core Losses | 20% | Magnetic Core Losses | 57% |
| Friction and Windage Losses | 9% | Friction, Windage and Stray Load Losses | 4% |
| Stray Load Losses | 16% | | |

It is observed from the comparison of the performance and losses that the

- PMSM is Highly Efficient with reduced full load current and increased full load voltage.
- PMSM is compact in size as instead of rotor winding permanent magnets are used. The stack length for the required output gets reduced.
- As the efficiency if High, it will act as a Energy Saver.

## 7. CONCLUSION

This paper presented the design of (IPMSM) Interior Permanent Magnet Synchronous Motor and the analysis shows that the motor is compact in size, have high efficiency, constant full load torque and adjustable speed up to rated speed.

The final rating of the motor is 35 kW, 1000 rpm, 440 V, 8 Pole, 100 Hz frequency, rated torque 333 N-m, torque angle 70° and maximum output power is 37 kW. Volumetric ratios are 1) armature copper to core = 2.02 2) Armature copper to steel = 0.99 3) Armature copper to Magnet = 6.64 as per the finite element analysis and design calculations.

The existing 3-phase Induction Motor is larger in size and can be replaced by PMSM for the same frame size but with reduced weight and stack core length.

The Adjustable Speed Permanent Magnet Synchronous Motor with better dynamic performance is proposed. The analytical results verify that the satisfactory performance can be achieved with the proposed machine.

The proposed IPMSM has minimum total loss, improved efficiency and maximum torque as per kW and speed rating of the motor. The full load and no-load parameters are optimized by analyzing the machine for different voltage ratings, power ratings and stator outside diameters.

The proposed motor is compact in size as NdFe permanent magnets with bridge type structure is used and cost effective, saves energy as reduced generator rating is used which reduces the operating cost.

When compared with the 3-Phase Induction Motor, the Proposed PMSM has several advantages as follows:

1) No excitation losses
2) Simplified Construction
3) Improved Efficiency
4) Fast Dynamic Performance
5) High Torque or Power per unit volume

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