Modelling and Simulation of 100 kg Hoist Operated by Permanent Magnet Direct Drive

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Abstract: An overhead crane, also known as an industrial crane, crane, or overhead travelling crane, is a device that lifts, lowers, and transports items horizontally. It is used to carry extremely heavy or bulky loads through the overhead area of a facility, as opposed to through aisles or on the floor. Gear box is used with purpose of reduction in speed; as a result, torque output will be increased. In place of gear box for achieving lower rpm at high torque, use of a permanent magnet direct drive (PMDD) in conjunction with a variable frequency drive (VFD) is written in this paper. Prototype of the same is designed to lift 100kg load and checked for its performance. Modelling and simulation are done in Simcentre MotorSolve for PMDD. This alternate arrangement can be used for hoisting mechanism of EOT crane which is able to give the torque of 40-65 N.m at 25-50 RPM to lift 100 kg load.

Keywords: *Alternative of Gearbox, Hoisting Mechanism, Permanent Motor Direct Drive EOT Crane, Simcentre MotorSolve by Siemens*

Introduction

Most of the engineering industries are using the Electric Overhead Traveling (EOT) Crane to hoist loads. In the conventional EOT, induction motor, gear box, coupling and rope drum assembly are used. This EOT crane is subjected to lift and lower the load, as well as cross and long travel. Out these four major functions, lifting and lowering the load requires high torque at lower rpm. So, for performing these tasks, three sets of motor – gear box sets are required. For two functions of EOT crane of lifting and lowering the load, we will replace the conventionally used motor and gear box with PMDD in connection with VFD.

The PMDD is to be used in EOT crane for utilizing the natural, free, and sustainable energy of permanent magnets. Samarium-cobalt (Sm-Co) and Neodium-iron-boron (Nd-Fe-B) are two magnetic materials that are readily available PM and which are having exceptional high temperature performance. The first rare earth PM materials to be released were the samarium cobalt variants $SmCo_5$ and Sm_2Co_{17}. In the late 1960s, they were made accessible [3]. In the 1980s, Neodymium Iron Boron ($Nd_2Fe_{14}B$) magnets were first made available with the promise that they would be far less expensive than Samarium Cobalt magnets [4]. The temperature range of early $Nd_2Fe_{14}B$ magnet materials was quite small. Beyond 120°C, they lost their powers and became particularly susceptible for demagnetization [5]. An array of additional viable options, including PMDD, fluid coupling, and electromagnetic gearing, were discovered after a review of the available literature. PMDD in conjunction with a variable frequency drive was determined to be the optimal solution for increasing the high torque at reduced RPM. Replacement of the gearbox with PMDD is made feasible in enhancement of the performance of the EOT crane. Long term, this will result in more significant benefits. With the stator and rotor assembly of the PMDD, more torque at lower RPM can be generated. Because of this, traditional gearbox is replaced which was utilised in the hoisting mechanism to provide more torque and low RPM.

The goal of this effort is to simplify the present system because it is more prone to frequent maintenance issues and failures. Here, a novel proposal is made to replace the transmission with a permanently attached magnet direct drive coupled with a variable frequency drive to provide the required high torque at low rpm. The recommended mechanism also comes with built-in benefits including minimal maintenance requirements, reduced noise, vibration, and lubrication, mechanical isolation, and reduced power usage [7]. This study was conducted as a result of the frequent gearbox failure, coupling failure, frequent lubrication and maintenance, excessive vibration, and noise problems in traditional hoisting mechanisms. The parts may steadily degrade as a result of vibration, which eventually results in failure. Additionally, there will be a significant financial loss, particularly in the steel and railroad industries. In order to meet the frequent failures; the shop floor requires need excess inventory which may not lead to interrupt the operating of EOT crane for various important activities.

In this paper the analytical equations to design PMDD to lift the 100kg load are presented. With the calculated dimensions using the analytical equations a modelling of PMDD is done in Simcentre MotorSolve. To analyse the performance PMDD is analysed in Simcentre MotorSolve by Siemens. With the results of the analysis, we may use the designed PMDD for hoisting mechanism in EoT crane.

The remainder of this essay is divided into the following sections: A succinct summary of pertinent literature is given in the second part. The design technique for PMDD is described in Section 3. An examination of PMDD is provided in the fourth part. The Discussion is covered in Section 5, while the paper's conclusion and outlook are covered in Section 6.

Literature Review

To find the best replacement for the commonly used hoisting mechanism and to replace the gearbox owing to frequent breakdowns, lubrication, maintenance, etc., a thorough literature review has been conducted. Magnetic Gears, Fluid Coupling, and PMDD with Variable Frequency Drive are a few solutions that have been researched.

Worldwide, industries use conventional geared machinery extensively. A gear-driven system's main objective is to synchronise the input shaft's rotational velocity with the desired output velocity for the output load. For this application, conventional mechanical motion gears are frequently employed. As load is communicated by a single tooth according to the Lewis equation of gear design, the major drawback of utilising mechanical gear is that it is subject to frequent wear and tear, temperature rise that may cause overheating, and occasionally even breakage from excessive torque transmission. Lubrication and maintenance are crucial. It took 100 years before magnets could be utilised because magnetic forces precluded true physical contact between gear teeth and torque transfer [7]

Magnetic Gears.

Magnetic gear (MG) Magnetic gears (MGs) are receiving more interest from the research point of view and from companies as well in the world of technology that is changing quickly. It can be summed up as follows: Development and commercialization of MG are obtaining increased attention as a result of the rapid advancement of technology. Significant advantages include reduced acoustical noise, little vibration, free of maintenance operation, improved dependability, intrinsic overload protection, and physical isolation [8, 9, and 10]. In permanent magnet machinery, magnetic gearing enables low-speed, high-torque direct-drive operation. The ferrite permanent magnet (PM) material was not widely used in industry due to its poor performance and low utilization. Up until the introduction of high-performance neodymium iron-based (Nd-Fe-B) MGs, the iron core's slots and teeth were replaced by the N- and S-poles of PMs, respectively. About 100kNm/m3 are displayed by magnetic planetary gears with six magnetic planet gears. [12]. The iron core's slots and teeth were simply swapped out for PM N-Pole and S-pole in these modified MGs. Nearly 100kNm/m^3 is displayed by the Magnetic Planetary Gears, which include six magnetic planet gears [12].

Fluid Coupling.

To transmit rotational mechanical power, a Utilised is a type of fluid coupling or hydrophilic coupling, which is a hydrodynamic or "hydrokinetic" device. To protect the power transmission system from shock overload, controlled start-up at various speeds is crucial in marine and industrial machine drives, where it is also commonly utilised. [12]. Utilising gearbox fluid, a fluid coupling is a hydraulic device used to transfer rotational power from one shaft to another. It can be substituted, but because it can't transfer more torque at a changing speed, its application is limited to circumstances when high torque is necessary. [13]

Permanent Magnet Direct Drive with Variable Frequency Drive.

In order to address the frequent issues in the industries, it is advised employing motor direct drive technology to do away with the four-component transmission structure of the shaft, reducer, drum, and achieve direct drive. In motor drive technology, there is no intermediary mechanical transmission. Applications of direct drive technology include both the linear motion component with a linear motor serving as the core drive element and the rotational motion component with a torque motor acting as the core drive element. At the moment, direct drive technology is widely used in the elevator, machine tool, belt, mining, wind power, and other sectors. As low speed and high torque motor technology advances, eliminating the intermediary gearbox is becoming increasingly common to provide direct motor driving.

In a variety of uses for renewable energy where the source of power typically flows at a moderate speed over the electricity translator, permanent magnet instruments are strong candidates for the optimal solution. [14]. Ten years ago, permanent magnets were only utilised in a few specialised applications, low power equipment, and tiny appliances [15]. Today, permanent magnets are used more commonly. This trend has mostly been ascribed to the advancement of magnetic materials' properties and the decline in their price [16]. But the latter has just experienced a dramatic change [17]. This is due to the fact that magnets account for a significant portion of the electric machine's price. A design that is effective for magnets at one cost is ineffective at a different one [18]. Although there is less ambiguity around their costs, this also occurs with copper and magnetic steel [19-22].

Method

Method to Design Permanent Magnet Direct Drive Analytically

Here, an attempt is made to design a permanent magnet direct drive motor. The fundamental variables and notations used for the design are as follows [23-24-25];

Basic Notations and Abbreviation.

d: Air Gap diameter
l: Stator length
h_s: Slot height
τ_P: Pitch of Pole
J_B: Density of Current
h_m: Height of Magnet
b_d: Width of Tool
h_s: Height of Slot
h_{ys}: Stator Yoke height
h_{yr}: Rotor Yoke height
h_{s1}: Tool Tip height
h_{s2}: Slot Wedge height
b_{s1}: Slot openings
h_i: Thickness of insulation
δ: Air gap (Mechanical)
q = slots/pole and phase

f= frequency
p= pole pair
W= pitch of winding
lb: length of the final winding
le: equivalent core length
l_u and k_{es}: iron length and iron fill factor
d_{se}: outer diameter of Stator

Design Equations [23-24].

To design the PMDD motor with the basic notations and abbreviations are mentioned above and using the following sets of equations the PMDD is designed. The dimensions for main parts stator and rotor are also calculated.

The pole pairs are determined by the diameter and pole pitch;

$$N = \frac{120 \times f_s}{P} \tag{1}$$

$$\text{where, } N = RPM$$
$$f_s = frequency$$
$$P = Number\ of\ poles$$

The measurement of the diameter and pole pitch determine the pole pairings;

$$p = \frac{1}{2} \frac{\pi d}{\cdot \tau_p} \tag{2}$$

$$p = pair\ \text{pole no.}$$
$$\tau_p = Pole\ pitch, m$$
$$d = Air\ gap\ diameter, m$$

The stator's whole number of slots is;

$$Q = 2\,\mathrm{p\,m\,q} \tag{3}$$

$$\text{where, p = pole pair no.}$$
$$\text{q = per pole slots}$$
$$\text{m = no. of phase}$$

The slot pitch is;

$$\tau = \frac{\tau_p}{m\,q} \tag{4}$$

The tool width b_d and slot pitch can be used to calculate the slot width as follows;

$$b_s = \tau - \mathrm{b}_d \tag{5}$$

$$where, b_s = slot\ \text{width}$$
$$\mathrm{b}_d = \text{tooth width}$$
$$\tau = \text{slot pitch}$$
$$\mathrm{h}_s = slot\ \text{depth}$$

The slot opening b_{s1}, height of tip of tooth h_{s1}, and the height of wedge of slot h_{s2} are all estimated to be 3mm, 1mm, and 4mm, respectively. Height of winding is h_{s3}.

$$h_{s3} = h_s - h_{s1} - h_{s2} \tag{6}$$

Height of winding, slot width & coil insulation thickness hi all affect the conductor's height h_{cu} and width b_{cu};

$$h_{cu} = \frac{h_{s3} - 4h_i}{2} \tag{7}$$

h_{cu} = conductor height

h_i = insulation height

$$b_{cu} = b_s - 2h_i \tag{8}$$

b_{cu} = conductor width

Magnet cost per torque must be kept as low as possible for a three-phase machine, according to Lampola et al. 1996, The combination of the ratio of magnet width to pole distance must lie between 0.6 and 0.9. The proposed design maintains the magnet width at 0.7 times the pole pitch that is,

$$b_m = 0.7\ \tau_p \tag{9}$$

b_m = magnet width

The winding pitch W is; since it is a whole pitch winding;

$$W = \tau_p \tag{10}$$

The length of the final winding;

$$l_b = 2\,W \tag{11}$$

To get the equivalent length of core

$$l_e = l + 2\,\delta \tag{12}$$

An appropriate iron length is

$$l_u = k_{Fes} l \tag{13}$$

where, k_{Fes} = iron fill factor

With rated speed, the frequency is

$$f = p\,\mathrm{n}_N \tag{14}$$

where, p = pole pair

In order to reduce the amount of permanent magnet required, the iron gap should be tiny. The smallest air gap that can be used is limited by mechanical stiffness and thermal expansion.

$$\delta = 0.001\,d \tag{15}$$

The carter factor will be 1, since the air gap exceeds the slot opening. The d_{se} outer diameter of the stator

$$d_{se} = d + 2\,h_s + 2\,h_{ys} \tag{16}$$

The stator's approximate overall length

$$l_{total} = l + 3\,W \tag{17}$$

Magnetic Circuit.

The stator yoke thickness h_{ys}

$$h_{ys} = \frac{\hat{B}_{\delta 0}\ \mathrm{b}_m\ \mathrm{l}_e}{2\hat{B}_{ys}\ \mathrm{l}_u} \tag{18}$$

The rotor yoke thickness h_{yr}

$$h_{yr} = \frac{\hat{B}_{\delta 0}\ \mathrm{b}_m\ \mathrm{l}_e}{2\hat{B}_{yr}\ \mathrm{l}} \tag{19}$$

The stator tooth width bd

$$b_d = \frac{\hat{B}_{\delta 0}\, \tau\, l_e}{\hat{B}_{d0}\, l_u} \qquad (20)$$

where, $\hat{B}_{\delta 0}$ = no load peak flux density
$\hat{B}_{d0}$ = no load peak flux density of teeth

The magnetization curves for the main materials of the stator and rotor, namely $H_s(B)$ and H_r, may be used to compute the iron core's mmfs (B). The mmfs required for the magnetic flux between two poles in the stator yoke may be roughly calculated as

$$\hat{v}_{ys} = c\left(\tau_p + \frac{\pi\left(h_s + 0.5\, h_{ys}\right)}{p}\right) H_s\left(\hat{B}_{ys}\right) \qquad (21)$$

You may roughly express the mmf required for the teeth as

$$\hat{V}_d = H_s\,(\hat{B}_{d0})\,(h_{s3} + 0.5\, h_{s2}) + H_s(\hat{B}_\delta)\,(0.5\, h_{s3} + h_{s1}) \qquad (22)$$

The rotor yoke's mmf is

$$\hat{v}_{yr} = c\left(\tau_p - \frac{\pi\,(\delta + \boldsymbol{h}_m + 0.5\, \boldsymbol{h}_{yr})}{p}\right) H_s(\hat{B}_{yr}) \qquad (23)$$

The magnet's mmf falls by $\hat{V}_m = \boldsymbol{h}_m \frac{\hat{B}_{\delta 0}}{\mu_m\, \mu_0}$ (24)

The air gap's mmf falls by

$$\hat{V}_\delta = \delta_{ef} \frac{\hat{B}_{\delta 0}}{\mu_0} \qquad (25)$$

The magnetic circuit of two poles has zero mmfs added to it.

$$2H_c h_m - \hat{v}_{ys} - \hat{v}_{yr} - 2\hat{v}_d - 2\hat{v}_\delta - 2\hat{v}_m = 0 \qquad (26)$$

where Hc is the PM material's coercitivity
Now, the equation (26) & may be used to get the required magnet height (24).

$$h_m = \frac{0.5\, \hat{v}_{ys} + 0.5\, \hat{v}_{ys} + \hat{v}_d + \hat{v}_s}{H_e - \frac{B_{\delta 0}}{\mu_m \mu_0}} \qquad (27)$$

The flux density wave's shape in the air gap is influenced by the magnet's height, width, pole pitch, and air gap.

Material Volume and Weight [25,30].

For the windings mcu, stator yoke mFeys, stator teeth mFed, rotor yoke mFeys, and magnets mm, the volumes of the various materials are multiplied by their corresponding weights:

$$V_{cu} = 2(l + l_b)Q\, h_{cu}\, b_{cu}\, k_{cu} \qquad (28)$$

$$M_{cu} = \rho_{cu} V_{cu} \qquad (29)$$

$$V_{Fes} = l_u\, \pi\, (d + 2h_s + h_{ys})\, h_{ys} \qquad (30)$$

$$m_{Fes} = \rho_{Fe} V_{Fes} \qquad (31)$$

$$V_{Fed} = l_u \, \mathbf{Q} \, (b_d \, h_{s3} + \frac{(\tau - b_{s1}) + b_d}{2} \, h_{s2} + (\tau - b_{s1}) \, h_{s1} \qquad (32)$$

$$m_{Fed} = \rho_{Fe} V_{Fed} \qquad (33)$$

$$V_{Feyr} = l\pi(d - 2\delta - 2h_m - h_{yr})h_{yr} \qquad (34)$$

$$m_{Feyr} = \rho_{Fe} V_{Feyr} \qquad (35)$$

$$V_m = 2plb_m h_m \qquad (36)$$

$$m_m = \rho_m V_m \qquad (37)$$

Design of Permanent Magnet Direct Drive in Simcentre MotorSolve.

Modelling of PMDD in Simcenter MotorSolve.

Modelling and Analysis of PMDD is done by giving input of calcualted values geting from the particular design equation discussed above. Simcenter Motorsolve is used here which is efficient design and analysis software for permanent magnet machines.

Step: 1 Basic input parameters for default prototype generation

Supply voltage of 415 volts, three phases, sixteen poles, and thirty-six slots with an air gap of 1mm.

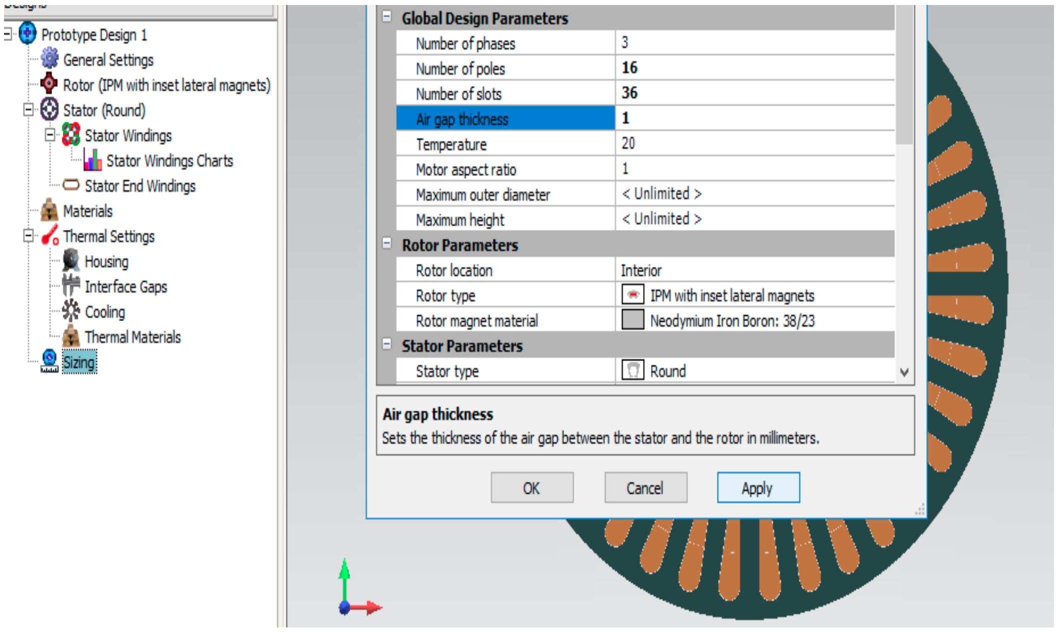

Figure: 1 Input paramenter

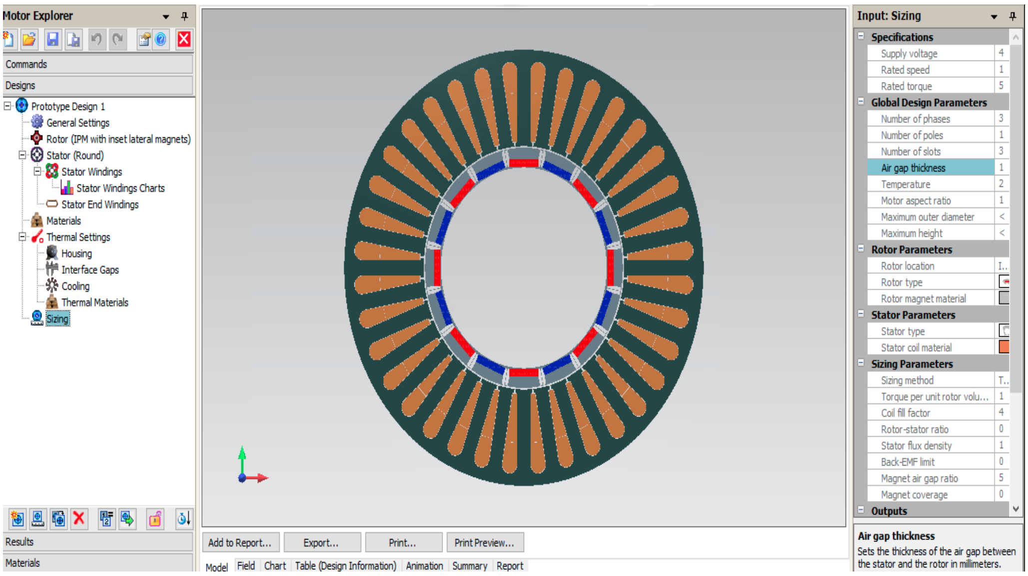

Figure: 2 Prototype generated

Step: 2 Input Parameters for Rotor
Rotor Outer Diameter: 133mm Rotor Inner Diameter: 40mm

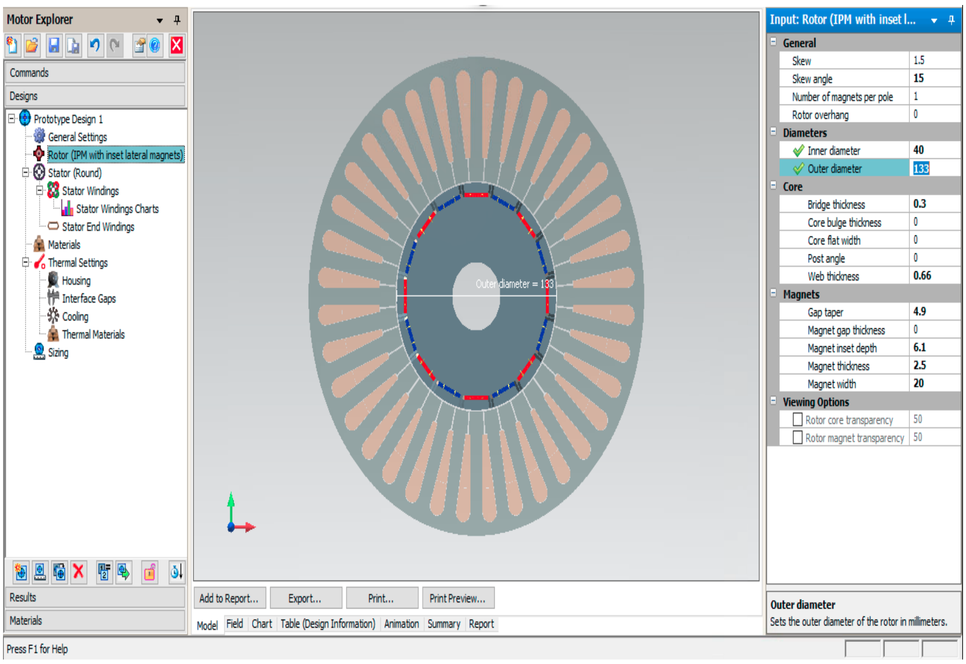

Figure: 3 Rotor generated with designed dimensions

Step: 3 Input Parameters for Magnet
Magnet Depth: 6.54 mm, Magnet Width: 23mm, Magnet Thickness: 2.1mm

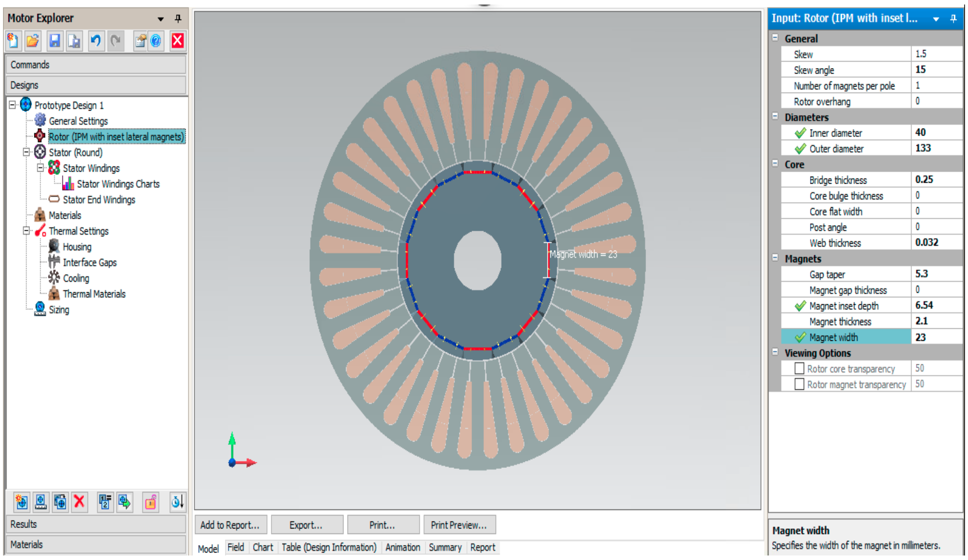

Figure: 4 Magnet generations with designed dimensions

Step: 4 Input Parameters for stator
Stator outer diameter: 220 mm
Inner diameter: 145 mm

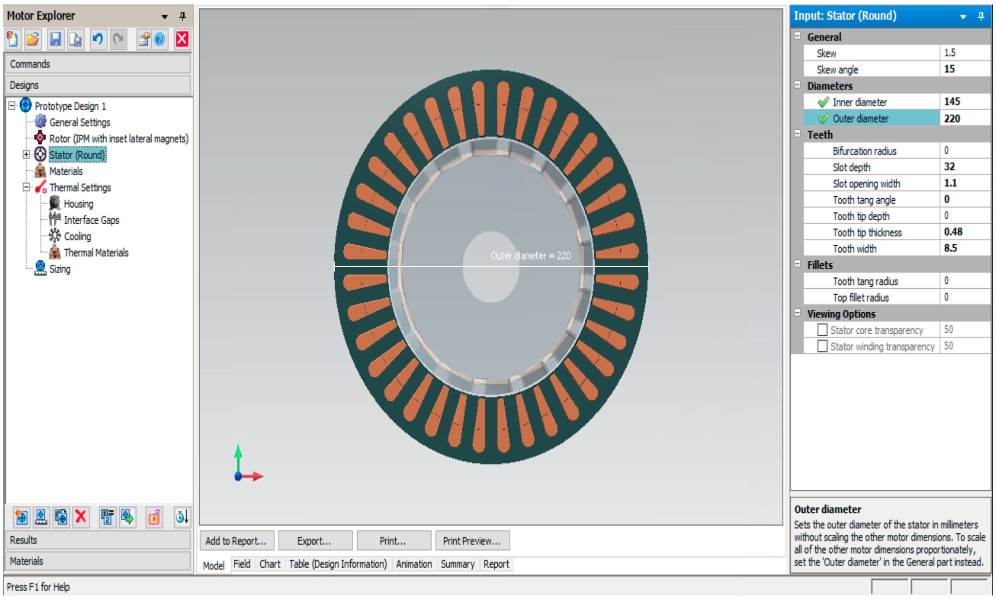

Figure: 5 Stator generated with designed dimensions

Step: 5 Final motor assembly with Permanent Magnet Material Neodymium Iron Boron 38/23 selection with gives higher magnetic flux density required for high torque.

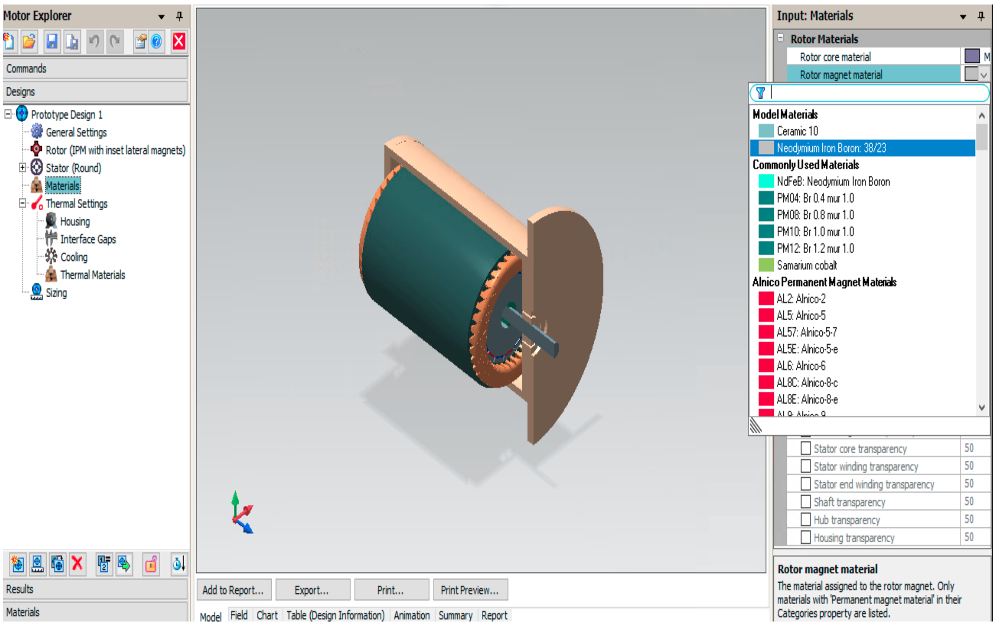

Figure: 6 Assembly of PMDD motor

Block Diagram of Complete approach.

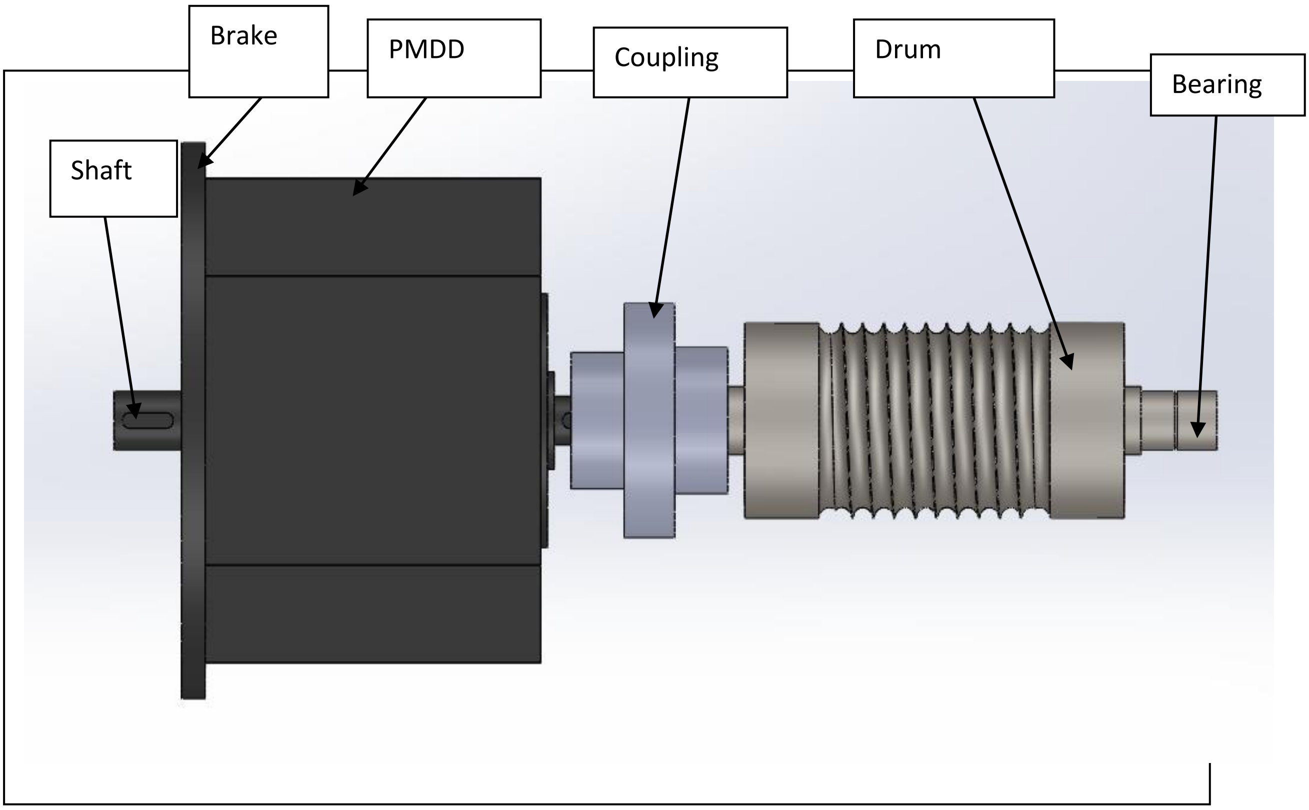

Figure: 7 Block diagram of complete approach

Above is a block schematic of the entire model. Here, the rope drum assembly is directly coupled to the PMDD to carry out the hoisting function. Instead of the configuration depicted in figure 1, a PMDD motor is connected to an EMCO DC brake and coupled to a rope drum assembly, which lowers and raises the necessary load in accordance with industry standards.

Results

Simcentre Motorsolve, a very effective tool for motor modelling and analysis, is used to analyse the PMDD model. Here, we have made an effort to gather several Performance Charts that are crucial to our study, such asTorque Vs Phase Angle chart

- Torque Vs Speed chart
- Efficiency values are given for the range of 0 to 60 NM torque and rpm
- Pulse width Modulation is given for torque, voltage, current and back emf
- Maximum Torque
- Instantaneous Field
- Magnetic Field
- Thermal Field

By going through the various performance charts we may predict the possibility of using the designed PMDD.

Analysis Of PMDD In Simcentre Motorsolve

Performance Charts

Torque Vs Phase Angle chart is plotted below which gives value around 40- 70 N.m torque for the phase angle starting from 0 degree to 360°.

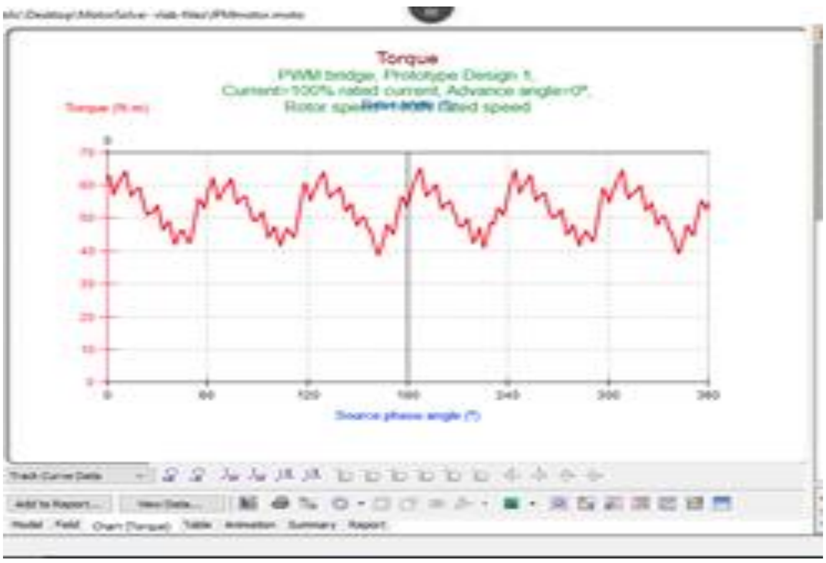

Figure: 8 Torque Vs Phase Angle chart

Torque Vs Speed chart is plotted below which gives torque up to 60 N.m for different speed at interval of 15^0

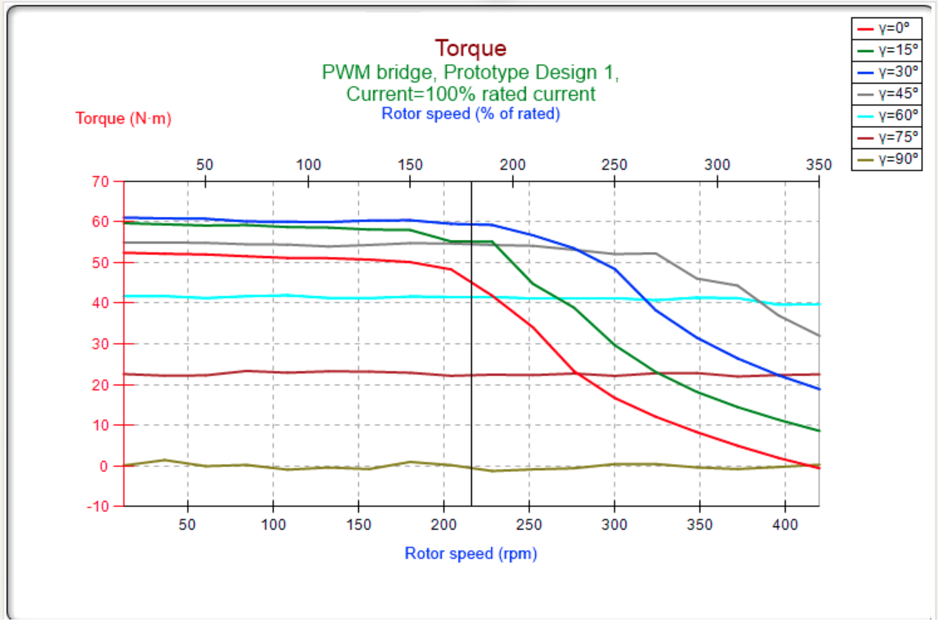

Figure: 9 Torque Vs. Speed

Efficiency values are given for the range of 0 to 60 NM torque and 0 to 400 rpm

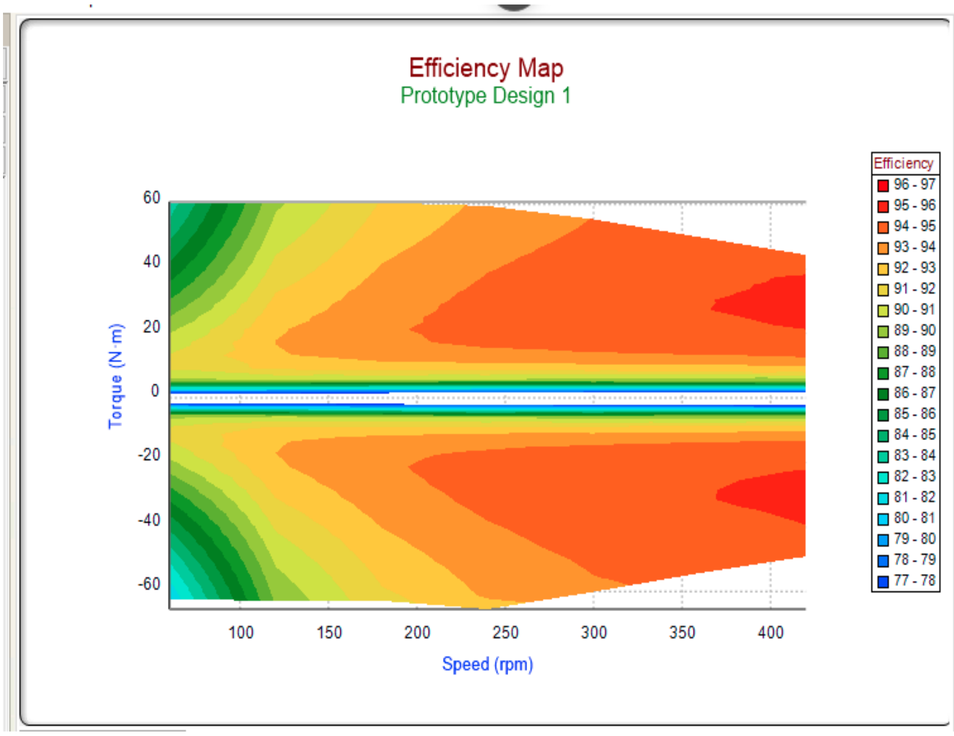

Figure: 10 Efficiency Map

Pulse width Modulation is given for torque, voltage, current and back emf

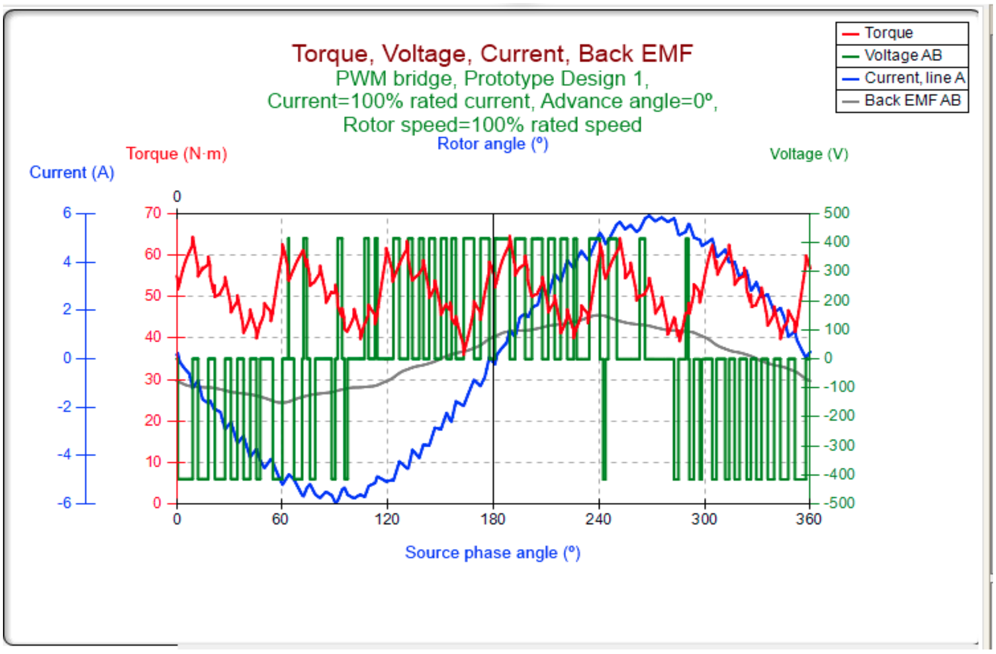

Figure: 11 PWM Analysis

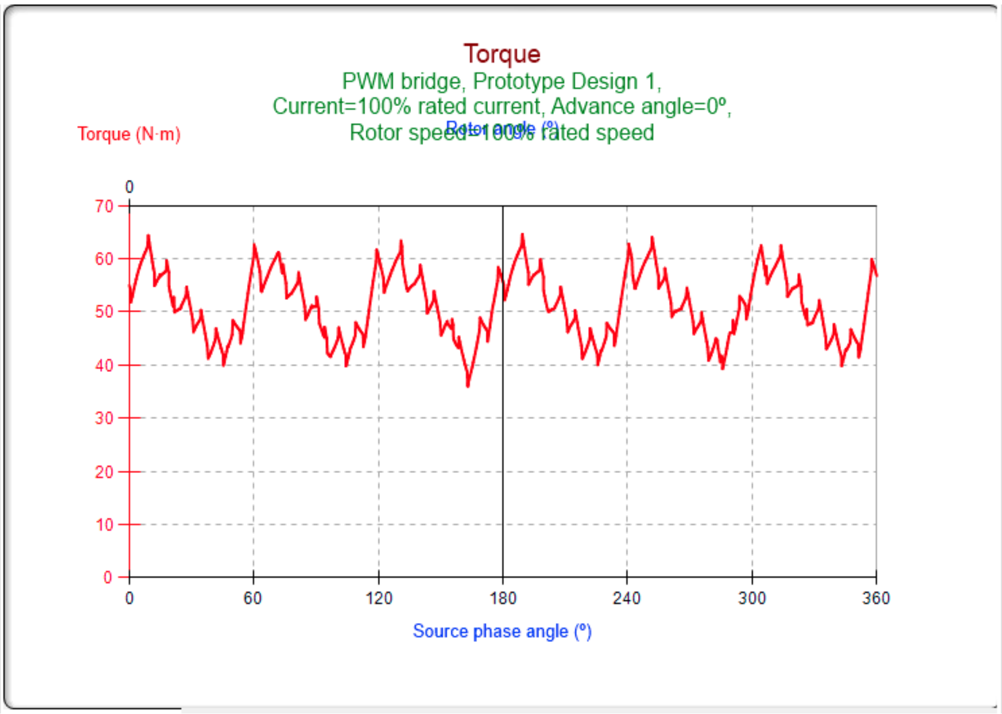

Figure: 12 Display method: Waveform Result Quantity: Torque

Here getting maximum torque of 60 n.m which is sufficient to lift the load of 100 kg by the hoist.

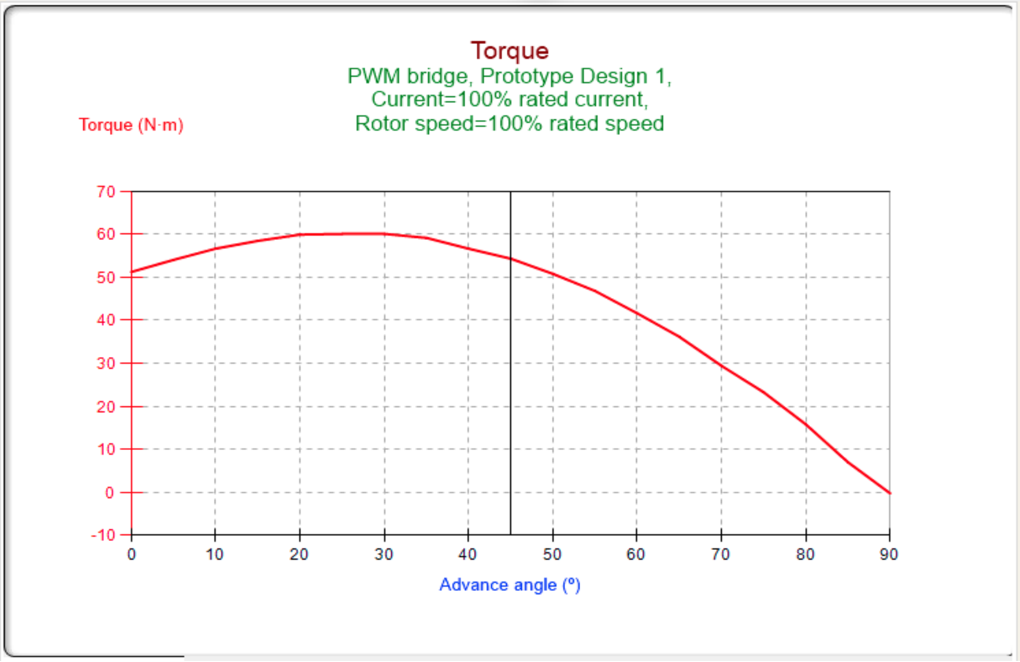

Figure: 13 Maximum Torque

Instantaneous Field
Shaded plot lower bound 0
Shaded Plot upper bound 2
Peak line current percentage: 0

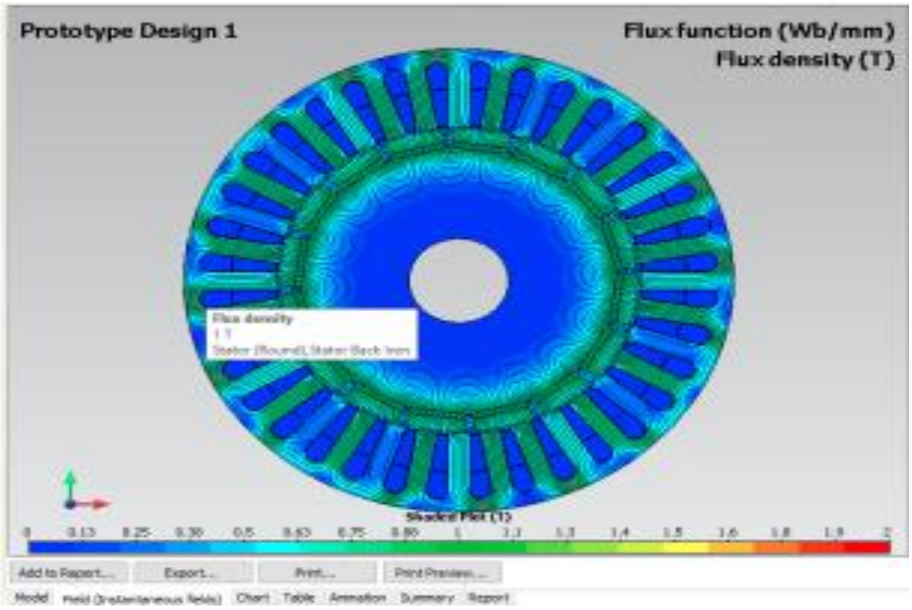

Figure 14: Magnetic Fields

Magnetic Fields
Instantaneous Field
Shaded plot lower bound 0

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Shaded Plot upper bound 2
Peak line current percentage: 100

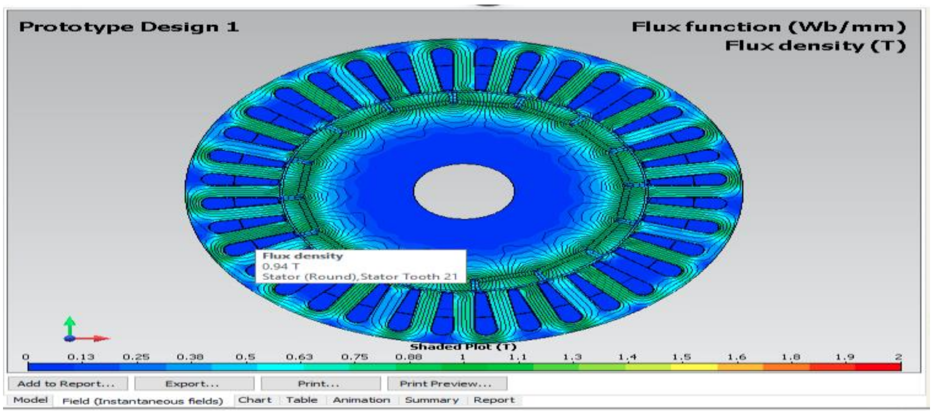

Figure: 15 Magnetic Fields

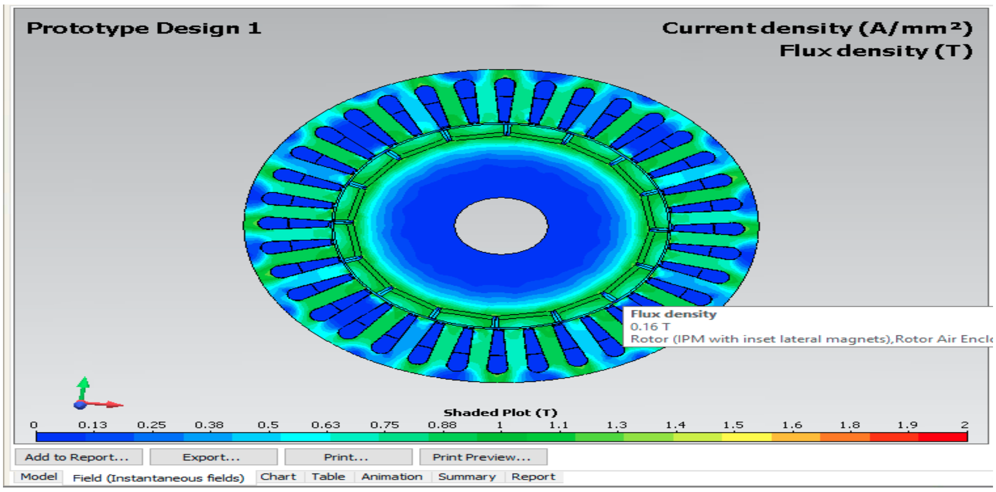

Figure: 16 Current Density

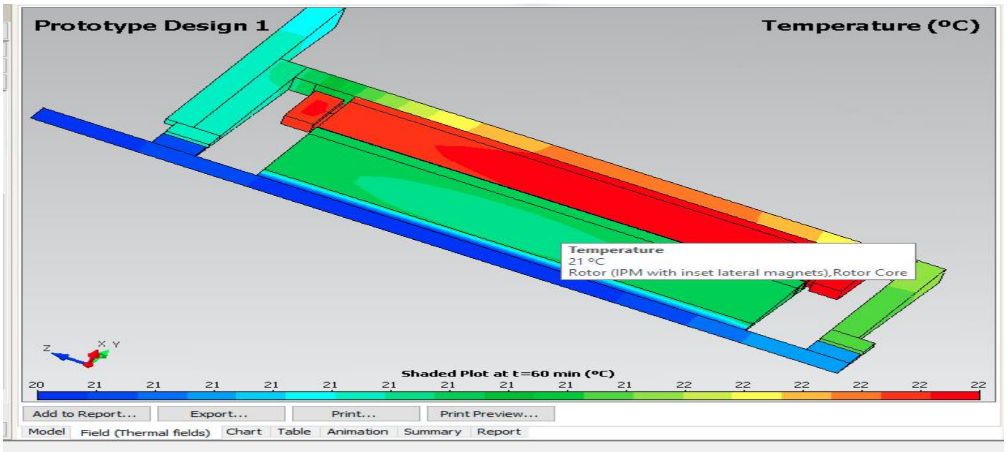

Figure: 17 Thermal Fields

After reviewing every performance chart, we can forecast that the intended and simulated PMDD will produce a maximum torque of 60 N.m. This torque is enough to raise a 100 kg load with a hoist.
The created set up will be subjected to several readings for various combinations of altering height, RPM, and load. The outcomes will also be contrasted with those obtained using a standard hoist driven by a gearbox for the same combinations.

Developed Model of 100kg hoist with PMDD

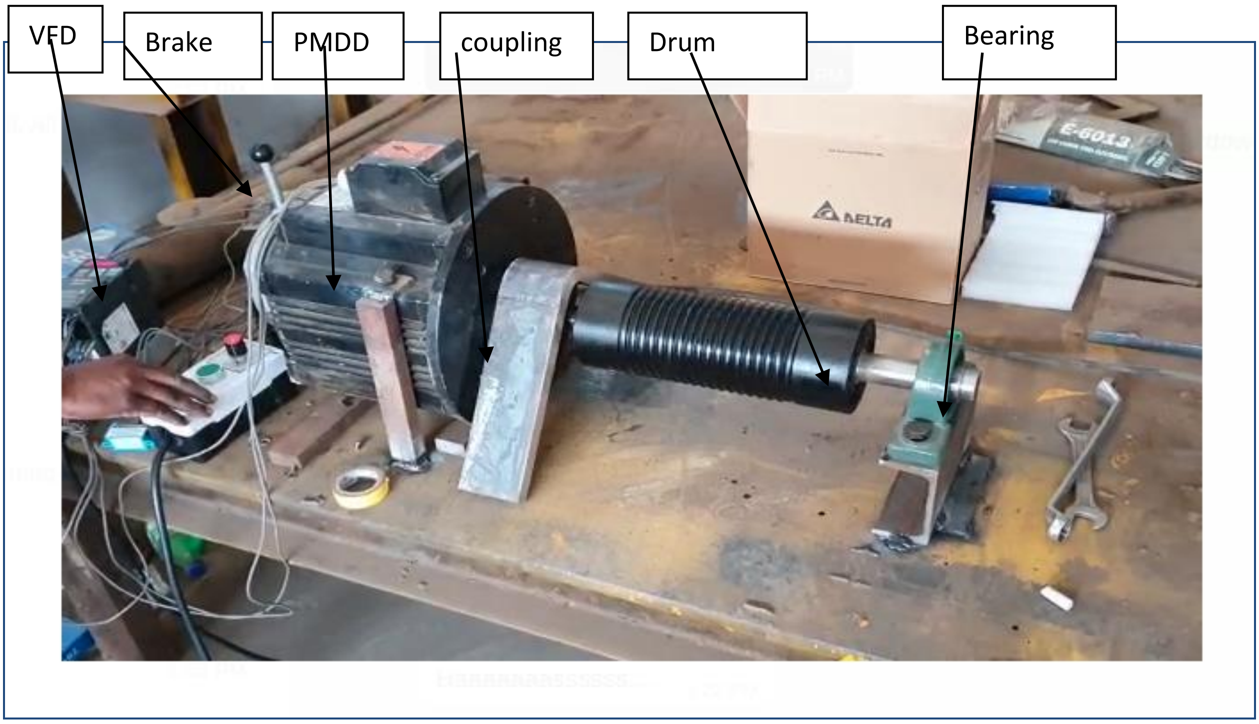

Figure : 18 Actual Set up

Developed Model of 100kg hoist with PMDD lifting load

Discussion

The analytical equations are used to construct the Permanent Magnet Direct Drive. The analytical design yields the primary dimensions, which are used in Simcentre Motorsolve modelling to create a precisely designed PMDD. The same methodology is utilised for analysis, and the important conclusions drawn from each performance chart individually are listed below.

Table :1 Results

Parameter	Values
Torque Vs Phase angle	Torque: 40- 70 N.m
	Phase angle: 0-360°
Torque Vs Speed	Torque: 60 N.m
	Speed Interval: 15^0
Efficiency	60 N.m
	Speed: 0-400 RPM
PWM	Torque: 60 N.m

.

Magnetic flux density is shown in Figures 14 and 15, whereas current density is shown in Figure 16. Thermal fields are seen in Figure 17. From all of the plots and findings, it is clear that the developed PMDD motor is strong enough to be used in the EOT crane's hoisting mechanism since it can provide the necessary high torque of 50 n.m. at a low rpm of 15–25.

Limitation: In some situations, the setup's size and weight may be a limiting factor. Another limiting element is the setup's initial cost. However, the PMDD motor requires almost no maintenance. Therefore, the overall operating cost will be much lower than the conventional hoist, producing far superior outcomes. Other important benefits of PMDD include reduced vibration, less noise, no physical touch, overload protection, the need for minimal lubrication, and nearly no maintenance.

Conclusion And Future Work

According to the numerous analysis plots shown above, the developed and analysed PMDD can provide high torque of 40 to 65 n.m at 25 to 35 rpm, which is sufficient to lift the 100 kg weight. In order to completely remove the need of gear boxes, the developed motor will be utilised in place of the currently used motor and gearbox arrangement. it also makes the hosting system simpler. Must raise a 100 kg burden, a house needs 50NM of torque and to run at a relatively low speed of 25 rpm. With the aid of VFD, we may accomplish our desired objective in PMDD.

Future Work: Experiments are now being conducted as part of this research project, and the physical setup has been developed according to the components chosen. By making adjustments to the drum and rope fall arrangement on the same hoist, a weight may be raised while maintaining the same configuration.

Acknowledgement

I want to express my gratitude to Dr. U. V. Shah, my mentor, motivator, and research adviser, for his ongoing inspiration.

Conflicts Of Interest

The authors have no conflicts of interest to declare.

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