DESIGN, ANALYSIS AND DEVELOPMENT OF HOIST FOR EOT CRANE USING PERMANENT MAGNET DIRECT DRIVE

A Thesis submitted to Gujarat Technological University

for the Award of

Doctor of Philosophy

in

Mechanical Engineering

by

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Enrollment No: 189999919071

Under supervision of

Dr. Utpal Vinodchandra Shah

GUJARAT TECHNOLOGICAL UNIVERSITY
AHMEDABAD

[March – 2024]

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ABSTRACT

Electric overhead travelling (EOT) crane is widely used in industries to move extremely heavy or bulky loads through the overhead space. EOT crane lifts, lowers and also moves load horizontally. The hoist of the conventional EOT crane is consisting of a motor-gearbox -coupling- drum and rope assembly. The hoist of EOT crane needs high torque to lift the load at the same time speed must be very less. The purpose of a gearbox is to increase or reduce speed at the required high torque. As a result torque output will be the inverse function of the speed. If the enclosed drive is a speed reducer (speed output is less than speed input), the torque output will increase and if the drive increases speed, the torque output will decrease.

The various components of hoist needs frequent maintenance. Especially gearbox of the hoist needs regular checks like; checking of oil level lubrication, cooling, inspection of gear teeth of mating gear is also required; need to keep eye on noise related to balancing and vibration. Ignorance to above mentioned check list leads to failure. Due to failure of any of the components of hoist the EOT needs to shut its operation. This leads to monetary loss. In place of the conventionally used hoist having gearbox to achieve a high torque at low speed, various possible alternatives are explored like; fluid couplings permanent magnetic gears and permanent magnet direct drive (PMDD).

PMDD in conjunction with a variable frequency drive (VFD) is found to be best alternative. In Motor drive technology, there is no intermediate mechanical transmission. Implementation of PMDD can completely eliminate use of gearbox. Currently the direct drive technology is widely used in elevators, machine tools, belt machines, mines, wind power generation and other industries. The PMDD also offers many other significant advantages over conventional mechanism like; simple, compact and light structure, high driving efficiency, great reliability, lubrication not required, physical isolation, less vibration, economic in power saving and almost zero maintenance; which leads to no idle time on the shop floor, gives un-interrupted mass production which is very much important for EOT crane in steel industries, railway yards etc. As idle time for maintenance is directly related to cost factor.

For research; here the hoisting motion (lowering and lifting of load) is considered due to frequent usage and higher failure rate of hoisting. Prototype of the hoist operated by direct drive is attempted to design and developed to lift the load of 100 kg and checked for its analysis and performance. Drafting of PMDD motor is done is Solid works. Modeling and simulation is done in Simcenter Motorsolve for PMDD. Designed and analyzed PMDD is able to give the torque of 40-65 N.m. at 15-50 rpm to lift 100 kg load so can be used for hoisting mechanism of EOT crane. Experimentation on the PMDD hoist is performed for various combinations to check the feasibility and implementation by varying the different parameters affecting the performance of the EOT crane like lifting capacity (10-100 kg), working speed (10-50 rpm) and height (2-4 m). The lifting and lowering time is compared for conventional hoist and PMDD hoist. That almost gives nearby results. Hence it proves the feasibility and implementation of the proposed concept. Further vibration analysis is also done for conventional hoist and PMDD operated hoist. Where PMDD operated hoist gives better results as per vibration severity ISO 10816.

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Trivedi Parita K.

Trivedi Parita Kishorbhai

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List of Abbreviation

MHE	Material Handling Equipment
EOT	Electric Overhead Travelling Crane
PMDD	Permanent Magnet Direct Drive
ASRS	Automatic Storage and Retrieval System
RPM	Revolution per Minute
MG	Magnetic Gear
VFD	Variable Frequency Drive
CMG	Concentric Magnetic Gear
MGPM	Magnetic Geared Permanent Magnet
PM	Permanent Magnet

List of Symbols

N	RPM
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
l_b	Length of the final winding
l_e	Equivalent core length

l_u and k_{es}	Iron length and iron fill factor
d_{se}	Outer diameter of Stator
T_{LF}	Lifting Time
T_{LW}	Lowering Time
T_{LFC}	Lifting Time of Conventional hoist
T_{LFP}	Lifting Time of PMDD hoist
T_{LWC}	Lowering Time of Conventional Hoist
T_{LWP}	Lowering Time of PMDD
d_c	Displacement for conventional hoist
v_c	Velocity for conventional hoist
a_c	Acceleration for conventional hoist
d_p	Displacement for PMDD hoist
v_p	Velocity for PMDD hoist
a_p	Acceleration for PMDD hoist

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CHAPTER – 1

Introduction

This chapter reflects upon the theoretical aspects of the thesis entitled as design, analysis and development of hoist for electric overhead travelling (EOT) crane using permanent magnet direct drive (PMDD). This chapter presents; introduction to the problem attempted, motivation for the work, research gap, research objective, research methodology and thesis outline.

1.1 Introduction to the problem attempted

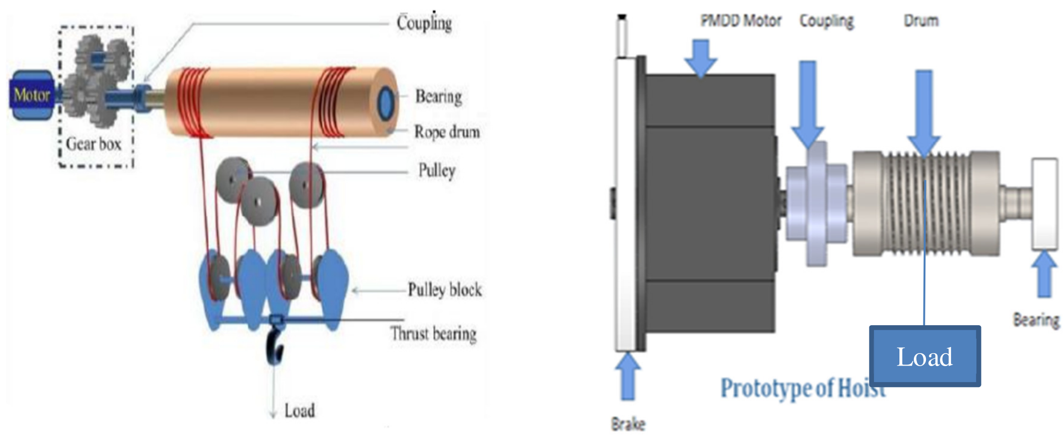
Industries frequently employ the EOT crane to hoist load. Hoist of EOT crane is consists of induction motor-gear box-coupling and rope drum assembly. To lift the weight, high torque must be applied while the rpm of the drum must be less. Gearbox is used in conjunction with induction motors to handle these properties, resulting in high rpm and low torque. For research; here the hoisting motion (lowering and lifting of load) is considered due to frequent usage and higher failure rate of hoisting.

Following a thorough literature review a number of other viable options were researched, including PMDD [22-69], fluid coupling and magnetic gears [13, 14-21]. In order to raise the high torque at lower RPM, PMDD in conjunction with a variable frequency drive was found to be the most suited choice. Without compromising performance, we could replace the gearbox using the developed and analysed PMDD. In long term, this will result in more significant benefits. With the stator and rotor assembly of the PMDD, we can generate high torque at lower RPM. Because of this, we are able to completely replace the traditional gearbox utilised in the hoisting mechanism to provide high torque and low RPM. In existing hoist it is intended to use PMDD to replace the gearbox. There are numerous reasons to replace the gearbox and implement the PMDD drives [70-78], listing a few are;

- Industries are facing frequent breakdown due to failure of gearbox or coupling
- Vibration and high acoustic Noise
- Frequent lubrication of gearbox

- Simplify the mechanism
- Physical isolation of stator and rotor
- Utilizing the natural, free, and sustainable energy of permanent magnets is what motivated the permanent magnet motor drive to be used in hoisting mechanisms.

The traditionally used hoist [2-4] and a proposed concept for the research is as shown in figure1.



(a) Conventional hoisting mechanism **(b) Proposed Concept for hoisting mechanism**

Figure 1.1 Hoisting Mechanism

Permanent magnet materials are used in PMDD drive. With the advancement in the permanent magnet materials like Samarium-cobalt (Sm-Co) and Neodium-iron-boron (Nd-Fe-B) are the magnetic materials that offer significant advantages like; offers exceptional high temperature performance, readily available etc. High temperature performance is required for high torque generation. 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 [79-80]. 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 [80]. The temperature range of early $Nd_2Fe_{14}B$ magnet materials was quite low. Beyond 120 °C, they lost their powers and became particularly susceptible to demagnetization [80].

1.2 Motivation for the work

The goal of this research is to simplify the present system because it is more prone to frequent maintenance issues and failures in industries. Here, we are trying to implement a novel idea that is to replace the gearbox and use a permanent magnet direct drive in conjunction with a variable frequency drive to provide high torque at the needed low rpm. The proposed mechanism also comes with built-in benefits including minimal maintenance requirements, reduced noise, no vibration, no lubrication, mechanical isolation, and reduced power usage [70-78]. This study was conducted as a result of the frequent maintenance/ failure of gearbox, frequent lubrication requirement, high 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 due to breakdown of crane. In order to meet the frequent failures; the shop floor need excess inventory of gearbox, coupling etc. for uninterrupted operating of EOT crane for various important activities.

1.3 Research Gap

By referring the various research papers it has been found that;

- The existing hoisting mechanism is totally mechanically operated and uses conventional gear box; which needs frequent maintenance [1-2, 9, 12].

- Preventive and periodic maintenance of a gearbox like checking of oil level, lubrication, cooling, inspection of gear teeth of mating gear, broken tooth, noise related to balancing and vibration etc. is must [1- 2, 12].

- Due to direct contact of gear teeth friction wear, noise, vibration, heat generation and reliability are frequent issues. If any tooth of the gear wears out, the complete gear needs to be replaced that causes idle time and ultimately delay in production time [1- 2, 9, 12].

- Hoisting mechanism which is fixed on girder of EOT crane is subjected to continuous vibration, which ultimately deteriorates parts of crane [3-8, 12] and ultimately leads to failure of the parts due to which idle time on the shop floor increases.

1.4 Research Objectives

Research objectives to be carried out as a part of research are as listed below:

- To study existing and alternative approach of hoisting mechanism of EOT crane.
- Design and Analysis of permanent magnet direct drive for the hoist (100 kg) of EOT crane.
- Fabrication of hoist operated by using permanent magnet direct drive.
- Testing and performance analysis of hoist operated by using permanent magnet direct drive.

1.5 Research Methodology

The research methodology followed for the research carried out is as under:

- Literature survey.
- Design of permanent magnet direct drive.
- Modeling and analysis in Simcenter Motorsolve by Siemens.
- Selection of components for hoist.
- Development/Fabrication of hoist and
- Testing & Performance analysis of hoist

1.6 Thesis Outline

Chapter 1 reflects upon the theoretical aspects of the thesis entitled as design, analysis and development of hoist for electric overhead travelling (EOT) crane using permanent magnet direct drive (PMDD). This chapter presents; introduction to the problem attempted, motivation for the work, research gap, research objective, research methodology and thesis outline.

Chapter 2 elaborates on the fundamentals of material handling equipment and electric overhead travelling crane. Features and failure of the crane are explained as per the scope of the work of the thesis. Further various feasible alternatives are proposed to replace gearbox in hoisting mechanism due to frequent maintenance and failures of gearbox. Various types of magnetic materials magnetic materials used in PMDD motor and its characteristics are also described. It also deals with the extensive review of literature based on failure and maintenance of components of hoist, study of fluid coupling, magnetic gears and PMDD, feasibility and advantages of PMDD, design of PMDD, analysis and development of hoist operated by PMDD.

Chapter 3 describes the design variables used in PMDD motor, analytical design of PMDD and drafting of PMDD in solid works and the overall flow of design process outlined in this chapter is explained using a block diagram for better comprehension of the analytical approach.

Chapter 4 presents modeling and analysis of PMDD in Simcenter Motorsolve software by Siemens. A complete 3 D model of motor is generated and various analysis and performance charts are plotted. By analyzing the results of various charts it is justified to use the proposed concept having PMDD in place of traditionally used mechanism having a gearbox.

Chapter 5 addresses the selection of components and development of prototype of hoist operated by PMDD. Experimentation is done on the developed hoist and conventional hoist by considering the factors affecting the performance of cranes and considering vibration too.

Chapter 6 represents and discusses the graphs plotted as per the experimental readings taken on the PMDD hoist and conventional hoist. Graphs are plotted by varying the height (2-3-4 m), speed (10-20-30-40-50 rpm) and load (10-20-30-40-50-60-70-80-90-100 kg) and comparison is done between PMDD hoist and conventional hoist. Further vibration analysis is also done for comparing the displacement, velocity and acceleration for conventional hoist and PMDD hoist.

Chapter 7 summarizes the findings and from various cases considered for the analysis for the performance of EOT crane and discusses the future scope of using PMDD in 1 T or higher capacity of EOT crane.

CHAPTER 2

Literature Survey

Electric overhead travelling crane is broadly falls under the category of material handling equipment (MHE). Some basics of MHE and EOT, their types, main components and failure of the parts are explained as per the scope of the work of the thesis. Further various feasible alternatives are proposed here to replace gearbox in hoist due to frequent maintenance / failures of gearbox**.**

2.1 Fundamentals of Material Handling Equipment [11]

All the industries whether they are small scale or large scale; for their day to day work use of various types of material handling equipment is inevitable. Material handling equipment is used in the production, distribution, consumption, and disposal processes to move, store, control, and protect materials, goods, and products.

2.2 Classification of Material Handling Equipment [11]

It may classify in to the four major categories:

- **Transport Equipment**

  Material can be moved using transport equipment inside a building or at a location, such as between offices, a loading dock and a storage space, etc. Ex: Conveyors, Cranes, Industrial trucks etc.

- **Positioning Equipment**

  Material is handled in a single location using positioning equipment to ensure that it is in the ideal position for storage, handling, and transport or machining. Positioning equipment; in contrast to transport equipment, is often utilized for handling at a one workplace. Additionally, material can be moved by hand without the use of any tools. Ex: Turn table, Hoist, Manipulators, and Industrial robots etc.

- **Unit Load Formation Equipment**

  For storage and transportation, unit load formation equipment is used to limit materials so they maintain their integrity when handled as a single load. Ex: Pallet, Skid.

- **Storage Equipment**

  Materials are held or buffered over time with the use of storage equipment. Ex: Automatic Storage and Retrieval System (ASRS), Storage carousel.

2.3 Basics of Electric Overhead Travelling Crane [11]

Electric overhead travelling cranes are industrial machine and used for material movement at variety of places like construction site, production workshops, assembly lines, power station, railway yards, heavy industry and many more. A crane is a type of machine or material handling equipment used for lifting and lowering large objects as well as moving them from one location to another. Typically, an overhead crane uses three distinct motions:

- The first motion is the lifting and lowering (hoisting).
- The second is the trolley motion (cross travel).
- The gantry or bridge motion (long travel) is the third motion.

A hoist is a device that uses a rope or chain wrapped around a drum or lift-wheel to raise or lower a load as shown in Figure 1.1. The functions of hoist mechanism include raising, holding, and lowering the maximum rated load. It is made up of a load block design, a motor drive, a coupling, brakes, gearing, and a drum. On a trolley, the hoist mechanism is installed. The EOT crane can operate in three different ways: by hooking up and down, moving in a lateral motion, or moving longitudinally for a long distance. The hoisting mechanism's driving force is applied by the motor.

For research; here the hoisting motion (lowering and lifting of load) is considered due to frequent usage and higher failure rate of hoisting. As shown in table 2.1; the failure rate of lifting mechanism with conventional hoist accounts for 45% of the failure rate of the whole machine [1-10, 12].

2.4 Types of Electric Overhead Travelling Crane [11]

Different types of electric overhead travelling cranes are as discussed below:

- **Single Girder Crane**

  A single bridge girder is supported by two end trucks in the single girder EOT crane. It is equipped with a trolley mechanism that rides on a bridge girder's bottom flange.

- **Double Girder Crane**

  The two bridge girders of the double girder EOT crane are supported by two end trucks, and a trolley rides on rails on the top of the bridge girders.

- **Gantry Crane**

  The trolley-carrying bridge in a gantry crane is steadily supported by two or more legs that run on other runways or fixed rails.

- **Monorail**

  For application such as production assembly or service assembly line, only a trolley or hoist is needed. The hoisting mechanism of a monorail is identical to that of a single-girder EOT crane, but the trolley runs on fixed girders and lacks a movable bridge.

2.5 Main Components of Electric Overhead Travelling Crane [11]

Main components of EOT cranes are as following:

- **Bridge Rail**

  This structure, which follows the runway, has either one or two girders. There are two design options for the bridge: box and beam girder, each with a set of benefits.

- **Runway Rails**

  The area that the crane can operate in is defined by this supporting structure. Important engineering factors are taken into account during its design, and it can be freestanding or attached to the building structure.

- **End Trucks**

  The legs of the crane are called end trucks, sometimes called end carriages. These end trucks support the girder(s). The crane bridge is moved along the runway track by these end trucks.

- **Hoist**

  The device that raises and lowers the load is called a hoist. It is made up of a drum assembly, rope, gearbox, motor, and coupling.

- **Trolley or Crab**

  The hoist can traverse the bridge horizontally with the help of a trolley or crab.

- **Buffer Controls**

  In order to avoid damage to structural work and equipment from travel units colliding with each other or the end of the track, buffers are necessary. Ensuring worker safety and avoiding hazardous working conditions are also critical.

2.6 Features of Electric Overhead Travelling Crane [11]

The features of EOT cranes differ significantly based on their primary operating parameters, such as

- Crane location
- Crane types and motion
- Type and weight of load
- Geometric features
- Environment condition etc.

2.7 Failures in Electric Overhead Traveling Crane [1-10,12]

As per the traditional crane failure rate distribution diagram shown in table 2.1; the failure rate of traditional lifting mechanism accounts for 45% of the failure rate of the whole machine that is the main source of fault of the crane. Failure rate for other mechanisms are given in table 2.1.

Table 2.1 Traditional Crane Failure Rate Distribution Diagram

SN	Mechanism	Failure Rate (%)	Main Failure
1.	Lifting mechanism	45%	Gearbox, motor, transmission shaft, coupling, brake, wire rope, lifting electric control system.
2.	Traveling mechanism	30%	Wheel group, traveling track.
3.	Bridge	5%	Bridge deformation and end beam cracking.
4.	Power supply and bridge operation electric control	20%	Wear and tear of slip line, insulation loosening and cracking, damage of relay, insulation damage of power supply.

In lifting mechanism, gearbox failure accounts for 22% of failure rate [12]. The reason for the failure includes the box body crack deformation, the oil quality, the oil quantity is not enough, oil leakage, broken teeth, gear heating and vibration. Damage or degradation of the wire ropes accounts for 5% of failure rate [12]. The best defense against damage or failure of a wire rope is to inspect it beforehand; if damage is found, the rope should be disposed of appropriately to stop use. Additional reasons for failure could be a damaged or bent hook, an electrification problem, etc.

2.8 Feasible Alternatives to Replace Gearbox in Hoisting Mechanism

Gearbox used in conventional hoist needs frequent maintenance, and more prone to failure if not subjected to proper preventive maintenance schedule [1-10, 12]. Various feasible alternatives to replace gearbox in the hoist are explored here like Fluid coupling [13], magnetic gears (MG) [14-21] and permanent magnet direct drive (PMDD) [22-69] in connection with a variable frequency drive [70-71] are presented to rotate the drum at high torque and low rpm. Out of which PMDD with VFD is found to be best suitable for high torque at low rpm as per the requirement of hoist of EOT crane [72-81].

2.8.1 Fluid Coupling [13]

A fluid coupling or hydraulic coupling [13] is a hydrodynamic or 'hydrokinetic' device used to transmit rotating mechanical power. It is also widely used in industrial and marine machine drives, where controlled start-up and variable speed operation are crucial to preventing shock loading of the power transmission system.

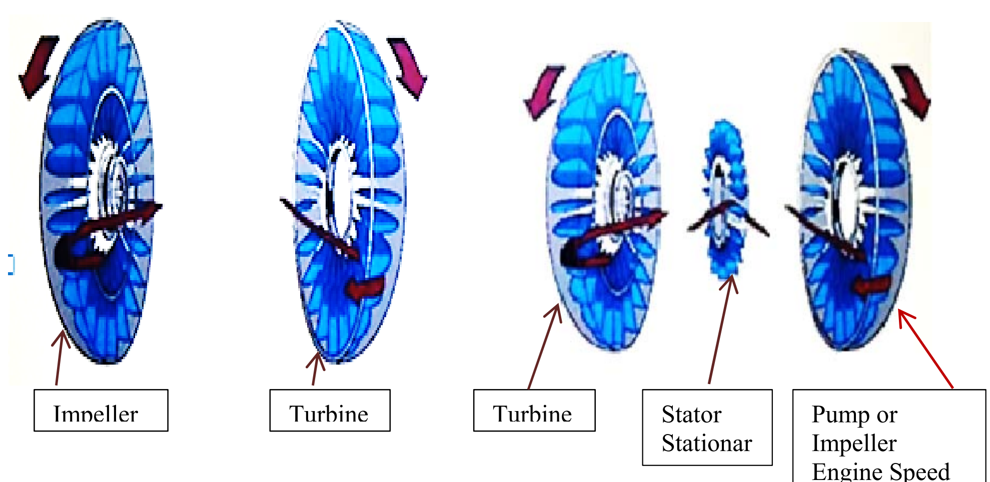


Figure 2.1 Fluid Coupling as Torque Converter [13]

2.8.2 Magnetic Gears [14-21]

Magnetism is the ability of a force to attract or repel objects at a distance because of its magnetic field. Strong magnetic fields cause materials like iron to be drawn to magnets. The north (N) and south (S) poles are the names given to magnets' two poles. Two magnets with opposing poles will be drawn to one another, and each magnet will repel the other magnet that is similar to it. Magnets apply torques and forces to one another. In a magnetic gear (MG), energy may be stored in the magnetic field, primarily in the air gap, as opposed to mechanical deflection in a gear. MGs are recognized as the benefit of magnetic gearing is that torque is not transferred through mechanical contact. Over the periphery, MG should have a small active air gap for good torque transmission**.** While gear lubrication and cooling are frequently necessary to achieve high torque densities, mechanical gearbox reliability, noise, and vibration are major problems. The aforementioned issues with mechanical gear boxes can be resolved by using the magnetic gear found in permanent magnet machines. Arrangement of magnetic gear is as shown in figure 2.2.

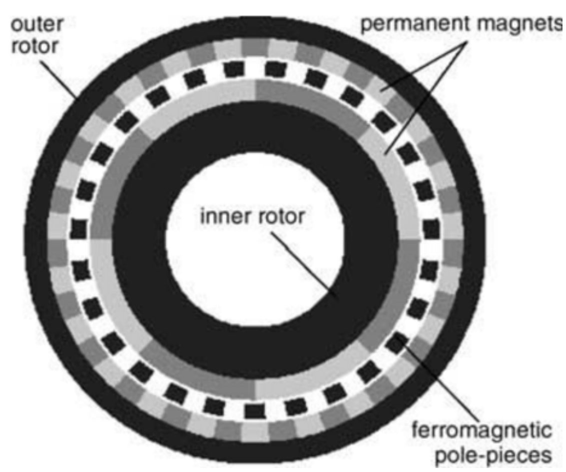


Figure 2.2 Magnetic Gear [14]

2.8.3 Permanent Magnet Direct Drive (PMDD) [22-69]

In order to solve the issues of failure in hoisting mechanism in crane industry, it is proposed to use motor direct drive technology to cancel the four part transmission structure of the shaft- reducer- drum and realize the direct drive. In Motor drive technology, there is no intermediate mechanical transmission. The application of the direct drive technology includes the linear motion component with linear motor as a core drive element and rotary motion element with the torque motor as the core drive element. Currently the direct drive technology is widely used in elevators, machine tools, belt machines, mines, wind power generation and other industries. With the continuous development in low speed and high torque motor, it is possible to eliminate intermediate transmission and realize direct motor drive. PMDD is composition of motor, electrical control system and safety brake system. To realize the direct motor drive, variable frequency drive is required to attach with PMDD. In electro-mechanical drive systems, a variable frequency drive (VFD) [70-71] is a type of adjustable speed drive that modifies input frequency and voltage to control the speed and torque of motor. Figure 2.3 shows the application of PMDD in wind power generation. As shown in figure 2.3 (a) conventional method with gearbox is required to get the required speed or torque depending upon the application. Whereas in figure 2.3 (b) with the implementation of direct drive technology, without use of gearbox the required speed or torque can be achieved. After going through all the alternatives PMDD with VFD is found to be the best suitable for implementation in hoist of EOT crane.

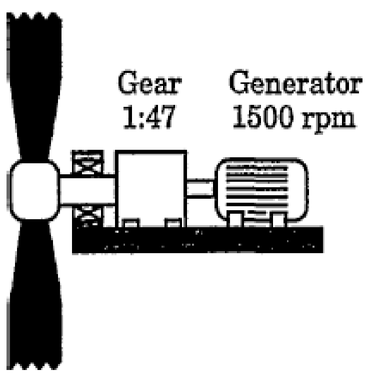


Figure 2.3 (a)

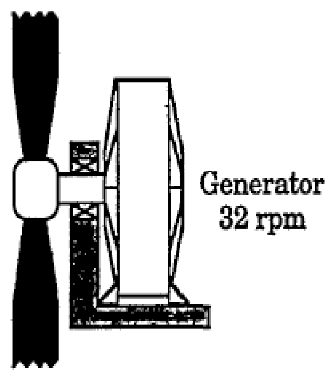


Figure 2.3 (b)

Figure 2.3 Application of PMDD in Wind Power Generation

2.9 Magnetic Materials for PMDD [82-91]

Modern technology heavily relies on magnetic materials. They are essential parts of transformers, generators, and motors. Widely used magnetic materials in permanent magnet machine are Neodium-iron-boron (Nd-Fe-B), Samarium-cobalt (Sm-Co), Aluminum-nickel-Cobalt (alnico), Ferrites (barium and strontium).Various Permanent magnet materials and their characteristics as are presented in the table 2.2.

Table 2.2 Permanent Magnet Material and its Characteristics [82-91]

Permanent Magnet Material	Characteristics
Neodium-iron-boron (Nd-Fe-B)	Very good properties for PM, except the curie temperature is only 150^0c; relatively abundant.
Samarium-cobalt (Sm-Co)	Excellent high temperature performance (550^0c) but expensive.
Aluminum-nickel-Cobalt (alnico)	Low cost and good properties, however, coercive force is too low.
Ferrites (barium and strontium)	Low cost, moderate service temperature (400^0c) but size of machine would be large.

The detailed study of the literature has been carried out related to all the important parameters necessary for the development of PMDD hoist in this section.

2.10 Literature Based on Design and Development of PMDD Hoist

In the research of condition-based maintenance of gears and bearings for fault detection, Sanjay Kumar, Deepam Goyal, et al. [1] came to the conclusion that vibrations eventually cause machine apparatus deterioration, which leads to the failure of a few subsystems, such as couplings and gears, or the machine itself. A collaborative gearbox failure analysis report on gearbox reliability was presented by R. Errichello and J. Muller [2]. The analysis of crane degradation resulting from operation was presented by Jozef Kulka et al. [10]. They also demonstrated a professional verification of the crane track beams, determined the residual durability of selected beams, and recommended necessary actions regarding the possibility of operating the entire crane in the future.

K. Atallah and D. Howe [15] in their investigation of a novel high-performance magnetic gear demonstrated that a torque density greater than 100 KNm/m^3 could be attained through the use of rare earth magnets. Both the high and low speed rotors being equipped with sintered NdFeB permanent magnets. Magnetic gearing has the benefit of not transmitting torque through mechanical contact, as demonstrated by D.E. Hesmondhalgh et al. [16]. MG could be immune to backlash and have built-in overload protection. Energy can be stored in mechanical deflection in a gear that is mechanical, but in a magnetic gear, it can be stored primarily in the air gap within the magnetic field. Poor toque/volume ratio results from the fact that only one or two magnetic teeth at a time contribute significantly to energy transfer. However, the mechanical gear experiences the same issue because the force transmitted across its teeth is many times greater than that of magnetic teeth of the same size. By increasing the ratio of the active to total number of magnetic teeth, the torque/volume ratio can be raised. In mechanical gear energy may be stored in mechanical deflection whereas, in a magnetic gear, energy may be stored in the magnetic field, mainly in the air gap. According to K. Tsuruinoto et al. [17], magnetic gear (MG) has several benefits, including physical isolation, minimal vibration, reduced acoustic noise, maintenance-free operation, enhanced dependability, and built-in overload protection. The idea of integrating magnetic gearing into permanent magnet machines allows for direct drive operation at low speeds and high torque. Mechanical Gear (MG) boxes are widely used to match the operating speed of prime movers to the requirements of their loads, as demonstrated by X. Li, K.-T. Chau et al [18]. For optimal torque transmission, Atallah et al. [20] suggested that MG have a small active air gap over the periphery. Prior to the invention of high-performance Neodymium iron boron (Nd-Fe-B), ferrite permanent magnet (PM) material was not widely used in industry due to its low utilization and poor performance. These modified MGs merely swapped out the iron core's slots and teeth for the N- and S-poles of PMs. NASA's electrified aircraft propulsion research on magnetic gearing was presented by Dr. Justin J. Scheidler et al. [21].

The fundamentals of permanent magnet generator electrical design for direct drive renewable energy systems were covered by H. Polinder [22]. A 3 MW permanent magnet (PM) generator with a 15 rpm speed for a direct drive wind turbine is discussed in terms of its electromagnetic design. It provides scaling laws that allow the size of direct drive generators to be estimated. The direct drive permanent magnet synchronous generator design for hydrokinetic energy extraction was introduced by Amshumaan [24]. Permanent Magnet Motor Technology was presented by J. F. Gieras and M. Wing [25–26–27], who also looked into the ideal design for a direct-driven wind turbine generator. Nebojsa Mitrovic [28] gave a presentation on multi-motor drives for use in cranes. When it comes to crane applications and load sharing requirements, multi-motor drives are standard solutions. The straight-flow permanent magnet synchronous generator design, which runs with PM synchronous generators directly coupled to the grid, was presented by X. Cui, A. Binder, and E. Schlemmer [35] for small hydro power plants. It is regarded as an inventive application form in the field of small hydro power. The development and optimization of a low-speed, high-efficiency permanent magnet generator for a micro hydroelectrical generating system was presented by Liangliang Wei, Taketsune Nakamura, and Keita Imai [36]. In order to power a low speed hydrokinetic turbine, a permanent magnet synchronous generator (PMSG) was created, assembled, and tested.

Design calculations for permanent-magnet generators were presented by David Ginsberg et al. [67]; these calculations provide a simplified approach to determining the performance of permanent-magnet generators using equations, concepts, and units that are commonly used by conventional generator designers. Chunting Chris Mi,et. al. presents an analytical method for the design of permanent-magnet (PM) traction-drive motors with emphasis on calculation of the magnet's volume and size. The method uses a set of formulas to properly size the magnets without the high effort of FEA. Minoru KONDO et. al. presented The development of a 235 kW totally enclosed permanent magnet synchronous motor for next-generation suburban trains is presented in this paper. A novel cooling structure was proposed, and its effectiveness was verified in a temperature rise test. The results of testing and calculation show that this new motor can reduce the energy consumption of the train by 12% and acoustic noise emission by 7 dB. Y. Alexandrova, R. S. Semken et. al [60] described a theoretical framework for a compact, high-power, direct-drive permanent magnet synchronous generator (DD PMSG) that uses direct liquid cooling (LC) of the stator windings to efficiently manage generator cooling, and therefore the temperature of the windings and permanent magnets. Direct liquid cooling enables a significantly lighter weight generator, and this lower mass design promises reliable and efficient power generation at substantially lower cost [60]. Gordon R. Slemon , Xian Liu presented Design models for the approximated analysis of torque capability. Y. Wang, M. Filippini, N. Bianchi, and P. Alotto discussed the main computational techniques generally adopted for coaxial magnetic gears are listed and described. Some key aspects concerning the design, the existed challenges and potential applications are also dis- cussed. K. Li and J. Z. Bird presented several new topologies have been proposed to achieve better performances. In this paper, a general review of magnetic gears. Bochen LI Yangkunhe at al. showed Basic design can reduce or compensate the torque by using special end pieces, and improve access to fields > 1000 mT at small rod separation. J.M.D.Coey given new methods of increasing magnet stability at elevated temperature are being developed, and integrated multi functionality of hard magnets with other useful properties is now envisaged.

Horng-Ching Hsiao et. al.presented the finite element magnetic circuit analysis software, RMxprt and Maxwell 2D by ANSYS, are used to modeling and analyze. Prathamesh Mukund Dusane analysed four models of a 1,500Watt, 380Rpm, 40 Nm & 48 Volt BLDC Motor are designed and simulated in the RMxprt module of Maxwell [24 Slot, 36 Slot, 48Slot, 72 Slot] The software enabled solving and simulation of magneto-static and transient fields based on Maxwell's equations in 2D & 3D. Andrzej Łebkowski [95] The final parameters of the motor designed for mounting inside the wheel of the vehicle are presented (Power = 53 kW, Torque = 347 Nm; Base speed = 1550 RPM). V. Sandeep , and Sharankumar Shastri designed motor rated at 1.5 kW, 3000rpm, 120 V radial flux surface mounted permanent magnet rotor, is then assessed using analyticaltools for design such as ANSYS's RMXprt to verify the analytically obtained results. Tushar Waghmare et. al. has explained software tool, RMxprt of ANSYS is used to build geometry of motor and to calculate basic design parameters, and then this design is taken into Maxwell 2D environment to further analyze it. Manuel Pinilla et. al. presented methodology is framed on thedesign of a wind energy generator, it can be extended to the design of permanent magnet machines for different application fields. A. K. Jassal, H. Polinder et. al. [23] explained FEMM 4.0 which is a Finite Element (FE) solver was used for validation of various magnetic force models. MATLAB Simulink was used. Gurutz Artetxe et. al. [41] presented a design and calculation procedure based on multi static finite element analysis is developed and experimentally validated via a 200 Nm, 160 rpm prototype SynRM. After that, machine designs with different rotor pole and stator slot number combinations are studied. Durmus Uygun et. al. [33] All specifications such like number of turns, winding area, stator pole height involving stator structure and the performance characteristics of the designed prototype are investigated using finite element method FEM. Donaghy-Spargo CM, Mecrow BC, Widmer JD has shown aanalysis through a combination of 2D & 3D FEA studies in conjunction with experimentally derived results on a prototype machine having 6 slot 4 pole motor.

Vladimir Kuptsov presented a new and powerful freeware software called Motor analysis-PM and discussed its application in electromagnetic design and analysis of permanent magnet (PM) motors. Hattory, T. explained analysis procedure and steps presented for JMAG software. Meeker, D presented FEMM is a suite of programs for solving low frequency electromagnetic problems on two-dimensional planar. M. Rezal et al. presented the static analysis of 18-slot/16-pole Permanent Magnet Synchronous Motor (PMSM) using Finite Element Analysis. Carunaiselvane et. al. showed The design P - Number of poles equations and results such as Projected 3D views,Flux patterns and Cogging torque are presented for 27 slots, 8 pole and O.7SkW PMBLDCM by Magnet. Cao Yongjuan et.al. In this paper, computer aided design (CAD) software of permanent magnet synchronous motor (PMSM) is drawn up. Tutorials and Webinar on Simcenter Motorsolve by Siemens Digital Industries Software explained Steps and Parameter to Design and Analyse motor.

Permanent magnet synchronous motor and variable frequency drive were introduced by Judah Schad et al. [70]. The primary cause of the PMSM's drawbacks is the sensor that was selected to meet the requirement for data feedback. The PMSM will not spin if it is directly connected to a power source with a constant frequency. To operate the motor, digital control and sensor feedback are needed. The rotor of a PMSM motor rotates at the same speed as the internal rotating magnetic field of the motor because it is a synchronously commutated motor. T. Zouaghi presented the operation of variable speed, stall regulated wind turbine PM synchronous generator, and is examined. The analysis and design of control system for an electric drive calls for a dynamic model of the machine.

The torque-speed regions that correspond to the defined criteria are where the highest efficiency region of each motor is situated. In terms of efficiency and sensor-less control, Demmel et al. [73] highlighted the benefits of PM-machines over induction machines in traction applications. The topic of permanent magnet motors for energy savings in industrial applications was covered by Melfi MJ, Roberts Evan S, and Martin B [74]. A comparison of interior permanent magnet, induction, and switched reluctance motor drives for EV and HEV applications is presented by Yang Z, Shang F, Brown IP, and Krishnamurthy M. [75]. Operating efficiency, dependability, variable speed operation, low running temperature, quiet operation, and affordability are highly valued in today's and tomorrow’s motor markets. These market expectations can now be met by permanent magnet (PM) motors over a wider range of ratings. PM motors offer superior efficiency, dependability, and other features over the widely used induction motor. They also have lower rotor temperature, superior power factor (low current), and synchronous operation. PM generator created, made, and examined a permanent magnet generator with low speed and high efficiency. A discussion of the technical and financial aspects of ultra high-efficiency three-phase motors was conducted by De Almeida et al. [77]. Ferreira FJ, De Almeida AT, and Baoming G. [79] demonstrated to increase efficiency beyond induction motor technological trends. The best emerging electric motor technologies, including the axial-flux PM synchronous motor, are examined in terms of efficiency. Induction motors are gradually being supplanted by permanent magnet (PM) motors. The torque-speed regions that correspond to the defined criteria are where the highest efficiency region of each motor is situated. Tower crane applications for permanent magnet synchronous motors were covered by Jacek Krupinsk [80]. Compared to squirrel cage induction motors, the operating parameters of contemporary permanent magnet synchronous motors (PMSM) are superior. The practicality of permanent magnet synchronous motors for industrial applications was demonstrated by Adly, A. Huzayyin [81]. In industrial applications such as compressors, fans, and pumps, permanent magnet motors are quickly taking the place of induction motors.

The performance of low-cost permanent magnet materials, such as Nd-Fe-B and its magnet properties, and Sm-Co and its magnet properties, in PM Synchronous machines was presented by Petrov and J. Pyrhonen [84]. Sebastian T. [89] used Nd-Fe-B magnets to investigate how temperature affects the torque output and efficiency of PM motors. In his discussion of the present and future state of rare earth permanent magnets, Hajime Nakamura [91] found that Nd-Fe-B magnets, which have superior magnetic performance, account for a significant portion of the market for permanent magnets, helping to preserve heavy rare earth elements.

In order to achieve a direct drive without the need for a mechanical transmission, G.H. Chen and K.J. Tseng [92] presented the design of a permanent-magnet direct-driven wheel motor drive for an electric vehicle. A ferrite permanent magnet assisted synchronous reluctance machine was designed, prototyped, and tested by Michele De Gennaroa et al. [102] for use in hybrid and electric vehicle applications. The motor is intended to be a low-speed, high-torque motor. Low-speed and high-torque permanent magnet synchronous motor development and application were presented by Cui JG et al. [105].

2.10.1 Summary of literature studied

The literature studied is summarized in the below table 2.3 related to the research done in the whole thesis. Literature related to Failure/ maintenance required for hoisting, Fluid Coupling, Magnetic Gears, PMDD design, VFD, Advantages of PMDD, Magnetic Material, Analysis of Permanent Magnet motors, Magnetic material used in PM motors, Prototype and Experimentation and Factors affecting performance of EOT crane are studied for the research.

Table 2.3 Summary of literature

Failure/ maintenance required for hoisting.	Sanjay Kumar, Deepam Goyal et al [1], R. Errichello and J. Muller [2], Yoshi P.V., Dhagat S.K.[3], Miner, M. A et al [4], Milman, R.S [5], Guarino, A., Garcimartin, A. and Ciliberton [6], Tinkey, B.V., Fowler, T.J., Kingler, R.E [7], G.P. Raymond[8], Jozef Kulka, Martin [10].
Fluid coupling	C. Pease,H.S. Wijesinghe, et.al [13]
Magnetic gears, construction, design, application etc.	P.M. Tlali, R-J. Wang, S. Gerber [14], K. Atallah and D. Howe [15], D.E. Hesmondhalgh [16], K.Tsuruinoto and S.Kikuchi[17], X. Li, K.-T. Chau et.al.,[18], Andreas Penzkofer [19], K. Atallah [20], Dr. Justin J. Scheidler [21].
PMDD introduction, design, applications etc,	H. Polinder [22], A. K. Jassal, H. Polinder [23], Amshumaan Raghunatha Kashyap [24], J. F. Gieras and M. Wing[25-27], Mitrovic et. al.[28], Anders Grauers [29], R. Krishnan[30], Hendershot [31], Ling L.[32], Durmus Uygun et. al [33], N. Boules [34], X. Cui, A. Binder[35], Liangliang Wei [36], Lu SM[37], Ruoho S.[38], Guo Q, Zhang C, Li[39], Manuel Pinilla[40], Gurutz Artetxe[41], Y.K. Chin[42], Minoru Kondo, Y. Honda, T.Higaki[43], C. Miet al.[44], M. Filippa et al. [45], Spooner E, Williamson[46], Dubois MR [47], R. Islam, I. Husain [48], Bilgin O, Kazan FA [49], Huger D, Gerling D [50], H. Li and Z. Chen [51], W. Fengxiang, B. Jianlonget al.[52], J.-Y. Choi, S.-M. Jang[53], T. Liu, S. Huang [54], D. C. Hanselman[55], M.Plikar Puva et al [56], D.J. Bang et al[57], Jie Meng et al [58], Xi Y., Li X.C.[59], Y. Alexandrova et al.[60], S.

	Jia, R. Qu, J. Li et al [61], I.M. Ducar, C.P. Ion[62], A.J.P. Ortega, S. Paul[63], Z.Q. Zhu ,D. Howe [64], Akar M, Eker M [66], David Ginsberg [67], G.H. Chen et al [68].
VFD	Judah Schad [70], B. K. Bose [71].
Advantages offered by PMDD	H. Polinderet al [72], Demmelmayr F, Troyer M [73], Melfi MJ, Rogers SD [74], Yang Z, Shang F [75], A. Boglietti, A. Cavagnino [76], De Almeida AT, Ferreira FJ [77,79], Lu SM., Jacek Krupinsk [80], A. A. Adly, A. Huzayyin [81].
Magnetic materials and its characteristics	Dexter [82-83], I. Petrov and J. Pyrhonen, C. Pease [84] ,H.S. Wijesinghe [85], Cheng Song, Bin Cui et.al [86], Anders Nordelöfa[87], Emma Grunditz, Mojbata BabaiReza Aamir[88], Sebastian T [89]. Bilgin O, Kazan FA Bilgin O, Kazan FA [90], Hajime Nakamura [91].
Analysis of PM motors by using various software available	H. Hsiao, C. Hsiao and G. Chen [92], J. I. Tapiador, L. A. Gan Lim and G. L. Augusto [93], Prathamesh Mukund Dusane [94], Andrzej Łebkowski [95], C M Donaghy-Spargo [96], H. A. Toliyat and G. B. Kliman [98], Guo Q, Zhang C, Li L, Zhang J, Wang M.[99], Huger D, Gerling D [100].
Prototype and experimentation	Michele De Gennaroa et al. [102], X. Li, K.T. Chau, M. Cheng [103], Liangliang Wei, Taketsune Nakamura, Keita [104], Cui JG, Xiao WS, Zhao JB et al[105] M. Valavi, A. Nysveen [106]

CHAPTER – 3

Design of Permanent Magnet Direct Drive for Hoist

As a prototype of the hoist of EOT crane, the PMDD to lift the load of 100 kg is designed here. In the proposed concept the gearbox due to its high maintenance / failure [1-12] is eliminated and implementation of PMDD is done. The basic function of gearbox with any conventional motor is to give higher torque at lower required rpm; it acts as a speed reducer. But here gearbox is eliminated so the designed and selected PMDD must be able to give required higher torque at a required lower speed.

In this chapter the design of permanent magnet direct drive is presented. Firstly the variables which are used in design of PMDD hoist are studied. The equations are presented to calculate the necessary parameters required for the development of PMDD required to be used in prototype of hoist to lift the load of 100 kg.

3.1 Design of PMDD to Lift the Load of 100 kg [22-69]

To lift the load of 100 kg, first the torque is required to be calculated for the design of PMDD. The designed PMDD will be used in conjunction with variable frequency drive to vary the speed by changing the frequency. The hoist of EOT crane needs higher torque but at the same time speed must be very less 15- 20 rpm or so on as per the capacity and application of crane.

- To calculate torque (T) of the hoist to lift 100 kg load, where N is speed,

$$Power = \frac{2\pi NT}{60} \tag{1}$$

- The magnitude of the magnetic field intensity produce by the element is proportional to the product of current, the magnitude of different length and sine of the angle lying between filaments is given by the equation no. (2)

$$H = \frac{I \times dl \times a_r}{4\pi R^2} \tag{2}$$

where, H = Magnetic Field Intensity, amperes per meter (A/m)
I = Current Flowing
dl = Length of filament
R = Radius
$a_r =$ sine angle

- Magnetic Flux (B) : (wb/m^2)

$$B = \mu_0 \times H \tag{3}$$

where, $\mu_0 =$ permeability of free space,$4\pi\times10^{-7}$

The basic variables which are required for the design of PMDD are given in the table and which can be very well understood by the figure shown below:

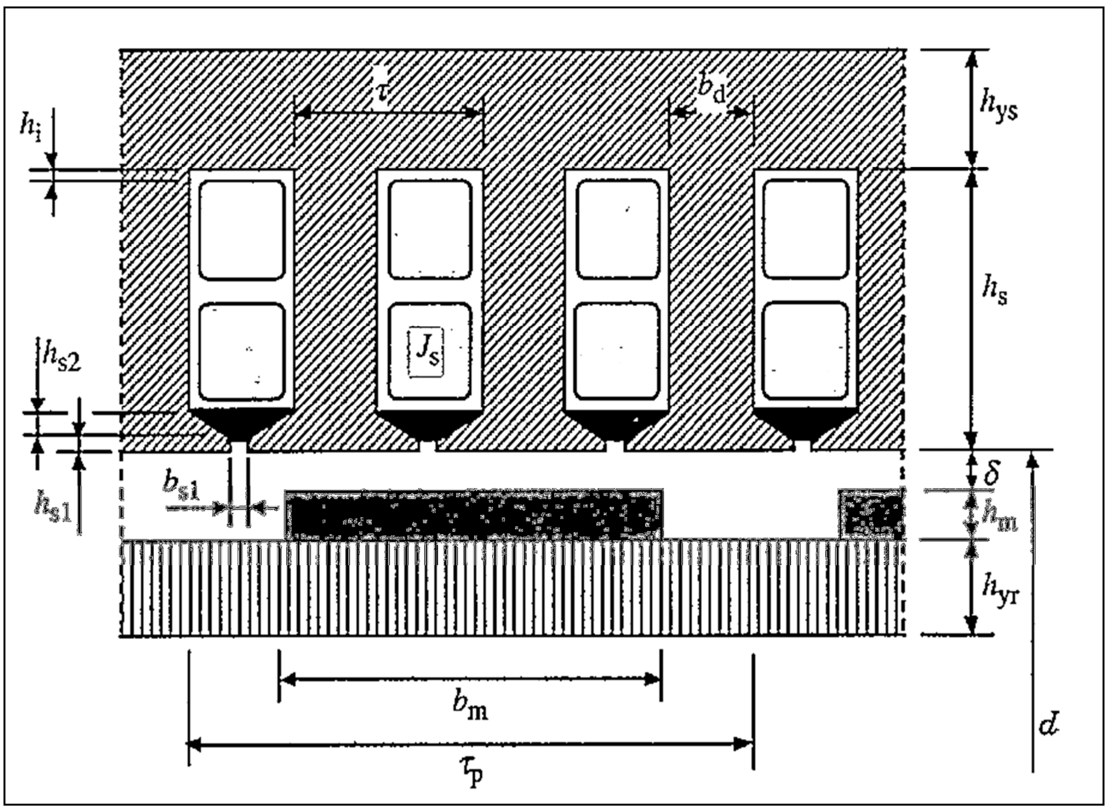


Figure 3.1 PMDD Stator and Rotor

3.1.1. The variables used in Design Method [22-29]

Following are the design variables and its corresponding basic variables used in design of PMDD.

Table 3.1 The Design Method's variables used in PMDD

Design Variables		Corresponding Basic Variables	
l	Stator length	l	Stator length
d	Air gap diameter	d	Air gap diameter
τ_P	Pole pitch	τ_P	Pole pitch
h_s	Slot height	h_s	Slot height
J_B	Current density	J_s	Current density
B_{d0}	Peak teeth flux density	b_d	Tooth width
$B_{\delta 0}$	Peak air gap flux density	h_m	Magnet height
Constant and Fixed Relations		**Corresponding Basic Variables**	
B_{yr}	Peak rotor yoke flux density	h_{yr}	Rotor yoke height
B_{ys}	Peak Stator yoke flux density	h_{ys}	Stator yoke height
$b_{s1} = 3\ mm$	Slot Opening	b_{s1}	Slot opening
$h_{s1} = 1\ mm$	Tooth tip height	h_{s1}	Tooth tip height
$h_{s2} = 4\ mm$	Slot wedge height	h_{s2}	Slot wedge height
$h_i = 1\ mm$	Insulation Thickness	h_i	Insulation Thickness
$B_m = 0.7\tau_p$	Magnet Width	b_m	Magnet Width
$q = 1$	No. of slots per pole & phase	τ	Slot Pitch
$\delta = 0.001\ d$	Mechanical Air gap	δ	Mechanical Air gap

3.1.2 Design Equations [22-29]

Following equations are used to design the PMDD;

To determine number of poles *P*; where *N*= rpm and f_s = frequency.

$$P = \frac{120 \times f_s}{N} \tag{4}$$

To determine the pole pairs (*p*); where *d* = diameter and τ_p = pole pitch.

$$p = \frac{\pi d}{2.\tau_p} \tag{5}$$

To find the total number of slots on stator (*Q*) is; where q = number of slots per pole, m = number of phase.

$$Q = 2\,\mathrm{p\,m\,q} \tag{6}$$

The Slot Pitch (τ) can be determine by;

$$\tau = \frac{\tau_p}{m\ q} \tag{7}$$

Figure 3.2 displays the two layer windings and the slots. The width b_s and depth h_s of the slot characterize it. Using the slot pitch τ and tooth width b_d, the slot width can be computed as follows:

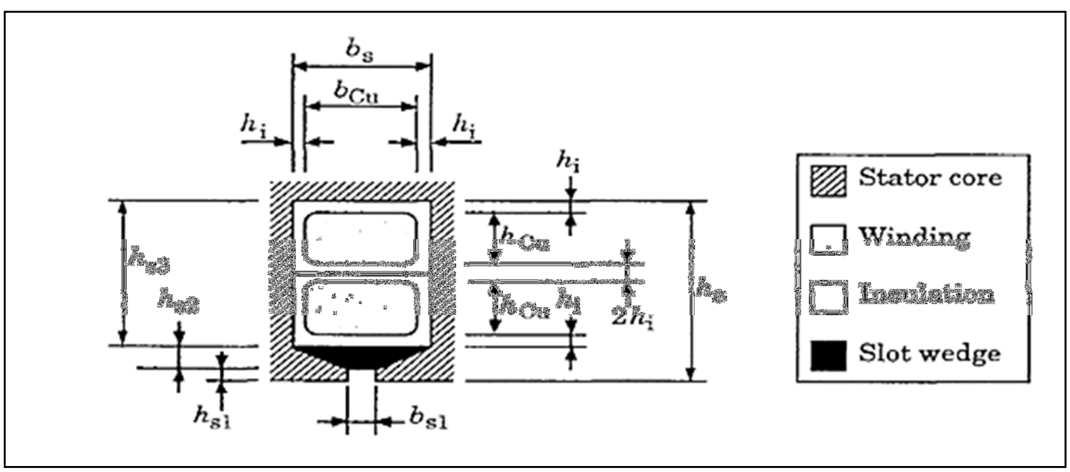


Figure 3.2 Slot and the Two Layer Winding

$$b_s = \tau - b_d \tag{8}$$

It is assumed that the tooth tip height h_{s1} = 1 mm, the slot wedge height h_{s2} = 4 mm and the slot opening b_{s1} are all 3 mm. H_{S3} is the winding height.

$$h_{s3} = h_s - h_{s1} - h_{s2} \tag{9}$$

The winding height, slot width, and coil insulation thickness *hi* determine the conductor height *hcu* and width *bcu*.

$$h_{cu} = \frac{h_{s3} - 4h_i}{2} \tag{10}$$

$$b_{cu} = b_s - 2h_i \tag{11}$$

$$b_m = 0.7\ \tau_p \tag{12}$$

The ratio of magnet width to pole pitch for a three-phase machine should be between 0.6 and 0.9 in order to reduce the cost of magnet per torque. The magnet width b_m in the suggested design is maintained at 0.7 times the pole pitch.

The winding pitch *W* is because the winding is a full pitch winding;

$$W = \tau_p \tag{13}$$

It is assumed that the end winding length l_b is;

$$l_b = 2\ W \tag{14}$$

An approximation of the equivalent core length is;

$$l_e = l + 2\ \delta \tag{15}$$

The following formula yields the useful iron length l_u, where K_{Fes} is the iron fill factor.

$$l_u = k_{Fes} l \tag{16}$$

At the rated speed, the frequency *f* is

$$f = p\ \mathrm{n}_N \tag{17}$$

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

$$\delta = 0.001\ d \tag{18}$$

The slot opening is narrow compared with the air gap, so carter factor will be 1.The outer diameter of the stator d_{se}

$$d_{se} = d + 2\ h_s + 2\ h_{ys} \tag{19}$$

Approximate total length of the stator

$$l_{total} = l + 3\ W \tag{20}$$

By using the above equations, the required parameters can be calculated. The table below shows the calculated dimensions for 100 kg Prototype.

Table 3.2 Calculated Dimensions for PMDD

Design Parameters	Calculated Value
Torque	50 N.m.
Speed	120 rpm
Voltage	415 V
Current	4-10 A
No. of Phase	3
Outer Diameter (Stator)	220 mm
Inner Diameter (Stator)	145 mm
Outer Diameter (Rotor)	133 mm
Inner Diameter (Rotor)	40 mm
No. of Poles	16
No. of Slots	36
Magnet Material	Neodium Boron Iron 38/23
Magnet Height	6.5 mm
Magnet Width	23 mm
Ambient Temperature	25-40^{0}c

3.2 Drafting of the PMDD

As per the calculated dimensions of PMDD given in table 3.2 the drafting of part drawing and assembly is done is Solid works. Drafting of stator stamping, stator stack, permanent magnet, rotor casting, rotor machining is done and the assembly of motor with brake is done. These drawings are provided for the customized manufacturing permanent magnet direct drive motor with brake. This can be used along with variable frequency drive to lift the load at higher torque and lower speed. With this permanent magnet direct drive motor one can completely eliminate the gearbox. The details regarding part drawing and assembly are shown in figure 3.2.2, 3.2.3 and 3.2.1 respectively. Rest part drawings are included in annexure for reference.

3.2.1 Assembly of PMDD Motor

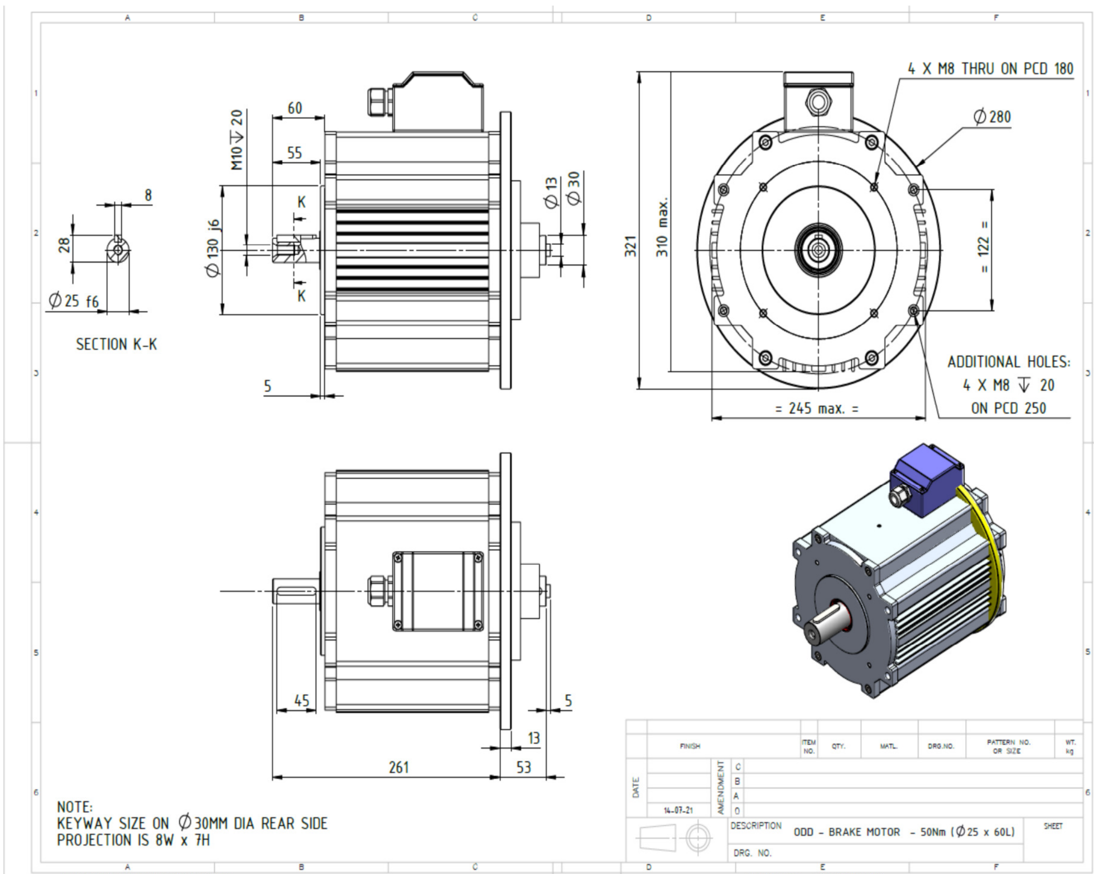


Figure 3.3 Assembly of PMDD

3.2.2 Drawing of PMDD Rotor

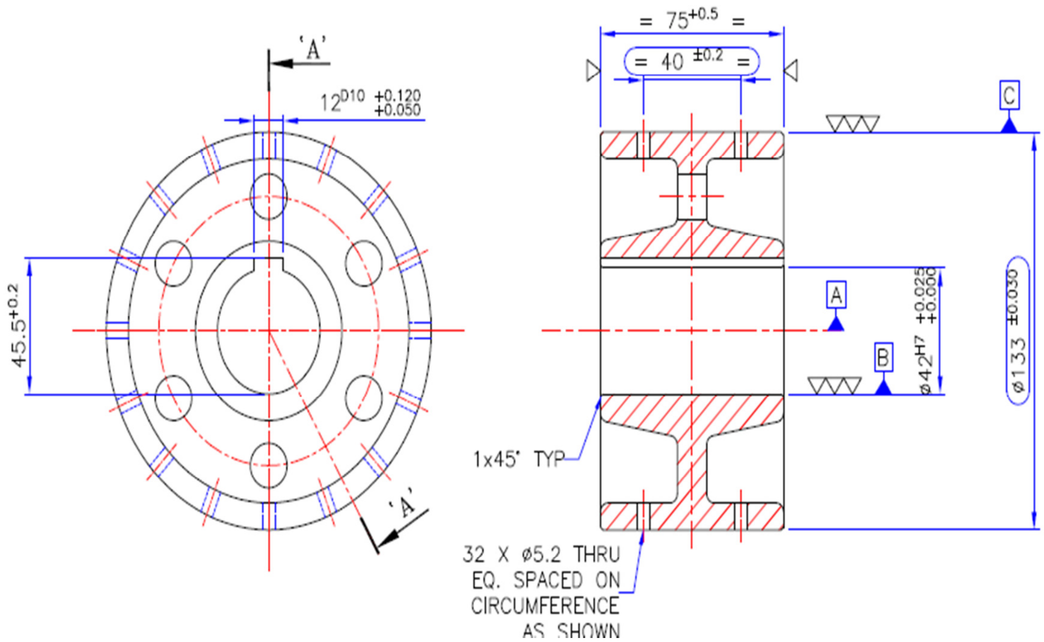


Figure 3.4 Part drawing of Rotor of PMDD

3.2.3 Drawing PMDD Stator

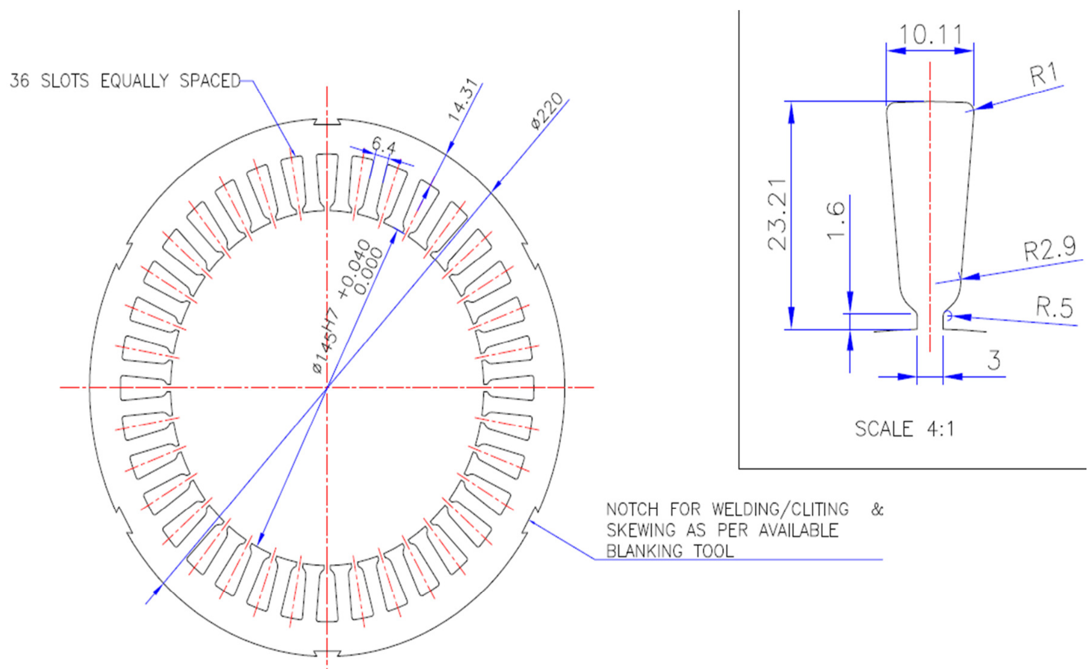


Figure 3.5 Part drawing of Stator of PMDD

3.2.4 Block Diagram of Design Process

The overall flow of design process outlined in this chapter is explained using a block diagram for better comprehension of the analytical approach.

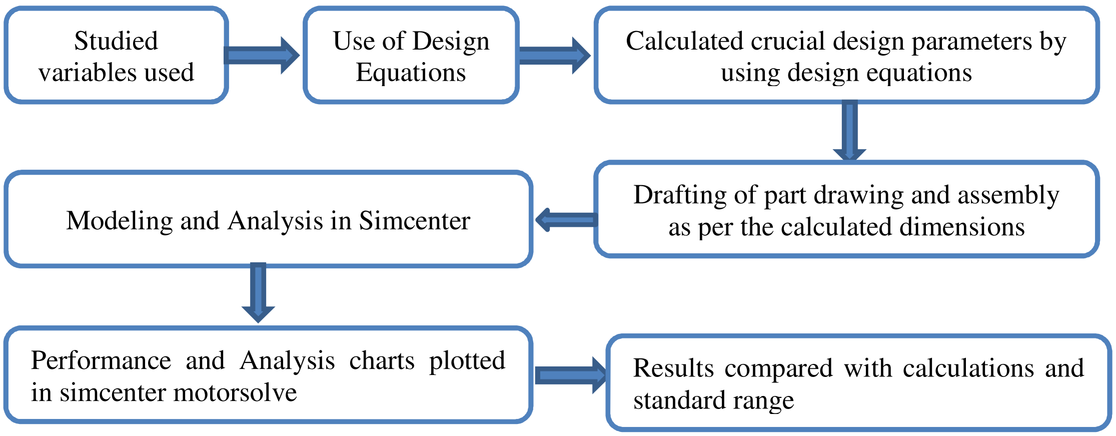


Figure 3.6 Block Diagram of Design Process

CHAPTER – 4

Modeling and Analysis of PMDD in Simcenter Motorsolve

Once the design process is completed, required dimensions are calculated as per the design equations. As per the calculated dimensions drafting is done in solid works so that the customized manufacturing of the PMDD motor with extended shaft and brake can be done. For Modeling and Analysis of permanent magnet motors various computational tools are available in the market like RMxprt, MATLAB, JMAG, Maxwell and Simcenter Motorsolve etc. Simcenter Motorsolve by Siemens is an efficient design and analysis software which is available with the stalwart cranes for modeling and analysis of permanent magnet machines. It is used to analyze the performance of PMDD too. In this section a complete assembly of PMDD is done; various analysis charts and performance chart are plotted for PMDD to predict its performance.

4.1 Modeling of PMDD in Simcenter Motorsolve [101]

Simcenter motorsolve is the software used for modeling and analysis of motor and generators too. Various softwares are available in the market for modeling of permanent magnet motor. But due to the ease of availability the particular software is chosen for the modeling and analysis. Simcenter motor solve is user friendly and efficient tool for permanent magnet motors. Step by step presentation of the modeling is shown below for the modeling as well as analysis of the PMDD motor. Following are the steps given to generate the model of motor.

Step: 1 Basic input parameters for default prototype generation

Input parameters: Supply voltage: 415 V; no. of phases: 3; phase, no. of poles: 16; No. of slots: 36; Air gap thickness: 1mm.

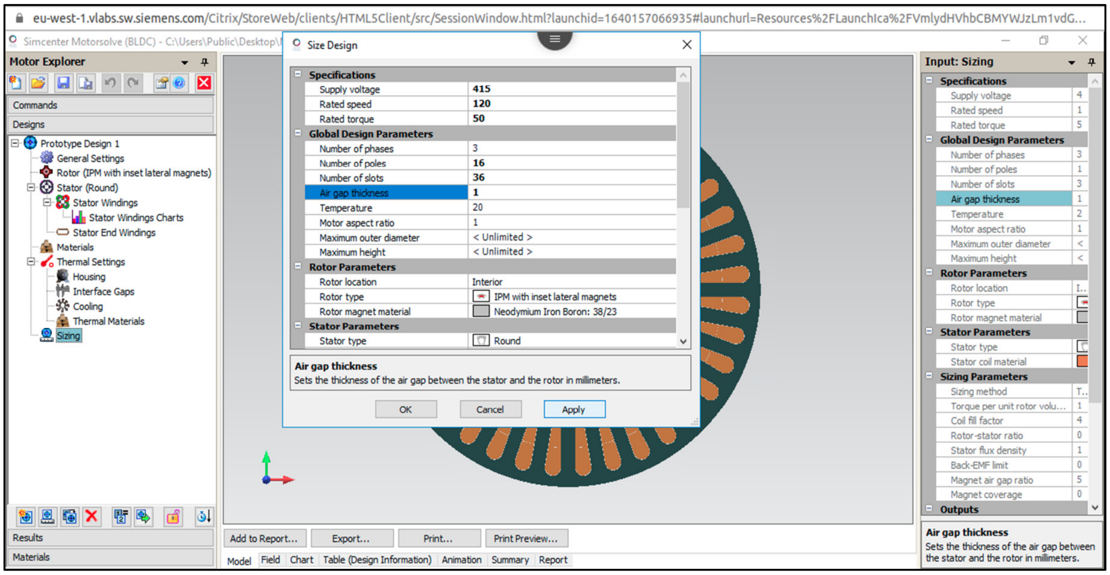


Figure 4.1 Basic Input Parameters

With the given input parameters default prototype of PMDD is generated as shown in figure 4.2 which has 16 poles and 36 slots which shown by yellow color. In this software by default the template is available having random poles, slots and air gap. Just like inventor or any 3 d modeling software provides template for gear which one can modify as per the requirement. In the same way here by giving the input parameters as per the calculations done in chapter 3; the basic prototype is generated as shown in figure 4.2.

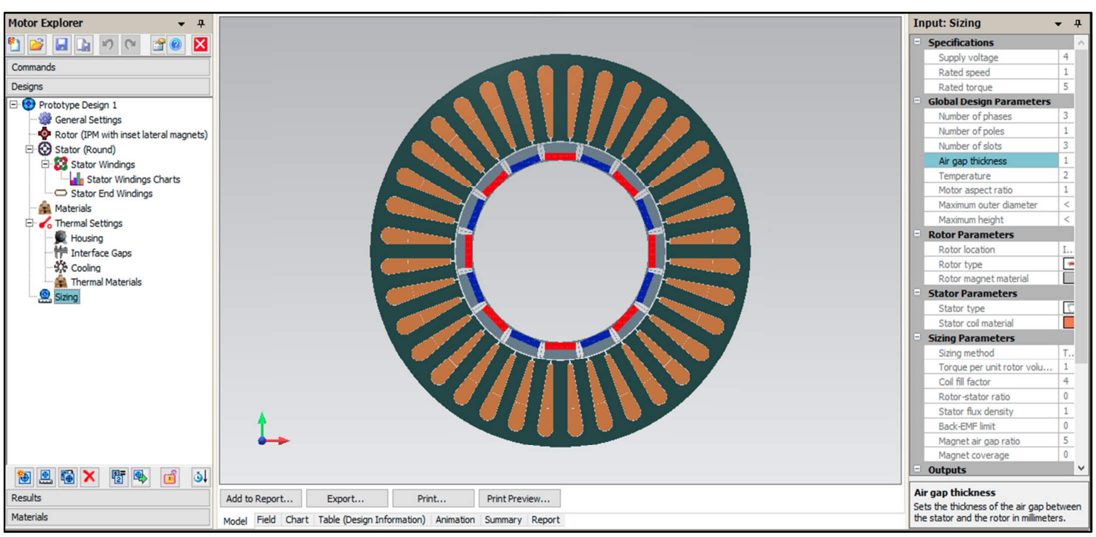


Figure 4.2 Default Prototype

Step: 2 Input parameters for rotor

Input parameters: Outer diameter of rotor: 133 mm; Inner diameter of rotor: 40 mm.

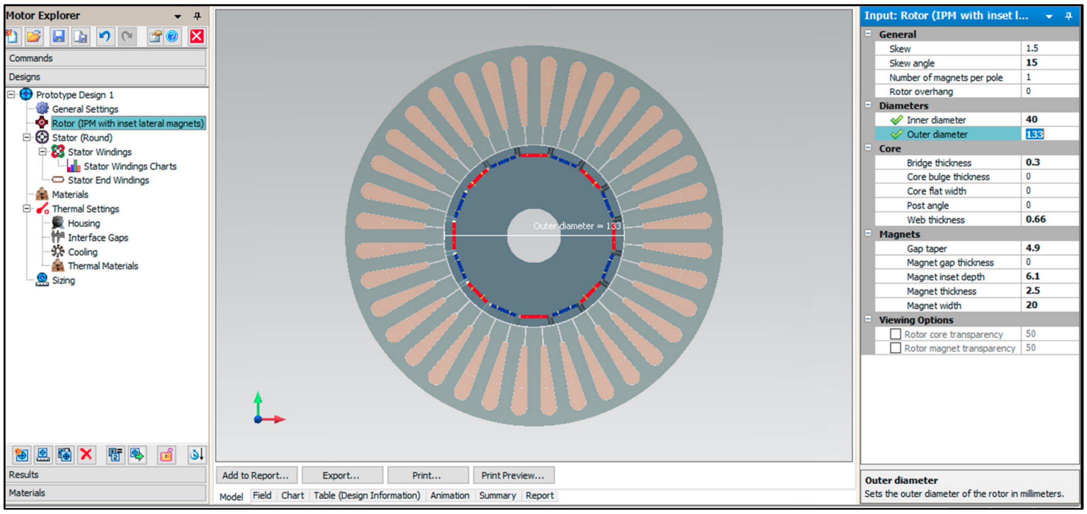


Figure 4.3 Rotor Generated with Designed Dimensions

Figure 4.3 shows that in the generated prototype; the dimension for the inner and outer diameters is given so that the rotor having the inner diameter of 40 mm and outer diameter of 133 mm is generated within the prototype.

Step: 3 Input parameters for magnet

Input parameters**:** Magnet depth: 6.54 mm; magnet width: 23 mm; magnet thickness: 2.1 mm.

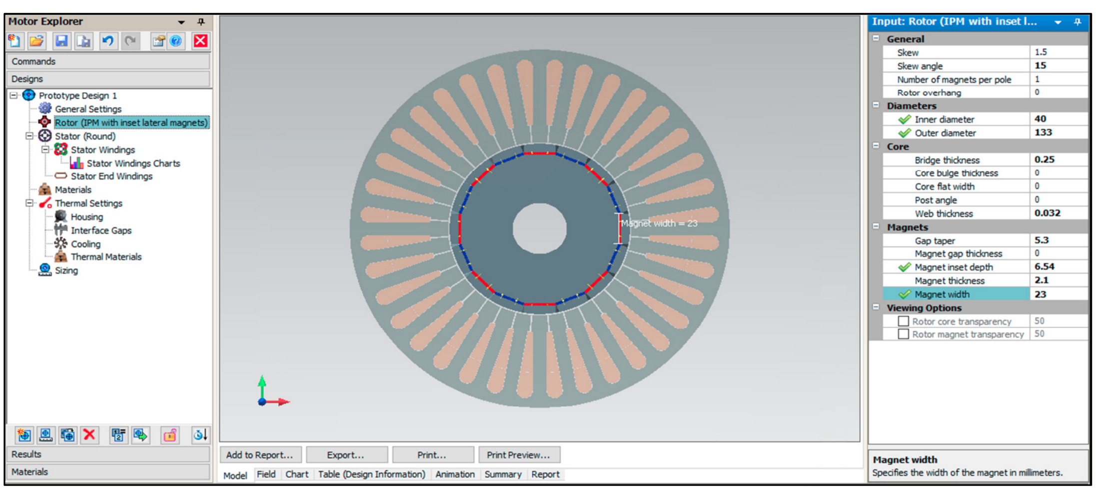


Figure 4.4 Magnet Generations with Designed Dimensions

Step: 4 Input parameters for stator

Input parameters: Outer diameter of stator: 220 mm; Inner diameter of stator: 145 mm.

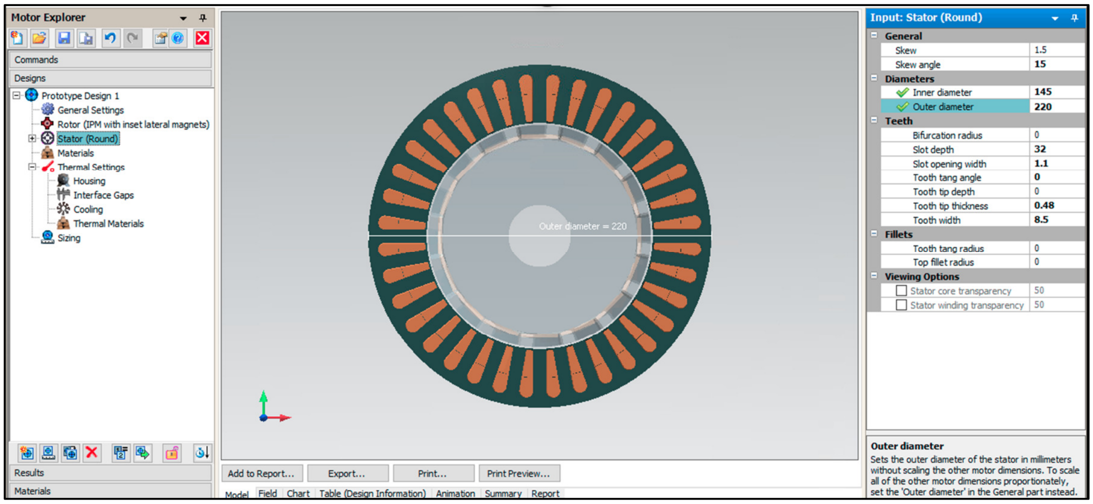


Figure 4.5 Stator Generated with Designed Dimensions

Step: 5 Final motor assembly with permanent magnet material Neodymium Iron Boron 38/23 selected as it gives higher magnetic flux density required for high torque.

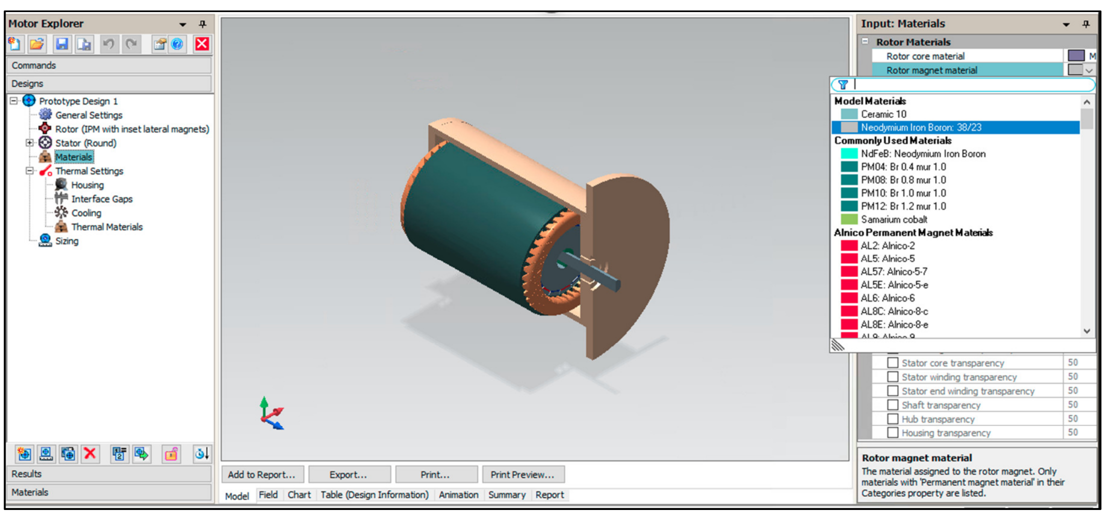


Figure 4.6 Assembly of PMDD Motor

Once the dimensions for rotor are given and the rotor is generated the dimensions for the magnet can be given. As shown in figure 4.4 the calculated dimensions for the magnet are given as; magnet depth: 6.54 mm; magnet width: 23 mm; magnet thickness: 2.1 mm. The individual magnets with the same dimensions are generated as per the parametric design.

Once the rotor dimensions and dimensions for magnet is given, dimensions for the stator can be given for the whole assembly generation. As shown in figure 4.5 dimensions for the stator are given as; outer diameter of stator: 220 mm; Inner diameter of stator: 145 mm. So the basic input parameters for the motor assembly generation are given and now by selecting the material for the permanent magnet the complete assembly can be generated. Here Neodymium Iron Boron is selected as the permanent magnet material. As the selected material gives higher magnetic flux density required for the higher torque.

4.2 Analysis of PMDD in Simcenter Motorsolve

Analysis of the generated PMDD model is done in this section and various performance charts, analysis charts, instantaneous field and thermal fields are plotted in below sections.

4.2.1 Performance Charts of PMDD

The generated model of PMDD is used for the analysis. Various performance charts are plotted to analyze the performance of generated 3D model. More emphasis is given on torque characteristics of the PMDD as the designed PMDD must be able to deliver high torque at lower rpm as per the requirement of the hoist for EOT crane.

- **Torque - Phase Angle**

As shown in figure 4.7 the torque performance of the PMDD is checked. Torque is the important research parameter for the designed PMDD as gearbox is eliminated in proposed hoist which is mostly require for high torque at low speed in hoist. So the designed PMDD must be able to deliver the required more torque at less speed. As per the performance chart; torque of 40- 65 N.m. can be achieved for the phase angle starting from 0 to 360^0. The torque given by this performance chart is sufficient to lift the load of 100 kg.

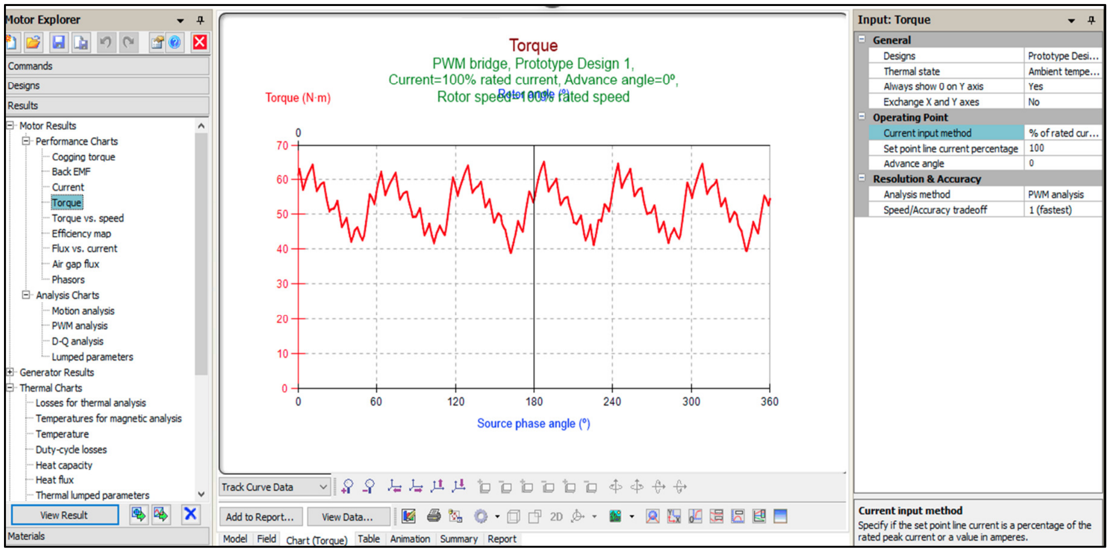


Figure 4.7 Performance Chart of Torque - Phase Angle

- **Torque - Speed**

Torque - Speed chart is plotted below which gives torque up to 60 N.m. for different speed at interval of 15^0. As per the below figure 4.8 it is understood that at the different speed intervals of 15^0, different values of the torque is available starting from the 0^0 to 360^0 different values of the torque which is available is given from 0 to 60 N.m. As per the research requirement the given torque is sufficient to lift the load of 100 kg.

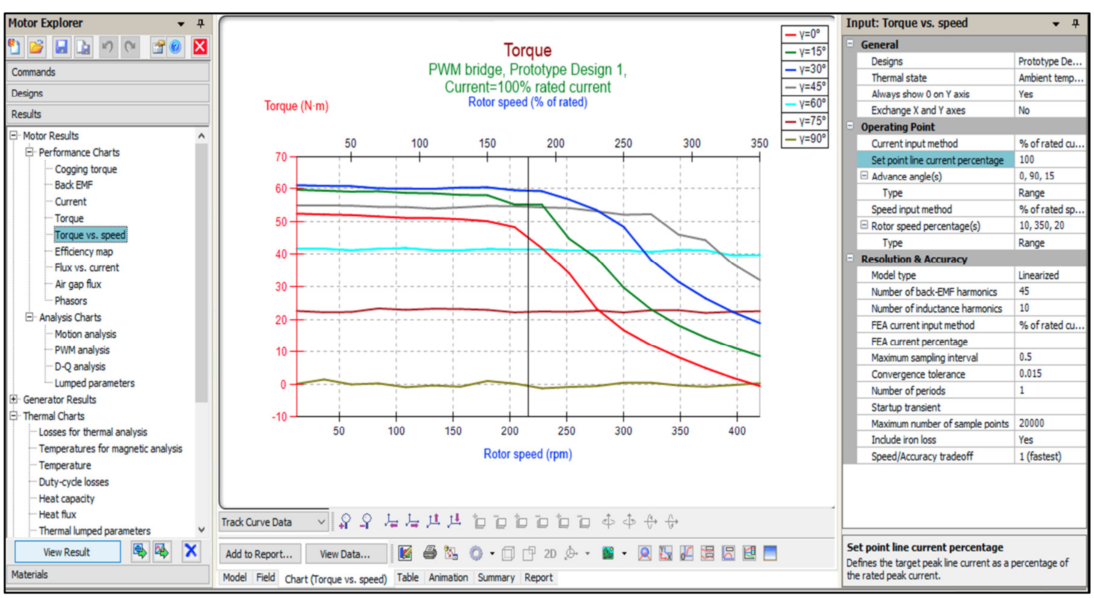


Figure 4.8 Performance Chart of Torque - Speed

- **Efficiency Map**

Figure 4.9 shows the efficiency values are given for a torque range of 0 to 60 N.m. with respect to speed up to 400 rpm. The designed PMDD gives speed of 120 rpm and by the implementation of variable frequency drive, the required lesser speed range can be achieved. The speed required by the hoist of EOT crane is very less up to 15-20 rpm depending upon the crane capacity, application and other parameters also. So as per the below efficiency map for the given range of torque at 120 RPM efficiency of 80-90% can be achieved.

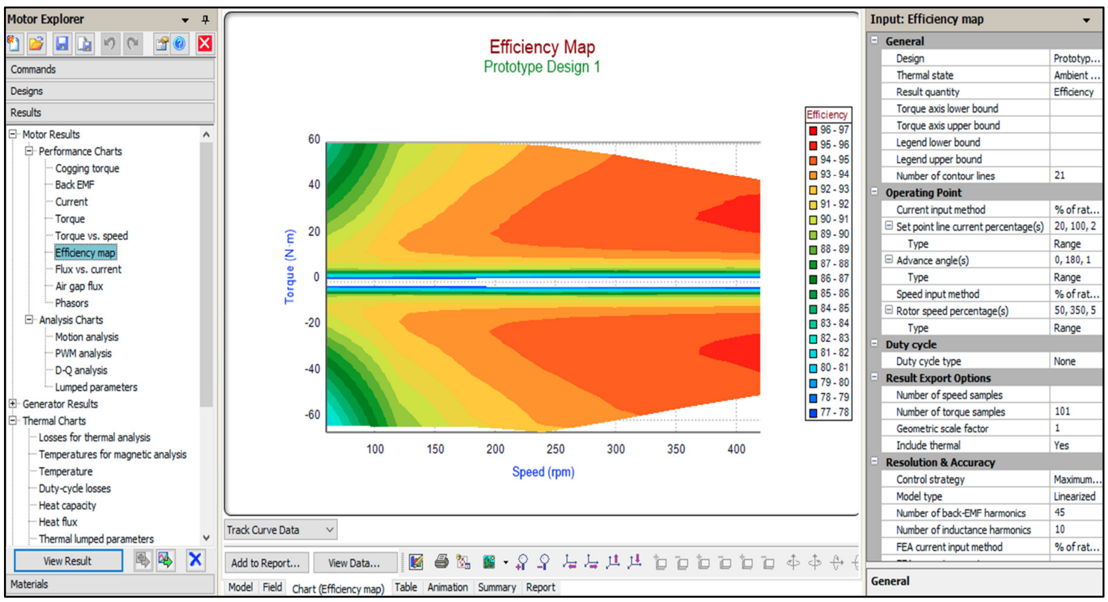


Figure: 4.9 Efficiency Map

4.2.2 Analysis Charts

Various charts for the analysis of required torque is plotted by considering pulse width modulation analysis. By considering the various parameters the value of torque is checked as higher value of toque is required to lift the load by hoist in EOT crane.

- **Pulse width Modulation (PWM) Analysis is done by considering Torque, Voltage, Current and back electro motive force (EMF)**

Pulse width modulation analysis is done as shown in figure 4.10, red color indicates torque ranges from 40-65 N.m., green color indicated voltage, blue color indicated current and grey color indicates back EMF. The torque values available in the results are sufficient to lift the load of 100 kg hoist as per the requirement of EOT crane. So with the designed motor we can completely eliminate the gear box that is required for higher torque at the lower speed.

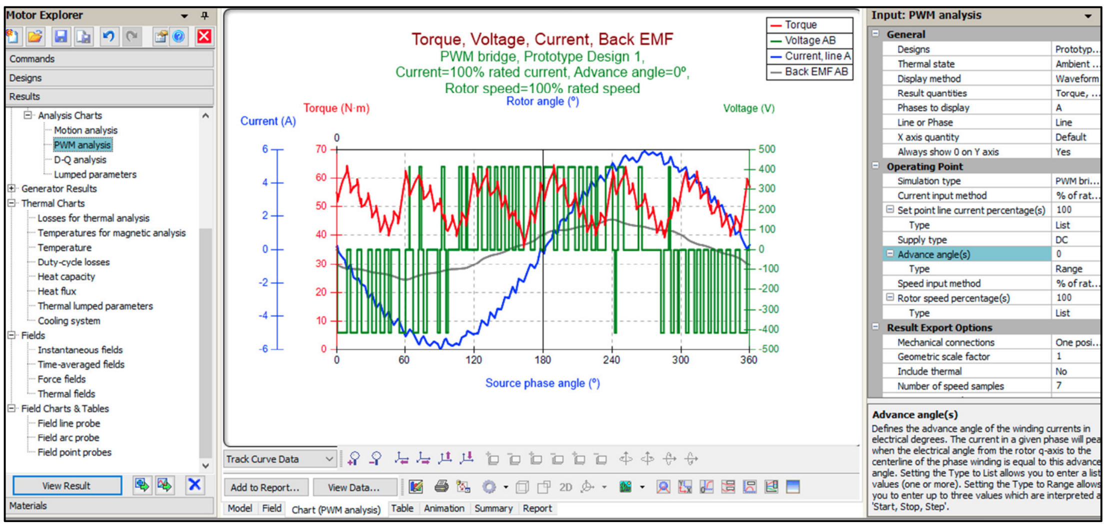


Figure 4.10 PWM Analysis: considering Torque, Voltage, Current and back EMF

- **Pulse width Modulation (PWM) Analysis with Display method: Waveform, Result Quantity: Torque.**

Figure 4.11 shows the torque range given by PWM analysis varies between 40 to 65 N.m. for phase angle starting from 0 to 360^0. Values of the torque will vary with the different phase angle which varies at 60^0. Values available in the results are sufficient to lift the load of 100 kg hoist as per the requirement of EOT crane. So with the designed motor we can completely eliminate the gear box that is required for higher torque at the lower speed.

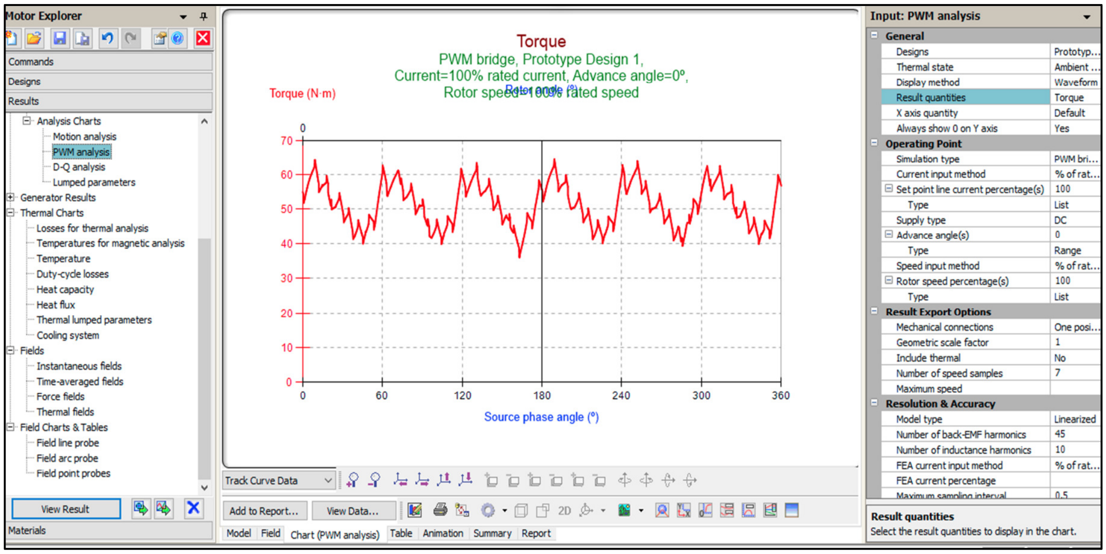


Figure 4.11 PWM Analysis Display method: Waveform Result Quantity: Torque

- **Maximum Torque**

Torque is the most important parameter for the research point of view. As a part of research here it is attempted to use PMDD that gives high torque at lower RPM which is the prime requirement of the hoist to lift the load. In conventional hoist the required higher torque at the lower speed is achieved by means of gearbox. So here the newly proposed design is modeled in simcenter motorsolve. And the analysis show that the Maximum torque of 60 N.m.is achieved for advance angle 0 to 90^0. The given torque 60 N.m is sufficient to lift the load of 100 kg.

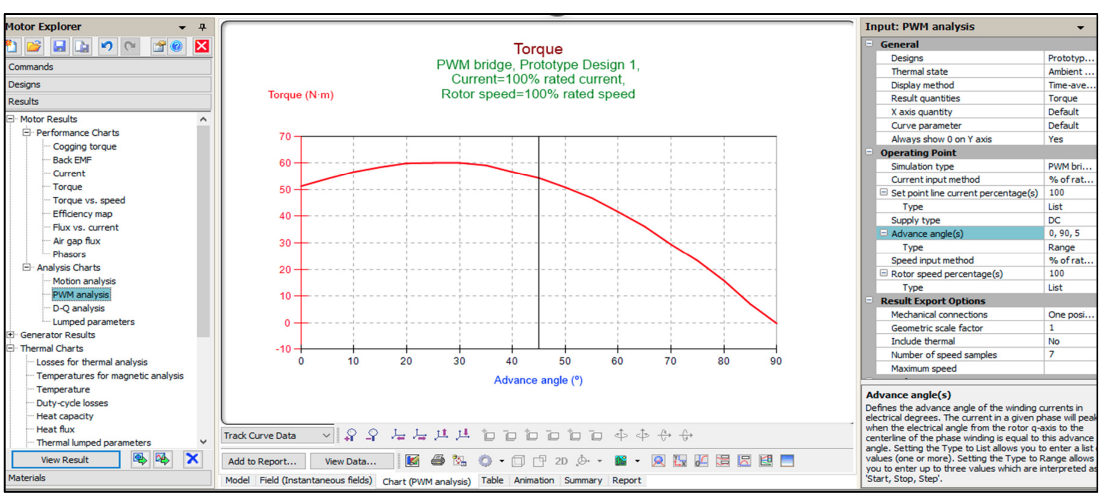


Figure 4.12 Maximum Torque

4.2.3 Instantaneous Fields

- Instantaneous fields are plotted for minimum and maximum peak line current percentage shows flux density of 0.0027 T on the rotor. **Input parameters are** taken as: Shaded plot lower bound 0, Shaded Plot upper bound 2, Peak line current percentage: 0.

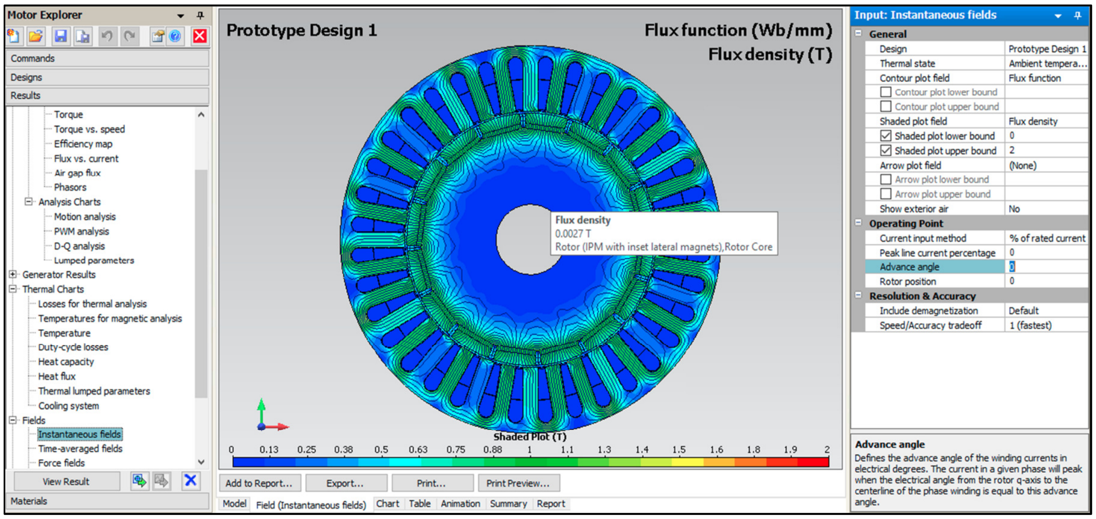


Figure 4.13 Magnetic Field Peak Line Current Percentage 0

- Instantaneous fields are plotted for minimum and maximum peak line current percentage shows flux density of 0.94T on stator. **Input parameters** are taken as: Shaded plot lower bound 0, Shaded Plot upper bound 2, Peak line current percentage: 100.

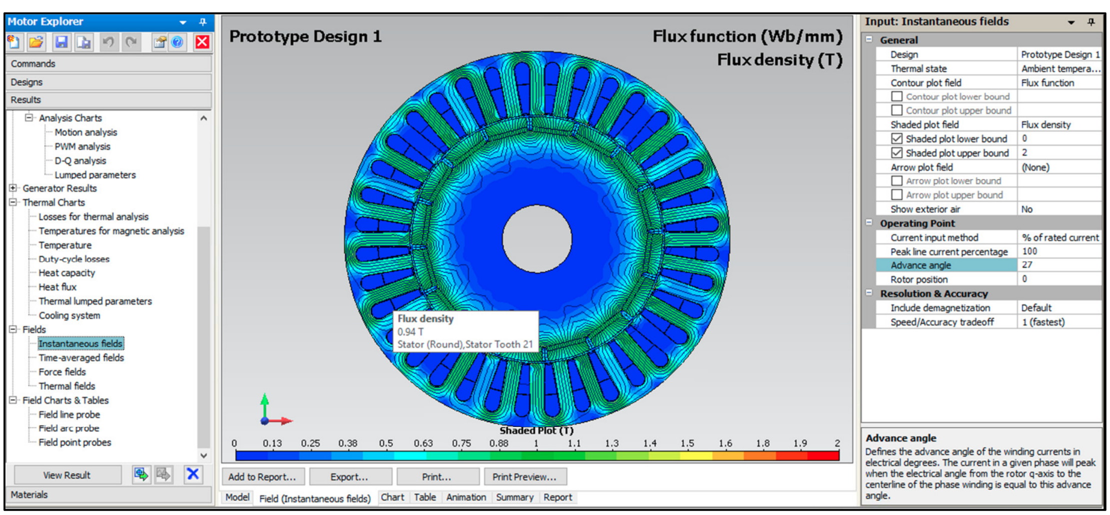


Figure 4.14 Magnetic Field Peak Line Current Percentage 100

Instantaneous fields are plotted for minimum and maximum peak line current percentage from minimum to maximum. For the first case the input parameters are shaded plot lower bound 0, Shaded Plot upper bound 2, and Peak line current percentage: 0; so for the minimum value of the current, the available flux density on rotor is 0.0027 T. Whereas in the second case the input parameters are shaded plot lower bound 0, Shaded Plot upper bound 2, and Peak line current percentage: 100; so for the maximum value of current, the available flux density on rotor is 0.94 T.

As per the guidelines for the electrical machines the range given for the flux density should not exceed from 1.2 T to 1.6 T. So the results which we are getting from the figure 4.13 and figure 4.14 is well within the limits and satisfied the guidelines for the electrical machines given by the volumetric international transactions on electrical energy systems.

4.2.4 Thermal Fields

The Thermal analysis is also done for the PMSM motor in Simcenter Motorsolve. As shown in figure 4.16 and figure 4.17 the value of temperature on the rotor and stator is indicated respectively. Thermal fields shows the temperature of 21^0 c on rotor which is well within the limits as per the NABL testing report of the motor. Thermal fields shows the temperature of 22^0 c on stator which is well within the limits as per the NABL testing report of the motor. So as per the NABL testing reports the temperature range is well within the limits.

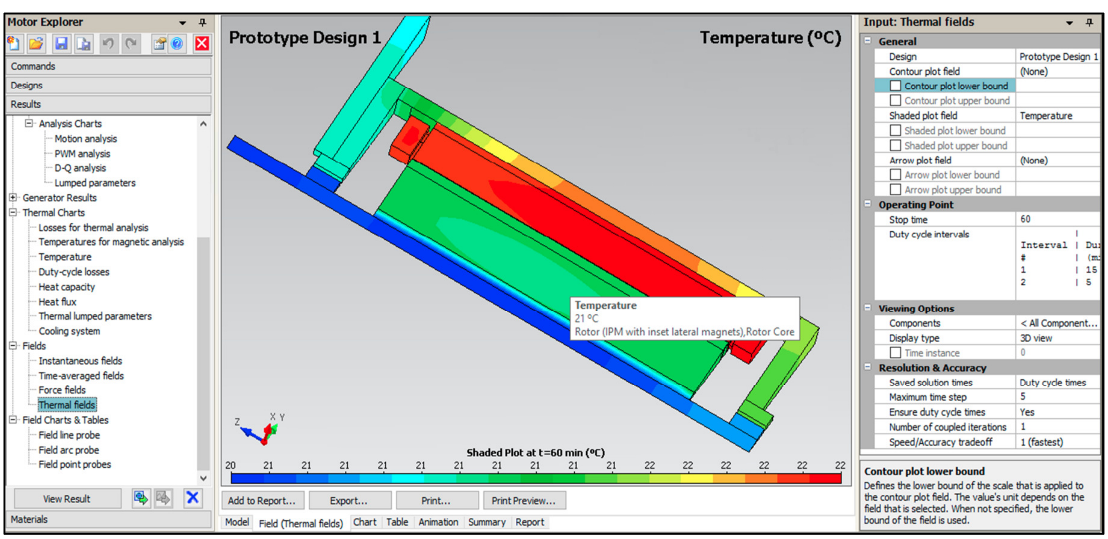


Figure 4.15 Thermal Field: Rotor

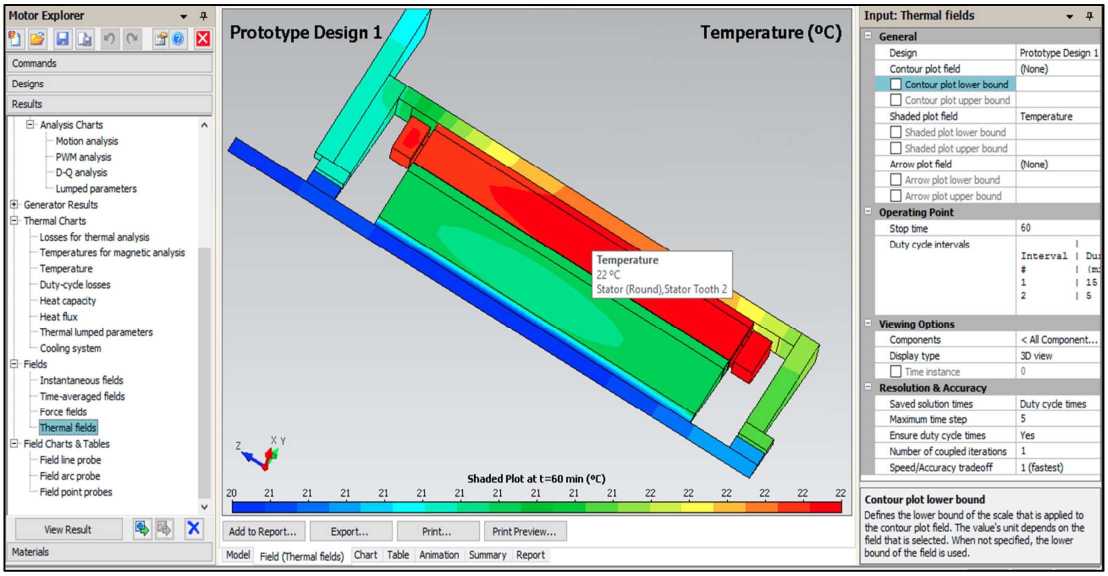


Figure 4.16 Thermal Field: Stator

In this chapter the basic prototype is generated by giving the basic raw data like voltage, no of phase etc. After giving the calculated dimensions for inner and outer diameter of rotor, giving dimensions for magnet as well as stator basic prototype is generated. Once the selection for the permanent magnet material is done the whole assembly is generated. On the generated model the analysis is performed. Various performance charts, analysis charts, efficiency and thermal field are plotted.

Under the head of performance charts various combinations are available for plotting but as per the research more emphasis is given on the torque characteristics as high torque is required at less speed for permanent magnet motor. Torque vs. speed and torque vs. phase angle is plotted that shows that the maximum torque of 60 - 65 N.m is available which is sufficient to lift the load of 100 kg.

Efficiency plot as shown in figure 4.9 shows a torque range of 0 to 60 N.m. with respect to speed up to 400 rpm. As per the efficiency map for the given range of torque at 120 RPM efficiency of 80-90% can be achieved.

Various analysis charts shows; pulse width modulation analysis as shown in figure 4.10, red color indicates torque ranges from 40-65 N.m. Figure 4.11 shows PWM Analysis with display method: Waveform; Result Quantity: Torque. That gives the torque range between 40 to 65 N.m. for phase angle starting from 0 to 360^0. Values available in the results are sufficient to lift the load of 100 kg hoist as per the requirement of EOT crane. Maximum torque given by PWM analysis is 60 N.m. for advance angle 0 to 90^0 as shown in figure 4.12. The given torque 60 N.m that is sufficient as per the research requirement.

As per the figure 4.13; Instantaneous fields are plotted for minimum and maximum peak line current percentage shows flux density of 0.0027 T on the rotor and 0.94T on stator. As per the guidelines for the electrical machines the range given for the flux density should not exceed from 1.2 T to 1.6 T. So the results which we are getting from the figure 4.13 and figure 4.14 is well within the limits and satisfied the guidelines for the electrical machines given by the volumetric international transactions on electrical energy systems.

Figure 4.16 and figure 4.17 indicated the values of 21^0 c temperature on the rotor and 22^0 c temperature on stator respectively. These values are well within the limits as per the NABL testing report of the motor.

So as per modeling and analysis done in Simcenter motorsolve the results of existing design is justified. And it can be proceed for the next phase of part selection and manufacturing of prototype of hoist.

CHAPTER – 5

Development of Hoist Operated by using PMDD and Experimentation

The design and analysis is done successfully for the PMDD. The next step is the part selection for the development of the PMDD hoist. Following are the parts selected for development of hoist. The development/manufacturing of hoist is done at Stalwart Cranes, bakrol, Ahmedabad.

5.1 Development of Hoist operated by using PMDD [102-105]

The designed and analyzed PMDD is used for the development of hoist. The other components of the hoist like brake, VFD, coupling, bearing, drum and rope are selected as per the requirement to lift the load of 100 kg and confirms with the same design of conventional hoist. The only change is in place of induction motor and gearbox here PMDD is implemented to give high torque at low speed. The detail specifications are given in table 5.1.

Table 5.1 Parts Specification

SN	Name of Component	Specification
1.	PMDD	"Pro-Syn" make, PMS Machine, volt 415, rated torque: 50 N.m., speed: 120 rpm, current: 2.5 amp.
2.	Brake	EMCO DC brake size 16, Torque : 100 N. m
3.	VFD	VFD 2A7 MS 43 A N S A A (MS-300, 3 PH)
4.	Drum diameter	100 mm (17 to 23 times wire rope diameter IS3377)
5.	Drum length	260 mm
6.	Rope	Diameter: 6 mm, 6 X 36 fibre core IS2266
7.	Coupling	Flexible coupling, size 4 inch, 30 mm thickness
8.	Bearing	P 25 TR SKF

Part 1- Permanent Magnet Direct Drive

"Pro-Syn" make, PMS Machine, volt 415, rated torque: 50 N.m., speed: 120 rpm, current: 2.5 amp.

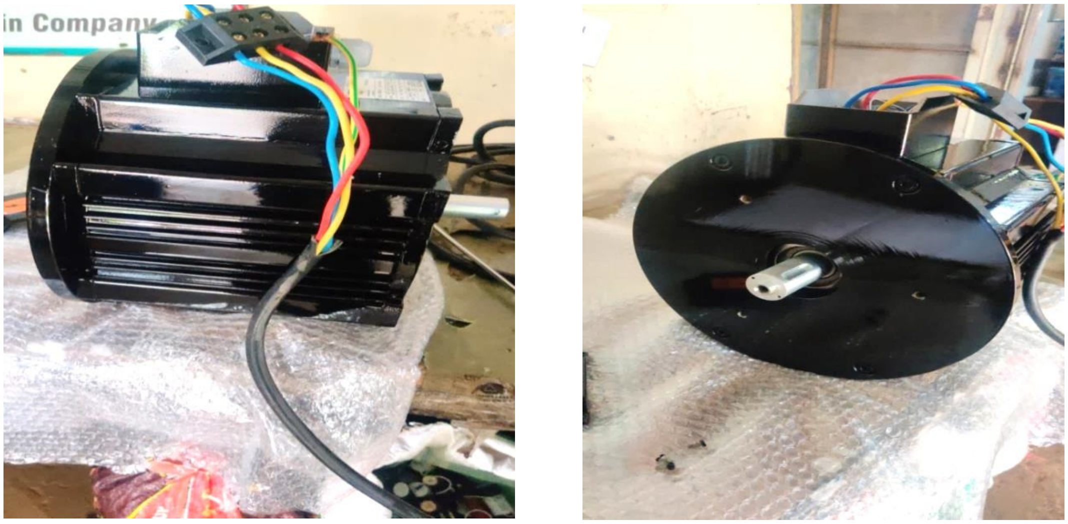


Figure 5.1 PMDD Motor with Back Extended Shaft to Accommodate Brake

Part – 2 Brake

EMCO DC Brake Size 16, Torque: 100 N. m

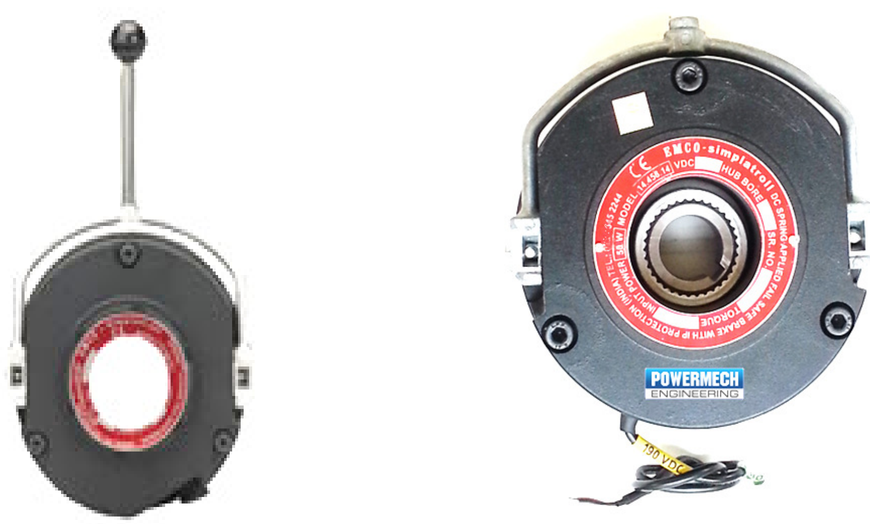


Figure 5.2 EMCO DC Brake

Part- 3 Variable Frequency Drive

VFD 2A7 MS 43 A N S A A (MS-300, 3 ph)

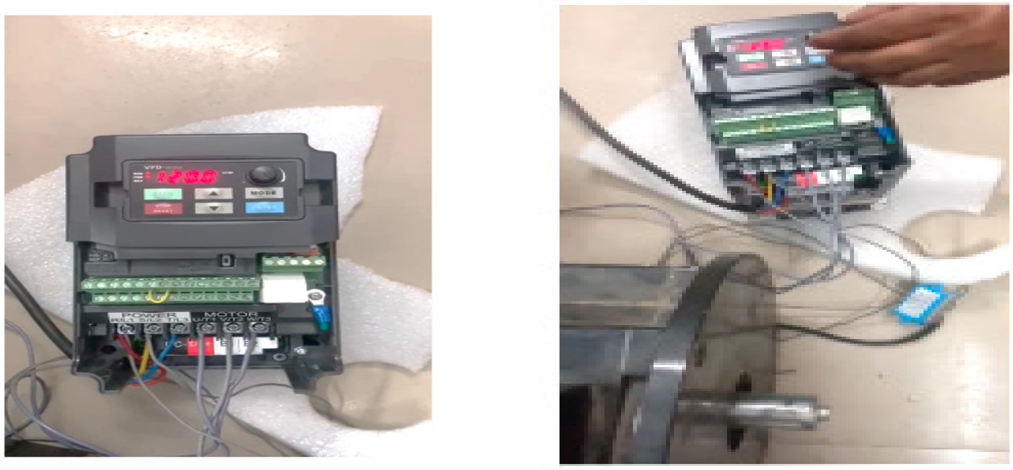


Figure 5.3 Variable Frequency Drive

Once the parts are selected as per the requirements of the PMDD hoist to lift the load of 100 kg assembly of the selected components are done. Figure 5.4 shows assembly of PMDD and brake.

Figure 5.4 Assembly of PMDD and Brake

A 3-D model of assembly of the prototype of PMDD hoist to lift the load of 100 kg is as shown in figure 5.5.

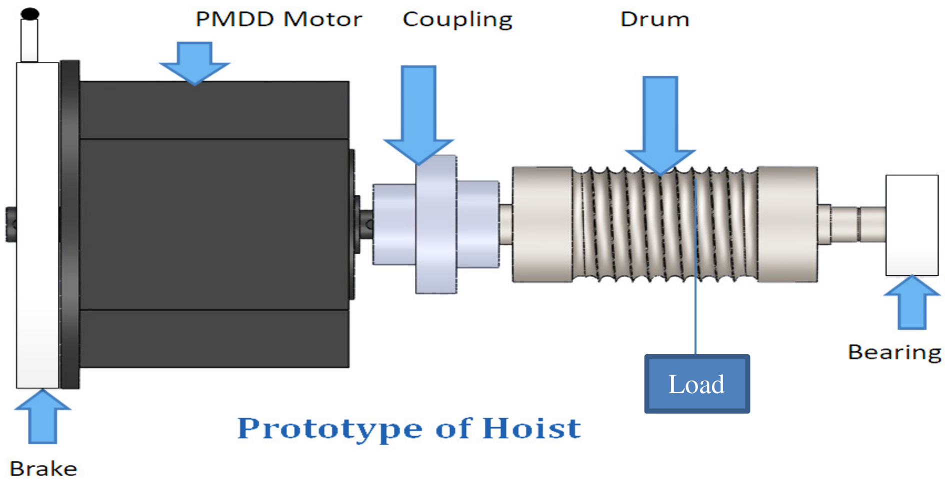


Figure 5.5 A 3-D Model of Assembly of the PMDD Hoist to Lift the Load of 100 kg

An assembly of hoist on the shop floor is shown in figure 5.6. which shows the assembly of PMDD-brake-VFD-grooved drum and bearing.

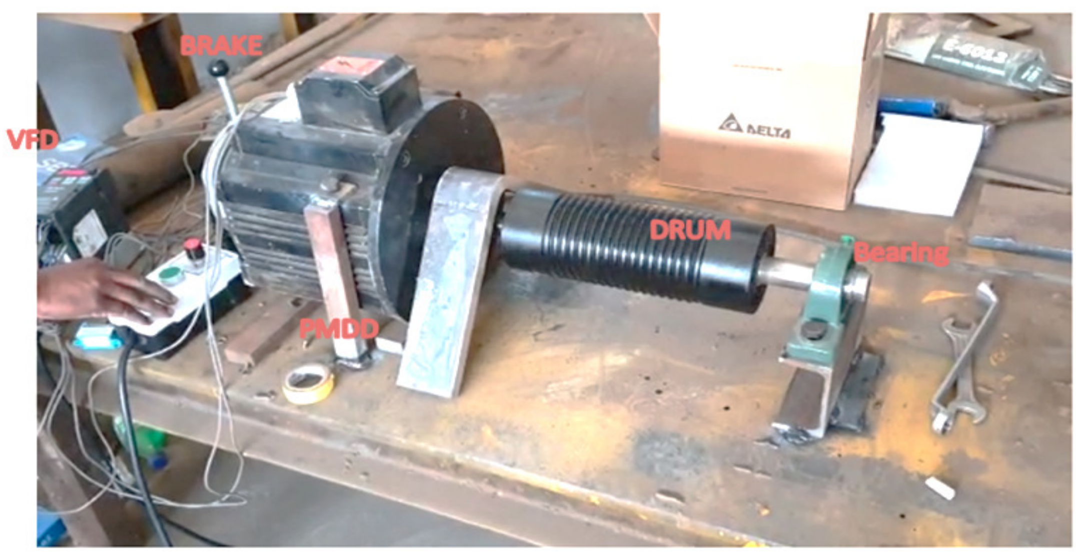


Figure 5.6 An Assembly of PMDD Hoist on Shop floor
(PMDD- Brake-VFD- Grooved Drum- Bearing)

The assembled hoist is mounted at the height of 2 m initially as shown in figure 5.7 (a). To carry out the set of experiments for variable parameters the hoist is again mounted at the height of 4 m as shown in figure 5.7 (b).

Figure 5.7 (a) PMDD Hoist at 2m Height **Figure 5.7 (b) PMDD Hoist at 4 m Height**

Figure 5.7 Mounting of Hoist at 2 m and 4 m Height

5.2 Parameters Affecting the Performance of EOT Crane [106,111-116]

The main parameters affecting the performance of hoist for the EOT crane includes overhead crane capacity - load (kg), lifting torque - T (N.m), overhead crane lifting height- h (m), overhead crane working speed- N (rpm), time required to lift and lower the load- t (sec) [106,111-116]. The details of the same are as explained in the table 5.2. Maximum torque given by the developed PMDD hoist is up to 65 N.m. and which will vary depending upon the load capacity and speed. So for the various combinations of the rest of the parameters like lifting capacity, working speed and lifting height are considered for the experimentation to be done on PMDD hoist and the time taken to lift (T_{LF}) and time required lower (T_{LW}) the load is measured. The measured lifting time of PMDD hoist (T_{LFP}) is compared with lifting time of conventional hoist (T_{LFC}) and lowering time of PMDD hoist (T_{LWP}) is compared with lowering time of conventional hoist (T_{LWC}) with gearbox.

Table 5.2 Parameters Affecting the Performance of EOT Crane [106,111-116]

SN	Parameters	Details
1	Overhead crane capacity - load (kg).	It refers to the maximum load carrying capacity; which crane can lift.
2	Lifting torque- T (N.m.)	The lifting weight of the crane multiplied by the corresponding amplitude equals the lifting moment. It is a crane's total lifting capacity parameter, which can accurately and completely represent a crane's lifting capacity.
3	Lifting height of overhead crane - h (m)	The lifting height is the height measured from the ground to the hook's center, and the rated lifting height is typically used to express the calibration value of the hook's parameters.
4	Working speed of overhead crane -N (rpm)	The crane's lifting speed is part of its working speed. The hoisting mechanism's lifting speed and the crane's lifting speed are correlated.
5	Time- t (sec)	The time required to lift and lower the load.

5.3 Experimentation on PMDD Hoist to Test and Analyze the Performance [102-105]

For testing and analyzing the performance of the developed PMDD hoist the important parameters affecting the performance of the EOT crane are studied and explained above. For the different combinations of lifting capacity, working speed and lifting height approximate 300 nos. of readings are taken on the developed PMDD hoist. The variations taken for lifting capacity ranges between 10-100 kg at the interval of 10 kg. The variation for working speed ranges from 10-50 rpm at the interval of 10 rpm and the lifting height varied from 2-4 m at the interval of 1 m. The lifting time (T_{LF}) and lowering time (T_{LW}) is measured for all of the above combinations and comparison is done between developed PMDD hoist and conventional hoist to check the feasibility and implementation of the developed hoist.

Table 5.3 Experiment Reading Matrix for Performance Analysis

Parameters	Lifting Time T_{LF} (sec) & Lowering Time T_{LW} (sec)	Lifting capacity (kg)	Working speed (rpm)	Lifting height (m)	Total No. of Readings
Readings	Lifting Time for conventional Hoist : T_{LFC} Lowering Time for conventional Hoist : T_{LwC} Lifting time for PMDD hoist : T_{LFP} Lowering Time for PMDD hoist : T_{LWP}	10-100 at an interval of 10 kg	10,20,30, 40,50	2,3,4	150 for conven-tional hoist
		10-100 at an interval of 10 kg	10,20,30, 40,50	2,3,4	150 For PMDD hoist
Number of readings for different Lifting capacity (kg), Working speed (rpm) and Lifting height (m) for (i) Conventional and (ii) PMDD hoist.					Total No. Readings : 300

5.3.1 Experimental Readings: Speed at 10 rpm; Height at 2 m

Table 5.4 Experimental Readings: Speed at 10 rpm; Height at 2 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
10	2	10	5.55	5.50	5.60	5.59
10	2	20	5.70	5.69	5.62	5.60
10	2	30	5.48	5.47	5.50	5.51
10	2	40	5.80	5.81	5.77	5.70
10	2	50	5.90	5.92	5.87	5.80
10	2	60	5.92	5.91	5.89	5.85
10	2	70	5.97	5.95	5.94	5.91
10	2	80	6.15	5.96	6.11	6.10
10	2	90	5.00	6.00	4.97	5.97
10	2	100	6.10	6.10	6.01	6.01

The above table shows the experimental readings at the speed of 10 rpm and height of 2 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.8 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

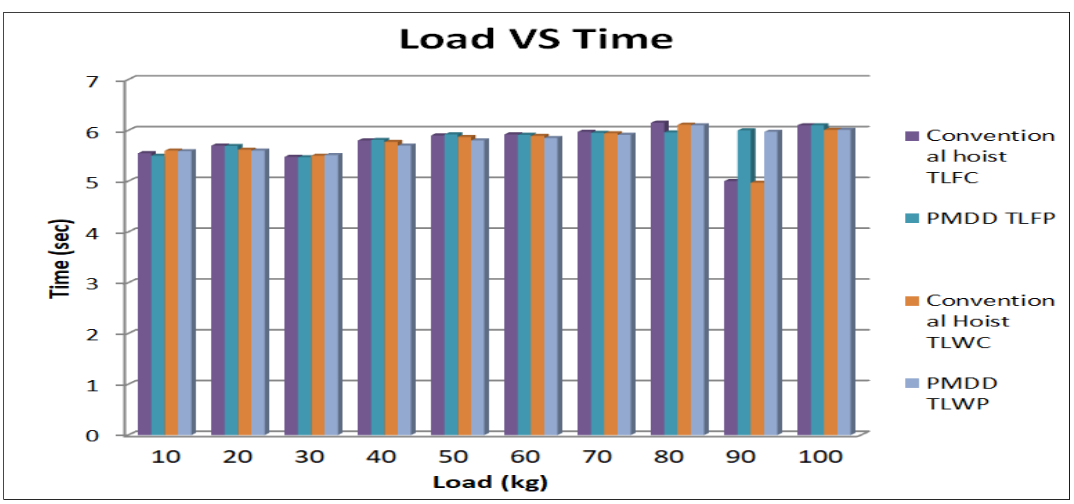


Figure 5.8 Graphical representations of readings: Speed at 10 rpm; Height at 2 m

5.3.2 Experimental Readings: Speed at 20 rpm ;Height at 2 m

Table 5.5 Experimental Readings: Speed at 20 rpm; Height at 2 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
20	2	10	4.70	4.61	4.70	4.60
20	2	20	4.58	4.56	4.60	4.60
20	2	30	4.75	4.55	4.67	4.61
20	2	40	4.61	4.60	4.58	4.55
20	2	50	4.70	4.65	4.67	4.65
20	2	60	4.81	4.70	4.85	4.80
20	2	70	5.31	5.51	5.29	5.20
20	2	80	5.05	5.45	5.00	5.01
20	2	90	4.70	4.90	4.66	4.65
20	2	100	4.95	4.85	4.91	4.90

The above table shows the experimental readings at the speed of 20 rpm and height of 2 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.9 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

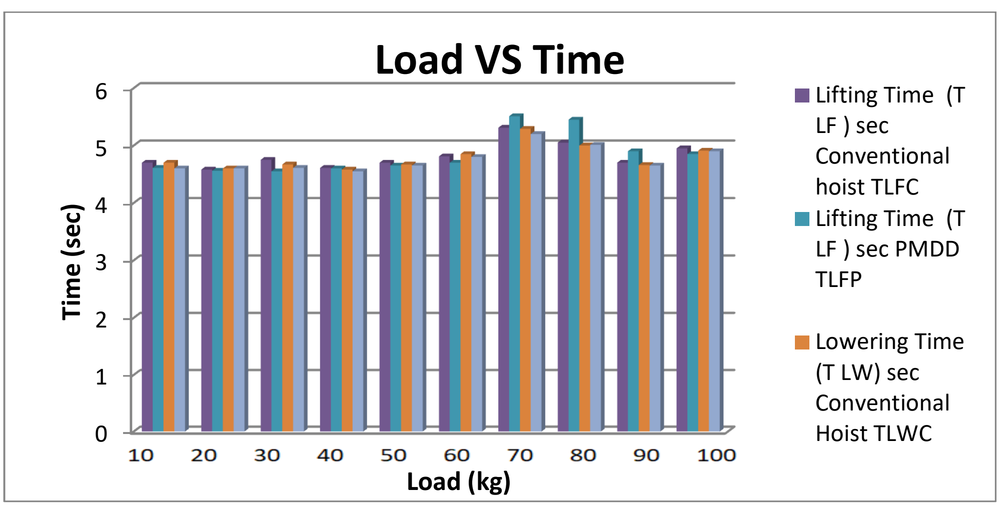


Figure: 5.9 Graphical representations of readings: Speed at 20 rpm; Height at 2 m

5.3.3 Experimental Readings: Speed at 30 rpm; Height at 2 m

Table 5.6 Experimental Readings: Speed at 30 rpm; Height at 2 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
30	2	10	4.07	4.05	4.10	4.09
30	2	20	3.87	3.80	3.84	3.82
30	2	30	4.35	4.32	4.31	4.30
30	2	40	4.25	4.20	4.23	4.21
30	2	50	4.20	4.18	4.17	4.18
30	2	60	4.30	4.16	4.27	4.25
30	2	70	4.25	4.20	4.21	4.20
30	2	80	4.13	4.15	4.15	4.12
30	2	90	4.60	4.51	4.57	4.52
30	2	100	4.62	4.61	4.58	4.56

The above table shows the experimental readings at the speed of 30 rpm and height of 2 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.10 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

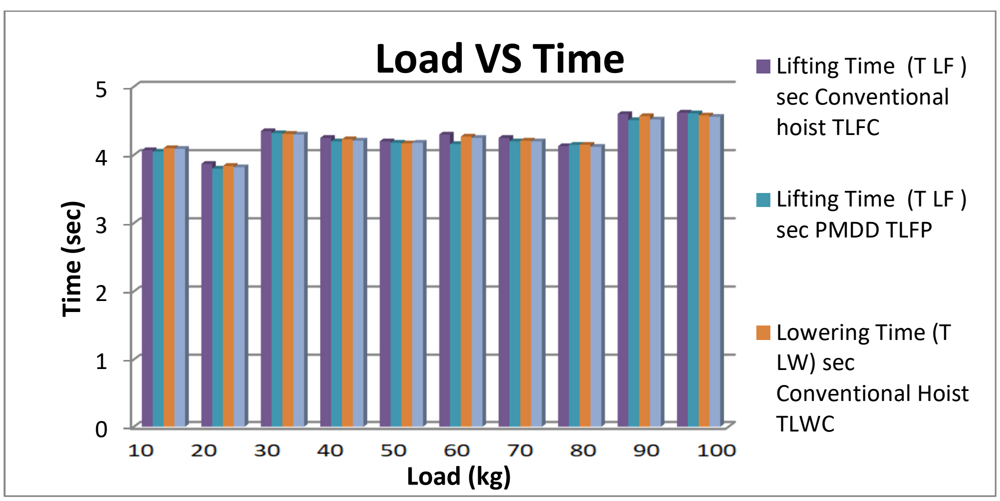


Figure: 5.10 Graphical representations of readings: Speed at 30 rpm; Height at 2 m

5.3.4 Experimental Readings: Speed at 40 rpm; Height at 2 m

Table 5.7 Experimental Readings: Speed at 40 rpm; Height at 2 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
40	2	10	3.60	3.55	3.58	3.57
40	2	20	3.60	3.58	3.61	3.60
40	2	30	3.55	3.55	3.49	3.45
40	2	40	3.58	3.52	3.60	3.61
40	2	50	4.00	4.02	3.97	3.90
40	2	60	3.78	3.76	3.74	3.73
40	2	70	3.65	3.66	3.62	3.60
40	2	80	3.84	3.69	3.81	3.80
40	2	90	3.70	3.70	3.67	3.65
40	2	100	3.55	3.55	3.51	3.50

The above table shows the experimental readings at the speed of 40 rpm and height of 2 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.11 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

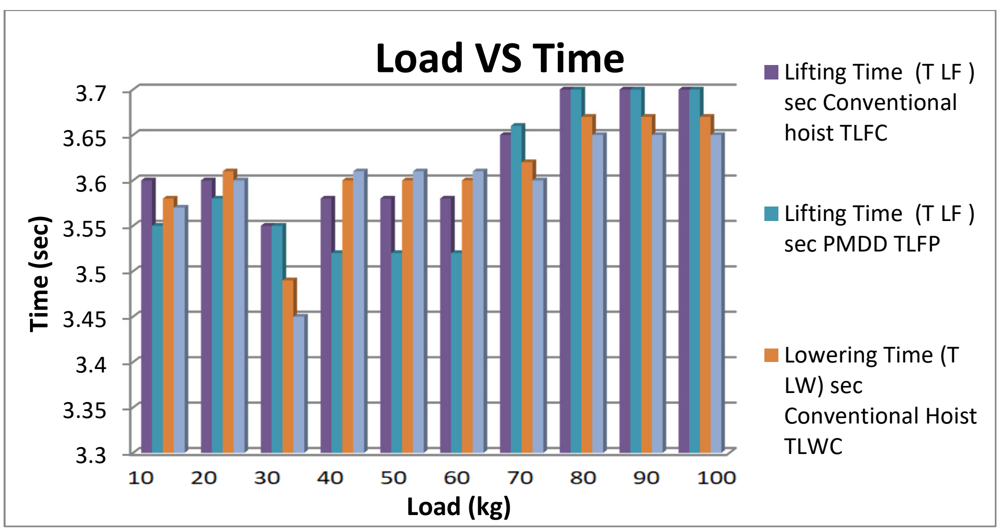


Figure: 5.11 Graphical representations of readings: Speed at 40 rpm; Height at 2 m

5.3.5 Experimental Readings: Speed at 50 rpm; Height at 2 m

Table 5.8 Experimental Readings: Speed at 50 rpm; Height at 2 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
50	2	10	3.25	3.23	3.22	3.21
50	2	20	3.28	3.25	3.25	3.23
50	2	30	3.50	3.51	3.47	3.47
50	2	40	3.50	3.53	3.48	3.49
50	2	50	3.52	3.51	3.50	3.51
50	2	60	3.40	3.42	3.38	3.36
50	2	70	3.37	3.35	3.34	3.33
50	2	80	3.62	3.39	3.65	3.64
50	2	90	3.40	3.41	3.38	3.36
50	2	100	3.17	3.15	3.05	3.05

The above table shows the experimental readings at the speed of 50 rpm and height of 2 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.12 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

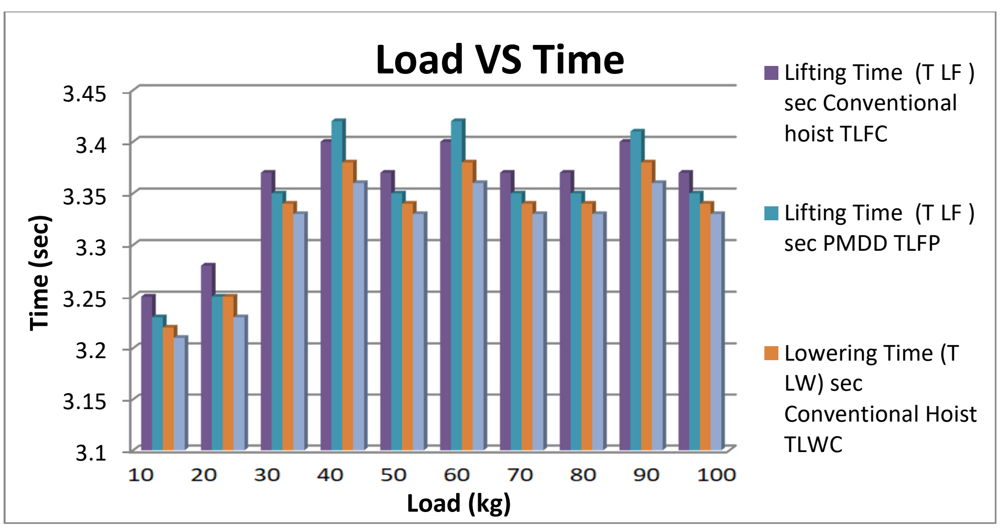


Figure: 5.12 Graphical representations of readings: Speed at 50 rpm; Height at 2 m

5.3.6 Experimental Readings: Speed at 10 rpm; Height at 3 m

Table 5.9 Experimental Readings: Speed at 10 rpm; Height at 3 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
10	3	10	7.80	7.81	7.79	7.78
10	3	20	7.70	7.71	7.67	7.67
10	3	30	7.53	7.52	7.50	7.49
10	3	40	7.90	7.94	7.88	7.85
10	3	50	7.75	7.71	7.60	7.55
10	3	60	7.54	7.51	7.50	7.45
10	3	70	7.35	7.31	7.20	7.22
10	3	80	7.28	7.24	7.19	7.18
10	3	90	7.17	7.15	7.24	7.23
10	3	100	7.20	7.23	7.35	7.32

The above table shows the experimental readings at the speed of 10 rpm and height of 3 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.13 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

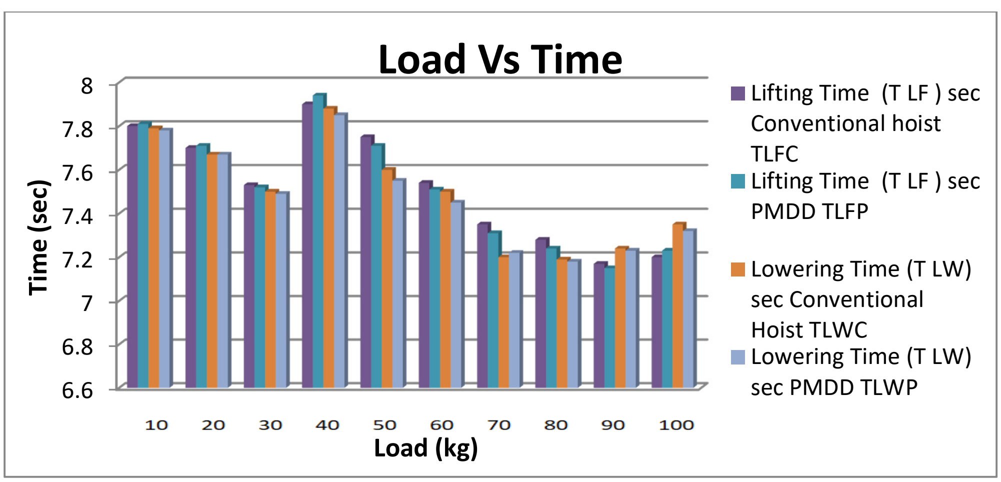


Figure: 5.13 Graphical representations of readings: Speed at 10 rpm; Height at 3 m

5.3.7 Experimental Readings: Speed at 20 rpm ; Height at 3 m

Table 5.10 Experimental Readings: Speed at 20 rpm; Height at 3 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
20	3	10	6.55	6.53	6.51	6.5
20	3	20	6.15	6.13	6.17	6.15
20	3	30	6.38	6.3	6.4	6.43
20	3	40	6.72	6.75	6.7	6.72
20	3	50	6.35	6.32	6.33	6.35
20	3	60	6.3	6.31	6.2	6.23
20	3	70	6.1	6.15	6.08	6.04
20	3	80	5.9	5.92	5.85	5.84
20	3	90	5.85	5.81	5.78	5.73
20	3	100	5.95	5.96	5.85	5.83

The above table shows the experimental readings at the speed of 20 rpm and height of 3 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.14 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

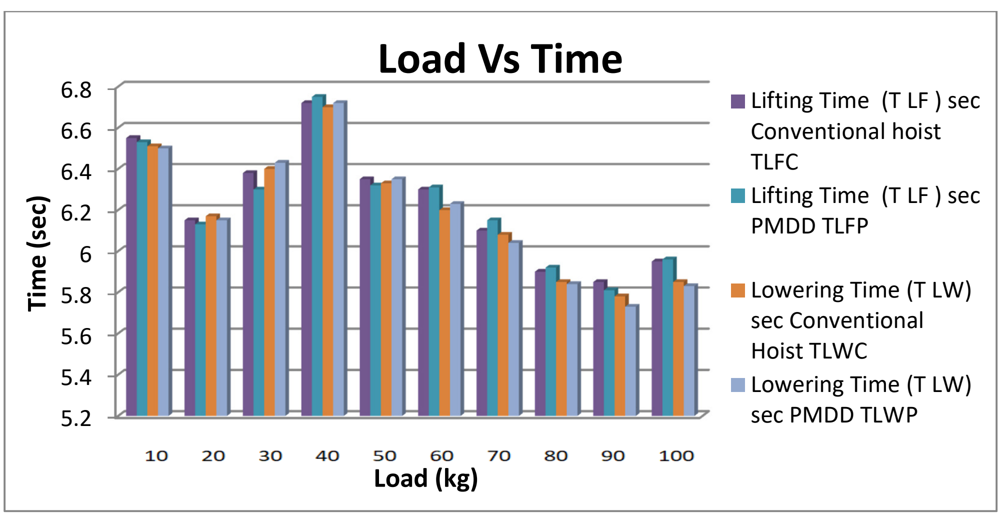


Figure: 5.14 Graphical representations of readings: Speed at 20 rpm; Height at 3 m

5.3.8 Experimental Readings: Speed at 30 rpm ; Height at 3 m

Table 5.11 Experimental Readings: Speed at 30 rpm; Height at 3 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
30	3	10	5.48	5.45	5.50	5.49
30	3	20	5.45	5.42	5.38	5.35
30	3	30	6.60	5.50	6.58	6.59
30	3	40	5.32	5.33	5.32	5.33
30	3	50	5.65	5.63	5.70	5.71
30	3	60	5.15	5.13	5.10	5.11
30	3	70	5.37	5.35	5.33	5.32
30	3	80	4.75	4.78	4.70	4.69
30	3	90	5.40	5.46	5.38	5.37
30	3	100	5.35	5.36	5.48	5.47

The above table shows the experimental readings at the speed of 30 rpm and height of 3 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.15 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

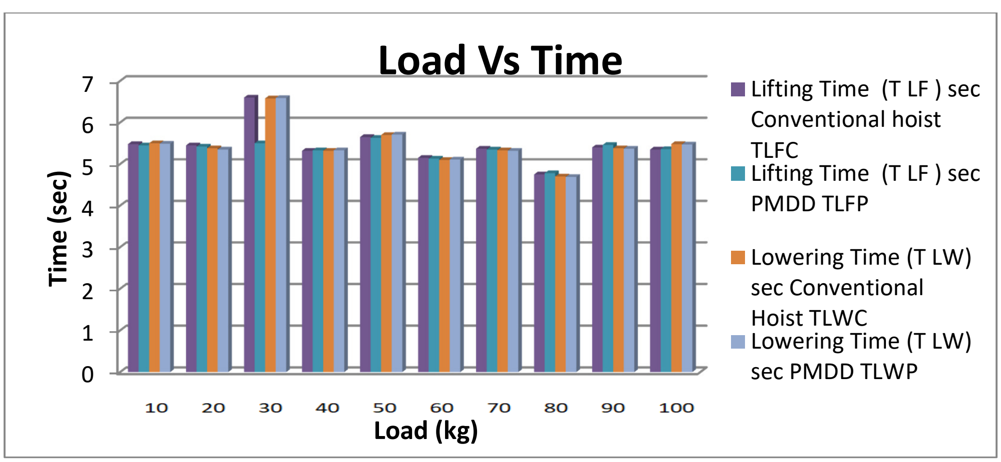


Figure: 5.15 Graphical representations of readings: Speed at 30 rpm; Height at 3 m

5.3.9 Experimental Readings: Speed at 40 rpm ; Height at 3 m

Table 5.12 Experimental Readings: Speed at 40 rpm; Height at 3 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
40	3	10	4.85	4.80	4.73	4.74
40	3	20	5.00	5.01	5.01	5.03
40	3	30	5.54	5.51	5.50	5.49
40	3	40	4.81	4.82	4.78	4.79
40	3	50	4.91	4.92	4.80	4.82
40	3	60	5.20	5.19	4.85	4.83
40	3	70	4.90	4.91	4.70	4.72
40	3	80	4.25	4.24	4.20	4.21
40	3	90	4.80	4.81	4.76	4.71
40	3	100	4.75	4.75	4.70	4.74

The above table shows the experimental readings at the speed of 40 rpm and height of 3 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.16 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

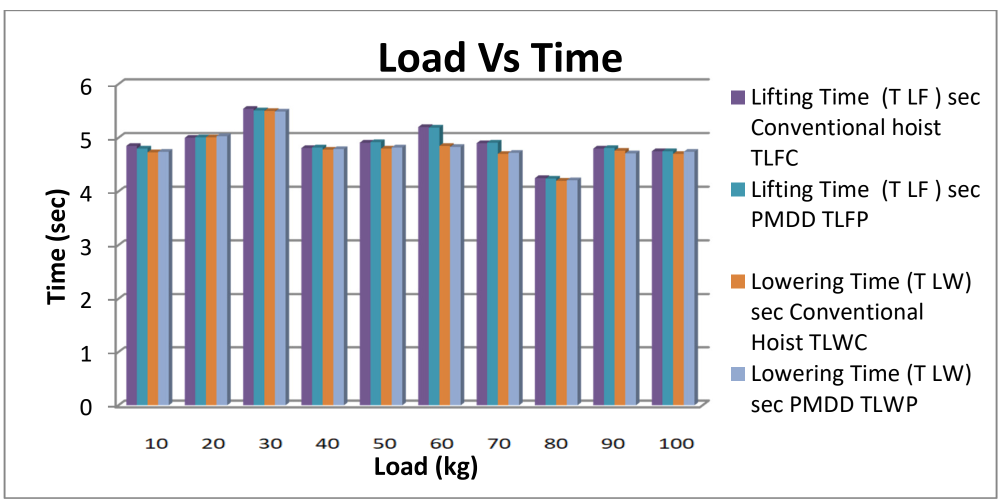


Figure: 5.16 Graphical representations of readings: Speed at 40 rpm; Height at 3 m

5.3.10 Experimental Readings: Speed at 50 rpm ; Height at 3 m

Table 5.13 Experimental Readings: Speed at 50 rpm; Height at 3 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
50	3	10	4.30	4.31	4.28	4.25
50	3	20	4.70	4.69	4.67	4.66
50	3	30	5.20	5.22	5.18	5.17
50	3	40	4.91	4.93	4.80	4.79
50	3	50	4.85	4.82	4.77	4.78
50	3	60	4.40	4.41	4.80	4.80
50	3	70	4.28	4.24	4.43	4.50
50	3	80	4.15	4.16	4.12	4..26
50	3	90	4.32	4.38	4.30	4.31
50	3	100	4.35	4.39	3.45	3.44

The above table shows the experimental readings at the speed of 50 rpm and height of 3 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.17 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

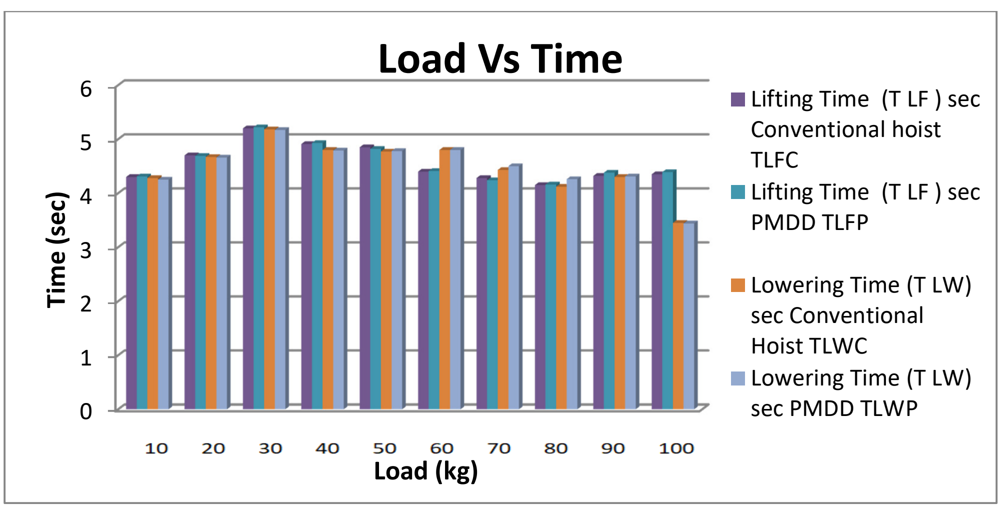


Figure: 5.17 Graphical representations of readings: Speed at 50 rpm; Height at 3 m

5.3.11 Experimental Readings: Speed at 10 rpm ; Height at 4 m

Table 5.14 Experimental Readings: Speed at 10 rpm; Height at 4 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T LF) sec		Lowering Time (T LW) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
10	4	10	10.90	10.10	9.38	9.37
10	4	20	8.40	8.39	8.50	8.51
10	4	30	10.40	10.40	10.40	10.40
10	4	40	10.50	10.50	10.40	10.40
10	4	50	10.40	10.40	10.30	10.20
10	4	60	10.50	10.50	10.10	10.20
10	4	70	10.90	10.90	10.40	10.40
10	4	80	11.00	10.90	10.50	10.50
10	4	90	7.90	8.91	7.75	8.01
10	4	100	9.10	9.12	8.90	8.80

The above table shows the experimental readings at the speed of 10 rpm and height of 4 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.18 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

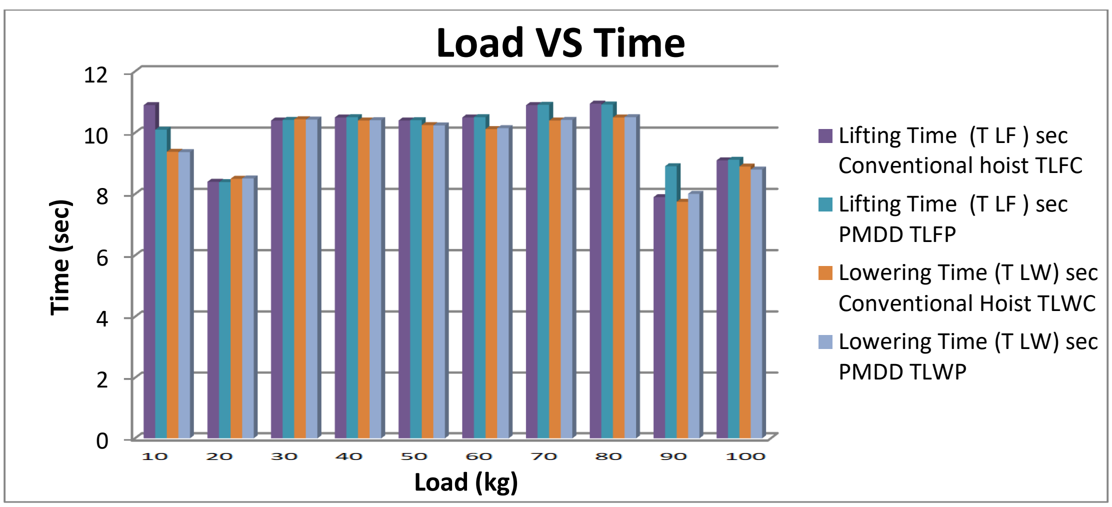


Figure: 5.18 Graphical representations of readings: Speed at 10 rpm; Height at 4 m

5.3.12 Experimental Readings: Speed at 20 rpm ; Height at 4 m

Table 5.15 Experimental Readings: Speed at 20 rpm; Height at 4 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
20	4	10	8.70	8.72	8.50	8.45
20	4	20	8.40	8.35	8.50	8.56
20	4	30	8.65	8.50	8.70	8.66
20	4	40	8.80	8.60	8.60	8.61
20	4	50	9.04	9.10	8.80	8.80
20	4	60	9.20	9.21	9.11	8.80
20	4	70	9.20	9.19	8.70	8.71
20	4	80	9.30	9.21	8.85	8.82
20	4	90	8.30	8.50	7.90	7.93
20	4	100	7.75	7.50	7.65	7.75

The above table shows the experimental readings at the speed of 20 rpm and height of 4 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.19 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

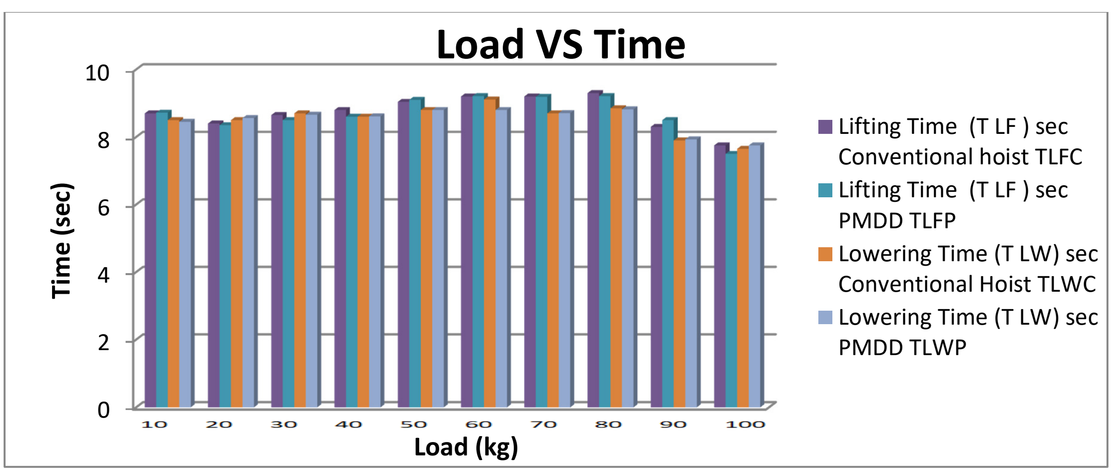


Figure: 5.19 Graphical representations of readings: Speed at 20 rpm; Height at 4 m

5.3.13 Experimental Readings: Speed at 30 rpm; Height at 4 m

Table 5.16 Experimental Readings: Speed at 30 rpm; Height at 4 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
30	4	10	7.43	7.40	7.80	7.80
30	4	20	7.50	7.48	7.30	7.30
30	4	30	7.50	7.51	7.35	7.35
30	4	40	7.40	7.45	7.40	7.40
30	4	50	7.45	7.43	7.30	7.30
30	4	60	7.25	7.22	7.09	7.15
30	4	70	7.70	7.52	7.37	7.35
30	4	80	7.90	7.21	7.45	7.40
30	4	90	6.60	7.12	6.10	7.10
30	4	100	7.30	7.10	7.18	7.15

The above table shows the experimental readings at the speed of 30 rpm and height of 4 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.20 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

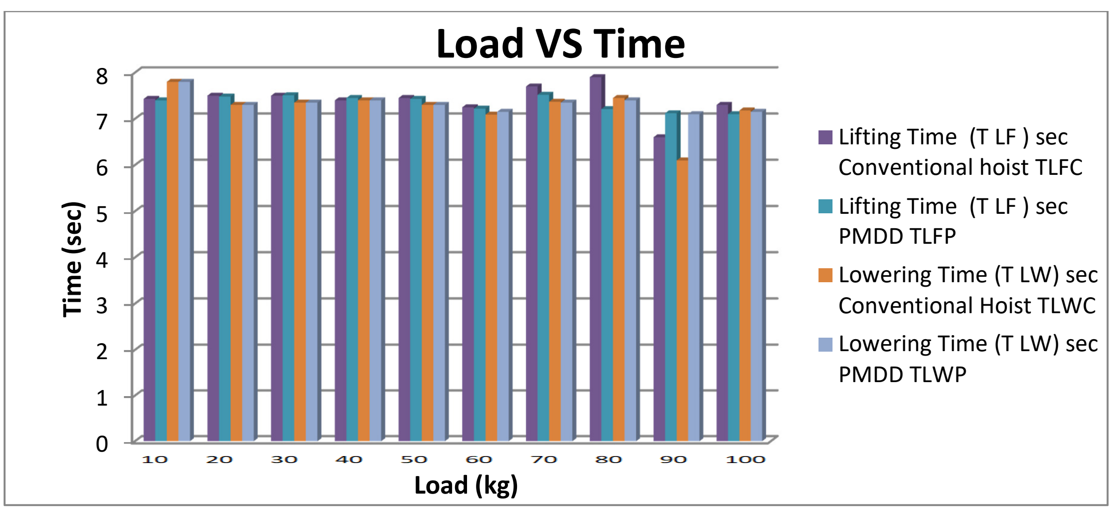


Figure: 5.20 Graphical representations of readings: Speed at 30 rpm; Height at 4 m

5.3.14 Experimental Readings: Speed at 40 rpm; Height at 4 m

Table 5.17 Experimental Readings: Speed at 40 rpm; Height at 4 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
40	4	10	6.68	6.69	6.40	6.42
40	4	20	6.30	6.32	6.50	6.51
40	4	30	6.25	6.24	6.20	6.23
40	4	40	6.70	6.69	6.55	6.50
40	4	50	6.60	6.62	6.50	6.52
40	4	60	6.50	6.55	6.35	6.33
40	4	70	6.40	6.44	6.30	6.31
40	4	80	6.75	6.73	6.55	6.21
40	4	90	6.00	6.01	5.90	5.91
40	4	100	6.45	6.43	5.40	5.44

The above table shows the experimental readings at the speed of 40 rpm and height of 4 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.21 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

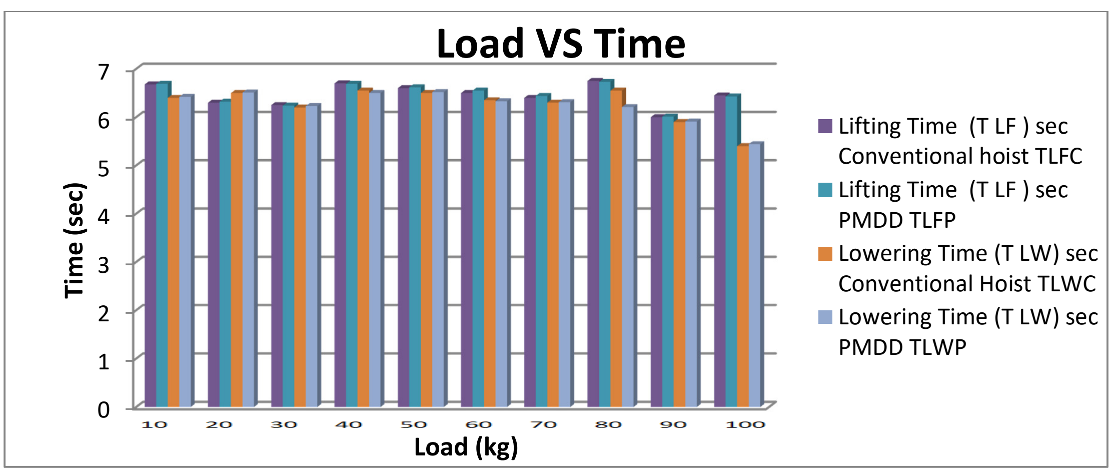


Figure: 5.21 Graphical representations of readings: Speed at 40 rpm; Height at 4 m

5.3.15 Experimental Readings: Speed at 50 rpm ; Height at 4 m

Table 5.18 Experimental Readings: Speed at 50 rpm; Height at 4 m

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Lifting Time (T_{LF}) sec		Lowering Time (T_{LW}) sec	
			Conventional hoist (T_{LFC})	PMDD (T_{LFP})	Conventional hoist (T_{LWC})	PMDD (T_{LWP})
50	4	10	5.75	5.74	5.30	5.60
50	4	20	5.55	5.54	5.40	5.45
50	4	30	5.90	5.44	5.75	5.40
50	4	40	5.30	5.32	5.90	5.20
50	4	50	5.90	5.40	5.75	5.30
50	4	60	5.45	5.49	5,25	5.30
50	4	70	6.20	6.16	5.88	5.70
50	4	80	6.75	6.71	6.55	6.65
50	4	90	5.80	5.85	5.70	5.75
50	4	100	5.30	5.60	5.15	5.25

The above table shows the experimental readings at the speed of 50 rpm and height of 4 meter which is constant for all the readings taken for the load ranges from 10 – 100 kg. The lifting time and lowering time for conventional hoist and PMDD hoist is compared. From the figure 5.22 it is clear that the designed PMDD hoist is able to almost same results as of conventional hoist without compromising the function of EOT crane.

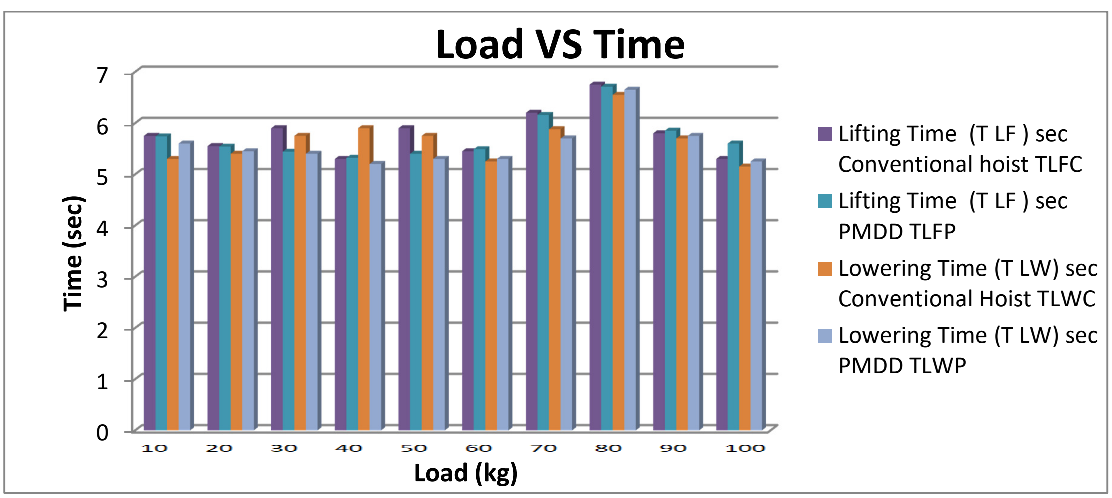


Figure: 5.22 Graphical representations of readings: Speed at 50 rpm; Height at 4 m

5.4 Vibration Measurement

Rokade vibration analyzer and balancer (VAB100) is used for vibration analysis. With the help of vibration analyzer readings for displacement (mm), velocity (m/sec) and acceleration (m/sec^2) are taken for conventional hoist and PMDD hoist and compared to analyze the performance of PMDD hoist for implementation in EOT crane. The displacement for conventional hoist (d_c) is compared with the displacement of PMDD hoist (d_p), the velocity for conventional hoist (v_c) is compared with the velocity of PMDD hoist (v_p) and the acceleration for conventional hoist (a_c) is compared with the acceleration of PMDD hoist (a_p).

5.4.1 Experiment Reading Matrix for Vibration Measurement

The variations taken for the velocity displacement and accelerations are; lifting capacity varied between 10-100 kg at the interval of 10 kg, working speed varied from 10-50 rpm at the interval of 10 rpm and the lifting height varied from 2-4 m at the interval of 1m. Comparison of displacement, velocity and acceleration is done between conventional hoist and PMDD hoist to check the performance of developed PMDD hoist. In table 5.19 the experimental reading matrix is shown and approximate 300 readings are taken for conventional hoist and PMDD hoist. Few sample readings are shown in table 5.20, 5.21 and 5.22 for the analysis purpose.

Table 5.19 Experiment Reading Matrix for Vibration Measurement

Parameters	Displacement (mm), Velocity (mm/sec) and Acceleration (mm/sec^2)	Lifting capacity (kg)	Working speed (rpm)	Lifting height (m)	Total No. of readings
Displace-ment (mm), Velocity (mm/sec) and Acceleration (mm/sec^2)	Displacement for conventional hoist : d_c Displacement for PMDD hoist: d_p Velocity for conventional hoist: v_c Velocity for PMDD hoist: v_p Acceleration for conventional hoist : a_c Acceleration for PMDD hoist: a_p	10-100 at an interval of 10 kg	10,20, 30,40, 50.	2,3,4	150 for conven-tional hoist
		10-100 at an interval of 10 kg	10,20, 30,40, 50.	2,3,4	150 for PMDD hoist
Number of readings for different Lifting capacity (kg), Workings speed (rpm) and Lifting height (m) for (i) Conventional and (ii) PMDD hoist.					Total readings :300

5.4.2 Experiment Readings: at 20 rpm, 2-3-4 m & 20-60-100 kg

Table 5.20 Experiment Readings: at 20 rpm, 2-3-4 m & 20-60-100 kg

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Acceleration (mm/sec^2)		Velocity (mm/sec)		Displacement (mm)	
			Conven-tional (a_c)	PMDD (a_p)	Conven-tional (v_c)	PMDD (v_p)	Conven-tional (d_c)	PMDD (d_p)
20	2	20	3.5	0.5	3.4	0.4	3.5	0.5
20	3	20	3.5	0.5	3.4	0.3	3.5	0.5
20	4	20	3.5	0.5	3.4	0.4	3.5	0.5
20	2	60	3.3	0.3	3.3	0.3	3.5	0.5
20	3	60	3.3	0.3	3.3	0.2	3.5	0.3
20	4	60	3.3	0.3	3.3	0.3	3.5	0.5
20	2	100	3.4	0.4	3.2	0.2	3.5	0.5
20	3	100	3.4	0.3	3.2	0.1	3.5	0.4
20	4	100	3.5	0.4	3.1	0.2	3.8	0.5

The readings for the displacement, velocity and acceleration is taken for the load ranges from 10-100 kg, height 2-3-4 meter and speed 10-50 RPM for the conventional crane as well as PMDD hoist. More than 300 readings are taken for vibration measurement. But only few sample readings covering the complete range is shown in table 5.20, 5.21 and 5.22. The above table shows the experimental readings at the speed at 20 rpm and height of 2- 3- 4 meter for the load ranges from 20 - 60 - 100 kg. The displacement, velocity and acceleration are compared for conventional hoist and PMDD hoist. From the values given in the above table it is clear that the designed PMDD hoist gives less vibration as compare to conventional hoist.

5.4.3 Experiment Readings: at 40 rpm, 2-3-4 m & 20-60-100 kg

The table 5.21 shows the experimental readings at the speed at 40 rpm and height of 2- 3- 4 meter for the load ranges from 20 - 60- 100 kg. The displacement, velocity and acceleration are compared for conventional hoist and PMDD hoist. From the values given in the above table it is clear that the designed PMDD hoist gives less vibration as compare to conventional hoist.

Table 5.21 Experiment Readings: at 40 rpm, 2-3-4 m & 20-60-100 kg

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Acceleration (mm/sec^2)		Velocity (mm/sec)		Displacement (mm)	
			Conventional (a_c)	PMDD (a_p)	Conventional (v_c)	PMDD (v_p)	Conventional (d_c)	PMDD (d_p)
40	2	20	3.5	0.5	3.3	0.3	3.5	0.5
40	3	20	3.5	0.4	3.4	0.5	3.5	0.4
40	4	20	3.3	0.5	3.2	0.3	3.8	0.5
40	2	60	3.3	0.3	3.2	0.2	3.3	0.3
40	3	60	3.3	0.2	3.3	0.3	3.5	0.2
40	4	60	3.1	0.3	3.2	0.2	3.4	0.3
40	2	100	3.3	0.3	3.1	0.1	3.4	0.4
40	3	100	3.4	0.5	3.2	0.3	3.5	0.5
40	4	100	3.8	0.3	3.1	0.1	3.8	0.4

5.4.4 Experiment Readings: at 50 rpm, 2-3-4 m & 20-60-100 kg

Table 5.22 Experiment Readings: at 50 rpm, 2-3-4 m & 20-60-100 kg

Working speed (rpm)	Lifting height (m)	Lifting capacity (kg)	Acceleration (mm/sec^2)		Velocity (mm/sec)		Displacement (mm)	
			Conven-tional(ac)	PMDD (ap)	Conven-tional (vc)	PMDD (v_p)	Conven-tional (d_c)	PMDD (d_p)
50	2	20	3.5	0.4	3.4	0.3	3.5	0.3
50	3	20	3.5	0.5	3.3	0.3	3.5	0.5
50	4	20	3.5	0.5	3.3	0.3	3.5	0.5
50	2	60	3.3	0.2	3.3	0.2	3.5	0.2
50	3	60	3.3	0.3	3.2	0.2	3.3	0.3
50	4	60	3.3	0.3	3.2	0.2	3.3	0.3
50	2	100	3.4	0.5	3.2	0.2	3.5	0.1
50	3	100	3.3	0.3	3.1	0.1	3.4	0.4
50	4	100	3.3	0.3	3.1	0.1	3.4	0.4

Few sample readings are shown in above tables to understand the performance and characteristics of displacement, velocity and accelerations. The table 5.22 shows the experimental readings at the speed at 40 rpm and height of 2- 3- 4 meter for the load ranges from 20 – 60- 100 kg. The displacement, velocity and acceleration are compared for conventional hoist and PMDD hoist. From the values given in the above table it is clear that the designed PMDD hoist gives less vibration as compare to conventional hoist.

CHAPTER – 6

Results Analysis and Discussions

To analyze the performance of developed hoist, factors affecting the performance of the hoist are studied and experimental readings taken on the PMDD hoist and conventional hoist accordingly. As per the experimental readings taken on the PMDD hoist and conventional hoist, graphs are plotted for various combination of height, working speed and load. Graphs are plotted for all the combinations between the conventional hoist and PMDD hoist by considering the following three cases:

6.1 Effect of Varying Height on Lifting Time of Conventional Hoist (T_{LFC}) vs PMDD Hoist (T_{LFP}) and Lowering Time of Conventional hoist (T_{LWC}) vs PMDD Hoist (T_{LWP}). (Constant Load and Speed)

The lifting and lowering time is compared for conventional hoist and PMDD hoist with respect to its effect on height is studied while keeping the load and speed constant. Effect of varying height by 2, 3 and 4 m lifting and lowering time for conventional hoist and PMDD hoist is compared.

- For the different set of speed range of 10,20,30,40 and 50 rpm
- For the different set of load range of 10,20,30,40,50,60,70,80,90 and 100 kg

6.1.1 Graph for Height - Time at 10 rpm

Figure 6.1 shows the graph of height - time for the different speed 10 to 50 rpm whereas the different load range starting from 10 to 100 kg. Grey color bar shows lifting time for conventional hoist (T_{LFC}), blue color bar shows the lifting time for PMDD hoist (T_{LFP}), red color shows lowering time for conventional hoist (T_{LWC}) and green color shows lowering time for PMDD hoist (T_{LWP}).

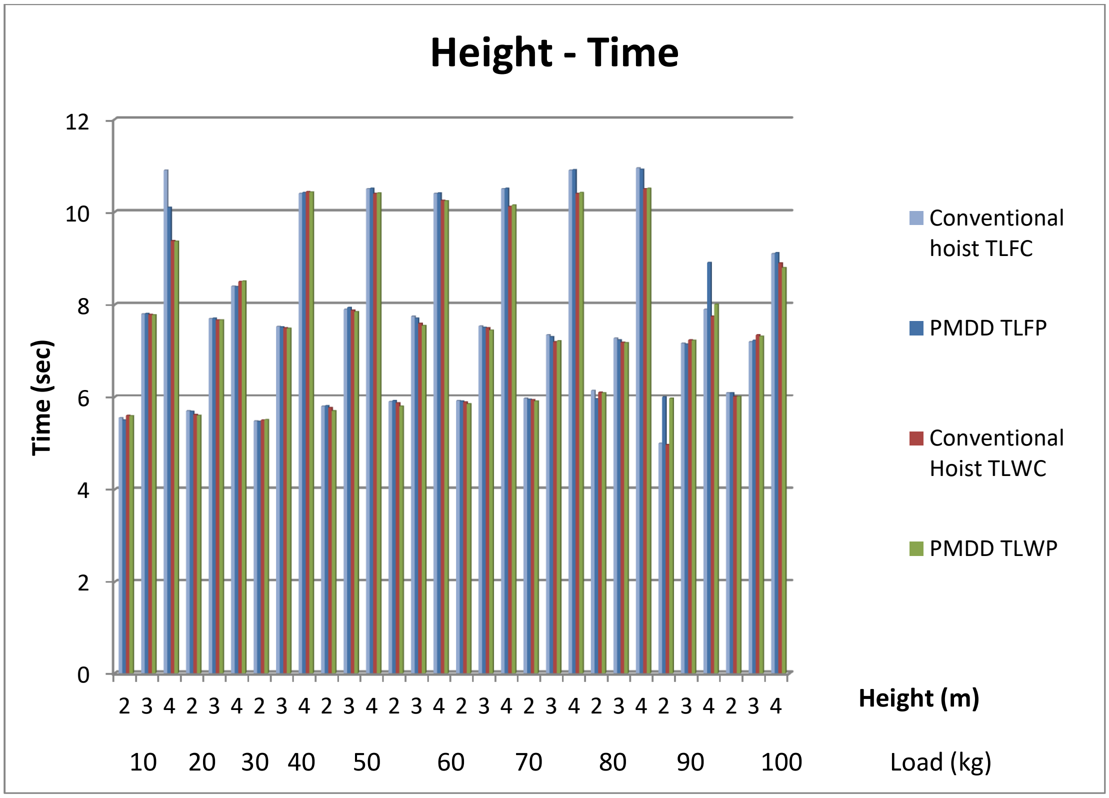


Figure 6.1 Height - Time at 10 rpm

The figure 6.1 shown above indicates the time required to lift or lower the load with respect to the height at 10 rpm speed. For the different combinations of load starting from 10 kg to 100 kg is taken in to consideration for experimental readings. The above graph shows that as the height increase the time required to lift the load also increases. That is logically justified too. As such there is no variation or little variation is lifting time of conventional hoist and PMDD hoist. Similarly the time taken for lowering the load for conventional hoist and PMDD hoist is almost similar with little variation. Hence it can be said that the PMDD can be used in place of conventional hoist without compromising the function or performance of hoist.

6.1.2 Height - Time at 20 rpm

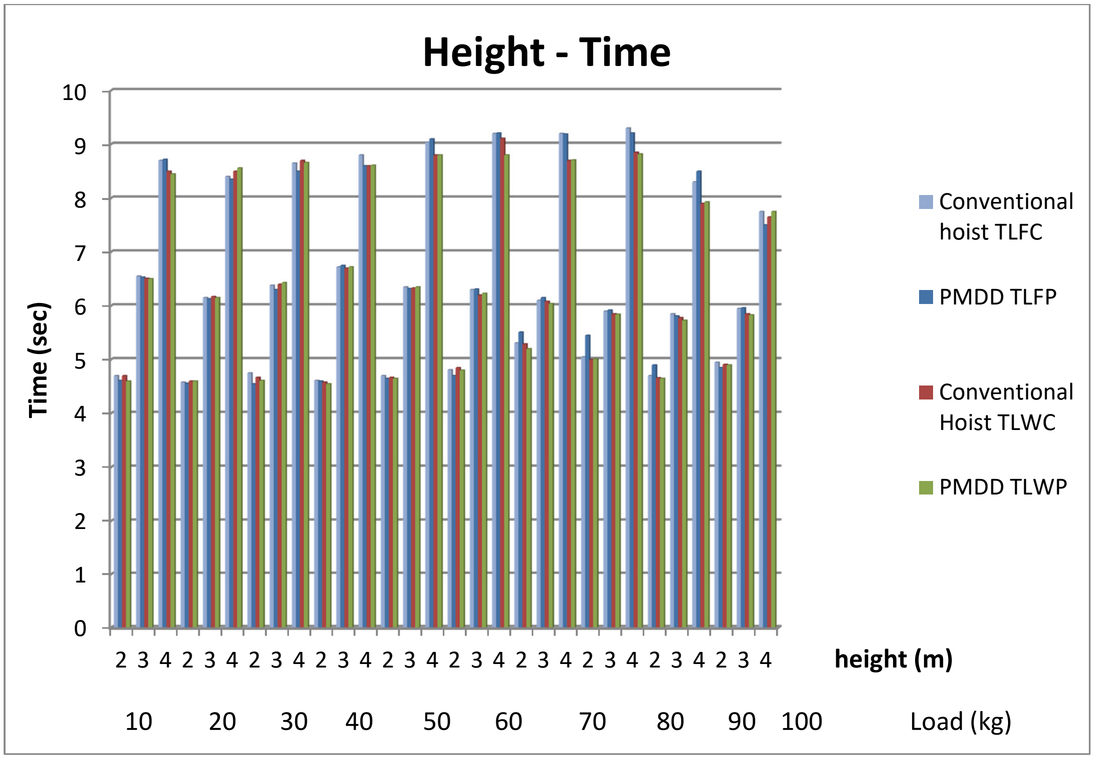


Figure 6.2 Height - Time at 20 rpm

The figure 6.2 shown above indicates the time required to lift or lower the load with respect to the height at 20 rpm speed. For the different combinations of load starting from 10 kg to 100 kg is taken in to consideration for experimental readings. The above graph shows that as the height increase the time required to lift the load also increases. That is logically justified too. As such there is no variation or little variation is lifting time of conventional hoist and PMDD hoist. Similarly the time taken for lowering the load for conventional hoist and PMDD hoist is almost similar with little variation. Hence it can be said that the PMDD can be used in place of conventional hoist without compromising the function or performance of hoist.

6.1.3 Height - Time at 30 rpm

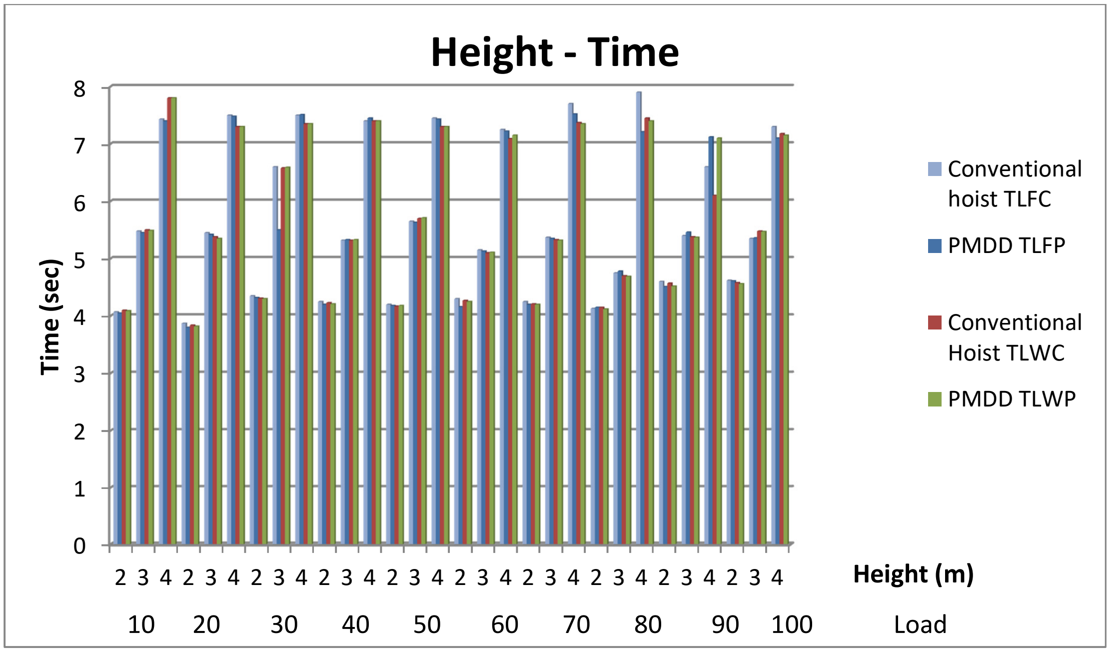


Figure 6.3 Height - Time at 30 rpm

The figure 6.3 shown above indicates the time required to lift or lower the load with respect to the height at 30 rpm speed. For the different combinations of load starting from 10 kg to 100 kg is taken in to consideration for experimental readings. The above graph shows that as the height increase the time required to lift the load also increases. That is logically justified too. As such there is no variation or little variation is lifting time of conventional hoist and PMDD hoist. Similarly the time taken for lowering the load for conventional hoist and PMDD hoist is almost similar with little variation. Hence it can be said that the PMDD can be used in place of conventional hoist without compromising the function or performance of hoist.

6.1.4 Height - Time at 40 rpm

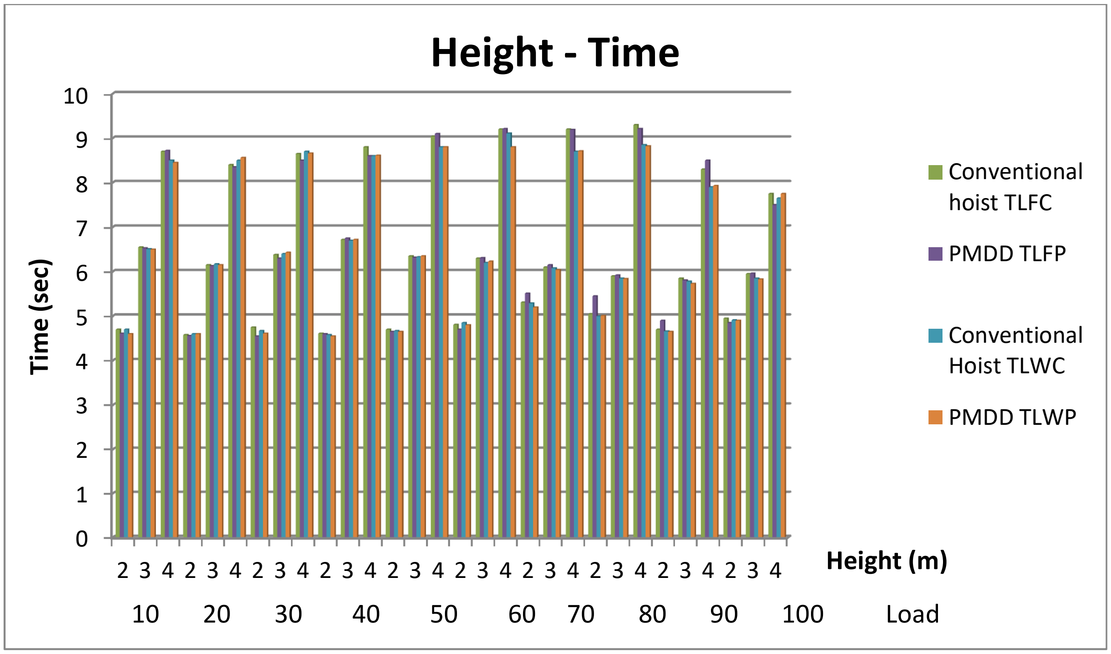


Figure 6.4 Height - Time at 40 rpm

The figure 6.4 shown above indicates the time required to lift or lower the load with respect to the height at 40 rpm speed. For the different combinations of load starting from 10 kg to 100 kg is taken in to consideration for experimental readings. The above graph shows that as the height increase the time required to lift the load also increases. That is logically justified too. As such there is no variation or little variation is lifting time of conventional hoist and PMDD hoist. Similarly the time taken for lowering the load for conventional hoist and PMDD hoist is almost similar with little variation. Hence it can be said that the PMDD can be used in place of conventional hoist without compromising the function or performance of hoist.

6.1.5 Height - Time at 50 rpm

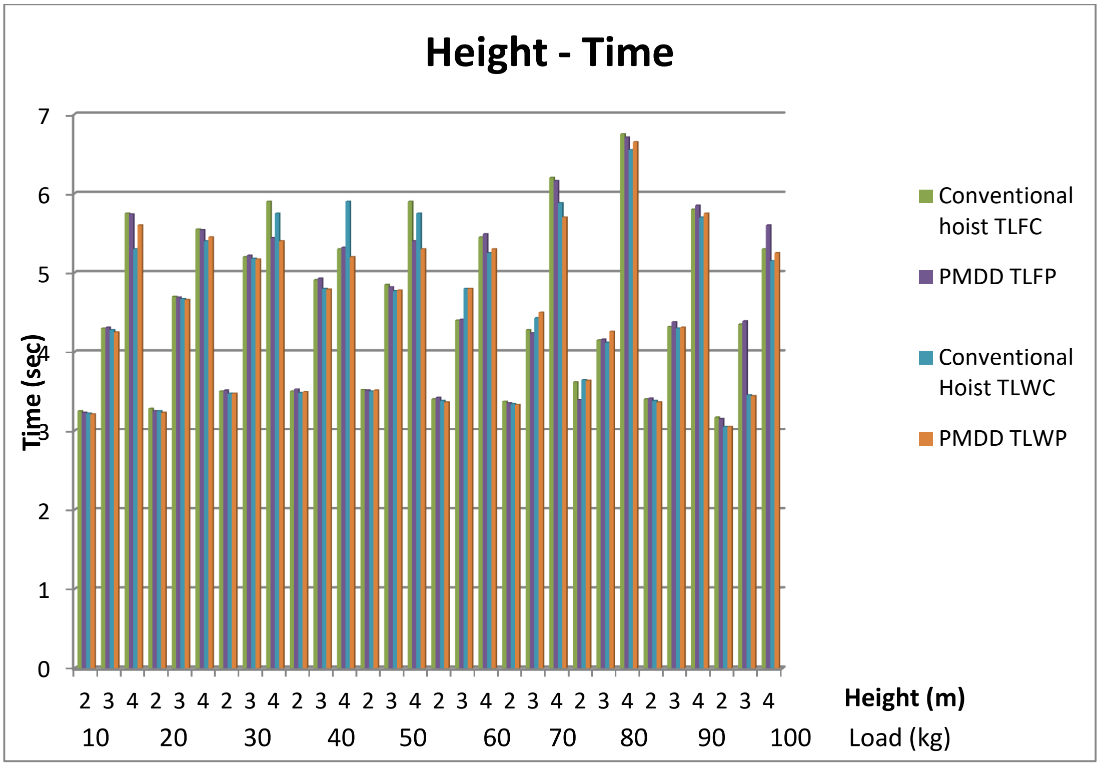


Figure 6.5 Height - Time at 50 rpm

The figure 6.5 shown above indicates the time required to lift or lower the load with respect to the height at 50 rpm speed. For the different combinations of load starting from 10 kg to 100 kg is taken in to consideration for experimental readings. The above graph shows that as the height increase the time required to lift the load also increases. That is logically justified too. As such there is no variation or little variation is lifting time of conventional hoist and PMDD hoist. Similarly the time taken for lowering the load for conventional hoist and PMDD hoist is almost similar with little variation. Hence it can be said that the PMDD can be used in place of conventional hoist without compromising the function or performance of hoist.

From the plotted graphs figure 6.1 to 6.5; it can be concluded that as the height of lifting load increases the time required to lift and lower the load also increases.

6.2 Effect of Varying Speed on Lifting Time of Conventional Hoist (T_{LFC}) vs PMDD Hoist (T_{LFP}) and Lowering Time of Conventional Hoist (T_{LWC}) vs PMDD Hoist (T_{LWP}). (Constant Load and Height)

The lifting and lowering time is compared for conventional hoist and PMDD hoist with respect to its effect on speed is studied while keeping the load and height constant. Effect of varying speed by 10,20,30,40 and 50 rpm on lifting and lowering time for conventional hoist and PMDD hoist is compared.

- For the different set of height range of 2, 3 and 4 meter.
- For the different set of load range of 10, 20, 30, 40, 50, 60,70,80,90 and 100 kg.

6.2.1 Speed - Time at 2 meter

Figure 6.6 shows the graph of speed - time for the different height 2 to 4 m whereas the different load range starting from 0 to 100 kg. Purple color bar shows lifting time for conventional hoist (T_{LFC}), sea green color bar shows the lifting time for PMDD hoist (T_{LFP}), orange color shows lowering time for conventional hoist (T_{LWC}) and grey color shows lowering time for PMDD hoist (T_{LWP}).

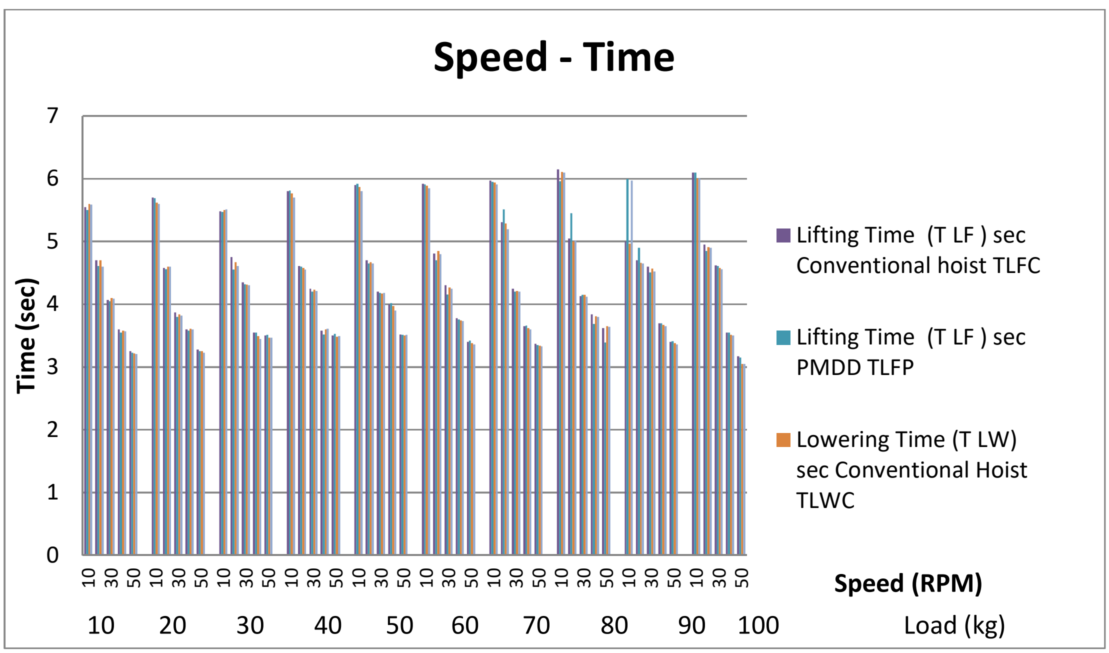


Figure 6.6 Speed - Time at 2 m

The figure 6.6 shown above indicates the time required to lift or lower the load with respect to the speed at 2 meter height. For the different combinations of load starting from 10 kg to 100 kg is taken in to consideration for experimental readings. The above graph shows that as the speed increase the time required to lift the load also decreases. That is logically justified too. As such there is no variation or little variation is lifting time of conventional hoist and PMDD hoist. Similarly the time taken for lowering the load for conventional hoist and PMDD hoist is almost similar with little variation. Hence it can be said that the PMDD can be used in place of conventional hoist without compromising the function or performance of hoist.

6.2.2 Speed - Time at 3 meter

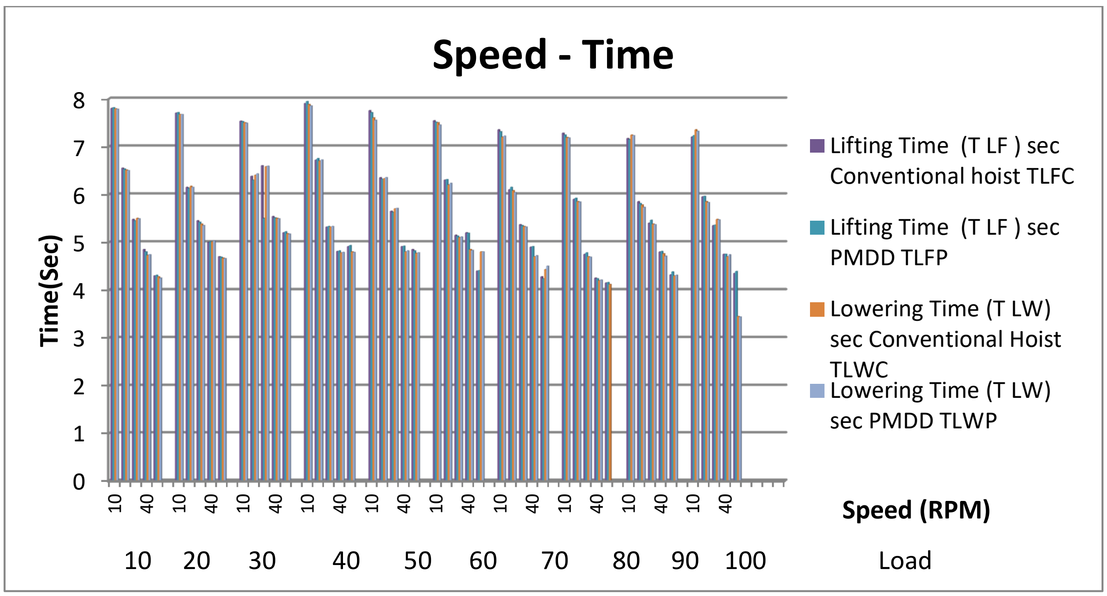


Figure 6.7 Speed - Time at 3 m

The figure 6.7 shown above indicates the time required to lift or lower the load with respect to the speed at 3 meter height. For the different combinations of load starting from 10 kg to 100 kg is taken in to consideration for experimental readings. The above graph shows that as the speed increase the time required to lift the load also decreases. That is logically justified too. As such there is no variation or little variation is lifting time of conventional hoist and PMDD hoist. Similarly the time taken for lowering the load for conventional hoist and PMDD hoist is almost similar with little variation. Hence it can be said that the PMDD can be used in place of conventional hoist without compromising the function or performance of hoist.

6.2.3 Speed - Time at 4 meter

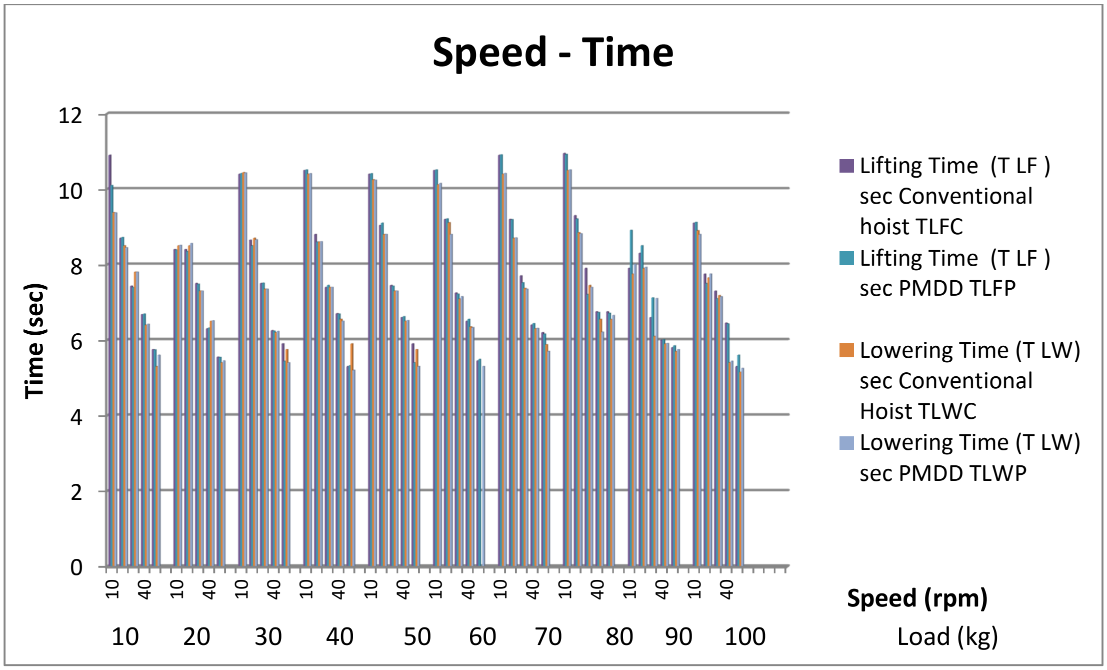


Figure 6.8 Speed - Time at 4 m

The figure 6.8 shown above indicates the time required to lift or lower the load with respect to the speed at 4 meter height. For the different combinations of load starting from 10 kg to 100 kg is taken in to consideration for experimental readings. The above graph shows that as the speed increase the time required to lift the load also decreases. That is logically justified too. As such there is no variation or little variation is lifting time of conventional hoist and PMDD hoist. Similarly the time taken for lowering the load for conventional hoist and PMDD hoist is almost similar with little variation. Hence it can be said that the PMDD can be used in place of conventional hoist without compromising the function or performance of hoist.

From the plotted graphs figure 6.6 to 6.8, it can be concluded that as the speed of lifting load increases the time required to lift and lower the load also decreases.

6.3 Effect of Varying Load on Lifting Time of Conventional Hoist (T_{LFC}) vs PMDD Hoist (T_{LFP}) and Lowering Time of Conventional Hoist (T_{LWC}) vs PMDD Hoist (T_{LWP}). (constant Speed and Height)

The lifting and lowering time is compared for conventional hoist and PMDD hoist with respect to its effect on load is studied while keeping the speed and height constant. Effect of varying load by 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 kg on lifting and lowering time for conventional hoist and PMDD hoist is compared.

- For the different set of height range of 2, 3 and 4 meter.
- For the different set of speed range of 10, 20, 30, 40 and 50 rpm.

6.3.1 Load - Time at 2 m

Figure 6.9 shows the graph of load - time for the different height 2 to 4 m whereas the different speed range starting from 10 to 50 rpm. Purple color bar shows lifting time for conventional hoist (T_{LFC}), sea green color bar shows the lifting time for PMDD hoist (T_{LFP}), orange color shows lowering time for conventional hoist (T_{LWC}) and grey color shows lowering time for PMDD hoist (T_{LWP}).

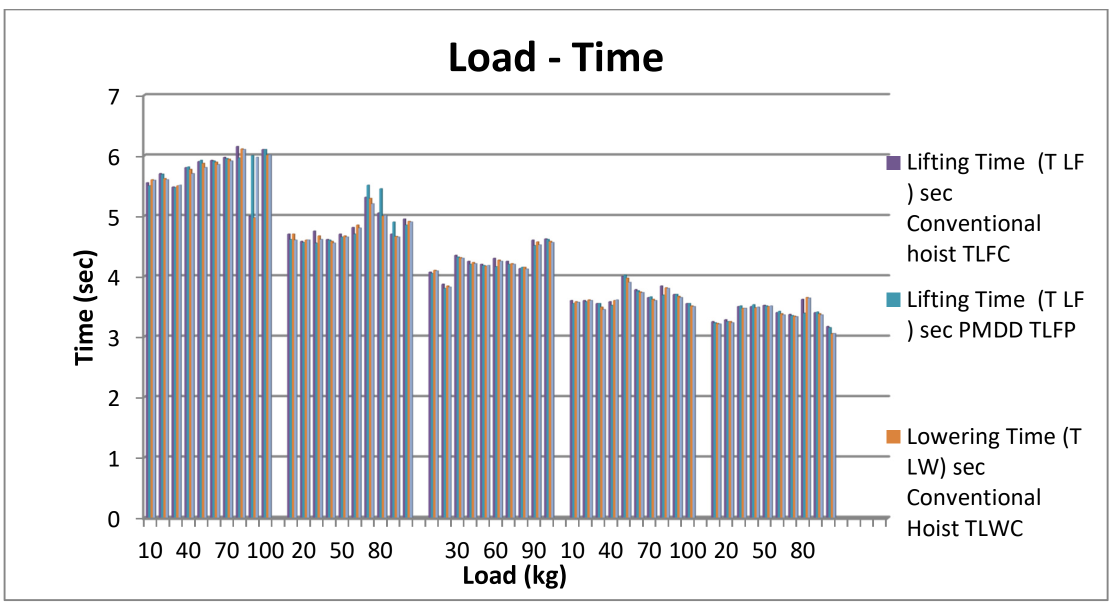


Figure 6.9 Load - Time at 2 m

The figure 6.9 shown above indicates the time required to lift or lower the load with respect to the load at 2 meter height. For the different combinations of load starting from 10 kg to 100 kg is taken in to consideration for experimental readings. The above graph shows a little variation because of the change in load as the variation of 10 kg load is very small entity to make difference in the results. But the conventional hoist for the larger load range shows that as the capacity of load required to lift increase the time required to lift the load will be increased. Similarly the time taken for lowering the load for conventional hoist and PMDD hoist is almost similar with little variation. Hence it can be said that the PMDD can be used in place of conventional hoist without compromising the function or performance of hoist.

6.3.2 Load - Time at 3 m

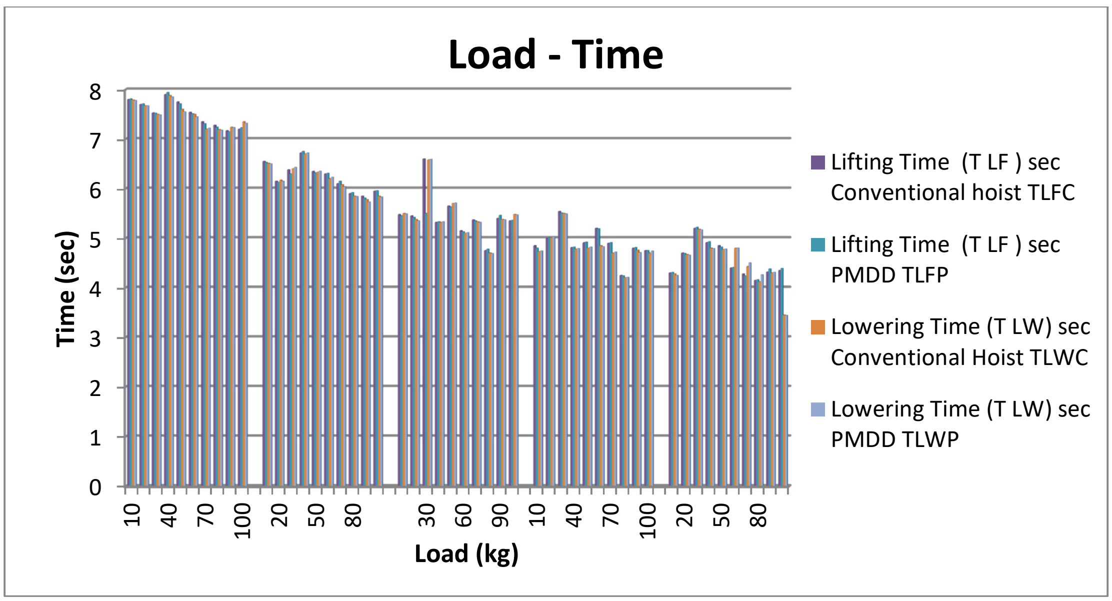


Figure 6.10 Load - Time at 3 m

The figure 6.10 shown above indicates the time required to lift or lower the load with respect to the load at 3 meter height. For the different combinations of load starting from 10 kg to 100 kg is taken in to consideration for experimental readings. The above graph shows a little variation because of the change in load as the variation of 10 kg load is very small entity to make difference in the results. But the conventional hoist for the larger load range shows that as the capacity of load required to lift increase the time required to lift the load will be increased. Similarly the time taken for lowering the load for conventional hoist and PMDD hoist is almost similar with little variation. Hence it can be said that the PMDD can be used in place of conventional hoist without compromising the function or performance of hoist.

6.3.3 Load - Time at 4m

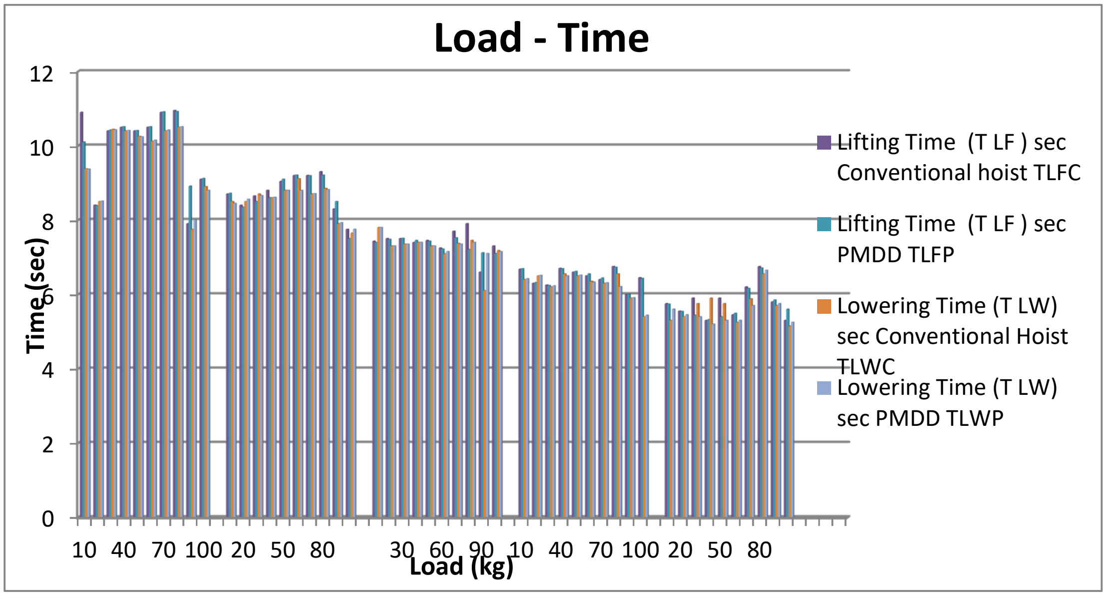


Figure 6.11 Load - Time at 4 m

The figure 6.11 shown above indicates the time required to lift or lower the load with respect to the load at 4 meter height. For the different combinations of load starting from 10 kg to 100 kg is taken in to consideration for experimental readings. The above graph shows a little variation because of the change in load as the variation of 10 kg load is very small entity to make difference in the results. But the conventional hoist for the larger load range shows that as the capacity of load required to lift increase the time required to lift the load will be increased. Similarly the time taken for lowering the load for conventional hoist and PMDD hoist is almost similar with little variation. Hence it can be said that the PMDD can be used in place of conventional hoist without compromising the function or performance of hoist.

The plotted graphs from figure 6.9 to 6.11 shows a little variation because of the change in load as the variation of 10 kg load is very small entity to make difference in the results. But the conventional hoist for the larger load range shows that as the capacity of load required to lift increase the time required to lift the load will be increased.

6.4 Vibration Analysis

The developed PMDD hoist is also tested for vibration analysis. The displacement (mm), velocity (mm/sec) and acceleration (mm/sec^2) are measured with Rokade vibration analyzer and balancer. The readings are taken on PMDD hoist and conventional hoist and are compared for the performance analysis. As per the experimental readings taken on the PMDD hoist and conventional hoist in art 5.4, graphs are plotted by considering the following cases for vibration analysis:

6.4.1 Displacement, Velocity and Acceleration for conventional hoist (d_c, v_c & a_c) and PMDD Hoist (d_p, v_p & a_p) at 20 rpm, 2-3-4 m & 20-60-100 kg.

Displacement given by conventional hoist lies between 3.5 to 3.8 mm whereas by PMDD hoist is 0.3 to 0.5 mm. Vibration velocity given by conventional hoist lies between 3.1 to 3.4 mm/sec while for PMDD hoist it lies between 0.1 to 0.4 mm/sec. Acceleration values given by conventional hoist are 3.3 to 3.5 mm/sec^2 whereas by PMDD are 0.3 to 0.5 mm/sec^2.

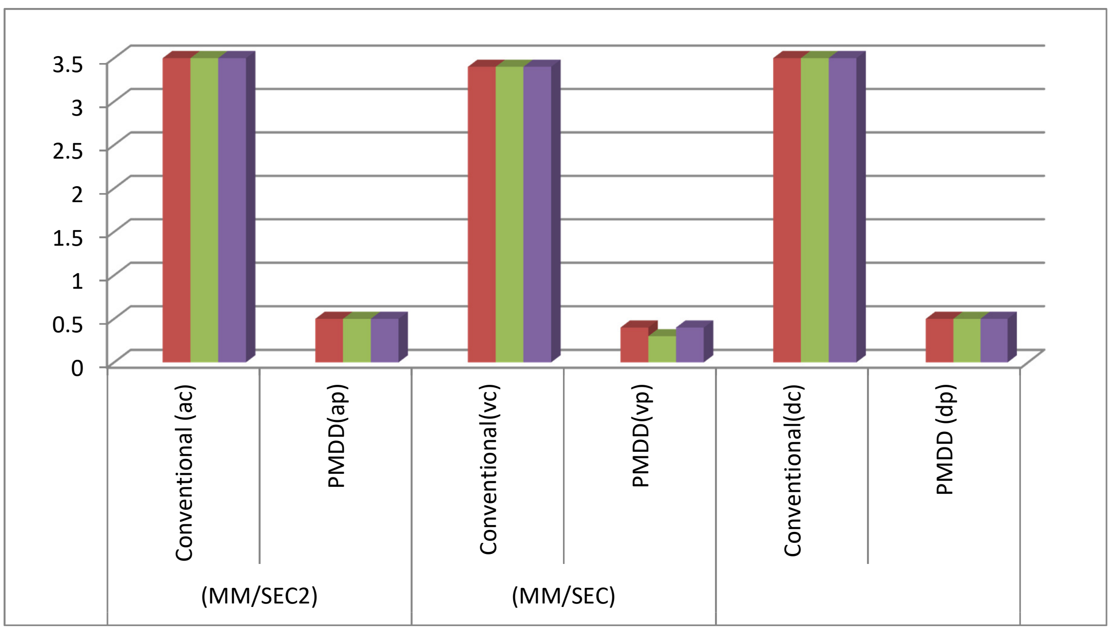


Figure 6.12 Graphs for Displacement, Velocity and Acceleration at 20 rpm, 2-3-4 m & 20-60-100 kg

6.4.2 Displacement, Velocity and Acceleration for conventional hoist (d_c, v_c & a_c) and PMDD Hoist (d_p, v_p & a_p) at 40 rpm, 2-3-4 m & 20-60-100 kg.

Displacement given by conventional hoist lies between 3.4 to 3.8 mm whereas by PMDD hoist is 0.2 to 0.5 mm. Vibration velocity given by conventional hoist lies between 3.1 to 3.4 mm/sec while for PMDD hoist it lies between 0.1 to 0.5 mm/sec. Acceleration values given by conventional hoist are 3.1 to 3.8 mm/sec^2 whereas by PMDD are 0.3 to 0.5 mm/sec^2.

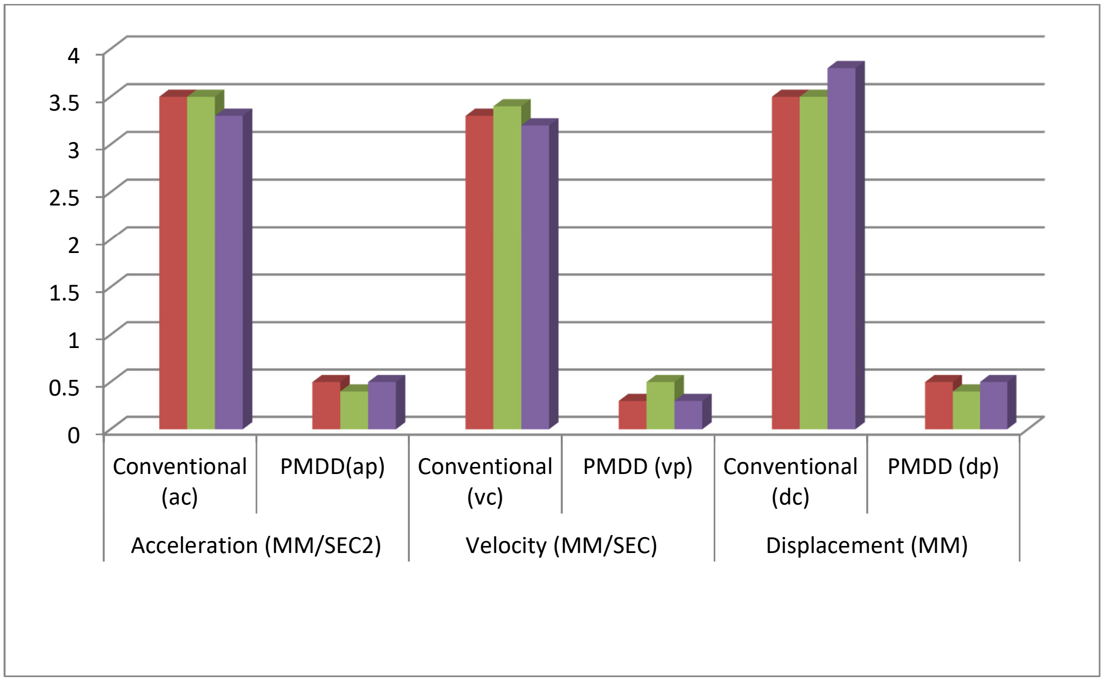


Figure 6.13 Graphs for Displacement, Velocity and Acceleration at 40 rpm, 2-3-4 m & 20-60-100 kg

6.4.3 Displacement, Velocity and Acceleration for conventional hoist (dc, vc & ac) and PMDD Hoist (dp, vp & ap) at 50 rpm, 2-3-4 m & 20-60-100 kg.

Displacement given by conventional hoist lies between 3.3 to 3.5 mm whereas by PMDD hoist is 0.1 to 0.5 mm. Vibration velocity given by conventional hoist lies between 3.1 to 3.4 mm/sec while for PMDD hoist it lies between 0.1 to 0.3 mm/sec. Acceleration values given by conventional hoist are 3.3 to 3.5 mm/sec^2 whereas by PMDD are 0.2 to 0.5 mm/sec^2.

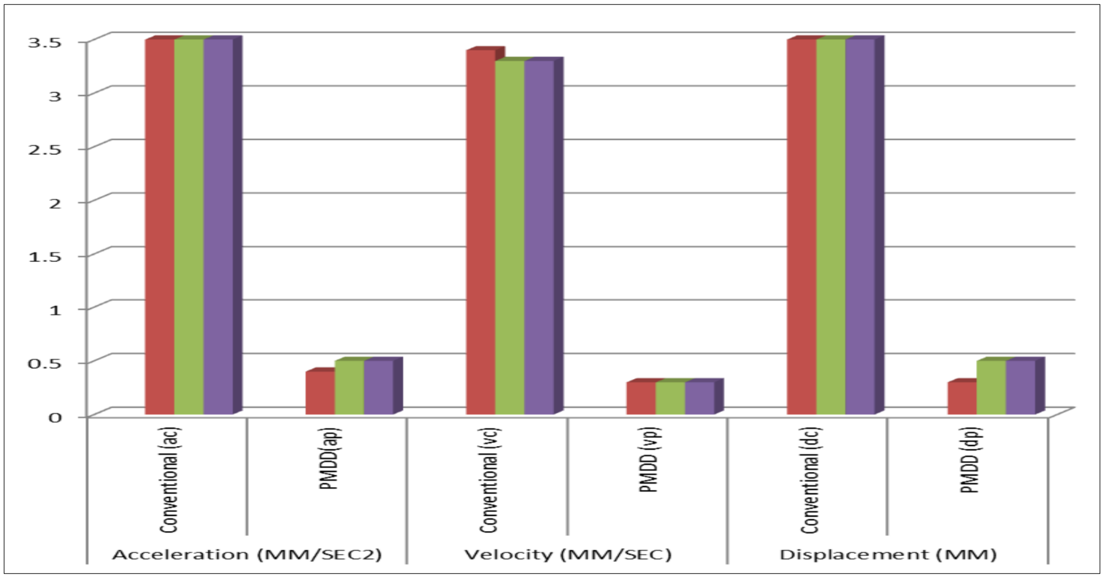


Figure 6.14 Graphs for Displacement, Velocity and Acceleration at 50 RPM, 2-3-4 M & 20-60-100 KG

As per Vibration severity ISO 10816 is performance given by PMDD hoist is better than the conventional hoist.

CHAPTER – 7

Conclusions and Future Scope

According to the numerous analyses of plots shown in chapter 4, it is concluded that the developed and analyzed PMDD can provide high torque of 40 to 65 N.m. at 15 to 35 rpm, which is sufficient to lift the 100 kg weight. In order to remove the motor and gear box assembly in conventional EOT crane, the developed PMDD motor can be utilized for reduction in service and maintenance cost also. It makes the hosting system simpler. The PMDD hoist is developed and analyzed for its performance by varying the parameters affecting the performance of EOT crane. Moreover vibration analysis is also done on the hoist to check the vibration and stability. A referred literature review also supports the comparison of failure rate between conventional and PMDD hoist. Other merits of PMDD hoist in comparison with conventional hoist are also discussed in this section.

7.1 Conclusions

- As per the parameters affecting the performance of EOT crane discussed in art 5.2; effect of speed, height and load is analyzed on lifting time of conventional hoist (T_{LFC}) VS PMDD hoist (T_{LFP}) and lowering time of conventional hoist (T_{LWC}) VS PMDD hoist (T_{LWP}). For the following cases:

  - Case-I : for the speed range of 10, 20, 30, 40 and 50 rpm
  - Case-II : for the height of 2, 3 and 4 meter
  - Case-III: for the load range of 10-100 kg at the interval of 10 kg.

From the experimental readings as well as graphs shown in figure 6.1.1 to 6.1.5 we can conclude that as the speed increase the time required to lift the load decreases for the case-I. For the second case, as per the experimental readings and graphs shown in figure 6.2.1 to 6.2.3 exhibits that as the height increases the time required to lift the load increases. All the readings and graphs show that lifting time is more than lowering time. All this findings are experimentally justified for the use of PMDD hoist. The plotted graphs from figure 6.9 to 6.11 shows a little variation because of the change in load as the variation of 10 kg load is very small entity to make difference in the results. But the conventional hoist for the larger load range shows that as the capacity of load required to lift increase the time required to lift the load will be increased.

- The lifting and lowering time found by the PMDD hoist gives almost similar results as of the conventional hoist with small marginal difference and the same is proved; as shown in readings and graphs of previous chapter 5 and chapter 6 respectively. Hence PMDD hoist can be used in place of conventional hoist without compromising with its function and performance.

- As per the vibration analysis given in chapter 6, it is concluded that vibration velocity for PMDD hoist lies between 0.1 to 0.5 mm/sec which gives excellent performance of the hoist as per the **Vibration severity ISO 10816** compared to conventional hoist which lies between 3.1 to 3.8 mm/sec [119].

- As per the literature review the PMDD hoist offers many other significant advantages over conventional hoist like [12,72-81];

Table 7.1 Comparison of Conventional Hoist and PMDD Hoist [12, 72-81]

SN	Parameters	Conventional hoist	PMDD hoist
1	Transmission Form	Complicated four link structure	High driving efficiency and great reliability
2	Volume	High	20-40% smaller
3	Self-Weight	High	20-60% lighter
4	Power saving	Low	25.7 %

- Comparison of failure rate of hoisting mechanism for conventional hoist and PMDD hoist is given in Table 7.2 as per the literature review [12,72-81];

Table 7.2 Comparison of the Failure rate of Conventional Hoist and PMDD Hoist

S N	Part	Traditional lifting Mechanism with Conventional Gear Box		Permanent Magnet Direct Drive	
		Failure Rate	Main Failure	Failure Rate	Main Failure
1.	Gear box	22%	The gearbox body crack formation, the poor oil quality and quantity, oil leakage, broken teeth, gear heating and vibration.	0%	0
2.	Motor	13%	Motor heating, Short circuit, installation base crack, fan failure etc.	5%	Motor heating, Short circuit, installation base crack, fan failure etc.
3.	Shaft	6%	Deformation, fracture, loose deformation of the joints.	0%	0
4.	Coupling	20%	The lubrication nut is loose, abnormal sound, deformation and wear	0%	0
5.	Brake	18%	The lubrication nut is loose, abnormal sound, deformation and wear, break wheel installed loose, crack, friction loss damaged, spring aging, tie pin, leverage and crack in bolt the bending the deformation and the wear, abnormal breaking torque, adjusting mechanism and the decreasing of the breaking torque.	7%	Spring aging, oil pipe leakage, bolt loosening etc.

S N	Part	Traditional lifting Mechanism with Conventional Gear Box		Permanent Magnet Direct Drive	
		Failure Rate	Main Failure	Failure Rate	Main Failure
6.	Wire Rope	5%	Wire rope break, fracture, leak core, skip rope groove.	5%	Wire rope break, fracture, leak core, skip rope groove
7.	Lifting Control Systems	16%	The inverter is burnt, the terminal is loose, the resistance chip is burnt, and the electrical components are aged.	16%	The inverter is burnt, the terminal is loose, the resistance chip is burnt, and the electrical components are aged.
Total		100%		33%	

It is concluded from the above table that the failure rate with PMDD is 67% lower than that of the traditional hoist, which greatly reduces the failure rate of the whole machine and the maintenance cost is correspondingly reduced.

- Successfully developed the PMDD hoist and met all the desired research objectives.

7.2 Future Scope

The same design PMDD hoist can be used for 1T lifting load by increasing the number of falls in the rope and slight change in drum design. After making the necessary changes in the design of hoisting elements PMDD drive shall be incorporated for higher capacity of EOT crane such as 2, 5, 10 T etc. This analysis and design can be used as a reference in future by the researcher to design EOT crane with PMDD drive as hoisting mechanism.

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List of Publications

1. P. K. Trivedi, Dr. U. V. Shah, Novel concept proposed for Hoisting Mechanism, International conference on Advancement in Design and Tribology (ICADT- 2021), SVNIT Surat. AIP Conference Proceedings, USA, ISSN: 0094-243X; E-ISSN: 1551-7616.

2. P. K. Trivedi, Dr. U. V. Shah, Design and Analysis of Permanent Magnet Direct Drive for hoist of 1 T Electric Overhead Travelling Crane, Industrial Engineering Journal, ISSN: 0970-2555, volume 52, March 2023.

3. P.K. Trivedi, Dr. U. V. Shah, Modeling and Simulation of 100 kg Hoist operated by Permanent Magnet Direct Drive, Journal of Propulsion Technology, and ISSN: 1001-4055.Vol 44, September 2023.

4. P.K Trivedi, Dr. U. V. Shah, Design and Development of hoist for EOT crane by using Permanent Magnet Direct Drive. International Journal of Design Engineering, Inder science Publisher **: Minor Revisions submitted**

Appendices

Appendix – NABL testing report of Direct Drive Motor

TEST REPORT

Name & Address of Customer			Test Report No:	TESLA/TR/2102/0016
Prospects origin Co. Shed No. 71, Licel, Nangargaon, Lonavla			ULR Number:	-
			Job No:	SRFT/2102/14/J1
			Issue Date of Test Report:	6-Jul-2021
			Date of Receipt:	6-May-2021
			Start Date of Testing:	30-Jun-2021
Condition of Equipment on receipt:		Good	End Date of Testing:	3-Jul-2021
Brand Name:		Pro-Syn	Issue Date of Amendment Report:	N/A
Discipline:- Electrical Testing / Group:- Rotating Electrical Machines				
Sample Description 3ϕ PMSM Motor				
Serial No.	sample		Rating(kW)	0.63
Machine Code	SAM/50-120		Rated Voltage(V)	415
Make	Pro-Syn		Rated Current(A)	-
			Rated Speed(RPM)	120
Mounting Type	Flange Mounted		Rated Frequency(Hz)	-
No of Poles	16		Starting Torque(%)	-

Sr. No.	Test Details	Test Clause No.
1	Measurement of resistance of windings of stator	-
2	No Load Test	-
3	Full load test to determine efficiency and power factor	-
4	Temperature Rise Test	-

Reviewed And Authorized By:Ankit Jain

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TEST REPORT TESLA/TR/2102/0016			URL No: -	Date: 6-Jul-2021	
Sr. No.	Test/Clause Ref.			Results	
1	**Measurement of resistance of windings of stator [-]**				
	Ambient Temperature	[°C]	----	29.44	-
	Between RY	[Ω]		43.745	
	Between YB	[Ω]		43.778	
	Between BR	[Ω]		43.792	
2	**No Load Test [-]**				
	Voltage	[V]	Motor shall run at rated voltage on no load condition to determine input current, power and speed	415.37	-
	Current	[A]		0.86	
	Input Power	[W]		68.06	
	Frequency	[Hz]		49.97	
	Speed	[rpm]		120	
3	**Full load test to determine efficiency and power factor [-]Method:Direct Method [Cl.No. 8.1.1 of IS 15999 (Part 2/Sec 1)]**				
	Voltage	[V]		415.16	Conforms
	current	[A]	≤ 2.34	2.18	
	Input Power	[W]		896.66	
	Frequency	[Hz]		49.97	
	Measured Speed	[rpm]		120	
	Output Power	[W]		614.28	
	Applied Torque	[Nm]		48.95	
	Efficiency	[%]	≥63.7(-5.4)	68.5	
	Power Factor			0.572	
4	**Temperature Rise Test [-]**				
	- θ1 Winding Temperature Cold	[°C]	The machine shall be loaded by suitable means, rating and operated until thermal equilibrium is achieved.	30.25	Conforms
	- θ2 Winding Temperature Hot	[°C]		53.95	
	- θa Coolant Temperature Hot	[°C]		26.24	
	- R1 Winding Resistance Cold	[Ω]		43.772	
	- R2 Winding Resistance Hot	[Ω]		56.596	
	- Temperature Rise	[°C]	< 125	81.75	

NOTE: Test Reports and its detail are related only to item tested. The details of test results in any form shall not be reproduced except in full, without written permission of the authorised person of TESLA laboratory. Any anomalies/discrepancies in this report should be brought to our notice within 45 days from the date of the issue of this report.

--- END OF REPORT ---

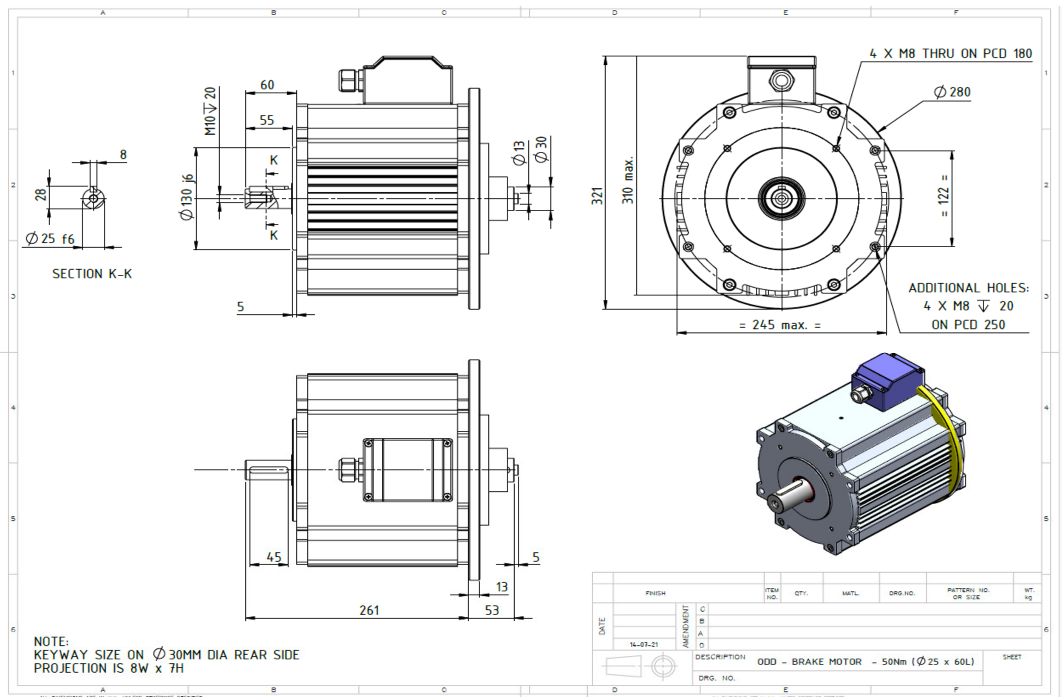
Reviewed And Authorized By:Ankit Jain

Appendix – B Specification Vibration Analyzer

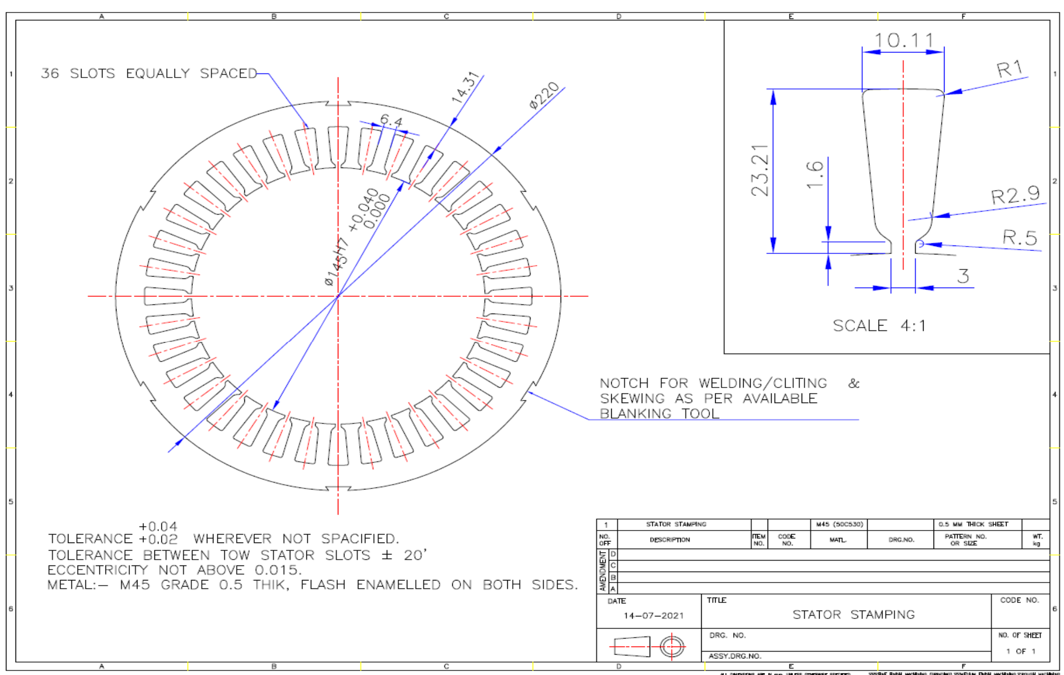
Rokade vibration analyser and balancer (VAB100)

- Display: Color LCD screen
- Storage: RAM 64 GB
- Power : Lithium Iron
- Operating time: > 8 hours
- Recharge time: 2-3 hours
- Size: 190 X 110 X 38mm
- Weight: 900 g
- Channel: 2 vibration + 1 speed
- Signal Type: Speed, Acceleration, displacement.

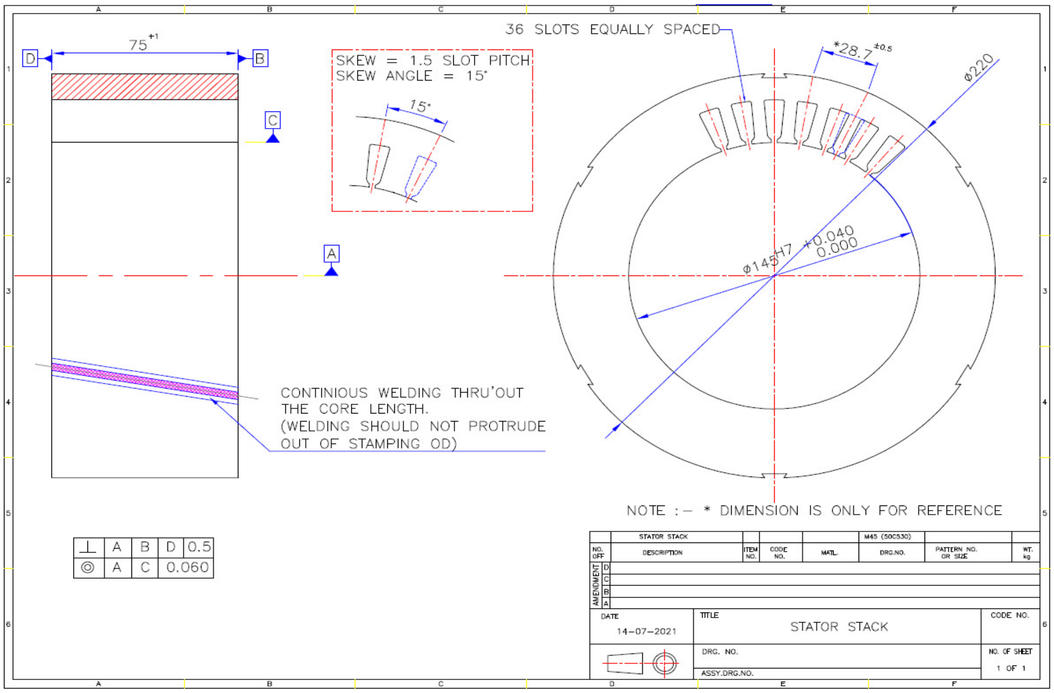
Appendix – C Drawings of PMDD Motor



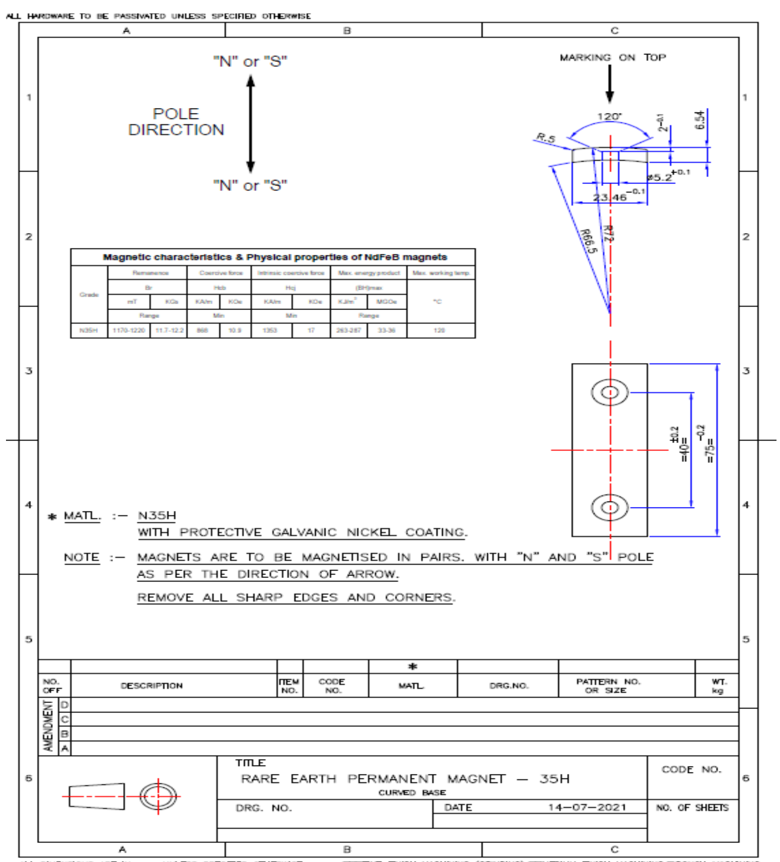
Motor with Brake



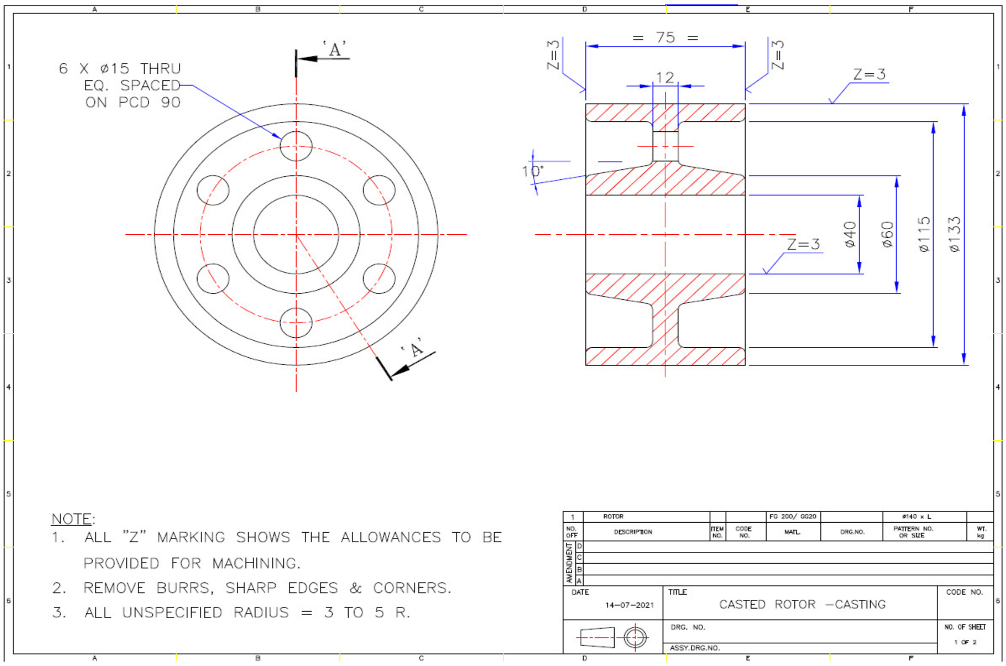
Stator stamping



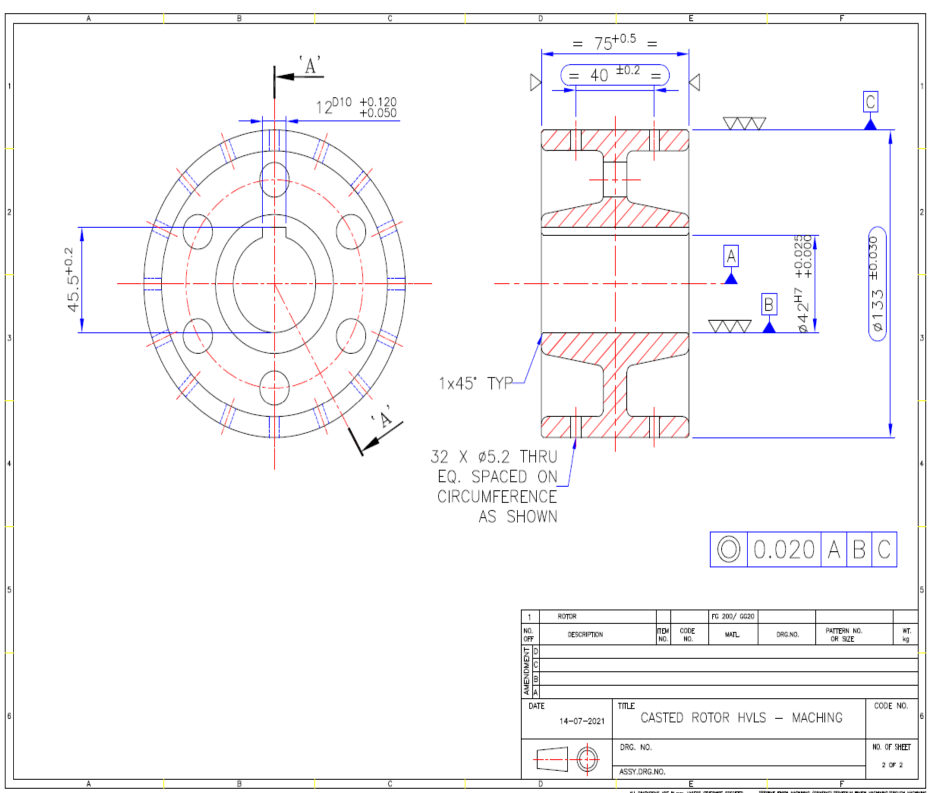
Stator Stack



Magnet



Rotor Casting



Rotor Machining

Appendix – D Vibration Severity as per ISO 10816

Reference Chart

The Vibration Severity Ranges in accordance with ISO 10816, VDI 2056, ISO 2372, BS 4675 Standard and subject to the mechanical condition, run-out of the Rotory elements.

VIBRATION SEVERITY PER ISO 10816						
MACHINE			CLASS I	CLASS II	CLASS III	CLASS IV
Vibration Velocity Vrms	in/s	mm/s	Small < 3.7kW-5HP	Medium < 373kW-500HP	Large rigid foundation	Large soft foundation
	0.01	0.28		Excellent		
	0.02	0.45				
	0.03	0.71				
	0.04	1.12		Good		
	0.07	1.80				
	0.11	2.80		Satisfactory		
	0.18	4.50				
	0.28	7.10		Unsatisfactory		
	0.44	11.2				
	0.71	18.0				
	1.10	28.0		Unacceptable		
	1.77	45.0				