REFINEMENT OF OUTER ROTOR PERMANENT MAGNET FLUX SWITCHING MACHINE FOR DOWNHOLE APPLICATION

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This dissertation is dedicated to my parents, my brother and sister, who always encouraged me with their love and prayers.
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ABSTRACT

There has been revitalized research interest in permanent magnet flux switching machine (PMFSM), mainly due to number of perceived advantages. Since all active parts such as armature windings and Permanent Magnet (PM) settled on the stator, direct yet suitable machine cooling can be easily associated. Furthermore, extra point of interest such as robust structure, high torque and power density, high efficiency and better flux weakening capability are completely analyzed and validate for different applications. An electric downhole machine should have the basic characteristics of superior reliability & robustness, high torque & power, and efficiency. Recently, a conventional inner rotor PMFSM was applied in downhole application due to high torque and power compared with previously modeled machines. However, it has high PM utilization and low efficiency due high number of turns. Shifting the rotor to the external surface will convey more torque along with easy maintenance, low total weight and cost. This research work is particularly focused on refinement of outer rotor PMFSM with various rotor poles configuration using analytical modeling, optimization based on deterministic method and performance investigation through 2D-FEA. Initially, key parameters for modeling are derived using sizing equations. Then, the various rotor pole configurations of outer rotor PMFSM are modeled and simulated using 2D-FEA JMAG v. 14.1 for the initial performance investigation. Since, 12slot-22pole has shown higher tendency to achieve desired goal of 25 Nm after implementation of refinement techniques. The model is optimized through deterministic method by shifting modeling free parameters in rotor and stator part. As a result optimum machine has accomplished higher output torque and power of 33.57 Nm and 3.84 kW with average efficiency of 94.74%. The PM weight is reduced to 37.3% with temperature stability up to 140°C. Based on these performances, it can be concluded that optimized model of 12slot-22pole outer rotor PMFSM is one the prominent candidate for the downhole application.
ABSTRAK

Berat PM telah dikurangkan sebanyak 37.3% dengan kestabilan suhu sehingga 140°C. Berdasarkan prestasi ini, dapat disimpulkan bahawa reka bentuk 12slot-22kutub mesin PMFSM dengan pemutar luar yang telah dioptimumkan adalah calon yang sesuai bagi aplikasi lubang-dasar.
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LIST OF SYMBOLS AND ABBREVIATIONS

$N_r$ - Number of rotor poles
$N_s$ - Number of stator slots
$\beta_r$ - Rotor pole width arc
$\beta_s$ - Stator tooth width arc
$\beta_{pm}$ - Permanent magnet width arc
$\beta_{slot}$ - Armature slot width arc
$R_{si}$ - Stator inner radius
$R_{so}$ - Stator outer radius
$R_{ro}$ - Rotor outer radius
$h_{ys}$ - Stator back length
$h_{yr}$ - Rotor yoke length
$h_{pr}$ - Rotor pole height
$A_{slot}$ - Half stator slot area
$N_c$ - Coil number of each phase
$m$ - Phase number
$N_a$ - Number of turns
$I_m$ - Peak injected current
$J_a$ - Armature current density
$\alpha$ - Filling factor
$f_e$ - Electrical frequency
$f_m$ - Mechanical frequency
$\phi$ - Flux Linkage
$\omega_r$ - Rotational speed
\( \eta \) - Efficiency
\( \alpha_{\text{cog}} \) - Electrical angle of rotation for each period of cogging torque
\( \lambda \) - Stack length
\( k_l \) - Leakage factor
\( P_c \) - Copper loss
\( P_i \) - Iron loss
\( \rho \) - Copper resistivity
\( k \) - Natural number
\( \beta_g \) - Maximum air gap flux density at open circuit
\( S_a \) - Slot area
\( L_{\text{end}} \) - End coil length
\( R_{\text{out}} \) - Outer radius of end coil
\( R_{\text{in}} \) - Inner radius of end coil
\( N_e \) - Electrical angle of revolution
\( V_1 \) - Volume of coil slot
\( V_2 \) - Volume of coil end
\( T \) - Torque
BLDC - Brushless Direct Current
CAD - Computer Aided Design
DC - Direct Current
DFT - Discrete Fourier Transform
DOM - Deterministic Optimization Method
EMF - Electromotive Force
ESP - Electrical Submersible Pump
FEA - Finite Element Analysis
FEFSM - Field Excitation Flux Switching Machine
FSM - Flux Switching Machine
GA - Genetic Algorithm
H - Height
HCF - Highest Common Factor
HEFSM - Hybrid Excitation Flux Switching Machine
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tr>
<td>HTHP</td>
<td>High Temperature High Pressure</td>
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<tr>
<td>IFP</td>
<td>Institute of Petroleum</td>
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<tr>
<td>IM</td>
<td>Induction Machine</td>
</tr>
<tr>
<td>IPSM</td>
<td>Interior Permanent Magnet Machine</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
</tr>
<tr>
<td>LCM</td>
<td>Least Common Multiple</td>
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<tr>
<td>MEC</td>
<td>Magnetic Equivalent Circuit</td>
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<tr>
<td>NEMA</td>
<td>National Electrical Manufacturing Association</td>
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<tr>
<td>PCP</td>
<td>Progress Cavity Pump</td>
</tr>
<tr>
<td>PM</td>
<td>Permanent Magnet</td>
</tr>
<tr>
<td>PMDC</td>
<td>Permanent Magnet Direct Current</td>
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<tr>
<td>PMFSM</td>
<td>Permanent Magnet Flux Switching Machines</td>
</tr>
<tr>
<td>SRM</td>
<td>Switch Reluctance Machine</td>
</tr>
<tr>
<td>VFD</td>
<td>Variable Frequency Drive</td>
</tr>
<tr>
<td>W</td>
<td>Width</td>
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Journals:


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CHAPTER 1

INTRODUCTION

1.1 Research Background

Energy is the main impetus of the world. It is a fundamental element of development and advancement. The anticipated energy prerequisite from various assets to guarantee the advancement of the worldwide economy from now to 2035 appeared in Figure 1.1 [1]. As depicted from the graph, oil and gas still remain the most imperative source in the coming decades since the advancement of renewable assets is not advancing as quickly as expected. The majority of the increased production of oil and gas in forthcoming years is from the following two main sources: mature fields and deep water reservoirs [2].

![Figure 1.1: Global energy consumption [1]](image)

Today, these mature fields represent more than 70% of the overall oil and gas production. The generation is gradually declining and the fields will be closed down rashly if the advance technology for enhancing recuperation financially savvy
operation and support are not set up. On the other hand, a review made by French Institute of Petroleum (IFP) inferred that 40% of the offshore oil and gas would originate from water profundities up to 500 m, 20% in the vicinity of 500 m and 1500 m and 40% from 1500 m to 3000 m. Until 2000, a negligible 2% of imminent assets had been explored in deep and ultra-deep waters [3]. The worldwide oil and gas chase for new oil and gas assets is driving us into ever more profound waters and harsher climate. The best technique to endeavor more oil and gas resources in the deep water and create them in an ensured, capable and more ecological way is a challenge. In the present time, traditionally fixed or drifting platform for processing are extensively utilized but they are costly to build and install. Furthermore, the dismounting of settled platform additionally costs in millions afterward. With the customary advancement in technology, numerous deep and ultra-deep water reservoirs may in this manner be useless to develop [4].

Downhole processing, by moving the processing from topside or inland to downhole cannot just take out the top stages or somewhat diminish the top territory but also generally improve production, extreme recuperation and preparing productivity while diminishing ecological effects. With the increase of the seawater depth, the downhole temperature and pressure increase. The risks and demanding performance requirements for High Temperature and High Pressure (HTHP) completions dictate special considerations and investments. The electrification of the downhole application has turned out to be promising for enhancing the oil recuperation all the more securely, monetarily and ecologically amicable, especially for deepwater seaward wells. However, there are still a few difficulties connected with the innovation due to the cruel HPHT condition such as power transmission, power electronics and electric machine [5].

An instruction to successfully transmit adequate power downhole for electrical engines in profound water by means of a little cross-sectional zone is still a test. In any case, by incorporating electrical conductors into the tubing, more than 200 kW has been effectively exchanged over a length of 3.6 km to a downhole electric device. With extra temperate water-cooling conditions, this power can be multiplied [6]. Moreover, conventional power electronic outline is not satisfactory confronting high-pressure condition in profound water and conceivably high surrounding temperatures in downhole bottoms. Today gadgets in the deep water drilling applications work dependable to around 135°C and capacity up to around
180°C with an exponential breakdown rate over 135°C. As of now, downhole machine are typically determined from either inland or from topside. Recently developed high-temperature semiconductor devices can withstand high temperature up to 210°C, which makes it conceivable to drive the motor downhole [7].

To legitimize secure, cost-effective and eco-accommodating practical answer for upgrading oil and gas efficiency from deep and ultra-deep water repository, new downhole technologies are prescribed. Since electric machine assumes the driving part in the downhole application, it is a crushing prerequisite for scientists to outline and create an advance electric machine that bears the qualities of high reliability, better efficiency, high torque density and easy control [8]. The current approved electric downhole machine is the induction machine which is slightly incompetent. Besides, the natural shortcoming of low beginning torque and high beginning current restraints induction machine to low torque, high-speed applications. In applications where high torque is mandatory, a mechanical gear is typically added to coordinate the torque, this not just further decline the framework effectiveness but also debases the framework dependability. On the contrary, Permanent Magnet (PM) machines having higher efficiencies, higher torque densities and smaller volumes, are generally utilized in modern applications to supplant traditional machines. However, few have been created for the downhole applications because of the high encompassing temperatures in deep wells and the low-temperature dependability of PM materials after some time. Today, with the improvement of cutting edge innovations and utilization of high-temperature magnets, it is progressively intriguing for oil and gas businesses to create PM machines for the downhole applications [9].

1.2 Electric Machine in Downhole Application

The prerequisites of a downhole machine are fundamentally reliant on particular applications. In general, an electric downhole machine should have the following basic characteristics of superior reliability & robustness, high torque & efficiency, and simple control.

Reliability and powerful structure are the most basic necessity for the downhole application, especially in seaward fields. Some offshore drilling companies commonly cite US$ 1 million as the cost of changing an Electrical Submersible
Pump (ESP). This estimation incorporates the cost of a drilling rig needed to install and evacuate an ESP, labour cost, seaward transportation, and so on, barring the cost of the ESP itself and the loss of production between the periods. The component failure in ESP systems listed in Table 1.1. As it can be seen that the greater part of the failures happen from the electric motors [10-11].

Table 1.1: Component failure in ESP system [10]

<table>
<thead>
<tr>
<th>Components</th>
<th>% Failure</th>
</tr>
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<tbody>
<tr>
<td>Assembly</td>
<td>1</td>
</tr>
<tr>
<td>Cable</td>
<td>21</td>
</tr>
<tr>
<td>Sensor</td>
<td>1</td>
</tr>
<tr>
<td>Pump</td>
<td>30</td>
</tr>
<tr>
<td>Gas Handler</td>
<td>1</td>
</tr>
<tr>
<td>Motor</td>
<td>32</td>
</tr>
<tr>
<td>Intake</td>
<td>4</td>
</tr>
<tr>
<td>Protector</td>
<td>10</td>
</tr>
<tr>
<td>Other</td>
<td>1</td>
</tr>
</tbody>
</table>

Keeping in mind the end goal to dispose of the gear system prescribed for high torque applications, and henceforth enhancing the reliability and proficiency of the entire system, the downhole machine ought to give high torque over a wide range. Whereas, high efficiency is constantly favourable for applications, particularly in downhole where it is hard to have an outer cooling system for dispersing heat in light of the restricted cross-sectional area. Whereas, high efficiency implies fewer losses and subsequently less heat produced [12-13]. Furthermore, it is challengeable to have estimation devices working precisely in the downhole environment. Sensor-less control is attractive for downhole applications in view of the accompanying focal points [14-15].

(i) Decrement in hardware complication and expenditure
(ii) Increased mechanical strength and general potency
(iii) Operation in unfriendly condition
(iv) Higher accuracy and noise immunity
(v) Low maintenance
1.3 Problem Statement

The current standard electric machine for downhole application is induction machine which is marginally ineffective. In addition, it has a peculiar inadequacy of low starting torque and high starting current restricts induction machine to low-torque, high speed applications. In high torque operations, a mechanical gear is routinely combined to facilitate the torque, this not simply further lessening the structure proficiency, similarly, degrades the system unaltering quality. Apart from this, PM machines having greater efficiencies, greater torque densities and more diminutive volumes, are universally employed in present day applications to supersede the conventional machines. However, few have been created for the downhole applications in view of the high climatic temperatures in underwater reservoirs and the low-temperature strength of PM materials over the time. Today, with the change of forefront developments and usage of high-temperature magnets, it is logically entrancing for oil and gas organizations to modeled and develop PM machines for the downhole applications [16-17].

A Permanent Magnet Direct Current (PMDC) downhole machine has been proposed for the downhole application. The direct current is easily transmitted through PMDC to downhole by diminishing the transmission losses. It is smooth to control since it doesn't need Variable Frequency Drive (VFD). Although, it has few flaws, for instance, the commutator framework in PMDC not just produces the complication in assembling, additional losses over the brushes and furthermore causes persistent failure. Besides, consistent substitution is required after 2-3 years. With a specific end goal to resolve the issue of brushes, a brushless Interior Permanent Magnet Synchronous Machine (IPMSM) has been modeled and developed but it requires extra cooling arrangement [18-19].

The Permanent Magnet Flux Switching Machine (PMFSM) has a concise history and is a quite new kind of PM machines. There have been resuscitated research interests in PMFSM, undoubtedly due to the number of anticipated benefits. Since dynamic parts, for example, armature windings and PM set on the stator, direct yet suitable machine cooling can be easily associated. Furthermore, additional
advantages, such as robust rotor structure, high torque and flux densities, high productivity and better flux weakening ability are comprehensively dissected and monitored for various applications. More recently, an inner rotor PMFSM was modeled and developed for the downhole application which has high average output torque and efficiency when compared with previously modeled machines but it has high copper losses mainly due the high number of turns. Furthermore, high utilization of PM weight makes machine heavier and expensive [20-22].

Setting the rotor on the outer surface may deliver more torque, appeared differently in relation to the routine inside rotor [23]. In any case, examination on the PMFSM has generally fixed on the electromagnetic examination and enhancement of the internal rotor machines with hardly gave cautious attention to the outer rotor PMFSM for the downhole application [24-25]. Therefore, an improved structure of outer rotor PMFSM with salient rotor is proposed for the downhole application to overcome all these problems.

1.4 Objectives of the Study

The primary target of this research is to model and improve outer rotor Permanent Magnet Flux Switching Machine (PMFSM) for downhole application. In accomplishing the primary goal, there are some specific objectives that have to be fulfilled, which are:

(i) To investigate the initial performances of outer rotor PMFSM for downhole application based on various rotor pole topologies.
(ii) To optimize finest topology based on rotor pole combination using deterministic for obtaining optimum torque and power.
(iii) To analyze the implication of optimized machine for the average torque, torque-power versus speed characteristics, torque and power density, iron losses, copper losses of windings, efficiency, PM demagnetization and stress are inspected through 2D-Finite Element Analysis (FEA).
1.5 Scope of the Research

The proposed configuration of outer rotor PMFSM for the downhole application is modeled through analytical approach where outer diameter, machine stack length and air gap fixed at 100 mm, 200 mm and 0.5 mm respectively. In addition, the limit of maximum current density is set at $5 \text{ A}_{\text{rms}}/\text{mm}^2$ for armature windings due to high ambient temperature [3]. Based on literature, 12slot-10, 14 and 22 pole topologies are initially modeled and investigated for downhole application [3,125]. The three phase model with various rotor pole numbers were inspected and compared initially through commercial Finite Element Analysis (FEA), JMAG-Designer ver.14.1, issued by Japan Research Institute (JRI) was utilized as 2D-FEA solver. The initial performance of the finest topology is optimized by deterministic method based on several parameter located on stator and rotor [25]. The electromagnetic performance, containing back EMF, cogging torque, flux pattern and average output torque were inspected and compared for initial and optimized model. The torque-power versus speed attributes were assessed by varying the armature phase angle, $\theta$. The iron and copper losses were computed in light of 2D-FEA and formulas, which help in figuring the efficiency of proposed outer rotor PMFSM for the downhole application. Furthermore, the demagnetization is carried under maximum temperature of 180°C [124].

1.6 Contribution to Knowledge

In this thesis, it is explained that outer rotor PMFSM is particularly suitable for downhole application having improved robust structure with high torque, power and efficiency validated by 2D-FEA. Initially, machine is sketched by utilizing analytical sizing equations. Then, the optimization technique has been carried out for the accomplishment of focused performance. As an outcome, the proposed machine has better torque, efficiency and low cogging torque when contrasted with the initial model. The optimized machine model has enhanced approximately 51.17 % of maximum torque while lessening the PM weight by 37.3 %. The diminishment in PM weight makes machines lighter, economical and simple to manufacture.
Furthermore, it have 0% reverse PM magnetization where the surrounding temperature of downhole application is 140°C without external cooling

1.7 Dissertation Organization

This thesis deals with modeling, optimization and performance investigation of outer rotor PMFSM for the downhole application. The thesis is divided into five chapters and the brief outline of each chapter is listed as follows:

(i) Chapter 1: Introduction
The first chapter set the brief background of downhole application and explains the importance of PM machine in this application. The issues associated with past machines are spotlighted and research targets to resolve the issues along with the real commitments are sketched out in this chapter.

(ii) Chapter 2: Review of Electric Machines for Downhole Application
The following chapter reviews the state-of-art about electric the downhole machine. The characteristics comparisons considering several parameters of these machines are thoroughly discussed. The wordy explanation is provided for structure review, performance analysis, analytical modeling and optimization of PMFSM. In the last section, the performance is compared to several machines for finding the best candidate for the downhole application.

(iii) Chapter 3: Research Methodology
This chapter three portrays the methodology of proposed external rotor PMFSM utilizing business 2D-FEA, JMAG-Designer ver. 14.1, issued by JSOL Corporation. Sizing equations, drawing procedure and armature coil arrangement analysis are highlighted. In a later segment, the technique of deterministic optimization and is disclosed to treat different parameters of the machine and upgrade its qualities. Finally, the path flow for the performance has been explored in detail.

(iv) Chapter 4: Performance Analysis of Outer Rotor PMFSM for Downhole Application
In this chapter, the basic working principle of flux switching with the salient rotor is depicted with the assistance of rudimentary structure and computing strategy of average electromagnetic torque is presented for outer rotor
PMFSM for the downhole application. Further, evaluation of finest slot-pole combination is executed under open and close circuit analysis based on 2D-FEA. Then the finest topology 12slot-22pole is optimized utilizing deterministic technique until the objective torque is accomplished. The outcomes of the preliminary and optimized model which met the target performances are analyzed and discussed. Finally, torque and power density, the mechanical strength of machine and reverse magnetization is calculated for optimized model.

(v) Chapter 5: Conclusion
The final chapter specifies the noteworthy outcomes and wrap up the synopsis of the research and additionally recommended future work for research.
CHAPTER 2

REVIEW OF ELECTRIC MACHINES FOR DOWNHOLE APPLICATION

This chapter reviews the types of rotating electric machine for downhole application. Different types of electric machines are clarified, from the early ideas to the cutting edge outline. Merits and demerits of various machines are highlighted and various methodologies are discussed to assess their performances. As the thesis is on outer rotor PMFSM, more detail and significance of these machines is provided in the last section.

2.1 Classification of Electric Downhole Machine

Concerning the interest for high reliability, efficiency and torque density, there are primarily three sorts of electric machines considered for the downhole applications:

2.1.1 Induction Machine (IM)

The induction machine is well-known and commonly employed electric machine in numerous industrial applications. It is also known as asynchronous machine since it keeps running at a speed not as same as the synchronous speed. Synchronous speed is the speed of rotation of the magnetic field in a rotating machine and it relies on the frequency and pole number of the machine. An induction machine dependably keeps running at a speed less than the synchronous speed in light of the fact that the turning magnetic field which is created in the stator deliver flux in the rotor which make the rotor to rotate, yet because of the lagging of flux current in the rotor with flux current
in the stator, the rotor will never accomplish its rotating magnetic field speed i.e. the synchronous speed. There are essentially two sorts of induction machine that based on the input supply i.e. single phase and three phase induction machine respectively. Single phase induction machine is not a self-starting machine while three phase induction machine is a self-starting machine. Besides, three phase induction machine is grouped into two kinds i.e. Wire wound induction machine and squirrel cage induction machine [26].

Since the inception of Electric Submersible Pumps (ESP) in the downhole application, polyphase squirrel cage rotor water-proof sealed induction motors have traditionally been used for ESPs where surrounding temperatures can frequently achieve 240°F. Squirrel cage induction motors are used in ESPs because of its ruggedness, reliability, simplicity, relatively good efficiency, low cost and wide scale availability. An IM motor, due to limitation dictated by bore diameter, has a high stack length to diameter ratio. Therefore, designing and developing a small-diameter IM to meet the horsepower requirements in the downhole application required major deviations from normal National Electrical Manufacturing Association (NEMA) motor designs. To comfortably fit inside common oil-well casings, the industry has mostly settled on outside diameters of 3.75, 4.56 or 5.62 inches for the motors. Figure 2.1 shows the geometrical schematic of a regular multi-rotor induction motor with an external diameter across is regularly between 3.9 mm to 11.8 mm and the length is typically from 5 to 10 m, even up to the length of 30 m or longer reliant on applications. The stator is twisted as a solitary unit and the rotor comprises of various electrically discrete rotors with bearings between them to suit the slender structure. The oil, having low compressibility, makes it perfect with the high surrounding pressure existing because of submergence. The most well-known power range is from 40 to 200 kW. More power can be accomplished with the incorporation of extra motors [27-29].

Furthermore, a series of motor designs with smaller diameter have developed by Berets Group for the downhole application shown in Table 2.1. These motors are economical, robust, and economical with relatively efficiency when working closed to its rated torque and speed [30]. At light loads, no balance in between copper and iron losses results considerable reduction in the efficiency. The part load efficiency and power factor is improved by making the motor excitation adjustment in accordance with load and speed. To implement the above goal, the induction motor
should either be fed through an inverter or redesigned with optimization algorithms. The optimization of induction motor design has been carried through several methods such as conventional optimization technique, AI based optimization technique and nature-inspired algorithm but none is able to resolve all problems [31-33].

![Multi rotor induction motor](image)

**Figure 2.1: Multi rotor induction motor (a) Internal view (b) External view [29]**

**Table 2.1: Standard induction machine from Borets Group [30]**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Borets EDB8-103B5</th>
<th>Borets EDB8-117B5</th>
<th>Borets EDB22-130B5</th>
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<tr>
<td>Outer Diameter [mm]</td>
<td>103</td>
<td>117</td>
<td>130</td>
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<tr>
<td>Power Rating [kW]</td>
<td>10.7</td>
<td>10.7</td>
<td>29.5</td>
</tr>
<tr>
<td>Rated Voltages [V]</td>
<td>300</td>
<td>380</td>
<td>660</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>79</td>
<td>82</td>
<td>81</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.8</td>
<td>0.83</td>
<td>0.87</td>
</tr>
<tr>
<td>Motor Weight [kg]</td>
<td>100</td>
<td>103</td>
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</tr>
<tr>
<td>Length [mm]</td>
<td>1740</td>
<td>1615</td>
<td>1828</td>
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<tr>
<td>Rated Current [A]</td>
<td>24.5</td>
<td>18.0</td>
<td>27.5</td>
</tr>
</tbody>
</table>

Besides, a survey was conducted that covers 2600 induction machines utilized in Norwegian offshore industry. The failure distribution is depicted in Figure 2.2. The most frequent failure in IM is caused by bearing fault. The prolonged passage of relatively small electric current, usually due to current leakage, e.g. from shorted lamination, or eddy currents which create fluting and that leads to typical bearing failure. Flutes are deep, exhibit noise, vibration, and fatigue. The second
most frequent failure of IM is produced by the stator winding insulation breakdown. There are three kinds of the stator winding insulation: phase-to-phase (primary insulation system), turn-to-turn (secondary insulation system) and phase-to-ground insulation (ground wall). The main failure root causes of the stator winding insulation deterioration: surges, mechanical stress, contamination, electrical and thermal stress. The third main reason of induction motor failure is broken, cracked or corroded rotor bars which are mainly caused by frequent duty cycle and pulsating mechanical load. These problems require high maintenance facility. Moreover, the induction machines inborn drawback of low starting output torque, high beginning current, and limits induction machine to low torque in speedy applications. For high torque, a mechanical gear is included to coordinate the torque and this will decrease machine efficiency [34-36].

![Failure distribution of offshore induction machines](image)

Figure 2.2: Failure distribution of offshore induction machines[34]

2.1.2 Switched Reluctance Machine (SRM)

The switched reluctance machine (SRM) is a kind of a stepper motor, an electric motor that keeps running by reluctance torque. Dissimilar to basic DC motor types, power is transferred to windings in the stator (case) rather than the rotor. This significantly simplifies mechanical design as power does not need to be delivered to a moving part, but it convolutes the electrical design as some kind of switching system needs to be utilized to provide power to the different windings. With modern
electronic devices, accurately timed switching is not a problem, and the SRM is a famous design for modern stepper motors [37-38].

The fundamental operating principle of the SRM is very straightforward; as current is passed through one of the stator windings. The torque is produced by the propensity of the rotor to adjust with excited stator pole as shown in Figure 2.3. The path of torque created is an element of the rotor position with respect to the energized phase, and is independent of the current flow direction through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase’s excitation with the rotor position. By shifting the number of phases, stator poles, and of rotor poles, a wide range of SRM geometries can be figured out [39-40].

Figure 2.3: Simple 2/2 switched reluctance motor [39]

The geometrical simplicity is one of the main attractive features of SRM. The rotor in SRM does not carries windings, magnets or any kind of conductors while stator is very simple, requiring only singly pitched coil and that are place over salient stator poles. Therefore, these machines can be one of the suitable candidates for the harsher environment based applications [41]. In addition, a four phase switch reluctance machine has been fabricated for ESP as depicted in Figure 2.4. The following machine has outer diameter limited to 139 mm with 8 stator slot and 6 rotor poles. The detailed specification of this developed machine is shown in Table 2.2. The machine draws less current with high efficiency and improved factor. In addition, the SRM provides a power and efficiency comparable to the IM the machine [42].
Table 2.2: Machine specifications for SRM

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Rotor Poles</td>
<td>6</td>
</tr>
<tr>
<td>Number of Stator Slot</td>
<td>8</td>
</tr>
<tr>
<td>Stator Outer Diameter [mm]</td>
<td>139</td>
</tr>
<tr>
<td>Stator Inner Diameter [mm]</td>
<td>70</td>
</tr>
<tr>
<td>Rotor Outer Diameter [mm]</td>
<td>69</td>
</tr>
<tr>
<td>Rotor Inner Diameter [mm]</td>
<td>42.04</td>
</tr>
<tr>
<td>Air Gap [mm]</td>
<td>0.5</td>
</tr>
<tr>
<td>Stack Length [mm]</td>
<td>70</td>
</tr>
<tr>
<td>Motor Speed [r/min]</td>
<td>3000</td>
</tr>
<tr>
<td>Output Power [kW]</td>
<td>2.23</td>
</tr>
<tr>
<td>Peak Current [A]</td>
<td>15</td>
</tr>
</tbody>
</table>

Their fundamental downside and exclusion criterion until now has been the high torque ripple at low speeds and a significant acoustic noise due to high air-gap induction [43]. Additionally, the control of the SRM is more complicated than that of a three-phase drive, due to the high non-linearity of the determination of the current switching angle. Therefore, few SRM has been designed and developed for the functional downhole application [3].
2.1.3 Permanent Magnet Machines (PMM)

Permanent magnet (PM) machines, having higher efficiencies, higher torque densities, and smaller volumes, have broadly been utilized in numerous industrial applications to supplant regular machines, yet few have been developed for the downhole applications due to the low temperature solidness of PM materials in past time. Today, with the improvement of cutting edge technologies and applications of high-temperature magnets, it is progressively fascinating for oil and gas businesses to fabricate PM machines for downhole applications where the machine outer diameters are typically limited to 100–200 mm by well sizes, but the axial lengths can be relatively long [44].

Previously, a Permanent Magnet Direct Current (PMDC) downhole motor with brushes was designed for the downhole application. Its speed is controlled by just changing the DC current from topside, and no Variable Speed Drive (VSD) is required. The fundamental impediment of this motor is that the brushes re-present additional maintenance that is amazingly expensive for seaward applications [3]. In this manner, this kind of motor is for the most part restricted to inland applications. To resolve the issue of brushes, a PM Brushless Direct Current (BLDC) was introduced, shown in Figure 2.5. It has capacity to produced high temperature and can withstand at high temperature around 230°C. Moreover, the outer diameter meter 80mm while axial length is relatively long, with operating torque of 420 Nm and peak power of 20 kW [5]. On the other hand, PM BLDC machine has physically larger size that requires complicated hardware and software for control system with high maintenance [45].

Figure 2.5: PMDC brushless machine for downhole application [5]
An interior PM synchronous machine (IPMSM) has been developed for ESP pump used in downhole application, shown in Figure 2.6. It has outer diameter of 100 mm with 10 rotor pole and 18 stator slots. The IPMSM has high average efficiency of 95.9% with high reliability and simple control. However, it has high cogging torque, ripples torque and requires extra cooling facility to avoid demagnetization [46-47]. Therefore in brief, it can be concluded that the PM machine for the downhole applications holds gigantic guarantee of conveying high torque over entire operation ranges including startup, yet is still in its outset [48].

Figure 2.6: Interior PMSM for downhole application [46]

2.1.4 Flux Switching Machines (FSM)

The alteration of permeance observed by armature with reference to rotor position alters the armature flux between the greatest (high state) and least (low state) values, and proposes another term called “flux exchanging”. Electric machines that work on this rule are known as flux exchanging machines. The hypothetical design of the inductor alternator in view of flux switching has been acknowledged since 1940s [49], yet the scientific approach seems to have come into utilization after 10 years [50]. In [51], a PMFSM, i.e. PM single-phase restricted angle actuator, or all the more outstanding as Laws' relay, has four stator slots and four rotor poles designed, while in [50] it was stretched out to a solitary phase generator with four stator openings, and four or six rotor poles. Inquire about work has been led on these machines for quite a long without utilizing the term flux exchanging [52-53]. Amid the advancement of power electronics technology in the late 1990s, this term was utilized and explored [54-55]. Computer Aided Design (CAD) tools with numeral
investigation exercises, regularly Finite Element Analysis (FEA) utilizing 2D or 3D, contributed a considerable measure in design and examination, and optimisation of switched flux machines. In the course of recent years, numerous novel FSM topologies have been produced for variety of applications, going from economical household appliances, automobiles, wind power, and aviation [56-57].

The basic mechanism of flux switching alternator depicted in Figure 2.7(a) and (b) with a couple of stator winding, a double arrangement of laminated yolks, and a pair of PMs were situated on the stator, while the rotor was appeared as a pair of salient pole with stacks laminations on the shaft. The path flow of flux is highlighted by arrows in Figure 2.7(a) demonstrate the stream of the flux flows from left to right in both windings. At the point when the rotor position was moved by a half-electric cycle, as in Figure 2.7(b), the flux linkage had a similar magnitude yet the direction had been turned around as in Figure 2.7(a). A total inversion of flux was accomplished by each revolution of the rotor. Therefore, the salient pole of the stationary part and stator worked in a customary pulsating flux manner.

Figure 2.7: A single phase switching alternator [50]

There are three classes of FSMs, to be specific permanent magnet FSM (PMFSM), field excitation FSM (FEFSM), and hybrid excitation FSM (HEFSM). They are comprehensively characterized and separated by field flux source i.e. PM or field winding and both PM and field windings, as represented in Figure 2.8 [58].
2.1.5 Various Topology of PMFSM

Over the past decade, PMFSM has become fascinating research interest in various applications mainly due to number of perceived advantages. Since every single active part, for example, armature windings and PM situated on the stator, clear yet feasible machine cooling can be easily associated [59]. Also, additional preferences, such as rigid rotor structure, high torque and flux densities, high efficiency and better flux weakening ability are thoroughly explored and inspected for plentiful applications. Furthermore, the flux produced by PMFSM is fixed and will not change-diverged which means it is constant flux [60-62].

The universal operating principle of the PMFSM is outlined in Figure 2.9(a) and (b), where the dark arrow demonstrates the flux line of PM for instance. In Figure 2.9(a) when rotor pole adjusts to the one of the stator teeth over which a coil is wound, the flux from PM is connected in the coil transfer into the rotor pole. Whereas, in Figure 2.9(b) when rotor advances to adjust to the next stator teeth has a place with a similar coil, the infused flux is stepped back to the stator tooth by the rotor pole, keeping a similar value of flux-linkage while turning the polarity, i.e. accomplishing the flux-switching idea. Therefore, as the rotor turns in forward direction, the flux linkage in the coil will change methodically, actuating back EMF. is manner, if current is appropriately nourished into the coil, an electromagnetic torque will be built up, driving the rotor to move ahead [63-64].

The group of PMFSM have been ceaselessly growing since the primary PMFSM was proposed. Plentiful designs of PMFSMs have been proposed globally by specialists to achieve better attributes of torque, speed, power and efficiency. The advancement and distinct structures have been reviewed in [65]. For low energy axial
fan applications, a single phase PMFSM with the 4/4 stator and rotor poles configuration and modest ferrite magnets was suggested as a cheap solution [66]. while a 2/2 structure with outer diameter of 64mm was presented as potential contender for high speed applications [67]. In these single phase machine, profiled asymmetric air gaps are needed in order to obtain self starting ability.

![Figure 2.9: Working principle of PMFSM (a) flux linkage correspond to one polarity (b) flux linkage switch polarity as the salient pole rotates](image)

Meanwhile, three phase ferrite based PMFSM with 6/4 and 6/5 setups were designed for low-cost medium-speed applications [68] but the major challenges of a ferrite based machine concern the low remnant flux density and low coercive [68]. Furthermore, three phase Nd-Fe-B based conventional 12/10 PMFSM was developed, where each stator tooth is wounded by concentrated armature coil shown in Figure 2.10 (a) [54]. A PM was set between U-shaped laminated segments and the polarity of PM was turned around starting with one magnet then onto the next while a three-phase PMFSM, alternate poles wound windings were explored to be fault tolerant, as appeared in Figure 2.10(b) [69]. In any case, these PMFSMs had the weakness of high magnet volume. To lessen the volume of PM, another structure of E-center PMFSM was produced by supplanting the alternate wound pole with a straightforward stator tooth, as showed in Figure 2.10 (c) [70]. Besides, to upgrade the attributes of E-center PMFSM, the stator tooth was expelled to augment the slot area and thus C-core PMFSM was produced, as represented in Figure 2.10 (d) [71]. In addition, the multi-tooth structure of PMFSM was used to enhance the torque density and lessen magnet utilization, as in Figure 2.10 (e) [72]. A three-phase segmental rotor PMFSM was also explained, as appeared in Figure 2.10 (f).
Figure 2.10: Topologies of PMFSM (a) 12S-10P PMFSM with all poles wound (b) PMFSM with alternate poles wound (c) E-core PMFSM (d) C-core PMFSM (e) Multi-tooth PMFSM (f) Segmental rotor PMFSM all poles wound
A machine with the 12/14 with inner rotor configuration and the conventional laminated structure depicted in Figure 2.11, was proposed for downhole applications. It has PMs in the stator with a doubly salient stator and rotor like a reluctance machine with an outer diameter of 100 mm and an active stack length of 200 mm. The complete design specification of inner rotor PMFSM for downhole application is illustrated in Table 2.3. In terms of performance, it can provide average output torque up to 25 Nm depicted in Figure 2.12 with output power of 2.7 kW. Additionally, it has efficiency of 88% where ambient temperature is 150°C [73]. Apart from this, the high utilization of PM not only increase the weight but also uneconomical with high chances of PM reverse magnetization. Additionally, it utilizes high number of turns that causes high copper losses which degrades efficiency of inner rotor PMFSM.

Figure 2.11: 12slot-14pole inner rotor PMFSM for downhole applications [73]

Table 2.3: 12/14 PMFSM machine design specifications

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Outer Diameter [mm]</td>
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</tr>
<tr>
<td>Stack Length [mm]</td>
<td>200</td>
</tr>
<tr>
<td>Synchronous Speed [r/min]</td>
<td>1000</td>
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<td>Air Gap [mm]</td>
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<td>Stator Slot</td>
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<td>Rotor Pole</td>
<td>14</td>
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<tr>
<td>Winding Factor [mm]</td>
<td>0.6</td>
</tr>
<tr>
<td>Current Density [A_{rms}/mm²]</td>
<td>4</td>
</tr>
</tbody>
</table>
Figure 2.12: Simulated output torque waveform of 12slot-14pole [3]

Keeping in mind the end goal to achieve higher torque density at low speed condition, an external rotor with 12slot and 22pole PMFSM has been proposed for urban electric vehicle propulsion. It has benefits of basically sinusoidal back-electromotive force (EMF) waveforms with high output torque of 25 Nm when phase current is set at 76 A [74]. Furthermore, the external rotor configuration also has lower total weight and cost. The former also has advantages such as ease of installation, maintenance and cooling [75]. Therefore, the outer rotor structure can be more suitable candidate in offshore applications when compared to inner rotor PMFSM [76].

2.1.6 Modeling Techniques for PMFSM

Today, with constantly expanding research interest in PMFSM, several modeling strategies have proposed and developed. Modeling techniques for the PMFSM can be classified into two different groups: the analytical and numerical. The analytical approaches are normally developed for particular geometry and topology can always facilitate prompt evaluations which can make them ideally suited for preliminary design and multi-parameter optimization. The closed form analytical approach can barely be accomplished for the PMFSM owing to its doubly-salient and highly-saturated nature [77]. A simplified analytical model based sizing procedure for the typical 12/10 PMFSM was presented and just sufficiently precise for the preparatory sizing and design [78]. In addition, magnetic equivalent circuit (MEC) methods have been broadly utilized to model the magnetic field of the PMFSM more machines more precisely. A nonlinear adaptive lumped MEC model has been developed for
12/10 PMFSM in order to anticipate the electromagnetic performance, i.e., the air-gap field distribution, the phase flux linkage and back-EMF, the self- and mutual inductances, the d- and q-axis inductances, and the electromagnetic torque [20]. Moreover, different nonlinear MEC models are built up for the PMFSM with 12/10 and 12/14 [79-80] topologies. It would include a lot of work to develop such expound MEC models for the assigned PMFSM, and henceforth variable global reluctance networks which can gather, adjust, and illuminate MEC models of various parts of the PMFSM quickly are proposed to limit the endeavors included [81]. All in all, the analytical strategies from the literature are limited to the most widely recognized setups of the PMFSM.

These days, FEA has been routinely utilized to anticipate the performance of the electrical machines because of the advances in development instruments and computer innovation. For the PMFSM, FEA has practically turned into the standard numerical modeling tool and been utilized as a part of all the current writing about the PMFSM either to approve the analytical methods or to straightforwardly assess the machine performance. For the radial flux, 2-D FEA is the most well-known numerical technique as it can convey sensibly precise outcomes with generally short computational time [82], while the tedious 3-D FEA is completed to represent the discernible end impacts [83]. Most importantly, FEA has been the standard of modeling since the PMFSM initially presented decades prior.

2.2 Optimization Approaches for PMFSM

In spite of the fact that the literature introduced are mainly concentrated on modeling strategies and topologies of PMFSM, they pretty much cover some examination or optimization of specific machines too. However, there are many literary works particularly dedicated to the optimization of certain qualities in PMFSM. A variety of research has been committed to the examination and reduction of the electromagnetic losses, such as eddy current losses, lamination iron losses and winding proximity losses in the PMFSM [84-86]. Additionally, the flux weakening capacity was considered during the design phase of a 12/10 PMFSM [64], while the back-EMF waveforms were investigated and optimized for both radial-flux and axial-flux PMFSM [87-88].
REFERENCES


