Design Enhancement and Performance Examination of External Rotor Switched Flux Permanent Magnet Machine for Downhole Application

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Abstract. The recent change in innovation and employments of high-temperature magnets, permanent magnet flux switching machine (PMFSM) has turned out to be one of the suitable contenders for seaward boring, however, less intended for downhole because of high atmospheric temperature. Subsequently, this extensive review manages the design enhancement and performance examination of external rotor PMFSM for the downhole application. Preparatory, the essential design parameters required for machine configuration are computed numerically. At that point, the design enhancement strategy is actualized through deterministic technique. At last, preliminary and refined execution of the machine is contrasted and as a consequence, the yield torque is raised from 16.39Nm to 33.57Nm while depreciating the cogging torque and PM weight up to 1.77Nm and 0.79kg, individually. In this manner, it is inferred that purposed enhanced design of 12slot-22pole with external rotor is convenient for the downhole application.

1. Introduction

To empower safe, economical and eco-accommodating economical answer for upgrading oil and gas productivity from deep water repositories, new downhole technologies are recommended. Since the electric machine is the heart of downhole application because more than 30% of electrical system failure happens in the machine appeared in Table 1[1]. The machine must bear the characteristics of high reliability, better proficiency, high torque & power density and simple control.

The present standard electrical downhole machine is induction machine which is modestly inefficient. Moreover, the characteristic inadequacy of low beginning torque and high beginning current limits induction machine to low-torque, high-speed applications. In applications where high torque is required, a mechanical gear is consistently added to coordinate the torque, this not simply additionally decreasing the system efficiency, likewise, degrades the system resolute quality [2]. Besides, permanent magnet (PM) machines having higher efficiencies, higher torque densities and smaller volumes, are for the most part used in present day applications to supplant customary machines, however few have been developed for the downhole applications in view of the high climatic temperatures in deep underwater wells and the low-temperature stability of PM materials over the time. Today, with the developments in cutting-edge innovations and uses of high-temperature magnets, it is continuously interesting for oil and gas organizations to develop PM machines for downhole applications [3]. 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 easy to control since it doesn't require variable frequency drive (VFD). Although, it has a couple of drawbacks, for instance, the commutator framework in PMDC not just presents the complexity in assembling, extra losses over the brushes and furthermore causes frequent failure. Besides, regular replacement is required each 2-3 years [4]. With a specific end goal to overcome the issue of brushes, a brushless interior permanent magnet synchronous machine (IPSM) was created yet it requires extra cooling facility [5].

The switched flux permanent magnet machines have a short history and are a decently unfamiliar breed of PM machines. The early PMFSM was represented as a single phase (1φ) alternator in 1955 applying a low-performance magnet while a three phase (3φ) machine was exhibited in 1997 where ferrite was grasped to analyze the flux centering impact [6-7]. More recently, there have been resuscitated research interests in PMFSM, doubtlessly in view of a number of perceived advantages. Since all active parts, for example, armature windings and PM put on the stator, clear yet feasible machine cooling can be easily associated [8]. In addition, supplementary preferences such as powerful rotor construction, high torque and flux densities, high efficiency and superior flux weakening capacity are thoroughly investigated and inspected for various applications [9-11].

Setting the rotor on the outer surface will deliver more torque, appeared differently in relation to the conventional inner rotor [12]. Nevertheless, examination on the PMFSM has, generally, fixated on the electromagnetic examination and optimization of the internal rotor type machines with barely gave attentive consideration to the outer rotor PMFSM [13-15]. This paper basically centered on design enhancement and efficiency analysis of external rotor PMFSM for the downhole application. Firstly, key design specifications are determined by using sizing equations then it is modeled and simulated on 2D-FEA Finite Element Analysis (FEA) package, JMAG-Designer ver.14.0. The intended configuration can't generate torque of 25 Nm. Consequently, the machine is refined through the deterministic approach where design free parameters are modified with a specific end goal to upgrade the output of the machine. Finally, the performance correlation of introductory and enhanced design including efficiency analysis is completed in the last section.

### Table 1 Component failure in ESP system for the downhole application [1]

| Components  | Failure Percentage |
|-------------|--------------------|
| Assembly    | 1                  |
| Cable       | 21                 |
| Sensor      | 1                  |
| Pump        | 30                 |
| Gas Handler | 1                  |
| Motor       | 32                 |
| Intake      | 4                  |
| Protector   | 10                 |
| Other       | 1                  |

#### 2. Sizing Equation for External Rotor PMFSM for the Downhole Application

The fundamental design parameters are compelled by geometric relationship, explained in an amplified local structure appeared in Figure. 1(a). The stator opening should be even multiple of phase numbers. In this way, the connection between stator slot number and \( N_s \), rotor pole number \( N_r \) is [16]

\[
N_r = \frac{(12 \pm n) \times N_s}{6}
\]  

(1)
where \( n \) is a positive whole number which should not to be multiple of three. So as to accomplish zero resultant magnetic force, \( N_r \) is selected to be even number. The key design parameters, for example, rotor pole arc width \( \beta_r \), stator tooth arc width \( \beta_s \), stator armature opening arc width \( \beta_{slot} \), and permanent magnet arc width \( \beta_{pm} \) are preparatory settled as:

\[
\beta_r = \beta_s = \beta_{pm} = \frac{\beta_{slot}}{3} = \frac{\pi}{3N_s} \quad (2)
\]

Simultaneously, supplementary interconnection of stator inner radius \( R_{si} \), and outer radius \( R_{so} \), stator back length \( h_{ys} \) and rotor yoke length \( h_{yr} \) are basically resolved at:

\[
R_{si} = \frac{R_{so}}{2} \quad (3)
\]

\[
h_{yr} = 1.5^* h_{ys} \quad (4)
\]

Hence, the ratio between stator inner radius and stator outer radius is 0.5. Moreover, to get adequate rotor saliency, the rotor pole height \( h_{pr} \) is decided as:

\[
h_{pr} = \frac{R_{so}}{8} \quad (5)
\]

Additionally, coil number of each phase \( N_c \) and stator slot winding area \( A_{slot} \) can be calculated as:

\[
N_c = \frac{N_s}{m} \quad (6)
\]

\[
A_{slot} = \frac{R_{so}^2 \sin \left( \frac{\pi}{2N_s} \right)^2}{2 \tan \left( \frac{\pi}{N_s} \right)} \quad (7)
\]

Where, \( m \) is the phase number. Beside this, the number of turns \( N_a \) for one stator slot and peak injected current \( I_m \) in each coil can be computed as:

\[
N_a = \frac{2A_{slot}^* \alpha}{\pi d^2} \quad (8)
\]

\[
I_m = \frac{J_a A_{slot}^* \alpha}{2 N_a} \quad (9)
\]

Where, \( \alpha \) represents filling factor while \( d \) and \( J_a \) stands for diameter of wire and peak injected current density respectively. Finally, the rotor outer radius can be derivated as:

\[
R_{ro} = \left( \frac{9}{8} + \frac{\pi}{2N_s} \right) * R_{so} + g \quad (10)
\]

The design specifications are illustrated in Table 2 while complete schematic of machine is depicted in Figure 1(b). It can be observed that 80% area of the initial machine design is occupied by stator which is valid according to outer rotor PMFSM design principle [17]. In electric prospective view, the motor rotation through \( 1/N_r \) of a revolution, the flux linkage of armature has one periodic cycle and thus, the frequency of back-EMF induced in the armature coil is \( N_r \) times of the mechanical rotational frequency. In general, the mechanical rotation frequency, \( f_m \) and the electrical frequency, \( f_e \) for the proposed machine can be expressed as in Equation 11 and end time, \( t \) is calculated using Equation 12.
\[ f_e = N_r f_m \]
\[ t = \frac{1}{f_e} \]

Fig. 1. (a) Magnified local structure (b) Complete schematic of outer rotor PMFSM

| Parameters                        | Abbreviation | Value | Units  |
|-----------------------------------|--------------|-------|--------|
| Number of stator slots            | \( N_s \)    | 12    |        |
| Number of rotor poles             | \( N_r \)    | 22    |        |
| Rotor outer radius                | \( R_{ro} \) | 50    | mm     |
| Rotor inner radius                | \( R_{ri} \) | 40.5  | mm     |
| Stator inner radius               | \( R_{si} \) | 20    | mm     |
| Stator outer radius               | \( R_{so} \) | 40    | mm     |
| Stator back length                | \( h_{ys} \) | 3     | mm     |
| Rotor yoke length                 | \( h_{yr} \) | 4.5   | mm     |
| Rotor pole arc width              | \( \beta_r \) | 5     | \(^\circ\) |
| Stator tooth arc width            | \( \beta_t \) | 5     | \(^\circ\) |
| Permanent magnet arc width        | \( \beta_{pm} \) | 5     | \(^\circ\) |
| Slot area                         | \( A_{slot} \) | 50.732 | mm²   |
| Air gap                           | \( g \)      | 0.5   | mm     |
| Stack length                      | \( l \)      | 200   | mm     |
| Number of Turns                   | \( N_a \)    | 33    |        |
| Synchronous speed                 | \( \omega \) | 1000  | r/min  |
| Armature current density          | \( J_a \)    | 30    | A/mm²  |
| Split ratio                       | \( \lambda \) | 0.8   |        |
3. Design Enhancement Technique

The yield torque acquired from the introductory design of 12slot-22pole external rotor PMFSM for the downhole application is 16.39Nm which is a long way from the focused target. In understanding the frail execution of proposed machine and its potential capacity to accomplish even superior performance, therefore design complementary parameters, L1 to L7 represented in rotor and stator sides as illustrated in Figure. 2, these parameters will be enhance through deterministic approach, so the optimal torque can be generated. Pertaining to the figure, the design parameters are classified into groups such as those identified with rotor core, PM shape, and armature coil slot shape. The rotor parameters are rotor radius (L1), rotor pole width (L2), and rotor pole height (L3). The PM shape parameters are PM width (L4), PM radial length (L5) while armature coil slot consist of armature coil width (L6), and armature coil height (L7), respectively.

![Design Parameters of 12slot-22pole for Design Enhancement](image)

The deterministic approach is applied to discover the best performance of machine by changing the design complementary parameters while placing the air gap, motor external radius and stack length steady all through the refinement procedure. The flow chart of the deterministic technique is portrayed in Figure. 3. The refinement strategy starts by refreshing rotor parameters L1, L2 and L3 separately while L4 up to L7 are kept consistent. Essentially, rotor radius, L1 is dealt with at the primary spot in a sense to figure out the perfect estimation of split ratio since it has fundamental impacts on average output torque. The finest L1 result is then conveyed forward and continually unaltered while treating rotor pole width, L2. Correspondingly, the précised L2 result will be kept as the rotor pole height, L3 is experiencing improvement process. In various applications, high use of PM originates the unacceptable effects of high cogging torque that can disturb execution of the machine. Henceforth it is obligatory to describe the finest estimation of PM in machine designing. This could be conceivable by reshaping PM width L4 while keeping different parameters steady. Then the next step is to adjust PM radial length L5 because it influences the torque characteristics, loss, and efficiency. Finally, armature coil height, L6 and armature coil width, L7 are modified in order to oblige the whole number of turns, Na for armature coil. The increment in the number of turns will leads to higher average electromagnetic torque. Although, armature current density remains same but slot area has been enlarged.

The above-mentioned design enhancement method is treated repeatedly for several number cycles until maximum torque is achieved. The comparison between the initial and final design parameters are listed in Table 3.
Fig. 3. Work flow diagram of deterministic method

| Abbreviation | Parameters                           | Initial  | Improved |
|--------------|-------------------------------------|----------|----------|
| L1           | Rotor inner radius [mm]             | 40.5     | 43.5     |
| L2           | Rotor pole width [mm]               | 3.49     | 4.4      |
| L3           | Rotor pole height [mm]              | 5        | 3.5      |
| L4           | Permanent magnet width [mm]         | 3.49     | 1.9      |
| L5           | Permanent magnet length [mm]        | 20       | 23       |
| L6           | Armature slot width [mm]            | 10.41    | 13.94    |
| L7           | Armature slot length [mm]           | 17.26    | 21.20    |
| g            | Air gap [mm]                        | 0.5      | 0.5      |
| $A_{slot}$   | Armature slot area [mm$^2$]         | 50.73    | 89.16    |
| $W_{pm}$     | Permanent magnet width [kg]         | 1.26     | 0.79     |
| $T_{avg}$    | Average torque [Nm]                 | 16.39    | 33.57    |
4. Performance Capability of Initial and Refined Design
The execution examination is finished under open circuit and close circuit. The no load examination consolidates flux linkage and distribution, cogging torque and initiated voltages while load investigation comprises of average output torque, torque-power versus speed characteristics, and efficiency inspection.

4.1. Magnetic Flux Linkage at Open Circuit Condition
For introductory and improved design, the aggregate flux in the machine is produced by PM just when the rotor is pivoted at speed of 1000r/min while the armature current density is settled at 0A/mm². From the Figure. 4, in improved design, the u-phase flux linkage of external rotor PMFSM has been extended to 0.2Wb which is two times of preparatory design. The flux is multiplied because the rotor pole height is abbreviated so it implies the flux will set aside shorter time to finish one cycle.

![Fig. 4. U-phase flux linkage of initial and refined design](image)

4.2. PM Flux Distribution
The target of flux circulation is to control the flood of flux while checking the effect of flux saturation in the machine. In the interim, Figure. 5(a) demonstrates that underlying design encounters leakage and flux cancellation impact highlighted in red circles. After usage of deterministic streamlining method, the spillage element is enhanced from 0.75 to 0.95 while wiping out the impact of flux cancellation portrayed in Fig. 5(b). In addition, the maximum flux density decreased to 2.0T in order to provide better room for flux to be thoroughly distributed.

![Fig. 5. Flux circulation at 1000r/min (a) Initial design (b) Improvised design](image)
4.3. Detent Torque
Cogging torque is additionally known as no-current torque that makes commotion and fluctuation in machine operation. The PM produced cogging torque examination for one electrical cycle is represented in Figure. 6. The output waveform of cogging torque has 6 cycles that are resolved as [18]

\[ N_p = \frac{N_r}{HCF[N_r, N_S]} \quad (13) \]

\[ N_e = \frac{N_p N_S}{N_r} \quad (14) \]

The preliminary outline of external rotor PMFSM for the downhole application with 12slot-22poles has high peak to peak cogging torque of around 3.2Nm which is lessened to 1.74Nm after refinement because of decrement in PM weight.

![Fig. 6. Cogging torque of 12slots-22pole](image)

4.4. Back-Emf for One Electric Cycle
Advance examination of both outlines on back-Emf at open circuit circumstance is completed at the speed of 1000 r/min. The results gained for back-Emf are plotted in Figure. 7. The enhanced outline has higher initiated voltages than the underlying plan in light of the way that the instigated Emf \( E \) is straightforwardly relative to the flux linkage \( \Phi \), showed in Equation 15 while \( k \) is the consistent esteem, relies on the machine geometry and \( \omega \) is speed.

\[ E = k\Phi\omega \quad (15) \]

Further, initiated voltages of upgraded configuration are more noteworthy than applied voltages yet can be utilized for regenerative braking mechanism with a specific end goal to charge the source.

![Fig. 7. Induced voltage waveform at 1000r/min](image)
4.5. Average Electromagnetic Torque at Distinct Armature Current Densities

The average output torque of implied arrangement can be figure out as [19]

\[
T_{avg} = \frac{\pi}{8} N_r K_d B_G J_a A_{slot} R_{so} l \alpha
\]

where \( B_G \) is utmost air gap flux density at open circuit analysis, \( K_d \) serves as leakage factor which is firmed at 0.75 for starting design while for enhanced outline it is 0.95. The outcomes obtained from estimations and simulations are plotted in Figure. 8, in which armature current density for downhole application is shifted from 0A/mm² to 5A/mm².

![Fig. 8. Comparison of output torque at various \( J_a \)](image)

4.6. Torque-Power versus Speed Characteristic Curve

For starting and refined outer rotor PMFSM for the downhole application, the torque and power versus speed curve is plotted in Figure. 9(a) & (b). At the base speed 2406.55r/min and 973.32r/min, the maximum torque of 16.39Nm and 33.57Nm is obtained and torque start to decline if the machine is operated beyond the base speed. The power accomplished by preliminary and improved design is 4.13kW and 3.84kW respectively. The improved design has less power than initial design but it is still above the targeted value.

![Fig. 9. Torque and power against speed analysis (a)Initial (b)Enhanced](image)
4.7. Machines Losses and Efficiency Prediction

The machine copper losses in the armature coil, iron losses in all laminated cores, and efficiency are figured by 2D-FEA. The equation used to ascertain the copper losses is as per the following [20]

\[ P_c = (2L + 2l) J_d * I * N * N_{slot} \]

(17)

where \( P_c \), and \( L_{end} \) are copper losses and approximated end coil length, respectively, while \( J, I, N \) and \( N_{slot} \) are armature current, current density, number of turns, and number of slots and \( \rho \) is copper resistivity, having a consistent estimation of 2.224 × 10⁻⁸ Ωm.

The specific working point’s at most extreme torque and customary working point under light load driving condition noted as No. 1 to No. 8 are previously indicated in torque-power versus speed chart for starting and upgraded design. In the interim, the detail losses analyses and machine efficiency of the initial and enhanced designs are delineated in Figure. 10 (a) and (b). Specifically, point 1 and 2 serve as the most extreme operating torque and speed of both designs while point 3 up toward point 8 falls under the comparative normal working points of beginning and enhanced designs. At each design's base speed where most noteworthy torque is adept, the refined machine design radiates an impression of being the most astonishing efficiency of 94.74% regardless of the fact that it has the most copper losses, trailed by beginning machine design with 92.08%. Other than this, while running at the typical working points, the most extreme efficiency is obtained for enhanced outline at point 5 with the result of 95.57%.

5. Conclusion

This research work has presented the characteristic investigation and performance examination of external rotor PMFSM for the downhole application. The enhancement strategy has been precisely illustrated for the achievement of intended performance. As a result, the enhanced machine has better output torque, efficiency and low cogging torque when distinguished with the introductory design. The refined machine configuration has improved roughly 51.17% of average output torque while reducing the PM weight by 37.3%. The reduced in PM weight makes machines lighter and easy to develop prototypes for the downhole application. Lastly, it can be closed with all the expository review that enhanced design of external rotor PMFSM is one of the outstanding candidates for the downhole application.

Acknowledgement

This research effort was encouraged by Research, Innovation, Commercialization and Consultancy (ORICC) UTHM, Batu Pahat under Vot number U519 and Ministry of Higher Education Malaysia (MOHE)
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