A Comparison of Electric Motors for Electrical Submersible Pumps Used in the Oil and Gas Industry

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Abstract. Where the pressure in oil or gas reservoir is not sufficient, in order to increase the production rate, an artificial lift method is required. There are several methods for obtaining artificial lift, including gas injection and electrical submersible pumps. Electrical submersible pumps are more controllable, offer faster installation, and are more economic than other methods, especially for vertical and deviated wells. Electrical submersible pumps systems consist of several parts, including the pump, an electric motor, cables, and a control board. The electric motor plays an important role in an electrical submersible pump system, and it must produce high torque under high temperature and high-pressure conditions. For small diameter wells, there is also a constraint on the motor diameter. These harsh conditions and constraints require special motors. In this article, the desired criteria for such a motor for this application are represented; then, a comparison is made among several types of motors, including induction motors and various permanent magnet motors, and the resulting best choices are proposed.

1. Introduction

Usually, oil and gas reservoirs have sufficient pressure to overcome gravitational and friction force and provide appropriate production rates. However, some reservoirs do not have enough pressure; additionally, the pressure of a reservoir at the end of a well may be reduced after a period of production. Under these conditions, an artificial lift must be used to obtain the desired production rate[1]. Various artificial lift methods exist, such as the gas injection or gas lift[2], sucker rod pump[3], hydraulic jet pump[4], progressive cavity pump (ESPCP)[5], and electrical submersible pump (ESP)[2]. Different methods have different advantages and disadvantages, and each method can be useful under certain conditions. However, researchers have indicated that ESP is likely to increase due to the benefits of ESP such as its usability in vertical and deviated wells, easy installation and operation, low cost at high volume, and controllability[6].

ESP systems include two categories of equipment: that installed and operated on the surface, known as surface equipment; and equipment installed and operated in the wells, known as underground equipment. As indicated in figure 1, the surface equipment consists of an electric power supply, a transformer, a control board, and a control valve, and the underground equipment comprise a centrifugal pump, an electric motor, cables, and sensors[7]. The electric motor is an important part of the ESP system that can extensively affect ESP performance. Thus, designers of such systems require a set of complete and accurate criteria to select the correct motor type. Since the first uses of ESP, and until very recently, only three phase and two pole squirrel-cage induction motors (I.Ms) were used in
ESP systems[8],[9]. Most other motor types didn't work under the harsh working conditions required, especially the high temperatures. Recently, however, advanced technology and materials have been developed which have enabled other electric motors can work at high temperatures, and thus the interior permanent magnet motor (IPM) is now used for ESP for some wells[10].

Figure 1. ESP system schematic [7]

In this article, the electric motor working conditions for ESP are reviewed and the requirements of the electric motor identified; then, the characteristics of several electric motor types are studied and compared within this paradigm.

2. Motor working conditions
Oil and gas reservoirs are usually located at a depth over 12,000 ft.[8]. This requires the creation of very deep wells to produce oil or gas. The electric motors of ESPs are usually located at the bottoms of these wells, which have high temperatures due to the increased well depth. Furthermore, these wells are frequently of limited diameter, and thus the maximum diameter of the ESPs is similarly limited[11]. The diameter limitation causes a motor length increase to provide the required power such that the length to diameter ratio is unusual. In addition, a very long cable is necessary to provide electric power for the electric motor at the bottom of well. Voltage drop control is very important on such a long cable, and thus current amplitude and frequency must be minimised, especially during starting-up.
In addition, ESP replacement is relatively expensive[11]; therefore, robustness, reliability, and overall lifetime are very important factors.

3. Motor selection criteria and requirements
As introduced in the previous section, the first requirement of the motor is the ability to work at high temperatures. Permanent magnets (PM) are very sensitive to temperature and the probability of
demagnetisation is increased when the temperature is high, creating a constraint for using permanent magnet motors (PMMs) on ESP for a long time. PMs have, however, now been developed that can work more easily at high temperatures. A high-temperature PM B-H curve is represented in figure 2[12].

![Figure 2. An example of a high-temperature PM B-H curve [12]](image)

Diameter constraints lead to high power and torque density becoming requirements. Furthermore, good motor efficiency and power factor are also requirements, as higher efficiency and power factor cause a reduction in voltage drop along the required long power cable, as well as reducing power losses to the electric motor, thus reducing the temperature gradient of the motor. If the outside temperature is specified, then a reduction of the temperature gradient causes a reduction in the internal temperature, which can increase insulation lifetime; temperatures rising by 10 degrees can cause insulation lifetime be halved[13].

As mentioned above, reliability and lifetime are very important parameters, and these parameters depend on factors such as insulation and motor structure, including components such as robust rotors. Motor robustness is thus one of the key criteria for motor selection; other important criteria include low start-up current, soft-start ability, and controllability.

4. Motor types and specifications
In general, electric motors can be classified into three categories: radial flux, axial flux, and transverse flux. An axial flux motor can be optimised when the length to diameter ratio is low. This means that many rotors and stators must be used to provide the required power and torque at a limited diameter. An example of an axial flux motor with multi-rotor and stator is represented in figure 4. However, it is difficult to supply and control such a motor within a deep well; this motor also has lower reliability. This suggests that axial flux and transverse flux structures are not suitable for use in ESP applications. Further, some previous literature focused on these types of motors deduced that axial flux and transverse flux motors are not suitable for high speed and speed applications (such as ESP)[14] because of their low torque, and efficiency, reliability, and robustness issues.
The output torque equations for radial flux permanent magnet, axial flux permanent magnet, and transverse flux permanent magnets are represented in equations (1) to (3).

\[
T = \frac{1}{2} k_t \pi S B_{g1} D_0^2 \lambda^2 L \quad \text{for RFPM} \tag{1}
\]

\[
T = k_t \pi S B_{g1} \lambda \left(1 - \lambda^2\right) \quad \text{for AFPM} \tag{2}
\]

\[
T = \frac{1}{2} k_{\sigma} k_t m \pi S B_{g1} D_0^2 \lambda^2 l_m \quad \text{for TFPM} \tag{3}
\]

where \( S, k_t, B_{g1}, L, D_0, D_1, R_{sto}, p, m, k_\sigma \) and \( l_m \) are electrical loading with unit A/m, machine constant that depends on both the actual airgap flux density distribution and the winding arrangement, the RMS value of the fundamental airgap flux density, the active length of the machine windings, the machine outer-stator diameters, the machine inner-stator diameters, the outer-stator radius of the AFPM machines (dependent of pole number and evaluated by (5)), pole number, phase number, the flux leakage factor representing the amount of flux from the airgap to the stator teeth and the magnet depth in the TFPM machine, respectively.

\[
\lambda = \frac{D_1}{D_0} \tag{4}
\]

\[
R_{ox} = \begin{cases} 
\frac{D_o}{2} & : \text{NN type} \\
\frac{\sin \left(\frac{\pi}{p}\right) + \cos \left(\frac{\pi}{p}\right)}{p B_{sat} D_0} & : \text{NS type} \\
\frac{2 p B_{sat} + B_g \alpha_{pm} \pi (1 + \lambda)}{2 p B_{sat} + B_g} &
\end{cases}
\tag{5}
\]

where \( \alpha_{pm}, B_{sat}, \) and \( B_g \) are the magnet coverage, the iron saturation flux density, and the flux density in the air gap over the magnets, respectively.

To compare radial flux, axial flux, and transverse flux structures for ESP applications, several parameters must be assumed as constraints as seen in table 1.

**Table 1. Assumed constraints [14]**

| Parameters                  | Values       |
|-----------------------------|--------------|
| Well diameter               | 100mm        |
| Machine axial length        | 0.1–1m       |
| Saturation flux density     | 1.8T         |
| Air gap                     | 1.5 mm       |
| Ambient temperature         | 150°C        |
| Speed                       | 1000rpm      |
| Copper conductivity@20 ºC   | 1.72 \(10^8\)Ω/m |
| Current density             | 4A/mm²       |
| Electrical loading          | 20 kA/m      |
| PM remanence @20ºC          | 1.2T         |
| PM temperature coefficient  | -0.00045K⁻¹  |
| Specific loss factor        | 2.7W/kg      |
| Winding fill factor         | 0.6          |
| Temperature coefficient (Cu)| 0.0039 K⁻¹   |

By considering these constraints, a comparison of efficiency and torque density among RFPM, AFPM, and TFPM can be represented, as in figure 3. The other criteria for comparison of these motors are compared in table 2. These comparisons show that radial flux may be a suitable structure for ESP applications. Thus, to continue the comparisons among motor types, the radial flux structure is selected.
Table 2. A comparison among Radial-, axial- and transverse-flux motor

|                      | Limited diameter | Reliability | Controllability | Robustness | High speed |
|----------------------|------------------|-------------|-----------------|------------|------------|
| Radial flux          | Good             | Good        | Good            | Good       | Good       |
| Axial flux           | Poor             | Poor        | Poor            | Poor       | Poor       |
| Transverse flux      | Poor             | Poor        | Poor            | Poor       | Poor       |

Radial flux motors can be further classified into DC motors, IMs, brushless DC (BLDC) motors, and brushless AC (BLAC) motors. The reliability and efficiency of DC motors are low compared with other electric motor types. In this section, four motor types, IM, PPM, hysteresis interior permanent magnet (HIPM), and flux switching permanent magnet (FSPM) are studied and compared.

Figure 3. Torque density with respect to the axial lengths and pole numbers (a) RFPM (C) AFPM and (e) TFPM. Efficiency with respect to the axial lengths and pole numbers (b) RFPM (d) AFPM and (f) TFPM. [14]
4.1 Induction Motors

The IM was the first motor used for ESP[15],[16],[9],[17]. Figure 5 shows a sample schematic of a multi-rotor IM used for ESP[18]. This motor type has a simple structure and is easy to manufacture. It can also be designed for very high temperature use, as it has only insulation limitations in terms of working at high temperatures. The IM also has starting torque, and thus does not need a driver to start. Average performance curves of IM on ESPs are represented in figure 6. However, while the IM has some advantages and is used frequently in ESP, it is not always the best choice for this application because of its disadvantages, including a low power factor and efficiency[16]; the probability of shaft breakdown especially during start-up[1]; high inrush current on starting[17]; low reliability of the ESP driven; and a short lifetime[19].

Figure 4. A sample of multi-rotor and stator axial flux motor [20]

Figure 5. Cross-section of a typical multi-rotor IM[18]

Figure 6. Average induction motor performance curves on an ESP application [21]
4.2. **Permanent Magnet Motors**

Recently, PMMs have been used in some ESPs[10],[6]. A sample of PMM for ESP application is shown in figure 7[10]. PMM has several benefits over IM, including better efficiency and an improved power factor, with higher power and torque density, and a reliable driver[16],[17]. PMM advantages as compared with IM are represented in figure 8. However, the PMM also has some disadvantages, including no starting torque[1],[19], a high probability of PM demagnetization especially at high temperature[22], and a requirement for accurate control[1]. To study the effect of temperature on PMMs, a variation of maximum torque per Amp vs. current amplitude and angle at different temperatures is represented in figure 9. This figure illustrates the negative effects of high temperatures on motor performance.

![Figure 7. Schematic of PMM [10]](image)

**Figure 7.** Schematic of PMM [10]

![Figure 8. Comparison of PMM and I.M[10]](image)

**Figure 8.** Comparison of PMM and I.M[10]
4.3. Hysteresis Interior Permanent Magnet Motors

Recently, a new structure that combines a hysteresis motor and an IPM motor, known as a hysteresis interior permanent magnet motor (HIPM), has been proposed for use in ESP[1],[19]. In this motor type, the stator is like IPM and the hysteresis ring is added to the rotor. The structure of the rotor of the HIPM is shown in figure 10. This offers many of the IPM benefits and improves some IPM disadvantages, for example, increasing the starting torque (see figure 11) and reducing the required accuracy of the rotor position for the motor drive[1],[19]. A performance analysis of HIPM is given in figure 12. However, this design has not been fully tested[19], and other disadvantages have not really been studied. It also retains some of the disadvantages of IPM such as a high probability of demagnetization. In addition, the structure has more complexity than IPM and allows minimal space to place PMs on the rotor.

Figure 9. Variation of maximum torque per Amp versus current amplitude and angle at different temperatures [23]

Figure 10. Schematic of HIPM rotor[1]

Figure 11. IPM and HIPM run-up responses for high inertial load[24].
Figure 12. Performance analysis of HIPM: (a) efficiency and (b) power factor[24].

4.4. Flux switching Permanent Magnet Motors

FSPM is a new motor that is proposed for use in ESPs[11]. A sample of FSPM structure is shown in figure 13[25]. In this motor type, both PMs and armature coils are placed on the stator; this topology increases the robustness of rotor, creating no need to protect the PMs against centrifugal force and reducing the working temperature of the PMs. Figure 14 shows how the magnets in FSPM structure are placed in the lower temperature position rather than in positions on the rotor, as well as reducing the armature effect on PMs due to the coils' field being perpendicular to the PMs' fields[11]. While FSPM has better specifications than IPM, it still has some disadvantages, such as requiring a higher frequency to provide the same speed[26]. It is also not fully tested for this application (like HIPM) and thus may have unknown disadvantages.

The motors types are ranked in table 3. The ranking is ascending; rank 1 for each criterion has the highest value.

| Table 3 Radial flux motors ranking |
|-----------------------------------|
| IM      | PMM     | HIPM    | FSPM    |
| Starting torque | Reliability | Controllability | Robustness | High speed | Efficiency & power factor | Power/Torque density | Resistant to temperature |
| IM      | 1       | 2       | 3       | 2         | 2          | 3                        | 4           | 1                        |
| PMM     | 3       | 3       | 1       | 3         | 3          | 1                        | 1           | 3                        |
| HIPM    | 2       | 3       | 1       | 3         | 3          | 2                        | 3           | 3                        |
| FSPM    | 4       | 1       | 2       | 1         | 1          | 2                        | 2           | 2                        |
The procedure for motor type selection is represented in figure 15.

**Figure 15.** Chart of motor type selection for ESP applications

5. **Conclusion**

In this article, ESP working conditions were delineated and the criteria for the required electric motors studied. Several motor types were investigated, and it was found that axial flux and transverse flux motors are not suitable for ESP applications. Of the remaining radial flux motor types, the DC motor was also found to be not suitable for this application. IMs have some disadvantages, but until recently, only this type of motor has been able to work in very high-temperatures. Other motor types that use PM in their structures can work at lower temperatures, with a modern maximum of about 230 °C.

If the maximum temperature of working in a well can be made acceptable for PMMs, they can provide better characteristics than IMs. In terms of PM motor structures, PMMs are used in ESPs for some wells, while other structures have not yet been used; researchers are currently working on these options, though HIPM and FSPM do appear to offer the potential for better properties. HIPM has starting torque and does not require accurate rotor position control, whereas FSPM offers a more robust rotor and has a lower probability of demagnetisation.

6. **References**

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