A Review on Electrical Submersible Pumping System

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***Abstract*— Electrical Submersible Pump (ESP) is one of the efficient lifting methods for oil, gas and water which is widespread around the world. ESP System (ESPS) consists of several components: surface components and underground components. The surface components include an electric power supply, a transformer, a control board, and a control valve. The underground components include a centrifugal pump, an electric motor, a cable, and sensors. The existence of the components down the well exposes the system to severe challenges. The challenges that must be taken into account are several, such as depth, high temperature, high pressure, limited well diameter, corrosive surrounding material, high flow rate and high power consumption. In this paper, a comprehensive review of the ESPS is presented. It aims to provide a broad perspective on the various components of the ESPS and the trends to tackle the challenges of this type of systems.**

Keywords—Electrical machines, electrical submersible pump, adjustable speed drive.

I. Introduction

The natural flow rate of the wells stops when the pressure at the bottom is not enough to overcome the pressure losses along the path toward the surface. Lifting methods are used to lift the oil from deep wells and increase the production rate. ESP is one of the lifting methods that was invented in the late 1910s [1]. It is distinguished by its controllability, usability in different types of wells, efficiency, low maintenance requirement, high production rate and adaptability to highly deviated wells [2]. The components of the ESP system (ESPS) are placed in two main spots: at the bottom of the well and on the surface. The function of each component of the ESP is discussed. There are massive challenges that are considered during the choice of each component type and the design of the motor[3]–[5]. Direct on-line (DOL) method is the easiest and cheapest way to supply the motor, but in this case, there will be no control over the operation of the ESP [6]. The lack of control causes major problems and losses in the system, so the use of the adjustable speed drive (ASD) along with the monitoring tools is the most efficient solution. The ASD types are discussed in detail to choose the suitable one according to the rating of the motor and cost of the system [1], [7], [8]. The different designs of the winding lead to different types of fluxes: radial, axial and transverse flux. Comparisons are made between the three types to choose the suitable one for the motor of the ESP [9]. Different types of motors are discussed in detail to measure the suitability of each type with ESPS [2], [10].

II. Electrical Submersible Pump System

The ESPS consists of two subsystems: one is at the bottom of the well and consists of sensors, a motor, a motor protector, an intake and a pump. The other subsystem is on the surface that supplies the required power to the devices at the bottom of the well and manipulates the output signals from the sensors. The components of the ESP are shown in Fig. 1.

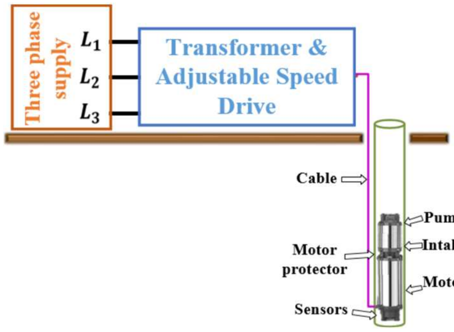


Fig. 1. Main components of ESP system.

A. Well bottom

1) Sensors: The sensors are monitoring tools that are installed downhole to check the pressure, temperature, vibration and position. The pressure sensor is required to optimize the production. The temperature and vibration sensors are used to avoid damage due to overheating or extreme vibration. The position sensor is used only in the case of controlling the motor speed. In [7], a magnetic sensor is designed to detect the contamination of the motor oil. The base idea behind the operation of the contamination detector is that it depends on the disparity of electric conductivity between two electrodes in the sensor. All the sensors transmit a DC signal that includes the readings to the surface unit and the surface unit supplies the sensors with sufficient DC power to operate. It would be inefficient and cost-ineffective to provide a separate data cable for the sensors. The most common transmission method is to utilize a DC signal over the phases of the main power cable and in this case, the ground is used as a return path [11]. An inductive filter is used on the surface to extract the DC signal [12]. This method will not work in the case of failure due to single phase to ground fault. The problem is solved in [13], as they developed a new phase-to-phase communication scheme. The scheme uses deliberate disturbances in phase currents for sending a signal. An impedance and a thyristor are connected in series, then they are connected between two phases at the bottom of the well. The thyristor is controlled to conduct certain short cycles, and the result is a current loop between the two phases. A case study was carried out and the proposed communication scheme showed its effectiveness.

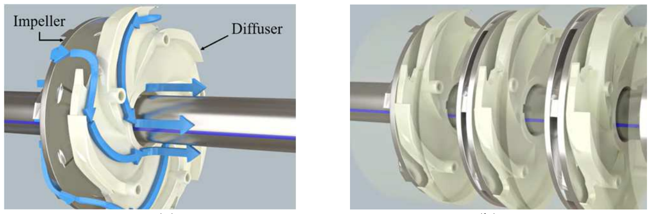
2) Cable: In oil industry, ESPs are installed in deep wells that can reach more than 4000 meters depth [4], [14]. The electric energy is transmitted to the motor at the bottom of the well using a cable. Voltage drop occurs along the cable due to the resistance of the conductor. The surface voltage is determined by calculating the voltage drop along the cable and then adding it to the required voltage at the motor terminals. High motor efficiency and power factor are required to reduce the voltage drop along the cable [15]. An increased temperature due to heating is caused by the high current flow and the environmental conditions in the well. This increased temperature is fatal, so the right choice of the cable size and material have a vital impact on the cable lifetime [16]–[18]. The power cable is also used to provide DC power to the sensors and to transmit data from the sensors to the surface unit. An electrical modelling of the impedance and phase behaviour of a 2036 m long cable is proposed in [12]. The model is an electronic circuit that allows a deep analysis of the cable, as it is hard to test the cable under the real operation conditions.

3) Motor: The motor provides torque needed to drive the pump to pump out the fluid from the well. There are several types of motors that can be used in ESP systems, which are discussed in Section IV.

4) Motor protector: The motor protector connects the motor to the pump and transfers torque from the motor to the intake (or gas separator) and the pump. It protects the motor from the well fluid and equalizes the internal motor pressure with the wellbore [19]. The clean cooling oil of the motor is partially contained within elastomeric bags in the motor protector at the time of installation. These bags expand with the oil due to temperature rise caused by the immersion in the well and thermal expansion during the operation of the motor. The cooling oil cools and contracts during the stopping of the motor. The contraction of the oil causes the bags to contract too [20]. Sometimes the protector allows the well oil to get to the motor as it has insulation features, but the contamination in the well oil degrades the life of the insulation.

5) Intake: The standard intakes do not separate or prevent gas from entering the pump. The entrance of free gas into the pump affects its performance badly by reducing the liquid rates and pressure. The developed intake is equipped with a gas separator to prevent free gas from entering the pump [21].

6) Pump: The submersible pump is a centrifugal pump, but installed downhole. They both depend on the centrifugal force to pump out the fluid. Inside the pump, there are many impellers that are connected to a single shaft and the shaft is driven by a motor. The impeller is a rotating component equipped with blades that is used to increase the pressure and flow of a fluid. The fluid particles gain kinetic and pressure energy from the first impeller. Then a diffuser is used to pass the fluid efficiently from the first impeller to the next one. Fig. 2 (a) shows one impeller and one diffuser. The several impellers increase the pressure through each stage as shown in Fig. 2 (b) [22], [23].



(a) (b)

Fig. 2. The diffuser passes the fluid from the first impeller to the next [23]: (a) One stage; (b) The multistage pump.

B. Ground surface

1) Transformer: For offshore areas, a local generator is used to supply power for the motor through the control of the adjustable speed drive (ASD) or variable speed drive (VSD) [24]. Otherwise, in remote onshore areas, the available voltage from the electrical grid is medium voltage. A step-down transformer is needed to transfer electrical power from the three-phase power supply to the adjustable speed drive (ASD). A step-up transformer is used after the ASD to increase the voltage and hence decrease the current to decrease the voltage drop along the cable to the motor [15]. In some cases, medium voltage switches are used for ASD and that leads to avoiding the use of step-down and up transformers.

2) Adjustable Speed Drive: The first application of ESP depended on supplying the motor through the three-phase supply directly without control. The DOL and the star/delta starter methods are still used until now with the low voltage and low power ESP [6]. This is considered a low-price method, but it causes a high inrush current flow, which leads to a high voltage drop and a decreased voltage at the motor terminal as a result. The sudden change in current and voltage causes fluctuation in torque and speed, which exposes the shaft to huge mechanical stress. This stress on a long rotor may lead to disastrous results. As a result, the use of ASD is mandatory to increase the lifetime of the ESP system [1]. The control of the torque and speed improves the ESP efficiency and reliability. The speed control enables the control of the flow. The flow control enables the adjustment of the fluid production rate according to the well conditions. During the starting period, torque control is important to reduce the stress on the ESP and hence reduced maintenance. There are two types of ASD that are chosen: low voltage and medium voltage [25].

a) Low voltage Adjustable Speed Drive: The most common type of power circuit for low voltage ASD is the use of a rectifier followed by a DC link followed by a Voltage Source Inverter (VSI) as shown in Fig. 3. The VSI needs a modulation scheme to generate pulses for its switches. There are different Pulse Width Modulation (PWM) schemes and one of them can be selected according to its features [5]. The use of power electronics leads to the existence of harmonics. An active or passive filter is used to mitigate the harmonics output of the ASD and produce a sine wave. For low power ESPs that work on a very small depth around hundred meters, the output is connected directly to the motor that works on a low voltage [26]. For high power ESPs, the output of the ASD is stepped up using step up transformer to supply the medium voltage motor [10].

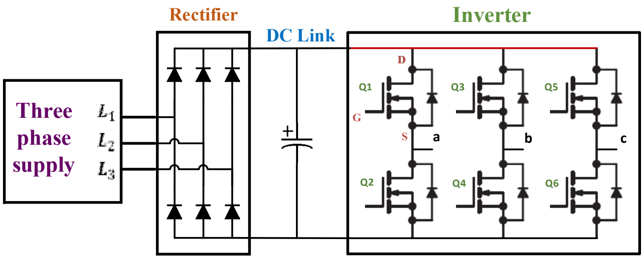


Fig. 3. Schematic diagram of the power circuit of low voltage ASD.

b) Medium voltage Adjustable Speed Drive: The use of step-up transformer is mandatory after a low voltage ASD in case of a high rating ESP. In order to exclude the step-up transformer, a medium voltage ASD is used as shown in Fig. 4. The medium voltage ASD uses a Current Source Inverter (CSI) instead of VSI [27]. The CSI uses an inductor in the DC link. The Large inductor of the CSI helps in minimizing the current ripple, supporting the energy storage for the motor and limiting the fault current. The CSI is more suitable for high-power applications because of the filtering effect of the capacitors Cf that supply a semi-sinusoidal voltage to the motor without sharp edges [28], [29]. In [5], it is stated that for ESP motors with ratings over 500 HP, the use of a medium voltage ASD is the best choice. The voltage can reach up to 6600 V [30].

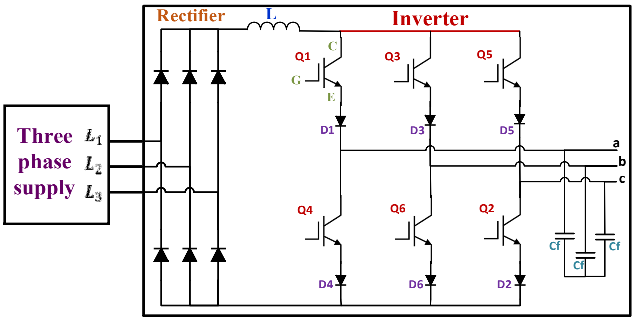


Fig. 4. Schematic diagram of the power circuit of medium voltage ASD.

III. Electrical Submersible Pump Specifications and Challenges

The need for water and oil from deep well made the ESP an important choice. It's an efficient lift method that fulfils the requirements of the application and withstands the surrounding circumstances [8]. The ESP faces massive challenges that must be considered during the design process. The ESP specifications are determined according to the surrounding circumstances, as illustrated in Fig. 5.

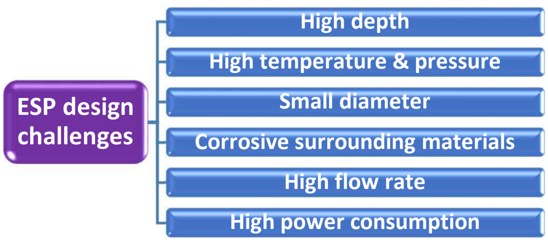


Fig. 5. Surrounding circumstances and challenges facing ESP.

A. Depth

The depth of the well can reach more than 4000 m. This high depth makes it mandatory to obtain a motor with a high rating of horsepower (HP) to provide the required torque for the pump. The motor rating can reach up to 1000 HP [5]. A long cable is mandatory to provide electric power for the motor. The maintenance and replacement of any component of the ESP system is hard and expensive, so a reliable and efficient system is indispensable [31].

B. Temperature and pressure

The ESP works in very bad environmental conditions of high temperatures up to 200 °C and high pressures around 28 MPa [7], [32]. Due to these harsh conditions, the Induction motor (IM) was the first motor to be used for an ESP system. In the past, it wasn't possible to use a Permanent Magnet motor (PMM) because it was sensitive and more susceptible to demagnetization. The development in material and technology has made it possible for the other motor types such as PMM to withstand these harsh conditions [10], [33]. The high temperature decreases the motor insulation lifetime, so a cooling method is included [2].

C. Diameter

All the deep wells are characterized by their small diameters that range from 5 cm to 25.4 cm [8][34]. The small diameter makes it obligatory to use a long motor to provide the pump with the required torque for its operation. The long rotor suffers from torsional stresses. The shaft transmits torque to the load, so there is a twisting effect that occurs to the rotor. The twisting effect means that there is a difference in the angle between the beginning and the end of the shaft. This effect causes a decrease in the produced torque [35]. The use of a low-voltage cable is not possible with a significant depth because an increase in the ampere transmitted by the cable leads to an increase in the conductor diameter. A medium voltage cable is used to transmit the power to the motor to decrease the diameter and the voltage drop [15].

D. Corrosive surrounding materials

Contaminants in the motor oil lead to the loss of insulation, which may burn out the motor by the time [36]. The existence of the free gas results in the problem of cavitation of the pump, which reduces the lifetime of the system. The fluid contains sand and paraffin that leads to erosion and choking inside the pump [8].

E. Flow rate

High production rate is required from the ESP that can reach 46000 barrels per day (B/D) [4], [8]. To calculate the rating of the required motor, the next steps are followed [10]:

The B/D is a known required number, then the flow Q can be obtained from (1) and is measured in Liters per minute (L/min). The oil barrel is 158.987 Litre.

$$B/D = 9.06111 * Q, \tag{1}$$

The hydraulic horsepower (HHP) is obtained as follows:

$$HHP = 0.000219 * H * Q, \tag{2}$$

where H is the head in meter. The rating of the motor is calculated after considering the efficiency of the pump.

$$HP_{motor} = HHP/\eta_{pump}, \tag{3}$$

where HP_{motor} is the horse power required By the motor to drive the pump and η_{pump} is the efficiency of the pump.

Fig. 6 shows a relation between depth, flow rate and series of ESPs that are available in the industry.

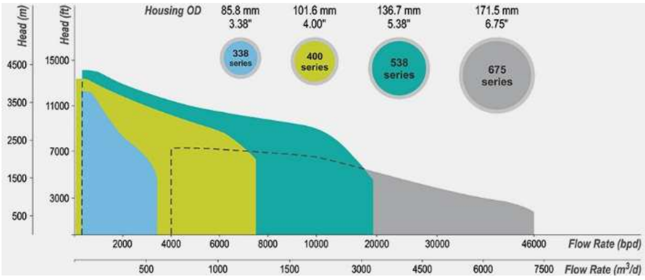


Fig. 6. Depth, flow rate and outer diameter for ESP [4].

F. Power consumption

ESP system has high power consumption rate due to several types of losses that are encountered due to the previous challenges. The power flow from the surface to the output power of the pump is shown in Fig. 7 [19].

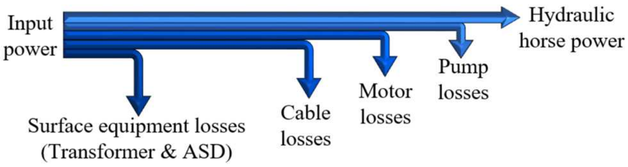


Fig. 7. Power flow of the ESP system.

Power consumption calculation for ESP systems is important to reduce the cost. There are two methods of calculation, the first is the lifting cost in kilowatt-hours per barrel meter and the other is the pump-system efficiency [19].

1) Lifting cost

The power cost can be calculated by the lifting cost using the measured kilowatt-hours during a defined period and dividing the result by the production rate in B/D and by the lifted fluid in meters.

$$Lifting\ Cost = \frac{(kWh_f - kWh_i)}{B/D * h_{wfl} * N_d} \quad (4)$$

where B/D refers to the fluid production rate in barrels per day, h_{wfl} is the net vertical lift in meters as in Fig. 8, N_d is the number of measuring days, kWh_f is the final measured kilowatt-hour value at the end of the measurement period and kWh_i is the initial measured kilowatt-hour value at the beginning of the measurement period [19].

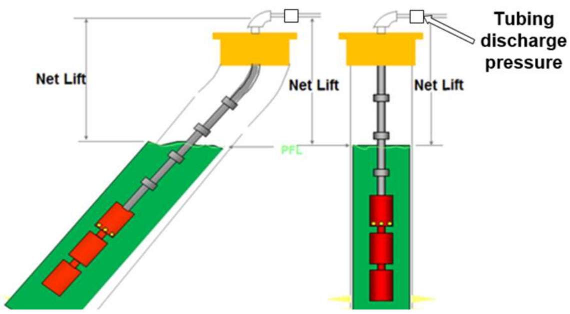


Fig. 8. The net vertical lift [37].

2) Well and Pump system Efficiency

The well-system efficiency is defined as the ratio between the hydraulic horsepower at the tubing discharge and the input electrical power to the system, as follows [19]:

$$Well - system\ efficiency = \frac{HP_{hy\_tubingdischarge}}{kW_{system\_input}} \quad (5)$$

This hydraulic horsepower can be calculated by measuring the tubing discharge pressure as shown in Fig. 8.

The pump-system efficiency is defined as the ratio between the output power of the submersible pump to the electrical power in kilowatts supplied to the system.

$$Pump - System\ Efficiency = \frac{HHP}{kW_{system\_input}} \quad (6)$$

$$HHP = B/D * \frac{\Delta P}{6894{,}76} * 1.7 * 10^{-5} \quad (7)$$

$$kW_{system\_input} = \sqrt{3} * V * I * PF \quad (8)$$

where HHP is the hydraulic horsepower that is transmitted to the fluid by the pump, kW_{system_input} is the total amount of electrical power in kilowatts supplied to the system, B/D is the volumetric flow rate through each stage, ΔP is the pressure increase across the pump in pascal, and V is the fundamental line-to-line voltage, I is the fundamental current and PF is the power factor at the input of the system, the primary of the transformer.

If the pressure increase across the pump (ΔP) can't be measured, another method can be used, as follows:

$$HHP = kW_{motor\_input} * \eta_{motor} * \eta_{pump} \quad (9)$$

where kW_{motor_input} is the input power at the motor in kilowatts, η_{motor} is the efficiency of the downhole motor in percentage and η_{pump} is the efficiency of the downhole pump in percentage.

According to Fig. 7, the following formula is deduced:

$$\frac{kW_{motor-input}}{kW_{system-input}} = \eta_{surface\_eqp} * \eta_{cable} \quad (10)$$

where $\eta_{surface\_eqp}$ is the efficiency of the surface equipment in percentage, and η_{cable} is the efficiency of the downhole cable in percentage.

The surface equipment includes the transformers and the ASD, and their efficiency can be determined as 96%. The cable length on the surface is short, so its losses can be neglected. The efficiency of the cable along the well is the ratio of the output of the cable at the entrance of the motor to the input of the cable at the surface.

$$\eta_{Cable} = \frac{(kW_{system\_input} * \eta_{surface\_eqp}) - P_{Cable\_Losses}}{(kW_{system\_input} * \eta_{surface\_eqp})} \quad (11)$$

where P_{Cable_Losses} is the losses along the well cable which can be calculated as follows:

$$P_{Cable\_Losses} = 3I_{Cable}^2 R_{Cable} \quad (12)$$

where I_{Cable} is the current per phase in A and R_{Cable} is the total resistance of the cable in Ω.

By substitution from (9) into (6) and using (10), the pump-system efficiency can be expressed as [19]:

$$Pump\ System\ Efficiency = \eta_{surface\_eqp} * \eta_{cable} * \eta_{motor} * \eta_{pump} \quad (13)$$

IV. Electric motors for Electrical Submersible Pump system

The design of the motors for the ESP don't follow the standard stated by National Electrical Manufacturers Association (NEMA) because of the harsh conditions surrounding the motor. For NEMA motors, the common insulation classes of temperature ratings are from A to H as listed in Table TABLE I. for ambient temperature 40 °C and service factor 1 [38]. For some special applications, robust insulation materials are used to cover the temperature ratings of classes N & R and more [3], [10], [39], [40].

TABLE I. Insulation Classes of Temperature Ratings [38]

IEC Thermal Class Designation	Letter Designation	Temperature Rise Allowed at full load	Maximum Hot Spot Allowed Temperature
105	A	60 °C	105 °C
120	E	75 °C	120 °C
130	B	80 °C	130 °C
155	F	105 °C	155 °C
180	H	125 °C	180 °C
200	N		200 °C
220	R		220 °C
250	S		250 °C

The electric motors can be categorized according to the orientation of the magnetic field to the electric coil into three categories: radial flux, axial flux and transverse flux [41]. In [2], a comparison is made among the three types, and it is found that the radial flux is the suitable one for ESP applications as in TableTABLE II. [9], [41]. The winding of radial flux concept is shown in Fig. 9.

TABLE II. Comparison of radial, axial and transverse flux [2]

	Limited diameter	Reliability	Robustness	High speed
Radial flux	** [a]	**	**	**
Axial flux	*	*	*	*
Transverse flux	*	*	*	*

[a] Each category takes an asterisk "*" according to its suitability to each feature.

(a) (b)

Fig. 9. The winding of radial flux concept: (a) Concentrated winding [41]; (b) Distributed winding [42].

There are many types of electric motors that are categorized according to their construction and principle of operation. DC motor is not suitable for ESP applications because it needs high maintenance due to the existence of the brushes [43],[44]. The use of an ordinary synchronous motor with a DC field winding complicates the machine. Moreover, the slip rings and brushes need periodic maintenance. This motor is not suitable for ESP applications [45], [46]. The Synchronous Reluctance Motor (SynRM) is not suitable for ESP applications due to its poor power factor, absence of starting capability and low torque density [47], [48]. There are some types of motors that have been already used with the ESP, some of them are involved in the industry and others are still under research:

A. Induction Motor

For a long time, the 3-phase squirrel cage IM was the common type of motor to be used in ESP [8], [49]. IM is featured by its simple construction, cheap price that decreases the overall price of the ESP system and self-starting capability that made it the best choice in the past when the use of ASD was not common [10]. However, there are some demerits related to the IM as low power factor that leads to an increased voltage drop across the cable, Low efficiency and High inrush current during starting in case of no ASD [2].

B. Permanent Magnet Motor

The stator of the PMM is the same as the IM, but the rotor of the PMM is equipped with PM [50]. The PMM has several advantages, such as high efficiency as there are no losses in the rotor [10], high torque density due to the increase in the torque caused by the flux component [51], less power consumption if compared with IM for the same operation conditions [10] and high power factor due to the existence of the PM flux so the current drawn by the supply tends to be an active current [51]. These advantages are convenient for the requirements of the ESP and give the PMM a lead over the IM as shown in Fig. 10 [2], [52]. However, the PMM suffer from some drawbacks, such as high price due to the use of rare-earth permanent magnet [53], complicated design of the rotor as compared with IM, absence of starting torque as there is no cage in the rotor and probability of PM demagnetization due to high temperature [54].

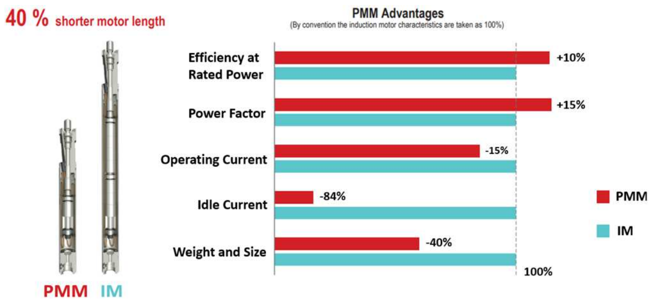


Fig. 10. Comparison between PMM and IM [55].

The PM brushless DC (BLDC) motor has three-phase winding in the stator and surface-mounted permanent magnet in the rotor. It has the same merit and demerits as the PMM with an extra demerit of high flux leakage, however the advancement in the design topologies solves this problem [56]. The use of rare earth magnet increases the cost of the PMM, so ferrite magnets can be used instead [53][57]. In [58], a PM BLDC motor is designed to be used in a well with diameter 10 cm. The spoke type rotor is chosen to place the PM in order to increase the flux concentration. The flux barrier reduces the flux leakage in the rotor. In [59], the use of ferrite magnet decreases the cost to 51.2%. In [40], a comparison is made between slotless and slotted stator core. The possibility of using the slotless stator design is checked, and it is found that the slotless design can fulfil the high demands of ESP.

C. Hysteresis Interior Permanent Magnet Motor

A hysteresis interior permanent magnet (HIPM) motor is a motor that starts depending on the induction phenomenon along with the hysteresis torque. Hysteresis torque in the rotor develops when the rotor magnetic material has high hysteresis loss. Then, the stator pulls the rotor into synchronism and the motor works as a synchronous motor during the steady state [14]. The hysteresis IPM motor has several advantages, such as self-starting capability due to the eddy current torque and the hysteresis torque which is a benefit over the PMM [60] and better efficiency than the IM but less than the PMM and that is because of the rotor losses at starting [14]. The hysteresis IPM motor has the same drawbacks as the PMM except that it can self-start.

D. Switched Reluctance Motor

The Switched Reluctance Motor (SRM) is newly used in ESP [61]. It is featured by its robust construction because the rotor has no PM or winding [62]. The SRM has the following advantages: high starting torque, high efficiency as there is no losses in the rotor, low manufacturing cost for the motor and high torque density. Despite all these features that could make it the best choice for ESP, the SRM needs very precise control and position sensing. It is supplied by a waveform of pulses that is synchronized with the position of the rotor. These requirements make the SRM a difficult choice because these precise signals must be transmitted over a long cable [61].

E. Flux-Switching Permanent Magnet Motor

The Flux Switching Permanent Magnet (FSPM) motor entered the area of ESP applications due to its robust construction. It is a synchronous motor with armature coils and permanent magnets in the stator [63]. Both the stator and the rotor are salient [64]. It is a reliable motor as it has a rotor similar to that of the SynRM and SRM, but it takes the advantages of the PMM in increasing the torque density [65]. The FSPM has extra advantages [64], such as the temperature rise of the magnets is limited due to the help of the stator surface in heat dissipation, less possibility of demagnetization due to the armature reaction because the magnetic fields of the armature coils and the magnets are perpendicular. In [64], the maximum temperature of the machine can't exceed 200 °C, so for higher temperatures it would be a challenge in design to place the PM and the winding with its insulation in the stator.

A comparison among all the motor types is introduced in Table TABLE III.

TABLE III. COMPARISON OF MOTORS FOR ESP

	IM	PMM	BM BLDC	HIPM	SRM	FSPM
Construction	S	C	C	VC	S	VC
price	L	H	H	H	L	H
Self starting capability	✓	X	X	✓	X (need precise control)	X
Power factor	L	H	H	M	H	H
Efficiency	L	H	H	M	H	H
Torque density	L	H	H	M	H	H
Robustness against temperature	H	L	L	L	H	M

The symbols used are L for low, M for medium, H for high, S for simple, C for complicated and VC for very complicated.

V. CONCLUSION

The ESPS components are discussed to recognize their function and the bases on which they can be chosen. The low-voltage ASD can be used in the case of a low-rating motor of power, but a step-up transformer is needed after it. For high-power motors, medium-voltage ASD is used. Both types of ASD require a filter to mitigate the effect of switching and produce a sine wave. It is found that the winding of the radial flux concept is a convenient one for the ESP. The IM was used for years with the ESP system, however, the advancement in industrial technology and material bring other types of motors to usage. The motors that use PM in their construction provide a leading step in fulfilling the demand for the ESP system. The compromise among them is done according to robustness and reliability.

ACKNOWLEDGMENT

The authors acknowledge the Special Research Fund of Ghent University, Belgium (BOF 01W00222).

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