



Rigorous review of electrical submersible pump failure mechanisms and their mitigation measures

Sherif Fakher¹ · Abdelaziz Khlaifat¹ · M. Enamul Hossain¹ · Hashim Nameer^{1,2}

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Abstract

Artificial lift is a vital part of the life of many oil wells worldwide. Using several artificial lift methods can prolong the life of the wells and increase oil recovery significantly. One of the most applied artificial lift methods nowadays is the electrical submersible pump (ESP). This artificial lift method has the ability to handle large volumes of hydrocarbons and is applicable under many conditions in both offshore and onshore reservoirs. Even though ESP has been applied extensively for many years, it still suffers from many failures due to electrical, mechanical, and operational problems associated with the ESP downhole assembly. Understanding the main reasons behind ESP failures and how to rapidly and effectively avoid and mitigate these failures is imperative to reduce cost and damage and improve operational and rig-personal safety. This research performs a comprehensive review on ESP failure mechanisms and analyzes these failures in order to determine the optimum conditions to operate the ESP. This can help minimize and avoid these failures. Also, should these failures occur, the research proposes several mitigation methods for each failure based on analysis of different field cases worldwide.

Keywords Electrical Submersible Pump · ESP Failures · ESP Mitigation Technique · ESP Review

Introduction

In order to increase recovery from oil reservoirs, several methods are implemented to support the reservoir pressure and also help mobilize the crude oil (Gonzalez et al. 2015; Graham et al. 2017; Knight and Bebak 2000). Artificial lift involves utilization of a mechanical method to displace the crude oil from the wellbore to the surface (Cui et al. 2016; Rushby and Denholm 2013; Stavale 2001; Wensheng et al. 2012; Zhu et al. 2016). Different oil recovery methods can be used based on the applicability range, cost, availability, and need of each method. ESP is usually used in high flow rate wells (Ballarini et al. 2017; Guindi et al. 2017; Hamzah et al. 2017; Refai et al. 2013; Seczon and Sagalovskiy 2013). It can be applied in offshore and onshore wells at various depths and under different wellbore and fluid conditions through adjustments to the ESP string.

To reduce the problems associated with ESP, it is important to understand the failure mechanism of the ESP string and the factors that can increase the risk of failure of the downhole components. Based on the previous ESP case studies, the ESP failures can be grouped into three main categories, namely: electrical failures, mechanical failures, and operational failures.

Electrical failures are associated with both downhole and surface facilities. The surface facilities failure are mainly due to overloading of the electricity source resulting from the increase in downhole conditions. This can result in failure of the power source or tripping of the electrical components. Failure of the downhole facilities lies in the failure of any of the electrical components in the ESP assembly including, but not limited to, the electric cable, the motor electrical components such as the stator, and the downhole sensor. Many case studies have reported severe electrical failures during ESP operations. Failures associated with the cable were mainly caused by electric cable failure, cable insulation failure due to corrosion, material failure, and abrasion, and cable failure due to overload. Electrical failures associated with the motor are usually a resultant of the stator failure. The stator has been reported to fail due to improper design, current overload, and overheating due to temperature. The

✉ Sherif Fakher
sherif.fakher@aucegypt.edu

¹ Petroleum and Energy Engineering, The American University in Cairo, Cairo, Egypt

² Baiti, Iraq

downhole sensors are reported to fail in extreme conditions including high temperature, and hydrogen sulfide and carbonic acid corrosion (Abou-Houzifa and Ahmed 2016; Al-Khalifa et al. 2015; Arteaga et al. 2020; Chen et al. 2019). Understanding the mechanisms of the electrical failure is imperative in reducing the component wear and tear and prolonging the life of the ESP assembly.

Mechanical failures of the ESP are usually associated with moving components and thus are mostly, if not entirely, related to downhole components. The ESP assembly is composed of multiple mechanical components that function to transmit power, connect the different assembly components together, and displace the downhole fluids to the surface. These components vary in size, material, position in the assembly, and function, all of which are conditions that may contribute to their failure. Mechanical failure of the ESP assembly has been observed in onshore and offshore fields in more than thirty different countries. Mechanical failures associated with the motor were due to rotor damage and failure caused by corrosion, abrasion due to the solid presence in the produced fluid, overheating due to improper cooling, and motor protector failure (Noui et al. 2017; Nikonov et al. 2018; Strikovski and Davalath 2016). Many downhole components have also been reported to break due to wear and tear. Also entire loss of components or part of the string can occur due to extreme corrosion (Jinjiang et al. 2020). If parts of the downhole assembly are partially corroded or severely eroded, leakages could occur from the system causing pressure loss and motor and pump overload and, eventually, failure. Mechanical failures of the ESP assembly can be avoided if proper selection of the assembly components and their location and properties is designed.

Operational failures are usually focused on downhole conditions that may result in failures of the ESP assembly components. Unlike electrical or mechanical failures, operational failures are tied to conditions of the wellbore fluids and thermodynamics that may result in mechanical or electrical failures. These failures can be a resultant of severe downhole temperature, sudden change in pressure gradients, introduction of gaseous phase due to reservoir pressure decline, and deposition of scale, asphaltene, or wax on the downhole ESP components (Rodrigues et al. 2015; Morrison et al. 2014; Nallipogu et al. 2012). In many ESP cases worldwide, operational failures resulted in the shortening of the ESP mean time between failure significantly and impact the operational costs greatly. Temperature failures have been reported in many cases worldwide (Noonan et al. 2009). This indicates that temperature is one of the most problematic factors during ESP operations. Although pressure itself has not been reported to cause problems, sudden and abrupt differential pressures due to abnormalities in downhole conditions have caused multiple component failures in the ESP string (Williams and Shipp 2019). During

production, the presence of emulsions can also cause severe operational problems and may impact ESP components. Emulsions occur during the existence of oil and water in the produced fluid and thus are very common (Bulgarelli et al. 2021a, b). Operational failure mechanisms cannot be controlled since the properties of the formation and fluids cannot be altered; however, these failures can still be avoided with proper understanding of the ESP assembly components and the downhole conditions.

Based on the aforementioned, it is important to have a guideline to the most common ESP failure mechanisms. An understanding of how to avoid these failures and, should they occur, how to detect and quickly mitigate them before they result in failure of other downhole components is paramount. This research undergoes a wholistic review of the different ESP failures and provides a roadmap to their avoidance, detection, and mitigation based on multiple field cases worldwide that have reported ESP failures. This can help prevent costly remediation and replacement operations and can also increase the mean time between failures of the ESP assembly.

ESP operating mechanism

Electrical submersible pump is classified as a downhole artificial lift method. This is mainly due to the presence of most of the ESP assembly downhole. As such, it is more prone to failure due to severe downhole conditions, and direct contact with the wellbore fluids and contaminations (Keith and Cox 2018). It is important to note that recent studies have investigated placement of the ESP outside the wellbore such as on the surface of the seabed (Verde et al. 2021; Vieira et al. 2021). The ESP string is composed of multiple components other than the ESP itself. These components work to prolong the ESP life and ensure protection of downhole components from different factors that may result in failure.

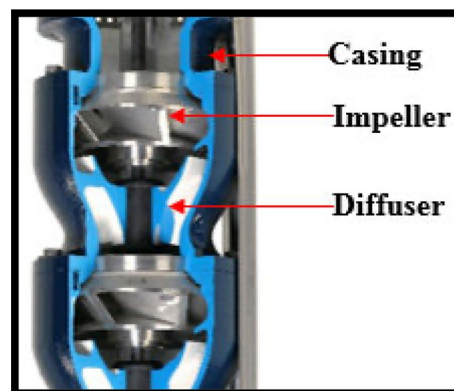


Fig. 1 ESP Main Components (Zhu and Zhang 2018)

The pump itself is composed of three main components, namely: impeller, diffuser, and housing, or casing (different from the wellbore casing). The ESP components are presented in Fig. 1. The impeller rotates at high speeds to provide a pressure head for the wellbore fluids in order to lift the fluid upwards to the surface (Zhu and Zhang 2018). Once the fluid moves through the impeller it passes through the diffuser. The diffuser converts the kinetic energy from the impeller into pressure head. Both the diffuser and impeller are referred to as an ESP stage. Several stages are usually present in the ESP string based on the depth of the wellbore, and the required lift, which is dependent on the reservoir and fluid properties. The housing is a steel or hardened case that protects the impellers and diffusers from outside factors and prevents differential pressure loss during lift.

The ESP assembly is composed of the ESP itself along with other necessary components that ensure that the ESP functions properly and protect the assembly. The most basic ESP assembly is composed of an electric cable, pump, intake, protector, motor, sensor, and discharge, shown in Fig. 2. The function of each of these components is as follows:

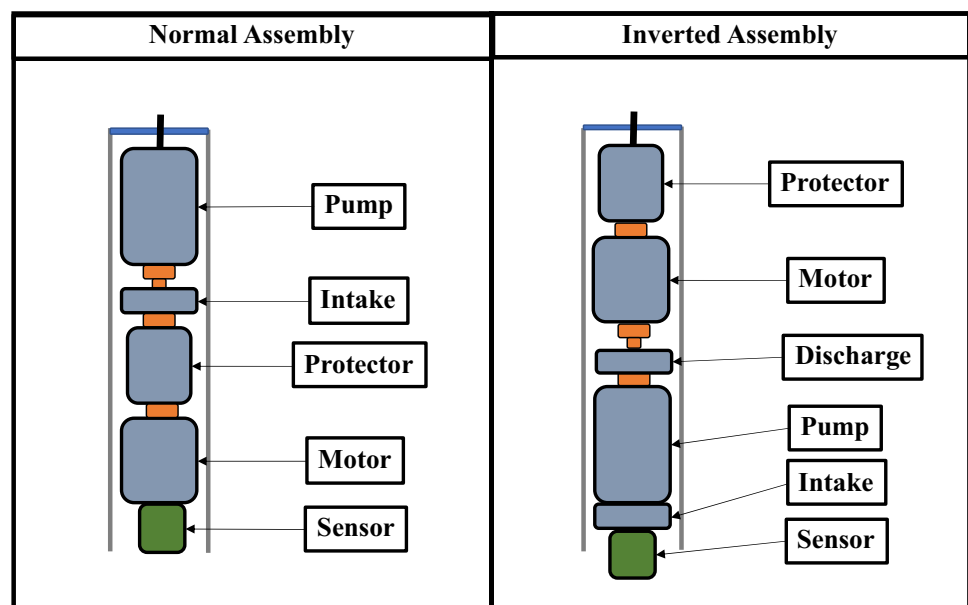
- **Electric Cable:** The electric cable is the main power source for the ESP assembly. It is connected to an electricity source on the surface and is then extended downhole to provide power to the motor. It can also be used to provide power to other downhole components such as sensors, electric manifolds, and other additional tools.
- **Pump:** The ESP is the main component of the downhole assembly. It provides the required head to lift the reservoir fluids to the surface. Multiple ESP stages can be

present in the downhole assembly based on the wellbore conditions (see Fig. 1).

- **Intake:** The intake is the point of entry of the reservoir fluids into the ESP string. Having an intake ensures that the fluid entry is controlled and thus prevents influx of unwanted fluids to the surface which may result in a kick.
- **Motor:** The motor is the powerhouse of the downhole assembly, especially the ESP. It provides the required mechanical power for the components of the ESP to move. This is done by converting the electrical energy provided by the cable into mechanical energy that is required to rotate the ESP impellers.
- **Sensors:** The downhole sensor can measure multiple parameters and transmit the data to the surface in real time. This can ensure smooth operations and reduce failures. The main data that the sensor can detect is temperature, pressure, fluid composition, total dissolved salts, hydrogen sulfide, carbon dioxide and gas, and also some data on the motor and pump such as torque and rotation per minute.
- **Discharge:** The discharge is the point at which the fluids are discharged from the ESP string and move into the production tubing for recovery. This point is usually located near the top of the ESP string. Multiple discharge points can be included in the string for extremely high flow rate or for special operating conditions.

The downhole assembly can either be stacked in a normal manner or an inverted manner, as shown in Fig. 2. The main difference between both assemblies is the location of the motor and pump. In the normal assembly, the motor is located below the pump, closer to the intake. This reduces the risk of ESP failure since the pump is located in the upper

Fig. 2 Normal and Inverted ESP Assemblies



section of the string; however, it may increase the risk of motor failure and also results in the need for a prolonged electric cable to feed the motor since the motor is located near the bottom of the assembly. In the inverted assembly, the ESP is located close to the intake and the motor is placed closer to the discharge. This is beneficial in protecting the motor and also reducing the length of the electric cable. The drawback is that since the ESP is closer to the intake, there is a higher risk of gas inflow in the assembly. This can be reduced by locating the pump above the perforations; this should be incorporated in the original design.

The ESP assembly can be placed downhole through different methods and techniques all of which have their advantages and drawbacks (Chen et al. 2019; Gorbunov 2017; Liley and Maclean 2018; Zamanuri et al. 2019). The most common methods to place the ESP assembly downhole are as follows:

- **Tubing Conveyed:** In this method, the ESP string is part of the tubing itself. This method is extremely common due to the reduced complication associated with it. The main drawback of the tubing conveyed assembly is that if any failure occurs, or if there is a need to retrieve the downhole assembly, a workover rig is required. This increases the time needed to recover the string and also the cost of the overall operation.
- **Tubing Conveyed—Casing Dependent:** This method is the same as the tubing conveyed; however, some of the ESP components are fixed in the permanent completion. This provides protection for these components; however, they are non-retrievable or extremely tedious and costly to retrieve.
- **Slickline Conveyed:** A slickline is a steel cable that can be used to suspend different tools downhole. Slickline conveyed ESP assembly has the advantage of being extremely easy and quick to lower in the hole and to pull out of the wellbore without the need for a workover rig. The main drawbacks of this method include limitations

for the ESP assembly weight since the slickline will have a weight limit that cannot be exceeded, and the need for an electric cable since the slickline cannot transmit electricity.

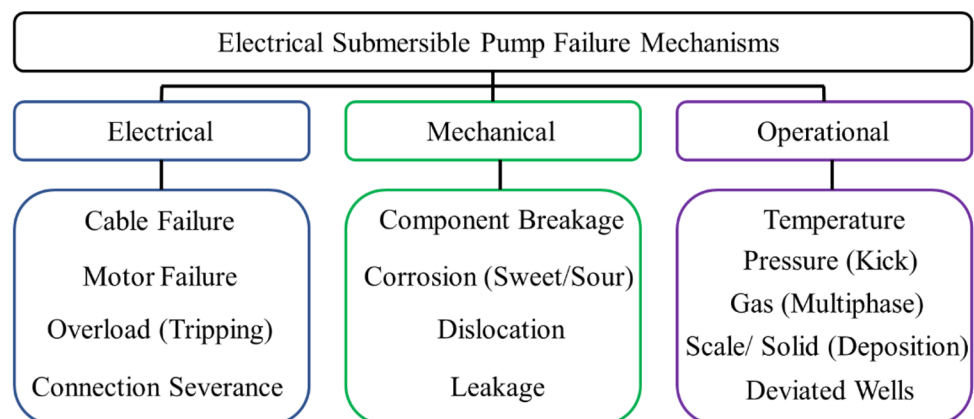
- **Wireline Conveyed:** This is the same as the slickline conveyed ESP; however, a wireline has the advantage of being able to transmit electricity and thus removes the need for an electric cable. The main limitation of this method is that the wireline will usually have a lower load capacity compared to the slickline and thus the ESP string needs to be lighter.

ESP failures and mitigation

The main problem with ESP is that since it is an assembly, failure of a single component in the assembly will pave the way for the failure of other components. This increases the need for a rapid diagnostic of the ESP string should any failure occur. Since the ESP string is located downhole, it will be subjected to the wellbore conditions which can be extremely severe in many cases. The most common ESP assembly failures can be grouped into three main categories including electrical, mechanical, and operational failures. The subclassifications of these failures are summarized in Fig. 3. Each of these failures will be discussed in detail including the reasons behind each failure, failure detection, and finally how to quickly mitigate each failure to avoid further downhole complications.

A typical failure analysis diagram for the ESP assembly is shown in Fig. 4. The different failure mechanisms are identified and analyzed. The conditions at which a failure mechanism may occur are determined, and the prevention and mitigation methods are proposed accordingly. Following the diagram methodology should result in safe operating conditions through appropriate prevention and mitigation methods.

Fig. 3 ESP Assembly Failure Mechanisms



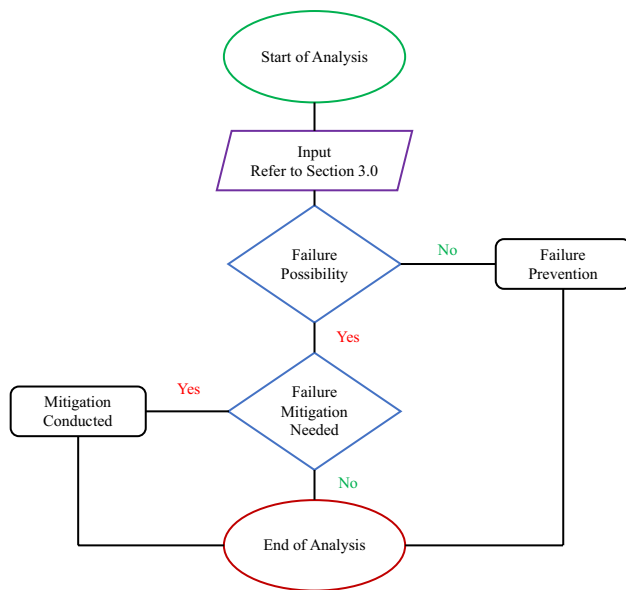


Fig. 4 ESP Failure Analysis Tree

Electrical failures

The electrical failures are the most common among the three main failure mechanisms of ESP. These failures are also considered the most severe since any electrical failure will result in a complete failure to the entire assembly and thus retrieval of the assembly becomes mandatory. The electrical failures discussed in this research include cable failure, motor failure, overloading failure, and connection severance.

Cable failure

In order to ensure that the downhole cable can withstand the wellbore conditions including high temperatures and pressures, and corrosive fluids and solids, the electric cable is usually coated in multiple layers of insulation and protection. However, even with these multiple layers, the electric cable can still fail. This could be due to failure of the insulation or due to failure of the cable itself without insulation degradation. The cable itself could fail if there is instability in the power source or if a sudden surge in the power requirements occurs which may increase the load on the cable. This sudden surge could occur due to increase in motor rotor rotation due to gas phase increase which causes the ESP to overload due to false-lifting.

The cable insulation is usually composed of multiple layers. These could include several materials based on the predicted downhole conditions (Kalu-Ulu et al. 2017; Lucas et al. 2018; Saveth 2014; Jinjiang et al. 2020). The most common materials used to insulate the electric cable are as follows:

- **Metals:** Several types of metals and metal alloys can be used as insulators. They are usually chosen to be temperature resistant and durable. The metal insulator is usually the outermost layer of the insulation and thus handles the majority of the severe conditions in the wellbore. Even though some metal alloys are extremely durable and can handle severe conditions, metals usually suffer from anodic–cathodic corrosion and thus metal compatibility is an extremely important parameter in the insulation design.
- **Polymeric-Based Materials:** Polymeric-based materials are various in types and uses. They include different polymers including thermosetting and thermoplastic polymer, and resins. Polymers are usually used in the inner insulations due to their low permeability and porosity and thus inhibit passage of any fluids through them. They suffer from low durability compared to other material and in some cases are extremely brittle. Some polymeric materials are also high in cost and readily available.
- **Rubber:** Rubbers vary significantly in terms of applications and endurance. They are considered good insulators since they are corrosion resistant and low in permeability. Their main drawback is solid contamination which cause degradation in the rubber layers and thus result in insulation failure.
- **Ceramic:** Ceramic materials share many advantages with metals including temperature resistance and durability. They also have the advantage of being corrosion resistant since they do not suffer from anodic–cathodic corrosion as long as they are metal free. Their main drawback compared to metals, however, is that they are extremely brittle, not ductile, and thus are prone to breakage.

Cable insulation failure occurs due to many factors including, but not limited to, corrosion, temperature, solids and scale, and high differential pressures. An example of an ESP cable insulation failure is shown in Fig. 5.

Detection of cable insulation failure is extremely difficult since it requires visual inspection. Another method of detection includes sample analysis of the produced fluids for metal, rubber, and polymeric contamination; however, even with this analysis, it is difficult to pinpoint the failure to the cable insulation since multiple downhole components are made of similar material. Detection of cable failure is extremely simple since when the cable fails, the entire string will cease to function and so it is considered a severe failure. In order to prevent cable failure, the insulation material must be selected properly. Proper selection includes compatibility with downhole conditions, and insulation layers compatibility. Also, the cable itself should be designed with a safety factor to account for sudden surge in power requirements.



Fig. 5 Example of ESP Assembly Cable Failure (Pastre and Fastovets, 2017)

Motor failure

ESP assemblies usually rely on two types of downhole motors including three-phase asynchronous induction motors, and four-pole synchronous permanent magnetic motors. In both cases, the motor is composed of two main components including the stator and the rotor. The stator's, electric component of the motor, main function is to convert the electric power supplied by the cable into a magnetic flux that induces rotor rotation. The stator is composed of metal coils. The main mechanisms of the stator failure include coil degradation and overloading (Dennis et al. 2017). Also, overheating can result in motor failure due to the degradation of material in the motor assembly, many of which are not designed to handle extremely high temperatures (Ye et al. 2019).

Stator coil degradation can result because of two main factors: misalignment and motor compromise. Misalignment is due to improper stator design which may result in a delay or cessation of magnetic flux; this is not very common in induction motors but can be a severe problem in permanent magnet motors. The motor will be compromised if the wellbore fluids enter within the motor. The wellbore fluids can then contaminate the motor oil which will, in most cases, result in complete motor failure, especially if the problem is not detected early (Lastra et al. 2019).

Detection of motor problems relies on the continuous analysis of the motor performance with time. If any abnormality in the motor performance is observed, then this could be a strong sign of the motor beginning to fail. The motor performance can be traced real time using data from the downhole sensor. The main issue with this method, however,

is that the only way to be completely sure that the motor is malfunctioning to retrieve the string, and this may be costly especially in tubing conveyed ESP assemblies.

Prevention of motor failure relies on proper motor design, especially in permanent magnet motors, and motor-seal testing on the surface before lowering it in the hole. The seal must be strong enough to endure the downhole conditions to avoid failure which will result in motor oil contamination. Mitigation of motor problems involves retrieving the motor in order to assess the extent of the damage and remedy the problem.

Overloading

ESPs are usually operated via variable speed drives (VSD). The VSD varies the frequency based on the power needs downhole. In some cases, the ESP will require an excess of power to lift the fluids. This can occur if gas begins producing or if the gas saturation increases. The motor will then have to provide more power to increase the lifting capacity of the ESP. If gas lock occurs, the VSD may receive a false indication that the ESP lift is not sufficient even though no fluids are flowing through the string. This will result in an extreme surge in load on the motor, referred to as overloading which can result in motor failure (Amijaya et al. 2019; Heninger et al. 2019).

Detection of motor overloading is reliant on two major observations. The first is continuous monitoring of the motor performance to detect abnormalities. If abnormalities are detected, a good indication of overloading is the downhole gas concentration at the intake, which can be monitored using the downhole sensor. The second observation is gas concentration which can indicate a gas lock. A third indication is the reduction in the overall volume of the produced fluids on the surface.

Prevention of overloading relies on tackling the causes of this phenomenon. This includes placing a gas separator or a gas handling pump downhole to prevent gas lock. Another method to prevent this is to limit the VDS frequency based on the motor capacity to avoid motor overloading. If overloading occurs, the system should be shut down to allow for the motor to cool down. If the problem of overloading is gas, then the gas must be vented, or the gas flow must be homogenized before production resumes.

Connection severance

Connection severance refers to loss of communication with the downhole assembly. This can occur due to electric cable failure or severance, explained previously, or due to downhole sensor failure. If the electric cable fails all operations will stop. Sensor failure or malfunction can be a catastrophic problem. If the sensor fails, then sensor reading will cease to

be transmitted to the surface. In the case of sensor malfunction, the sensor will transmit erroneous readings to the surface. This can result in false indications of normal downhole operations even if problems are occurring downhole. In this case, multiple string components may fail or be damaged before knowledge of a problem is acquired (Medina et al. 2012).

Detection of sensor failures is simple since it will cease to transmit information to the surface. Detection of sensor malfunction is a much more difficult process, however. This can be done via two methods. The first is the inclusion of multiple downhole sensors to compare the readings. The second method is to trace the VSD to determine if any severe change in frequency is occurring which may indicate a downhole problem. Analysis of the produced fluid may also indicate downhole problems; however, in many cases it may be difficult to tie this to sensor malfunctioning.

Prevention of sensor failure or malfunction can be done by designing the sensor to withstand downhole conditions. Mitigation of downhole sensor requires retrieval of the sensor. It is therefore advisable to include more than one sensor downhole to avoid operational disruption in case of sensor failure or malfunction.

Mechanical failures

Mechanical failures are usually tied to the moving components in the ESP assembly; however, they can also include stationary components in some cases. The stationary components include bearings and threads. Mechanical failures are extremely difficult to remedy and usually require component retrieval and replacement. This can disrupt operations for a lengthy duration thus increasing the overall operational costs. The main mechanical failures to be discussed in this research include component breakage, corrosion, dislocation, and leakage.

Component breakage

Any downhole component in the ESP assembly is prone to breakage. The materials can break due to wear and tear resulting from prolonged exposure to downhole conditions, improper material designs, and abnormalities in downhole conditions such as sudden increase in pressure differentials due to gas pockets or introduction of new phases. Component breakage can cause malfunctioning, and failure, of components downhole the most severe of which is ESP and motor failure due to impeller or rotor breakage, respectively. Another major complication due to component breakage is partial loss of downhole components that may be completely severed from the string (Xiao et al. 2020; Ye and Wilcox 2018; Tiofiolo et al. 2018; Xiao and Lastra 2019; Pino et al. 2015).

Detection of downhole breakage can be done using multiple methods based on the component. If the ESP impeller breaks, a reduction in the lift capacity will be noticed on the surface. If the motor rotor breaks, operations will cease due to motor failure. Breakage of other downhole components can also be detected without retrieval of the string via leakage detection or overall pressure loss.

Prevention of component breakage is almost entirely reliant on material selection. Proper material design should account for the downhole conditions and must also account for any abnormalities that may occur. Also, rigorous surface testing of the material should be conducted, taking into account the duration for which the components will remain downhole.

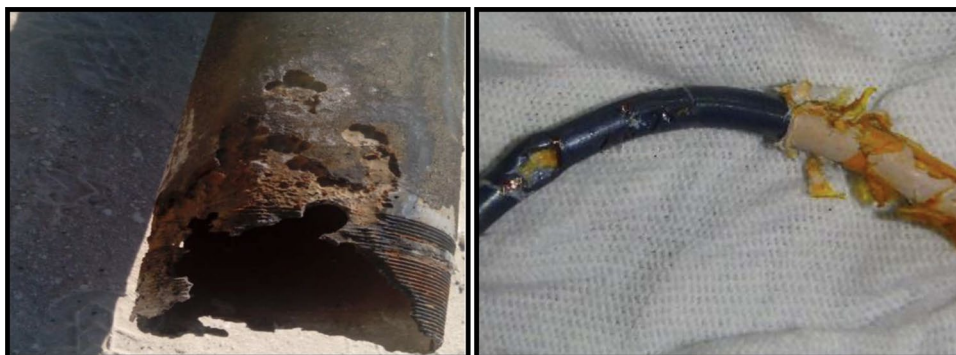
Mitigation of component breakage can be done in two ways depending on the severity of the breakage. In case of slight breakage, the component should be retrieved by pulling the string. The component will then be replaced with a more durable one. In case of loss of components in the hole due to complete severance, the assembly will be pulled out of the hole, and a fishing tool will be lowered to retrieve the lost components.

Corrosion

Corrosion can affect any metallic component in the downhole assembly. Although different types of corruptions exist, the main two types that can affect the downhole assembly include pitting and anodic–cathodic corrosion. Pitting is a type of corrosion that results from the exposure of the surface of the metal to the wellbore conditions. It therefore requires initiation, which comes in the form of surface erosion resulting from solid particles such as sand. Pitting can occur even in the smallest surface erosions. It then begins to expand until it causes severe failures to the metallic components. Anodic–cathodic corrosion occurs when three main components are present including an anode, a cathode, and an electrolyte. The anode and cathode represent two different metals with different potential; the electrolyte is a media that can transmit ions, in other words electricity. If the potential of the two metals is different by 0.10 to 0.15 V or larger, anodic–cathodic corrosion will take place. In this case, one of the metals will become an anode and will begin to corrode, while the cathode will not. Corrosion can cause failures in the electric components and also in the mechanical components, most of which are made of metals (Elichev et al. 2010; Kalu-Ulu and Albori 2019; Christie and Cox 2018). An example of corrosion of a metal pipe and the cable protector is shown in Fig. 6.

Detection of corrosion can be done in three ways. Analysis of the produced fluid can determine if corrosion is happening by observing corrosion byproducts. Also, the downhole sensor can determine the presence of components that

Fig. 6 Metallic Thread Failure and Electric Cable and Insulation Degradation Corrosion (Kalu-Ulu and Albori, 2019; Christie and Cox, 2018)



may enhance corrosion such as carbon dioxide (sweet corrosion), hydrogen sulfide (sour corrosion), or high percentage total dissolved salts (TDS) in the formation water. The second method to determine corrosion is the detection of failure in one of the downhole components. If one of the downhole components fails without indications of electrical failures, corrosion could be the main reason. Finally, loss of pressure in the production tubing could also be an indication of corrosion that resulted in leakages through the production tubing.

Prevention of corrosion problems comes in two phases. The first phase is to understand the downhole conditions and the properties of the downhole fluids to determine the possibility of corrosion occurrence. The second phase is the proper selection of material to prevent downhole corrosion problems. This selection includes choosing compatible metals, and also materials that are resistant to erosion to prevent anodic–cathodic and pitting corrosions.

If corrosion occurs, the only reliable method of mitigation is replacement of the corroded component. Since pulling the entire string will be required, it is also recommended to study the properties of the replacement component to avoid future corrosion problems. The replacement material should be close in potential to the neighboring component and should also be hydrogen sulfide resistant and erosion resistant if a high concentration of solids is observed.

Dislocation

Dislocation will occur only in the moving components downhole. It is one of the least common failures in the ESP assembly since most of the components are fixed extremely well in the string. Dislocation will occur due to several reasons including wear and tear of fixation components such as bolts, bearings, and shafts, corrosion of fixation components, and breakage of downhole components. Dislocation will impact the affected component initially. It can result in multiple component failure if the affected component is an integral part of the string (Elichev et al. 2010).

Detection of dislocation, similar to corrosion, can be through detection of pressure losses or abnormal downhole operating conditions. In some cases, however, the only way to detect this type of failure is to recover the entire assembly since detection methods may give a false indication of other failures such as corrosion or leakage.

Prevention of dislocation can be done by protection of the downhole components from erosion and corrosion. This can be done using effective insulators for the electric components and housing, casing, for the mechanical components. Should dislocation occur, mitigation involves retrieval of the string and assessment of the affected component. If the component can be fixed in a safe and timely manner, then this should be done by a well-trained crew. If the component cannot be fixed, then it should be replaced by a similar, or more durable component.

Leakage

Leakage occurs in the components of the assembly that bear fluids. Leakage can occur by influx of the fluid out of the string, or into a sealed component of the string. Leakage of the fluids outside the string usually occurs in the form of expulsion of the produced fluid from the ESP string into the tubing, or the wellbore. This will occur due to breakages of a component in the ESP assembly or due to protector failure. Influx of the fluid into a component is usually tied to the motor. If the motor protector fails, the wellbore fluid may contaminate the motor oil which will eventually result in motor failure. Leakage of fluids can result in loss of pressure which will exert more power requirement on the motor since the ESP will be signaled to work harder in order to accommodate for the pressure loss. It is therefore extremely important to detect leakages as soon as possible (Elichev et al. 2010; Kalu-Ulu and Albori 2019; Christie and Cox 2018).

Detection of leakages is fairly simple if the downhole sensor is equipped with the proper detection components and is functioning properly. The sensor will detect pressure losses in the system which is a strong indication of leakages.

Also, if the VDS suddenly signals for higher motor operation without any apparent and reasonable justification, then leakages have most likely occurred.

Prevention of leakages is done by proper selection of material and proper operational conditions to avoid rapid material degradation. Mitigation of leakages will, in almost all cases, require the retrieval of the assembly and replacement of the affected component.

Operating failures

Operating failures can refer to any failure that cannot be classified as mechanical or electrical in origin. This means that operational failures will result due to an operational condition or error; however, it may result in mechanical or electrical failure. The operating failures discussed in this research include temperature, pressure, multiphase flow, and scale/solid deposition.

Temperature

Temperature is one of the main contributors to equipment failures downhole. High temperatures can cause failures of electrical components that cannot handle the temperature conditions. The most affected electrical components include the cable and downhole sensor. Temperature can also initiate other failures to occur such as corrosion. It also affects materials and causes metal expansion which exerts tensile force on the materials (Ye et al. 2019).

Detection of downhole temperature is reliant on the downhole sensor. The sensor should be designed to withstand extreme temperatures. This can be done using heat-resistant material for the sensor components. One of the proposed materials for the sensor includes fiber optics, which can withstand temperatures up to 220 C (Medina et al. 2012). A temperature gradient can also be calculated for extremely deep wells to determine the temperature distribution along the well.

Since temperature is one of the factors that cannot be controlled, failure prevention is an imperative step in avoiding failures. Temperature impacts different components in a different manner; therefore, it is important to accommodate for temperature effect in the design of all components. For electrical components, heat-resistant insulation must be used in extreme temperature wells. For the mechanical components, the material selection must be heat and temperature resistant.

If failures associated with temperature or aggravated by temperature occur, understanding the main reason behind the failure is the first step in mitigating it. If a component needs to be replaced, the replacement component should be designed to withstand temperature if this was the cause, or part of the cause, for failure.

Pressure

The downhole ESP assembly is usually designed to handle high pressures since ESP is usually used in high-rate wells. The problems with pressure occur when a sudden surge in pressure occurs or a sudden loss in pressure occurs. A sudden surge in pressure can result from a fluid influx such as a gas pocket. A sudden decrease in pressure can result from leakages in the ESP assembly. In both cases, abnormalities in the flow will occur. If the system is not fast enough to adapt to the changes, the downhole equipment may be degraded (Margarida et al. 2017; Marra and Girard 2017; Martinez et al. 2018).

Detection of pressure losses or gains can be easily analyzed from the downhole sensor. Once the pressure abnormality is detected, the cause for the problem should be identified in order to be able to take the proper mitigation action. Prevention of pressure problems involves integration of downhole conditions that can handle gas flow to anticipate pressure increases. For pressure loss, proper selection of material should be done to avoid leakages in the downhole components.

Multiphase

Multiphase flow refers to the presence of multiple phases associated with the oil. The most common fluids associated with the oil are water and gas. Water can cause system overload if the water cut is extremely high. Also, water–oil emulsions can be extremely problematic during production. The gaseous phase can also cause severe problems. These include corrosion, gas lock, and a surface kick (Barrios et al. 2012; Dwitiya et al. 2015; Mali et al. 2020).

Detection of the gas can be done via the downhole sensor. If the gas saturation begins to increase, this must be noted in order to accommodate for future operation problems. Prevention of gas problems therefore require continuous monitoring of the wellbore fluids. Different equipment can be used to overcome gas problems. These include downhole gas separators, gas handling pumps, or gas venting equipment. If gas problems occur, such as gas lock, operations must be stopped until the excessive gas is vented.

Scale/solid deposition

Solids in the wellbore can be classified as organic and inorganic solids. Organic deposits include solid components of the crude oil such as asphaltene and wax. These deposits can stick to the surface of the ESP assembly and result in equipment overload and failure. Inorganic deposits include sand and salt deposits from the formation water. These solids can cause equipment erosion and, with time, equipment failure (Elichev et al. 2010). Figure 7 shows an example of



Fig. 7 Metal Piping Crack due to Solids (Pastre and Fastovets, 2017)



Fig. 8 Asphaltene Solid Deposit on the Surface of ESP (Jennings et al. 2020)

component erosion and breakage due to solids in the production fluid.

Detection of downhole solids and scale can be done by analyzing the produced fluids on the surface. This analysis can include compositional analysis of the crude oil to detect asphaltene and wax concentration, and analysis of the formation water to determine the most common salts that can result in scale. Asphaltene has the tendency to adsorb to the surface of the equipment and deposit on the wellbore and on the perforations (Jennings et al. 2020). This can cause severe buildups which, if not handled immediately, can result in operational failure. An example of asphaltene deposition on the surface of an ESP is shown

in Fig. 8. Wax can also form buildups on the surface of the equipment which can result in component failures. High salinity formation water must be addressed with caution especially in the presence of hydrogen sulfide and carbon dioxide to avoid further complications.

Prevention of solid and scale problems during production using ESP involves having a good understanding of the properties of the downhole fluids and the production zone formation. This can allow for the generation of safe operating conditions to prevent the occurrence of buildups. For example, asphaltenes will precipitate from the crude oil under specific conditions. If asphaltene is determined to be present in the crude oil, operational conditions can be altered to avoid asphaltene precipitation and buildup. Also, wax will only be problematic if its cloud point is reached. If wax is found in the crude oil, the cloud point should be determined and avoided. Also, including specialized components to handle solids, such as gravel pack or a sand filter can avoid solids' erosion problems. As for scale, proper operations can prevent the precipitation of salts in the ESP assembly. Also, proper selection of material can prolong the life of the equipment and prevent scale-related corrosion.

Should problems occur due to solids and scale, mitigation of these problems is dependent on the severity of the failure. In case of severe wax or asphaltene buildup, inhibitors can be used to treat the deposits. If inhibitor treatment fails, the assembly could be pulled out of the hole and then water jetting can be applied to remove the buildup. In case of sand, if the tools are severely eroded, they could require replacement. Also, if no sand filter or gravel pack is present, it should be included in the assembly to avoid further components' failure.

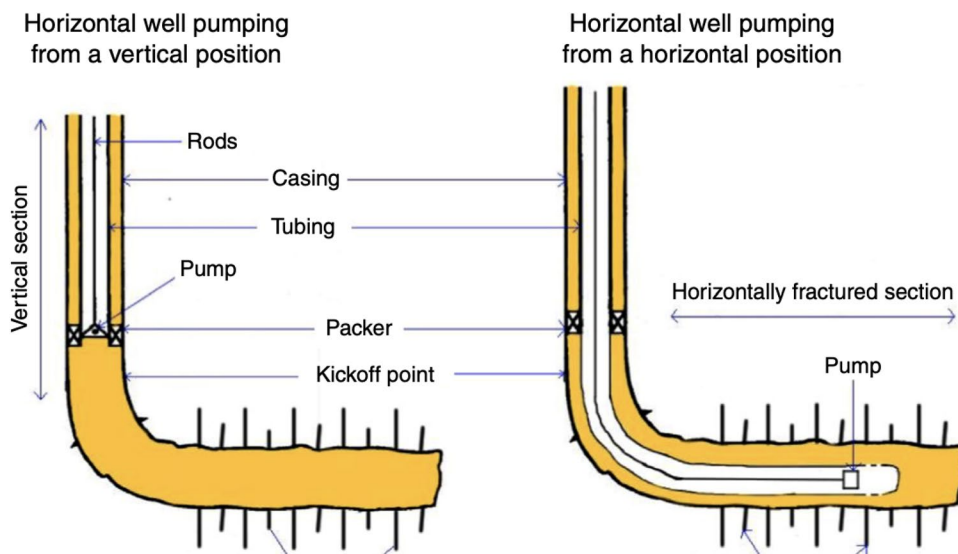
Deviated wells

Recently, deviated wells have become extremely common due to advancements in drilling technologies. The main issue with deviated wells is the ESP assembly getting stuck at the dogleg. To avoid this problem, the assembly can be located before the dogleg. Another method is to reduce the inner diameter of the string to accommodate for the deviation. These cases are illustrated in Fig. 9 (Kolawole et al. 2020).

Failure and mitigation summary

The mitigation methods discussed previously are focused on specific scenarios. Recent technological advancements have allowed for the integration of advanced algorithms and machine learning to predict the occurrence of a failure and thus provide early warning. This can help provide the time needed for failure prevention and mitigation (Ujjwal et al.

Fig. 9 ESP Application in Deviated Wells (Kolawole et al. 2020)



2019; Amendola et al. 2019; Gryzlov et al. 2020; Teplyakov et al. 2018). Artificial intelligence models that have been integrated with ESP include response surface model (Sanusi et al. 2021), high performance random forests (Sneed 2017), decision trees, and gradient boosting (Wasfi et al. 2019).

Jansen Van Rensburg et al. (2019) used autonomous surveillance to train artificial (AI) intelligence systems to provide early detection of ESP abnormalities. By connecting the ESP to the AI system, the ESPs performance can be monitored real time. Should any abnormalities be detected, proper mitigation procedures are followed to avoid failures. Figure 10 shows an illustration of the AI process explained.

Based on the failure mechanisms mentioned above, it is clear that the main method by which all of these failures can be avoided is properly designing the ESP string and accounting for all the conditions that may initiate or enhance ESP assembly failure. A summary of the ESP failure mechanisms, main components that can be affected by each failure,

and the most common and suitable mitigation method for each failure is provided in Table 1.

Conclusions

This research performs a comprehensive critical review of the most common failure mechanisms of ESP pumps based on cases presented worldwide and attempts to determine the most suitable mitigation method for these failure in order to prolong the ESP life in the well. The main conclusions obtained from this research are as follows:

- Proper material selection can prolong the life of the ESP assembly significantly by avoiding component failures.
- Electrical failures are one of the most severe forms of ESP failures since they can result in immediate opera-

Fig. 10 AI integration with ESP Pumps Jansen Van Rensburg et al. (2019)

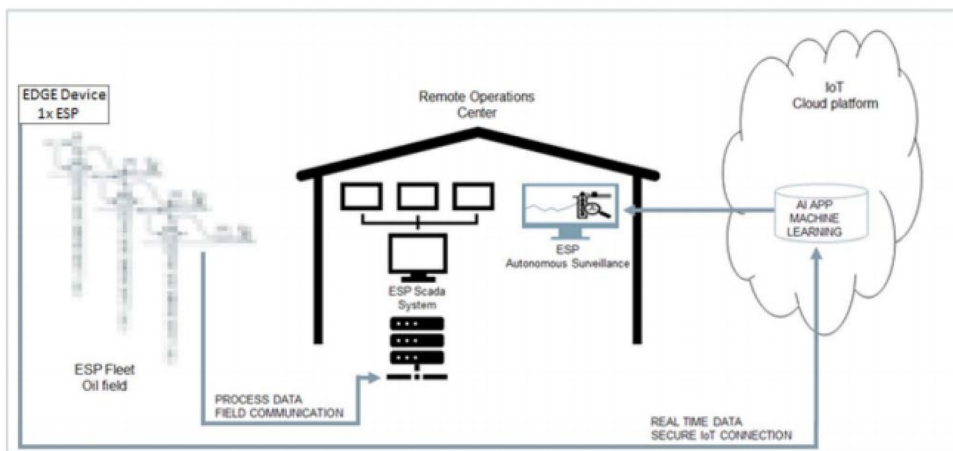


Table 1 ESP Failure Mechanisms Summary

Failure classification	Failure	Description	Detection method	Mitigation methods	References
Electrical	Cable	The cable can degrade with time due to downhole conditions or can be completely severed	Sudden operational cessation due to power loss	Cable replacement, and better insulation	(Kalu-Ulu et al. 2017; Lucas et al. 2018; Saveth, 2014; Jinjiang et al. 2020)
	Motor	Can fail due to electrical cuts in the stator or mechanical breakage in the rotor		Motor replacement and improvement in motor protector	(Dennis et al. 2017; Lastra et al. 2019)
Mechanical	Overloading	Gas lock can result in false signals to the VSD which may result in overload	Surface readings	Proper ESP material selection	(Amijaya et al. 2019; Heninger et al. 2019)
	Connection severance	Occurs mainly due to downhole sensor failure or malfunction	Sudden operational cessation	Replacement of sensor with proper material	(Medina et al. 2012)
	Breakage	Can occur due to material degradation, solid particle erosion, or corrosion	Fluid analysis on the surface. Also, abnormal pump or motor operating conditions	Replacement of component with a more durable material	(Xiao et al. 2020; Ye and Wilcox, 2018; Tiofiolo et al. 2018; Xiao and Lastra, 2019; Pino et al. 2015)
	Corrosion	Usually occurs in the form of pitting or anodic-cathodic corrosion			(Elichev et al. 2010; Kalu-Ulu and Albori, 2019; Christie and Cox, 2018)
	Dislocation	Usually occurs in the moving components of the downhole assembly			(Elichev et al. 2010)
Operational	Leakage	Occurs due to breakage of downhole components bearing fluids			(Elichev et al. 2010; Kalu-Ulu and Albori, 2019; Christie and Cox, 2018)
	Temperature	Can affect electric and mechanical components	Temperature and pressure sensors. operational cessation	Use temperature resistant Material	(Ye et al. 2019; Medina et al. 2012)
	Pressure	Electrical surges and mechanical failures		Avoid excessive pressure abnormalities	(Margarida et al. 2017; Marra and Girard, 2017; Martinez et al. 2018)
	Multiphase	The most severe damage of multiphase flow is gas lock, and corrosion	Produced fluid analysis	Gas prevention and venting	(Barrios et al. 2012; Dwitiya et al. 2015; Mali et al. 2020)
	Scale/solid	Cause mechanical and electrical failures		Proper operations and sand filter	(Elichev et al. 2010)

tional cessation. Electrical failures can be mitigated using proper selection of equipment and material.

- Mechanical failures are mostly material dependent. It is therefore important to properly select material that is compatible and corrosion resistant.
- Operational failures are best prevented by proper planning. This depends heavily on knowledge or reservoir thermodynamic properties and rock and fluid properties.
- Many of the failures associated with the ESP assembly are connected and can aggravate or initiate other failures. This indicates that avoiding some failures can result in the prevention of many other failures as well.

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Declarations

Conflict of interest On behalf of all the co-authors, the corresponding author states that there is no conflict of interest.

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