SPE Brazil Flow Assurance Technology Congress
Rio de Janeiro, Brazil, November 06 – 08 2024

Failure analysis and diagnosis in electrical submersible pumping systems

Flávio L. Leandro[1], Valdir Estevam[1], Marcelo S. Castro[1]
[1]Department of Mechanical Engineering, Unicamp, Brazil. flavio.epd@gmail.com

Abstract

The petroleum industry is characterized by its costly and cyclical activities. Therefore, the companies seek to maximize their revenues while directing efforts to decrease their operational and maintenance costs. In this context, the Electrical Submersible Pump (ESP) system synthesizes this context given its capacity to improve the production performance of oil wells and because of the high costs involved in its operationalization. The aim of this work is to develop a failure analysis and diagnosis system for the ESP system and its components: pump, motor, cable, and protective seal, based on expert's knowledge and statistical analysis represented by reliability indicators. To support this modeling, data on variables such as intake and discharge pump pressure, electrical current, motor temperatures and vibration were obtained from downhole sensors. The problem characterization was based on calculations involving the homogeneous gas-liquid model, estimation of oil viscosity using correlations such as the ASTM method, correction of the pump curves, characterization of the gas boundaries, among other information related to operational limits according to the *API RP 11S8* and the expert's experience. The results found explored the possible causes of the failures based on the combinations between the variables influenced the diagnoses.

Keywords

Electrical Submersible Pump (ESP); Failure analysis and diagnosis; Modeling and Simulation.

Introduction

The importance of the ESP system in the oil industry is recognized for its ability to improve the production performance of oil wells. This technology is implemented in many oil wells worldwide due to its high production volume and operational flexibility [1] and [2] highlight that ESP can be deployed in both dry and wet completion being characterized for wells containing high liquid flow rates, between 50 m³/d to more than 5000 m³/d, in addition to the ability to operate in wells with different geometries (vertical, horizontal or deviated).

According to this context, a premature failure in the ESP equipment due to several situations and conditions inherent to the pumping process implies in unscheduled well intervention, which generates high costs and compromises production viability in the field. Therefore, the reliability of this system has great relevance given the costs involved in oil production fields.

The use of real time data acquired from sensors installed in the wells, along with a system based on expert knowledge, allows the failure diagnosis modeling using parameters such as: pressure, temperature, vibration, and electric current. In addition, aiming to infer more robustness to the real time failure diagnosis system modeling, the reliability indicator concept of mean time to failure (MTTF) was implemented in this work based on a database containing information regarding the times to failure of the ESP's equipment and the entire ESP's system itself.

This work used the MAICE software [3] as a solution model of expert knowledge that can represent the rules that govern a given universe of knowledge, regardless of the area, so that it can later be integrated into other systems. The results of failure diagnosis modeled using the aforementioned concept are presented by simulating a fault tree-based mechanism called the Human Machine Interface (HMI).

The HMI is the visual feature that allows the user to track the status of the system in real time or on a specific date. There were three possible signal options: Normal Operation, Monitoring, and Failure; along with their respective verification and recommendation messages for each status of the failure diagnosis results. The way the system was modeled allows users to check the possible causes of failures of the entire system and its components. Users can also recognize patterns and evaluate whether the real-time failure diagnosis matches the MTTF-based statistical analysis, and thus support decision making.

Methodology

The complexity involved in centrifugal pumping systems is notorious because there are many physical and operational variables directly influencing their proper operation. There are two crucial issues concerning production that can define (or not) the implementation of ESP systems: the first is economic bias and relates to the average time of continuous operation of the pump before a stop for maintenance or equipment replacement; the other is technical bias and considers the restriction of pumping two-phase gas-liquid mixtures capable of reducing or even blocking production depending on the fraction of free gas admitted by the pump [4]. In addition to the technical bias, the performance degradation suffered in the ESP due to the pumping of fluids with high viscosity along with the increase in power required to drive the pump [2].

One can then observe the importance of obtaining and processing information acquired via sensors in real time that can not only present the current state but diagnose system failures. There are authors involved in predictive studies of failures using background sensors as a support tool, along with the modeling of intelligent systems using various techniques that aim to monitor the state of the equipment [5] [6] [7] [8] [9] [10]. In recent years, real-time monitoring technologies based on machine learning algorithms have gained momentum due to their ability to leverage historical equipment data to predict future events.

Regardless of the technique applied in the modeling of the intelligent system, we highlight the importance that any failures inherent in the process are diagnosed and made available to decision makers. With this, one can improve the schedule regarding the programming of stops for rig intervention, change operational procedures that allow the optimization of the production process, and reduce operational costs from unwanted stops due to equipment failure.

Therefore, this study proposes a hybrid system model based on expert ESP knowledge that can analyze operational parameters acquired from downhole sensors (temperature, pressure, vibration, electric current) and provide the decision makers with an interface containing the operational status (alarms) along with the failure diagnosis of the system and its equipment in real time by using the HMI (MAICE).

The MAICE software was used to model and simulate the failure diagnosis in the ESP system and the results were presented via panel, according to the following characteristics: if the color is green, it indicates normal condition; if the color is yellow, it indicates monitoring condition; if the color is red, it indicates a possible failure. The system can also offer the possible verifications and/or recommendations regarding the system's operational condition. It also allows to find out the root cause of a certain issue by going further in each diagnosis and technical analysis. MAICE is an abbreviation that means Methodology for the Storage and Integration of Expert Knowledge. It is characterized as a computational system based on artificial intelligence techniques for the construction, simulation, and storage of models of physical systems created based on the knowledge of specialists in the operation of these systems. The MAICE-Editor is a computational component of the MAICE system responsible for creating the models itself that represent the physical systems, using a set of functionalities through the manipulation and interconnection of functional blocks.

The modeling of the system containing the technical analyses were based on previous calculations regarding the fluid properties and other system characteristics, such as the respective load losses involved, aside from implementing specific rules for the partial and system failure diagnosis. We highlight that the operational conditions that have been diagnosed were: Normal; Short-Circuit; Pump/Surging Problems, and Excessive Vibration.

System Modeling

As evidenced in the previous chapter, there are several variables that act directly on the performance of ESP systems. To understand the influence of these variables in the failure diagnosis of the analyzed equipment, rules using fuzzy logic were defined and modeled using MAICE.

At each stage/level of system modeling, reference triggers were inserted to allow the users to verify the possible causes referring to the partial and system diagnoses along with their respective verifications and recommendations suggested by the expert. These triggers are signals capable of indicating when a given variable has reached a certain value that denotes a certain critical state (or not) according to the criteria established in the model.

Analyses were established on three levels, as follows. The results of a previous level are used as input in the next level.

•*Level 1* - Technical analyses of the input variables. In this paper input variables means getting relative variable values from the relationship between the measured values obtained from the sensors divided by a reference value either from the previous calculation based on the literature or based on the expert’s knowledge, as follow: *Relative Inlet Pump Pressure; Relative Discharge Pump Pressure; Relative Surging Indicator - Gas boundaries; Relative Electric Current; Relative Vibration; Relative Motor Temperature; Relative Motor Housing/Intake Temperature.*

•*Level 2* - Technical analysis of the combination the input variables. To better understand the influence of these variables on the system, evidence of failures produced by the combination of the input variables were implemented. Empirically, the combinations of these variables were modeled in pairs to present the reality observed in the industry.

•*Level 3* – Technical analysis of system component. These analyses were grouped by equipment and/or operational condition considering the following assumptions:

-Level 3 technical analysis considers normal operation if, and only if, all level 2 technical analyses indicate normal operations.

-The Level 3 technical analysis considers failure if at least one of the Level 2 technical analyses presents at least one failure indication.

-The level 3 technical analysis considers operational monitoring and surveillance to be necessary if none of the previous hypotheses are true.

The concept of lifespan is used in both partial and system diagnoses. Originally, this is a suggestion of an indicator based the relationship in between the elapsed time and a reliability indicator (MTTF calculated by q-Weibull).

Partial Failure Diagnosis

The definition of partial failure diagnosis involved the subdivision of the analyzed pumping system into groups consisting of: Complete Pump (Pump and Surging), and Electrical Equipment (Motor, Cable, and Protector Seal). In this step, the modeling was extended by evaluating the level 3 technical analyses results allowing to verify whether or not the partial failure diagnoses obtained through the implementation of the rules suggested by the specialist's knowledge are aligned with their respective lifespan.

Next, the summaries containing the schematics regarding the logics and rules involved in modeling the partial diagnostics were obtained along with the respective variables contained in each group, as indicated from Fig. 1 to Fig. 2.

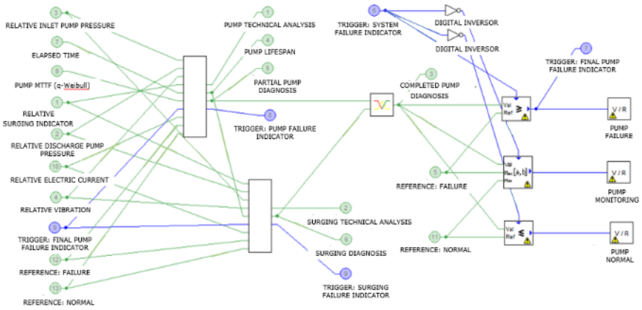

Figure 1. Partial Failure Diagnosis Modeling – Complete Pump.

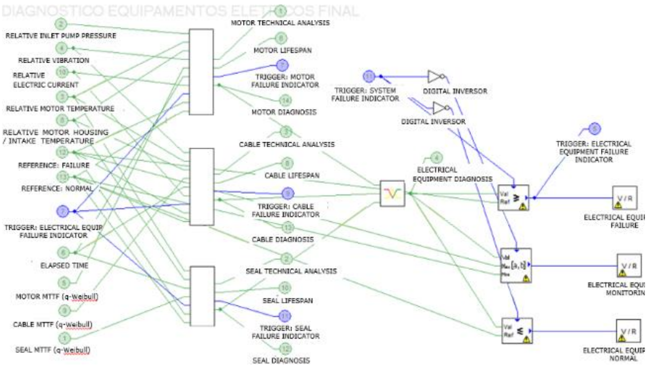

Figure 2. Partial Failure Diagnosis Modeling – Electrical Equipment.

System Failure Diagnosis

The modeling of the system failure diagnosis follows the same steps as described in the modeling of the partial failure diagnoses. However, there is a first reference trigger responsible for determining the activation of the entire process of calculations implemented in MAICE.

This procedure consisted of verifying whether the input variable called measured flow rate is within the range of operating flow rates contained in the pump's catalog. If this condition is not met, a warning is displayed recommending that the flow rate be adjusted to the operating limits indicated by the manufacturer. Once an adequate flow rate exists, a first trigger named main triggers all the secondary triggers involved in the modeling of the failure diagnosis of the entire system. The HMI feature provided by MAICE and the complete implemented logic of the system failure diagnosis concept are presented in the following Fig.3 to Fig4.

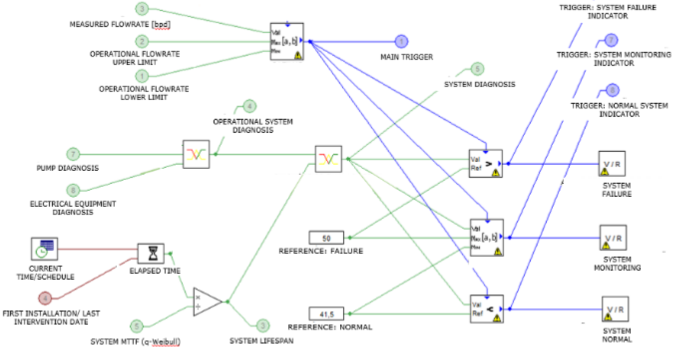

Figure 3. System Failure Diagnosis Modeling.

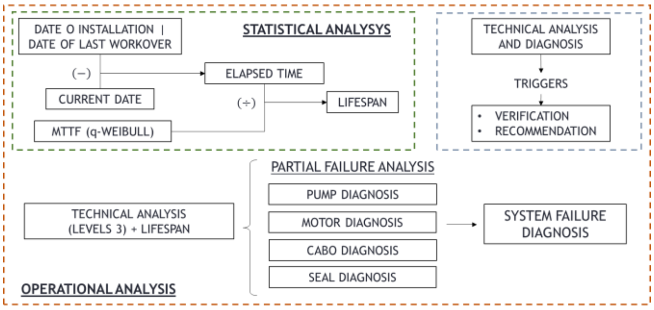

Figure 4. Schematic of the failure diagnosis concept.

Results and Discussion

The simulations were carried out using specific variable values that characterized the ESP operational condition as aforementioned (Normal, Pump/Surging, Excessive Vibration, and Short-Circuit). The context was to understand if the implemented system modeling logic following the expert knowledge could properly present the operational reality and compare the MTTF with the elapsed time of the ESP first installation or last workover. In sequence, is presented the results of the ESP's failure analysis and diagnosis.

The first intended simulated result named as Normal were set to Gas/Oil Ratio (GOR) = 60 m^3/m^3std, apart from others measured (by sensors) and reference's variables to calculate the relative variables used in the simulation. Those reference variables of each condition were calculated according to the literature, from pump's catalog or suggested by the expert`s knowledge in Table 1, as follow.

Table 1. Inputs for operational conditions.

ESP OPERATIONAL CONDITION		NORMAL	PUMP/SURGING	VIBRATION	SHORT-CIRCUIT
VARIABLE	REFERENCE	MEASURED			
INLET PRESSURE	183.75 kgf/cm^2 (Calculated - MAICE)	165 kgf/cm^2	**145 kgf/cm^2**	165 kgf/cm^2	165 kgf/cm^2
DISCHARGE PRESSURE	226,96 kgf/cm^2 (Calculated - MAICE)	210 kgf/cm^2	**185 kgf/cm^2**	**200 kgf/cm^2**	**165 kgf/cm^2**
ELECTRICAL CURRENT	65A (Catalog)	60A	**50A**	60A	**85A**
MOTOR TEMPERATURE	150 °C (Expert's Knowledge)	110°C	110°C	110°C	**165°C**
MOTOR HOUSING/INTAKE TEMPERATURE	140 °C (Expert's Knowledge)	100°C	**110°C**	100°C	**155°C**
VIBRATION	15G (Expert's Knowledge)	12G	12G	**15G**	12G

The Fig. 5 illustrate the Normal condition settled as default and synthesizes the activation of the HMI simulation based on the modeled rules presented from Fig. 1 to Fig. 3. This method allows the decision maker to further investigate the possible causes of an eventual system failure by popping up HMI of the partial failure diagnosis levels.

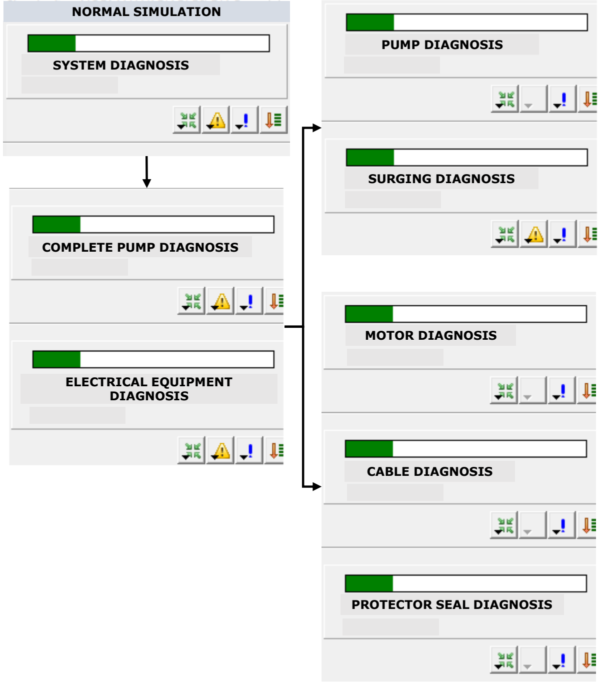

Figure 5. Failure Diagnosis – HMI – Normal.

It was varied the GOR applying the respective variable's values from each column presented in Table 1, the simulated results converged with their respective proposed modeling conditions, as showed from Fig 6 to Fig 8.

The Fig 6 presented the failure diagnosis for Pump/*Surging.* The interpretation of the possible causes of this system failure diagnosis due to pump problems by the technical analysis composed of the pair of the variables, relative inlet pressure, and relative current present in this context as responsible for inferring pump equipment failure with failure indication ≈80%) and the pair of variables relative surging indicator and relative discharge pressure are responsible for inferring surging failure with failure indication ≈100%).

On the date of the simulation, the analysis of the pump's lifespan indicated that the elapsed time since the first pump's installation or its last workover exceeds the MTTF calculated for this equipment. Therefore, it becomes evident the need to act on the failure indication, avoiding greater damage to the pump. It is important to investigate the real reasons that are not only changing the electric current, but the conditions regarding the inlet and discharge pump pressures. At this point, it is worth mentioning that a workover is necessary to avoid worsening this condition by inducing the pump to work in gas block boundary conditions, and consequently fail.

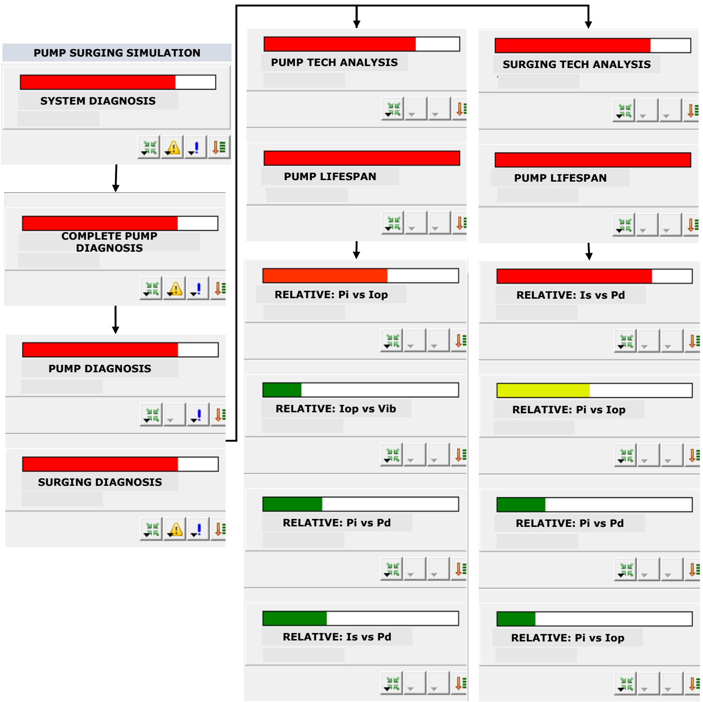

Figure 6. Failure Diagnosis – HMI – Pump/Surging.

The Fig 7 presented the failure diagnosis for Excessive Vibrations. The boundary conditions related to the variables obtained for this condition are equivalent to the normal condition, except for the reduction of the measured pump discharge pressure and the increase of the measured vibration. Verifying the possible causes regarding the system failure diagnosis due to pump problems, it is possible to observe through the technical analysis that the pair of variables composed by the relative current and relative vibration were responsible to infer the equipment failure with the failure indication of ≈35%.

Analyzing the vibration condition above, one may conclude that, for the minimum failure indication, it is necessary to act over the failure presented. As previously reported, the parameters that influence the performance of the equipment can be checked by the user and a maintenance plan could be put in place before major damage. The condition related to the increased vibration in the pump may be related to a malfunctioning shaft, for instance.

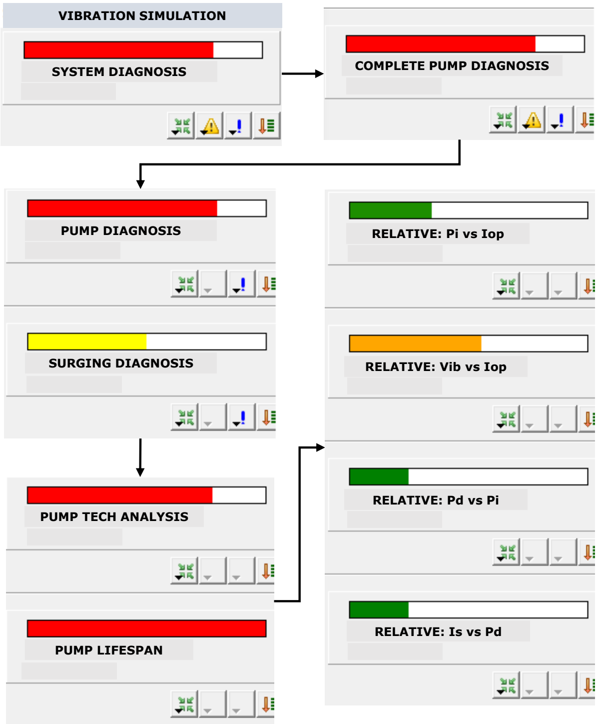

Figure 7. Failure Diagnosis – HMI – Excessive Vibration.

The Fig 8 presented the failure diagnosis for Short-Circuit. The possible causes concerning the motor issues that influence the system fault diagnosis, it was observed from the technical analysis that the relationship between relative inlet pressure and relative current with fault indication ≈98%, the relationship between relative current and relative vibration with fault indication ≈45% and the relationship between relative temperature in the motor and relative temperature in the motor/intake housing with fault indication 75% were responsible for this scenario. Additionally, the possible causes concerning the cable issues that influence the system fault diagnosis, the technical analysis of the relationship between relative temperature in the motor and relative temperature in the motor housing/intake with a fault indication of ≈100% is shown to be the most critical for the occurrence of this scenario. The aforementioned condition justifies the failures in the motor and cable, reflected by the considerable increase in temperature of this equipment, resulting a ESP's overload failure.

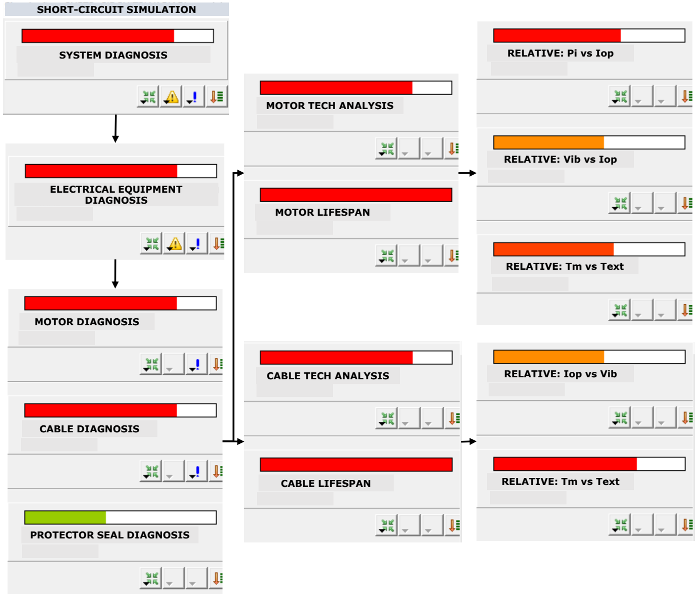

Figure 8. Failure Diagnosis – HMI – Short-Circuit.

A summary of the failure diagnosis system based on the expert's knowledge along with the software (MAICE) used in this modeling is presented as follow.

Strengths points:

- Allows diagnosis to be carried out both online and after analyzing operational data;
- The diagnosis presented the probability of each failure to occur inferring the percentages of the variables related to each failure occurrence.
- The prediction of future failure based on a reliability indicator (MTTF *q-Weibull*) allows the decision maker to have enough time to take appropriate action before the failure occurs;
- By recommending possible actions to mitigate a possible premature shutdown of the ESP set, the MAICE system offer the opportunity to plan a new ESP set order or call for intervention rig.

Weaknesses points:

- The knowledge base depends on the expertise of a specialist and requires great attention when setting up the rule networks;
- The system does not accumulate knowledge, such as neural networks or other more advanced machine learning. This requires constant external action to update the knowledge base;
- The system requires a lot of speed and computing power to carry out the diagnoses in order to work well online.

Conclusions

In this work, through the analysis and interpretation of the results presented, as verified that a failure diagnosis system based on expert`s knowledge along with the implementation of consistent statistical analysis can provide relevant information to decision makers in scenarios involving ESP systems.

Therefore, the hybrid system developed proved efficient within the proposed scope by presenting partial and total failure diagnosis concerning the ESP system.

Acknowledgments

The authors would like to thank CAPES for their financial support and thank the Artificial Lift & Flow Assurance Research Group, the Center for Energy and Petroleum Studies, and the School of Mechanical Engineering, all part of the University of Campinas.

Responsibility Notice

The authors are the only responsible for the paper content.

References

[1] Estrada, Cristhian Porcel. Experimental study of electrical submersible pump ESP operating with ultraviscous oil. 2019. 157 f. Universidade Estadual de Campinas. Campinas, 2019.

[2] Monte Verde, William. Performance modeling of ESP pumps performance operating with gas-viscous liquid mixtures. 2016. 408 f. Universidade Estadual de Campinas. Campinas, 2016.

[3] Corrêa, José F; Oliveira, Fabricio M; Schnitman, Leizer. MAICE - an Expert Knowledge Modeling Tool applied to Oil Well Automation. Congresso Ibero-Americano de Inovação Tecnológica e Áreas Estratégicas. Rio de Janeiro: 2007.

[4] Amaral, Gilmar Dutra Leite Do. On the Influence of Viscosity upon Electrical Submersible Pumping Performance. 2007. 234 f. Universidade Estadual de Campinas. Campinas, 2007.

[5] Castellanos, Mauricio Barrios. Monitoring of operational failures in multistage centrífugal pumps. 2019. 108 f. Universidade Estadual de Campinas. Campinas, 2019.

[6] Marin, Antonio Andrade et al. ESP Well and Component Failure Prediction in Advance using Engineered. Abu Dhabi International Petroleum Exhibition & Conference, p. 11–14, 2019.

[7] Ganda, Wenderson L.; Munaro, Celso J. Detecção e diagnóstico de falhas em um sistema de bombeio centrífugo submerso de produção offshore operando em múltiplas regiões. Anais do XXII Congresso Brasileiro de Automática. Campinas, 2018.

[8] Adesanwo, Moradeyo et al. Advanced analytics for data-driven decision making in electrical submersible pump operations management. Society of Petroleum Engineers - Nigeria Annual International Conference and Exhibition 2017. Lagos: 2017.

[9] Abdelaziz, Mohannad; Lastra, Rafael; Xiao, J. J. ESP data analytics: Predicting failures for improved production performance. Society of Petroleum Engineers - SPE Abu Dhabi International Petroleum Exhibition and Conference, p. 17, 2017.

[10] Rivera, Manuel Humberto Manyari. Fault Diagnosis in discrete event systems. 2007. 151 f. Universidade Federal de Rio de Janeiro, Rio de Janeiro, 2007.