INTELLIGENT SUPERVISION CONTROL FOR THE VASPS SEPARATOR

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Abstract. The Vertical Annular Separation and Pumping System, VASPS, has been applied to low-pressure subsea wells with high gas production potential. In this system, the separation is carried out on the sea bed, thus allowing the monophase transmission through different pipelines. In the present work, an analysis has been established between two conceptually distinct models for the control system, which is under development and uses the Fuzzy Control technique for the Electrical Submersible Pump (ESP) speed selection. The contrast is held on the objective of each controller, placing the operational performance against the stability of the control signal, which leads to the exploration of many specific aspects of the system, its behavior and requirements.

Keywords: VASPS; subsea separation; ESP; fuzzy control; smart control; performance; stability

1. INTRODUCTION

The Vertical Annular Separation and Pumping System, VASPS, consists of a vertical separator with a multiphase intake, an expansion chamber and a helix, connected to an Electrical Submersible Pump (ESP) on its bottom and two separate pipelines, for gas and liquid, installed on a “fake” well in the sea bottom. Its intake may be connected to a wellhead or to a manifold system, as illustrated in Figure 1, and it can be located some kilometers away from the well, in order to receive the production from as many other wells in a region as it is able to provide a certain production capacity.

This technology has been successfully applied to subsea wells with high GOR (gas-oil ratio) and low wellhead pressure, increasing its lifespan along with the production in places with low potential. This technique, whose installation and first operation are discussed in do Vale et al. (2002), was object of study in other previous works, as in França et al. (1996), given the interest of increasing production in offshore fields. In this system, the free gas is separated from the liquid phase during the flow in the helix, thus allowing single-phase transmission in different lines. Consequently, with the separation in the sea bottom and without the necessity of multiphase transmission, there is a significant increase in production, especially for the gas.

In spite of the interest for this technology, since its first field installation in Brazil the system has presented difficulties in keeping designed operation levels, given the disturbances caused by the slug inflow in the system. Such disturbances allied to the nonlinearities of the system imply high randomness on the system behavior, making it difficult to predict the necessary control actions and demanding the supervision of an operator. Finally, start-ups and stops must also be supervised in order to guarantee the performance, since frequent manual interventions are thereby required.

Such panorama justified the interest for designing a control system focused in
improving the performance of the system. A simplified model was idealized by Teixeira et al. (2004), reflecting the basic dynamics of the system, with the intent of conceiving a controller which allows a steady operation in laboratory, which provides the refinement of this model as well as the initiation of the computational simulations of the controlled system, evaluating response, stability and disturbances.

The model used in this work considers the controlled variable as the level of liquid in the reservoir inside the VASPS, depicted in Figure 2 as “pool”, and the manipulated variable as the rotation frequency of the pump, which is the control signal. The controlled variable must
follow a reference signal, which restrains to a closed interval. Its superior limit represents the threshold for the lowering of the gas separation efficiency in the helix, feeding the pump with a very high gas fraction in the fluid, and its inferior limit is determined by the physical height of the intake of the pump, which cannot receive purely separated gas. In both cases, the pumping will be compromised, causing the system to stop.

With the model developed by Teixeira et al. (2004), and with the instrumentation detailed in Teixeira et al. (2006), two studies were conducted with distinct approaches for the control system, and the contrast between both is object of discussion in this work. The first approach, herein called Solution A, reported by de Melo et al. (2007a) and de Melo et al. (2007b), focuses in improving the performance of the system by means of a Fuzzy-PID control for the “pool” level variation, minimizing the error against the reference signal. The second approach, named Solution B, focuses on the stabilization of the control signal, minimizing the amount of acceleration and deceleration ESP activation ramps, thus enlarging its lifespan and therefore reducing operational costs, in detriment of the level control, which must oscillate within the stability band, given by the interval allowed to the reference signal.

2. METHODOLOGY

The modeling of the dynamic system, including the ESP, a slug flow generator and the level dynamics, and the modeling of the two controllers are presented in three distinct sections, with their respective governing equations, block diagrams and discussions. The theoretical process model was simulated with each one of the control techniques in order to evaluate the behavior of the system and compare with the field experience. This step allowed the selection and correction of the most adequate technique for future experimental assemblies, resulting in the definition of a compromise between operational costs and performance of the system.

For the experimental stage of the project, with the control system already defined, the simplified model used for the three above-mentioned components – the ESP, the slug flow generator and the level dynamics – will be more rigorously calibrated and detailed. For the elaboration of the control loop, a set of differential equations defined is sufficient.

2.1. Process Model

The block diagram of the process model is presented in Figure 3, being the controlled variable (the level) governed by Equation 1, and the nonlinear curve of the ESP stated by Equation 2. Basically, this model uses the level error as the control parameter to find an ideal rotation by the controller in the frequency inverter. With this rotation, the ESP curve is used to identify the outflow imprinted in the system, which conjugates with the inflow calculated by the slug flow generator, allowing to compute the level variation given by Equation 1. The loop is closed to perform the feedback control, and reflects the basic principles of the VASPS in the real system.

\[
\frac{dN}{dt} = \frac{4}{\pi (d_e^2 - d_i^2)} \left( \dot{Q}_o - \dot{Q}_i \right)
\]

(1)

\[
\dot{Q}_o = -0.0577 \cdot f^3 + 8.0786 \cdot f^2 - 249.18 \cdot f - 263.36
\]

(2)

In Equations 1 and 2, \(d_e\) and \(d_i\) are respectively the internal and external diameters of the VASPS pool, in meters; \(N\) is the level, also in meters; \(\dot{Q}_i\) and \(\dot{Q}_o\) are the inflow (given by the generator) and the outflow (given by the
pump), in cubic meters per second; and \( f \) is the rotary frequency of the ESP, in Hertz.

The role of the slug flow generator in the system is of extreme importance for the conception and validation of the computational model, since it is the responsible for simulating all the field disturbances that make the operation of the separator complex, constituting an essential tool for the evaluation of the robustness of the considered controller and its sensitivity to variations in the flow. The first simulated behavior of the flow given by the slug flow generator is presented in Figure 4.

Throughout the project, the slug flow generator was being enhanced to simulate more severe conditions, in order to evaluate, for Solution B, if the objective of keeping the stability of the control signal was being accomplished, even though in a harsher condition. This validation credits the developed model higher conceptual confidence. By doing this, at the end of the simulations the slug flow had its frequency and amplitude randomized, composing the signal of disturbance presented in Figure 5.

2.2. Solution A

Solution A involves the application of the concept of Fuzzy PID supervision with the intention of improving the dynamic response of the VASPS. By keeping the original controller PID in the main loop of the system, the supervisor varies the constants P, I and D in real time, reinforcing the control signal next to the stabilization regions of the error and its variation, improving the performance without intervening directly in the process.

The concept of a hybrid controller is better visualized in Figure 6, which presents the intelligent controller in a hierarchical level superior to the PID, having the same inputs as its object, and modifying the designed constants of the classic controller, adjusting them along with the operational status of the system.

For the composition of the Fuzzy Logic, normalized variables were used, as presented in Figure 7. With these, Sugeno-type rules have

![Figure 4. Inflow rate of liquid inserted by the slug flow generator.](image1)

![Figure 5. Second and third slug flow generators, with random frequency and random amplitude.](image2)
been composed with the objective of reinforcing the control action at points where the control signal must act, reducing or eliminating it in situations of undesired contribution, thereby increasing or reducing the value of the control constant (K_P, K_D or K_I), and therefore the control signal.

2.3. Solution B

Because of the elevated costs of maintenance and replacement of an ESP, it is highly desired to increase its lifespan. For this, it is necessary that the control signal be modified the least as possible, in order to keep the level of liquid within the stability band. Thus, two values, P_S (pressure of separation) and P_F (pump failure) have been defined for the upper and lower thresholds of the interval within which the reference signal can vary. In simulations the values of 40 and 20 meters have been used, and then two concepts have been explored:

- **Average Level Model**: the rotation of the ESP is varied only when it has a significant variation in the average of the reading level (response signal), or when the instantaneous level is next to the established thresholds;

- **Classifier Model**: the real level is classified with a value of pertinence according to dynamic functions which are altered with the value of the reference signal, giving a parameterized rotation value (control signal) as output, which is modified at critical rotation values.

In both models, there are work regions within the stability band to prevent great variations in the rotation. These regions are defined by the Fuzzy Sets for each model, also using Sugeno-type rules for the computation of the output variable.

2.3.1. Average Level Model

A parameter n defines the amount of points used to compute the mobile level average. The
corresponding model diagram is presented in Figure 8. The normalized level is applied to the Fuzzy Sets in Figure 9, and the output (the rotation), defined by region, assumes the values defined in the rulebase shown in Figure 9.

2.3.2. Classifier Model

In this model, the work region allows variation of the Set Point – the reference signal –, differently of the previous model, since this variation makes the pertinence function to have its inclination modified, as presented in Figure 10, by fixing the values of $P_S$ and $P_F$ and varying the Set Point (SP) in the level axis.

The corresponding block diagram is presented in Figure 11, and the Fuzzy Sets are shown in Figure 12, where it is possible to verify that there is a wide interval of fixed rotation in the stability band, changing the control signal to other values (rotations) only when strictly necessary (next to the critical region). Although this intensely reduces the actuation on the pump, providing stability to the control signal, there is a great stationary error imprinted on the response signal, as can be seen by the results.

3. RESULTS

3.1. Solution A

The simulations performed have considered the start-up of the system with the “pool” level in its minimum value, in order to evaluate the performance in a critical case and with the measuring device indicating a level below the reference. This situation allows the evaluation of the response whilst the filling of the reservoir with liquid takes place, which is a more critical procedure than the emptying.

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**Figure 8.** Block diagram of the ‘Average Level’ Model.

**Figure 9.** Fuzzy Sets and Rulebase for the ‘Average Level’ Model.

**Figure 10.** Block diagram of the ‘Average Level’ Model.

**Legend**

<table>
<thead>
<tr>
<th>Rulebase</th>
<th>Instantaneous Level</th>
<th>Average Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLC: Low Level Critical</td>
<td>LLC: 48 Hz</td>
<td>LLC: 48 Hz</td>
</tr>
<tr>
<td>LL: Low Level</td>
<td>LL: 50 Hz</td>
<td>LL: 52 Hz</td>
</tr>
<tr>
<td>DL: Designed Level</td>
<td>DL: 58 Hz</td>
<td>DL: 54 Hz</td>
</tr>
<tr>
<td>HL: High Level</td>
<td>HL: 56 Hz</td>
<td>HL: 56 Hz</td>
</tr>
<tr>
<td>HLC: High Level Critical</td>
<td>HLC: 60 Hz</td>
<td>HLC: 60 Hz</td>
</tr>
</tbody>
</table>

**Legend**

<table>
<thead>
<tr>
<th>Fuzzy Set</th>
<th>Normalized Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLC: Low Level Critical</td>
<td>0.25</td>
</tr>
<tr>
<td>LL: Low Level</td>
<td>0.20</td>
</tr>
<tr>
<td>DL: Designed Level</td>
<td>0.15</td>
</tr>
<tr>
<td>HL: High Level</td>
<td>0.10</td>
</tr>
<tr>
<td>HLC: High Level Critical</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Figure 8.** Fuzzy Sets and Rulebase for the ‘Average Level’ Model.

**Figure 8.** Block diagram of the ‘Average Level’ Model.

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since the pump must be activated only when submerged. The existence of a controlled behavior is therefore strictly necessary. The reference level for the system was 30 meters and the simulations have been carried with and without the supervisory system, for comparison, by measuring the improvement in performance.

It is possible to notice the improvement in the overshoot – which is the value of the peak response – and in the stabilization time – which is the time the response takes to stop around a certain value. These effects are consequence of not saturating the control signal with the large errors of the transient prevention provided by the Fuzzy control when eliminating undesired contributions of the P, I and D measurements. Moreover, the early actuation on the system allowed to diminish the stationary error in the transient response, with a very similar control energy, an effect caused by the reinforcement

Figure 10. Pertinence Function, which classifies the input level used in the controller.

Figure 11. Block diagram of the controller for the ‘Classifier’ Model.

The imposed critical situation allows the evaluation of the response in the transient and the stationary response. This effect is reproduced in Figure 13, where the response signal is presented, both with the PID controller alone and with the FPID controller. Besides the response of the system, the control signal that generated the given response is also being evaluated.

Figure 12. Fuzzy Sets and Rulebase for the ‘Classifier’ Model.
of the control constant.

The performance demonstrated here, which was the object of study of this model, was reached without loss of quality in the control signal and without loss of stability. Besides, the data collected in the simulations disclosed improvements of performance that are applicable to other types of systems beyond the
VASPS, given that this is an application of intelligent control to an operating process using the spread-out PID control. Still, the advance in the studies allows new approaches to be taken in the exploration of different prerequisites for the good functioning of the separator and the ESP, being the supervision level proposed in this work ideal for adding new resources to the controller. In the minimum case, the system is open to the integration of more relevant variables in the process, since the application potential of the technology still allows for deeper exploration.

3.2. Solution B

3.2.1. “Average Level” Model

Simulations for the initial level of the reservoir at 60 meters have been carried out, simulating the completely full VASPS, using three values for $n$, namely 500, 2000 and 5000. The results are shown in Figure 14. This initial level is used for system start-ups with diesel before opening the multiphase fluid intake, enabling to evaluate the transient response under conditions of very large initial error.

The curves in Figure 14 display the effect of $n$. The smaller the $n$ value, the closest the average level is to the instantaneous level, and, therefore, the greater are the variations in the output signal, since the peaks are reflected in the average level. On the other hand, the greater the $n$ value, the slower and the more gradual is the reaction of the controller, which enables the formation of peaks which are more distant from the reference level. This behavior is noted in both simulations, and for the intermediate value of $n$, 2000, there are no peaks detached far away from the response. Furthermore, a smoother descending and ascending behavior of the control signal is observed, instead of great oscillations in each sampling.

There is a great conceptual difference from Solution A. The model provided by Solution B is much more robust regarding the quality of the control signal, in detriment of the performance. The controller is simpler, even computationally, and it is more connected to the field necessities. The idea of using the average level for the prediction of the behavior of the system was well received and it reveals a valid tool for experimentation.

![Figure 15. Response and Control Signal for two simulations of the “Classifier” Model.](http://www.portalabpg.org.br/bjpg)
3.2.2. "Classifier" Model

This controller model was developed with the intention of maximizing the robustness, since it monitors the stability band and provides a large region of constant pump rotation in the center of the pertinence function. As a result, some measurements have been taken to check such robustness. The first one involved the use of the same reference signal employed in all previous simulations with this controller, evaluating if it is possible to disturb the stability of the control signal. Moreover, the constants \( P_F \) and \( P_S \) have been moved towards the center of the stability band, in order to evaluate the effect caused by a tighter control in the process. This enables comparison with the previous values for these constants, which were 20 and 40 meters, to which simulations have also been made. Figure 15 shows the simulation for the initial level of 60 meters. The values of 25 and 38 meters were initially assumed for the \( P_F \) and \( P_S \) constants, respectively, as presented in Figures 15b and 15d.

As expected, the controller proved to be sufficiently robust, also showing a smoother transient response than in the “Average Level” Model. However, it presented the side effect of not following the reference signal – which makes sense, since there is no adjustment of the control signal within the stability band. This also explains the small oscillations which occur because of level stabilization next to the transition region (between the stability and the critical points), not minimizing the error.

4. CONCLUSION

This work illustrates the importance of knowing real systems and reveals the importance of control when designing improvements in a control system. It is important for the developer to know the behavior of the system prior to modeling, in order to construct simplified models that represent the basic rules to be handled, so that the detailing of the model can be given only in the experimental phase. Moreover, the objective of the industrial control on the control strategy may vary to the point of redefining the concept of performance of the system. The contrast between performance and stability is always a main issue in automation of processes, and can lead to the redevelopment of projects.

The performance of the VASPS model was satisfactory in fulfilling its tasks, but imposes very harsh conditions in pumping operations. When designing controllers focused on the stabilization of the control signal, the Average Level Model provided a well behaved signal, with soft variations throughout the stability band, although not accepting variations in the reference signal. The Classifier Model, on the other hand, provided a robust controller, however not acting on the system as desired, being insensitive to variations, which ultimately predicts the behavior of the system. For future projects, a hybrid model can be elaborated, also correcting the remaining oscillations in the transient response that happen when activating two Fuzzy Sets at a time, in order to design a controller with the advantages shown by each model as an effort to suppress the drawbacks obtained.

REFERENCES

