Robust Adaptive Control of a Sucker-Rod Pumping System of Oil Wells

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Abstract: Several studies have shown that the satisfactory oil well operations with sucker-rod pumps is attributed to the techniques and methods which are able to control the performance of the well. However, the presence of uncertainties in the sucker-rod dynamical models or parameter variations may jeopardize the desired performance of the control system and the rod pump system productivity. These parameters are normally related to, for example, fluid characteristics in the well, environmental properties at the bottom of the hole, electrical components and mechanical assembly. The purpose of this paper is to use a robust adaptive controller (called IVS-MRAC) to deal with some uncertainties in the system model, unmodelled dynamics, parameter variations, and the presence of perturbations in the automatic level control system of the annular well. The results obtained in simulated environment have shown that the adaptive controller is able to deal satisfactorily with uncertainties and variations, such as for instance, in the pumped fluid composition (water, oil and/or gas), a very common situation in real production fields. The fast transitory with no oscillations (typical characteristic of variable structure systems) is also observed in the plant output and control effort signals. The results are also compared with a conventional PID controller.

Key–Words: Adaptive control, Control applications, Oil industry, Process automation, Production control, Robust control, Sucker-Rod pump systems.

1 Introduction

The sucker-rod pump system is the artificial lift method most used in the current on-shore petroleum industry due to the simplicity of its equipments and facilities [1]. This method is also considered as the first technique used to lift oil up from wells. Studies have shown that its popularity is related to low cost of investments and maintenance, deep and outflow flexibility, good energy efficiency and the possibility for operating in different fluid compositions and viscosities in a wide range of temperatures [2].

Although this lift method is already well-known and widely used, there are still some circumstances in which improvements in the operational conditions are still possible, especially when dealing with production control strategies of the pump unit for increasing the system productivity. The development of low cost sensors turned possible the measurement of bottom-hole variables that assists the production monitoring, application of new control strategies, and enhancement of the process automation [3, 4, 5].

In terms of production control of the pump unit, the presence of uncertainties in parameters, parameter variations, unmodelled dynamics, and perturbations are challenges to the control system and they can jeopardize the good performance of a conventional controller, PID.

The aim of this paper is to use an Indirect Variable Structure Model Reference Adaptive Control (IVS-MRAC) based on [6] to deal with the challenges into the automatic control of the fluid level in the annular well. The negative effects caused by parameter variations and perturbations are related to some physical parameters of the system or faults of electrical and mechanical components. These effects may risk the satisfactory operation of the pump controller with consequences in the system oil productivity.

2 The Sucker-Rod Pump System

In this artificial lift method a rotary movement of prime mover (either an electric or a combustion mo-
tor) localized on the surface of the pump unit is converted in alternative movement of the rods column. This same column transmits the an alternative movement to the pump components that are located at the bottom of the well, that are responsible to elevate the fluid from reservoir up to the surface. The sucker-rod pump system could be divided in downhole and surface elements (see Fig.(1)).

Figure 1: Components of a sucker-rod pump system.

The rods column is the link between the pump unit localized on the surface and the bottomhole pump. The bottomhole pump is a kind of alternative pump of positive displacement of simple effect, in other words, the fluid is displaced in a one way direction of the alternative movement. The function of the bottomhole pump is providing energy to (increasing the pressure of) the fluid from reservoir [1]. In Fig.(2) the bottomhole scheme is presented. The annular well and pump inlet level are also shown.

Figure 2: Bottomhole scheme with sucker-rod pump system.

The pumping cycle generated by the relative movement of the valves have repercussions on the bottomhole pressure. The oil production is controlled by varying the prime mover velocity, which implies in the manipulation of the pumping speed, measured in cycles per minute (CPM). In this control strategy the variable speed drive (VSD) technique is used. That allows to adjust the pumping speed through a frequency inverter device [7, 8]. It is important to remark that the production performance is associated with the annular fluid level, and the operation with the minimum possible annular level (minimum bottomhole pressure) the reservoir oil outflow is maximized [9]. The control objective is to increase the oil production avoiding the effects caused by uncertainties in parameters, parameter variations, unmodelled dynamics, and perturbations. They are normally related to fluid characteristics in the well, environmental properties at the bottom of the hole, electrical components and mechanical assembly, for example.

3 The Control Technique

3.1 Adaptive Controller

In systems that are assembled with sucker-rod pumps, often it is desired that an operation range is very close to the pump inlet level. This operation range is characterized by the complete pump filling with the least bottomhole pressure possible. That provides the minimum back pressure on the production zone of the reservoir and, in turn, it increases the oil production [9].

In this work a robust adaptive controller (called IVS-MRAC) is applied to a sucker-rod pump. It could be also desired that the controller operates inside the range. Moreover, the controller must be able to adapt the parameters and show robustness in case of process changes, uncertainties, variations, unmodelled dynamics, and perturbations in the system.

The IVS-MRAC was initially proposed in [6], and appears as an alternative project to the direct approach called VS-MRAC [10]. The stability analysis and its proof in presence of unmodelled dynamics and perturbation, for the case of relative degree one, can be found in [11]. A simplified version with practical application of the IVS-MRAC to the speed control of a three-phase induction can be found in [12].

The base that this technique was developed is the indirect MRAC. By using the sliding mode control based on VSC (Variable Structure Control) [13], the MRAC is associated with faster transitory and robustness to the parameters uncertainties, variations, and perturbations. The IVS-MRAC could estimate the...
plant parameters instead of using the controller parameters.

This adaptive controller provides a straightforward design for the relays amplitudes used in switching laws of the controller algorithm [12], since these relays will be directly associated with the plant parameters. These parameters, in turn, represent the relationships among the physical parameters of the system such as the resistances, capacitances, moments of inertia, friction coefficients, etc., that have more easily known uncertainties. The block diagram shown in Fig.(3) may illustrate the general idea of using the IVS-MRAC.

\[ n_p(s) = s^{n-1} + \sum_{i=1}^{n-1} \beta_i s^{n-1-i}, \]  
\[ d_p(s) = s^n + \alpha_1 s^{n-1} + \sum_{i=1}^{n-1} \alpha_{i+1} s^{n-1-i}. \]

The desired response given by the transfer function of the model reference signal could be written as follows,

\[ \frac{y_m(s)}{r(s)} = M(s) = k_m \frac{n_m(s)}{d_m(s)}, \]

where \( y_m \) is the model reference output. It is assumed the reference input \( r \) is a part-continuous signal and uniformly bounded. The polynomials \( n_m \) and \( d_m \) are similarly defined as the polynomials of the plant

\[ n_m(s) = s^{n-1} + \sum_{i=1}^{n-1} \beta_{m,i} s^{n-1-i}, \]
\[ d_m(s) = s^n + \alpha_{m,1} s^{n-1} + \sum_{i=1}^{n-1} \alpha_{m,i+1} s^{n-1-i}. \]

The vector of plant parameters, supposed known, is set as,

\[ \theta_p = [k_p, \beta^T, \alpha_1, \alpha^T]^T, \]

where \( \beta \in \mathbb{R}^{n-1} \) contains the elements of \( \beta_i (i = n - 1, \ldots, 1) \), \( \alpha_i \in \mathbb{R} \) is the element \( \alpha_1 \) in (3), \( \alpha \in \mathbb{R}^{n-1} \) contains the elements of \( \alpha_{i+1} (i = n - 1, \ldots, 1) \) in (3), and, in the same way, one sets \( \beta_m, \alpha_{m,1} \) and \( \alpha_m \), in (5) and (6). When the plant parameters are unknown or known with uncertainties, the estimated vector is given by,

\[ \hat{\theta}_p = [\hat{k}_p, \hat{\beta}^T, \hat{\alpha}_1, \hat{\alpha}^T]^T. \]

The following assumptions regarding the plant and the reference model are made: [12]:

A1 the plant is completely observable and controllable with degree \( (d_p) = n \) and degree \( (n_p) = n - 1 \), where \( n \) is known;
A2 \( \text{sgn}(k_p) = \text{sgn}(k_m) \) (positive, for simplicity);
A3 \( n_p(s) \) is Hurwitz, i.e., \( P(s) \) is the minimum phase;
A4 \( M(s) \) has the same relative degree of \( P(s) \) and is chosen to be Strictly Positive Real (SPR);
A5 upper bounds for the nominal plant parameters are known.
For a first-order system, the vector of the estimated parameters could be rewritten as,
\[ \hat{\theta}_p = [\hat{k}_p, \hat{\alpha}_1]^T. \]  

(9)

The error equation between the plant response and the reference model output (desired response) is given by,
\[ e = y - y_m. \]  

(10)

If the previous assumptions are satisfied, one has the matching condition, i.e., \( y \to y_m \). The control law \( u \) could be rewritten as,
\[ u = \theta_n y + \theta_2 n r. \]  

(11)

\[ \theta_n = \frac{\hat{\alpha}_1 - \alpha_{m,1}}{k_p}, \]  

(12)

\[ \theta_2 n = \frac{k_m}{k_p}. \]  

(13)

The controller parameters are updated by using the estimates of the plant parameters, characteristic of the approach of IVS-MRAC. The estimates, in turn, are obtained according to the original laws proposed in [6],
\[ \dot{k}_p = k_p^{nom} - \overline{k}_p sgn(v_{av}), \]  

(14)

\[ \dot{\alpha}_1 = -\overline{\sigma}_1 sgn(e_0 \zeta_1), \]  

(15)

where \( sgn \) is called signal function and \( \zeta_1 \) is an auxiliary signal. In this work this signal is defined as \( \zeta_1 = y \). The values of \( k^{nom}_p \), \( \overline{k}_p \), and \( \overline{\sigma}_1 \) are constants. The values \( \overline{k}_p \) and \( \overline{\sigma}_1 \) are associated with the relays sizing in the switching laws in (14) and (15). From (14) the presence of \( k^{nom}_p \) (positive and nominal value of \( k_p \)) is justified to prevent that the estimate of the high frequency gain of the plant \( \hat{k}_p \) becomes negative, situation that would violate the assumption \( A2 \). Finally, the sufficient conditions to design the relays amplitudes and, in turn, to obtain the sliding mode,
\[ \overline{k}_p > |k_p - k^{nom}_p| \text{ com } k^{nom}_p > \overline{k}_p, \]  

(16)

\[ \overline{\sigma}_1 > |\alpha_1|. \]  

(17)

The argument \( v_{av} \) in (14) is a mean-value-first-order-filter with a time constant \( \tau \) and that it is sufficiently small (i.e., \( \tau \to 0 \)). It could be seen here as an inherent unmodelled dynamics that could influence in the system stability. The stability proof of the IVS-MRAC that considers this fact can be found in [11]. The function \( v_{av} \), therefore, could be set as,
\[ v_{av} = \frac{1}{\tau s + 1} v, \]  

(18)

where \( v \) is an auxiliary signal defined as \( v = -e_0 u_c \).

4 Simulations and Analysis Results

In the present work, the Matlab Simulink was used to simulate the proposed controller for the level control of the fluid in the annular well of a sucker-rod pump system.

From [14] one has the SISO transfer functions of the plant dynamical system and its reference model, respectively,

**Plant** \( P(s) = k_p \frac{n_p(s)}{d_p(s)} = \frac{3.522 \times 10^{-5}}{s + 6.973 \times 10^{-4}} \)

\( \Rightarrow k_p = 3.522 \times 10^{-5} ; \alpha_1 = 6.973 \times 10^{-4} \)

**Reference Model** \( M(s) = k_m \frac{n_m(s)}{d_m(s)} = \frac{3.874 \times 10^{-5}}{s + 7.671 \times 10^{-4}} \)

\( \Rightarrow k_m = 3.874 \times 10^{-5} ; \alpha_{m,1} = 7.671 \times 10^{-4} \)

In these models the level in the annular well (measured in meters) is considered as the process variable (PV), and the pumping speed (measured in cycles per minute - CPM) as the manipulated variable (MV).

The plant parameters \( k_p \) and \( \alpha_1 \) used in the simulations are with 10% of uncertainties around the model reference parameters. The initial conditions of the plant and the reference model were different to facilitate the observation of the tracking properties. The simulations were performed regarding the reference input \( r \), a set of step signals. It was adopted \( k^{nom}_p = 3,522 \times 10^{-5} \) and \( \overline{k}_p = 7,044 \times 10^{-7} \). The value of \( \overline{\sigma}_1 \) is chosen from the value \( |\alpha_1| = 6,973 \times 10^{-4} \). It was adopted 10% plus of uncertainty and the value was \( \overline{\sigma}_1 = 7,671 \times 10^{-4} \). The time constant \( \tau \) was adjusted along the simulation. It was adopted \( \tau = 0,01 \). In Fig.(4) the compared response between the reference model output and the plant output is presented. In Fig.(5) and Fig.(6) show the error signal (in meters) and the control effort (related to the variation of the CPM - in percent).

It could be observed in Fig.(4) that the reference model (desired response) output given was tracked by the plant output. The process variable (fluid level in the annular well) could be observed in Fig.(4) with no oscillations in transitory and stable in steady state. The error in steady state is small and bounded according to Fig.(5) and the control effort is also bounded in Fig.(6). However, Fig.(6) indicates an input usage ing to Fig.(5) and the control effort is also bounded.
controllers. It is introduced a 15% of variation in the parameters \( k_p \) and \( \alpha_1 \) and a step perturbation of 20% on the MV and PV variables. The results is shown in Fig.(7) and Fig.(8).

It could be seen in these new simulations that the references are tracked by the controllers. However, in the control system with conventional PID (Fig.(8)), the parameter variations and perturbations cause a performance loss deviating the plant output in relation to the reference and the desired operation range. In the Fig.(7) there is no performance loss and the IVS-MRAC shows robustness. It is important to remark that outside the operation range the oil production is lower. This deviation in the plant output can also cause a fluid pound [9]. The fluid pound phenomenon occurs due to entry of air in bottomhole pump, that is caused when the fluid level is below the pump inlet level. This phenomenon has influence on the oil production and the maintenance costs. The mechanical fatigue of the pump components is also increased by the fluid pound occurrence. The parameter variations
introduce in $k_{n} \text{ and } \alpha_{1}$ can be related to changes in fluid composition (water, oil and/or gas), a very common situation in real production fields. The perturbations on PV may be associated to faults on the power supply of the frequency inverter. Perturbations on MV may be related to the leaking in the travelling and/or standing valves [14].

5 Conclusion

In this paper a robust adaptive controller (called IVS-MRAC) was applied to a sucker-rod system of oil wells. It could be observed through the simulations and analysis results that the desired response given by the reference model was tracked by the plant response. The error signal could be seen bounded and small, and the control effort could be seen also bounded, though alleviating the chattering should be further studied. The results also show that the adaptive controller is able to control satisfactorily the fluid level in the annular well, in spite of the presence of model uncertainties, unmodelled dynamics, parameter variations, and perturbations. Moreover, the results reveal that the control technique could increase the production performance and diminishes the maintenance costs (for example, by avoiding the fluid pound). For future work is being considered the implementation of this adaptive controller in a real physical system.

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References:


