# A CONTROL STRATEGY FOR AN OIL WELL OPERATING VIA GAS LIFT

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Abstract: This article proposes a control strategy for an oil well operating via gas-lift. The well model is implemented in the OLGA simulator (Scandpower) using an orifice valve (no moving parts) downhole with control in the gas lift surface valve and production choke. The dynamic identification uses the knowledge of the process static gain as the nonlinear static block of a Hammerstein model representation. An Adaptive Notch Filter was designed to damp the resonant system frequencies. Simulation results showed that the control strategy proposed was able to move the well operating point along the region of economical interest and to reject the perturbation imposed on the downstream side of the production choke.


Keywords: Nonlinear process control, oil well production, continuous gas-lift

## 1. INTRODUCTION

At the beginning of an oilfield development program the producing formation pressure will be sufficiently strong to push the produced fluids to surface. Each well will have an Inflow Performance Relationship curve (IPR) relating the flow rate with the pressure in front of the perforated zone. Knowledge of the well geometry, the formation fluids characteristics and the pressure at the tubing head, can be used to estimate the tubing performance which gives the pressure at the bottom of the production tubing for different flow rates . The intersection of the Tubing performance with the IPR curve will define the well operating point (Flow rate and Pressure in front of the perforated zone). The tubing head pressure can be changed with a choke to put the well in different operating points along the IPR curve. As the formation pressure declines the IPR curve changes moving the intersection point towards zero flow rate. Several artificial lift methods are employed to boost the formation fluid flow rate. The gas-lift is one of these methods. Gas is injected in the production tubing lowering the tubing performance curve permitting intersection points with higher flow rates. At the surface, the production from several wells is directed to a common separator. Gas, oil and water are separated and part or the total amount of gas leaving the separator is treated, compressed and distributed to the wells for injection. Gas-lift wells are completed with several gas lift valves distributed along the production tubing. Except for the deeper gas-lift valve, the valves are used to start the well providing gas injection in the production tubing sequentially from the shallowest to the deepest valve. After the start-up the only valve providing gas entrance to the production tubing is the deepest valve, also named operating valve. A surface valve, used to control the gas injection flow rate and a production choke are also part of a gas-lift well setup. Gas lift valves are mechanical valves normally inserted in a gas lift mandrel and can be recovered for maintenance using slick-line operations. The costs involved with the maintenance of these valves, the risks associated with slick line intervention and the need to better control the dynamic of the gas lift wells may be the motivating factors which have led to the study of new gas lift control strategies. A common characteristic of these studies is the utilization of an orifice valve as the operating valve downhole and the control made with surface actuation.

Several contributions to the solution of this problem have been published (Eikrem *et al.*, 2004), (Eikrem *et al.*, 2002),(Imsland *et al.*, 2003).

This paper is organized as follows: in Section II the gas lift control strategy is presented; then the control algorithm is discussed in Section III; The results obtained for the simulated well are shown in Section IV and finally the conclusions are drawn.

## 2. GAS LIFT CONTROL

A typical steady state relationship between the gas injection mass flow-rate and the wellhead formation fluid mass flow rate, considering a constant wellhead pressure is shown in figure 1. The slope of the curve is steep for low gas injection mass flow rate due to the predominance of the gravity term of the pressure drop in the production tubing. As the gas injection mass flow rate is increased, the friction term becomes important decreasing the slope until the curve reaches a maximum at point $P_1$. The plot of the pressure in front of the perforated zone exhibit a curve which is almost a mirror image with the minimum occurring at the same point. The control of a gas-lift well is normally realized according to an optimization strategy. Although the gas used for injection is not lost, there is a cost for the gas compression. The oil, gas and water fluid fractions produced by each well, have different economical effects. The produced water is normally treated before disposal, the gas and oil have different market values. The resources available may also constrain the operation limiting the separation, transport or compression capacity and will have an impact in the distribution of compressed gas to a group of wells. Several works have treated this problem with different optimization approaches as in (Nakashima and Camponogara, 2005) and (G.A. *et al.*, December-2002). A more general approach is to consider the reservoir recovery optimization and to treat the gas lift optimization as a sub-problem. The upper optimization layer could give, for each well the optimum pressure range in front of the perforations. The gas lift optimization would find the optimum gas allocation to comply with the upper layer while minimizing costs for a certain gas injection mass flow rate availability and installations constraints. For the control it means that the well will operate within a defined region of the curve $Q_{liq.} = f(Q_{inj.})$ as shown in figure 1. A gas lift well flow rate can become very oscillatory when changing the gas injection flow rate or letting the wellhead pressure to vary due to perturbations on the downstream equipment. This oscillatory behavior is stronger when the pressure drop in the production tubing is dominated by the gravity term. It tends to diminish as the friction term becomes comparable. This explain the reason for well operators to increase gas injection as a last resort to stabilize a gas lift well. In most cases this is not the optimum solution. On the contrary, depending on the gas availability, well production, the costs involved, the optimum operating point may be much lower than the point $P_1$ of figure 1. Controlling a gas lift well with an orifice valve downhole was discussed in (Plucenio, 2002) using wellhead mass flow rate as the process variable and gas injection mass-flow rate as the control input. This study was realized in a well modeled in the OLGA 2000 simulator. Identification of the dynamics relating the two mass flow-rates was done at different operating points. The transfer functions obtained although different among themselves did not present any major difficulty for control application like transport delay or non-minimum phase behavior. Unfortunately, mass flow rate of a multiphase flow is still a very expensive measurement today and the oil industry is not ready to perform it for each gas-lift well. Some oil companies have started to adopt the installation of permanent downhole pressure gages in their gas lift wells. On the other hand, well tests are regularly conducted to determine the well performance for different gas injection flow rates. Some tests are also required by the regulatory agencies (ANP in Brazil). During these tests, measurements of oil, gas and water production, downhole pressure measurements can be plotted versus gas injection mass flow-rates by directing the well production to a test separator. Downhole pressure gages can be used to estimate the pressure in front of the perforated zone, even when not installed exactly in front it. This can be done using the knowledge of the well completion geometry, the produced fluid characteristics and flow-rates. In most cases the management of an oilfield is realized by allocating desired values for this pressure along the productive life of the oilfield in order to drain the reservoir in an optimum way. The pressure in front of the perforations can be written as

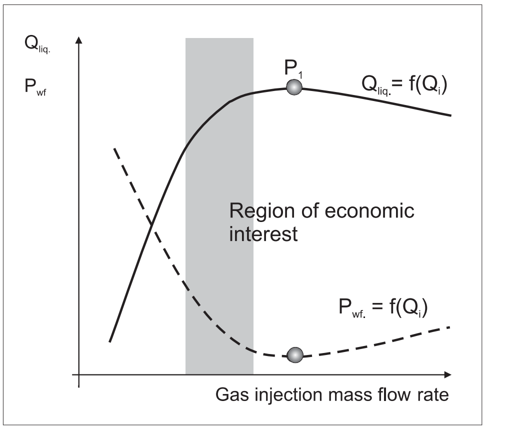


Fig. 1. Wellhead mass flow rate and Downhole pressure x Gas injection mass flow rate

$$P_{wf} = P_{wh} + P_{pt} + P_t, \qquad (1)$$

where $P_{wf}$ is the pressure in front of the perforations, $P_{wh}$ is the pressure in the wellhead, $P_{pt}$ is the pressure drop between the wellhead and the downhole pressure gage installation point and $P_t$ is the pressure drop in the tail between the depth of the downhole gage installation and the perforations. The pressure measured by a downhole pressure gage is normally

$$P_{dg} = P_{wh} + P_{pt}, \tag{2}$$

The desired $P_{wf}$ can be converted to a desired $P_{dg}$ if one considers that in steady state the value of the pressure drop $P_t$ can be estimated quite well with the measurements obtained during the periodic well testings. The pressure in the wellhead can be written as a sum of the separator pressure $(P_{sep})$, the pressure drop in the surface pipe connecting the wellhead to the separator $P_{sp}$ and the pressure drop in the production choke $(P_{pc})$.

$$P_{wh} = P_{sep} + P_{sp} + P_{pc}, \tag{3}$$

Changes in the downhole pressure $(P_{wf})$ will change the formation fluid flow rate and consequently the pressure drop in the production tubing, production choke and surface pipe. This changes the pressure $P_{wh}$ and the $P_{wf}$ itself. This interaction is typical of a multivariable control problem. The strategy presented in this study considers the control of the $P_{wh}$ acting in the production choke opening in order to keep it at a desired value $P_{whd}$. A cascade control is used to control the $P_{pt}$ at a desired value $P_{ptd}$ acting in the gas injection mass flow rate. The gas injection mass flow rate is accomplished controlling the gas injection valve opening. The desired pressure at the downhole pressure gage is obtained as

$$P_{dgd} = P_{whd} + P_{tpd}, \tag{4}$$

This strategy avoids the multivariable representation and transforms the problem into two SISO (Single Input, Single Output) problems. The response speed of the $P_{wh}$ control is much faster than the $P_{pt}$ loop response. Stabilizing $P_{wh}$ and $P_{pt}$ is equivalent to stabilizing the wellhead flow rate. The production choke nominal size should provide a minimum pressure drop when fully opened. It should operate partially closed in order to be able to compensate pressure increases in the downstream side.

The control strategy is shown in Figure 2.

Control of the wellhead pressure acting in the Production choke opening and the control of the gas injection mass flow rate acting in the surface gas injection valve will not be discussed. PI (Proportional and Integral) controllers were used for this purpose in both cases. These controllers were incorporated in the model in order to obtain an identification of the $P_{pt}$ vs. $Q_i$ dynamics. Figure 3 shows the steady state relation between the mass injection flow rate $Qi$ and the pressure drop in the production tubing $P_{pt}$. The region of economic interest elected is shown in the figure 3. The knowledge of the process static gain was used to assembly an identification algorithm based on the Hammerstein approach where a nonlinear memoryless function is applied on the input followed by a linear dynamic model. The identification was realized between the $P_{pt}$ variable and the transformed input variable $Qi' = f(Qi)$.

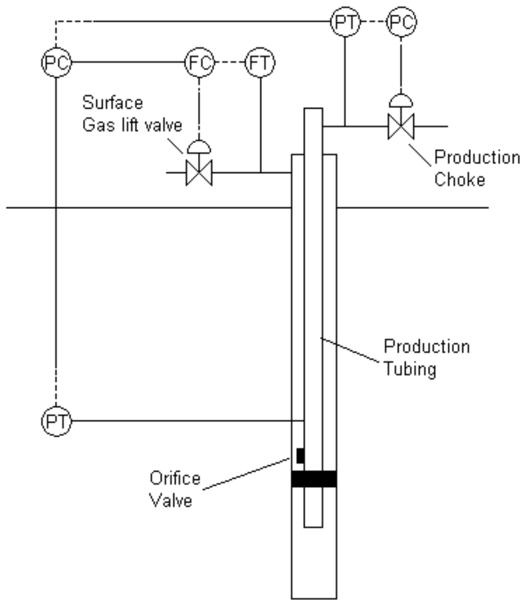


Fig. 2. Gas Lift Control Strategy

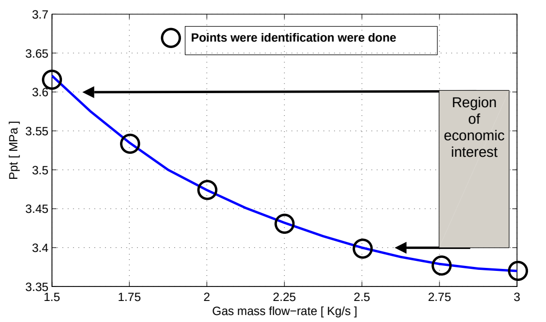


Fig. 3. Pressure drop in Production Tubing vs. Gas injection mass Flow-rate

The dynamic behavior of $P_{pt} = f(Qi')$ is non-linear along all the operating region of the plant. To obtain linear models, several ARX identifications were realized between $P_{pt}$ $and$ $Qi'$ exciting the system around the operating points indicated in figure 3. The representation of all linear models is shown as discrete transfer function in equation 5.

$$H(z) = \frac{b_1 z^2 + b_2 z}{z^3 + a_1 z^2 + a_2 z + a_3} \tag{5}$$

Figure 4 shows the identification result obtained exciting the well around $Qi = 1.5Kg/s$ using a multilevel PRBS signal.

The poles and zeros obtained with the linear models move smoothly as shown in Figure 5. The non-minimum phase characteristics is evident and can be easily explained. Gas is injected to decrease the pressure drop in the Production Tubing. For the gas to enter the tubing, the pressure on the upstream side of the orifice valve has to be increased. This has the initial effect of increasing the pressure on the downstream side of the orifice valve (Production Tubing) before

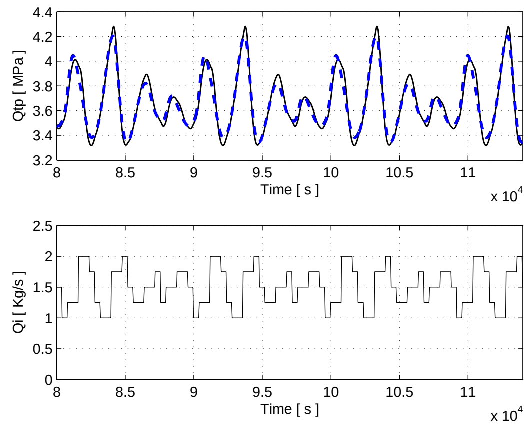


Fig. 4. Identification around Qi=1.5 Kg/s

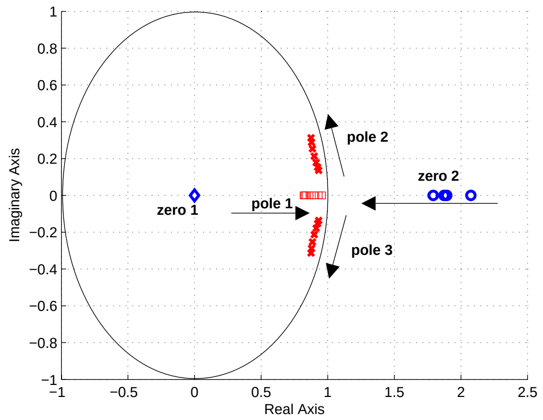


Fig. 5. Poles and Zeros of Linear Models

the benefit of the pressure drop is achieved when the gas moves up the tubing.

## 3. PROPOSED CONTROL ALGORITHM

The family of models obtained present one pole in the real axis plus a pair of complex conjugated poles. There is one zero at the origin and one non-minimum phase zero. The complex poles represent a resonant frequency which changes with the well operating point. It was decided to apply a control structure composed of a Reference filter, a PI (Proportional and Integral Control) with a linearizing gain look-up table plus an Adaptive Notch Filter. The control scheme is shown in Figure 6.

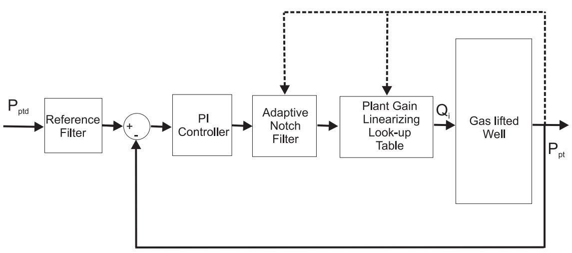


Fig. 6. Control Scheme

For every model obtained with the identification process, a Notch Filter was designed as

$$F(z) = \frac{f_1 z^2 + f_2 z + f_3}{z^2 + d_1 z + d_2}, \quad (6)$$

where $f_1$, $f_2$ and $f_3$ depend on the process variable $P_{pt}$ and are designed to provide zeros that will cancel the plant complex poles. A parameter $\alpha$ was found that can be used to derive any filter as a combination of the filters found at the limits of the operating region. This parameter is a function of the process variable $P_{pt}$. Omitting the $z$ operator, any filter can be expressed as

$$F_{Ptp} = \alpha F_{Ptp1} + (1 - \alpha) F_{Ptp2}, \quad (7)$$

where $F_{Ptp1}$ and $F_{Ptp2}$ are the filters designed for the limits of the operating range defined by the process variable $P_{pt}$. It is expected that the slow nature of the $P_{pt}$ control loop will permit to adapt the filter as the process variable moves along the operating region. The Linearizing look-up table block makes the plant to appear linear to the controller as far as static gain is concerned. The look up table is built using the parameters found in the identification of $Qi' = f(Qi)$ in the identification process and the expected operating range. The Reference Filter cancels the zero effect due to the PI control and defines the dynamic desired for the $P_{pt}$ set-point changes. The zero of the PI control is chosen at the left of the leftmost real pole among all the models. Figure 7 shows the Closed Loop Root Locus when applying the PI Control and the Adaptive Notch Filter for one of the ARX models identified. Figure 8 shows the detail of the model pole

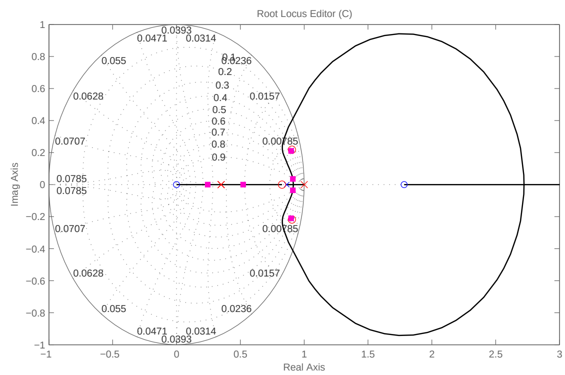


Fig. 7. Root Locus for the Closed Loop Control

cancellation due to the Notch Filter zeros and the direction to be followed for different operating points of the process.

## 4. RESULTS WITH OLGA SIMULATOR

This strategy was implemented in a well operating via gas lift modelled in the OLGA simulator. The model uses two constant pressure boundaries, one to represent the gas lift supply and the other to represent the separator. The gas injection is done at the mud line

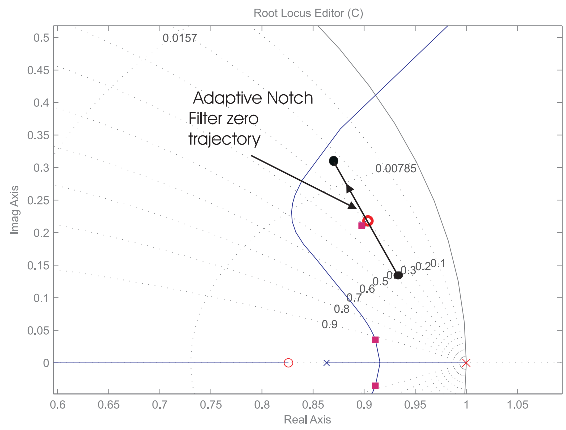


Fig. 8. Notch Filter Zero Trajectory

of an offshore well with a dry x-mass tree completion. The representation of the well is shown in figure 9 and details in table 1.

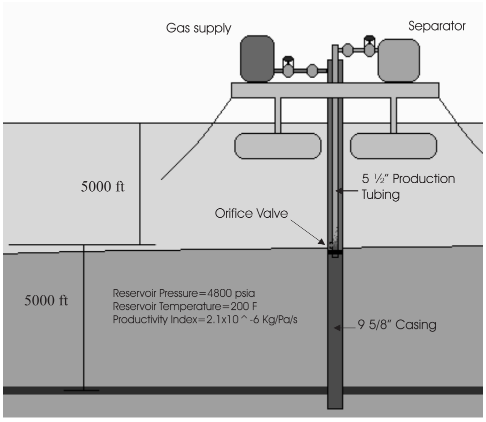


Fig. 9. gas lift well implemented in the Olga simulator

Table 1. Gas lift well implemented in the Olga simulator

$$
\begin{array}{c}
Total\,depth = 10000\,ft \\
Gas\,injection\,depth = 5000\,ft \\
Tubing\,size = 5\frac{1}{2}\,in. \\
Casing\,size = 9\frac{5}{8}\,in. \\
Gas\,lift\,surface\,valve\,nom.\,size = 1\frac{1}{2}in. \\
Production\,choke\,nom.\,size = 2\frac{1}{2}\,in. \\
Reservoir\,pressure = 33.0948\,Mpa\,(4800\,psi) \\
Separator\,Pressure = 2.5855\,Mpa\,(375\,psi) \\
Wellhead\,Pressure = 2.9992\,Mpa\,(435\,psi) \\
Reservoir\,temperature = 93.3\,\circ C \\
Reservoir\,Productivity\,index = 2.1\times 10^{-006}Kg/Pa/s
\end{array}
$$

The OLGA simulator ability to communicate with the Matlab environment permitted to test the control strategy performance. The well operating point was moved along different set-points within the region proposed as it can be seen in figures 10, 11 and 12. It can be noticed that the liquid flow rate moves much slower than the pressure drop in the production tubing $(P_{pt})$.

This behavior makes the control strategy proposed interesting since it does not require high gains for the $P_{pt}$ control loop. In order to test the control response to perturbations, a change in the pressure at the downstream side of the production choke (separator) was imposed beginning at time 9.72hs. The pressure was increased by 10 psi in 10 minutes, kept at this value for another 10 minutes and decreased to normal value at the same rate. The production choke opening presented in the second plot of figure 12 shows the quick response of the Wellhead pressure PI controller. The Wellhead pressure changed less than 2 psi as shown in the first plot of the same figure. The effect in the $P_{pt}$ pressure and liquid mass flow rate is nearly unnoticed.

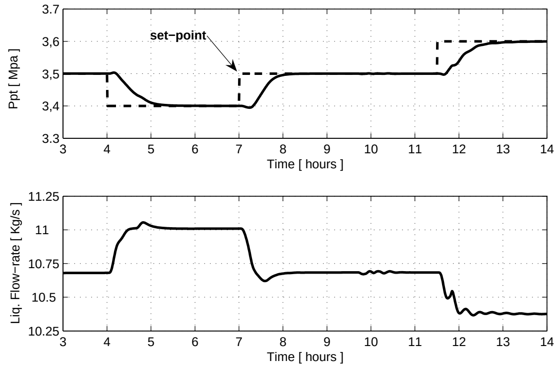


Fig. 10. Ppt and Liquid mass flow rate

Figures 13 and 14 show the response obtained without $P_{pt}$ control but keeping the local controllers for the gas injection flow rate and Wellhead pressure. The gas injection mass flow rate were forced to the steady state values reached in the closed loop experiment. The system resonant frequencies are clearly not damped and show up in the $P_{pt}$ and liquid flow rate. This oscillatory behavior is not acceptable on the management of an oil well. The rapid changes in the $P_{pt}$ pressure will also be present on the pressure in front of the perforated zones. This may cause several problems, from formation damage to sand production in case of well with unconsolidated formations. The liquid flow rate oscillations will make the separation process much more difficult requiring larger separators.

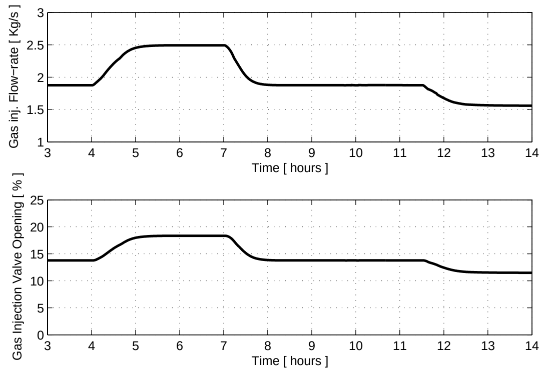


Fig. 11. Gas Injection flow rate and Gas valve opening

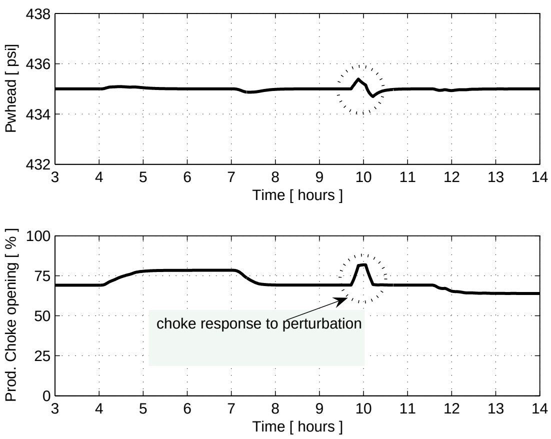


Fig. 12. Wellhead Pressure and Production choke opening

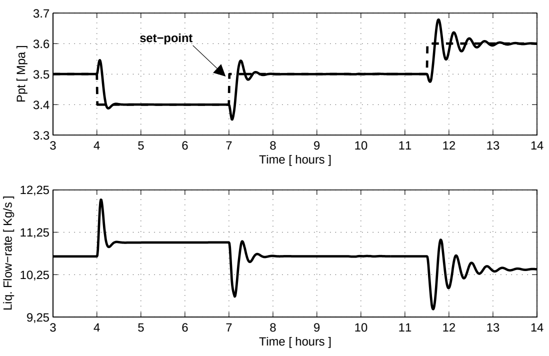


Fig. 13. Ptp, Liquid flow rate Open Loop response

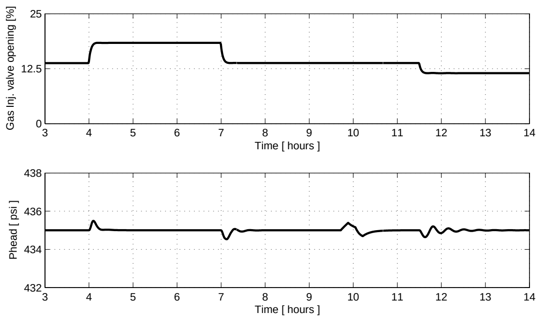


Fig. 14. Ptp, Liquid flow rate Open Loop response

## 5. CONCLUSIONS

In this paper, a strategy to control an oil well operating via gas-lift was presented. It uses measurements of gas injection mass flow rate, downhole pressure and wellhead pressure. The actuation is made on the surface gas lift valve and production choke openings. The strategy was tested in an oil well implemented in the OLGA simulator. It proved satisfactory to move the operating point along the region of economical interest of the well and to reject the perturbation imposed on the downstream side of the production choke. The strategy proposed can be easily implemented. It uses algorithms largely available as function blocks of industrial network control systems. The strategy was not tested to operate the well at lower gas injection mass flow-rates. The identification procedure would have to be applied to much more operating points in order to obtain the parameters needed for the Adaptive Notch Filter implementation.

## 6. ACKNOWLEDGMENTS

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