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Hybrid Intelligent Supervision Model of Oil Wells

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Abstract—**In this work is presented a hybrid intelligent model based on Evolutionary Computation and Fuzzy Systems to improve the performance of the Oil Industry, which is used for Operational Diagnosis in petroleum wells that require gas lift (GL). The model is used for an optimization problem where the objective function is composed by two criteria: maximization of the production of oil and minimization of the flow of gas injection, based on the restrictions of the process and the operational cost of production. We use the genetic algorithms to solve this problem, and the fuzzy logic to identify the operational scenarios in an oil well. In this way, our hybrid intelligent model implements supervision and control tasks.**

I. Introduction

With the increase of the degree of dependency of the society on complex technological systems, their right functioning has became a strategic matter. This fact is true for a multitude of industrial domains: aeronautical and aerospace industry, etc. In all cases, the wrong functioning of these systems can cause financial and human losses, undesired environmental impacts, among others. Many of these systems are highly associated to automation. The automatic control frees them of the human manual control, but it is not immunized against operational failures. Therefore, with the objective of finding the highest possible availability of the systems, it is necessary to complement the industrial automation systems with potent and accurate supervision tools that allow indicating undesired or unpermitted performance states, as well as taking the proper actions in order to keep the system within the optimal performance states.

On the other hand, the use of the Hybrid Intelligent Systems (HIS) on supervision tasks in production systems is becoming an area of great interest at industrial level [1], [3], [5]. The HIS have particularly started to gain more and more influence in the oil industry, as they allow approaching the problem of handling the complexity of the hydrocarbon production systems [1], [2]. These Advances in Computational Intelligence represent an attractive alternative to deal with highly varying, complex, and confusing problems [7].

So, in this work has been proposed a Hybrid Intelligent Systems (HIS) for optimizing production processes. The HIS is composed by a Multilayer Fuzzy Classifier System (MFCS) and a Genetic Algorithm (GA). The MFCS consists of a number of fuzzy systems hierarchically distributed, which have the advantage that the total number of rules of the knowledge base is smaller, and are simpler than a conventional fuzzy system. The GA defines a population of individuals, each of them representing a possible solution to the oil production optimization problem.

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In specific, the MFCS allows the identification of different operational scenarios in an oil well, to implement control tasks (in our HIS, it carried out the supervision tasks and will be the input to the second phase). The proposed MFCS allows, among other things, to detect faults that affect the process or the equipment involved, in real time and independently, in the production facilities at the level of well and reservoir [3], [5]. The system is initially tested in wells requiring artificial lift by Gas (ALG). We have defined two objectives to optimize: maximization of the production of hydrocarbons and minimization of the injection gas, which generates a zone of negotiation that allows finding the ideal production with GAs.

This paper is structured as follows: Theoretical aspects about Fuzzy Classifier Systems and the Production Process of wells are presented in Section 2. The design of our HIS is presented in Section 3, the experiments with our HIS are shown in Section 4. The paper ends with conclusions.

II. Theoretical Framework

A. *Fuzzy Classifier System*

A Fuzzy Classifier System (FCS) is a system whose rules are based on the theory of Fuzzy Logic (FL), which includes the same elements of a Classifier Systems (CS), but working in a fuzzy framework [3], [4]. In this way, the activation of a rule is achieved when in the "antecedent” some values of fuzzy variables from the environment are activated. In standard fuzzy systems, for a problem with n input variables described by m linguistic labels, the maximum possible number of rules in the fuzzy system is m^n. This exponential growth causes, in practice, that for a high number of variables the number of rules is so large that the interpretability of the system becomes impossible. This problem is not exclusive to fuzzy systems, and is known as the problem of dimensionality [4].

One way of reducing the number of rules and thus increase the interpretability, is to decompose the fuzzy system into simple modules, this is called multilayer fuzzy systems (MFS) [5]. A MFCS consists of a number of fuzzy systems hierarchically distributed, which have the advantage that the total number of rules of the knowledge base is smaller, and are simpler than a conventional fuzzy system. One of the main purposes of using MFS is to minimize the size of the fuzzy rules base and its associated computing requirement. There are numerous design proposals of such systems [5]. The more traditional type of MFS is one in which each module is a complete fuzzy system (FS) relates to a reduced set of variables, which can be input variables of the global system or internal variables generated as outputs of other modules [5]. There are other approaches, for example someone identify common set of rules and define common modules for them [7], or those in which each level corresponds to an increase in granularity of the variables [6]. Our work uses the first approach, which can be seen in Fig. 1.

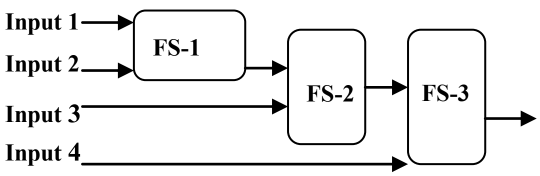

Fig 1. Classic Model of a Multilayer Fuzzy System

B. Production Process of Wells by the Gas Lift Method

The Gas Lift method consists of gas injecting at an established pressure at the lower part of the well pipe's fluid column, at different depths, with the purpose of decreasing its weight, thus helping the reservoir fluids rise from the bottom of the well to the surface.

The production curve of a well that produces by the gas injection method (see Fig. 2) indicates that when the Gas Lift Flow increases (GLF, expressed "mpcdg" thousands of gas cubic feet days), the production rate (Qprod, expressed "BNPD" Daily Production Net Barrels) also increases, until reaching its highest value (Stable Region), such that additional increases in the injection will cause a decrease in the production (Unstable Region) [1], [2].

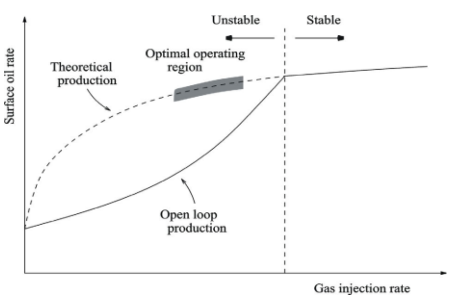

Fig. 2. Artificial Gas Lift well behavior´s model

The well's production curve is obtained by the characterization of the well using mass and energy balance techniques [1], [3]. The mechanical completion installed at the bottom and surface of the well allows the characterization of the physical properties of the fluid (Gravity of the oil, water cut, Bottom-hole pressure, Gas-liquid ratio). It is necessary because the oil production behavior in the wells injected with gas depends of variables, both of the reservoir and of the mechanical design (valves, production pipes, among others) [1]. The implantation of this ALG method needs an instrumentation and control arrangement. For that, the measurement and control of the following variables are required: Gas Lift Flow (Q_{iny}), Production Rate (Q_{prod}), Gas Lift Pressure (*Glp*), Gas Lift Pressure Differential (*Gldp*), Casing Pressure ($P_{g,inj}$), Production Tubing Pressure (P_{thp}) and Bottom Pressure (P_{wf}).

So, a simple gas lift model is proposed [1]: the oil and gas "Inflow" of the reservoir is modeled with the use of the productivity index (oil volume that the reservoir can provide) and the existing relation between the production rate (Q_{prod}) and the differential between the reservoir pressure (P_{ws}) and the flowing pressure at the bottom of the well (P_{wf}). Eq. (1) is used, which determines the capacity of contribution of the oil reservoir. This equation represents an instant of such capacity of contribution of the well of the reservoir, in a given time of its productivity life. It is normal for such capacity decreases through the time, due to the reduction of permeability of the well surroundings and the increase of viscosity of the oil. This equation is considered as the energy offered, or fluid affluence curve, that the reservoir yields to the well (P_{wf} *vs* Q_{prod}).

$$P_{wf} = P_{ws} * \left[\left(1{,}266 - \frac{1{,}25 * Q_{prod}}{Q_o} \right)^{0{,}5} - 0{,}125 \right] \quad (1)$$

Where Q_o represents a base production rate, which is determined through reservoir core tests.

As for the "outflow", gas is injected at a given depth to reduce the weight of the column and to reduce the bottom pressure of the well, allowing the establishment of a given production rate in which the capacity of fluid contribution from the reservoir equals the capacity of fluid extraction from the well. In this sense, in order to inject gas, it is assumed that the pressure at the level of the bottom injection valve located in the casing must be greater than the pressure in the space of the production pipe at the injection point ($P_{g,iny} \rangle P_{T,iny}$), to ensure a displacement of the gas towards the production pipe. This is described by the following equation

$$Q_{iny} = \begin{cases} c\sqrt{\rho_g \left(P_{g,iny} - P_{T,iny}\right)} & if \;\; P_{g,iny} \rangle P_{T,iny} \\ 0 & else \end{cases} \quad (2)$$

Where,

$P_{g,iny}$ = Pressure of Injection of Gas to the Valve

$P_{T,iny}$ = Pressure of the Production Pipe at the Point of Injection

ρ_g = Gas Density

c = Constant related to the characteristics of the valve

Q_{iny} = Gas Injection Rate

For the model, the node at the gas injection valve is assumed in order to establish the capacity of production of the lifting system [2], [3]. Thus, the production of the system responds to an energy balance in the form of pressure between the capacity of energy contribution from the reservoir and the energy demand from the installation [2], which is expressed in the node as follow:

Node arrival pressure: $Pvalve(\inf low) = P_{ws} - \Delta P_y$

Node output pressure: $Pvalve(outflow) = P_{thp} - \Delta P_p$

Where:

$\Delta P_y = P_{ws} - P_{wf}$ (Pressure Drop in the Reservoir)

$\Delta P_p = P_{thp} - P_{T,iny}$ (Pressure Drop in the Well)

And now Q_{iny} is defined as:

$$Q_{iny} = c\sqrt{\rho_{g,iny}(P_{g,iny} - P_{thp} + P_{wf})} \tag{3}$$

From equations (1), (2) and (3), the mathematical model that describes the behavior of a gas lift well is:

$$Q_{prod} = -\frac{Q_O * \left(\left(\frac{P_{thp} + P_{g,iny} - ((Q_{iny}/c)^2)/\rho_g}{P_{ws}} + 0{,}125\right)^2 - 1{,}266\right)}{1{,}25} \tag{4}$$

III. Design of our HIS

A. Hybrid Intelligent Systems

The use of HIS on supervision and control tasks in production systems is becoming an area of great interest at industrial level [1], [5]. Our HIS is composed by a MFCS and a GA. The MFCS consists of a number of fuzzy systems hierarchically distributed, which allows identifying the different operational scenarios present in the oil production process. Identified the operational scenario, the GA simulates the process of natural evolution. Every individual of the population represents a potential solution of the oil production problem. The evolution is guided by a strategy of selection of the individuals, with the intention of improving their "fitness", a measure based on the restrictions contextualized in the operational scenario determined by the MFCS. That means, the population of individuals will be specific to the operational scenario identified in the previous phase, so that the GA may optimize the production for that operational scenario.

B. MFCS Design

The proposed MFCS consists of 3 layers: the first layer is to determine the pressure drop in the production tubing. To calculate this drop are used the "bottom pressure" and "tubing pressure" (pressures that are present in the production tubing), which define the rules of the fuzzy system of the Fig. 3.A. In this way, the first fuzzy system determines the intermediate linguistic variable "P_{wf}_Thp" (see Fig 3.A). So, the HIS starts with the input variables bottom pressure and production tubing pressure to obtain "P_{wf}_Thp", which is the pressure drop between those pressures.

The second layer determines the rate of gas injection "Q_{iny}" (see Fig 3.B). In this sense, it consists of a set of rules that combine the pressure drop obtained in the first layer with the input variable “Casing Pressure”, to get the gas injection rate. These rules use such variables because the rate of gas that is injected into the well to extract the oil to the surface depends on the pressure of the casing and the pressure drop in the tubing according to [3], [5].

Finally, the last layer determines the production rate (see Fig 3.C). In this case the set of rules are defined by the bottom pressure (P_{wf}, fluid load capacity of the reservoir) and the gas injection rate (Q_{iny}, energy needed to extract the oil), because these variables determine the production rate according to [7], [8]:

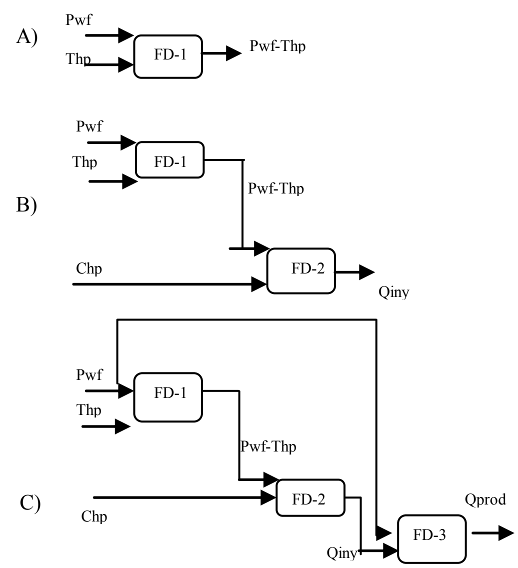

Fig. 3. Our Multilayer Fuzzy Classifier System

With the output of the last level (Q_{prod}, the production rate) the HIS determines the operational scenario of the well. Known the rate of production, the GA solves the problem of oil production optimization.

C. Optimization of the Production Process

The optimization problem of ALG wells consists of increasing the production of oil and minimizing the flow of injected gas, based on three variables: Q_{prod}, *Cost* and Q_{iny}. This type of multiobjective optimization problem can be solved very well with the GA, that is the reason why we have chosen this technique. This optimization problem is described by the objective function:

$$f = (PVPOil - CostProdOil) * Qprod - CostGas * Qiny \qquad (5)$$

Where,
PVPOil=Sell price of oil in terms of the daily barrel, \$/bl,
CostProductionOil=Production Cost,
CostGas=In \$/Mpcn.

And the restrictions of the process are: we assume that: P_{ws} is a constant, due to the slow dynamics of the reservoir; and P_{wf} is lower than the pressure of the reservoir, due to the fact that in a well the pressure of bottom is minor that the pressure of reservoir. Additionally, we establish the maximum production capacity that a reservoir can contribute as $Q_{prod,max}$, [3]. These restrictions are:

$$P_{ws} = Constant.$$
$$P_{wf} \langle P_{ws}$$
$$Q_{prod} \le Q_{prod,max}$$

Finally, the specific values of the variables $Q_{iny,}$and P_{wf} depend on the scenario identified in the previous phase. That is, the scenario identified determines the values of $Q_{iny,min}$, $Q_{iny,max,}$, $P_{wf,min}$, $P_{wf,max}$. With these values, we define the next restrictions:

$$Q_{iny,min} \le Q_{iny} \le Q_{iny,max}$$
$$P_{wf,min} \le P_{wf} \le P_{wf,max}$$

The structure of the individuals is composed by two fields that represent the variables Casing pressure ($P_{g,iny}$) and Tubing pressures (P_{thp}). These variables are used, because they are related to the gas behavior, and they can be manipulated at an operational level with an instrumentation arrangement. This is important, because such pressures can be adjusted in terms of the optimum values recommended by the GA, and thus achieve the best performances of the producing well (see equations (2), (3) , and (4) in section II.B, which describe the model of gas injection defined in [1], [2]). In this way, the optimum value of production and injection is established according to the current operational scenario, using the equation (5), in a way that the set of values allowed to variables P_{thp} and $P_{g,inj}$ depend on the operational scenario identified in the previous phase.

IV. Experiments

The well characteristics where the system was implemented are the following: The completation of the producing vertical well is 3489 ft and valves to 3184 ft, 25 API crude Gravity, 6% water Cut. It receives gas lift from the gas Manifold located at 508,53 ft far from it, and the Production Curve is shown in Fig. 4.

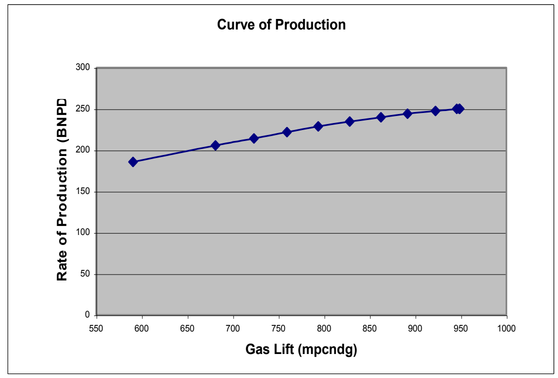

Fig. 4 Experimental Production Curve by a Pressure of Reservoir to 2400 psi.

A. *MFCS: Identification of the Operational Scenarios*

With the curve of the figure 4, and the historical data of the bottom and surface variables, we can characterize the input variables of the MFCS as follows (see Table I):

TABLE I.
MEMBERSHIP FUNCTION , INPUT VARIABLES

	Chp (psi)	P_{wf} (psi)	Thp(Psi)
Low	1000-1120	1-320	150-200
Medium	1100-1220	212-649	190-260
High	1190-1320	429-1093	230-300

In the case of the output variable (Q_{prod}) of the MCFS, its membership function is (Table II):

TABLE II.
MEMBERSHIP FUNCTION, OUTPUT VARIABLES

	Operational Scenarios
Under-Inyected	400-600
Normal	550-750
Over-Injected	700-900

In general, the following table shows the results with our MFCS for different entries in the first layer (see Table III): The first layer characterizes the pressure drop in the production tubing of the well. This characterization is important because operational failures that may affect well production can be identified.

TABLE III.
RULES FOR DETECTION OF OPERATIONAL FAILURES FD-1

Pressure Drop	Operational Diagnosis
3027,37 (High Drop)	High hydrostatic pressure in the tubing by: • Low Flow of Gas Injection. • High Flow of Gas Injection with presence of High Water Cut.
2890 (High Drop)	High hydrostatic pressure in the tubing by: • Low Flow of Gas Injection . • High Flow of Gas Injection with presence of High Wate Cut.
2870 (Medium Drop)	Medium hydrostatic pressure in the tubing by: • Low flow of Gas Injection with presence of High Water Cut and High Bottom Pressure. • High Flow of Gas Injection with Leak Gas at level of completation well.
2229,7 (Medium Drop)	Medium hydrostatic pressure in the tubing by: • Low flow of Gas Injection with High Water Cut and Low Bottom Pressure. • High Flow Gas of Injection with Leak Gas at Level Completation Well.
2165 (Low Drop)	Normal Flow of Gas and Production

So, to make that first detection of operational failures, we could define a system of rules based on the relationship *Pwf* vs *Thp*, which could give their diagnosis.

Regarding the second layer (FD-2), this allows us to identify the rate of gas that the well requires for production (See Table IV). With this value we could eventually determine the operational stage of production of the well due to the gas injection rate derived from the pressure drop and the casing pressure.

TABLE IV.
RULES OF DETECTION OF FAULTS GENERATED BY THE OUTPUT OF FD-2

Pressure Drop	Chp	Operational Scenario	Qiny MFCS
2164,78 (Low)	1190 (Medium)	UnderIny	517,8
2229,07 (Medium)	1320 (High)	Normal	666,67
2870,00 (Medium)	1250 (High)	Normal	735,23
2890,00 (High)	1090 (Medium)	OverIny	776,17
3027,37 (High)	1020 (Low)	OverIny	816,67

Finally with (FD-3) the well production is determined. Thus, the MFCS identifies operational failures at the completion of the wells, estimate rates of gas injection, which will determine the current operational scenario, that could be affecting the well production (Table V).

TABLE V.
DIFFERENT OPERATIONAL SCENARIOS DETERMINED BY THE MFCS

Qprod MFCS	Operational Scenario	Qiny MFCS
166,66)	UnderIny	517,8
200,38	Normal	666,67
213,33	Normal	735,23
243,09	OverIny	776,17
252,09	OverIny	816,67

B. Optimization using GA

The GA was applied for the operational scenario identified in the previous phase with MFCS, for the case study: normal. The optimization problem of AGL wells consists of increasing the oil production and minimizing the gas lift flow, based on the objective function and the operational restrictions described in section III.C (see equation (5)). In order to solve that problem, the GA used presents the following components:

Number of individuals: random, between 2 and 10.
Number of generations: 25,
Objective function: equation (5), including its respective restrictions.
Crossover operator: single point cross with 0.7 probability.
Mutation operator: random with 0.03 probability.

The final population given by the GA for the operational scenario detected by the MFCS (normal) is shown in Table VI. An individual gives the values of P_{thp} and $P_{g,inj}$, specified on a row of that table, which objective function is the value of *Profits*. That is, the optimum values for the normal operational scenario for the variables Tubing Pressure (P_{thp}) and Casing Pressure ($P_{g,inj}$) are shown in Table VI. These values are used in the models of gas injection for wells [1], [2] (see section II.B) and in the objective function (eq. 5), giving the results of Q_{iny}, Q_{prod} and *Profits* shown in the same Table VI.. It is important to note that these results are measured at the operational level with the instrumentation of the well, and represents the operational behavior of the well. The experimental behavior is well known since it is used for field testing.

Moreover the selection in the GA searches a balancing among the exploitation of a well and a good utilization of the resources (gas). With the set of parameters of the GA (small population, few generations) is enough to solve this optimization problem, without a very strong selection which may mean that sub-optimal individuals can take control over the population, or a weak selection, which results in a very slow evolution.

TABLE VI.
RESULTS OBTAINED.

P_{thp}	$P_{g,inj}$	Q_{inj}	Q_{prod}	$Profits$
170	1022	596,6	232	7093
170,4	1109,8	619,1	230,2	7034
172,5	1226,3	689,1	233,7	7133

According to the results of the Table VI, the production system presents an optimum behavior at a gas injection rate of about 596,6 mpcndg, with an associated production of 232,06 b/d, a casing pressure of 1022 psi and production pipe of 170 psi. On the other hand, for a gas flow of 619,1 mpcndg its production rate is 230,21 b/d, generating a smaller profit and greater consumption of gas with respect to the case of 596,6 mpcndg. Regarding the gas flow of 689,1 mpcndg, a production of 233,71 b/d is expected, higher than the one of 596,6 mpcndg (1,64892 b/d), but more gas flow is required. In this case, the profit differential is 39 $/d, which indicates that this case could be interesting (more optimum) because it better combines the two costs.

V. CONCLUSION

Our HIS uses MFCS and GA to define a control and supervision system for oil industrial production. The population of individuals in the GA, correspond to the operational scenario identified with the MFCS, generating the optimum value of production and gas injection for the current operational scenario.

MFCS for the Analysis of Wells allows the analysis and classification of data from the well. It generates information from the reservoir variables (downhole pressure), head variables (casing pressure) and the gas flow. These variables are related to the gas injection process and its effect at the level of the reservoir. With such information it is more accurate the determination of the operational scenario of a well from its operating conditions, since in the same system the bottom and surface variables are integrated, different with respect to the current systems used in the industry, in which they only use surface variables. So, this will allow the self-diagnose of the well, monitor its damage, and care the performance of its infrastructure underground/surface. Specifically, our system allows estimating the rate of production and the gas injection rate, from which the well can improve its level of production to lower gas injection rate.

The production using AGL wells was optimized due to the integration of subsoil and surface information, which will allow minimizing costs and guaranteeing the best distribution of the gas injection maximizing the production of oil. The subsoil-surface integrated approach is innovative in the sense that it integrates the reservoir/wellhead infrastructure behavior. This is carried out through an objective function, with the respective restrictions of the process, which allows contextualizing such objective function in the operational scenario and the reservoir conditions identified in the supervision scheme. The GA establishes the optimum production and the gas injection value for the identified operational scenario identified, from the relationship of the two costs of the productive process: reduce the production costs and optimize the gas injection.

Furthermore, the MFCS allows introducing a stepwise mechanism (in each layer) to detect/diagnose operational failures in each one of them, and thus throughout the completion of the Well. Each layer determines operational conditions from which we can establish the diagnosis of operational failures in the system. From this information, an online monitoring system could be developed at different levels of the well (for example, at the wellhead using the output of FD-1), with the aim of generating corrective actions based on the operational failure detected.

Finally, our hybrid intelligent system must be proved using other recognition techniques for the first phase, or other optimization techniques for the second phase, in order to compare the system performance (at level of the results quality or execution time).

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