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A METHODOLOGY FOR INVESTIGATING CONTROL LOOPS BEHAVIOR THROUGH THE ANALYSIS OF PATTERNS USING HISTORICAL DATA

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Abstract

Water injection is one of the techniques to increase pressure in a reservoir, with the objective of performing the secondary recovery of a producing well. This operation must be carried out carefully, since deviations in the process variables can result in overpressure situations, causing unexpected shutdowns and even putting the integrity of the well at risk. The aim of this work was to develop a methodology to analyze historical field data, based on the water injection plant operation and process control knowledge. It allowed the understanding of the system behavior, as well as the identification of anomalous behaviors causes. In addition to the immediate application, this methodology presents a great potential since it can be used as basis for the use of artificial intelligence tools, which allow, for example, analysis of a large amount of data and prediction of undesirable behavior.

Keywords: Historical data analysis. Control system. Water injection. Production. Petroleum.

1. Introduction

Historical data analysis of sensor signals from a process plant is a powerful tool for diagnosing problems in the control system. However, for systems involving many control loops and sensors, this can be a complex task due to the interaction between the loops, which causes oscillation of the signal in a given controller to replicate to others, creating undesirable oscillations in the system (Borges et al., 2014). Therefore, a methodology of data analysis is necessary to extract correlations that can clarify the causes that generate the oscillations (Borges, 2003).

This paper presents a methodology developed to investigate the causes of pressure and flow oscillations in a water injection system for secondary oil recovery.

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2. Description of the Water Injection System and Oscillation Problem

The studied water injection system is composed of seven control loops, being the corresponding controllers named as LIC-01, FIC-01, FIC-02, FIC-03, XC-01, PIC-03 and PIC-05. One is used for level control (LIC-01), three for flow control (FIC-01, FIC-02, FIC-03), one for limiting valve opening (XC-01) and two for pressure control (PIC-03 and PIC-05). The analyzed system comprehends the components from the deaerator vessel to the injection riser, including the main and the booster pumps as depicted in Figure 1. The controllers XC-01, FIC-03, PIC-03 and PIC-05 operate in an override control strategy over FCV-03A valve by a lower signal selector (LSS).

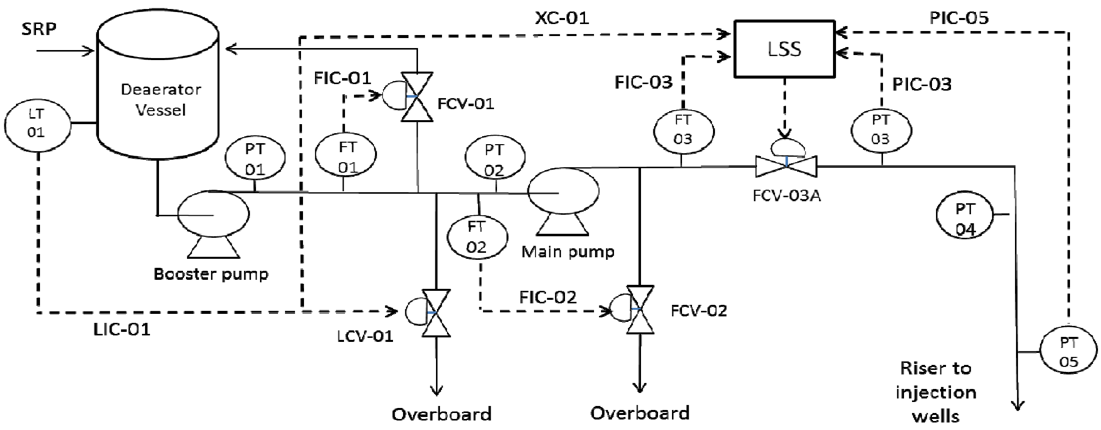


Figure 1. Water injection process control diagram.

Oscillations in the pressure and flow signals may occur during “system ramp up” (system startup by opening the injection wells) and eventually lead to system shutdowns. These oscillations were observed during “ramp up” as shown in Figure 2. In these events, all the controllers operating in override control mode over FCV-03A were in manual and the oscillations occurred over a specific injection flow range. A methodology has been developed to identify the causes of these oscillations using historical data.

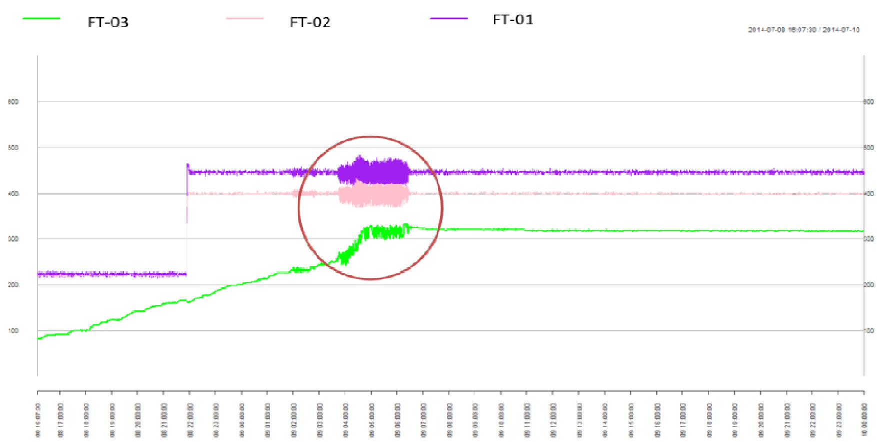


Figure 2. Flow oscillation during ramp up.

3. Methodology

The proposed methodology is based on the analysis and interpretation of historical data using both the understanding of the plant control system operation and heuristic knowledge of process control. In order to achieve this goal, the following procedures were established:

(1) Understanding the set of signals
The variables pertinent to the problem under analysis must be selected and grouped by type according to the controllers: Inputs (controlled variables) and Outputs (manipulated variables). Typical patterns must be identified by inspecting data.

(2) Inference of the "system operating state"
The possible inferences of the system operating state and the respective signal patterns must be identified.

(3) Inference of the "controllers operating state"
The possible inferences about the operating state of the controllers from typical signals patterns must be identified.

(4) Classification and selection of representative data periods
Inspect the data in order to identify periods corresponding to the situation under analysis using the operating and controllers states inferences. Ideally, both periods with and without abnormal behavior should be identified.

(5) Analysis of historical data curves using representative periods
Confront the selected periods' features with and without the abnormal behavior in order to identify elements that contribute to the malfunctioning state.

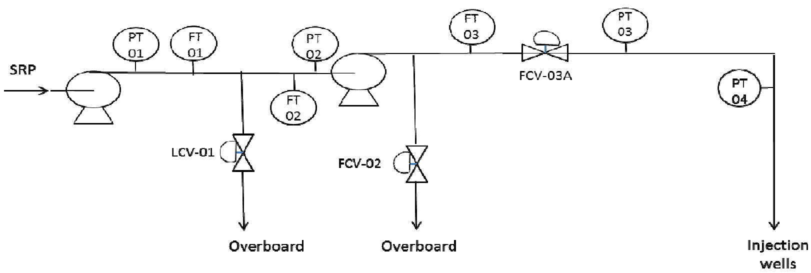
The methodology described above was evaluated in a real scenario confirming its efficacy. The major features of the investigated scenario are depicted in the following along with the methodology application and results.

4. Understanding the Set of Signals and Inferences

The variables pertinent to the region of interest were selected and grouped by type in relation to the controllers:

- Inputs (controlled variables): flow, pressure and level;
- Outputs (manipulated variables): valve opening (output of controllers).

Initially, the curves of historical data were analyzed by comparing the value between variables of the same type, considering the position of its sensors in the process and observing the flow direction in order to understand the process and infer which variable shall be greater or smaller.



(a)

Signals ordered in the flow direction	
Variable	Sensors Sequency
Pressure	PT-01
	PT-02
	PT-03
	PT-04
Flow	FT-01
	FT-02
	FT-03

(b)

Figure 3. (a) Position of the sensors in the process. (b) Selected variables ordered in the flow direction.

For example, as shown in Figure 3, pressure measured by PT-01 shall be greater than PT-2 due to pressure loss in the piping, but PT-03 pressure shall be greater than PT-02 because it is downstream the main pump. Additionally, flow measured by FT-03 shall be smaller than FT-02 because part of the flow goes to overboard through valve FCV-02.

Subsequently, the behavior of each signal was classified individually in relation to frequency and amplitude patterns. It was then classified what are the normal and abnormal behaviors of each variable and inferred the "system operating state" and the "controllers operating state" from the signal pattern.

Some possible inferences of the "system operating state" and the respective signal patterns of the sensors are:

- Ramp up operation - upward inclination of injection flow slope;
- Steady state operation - horizontal curves of injection flow rate;
- Half load operation - low average values of inlet flow rate;
- Full load operation - high average values of inlet flow rate.

Some examples of "controller operating state" inferences from the pattern of the valve opening signals are:

- Operating mode (manual / automatic) - continuous signal.
- Tuning (slow / fast response) - oscillatory signal (low / high frequency).
- Interaction between loops (coupled / decoupled) - both oscillatory signals at high frequency.

Figure 4 summarizes all the inferences for "system operating state" and "controller operating state" based on the pattern of the input and output signals, where A and T means:

A – For the inference to be true, all the variables signal pattern shall be present in it respective line. In the case of ramp up or ramp down, the two adjacent lines shall be true.

T –For the inference to be true, only the correspondent variable pattern shall be present.

	Controlled variables							Manipulated variable				
	Flow rate			Pressure				Valve opening				
Signal behavior	**FT-01**	**FT-02**	**FT-03**	**PT-01**	**PT-02**	**PT-03**	**PT-04**	**LCV-01**	**FCV-02**	**FCV-03A**	**Inference**	
Horizontal			A			A	A		A	A	Steady state regime	Operating state
Ascendent			A			A	A			A	Ramp up	Operating state
Descendent									A		Ramp up	Operating state
Descendent			A			A	A			A	Ramp down	Operating state
Ascendent									A		Ramp down	Operating state
Flow rate less than 230 m^3/h	A										Half load operation	Operating state
Flow rate greater than 230 m^3/h	A										Full load operation	Operating state
Oscillaton with big amplitude	A	A	A	A	A	A	A				Unstable system with respect to oscillations (presence of noise)	Operating state
Oscillaton with small amplitude	A	A	A	A	A	A	A				Stable system with respect to oscillations	Operating state
Flow rate between 238 and 330 m^3/h			A								Cavitation in FCV-03A valve	Operating state
Smooth curve								T	T	T	Controller in manual mode	Controller state
Curve with oscillation								T	T	T	Controller in autometic mode	Controller state
Low frequency oscillation								T	T	T	Controller with slow tuning	Controller state
High frequency oscillation								T	T	T	Controller with fast tuning	Controller state
Oscillatory at low frequency									A		Decoupled loops	Controller state
Oscillatory at high frequency								A			Decoupled loops	Controller state
Oscillatory at high frequency	A	A	A					A	A		Coupled loops	Controller state

Figure 4 - Matrix of “operating state” and “controller state” inferences.

5. Classification and Selection of Representative Data Periods

For the classification step, 19 sampling periods were chosen and grouped into "cases" according to the position of the oscillations in relation to the ramp up, totalizing 8 groups (denominated "a" to "h"). One group refers to cases in which there were no oscillations (called group a, composed of 4 periods) and the other seven groups refer to cases where oscillations occurred (corresponding to the 15 periods remaining). The most typical case is where the oscillation begins and extinguishes in the middle of the ramp up (denominated group c, composed by 8 periods).

6. Analysis of Historical Data Curves Using Representative Periods

For the sensor curves analysis two ramp up periods were selected, one “with oscillation” (group c) and the other “without oscillation” (group a).

6.1. Analysis of the “Ramp up With Oscillation” Period

In this analysis, the period was segmented in four sections: a) injection flow less than 150 m3/h, b) injection flow between than 220 and 230 m3/h, c) injection flow between 238 and 330 m3/h and d) injection flow greater than 330 m3/h.

Figures 5, 6 and 7 show the curves of flow, pressure and valve opening for the “period with oscillation”, segmented in the four sections (a, b, c and d).

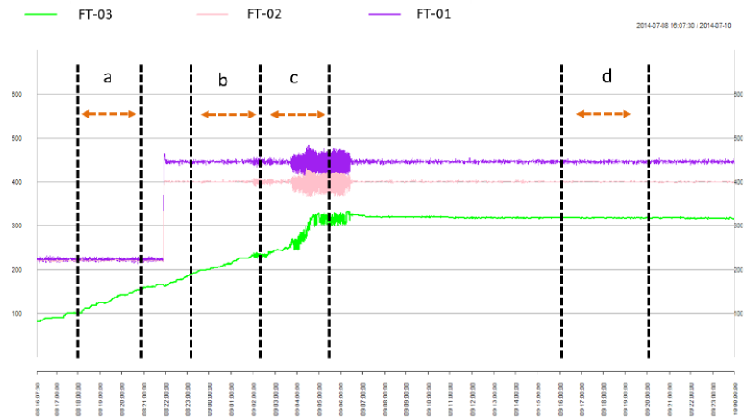


Figure 5. Flow curves for a period with oscillation**.**

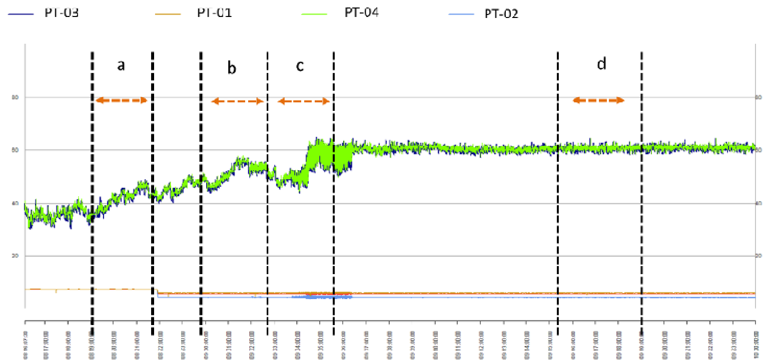


Figure 6. Pressure curves for a period with oscillation.

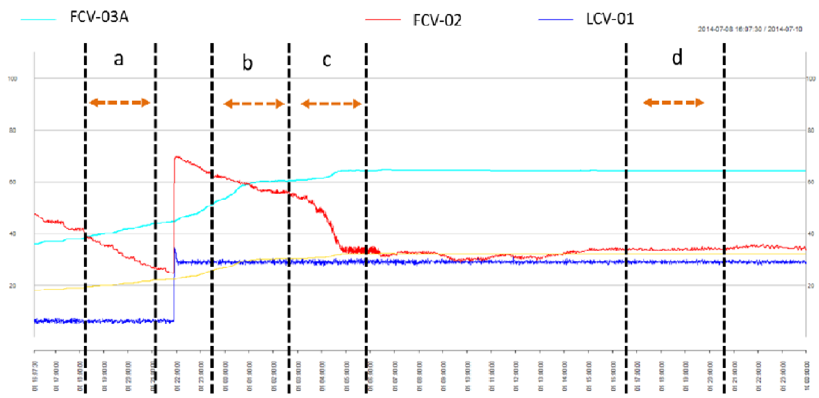


Figure 7. Valve opening curves for a period with oscillation.

Appling the matrix of inferences of Figure 4 to Figures 5, 6 and 7 in the section (a) it can be inferred for “system operating state” that it is in ramp up, with half loading operation and stable. For the “controller operating state” it can be inferred that the controller of LCV-01 valve is in automatic mode tuned for fast response, the controller of FCV-02 is also is automatic mode tuned for fast response and the controller of FCV-03A is in manual mode.

For section (b) it can be inferred for “system operating state” that it is in ramp up, with full loading operation and stable. One can infer for the “controller operating state” the same state as in section (a).

For section (c) it can be inferred for “system operating state” that it is in ramp up, with full loading operation, unstable and FCV-03A is suffering cavitation. For the “controller operating state” the same state as in section (a) and (b) can be inferred.

For section (d) it can be inferred for “system operating state” that it is in steady state, operating at full loading and stable. One can infer for the “controller operating state” the same state as in section (a), (b) and (c).

From the analysis of the “group (c)” curves it can be concluded that the instability problem occurs only in “section (c)”, where injection flow rate is between 238 and 330 m3/h, when the “system operating state” is in ramp up, operating at full loading and FCV-3A is in cavitation regime. In this group, the “controller operating state” inferred was: controller for LCV-01valve in automatic mode, tuned for fast response and controller for FCV-02 valve also in automatic mode, tuned for fast response.

6.2. Analysis of the “Ramp up Without Oscillation” Period

It was applied the same methodology for group (a), the period corresponding to “ramp up without oscillation”.

This period was also segmented in four sections: a) injection flow rate equal or less than 220 m3/h, b) injection flow rate between 220 and 238 m3/h, c) injection flow rate between 238 and 330 m3/h and d) injection flow rate greater than 330 m3/h.

Figures 8, 9 and 10 show the curves of flow, pressure and valve opening for the four sections (a, b, c and d).

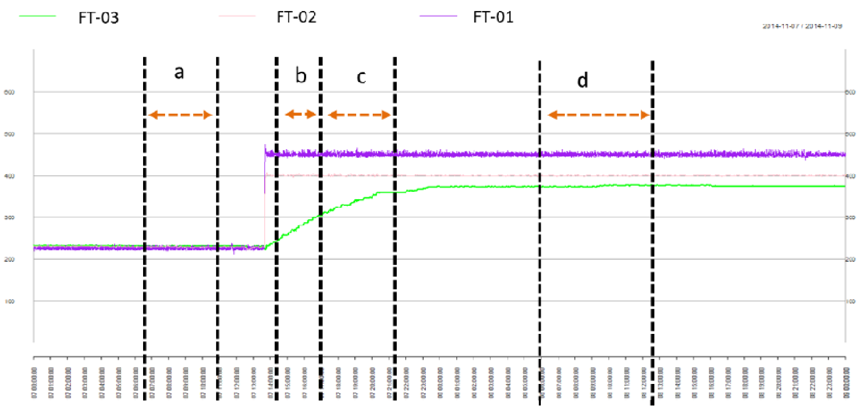


Figure 8. Flow curves for a period of “ramp up without oscillation”.

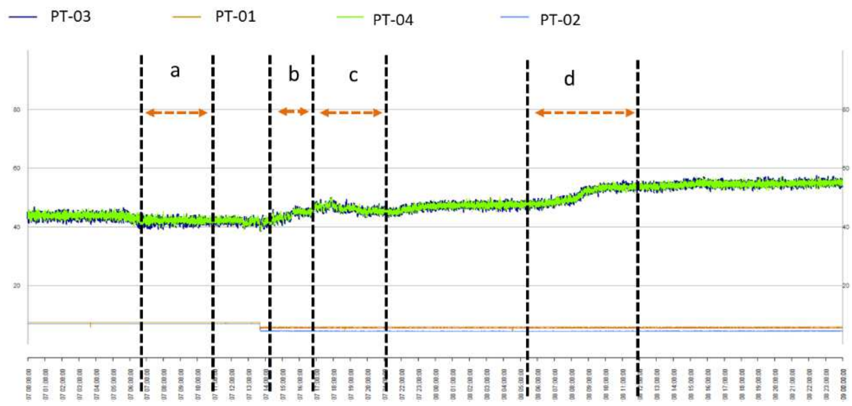


Figure 9. Pressure curves for a period of “ramp up without oscillation”.

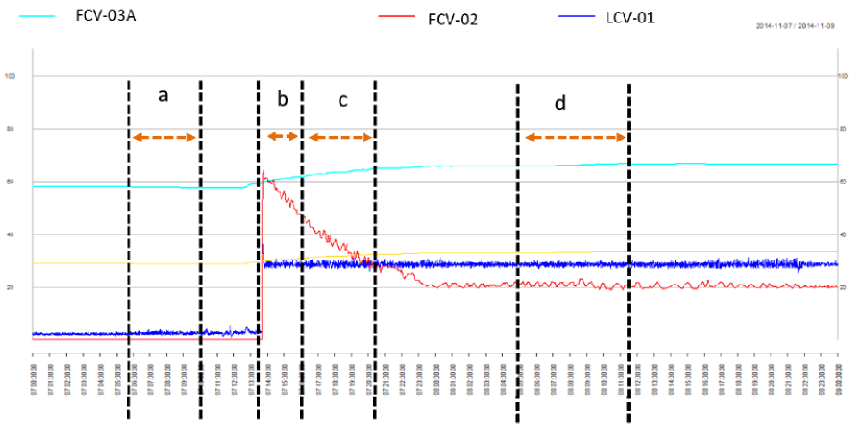


Figure 10. Valve opening curves for a period of “ramp up without oscillation”.

Appling the matrix of inferences of Figure 4 to the curves in Figures 8, 9 and 10, for the section (a) it can be inferred for the “system operating state” that it is in steady state, with half loading operation and stable. For the “controller operating state” it can be inferred that controller for LCV-01 valve is in automatic mode, tuned for fast response, and the controller for FCV-02 valve is also in automatic mode, but tuned for slow response. The controller for FCV-03A valve is in manual mode.

For section (b), it can be inferred for the “system operating state” that it is operating in ramp up, with full loading operation and stable. One can infer for the “controller operating state” the same state as in section (a).

For section (c), it can be inferred for the “system operating state” that it is operating in ramp up, with full loading operation and stable. For the “controller operating state” the same state can be inferred as in sections (a) and (b).

For section (d), it can be inferred for the “system operating state” that it is operating in steady state, with full loading operation and stable. One can infer for the “controller operating state” the same state as in sections (a), (b) and (c).

From the analysis of the “group (a)” curves it can be concluded that the instability problem did not occur in neither of the sections. In this group, the “controller operating state” inferred was: controller for LCV-01 valve in automatic mode, tuned for fast response and controller for FCV-02 valve in automatic mode tuned for slow response.

6.3. Inferred Diagnosis for the Oscillation Problem

From the comparison between the flow, pressure and valve opening curves of the four sections for the two periods of “group with instability” (group c) and “group without instability” (group a) one can conclude that:

- The most severe oscillations occurred only in group (c), section (c), where injection flow rate ranged from 238 to 330 m3/h. In this section, the system was operating in ramp up, at full loading and in the cavitation zone of FCV-03A.
- When the FIC-02 controller tuning was set to a slower response than the LIC-01 controller (group a), the two loops in question were decoupled, reducing the feedback of oscillations between them and the oscillations in section (c) disappeared for all pressure and flow measurements.
- Pressure oscillations measured by PT-03 sensor, even being FCV-03A in manual and the system in steady state (section c), suggest that this valve is operating in cavitation regime. This phenomenon intensifies in a certain range of valve opening (corresponding to a flow rate from 238 to 330 m3/h) which, when reached during ramp up, is amplified by the fast response of the FIC-02 controller.

The Logic Diagram that summarizes the diagnosis inferred above is depicted in Figure 11. If the “observed oscillatory state” is present, then the “inferred oscillatory state” shall be true in order to validate the diagnosis logic. This Logic Diagram can be tested in any section of data of the water injection system. If the result of the test is false, than others oscillations causes shall be investigated.

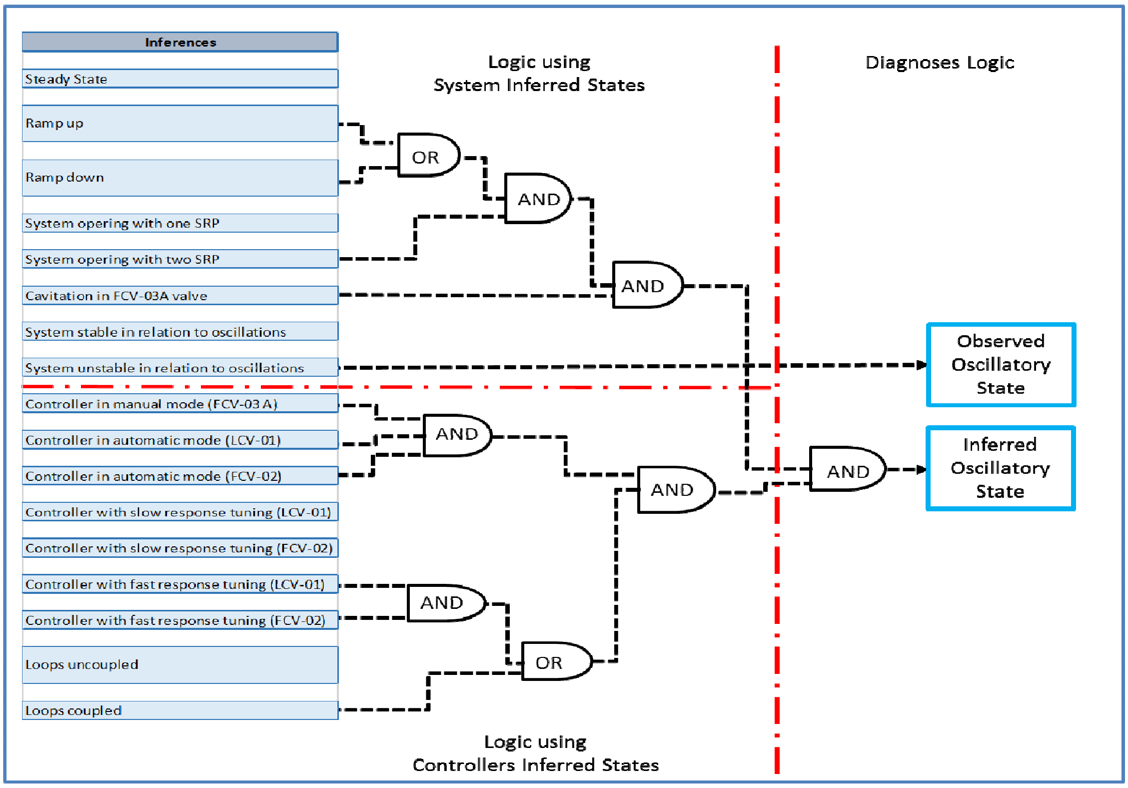


Figure 11. Logic Diagram to diagnose abnormal oscillation in the water injection system.

7. Conclusions

This study has demonstrated that it is possible to diagnose anomalies in a control system from the visual analysis and interpretation of the curves of sensors historical data. To accomplish that, it was necessary to understand the operation of the water injection system, to know some basic concepts of control system theory and to develop a methodology for classification of the signals in patterns that allows inferring the state of the system and of the controllers.

This methodology can be applied to other control systems and can be automated by an expert system software.

8. Acknowledgment

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9. References

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