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Key Parameters Calibration and Benefits Evaluation of a Closed Loop Performance Monitoring System

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Abstract: The paper presents results from field validation of a closed loop performance monitoring system installed on several units of a refinery plant. The system supervises more than 1200 base control loops and evaluates performance periodically, after scheduled data acquisitions followed by off-line analysis. The first point taken into account is a comparison between verdicts issued by the system and indications by control operators: the large number of issued verdicts indicating scarce performance, but considered still acceptable by operators, results practically in False Alarm and forced to revisit the criterion adopted to classify a response as excessively oscillatory. New threshold values for the widely used Hägglund criterion (1995) were found and similar criteria were proposed and compared in order to match operators practical indications. The efficiency of criteria and threshold values depend on the type of loop (i.e. flow, pressure, level or temperature). The second point examined concerns validation of valve stiction diagnosis: indications from the monitoring systems are compared with evidence before and after plant shut down. Results confirm that oscillations in valves indicated as sticky disappeared after the operation, while many valves which underwent the maintenance procedure on the basis of a time schedule did not require it. Therefore, a systematic application of diagnostics tools for maintenance scheduling would be beneficial in order to focus on real needs and avoid unnecessary revision costs..

Keywords: Closed Loop Performance Monitoring, Oscillation Detection, Valve Diagnostics

1. INTRODUCTION

The adoption of automatic performance monitoring of control loops is very important in the process industry, owing to their direct effect on product quality, energy saving, waste minimization, that is on key parameters correlated to the efficiency of an industrial plant.

A necessary condition to allow higher level control to carry on the optimization of the whole process is that base control loops operate at their best. For this reason, different causes of scarce performance should be detected and the right actions to do suggested by the monitoring system to the operators.

By considering the high number of control loops operating in a large scale plant, it is important that the monitoring system operates automatically, with a very simple and user friendly interaction with operator in order to be accepted as a tool to simplify every day routine and not as an additional work to be performed for plant supervision.

A direct link between academic research and industrial applications is crucial, in order to address real problems and to find solutions which can be promptly accepted by plant operators. Research activity in recent years have been focused on issues as incorrect tuning of controllers, anomalies and failures of sensors, presence of friction in actuators. The last topics brought to the development of many new techniques for automatic detection of stiction; for instance, to cite the ones referred in this application: Horch (1999), Rossi and Scali (2005), Choudhury et al. (2005), Yamashita (2006), Scali and Ghelardoni (2008). A comparison of results of 11 new techniques on an industrial benchmark can be found in Jelali and Huang (2009).

Implementation issues concern the right degree of interaction with control operators. Certainly a completely automated system would be desirable, but some degree of process knowledge must be incorporated in the monitoring system to improve diagnosis reliability. Parameter calibration and field validation are very important for this scope.

Parameter calibration consists in assigning threshold values which allow automatic techniques to distinguish between different phenomena, starting from the assessment of good or inadequate performance, in accordance with operator judgement. Here a compromise must be found between too generic and too detailed approaches; the first requires the setting of few parameters and allows to save time during the configuration of the system; the second implies a customization of individual loops and may become too time consuming. Field validation is the real issue, the moment when the verdicts of the monitoring system find a confirmation and the efficiency of the proposed action is checked. At this stage, wrong indications, both bad performing loops not detected (Missed Alarms) and good performing loops indicated as bad ones (False Alarms), become evident and the global reliability of the system is assessed.

The final stage after the adoption of a performance monitoring system is the evaluation of benefits. The assessment of single loop improvement in terms of reduced variability and error norms is quite simple, while it is much more difficult to get reliable evaluation of consequent economic benefits on global the process. *Ex-post* approaches, that is the comparison of some economic performance indicators before and after the adoption of the system, are commonly used; in this case a global indication of benefits is obtained, often cumulating effects of different actions on the plant, including both maintenance and revamping.

Following this introduction, the paper addresses the issues of parameter calibration and benefits assessment, regarding a performance monitoring system recently developed and implemented in a refinery plant of ENI, in Livorno (I). The architecture of the system and the logic of the module which performs loop data analysis will be shortly presented in next section (more details in Scali et al., 2009). Field validation will be focused on the problem of matching operator indication with verdicts issued by the monitoring system, through the comparison of different criteria and the calibration of thresholds. Evaluation of benefits will be devoted to results of valve stiction diagnosis by comparing indications of the monitoring system with evidence before and after a recent plant shut down.

2. THE SYSTEM ARCHITECTURE

A synthetic picture of the system architecture is depicted in Figure 1, where different modules, their interconnection and physical location are indicated.

The User Module (MU) starts the whole procedure by sending a message to the module of scheduling (MS) about the sequence of loops to analyse and the frequency of the operation. It allows to check the progress of operations and to interact with the database (DB). The user module also permits loop configuration which consists in the assignment of loop name, DCS address, loop info, priorities, constraints and in the setting of threshold parameters.

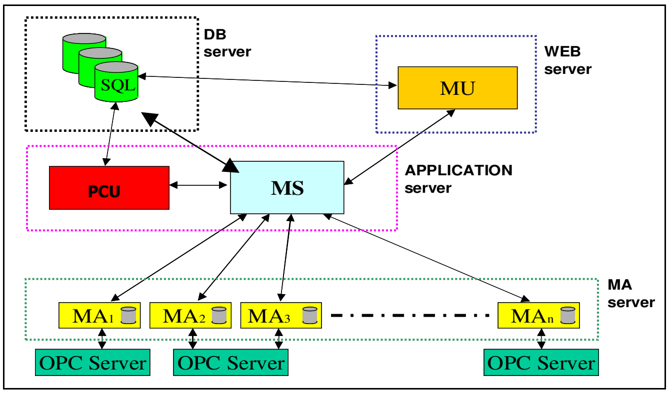

Fig.1: The system architecture

The Scheduling Module (MS), activates acquisition modules (MAi) which perform physically the acquisition of data from the DCS. For each loop, specific information are transferred to the Data Base (DB) trough MS: loop tag name, controller settings, ranges of controlled variable (PV) and controller output (OP), saturation limits, loop hierarchy.. Once acquisition is terminated, MS activates the performance analysis accomplished sequentially by the PCU (Plant Check Up) module. Loop data, together with verdicts generated by PCU are transferred into the DB.

Acquisition Modules (MAi) interact with DCS, from which receive data and updated loop parameters at each sampling time; they act in parallel (up to 7 loops) and sequentially on loops scheduled by MS.

3. THE PCU MODULE

The PCU module is the engine of the performance monitoring systems: it analyses each loop sequentially, interacting with the MS and with the DB. A schematic representation is reported in Figure 2, where main steps and a simplified logical flow is indicated.

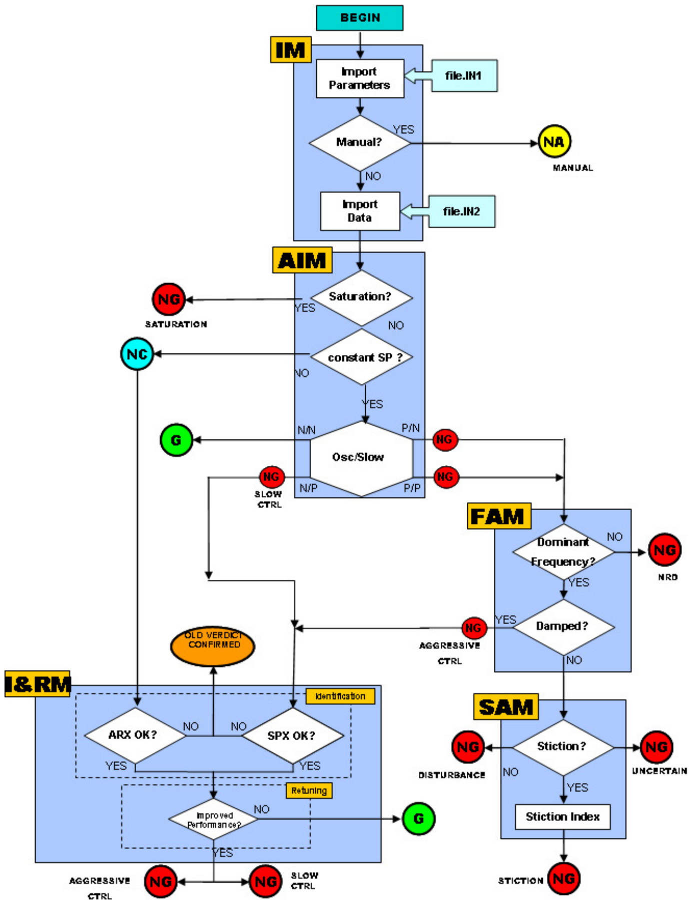

Fig.2: Schematic representation of the PCU module

The Initialization Module (IM) imports parameters values from file IN1 and performs a first check about loop status (quality of data, man/auto). If the case, the analysis stops and the loop receives a (definitive) label (NA: Not Analyzed); otherwise, analysis begins on recorded data (IN2 file).

The Anomaly Identification Module (AIM) accomplishes a first assignment of performance with verdicts: G (*Good*), NG (*Not Good*). Valve saturation is checked first and, if detected, the label NG (and the cause) is definitive. Loops subject to excessive set point changes are temporary labelled as NC

(*Not Classified*) and send to the Identification and Retuning Module (I&RM). Remaining loops are tested to detect oscillating or sluggish responses, mainly following Hägglund approach (1995, 1999), with minor modifications. In the case of both negative tests, the loop is classified as good performing (G). Slow loops are caused by the controller: they get a NG label and are sent to I&RM. Causes for oscillating loops can be aggressive tuning, external disturbance or valve stiction: for this reason, they are primarily sent to FAM, for a frequency analysis.

The Frequency Analysis Module (FAM) computes dominant frequencies to detect irregular loops labelled NG (without further enquiring of causes). Regular loops with decaying oscillations are sent to the I&RM, loops with permanent oscillations to the SAM for stiction/disturbance detection.

The Stiction Analysis Module (SAM) analyzes data of NG oscillating loops and performs different tests to detect the presence of valve stiction. They mainly consist in the application of two techniques: the Relay based fitting of trends of the controlled variable PV (Rossi and Scali, 2005) and the improved qualitative shape analysis (Scali and Ghelardoni, 2008), which extend the original technique (Yamashita, 2006). Other techniques proposed for stiction diagnosis are also applied, when appropriate; among them: the Cross-Correlation (Horch, 1999) and the Bichoerence (Choudhury et al. 2005). The appropriate technique to use is automatically selected by the system, according to different type of loops; final verdict takes into account indications coming from different techniques and from other auxiliary indices (see Scali et al., 2009), for details. The exit loop, already tagged NG, receives a cause *Stiction* or *Disturbance* (or *Uncertain*, in the case of lack of strong evidence).

I&RM: The Identification & Retuning Module accomplishes process identification and, if successful, controller retuning and evaluation of performance improvements. It analyses loops tagged NG, owing to controller tuning and loops tagged NC. In the case of constant SP, identification of process dynamics is carried out by means of a Simplex based search procedure (Scali and Rossi, 2009), while in the case of variable SP, an ARX algorithm (Ljung, 1999) is used. In both cases, if model identification is successful, new tuning parameters are calculated, the achievable performance improvement is evaluated and new controller settings are proposed. Otherwise, in the case of impossible identification, the previous assigned verdict is confirmed.

Therefore, after PCU analysis, every loop get a verdict as:
- NA (Not Analysed): Manual valve, invalid data acquisition, change of loop configuration;
- NC (Not Classified): unsuccessful identification;
- G (Good Performing);
- NG (Not Good performing): with an indication of cause (*saturation*, *sluggish, too oscillating, stiction, external disturbance*), or without indication for the cases of irregular disturbances or uncertainty between stiction and disturbance.

To conclude this synthetic illustration, the monitoring system has been designed to operate completely unattended: verdicts and causes are assigned only in case of strong evidence. Nevertheless, verdicts are issued as a consequence of threshold values assigned in the configuration stage by interaction with plant operators, therefore they depend on initial calibration. This point will be fully discussed in the next sections.

4. SYSTEM VS. OPERATOR INDICATIONS

The large number of loops under supervision (> 1200) caused many NG verdicts, that is loops indicated as Not Good performing and then needing improvements by appropriate actions. Their number was considered too large by plants operator claiming that their performance should be considered *acceptable*, according to *common practice*. Therefore the verdicts issued by the PCU package were felt as too severe (a sort of False Alarms), even though calibration was carried out together with plants operators. To be pointed out that the same threshold value was selected for different loop types; referring to the introduction, this choice gave the priority to saving time at the expense of a more specific loop customization.

An example of mismatch between PCU and operator verdicts is reported in Table 1.

Tab. 1: PCU and operators verdicts on acquired loops

Loop type	**PCU NG loops**	**Operators NG loops**	**Operators G loops**
FC	**48**	**18**	**30**
PC	**42**	**11**	**31**
LC	**26**	**3**	**23**
TC	**49**	**15**	**34**

Some observations about the loop selection in the table:
- all the loops indicated as NG by PCU reported two NG verdicts in the last two acquisitions (about 13% of total).
- the number of loops considered Good by operators is comparable for FC, PC, TC loops (ranging from 60% to 70% of total), while is much higher for LC loops (88%),
- all these loops show an oscillating trend; the problem of mismatch between PCU and operator verdicts was much less frequent for loops indicated as sluggish.

These considerations originate the need of a critical analysis of the criteria to classify an oscillation as significant; this point is expanded in the next section.

The basic idea is to filter NG verdicts in order to decrease the number of FA; this will happen at the expense of increasing the number of Missing Alarms (MA), that is loops bad performing (NG) which become classified as good ones (G). Referring to Figure 3, without filtering, all initial NG verdicts issued by PCU and considered G by the operator, are errors (FA), (NG_0=G_{OP}=FA); by increasing the value of the threshold from 0 to ∞, all PCU verdicts become G and the number of MA is equal to the number of loops considered NG by the operator (NG_∞=NG_{OP}=MA). The goal is to reach a good compromise, where the number of total errors (FA+MA) is significantly lower than initial errors (NG_0); the ideal situation would be to find a range where the number of FA is reduced to zero before MA begin.

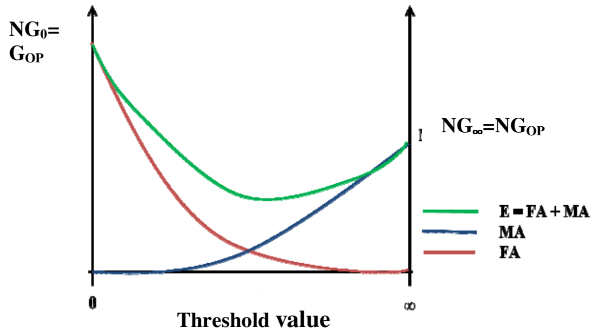

Fig.3: MA, FA and Errors by increasing filtering action

5. CRITERIA TO DETECT THE RELEVANCE OF AN OSCILLATION

Referring to Figure 2, in the AIM module, loops data are classified as oscillating following the Oscillation Detection Test (Hägglund, 1995). According to this criterion an oscillation is considered relevant if its Integral of Absolute Error overcomes an assumed value IAE_{lim}, for a certain number of times (N_{lim}), in the supervision time window T_{sup}. IAE is defined as:

$$IAE = \int_{t_i}^{t_{i+1}} |e(t)|\,dt$$

where the error ($e = PV - SP$) and t_i e t_{i+1} are two zero crossing times. For a pure sine wave (frequency ω and amplitude a), the value of IAE in each half period becomes:

$$IAE = \int_0^{\pi/\omega} |a \cdot sen(\omega t)|\,dt = \frac{2a}{\omega}$$

IAE_{lim} depends on the range of the controlled variable PV and the loop critical frequency $\omega_u = 2\pi/P_u$, and is defined as:

$$IAE_{\lim} = \frac{2a \cdot RangePV}{\omega_u}$$

The loop critical frequency very often is not known and it is suggested to get its order of magnitude from the value of the integral time constant (τ_i) of the controller (in the hypothesis of a Ziegler&Nichols tuning: $\tau_i = P_u/1.2$).

The technique is widely used as it allows to detect oscillations in the frequency rang of interest (low-middle) and to disregard high frequency oscillations, associated to instrumentation noise. Suggested values for the parameters are: $a=0.01$, $N_{lim}=10$, $T_{sup}= 50*P_u$.

It is evident that the choice of values is subjective and introduces the possibility of calibration on field data. Therefore the most immediate suggestion to *filter* NG verdicts, is to increase the value of the parameter *a*. Nevertheless, in the case of incorrect tuning, or irregular oscillations or SP variations, the criterion may give wrong indications. A modified criterion has been introduced (Thornhill and Hägglund, 1997) to face these problems and alternative techniques can be adopted to detect oscillations (for instance: Forsman and Stattin, 1999, Thornhill et al., 2003). The point addressed here is the definition of a criterion which might be more directly correlated with operator sensitivity in classifying an oscillation as relevant.

Two parameters were proposed and analyzed on loops data, both based on the average of the absolute error, expressed as percentage of the SP value or of the range of the controlled variable PV. An oscillation is considered relevant when the average error computed on *N* sampled data, overcomes a threshold (considered as acceptable value), respectively:

$$E_{SP} = \frac{1}{N}\frac{\sum_1^N |PV_i - SP_i|}{SP_i} \cdot 100 > E_{SP,\lim};$$

$$E_{PV} = \frac{1}{N}\frac{\sum_1^N |PV_i - SP_i|}{RangePV} \cdot 100 > E_{PV,\lim}$$

It is easy to realize that both parameters are correlated with IAE. For the particular case of a regular (analytical) periodic signal and constant SP, the IAE and the average error (E_{ave}) in the half-period ($P/2$) are correlated as:

$$IAE = E_{ave} \cdot \frac{P}{2}; \quad E_{ave} = \frac{\sum_1^N |PV_i - SP_i|}{N}$$

Therefore, for a regular signal, the different criteria become equivalent by changing the value of the threshold. In the case of real data (irregular signals, variable SP) and taking into account also other subjective elements adopted in the Hägglund test, there might be differences in classifying an oscillation as relevant. Also to be recalled that a constant threshold for all the loops is a desirable feature of the monitoring system: the threshold is fixed once for ever in the configuration phase, without the need of customizing each individual loop. Next section will present results and illustrate how and if this goal can be achieved.

6. APPLICATION TO LOOPS DATA

Loops data have been analyzed for increasing values of the treshold value for the three criteria, namely *2a* (for IAE), $E_{SP.lim}$, (for E_{SP}), $E_{PV,lim}$ (for E_{PV}) .

Flow Control loops (FC) were analyzed first, and results are shown in Figure 4 and 5, for the two criteria IAE and E_{SP}: the E_{PV} criterion gives intermediate results (not shown here). As expected, by increasing the value of the threshold, the number of FA decreases and the number of MA increases.

For the IAE criterion (Figure 4), the minimum number of total errors (MA+FA) decreases from 30 (FA, corresponding to the initial calibration for the threshold *2a=0.02*), to 10 (6 FA + 4 MA, corresponding to the threshold *2a=0.06*).

For the E_{SP} criterion (Figure 5), the minimum number of total errors decreases from 30 FA, to 6 (FA+MA), corresponding to threshold values $E_{SP,min}$= *1.0, 1.25, 1.75*, respectively; the relative numbers of MA and FA, changes with the threshold.

The E_{SP} criterion seems to give better results in reducing the number of total errors; the same result is achieved for different type of loops (only results for E_{SP} are shown).

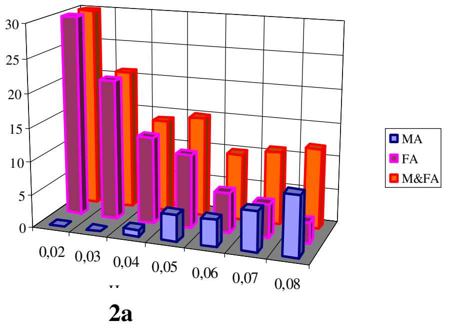

Fig. 4 Errors trend (FA, MA, total) for IAE (FC loops)

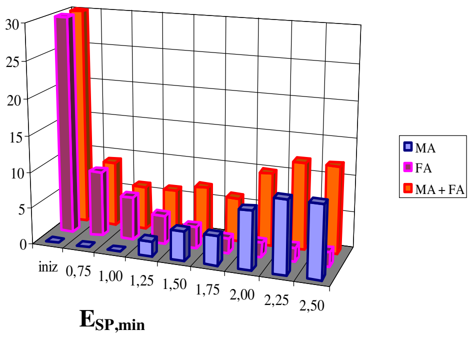

Fig. 5: Errors trend (FA, MA, total) for E_{SP} (FC loops)

Also in the case of Pressure control loops (PC), the E_{SP} criterion (Figure 6), allows to reduce significantly the number of errors, from 31 (initial FA), to 3 (FA+MA), corresponding to threshold values $E_{SP,min}$= *2.0 or 2.5*; the relative numbers of MA + FA, change with the threshold (from 0+3 to 1+2, respectively).

So the beneficial effect of filtering, in order to match operators indications, is confirmed also for PC loops; values of the threshold $E_{SP,min}$ are slightly different with respect to FC loops.

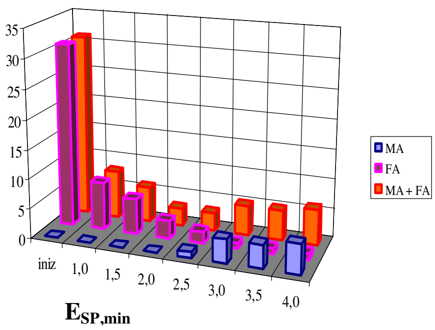

Fig. 6: Errors trend (FA, MA, total) for E_{SP} (PC loops)

For Level Control loops (LC), by increasing the threshold value, the number of errors (FA) reduces drastically and only for very large values of threshold 3 errors (MA) appears. This is a consequence of the fact that almost all loops were considered Good by operators (23/26). Performance of LC loops has a very low priority and does not seem worth of further attention in this application.

On the contrary, the case of Temperature Control (TC) is very important. The same procedure of increasing threshold values, allows to reduce the number of total errors (initially 34 FA) to about 20, as illustrated in Figure 7. The decrease of the number of FA by increasing $E_{SP,min}$ is not so fast and the number of MA increases very soon. So in this case the global effect is not so beneficial as for FC and PC. The case of TC loops probably can not be solved by referring to a simple criterion based on error norms, but should be based on specific information about the single loop (for instance the associated flow rate and related thermal duty). Further investigation is required for Temperature Control loops.

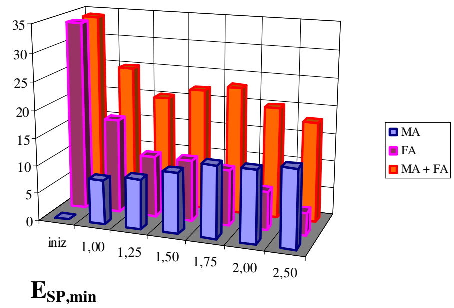

Fig. 7: Errors trend (FA, MA, total) for E_{SP} (TC loops)

Results for FC and PC loops have been validated on new data acquisitions, a total of 37 for FC and 12 for PC. Data Of loops, initially classified as NG, have been re-analyzed with new threshold values set to 1.75 and 2.5, respectively. Thereafter they were submitted to the same operators: only 2 (FC) and 3 (PC) mismatches were found, to confirm the validity of the new calibration of thresholds.

7. BENEFITS OF VALVE STICTION DIAGNOSIS

During the plant scheduled shut-down about 400 valves underwent maintenance, according to a policy of periodic revision. Of the total valves supervised by the monitoring system, a subset was selected according to the criterion of having reported at least two confirmed verdicts in the last three months (after the new calibration of thresholds). This produced 3 classes of valves, as reported in Table 2.

Tab. 2: Classes (numbers) of valves in selected subset

Stiction verdict	**YES**	**YES**	**NO**
Maintenance	**YES**	**NO**	**YES**
Class	**A (19)**	**B (44)**	**C (46)**

Examples of trends of loop variables before (left) and after (right) the shut-down are reported in the next figures.

Class A valves (Figure 8) reported a verdict NG (cause: stiction) before and G after: the beneficial effect of maintenance is evident in eliminating PV cycles around SP.

Class B valves (Figure 9) reported a verdict NG (cause: stiction) before and after: PV cycles around SP continue, as no maintenance was performed, while it was necessary.

Class C valves (Figure 10) reported a verdict G before and after: PV follows SP very well, before and after, as no maintenance was necessary.

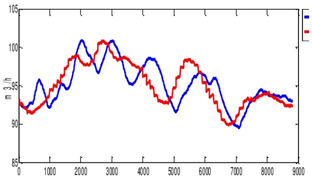
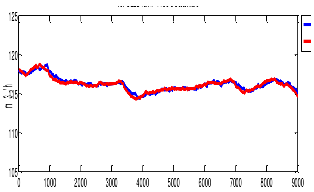

Fig. 8: Class A valves: PV and SP (red) trends

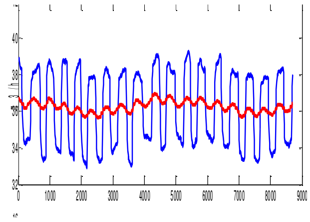
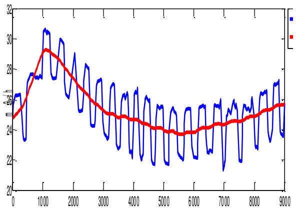

Fig.9: Class B valves: PV and SP (red) trends

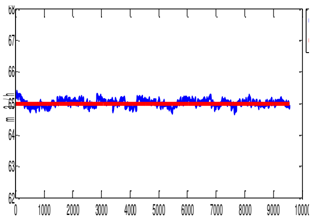
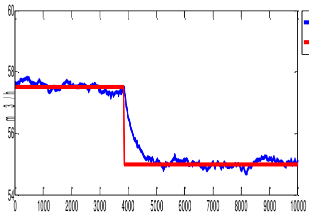

Fig. 10: Class C valves: PV and SP (red) trends

This illustration of results confirms that an appropriate maintenance when necessary would reduce PV variability, thus improving control loop performance; also, unnecessary maintenance of valve does not improve performance and its cost can be saved. Even though the selected subset of valves on the whole number under monitoring, does not constitute a complete validation, results are very promising and support a systematic application of diagnosis tools for maintenance scheduling.

8. CONCLUSIONS

A good matching between verdicts issued by the monitoring system and control operators indications is certainly the first objective to be achieved in field validation, before the assessment of possible benefits. Therefore it is worth to dedicate efforts interacting with operators in order to get a good compromise between the use of default values for all loops and the customization of each loop.

In the application illustrated, the number of False Alarms can be reduced, (with a reasonable increase of Missed Alarms) by increasing the threshold value of the oscillation detection test, based on IAE (Hägglund, 1995). Better results, in terms of minimum number of total errors (FA+MA), can be obtained by adopting a similar criterion based on the evaluation of the average error with respect to SP values.

Results can be considered very positive for the case of Flow and Pressure Control: by choosing slightly different threshold values for the two type of loops, it is possible to improve matching, without the need of single loop customization. In the case of Temperature Control, the problem has not been completely solved and further information on each individual loop seems necessary to improve verdicts matching. The case of Level Control is not relevant in this application (owing to the low priority assigned to their performance).

The evaluation of benefits of valve stiction diagnosis, even though restricted to a subset of the global number of valves under supervision, confirms that revising the valve when indicated would improve loop performance (sticky valves) and would allow to save costs of unnecessary maintenance (good valves). Therefore a systematic application of diagnosis tools for maintenance scheduling is strongly advised, compared with a policy of periodic revision.

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