DETECTION AND EVAUATION OF OSCILLATING LOOPS IN CLOSED LOOP PERFORMANCE MONITORING

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The paper focuses on an issue of great importance in loop performance monitoring, that is a criterion to evaluate the presence of oscillations of significant amplitude to be detected and eliminated by appropriate actions. The problem arises from the comparison between verdicts issued by an automatic system which supervises more than one thousand of loops in refinery plants 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. New criteria, in addition to the classical Hägglund criterion (widely used to classify a response as excessively oscillatory), are introduced and the effect of threshold values on False and Missed Alarms are analyzed by comparison on field data. A new calibration is performed in order to obtain a better matching with operators practical indications. As main result, different values of threshold are proposed to improve matching, depending on the type of loop (flow, pressure, level or temperature), something that is against the usual procedure of adopting constant values for all types of loops.
Keywords: Closed Loop Performance Monitoring, Oscillation Detection, Loop Diagnostics

1. INTRODUCTION

Detection of the presence of significant oscillations in controlled variables is the first step in closed loop performance monitoring. In fact, all loops present oscillation owing to the presence of noise, periodic disturbances, controller tuning or valve and sensor problems. Evaluating their extent is the first step to decide to start the analysis to detect causes and to suggest to the operators the right actions for their elimination. Nowadays, all the procedure is carried out by automatic performance monitoring systems which have been increasingly adopted in the last years in the process industry, owing to their direct effect on product quality, energy saving, that is on key parameters correlated to the efficiency of an industrial plant.
Even though main economic benefits derive from the application of multivariable control (i.e. Model Predictive Control) or real time optimization and scheduling, a necessary condition is that base control loops operate at their best. 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 and improve the quality of every day routine work.

Operator interaction is certainly one of the most important aspects to be faced in an industrial implementation (Hägglund, 2002; Scali et al. 2006); from one side, a completely automated system would be desirable, from the other, some degree of specific process knowledge must be incorporated in the monitoring system to improve diagnosis reliability. Parameter calibration, coming from field validation, is very important for this scope; it consists in the assignment of 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. In the initial configuration of the system, a compromise must be found between too generic and too detailed approaches; the first one requires the setting of few parameters and allows to save time; the second implies a customization of individual loops and may become too time consuming. Field validation is 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.
Issues as: oscillations detection, incorrect tuning of controllers, process identification, anomalies and failures of sensors, presence of friction in actuators, are research subjects which originate the techniques on the basis of the analysis carried out by the performance monitoring system. Some of these topics can be considered mature and have found a systematic definition in classical papers and textbooks, for instance: tuning (Visioli, 2006), identification (Liung, 1999); some other topics are still object of fervent research activity,for instance: oscillations (Thornhill and Horch, 2007), stiction detection (Jelali and Huang, 2009).

Following this introduction, the paper focuses on the issue of parameter calibration referring to a performance monitoring system recently developed and implemented in a refinery plant operating in Italy (Scali and Farnesi, 2010) and has the following structure: section 2 illustrates the logic and main techniques used in the module which performs loop data analysis, followed by a brief description of the architecture of the industrial monitoring system; section 3 reviews some techniques for oscillations detection and proposes new criteria to overcome possible limitations; in section 4 the problem encountered in the application and the improvement by application of new criteria are illustrated; finally (section 5) some conclusions and general indications are drawn.

2. THE MONITORING SYSTEM “PCU”

The PCU (Plant Check Up) module is the engine of the closed loop performance monitoring (CLPM) system: it analyses each loop sequentially, once data are made available by the acquisition system. A schematic representation is reported in Figure 1, where main steps and a simplified logical flow is illustrated.
The Initialization Module (IM) imports parameters values from the first file (IN1), performs a preliminary 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); in the case of both negative tests, the loop is classified as good performing (G); more on this point will be discussed in section 3 and 4. 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.

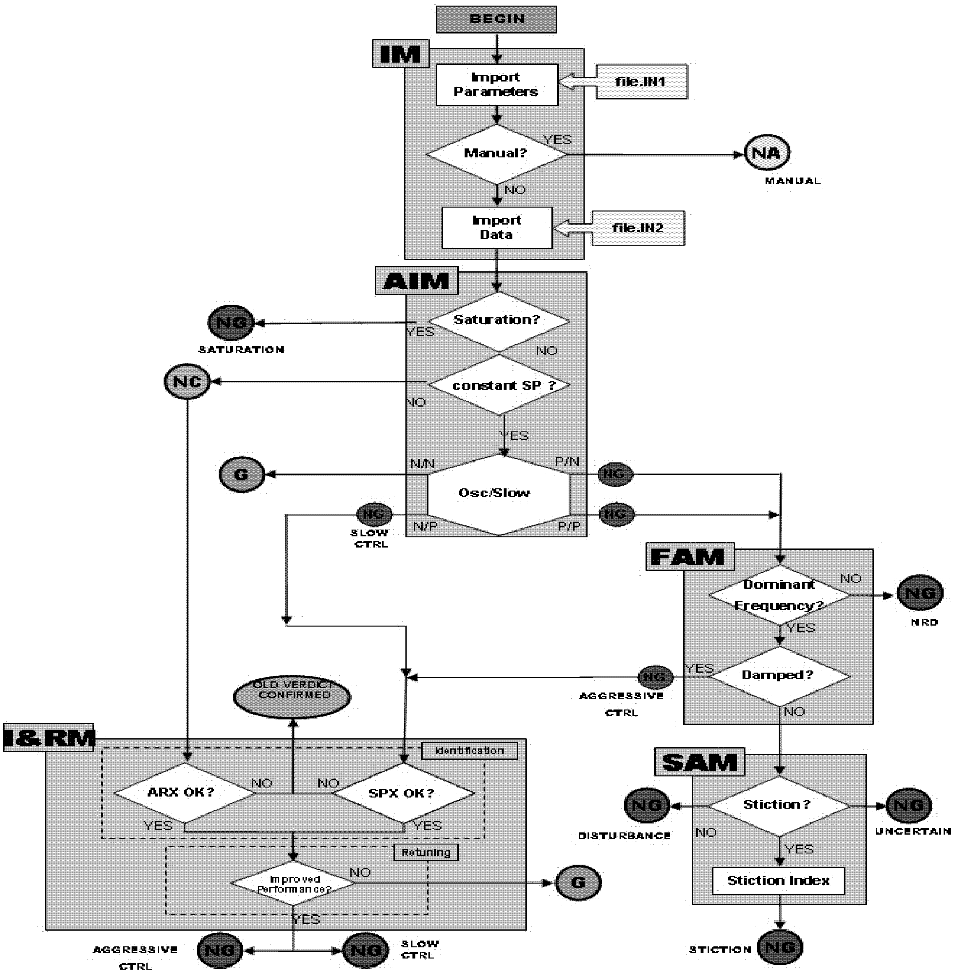

Fig.1: Schematic illustration of the PCU system

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.

A schematic illustration of the architecture of the monitoring system, is reported in Figure 2, where the role of different modules is put into evidence. The user module (MU) activates and checks the progress of the procedure, accomplishes the initial configuration (loops name, DCS addresses, threshold assignments), states priorities and constraints. The scheduling module (MS) activates acquisition modules (MAi) which interacts with DCS via OPC, thus transferring all the information about the loop to the Data Base (DB). Once a loop acquisition is terminated, MS starts the PCU module which accomplishes performance analysis and sends results (verdicts and values of key performance indexes) to DB; the interaction between PCU and DB is illustrated in the right part of Figure 2. The PCU analysis is off-line (with duration seconds/minutes), but is performed immediately after data acquisition (duration about 4 hours): therefore it can be considered almost a real time performance evaluation.

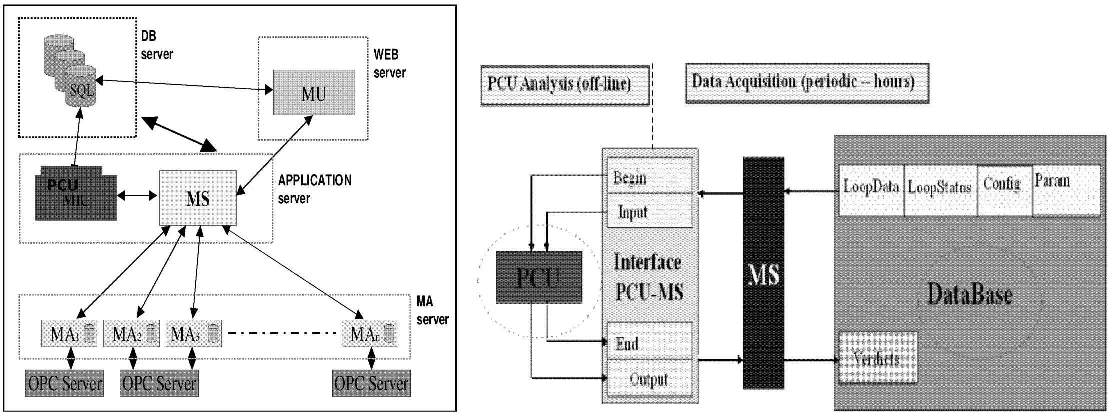

Fig.2: The CLPM architecture: main modules (left), interaction between PCU and DB (right)

In conclusion, 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 fixed in the configuration stage by interviewing plant operators, therefore they depend on initial calibration. Practical implication of this fact will be fully discussed in the next two sections.

3. OSCILLATION DETECTION TECHNIQUES

The Oscillation Detection Test. Referring to Figure 1, 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 when the number of oscillations (N_{osc}) having an Integral of Absolute Error (IAE) is larger than an assumed value IAE_{lim} (considered acceptable), 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} is correlated to the range of the controlled variable PV and the loop critical frequency ω_u, and is defined as:

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

Suggested values for the parameters are: $a=1\%$, $N_{lim}=10$, $T_{sup}= 50*P_u$, so the classification of an oscillation as relevant or acceptable is somewhat subjective. Further considerations allow a better understanding of the logical underneath the criterion and of possible limitations.

The first requirement for an oscillation being significant:

$2A/\omega > IAE_{lim}$

is verified for large A or low ω; this implies that, assuming the same IAE_{lim} as acceptable, larger amplitude is tolerated for higher frequency oscillations (see Figure 3):

$A_1=A_2\ (\omega_1/\ \omega_2)$

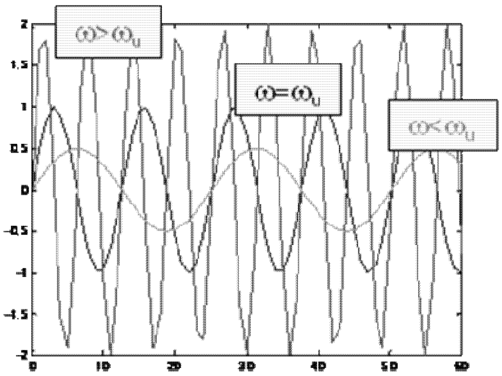

Fig.3: Examples of different frequency oscillations with same value of IAE_{lim}.

The second requirement:

$N_{osc} > N_{lim}$ for $0<t<T_{sup}$,

imposes limitation only on the frequency, being the maximum number of oscillations in T_{sup}:

$N_{osc}=T_{sup}/(\pi/\omega) >N_{lim}$.

Therefore two conditions on the frequency range are met:

$\omega < 2A/\ IAE_{lim}$

$\omega > N_{lim}\ \pi\ /\ T_{sup}$

Adopting the suggested values for the parameters *a, N_{lim}, T_{sup}*, the frequency range of interest becomes:

$\omega_u/10 < \omega < \omega_u$

These considerations explain why the technique is widely used, as it allows to detect oscillations in the low-middle frequency range (having larger interest in process control) and to disregard high frequency oscillations (which are generally attenuated by the process capacity). Nevertheless there are some issues that may become cause of errors and then possible limitations in the use of the criterion.

The value of the loop critical frequency is very important for previous evaluations; being not known in most cases, it is proposed compute it from the value of the integral time constant (τ_i) of the controller (in the hypothesis of a Ziegler&Nichols tuning: $\tau_i=P_u/1.2$, where: $P_u= 2\pi/\ \omega_u$).

It can be easily shown that when the loop is correctly tuned (also with different tuning rules) the estimate of the order of magnitude for ω_u is correct and the committed error acceptable; on the contrary, in cases of incorrect tuning the error can be large, thus affecting heavily the results of the Hägglund criterion.

Another possible cause of error lies in the fact that the criterion is based on the error (*e= PV - SP*) computed for constant SP; it is intuitive that for frequent SP changes (ω_r, for instance loops under cascade or advanced control) the error may not be a reliable index of the presence of significant oscillations due to disturbances (ω_d): a deeper investigation of this point allows to conclude that for $\omega_r > 3\ \omega_d$, the index loses its validity.
Results from the analysis of last two issues are reported in Del Mastro (2009).

The first point is illustrated in Figure 4, where the same oscillation (top) is classified as relevant or not, according to the value of IAE_{lim} and T_{sup}, both depending on the value of ω_u. In the first case (bottom, left), the number of oscillations (N_{osc}) with $IAE>IAE_{lim}$ in the assumed supervision time (T_{sup}) exceeds the maximum number (N_{lim}=10), while in the second one (bottom, right) it does not happen.

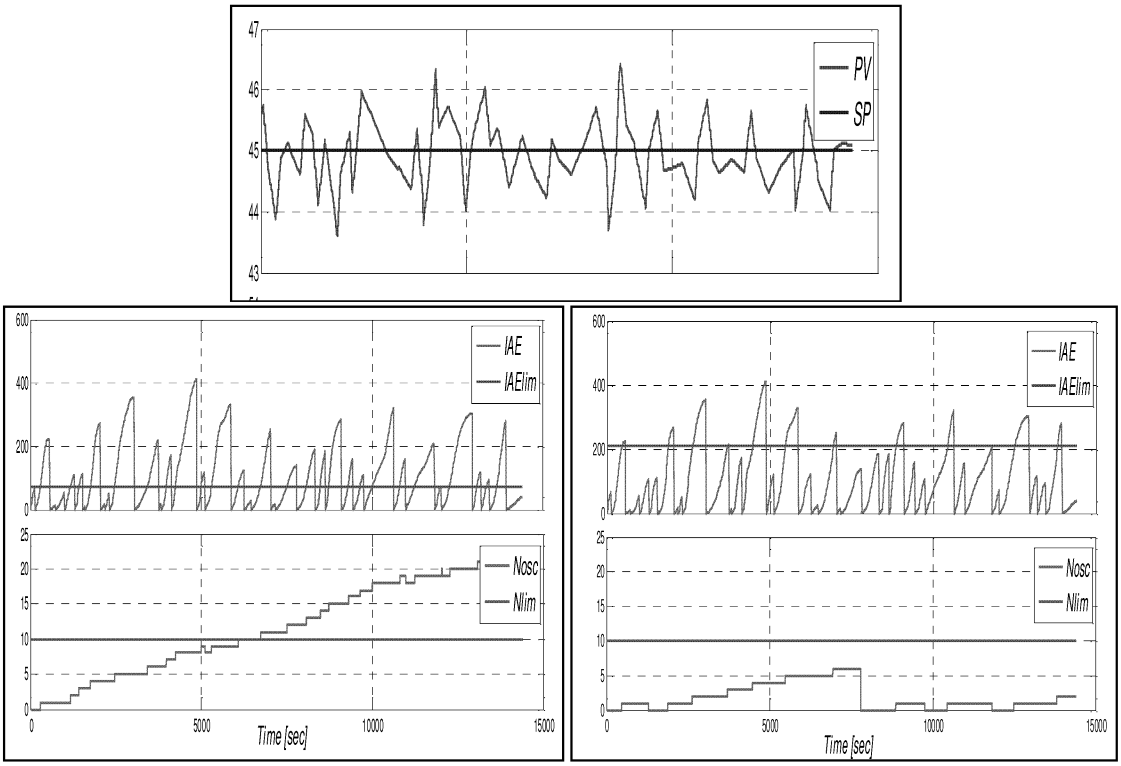

Fig.4: Oscillating loop variable (top). Classification according to Hägglund criterion: significant (bottom, left); acceptable (bottom, right).

Also, in the large majority of cases, oscillations affecting industrial loops are not regular signals, but have rather irregular patterns. 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).
These considerations suggest the possibility of a calibration based on field data for parameters *a, Nosc, Tsup*, with respect to default values, in order to improve the matching between operators and system indications. This is the point addressed in this paper, together with the definition of additional criteria which might be more directly correlated with operator sensitivity in classifying an oscillation as relevant.

The proposed criteria. 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 constant SP and regular (analytical) periodic signals (with amplitude A and period P), it can be easily verified that the IAE and the average error (E_{ave}) in the half-period (*P/2*) can be evaluated as:

- Square wave: IAE= PA/2, E_{ave}= A
- Triangular wave: IAE= PA/4, E_{ave}= A/2
- Sine/Cosine wave: IAE= PA/π, E_{ave}= 2A/π

bringing to the general relationship:

$$IAE = E_{ave} \cdot \frac{P}{2};$$

$$E_{ave} = \frac{\sum_{1}^{N} | PV_i - SP_i |}{N}$$

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. As mentioned in the introduction, it is evident that adopting a constant threshold for all the loops in the configuration phase has the desirable feature (time saving); the drawback, with respect to individual loop customization is a minor accuracy in evaluating performance.

Next section will show how the problem may rise in system applications and the way an improvement in matching verdicts from operators and automatic monitoring systems can be achieved.

4. MISMARCH BETWEEN OPERATORS AND SYSTEMS' VERDICTS

The system described above supervises a large number of control loops in refinery plants (> 1200); many NG verdicts where issued, 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 (becoming a sort of False Alarms), even though calibration was carried out together with plants operators (same threshold value selected for different loop types).

A summary of mismatches between PCU and operator verdicts is reported in Table 1.

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 (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.

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

These considerations originate the need of a critical analysis of the criteria to classify an oscillation as significant, as discussed in previous 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 5, 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 ($NG_\infty=NG_{OP}=MA$). The goal is to reach a good compromise, where the number of total errors (FA+MA) is significantly lower than initial errors (NG_0), as illustrated on the left. The ideal situation would be to find a range where the number of FA is reduced to zero before MA begin, as illustrated on the right.
Loops data have been analyzed for increasing values of the threshold for the three criteria, namely *2a* (for IAE), $E_{SP,lim}$, (for E_{SP}), $E_{PV,lim}$ (for E_{PV}).

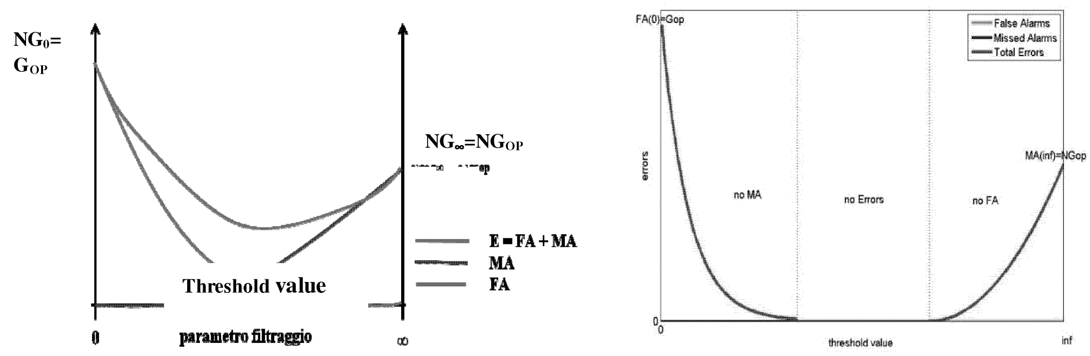

Fig.5: MA, FA and Errors by increasing filtering action: (left) practical, (right) ideal situation

Flow Control loops (FC) were analyzed first, and results are shown in Figure 6, where, in addition to the IAE criterion also the two new criteria (E_{SP} and E_{PV}), are reported. As expected, by increasing the value of the threshold, the number of FA decreases and the number of MA increases for all of them.
For the IAE criterion (top), 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 (bottom, left), 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.
For the EPV criterion (bottom, right), the minimum number of total errors decreases from 30 FA, to 8 (7FA+1 MA), corresponding to threshold values $E_{PV,min}$*=0.45*.
As expected, for all the criteria, the number of total errors decreases for increasing values of the threshold; the E_{SP} criterion seems to give better results in terms of minimum number of total errors.

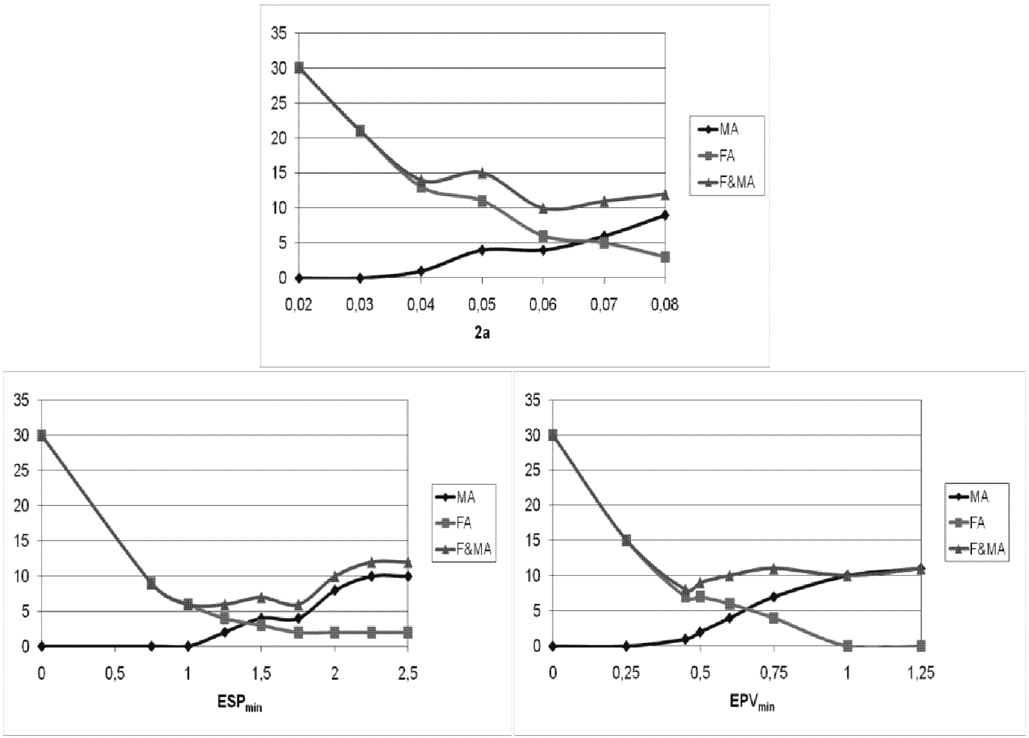

Fig. 6: Errors trend for FC loops (FA, MA, total: IAE (top), E_{SP} (bottom, left) E_{PV} criterion (bottom, right)

Also in the case of Pressure control loops (PC), the three criteria show similar results, but the ESP and the EPV outperform the IAE criterion in reducing the number of total errors. IAE allows to reduce to 15 the number of total errors (threshold *2a>0.05*), while the E_{SP} and the E_{PV} criteria, allow a larger reduction, respectively to 3 and 4 (FA+MA), corresponding to threshold values $E_{SP,min}$= *2.0 or 2.5* and $E_{PV,min}$= *1.25*. The relative numbers of MA + FA, change with the threshold. This is illustrated in Figure 7.

So the beneficial effect of filtering, in order to match operators indications, is confirmed also for PC loops; values of threshold values can be slightly different with respect to FC loops.

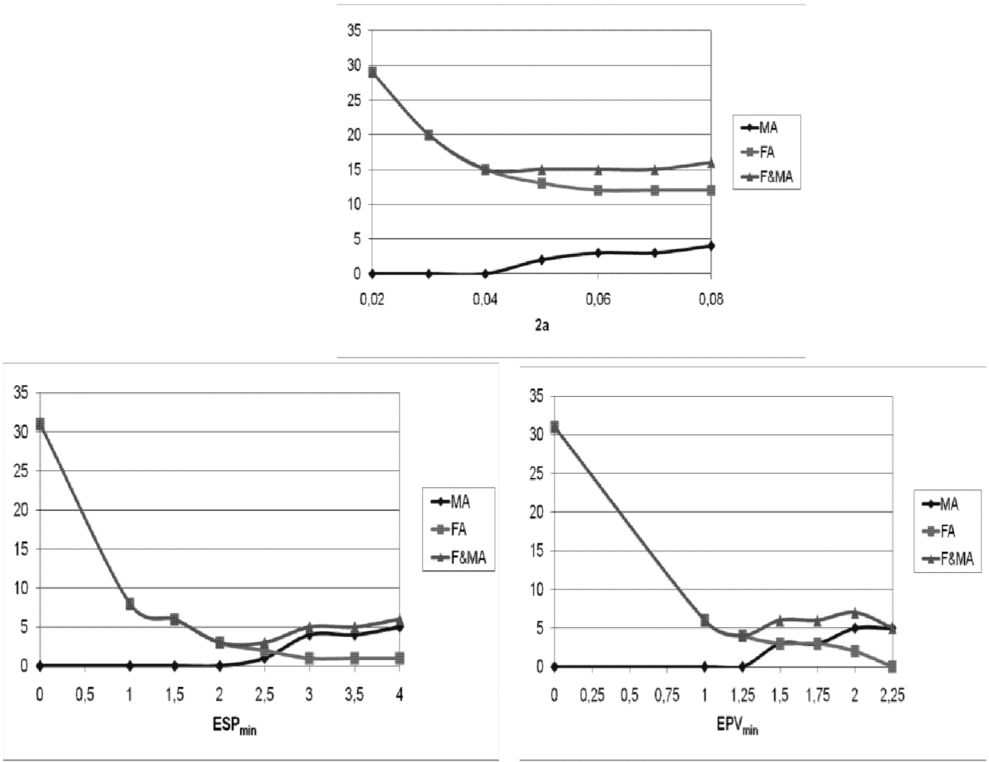

Fig.7: Errors trend for PC loops (FA, MA, total): IAE (top), E_{SP} (bottom, left), E_{PV} criterion (bottom, right)

<u>For Level Control loops (LC),</u> by increasing the threshold value, the number of errors (FA) reduces drastically and 3 errors (MA) appear only for very large values of threshold. This is a consequence of the fact that almost all loops were considered Good by operators (23/26), as performance of LC loops is considered low priority. The situation is reported in Figure 8 for E_{SP} and E_{PV} criteria.

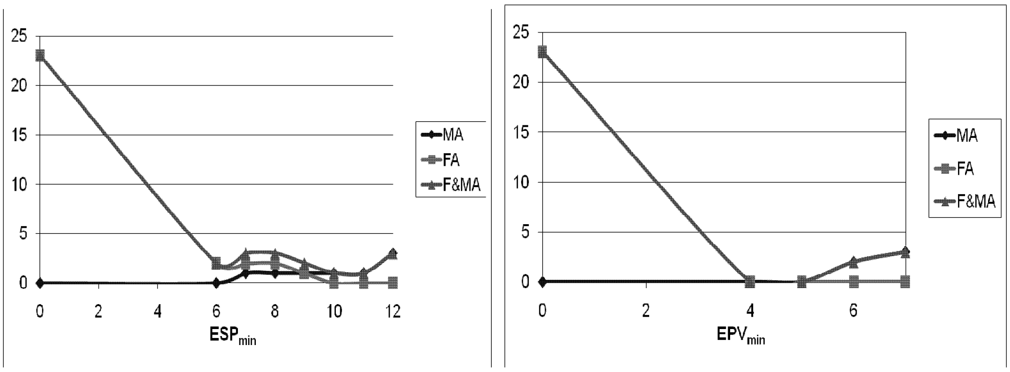

Fig.8: Errors trend for LC loops (FA, MA, total): E_{SP} (left), E_{PV} criterion (right)

On the contrary, the case of Temperature Control loops (TC) is very important. The same procedure of increasing threshold values, allows to reduce the number of total errors (initially 34 FA) to about 10, as illustrated in Figure 9, for the IAE and the EPV criteria. In this case the reduction of errors is less effective and not so beneficial as for FC and PC. Further investigation is required for Temperature Control loops to reach definitive conclusions; probably specific information about the single loop (for instance the associated flow rate and related thermal duty) should be used.

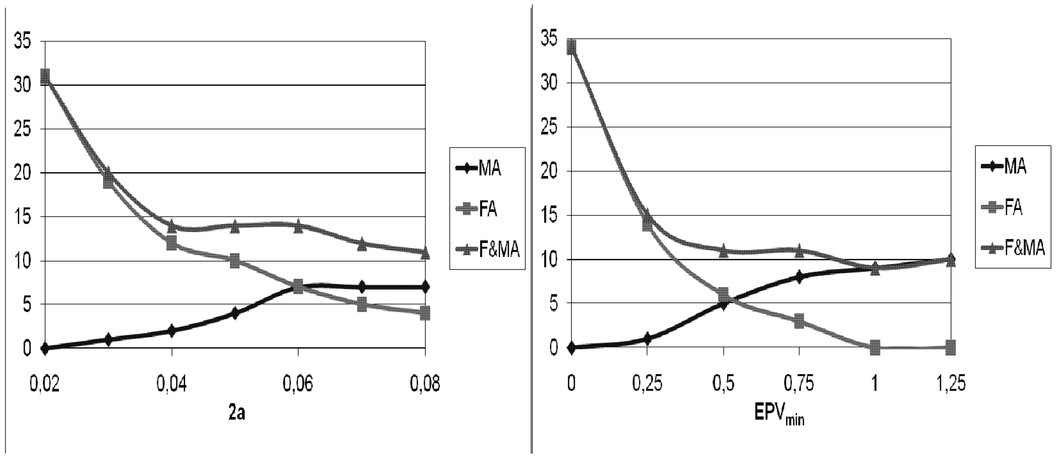

Fig.9: Errors trend for TC loops (FA, MA, total): IAE (left), E_{PV} criterion (right)

A deeper evaluation of results allows to make some remarks for FC and PC loops, for which a significant improvement in matching operators verdicts can be obtained by all the criteria for appropriate values of the threshold. The minimum number of total errors (False and Missed Alarms) can be obtained for threshold values: *0.06* (IAE), *1.75* and *2.5* (E_{SP}), *0.45* and *1.25* (E_{PV}). The value does not change with the type of loop for the IAE criterion, while it changes for E_{SP} and E_{PV}.

Best results (minimum numbers or errors) are given by the ESP criterion: 6 for FC and 3 for PC loops.
This criterion has 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 and 3 mismatches were found, thus confirming the validity of the new calibration. Similar improvements are obtained by the other criteria, with a slightly larger number of final errors. The IAE criterion, with higher threshold (0.06) has been adopted immediately in the closed loop performance system, while the new criterion will be included in the new release of the PCU module.

5. 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, of a performance monitoring system. Too many indications of bad performing loops, against operators' practice, are felt as False Alarms and then it is worth to dedicate efforts to improve matching between verdicts.
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. The case of Temperature Control, deserves further study and more information on each individual loop seems necessary to improve matching. Level Control does not seem relevant, owing to the low priority usually assigned.

For Flow and Pressure Control, the adoption of slightly different threshold values for the two type of loops, allows a significant improvement in matching, without the need of single loop customization.

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