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Experimental Characterization and Diagnosis of Different Problems in Control Valves

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Abstract: In the perspective of developing an integrated system able to include loop performance assessment and early diagnosis of anomalies, an experimental characterization of more common problems encountered in industrial valves has been carried out on a pilot scale plant. The primary scope was to investigate the possibility of detecting different types of valve anomalies from the analysis of routine data, by taking into account additional variables made available by intelligent instrumentation and field bus communication systems. Experimental results show that different problems (as: stiction, change in valve dynamics, air leakage and periodic disturbances), cannot be easily detected by referring to classical loop variables. On the contrary, their presence can be promptly identified by means of Travel Deviation and Drive Signal values, made available by the valve positioner. A key role is plaid by the availability of the valve stem position.

Keywords: Process Control Applications, Performance Monitoring, Valve Diagnostic, Stiction Detection

1. INTRODUCTION

The presence of problem in the control valve is widely recognised as one of major cause of scarce performance of base control loops in industrial plants. Recent surveys (Bialkowskii, 2003; Ender, 1993; Paulonis and Cox, 2003), indicate that up to 30% of total loops may show persistent oscillation, due to valve problems. Other causes of low performance can be found in the presence of external disturbances, incorrect controller tuning and interactions coming from other control loops.

Therefore the first objective is to be able to promptly diagnose the source of the observed undesired behaviour in the valve itself, thus separating it from other causes. The second one becomes to be able to distinguish among different valve problems.

Pneumatic valve are by far the most used in process industry. According to industrial experience, main problems can be seen in the presence of backslash, hysteresis, deadband, static and dynamic friction, variation in the elasticity of the spring, wear or rupture of the membrane, leakage in the air supply system. In the case that a valve positioner is present, other specific causes may appear.

In recent literature, a major interest has been devoted to the characterization of static friction (stiction) and its diagnosis from routinely acquired data, by means of automatic techniques. In the book edited by Jelali and Huang (2009), the state of the art and advanced methods for its diagnosis are reported, through illustration of eight different techniques (proposed in the last years) and their comparison on a benchmark of industrial data.

Also, the possibility of diagnosing the presence of stiction is included in some of the closed loop performance monitoring (CLPM) system, proposed by major software houses. The techniques for automatic recognition of stiction are usually based on the most widely acquired loop variables, that is: Set Point (SP), Controlled Variable (PV) and Controller Output (OP). Indeed these are the variables usually available in control loops acting on old design industrial plants. In many cases, valve problems indicated as stiction include also other causes.

The adoption of intelligent instrumentation, valve positioner and field bus communication systems in new design plants, opens new perspectives in the possibility of performing a more precise diagnosis of valve problems, as the number of variables which can be acquired and analyzed by the monitoring system increases. On the other hand, these devices allow the possibility of performing a distributed diagnosis on the valve itself, which can be faster and more efficient with respect to the performance assessment accomplished by a centralized monitoring system.

With the scope of developing an integrated system, able to include favourable characteristics of global performance assessment and early diagnosis of anomalies, ENEL (the largest Italian Electric company) started a project with the CPCLab of the University of Pisa, which developed and implemented in the last years the performance monitoring system denominated PCU (Plant Check Up, Scali et al. 2009, Scali and Farnesi, 2010). The first step of this project is devoted to an experimental characterization of anomalies and problems in the control valve and to a fine diagnosis on the basis of additional variables made available by intelligent instrumentation.

Preliminary results are reported in this paper, which has the following structure: section 2 illustrates the experimental plant (pilot scale) and its instrumentation; section 3 presents the logical and the realization of typical valve anomalies; section 4 illustrates and discuss experimental runs and comments; section 5 reports conclusions and indication of further work.

2. THE EXPERIMENTAL PLANT IDROLAB

A synthetic description of the experimental plant and its instrumentation follows.

The Idrolab plant is a pilot scale experimental facility having the scope of testing new technology to improve the efficiency and environmental compatibility of thermoelectric power plants. The specific project, including the activity reported in this paper, regards the development of innovative sensors, communication systems and advanced algorithms for improved performance monitoring and fault diagnosis.

The plant consists in two modules: the hydraulic one (water recirculation between two drums) and the thermal one (water evaporated in steam generator). The valve operates in the hydraulic module, as illustrated in Figure 1.

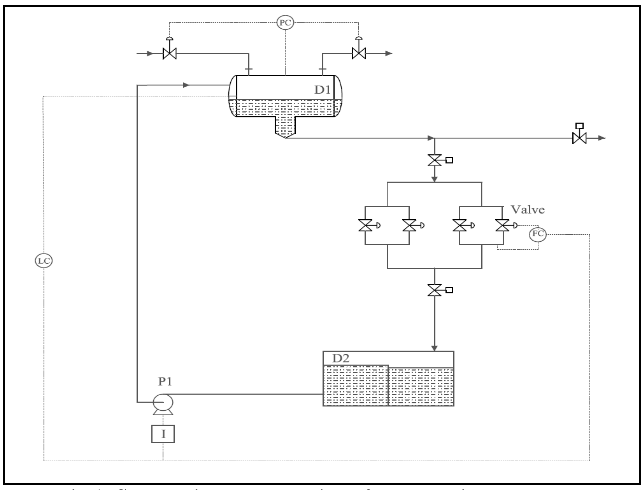

Fig.1: Schematic representation of the experimental plant.

The water circulates from the lower drum (D2) to the higher drum (D1) by means of a centrifugal pump. The pressure in drum D1 can be controlled (PC) by acting on inlet and outlet valves of compressed air. The flow rate is controlled (FC) by the valve object of the paper. The level control (LC) of the drum can act directly on the pump rotation rate by means of an inverter (I), or can operate in cascade on the flow control loop (FC).

The presence of bypass lines equipped with control valves and the possibility of acting on pressure and level of the higher drum, allows to carry out experiments in a wide range of operating conditions.

Automation of the hydraulic module and data acquisition can be performed by means of three different control systems: Siemens SIMATIC IT, ABB Industrial IT, Emerson Process DeltaV, according to the scheme reported in Figure 2.

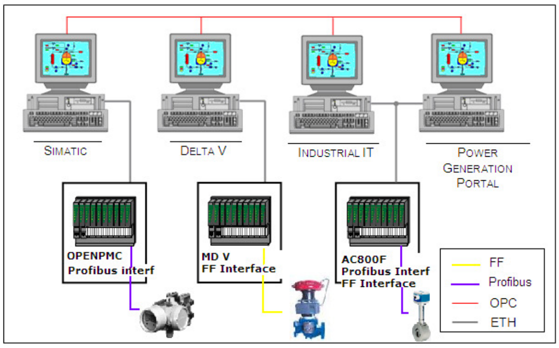

Fig 2: Scheme of the control and data acquisition system.

The experiments illustrated in the paper have been performed by means of the Delta V control system, consisting in: two controllers MD V in redundant configuration; two H1 cards for Fieldbus Foundation (FF) communication, in redundant configuration; traditional I/O cards in CPU rack; one Profibus Interface and the control and supervision system DeltaV integrated via OPC to the other control systems. Through the FF protocol, the control system can collect data from many "intelligent" instruments installed in the plant, among which the pneumatic actuator under test (Fisher Rosemount, DVC5020F type). The pneumatic actuator is coupled to a spherical valve which controls the water flow rate in one of the Idrolab recirculation line.

A picture of the pneumatic valve with the positioner is reported in Figure 3a.

Fig 3a: Picture of the pneumatic valve with positioner.

The positioner acts as an inner control loop on the valve position and allows to speed up the response of the valve. A schematic representation of an FC control loop with positioner, showing main variables, is reported in Figure 3b:

- SP, OP and PV represent the variables: Set Point, Controller Output and Controlled Variable (Flow rate) which are commonly available in an industrial Flow Control Loop (Ce).

- DS, P, MV represent the variable made available by the positioner. The Drive Signal (DS), is the electric signal generated by the inner controller (Ci) and, through the I/P converter, generates the pressure signal (P) acting on valve membrane and stem (Pi), thus determining the position of the valve stem (MV, also called Valve Travel); Pe indicate the "process" relating MV with PV.

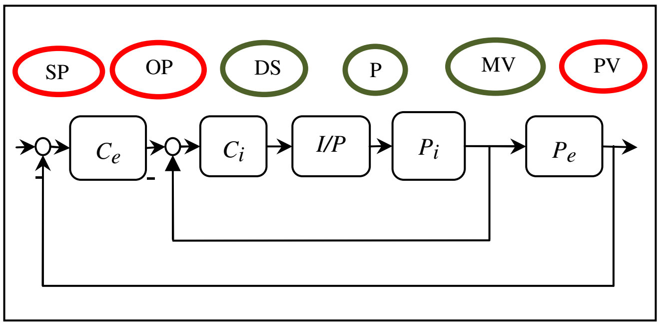

Fig.3b: Block diagram of an FC loop with positioner.

In addition to P, DS and MV, the positioner allows the acquisition of a large number of additional variables, most of them related to different levels of alarm, in increasing order of severity: Advisory, Maintenance and Failure. For most of them the user can specify a lower/upper threshold, a minimum duration and a deadband. These variables, very important to be included in the integrated diagnostic system, are not taken into account at this stage of the project.

3. PROBLEMS REPRODUCED IN THE VALVE

In this first stage of the project, attention was focused on three common causes of troubles encountered in industrial valves, recalled below (with the adopted identification label):

1) Static friction, also known as Stiction (Stick), is certainly the most common cause of scarce performance in valves. It can be concentrated in the seal packing which has the scope of avoiding the spill of the fluid flowing inside the valve. Degradation of the seal, lubricant consumption, inclusion of solid particles, and too tight packing (caused for instance by the need of complying with environmental restrictions about volatile emissions), can be causes of an excessive friction force acting on the valve stem. For this reason, a variation in the controller output signal OP (which becomes a proportional variation in the pressure signal P), does not produce an immediate change in the valve stem position and then in the flow rate. The valve remains blocked, requiring an increase in the control action up to larger value than required and then unblocks and moves bringing to limit cycle oscillations in the loop variables.

2) An other cause of valve performance deterioration can be seen in changes in the internal dynamics of the valve (Jam), due to variations of forces opposing the motion of valve plug and stem. These include for instance, changes of the fluid viscosity (related to variations of temperature or physical properties of the fluid), or of the spring elasticity (related to corrosion or fatigue stress).

3) Also the possibility of air leakage (Leak) from the supply system or from a rupture in the valve membrane contributes to a loss of efficiency of the valve action and can lead to a deterioration of performance of the control loop.

The three different problems have been reproduced in the experimental valve by means of a modular item mounted on top of the valve, as represented in Figure 4a and 4b.

Fig 4a: Picture of the modified control valve.

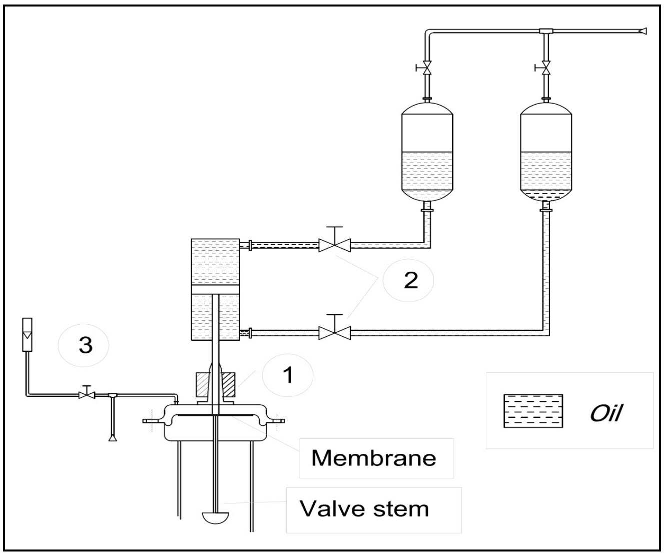

Fig. 4b: Details about the realization of anomalies in the control valve: (1) Stick, (2) Jam, (3) Leak.

1) Stiction is generated by acting on the metallic ring which operates on the valve stem as seal; by tightening the ring, the force on the stem and then the amount of stiction can be increased.

2) The second type of problem can be reproduced by varying the opening of two small control valves controlling the inlet and the exit of oil from a chamber, where a piston moves; the piston is welded to the head of the valve stem: therefore the force opposing the motion varies, correspondingly to changes in the valve position.

3) Finally an air leakage can be easily reproduced and its amount can be changed by acting on the valve placed on the discharge pipe from the valve hat.

In this last case the amount (loss of air) can be exactly quantified, by means of a rotameter; in the other two cases, the perturbation can be quantified in a semi-quantitative way.

It is evident that the three problems previously described require a different action by plant operators in order to counteract them and to restore the system efficiency. So it is important to know how they show up in the plant, in order to be able to give right indication about the cause.

4. EXPERIMENTAL RUNS

Experimental runs were carried out with the valve operating in Travel Mode and in Flow Control Mode.

Under Travel Control Mode, the position of the valve stem is controlled, by introducing different type of desired movements (step, ramp) having different amplitude, direction and velocity of actuation. This first operating mode allows a complete characterization of the valve intrinsic properties, as: dead band, open-close time, characteristic curve, hysteresis. These runs would allow an easy identification of valve problems by comparing the actual responses with the nominal case (brand new valve). Unfortunately, as general rule, this operating mode cannot be adopted when the valve works continuously on the plant, in order to not interrupt the operations. In the perspective of the final integrated performance monitoring and diagnosis system (which is the ultimate scope of this project), runs in Travel Mode might be included in the complete procedure, for instance to confirm on line analysis, then reserving them to off-line tests (on demand check). At this stage of the project, the focus is on the possibility of detecting different type of valve problems referring to on line analysis of available routine data.

The second operating mode, Flow Control Mode (FC), is one of the routine ways of operation of the valve in the plant, the other being the level control loop (LC) acting as primary loop on FC (Figure 1).

Runs in FC mode were carried out by introducing valve anomalies (Stick, Jam and Leak at different extent) in the system operating at steady state (no Set Point changes). With the same anomalies active, runs were repeated applying step SP changes of the flow rate.

A large number of experiments were performed in the allowed operating range of the valve and of perturbations. For brevity sake, only few illustrative examples are given below: they can be considered representative of general behavior of the system, thus allowing to draw some general conclusions.

As first, a typical response in terms of the loop variables OP and PV to SP step change in the flow rate is reported in Figure 5, for the nominal case and for the three problems introduced in the valve. As immediate remark, it can be seen that the presence of stiction shows up as oscillations in PV and OP. In the other two cases, time responses become only slightly slower with respect to the nominal case and it would be hard to distinguish between them, without any further information.

Figure 6 illustrates the response to a sudden air leakage: the flow rate PV decreases below the (constant) SP value, the Drive Signal in the positioner and the inlet Pressure to the valve increase to compensate for the air leakage, so that the flow rate is restored to the initial value. By observing only PV and OP it would not be possible to realize the presence of an air leakage: PV and OP trends can be seen as an usual response to a disturbance (load change) affecting the plant. The presence of this anomaly is evident from the onset of a persistent difference (Travel Deviation) between OP (desired

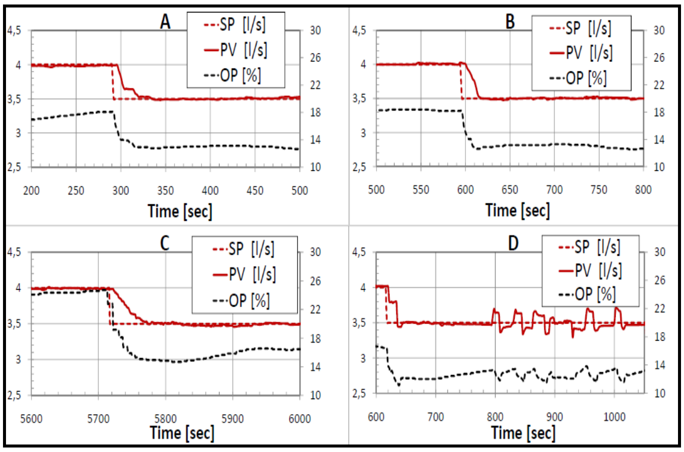

Fig. 5: Trends of PV, OP vs. time for SP changes: A) Nominal case, B) Jam, C) Leak, D) Stick.

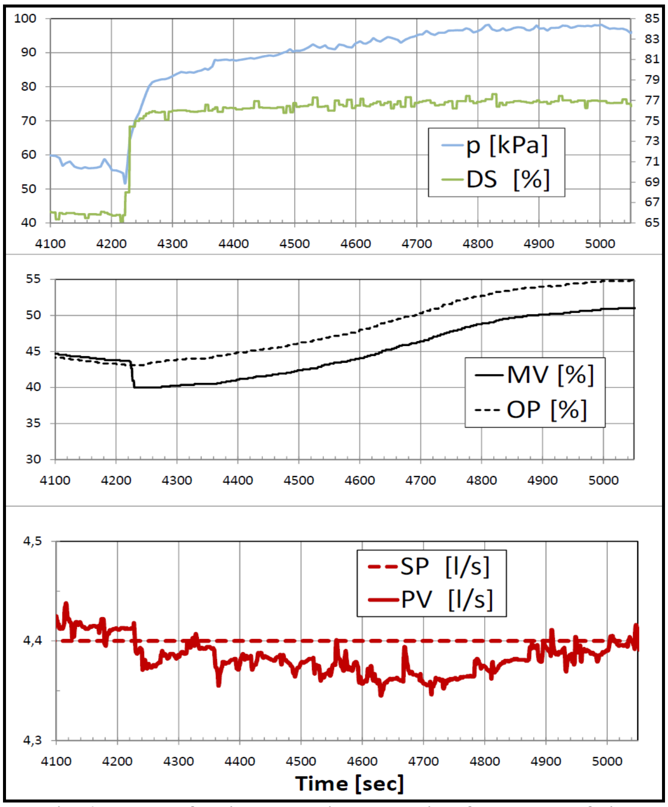

Fig. 6: Trends of main loop variables vs. time for the case of air leakage; top: P and DS; middle: OP and MV; bottom: SP and PV.

valve position) and MV (actual valve position): TD=OP-MV. Also, the Drive Signal increases from the initial value to a higher value at the new steady state, to compensate for the air leakage.

Fig. 7 illustrates the response of the system in the presence of stiction: the typical oscillation of the controlled flow rate PV around the constant SP is observed. Stiction causes a block in the valve motion and, once an (even very small) error (e=PV-SP) appears, the integral component of the controller increases the control action and the pressure in the valve in order to overcome the friction force; the valve moves but once the error changes sign it stops again and the same situation happens: as a consequence, all recorded variables show oscillating trends.

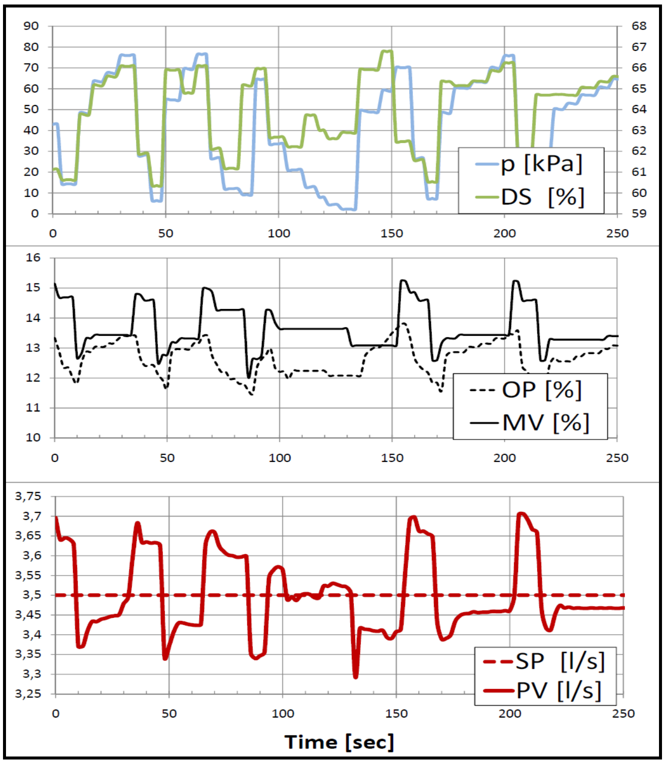

Fig. 7: Trends of main loop variables vs. time for the case of Stiction; top: P and DS; middle: OP and MV; bottom: SP and PV.

Figure 8 shows the behavior in the presence of changes in the internal valve dynamics. By comparing the response to a step SP change in the flow rate with the nominal case (no anomalies present), it can be seen that the problem cannot be diagnosed by analyzing PV and OP responses, which become slightly slower. In this case, also the Travel Deviation (TD=OP-MV) goes to zero in the new steady state conditions, because the effect of this anomaly disappears once the valve reaches the new position. On the contrary, during the transient there is a time interval where the desired valve position OP deviated from the actual one (MV). A similar behavior is showed by the Drive Signal which increases during the transient and return to initial value at new steady state. These two facts can be seen as peculiar behaviors associated to this problem.

A cross-comparison of previous figures, which represent reproducible trends observed during the experimental runs in different operating conditions, allows to draw more general considerations about the possibility of distinguishing different phenomena affecting the valve and to put into evidence the role of information associated with different loop variables.

An analysis based only on SP, PV and OP (which are the loop variables commonly available in industrial loops) does not allow to separate changes in the valve dynamics from air leakage, because the overall time responses become slower with respect to nominal conditions (no anomalies present), but the actual dynamics (delay and time constants) of the global process is not known in the real environment. In fact, process dynamics changes with operating conditions (for instance with changes in the flow rate) and is not known, as system identification is not performed.

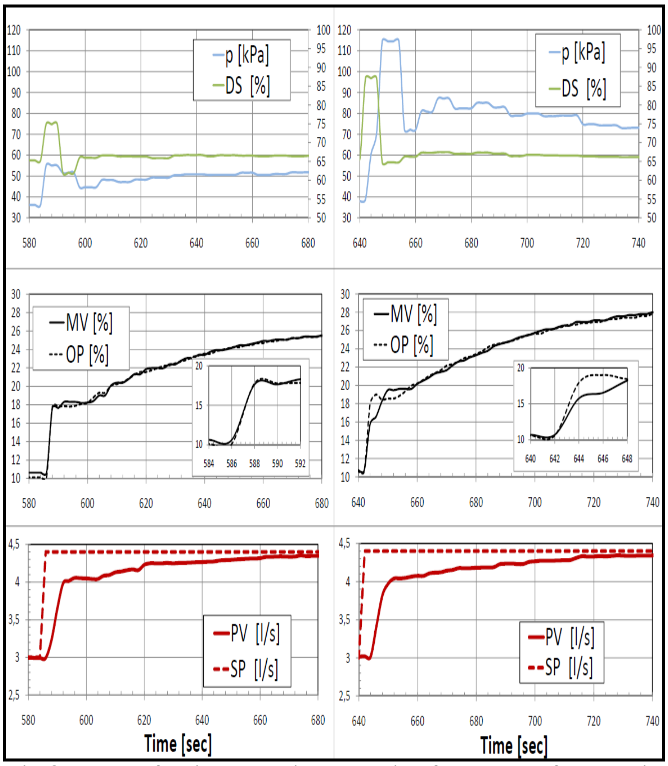

Fig. 8: Trends of main loop variables vs. time for the case of changes in the valve dynamics (right column), compared with nominal (left column); top: P and DS; middle: OP and MV; bottom: SP and PV.

The availability of the actual stem position (MV) or, equivalently, of the Travel Deviation (TD=MV-OP), would seem to permit to diagnose an air leakage, because a persistent offset appears. The same indication can be drawn by the analysis of the Drive Signal, which increases from the initial to the final value to compensate.

Troubles associated with valve dynamics can be diagnosed only during a change of operating conditions and by analyzing the trend of TD=MV-OP and of DS during the transient: deviations between MV and OP appear and also DS deviates from the initial value (during the transient), while initial and final values are coincident.

The presence of stiction always brings persistent oscillations in the loop variables; oscillations may be also caused by the presence of periodic disturbances or aggressive tuning of controllers. The availability of MV allows a clear distinction between the two phenomena: plots MV(OP) present a typical parallelogram shape in the case of stiction, while they have a linear shape in the case of disturbance. This is illustrated in Figures 9 and 10, respectively: the signature of stiction appears in MV(OP) plots, as can be predicted by stiction models (Choudhury et al., 2005; Yamashita, 2006; Scali and Ghelardoni, 2008) and observed in industrial data (Scali et al., 2009).

On the contrary, PV(OP) may have different shape in the more general case of not negligible dynamic elements between MV and PV; for both type of oscillations, the shape becomes similar to an ellipse, thus making very difficult the possibility of distinguishing between the two phenomena. In these cases, a simple analysis based only on SP, PV and OP

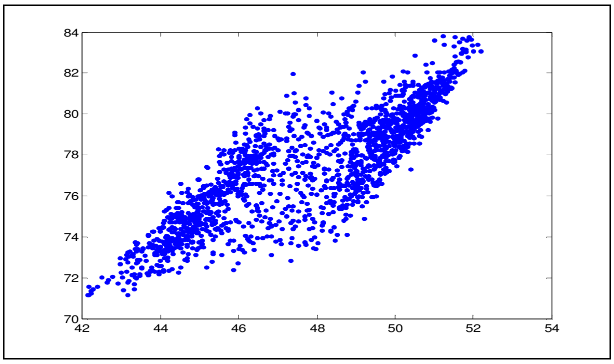

Fig. 9: MV(OP) plot in the presence of Stiction.

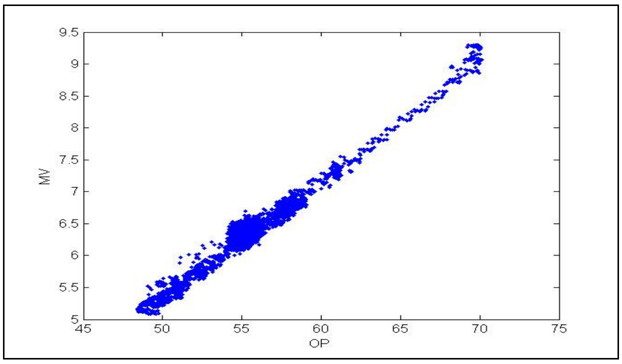

Figure 10: Trends of MV(OP) in the presence of periodic disturbance.

would not be sufficient to diagnose stiction. As mentioned in the introduction, more accurate and complex techniques are required to indicate the cause of oscillations: the reliability of their verdicts under different industrial conditions, are still object of improvement (Jelali and Huang, 2009). Therefore the availability of MV plays an even more crucial role for loop diagnosis.

Previously illustrated trends have been analyzed with the scope of performing a complete automatic analysis of data based on the Travel Deviation (and in some case on DS) as Key Performance Indexes. By adopting simple metrics (as mean values, integral of errors, number of times an acceptability range is exceeded), it is possible to define threshold values which give very promising results in distinguishing different anomalies and then to be included in a performance monitoring system.

6. CONCLUSIONS

The first series of experiments carried out for the characterization of valve problems in control valves (even though not exhaustive), allows to draw some general conclusions about the possibility of detecting different types of anomalies and about the role played by additional variables made available by intelligent instrumentation.

The presence of an air leakage cannot be detected by inspection of SP, OP and PV (loops variables usually acquired in industrial loops with classical instrumentation), because their trends can be confused with the presence of external perturbations. The onset of this anomaly can be promptly detected by analyzing the Travel Deviation and the Drive Signal in the positioner. The same happens for anomalies which reproduce changes in the internal dynamics of the valve: the speed of response changes, but also in this case, without information about the actual dynamic of the process, the anomaly cannot be detected by SP, OP and PV. An analysis of TD and DS allows to identify the problem.

The presence of stiction seems to be the easiest valve problem to detect, owing to the oscillating trend caused in all the loop variables and then also in OP and PV. As in the more general situation of an industrial plant, periodic perturbations of different origin are always present, the more effective and reliable way of identifying stiction is the analysis of MV, the actual valve position. Therefore MV, (necessary also to evaluate the Travel Deviation), appears to be the most important variable which can be made available by intelligent instrumentation.

To conclude, in the light of an automatic analysis of data, these results seem very promising; as these data come from a pilot scale plant, results must be validated on industrial scale data. In addition, it must be recalled that a choice have been made of focusing on process variables which can be available from on line acquisition of routine data, without referring to any off-line test. These tests, together with a management of alarm variables, will be included in the final integrated system having the scope of accomplishing global loop performance assessment and early diagnosis of anomalies.

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