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Comparative performance analysis of an electric actuator for control valves

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Abstract

This article deals with the analysis of performances of electric actuators for control valves in industrial control loops. The objective of the recent collaboration between University of Pisa and CLUI AS is to assess potentials and benefits of control valve electric actuators, by testing and comparing devices of different typologies and manufacturers.

As a premise, it should be noted that pneumatic actuators still represent the most commonly used actuation devices in the process industry, mainly because of high performance and fast response. In recent years, electric actuators, as a result of their enhanced features, are finding increasing applications in the area of process control.

Anyway, some practical aspects, such as the degradation of the valve seat, an excessive tightening of the seal, and an expansion of metallic components due to high temperature operation, can cause malfunctions, and in particular, phenomena of wear and friction within a control valve regardless of the type of actuator. In fact, pneumatic and electric valves differ only in the actuation system; while the valve body, subject to most of the friction forces, is absolutely the same.

In detail, the present work has been focused on the analysis of a recent electric actuator installed on an rotary control valve, and tested in the last biennium in an pilot plant, owned by ENEL in Livorno (Italy). Specific experimental tests were carried out, by collecting operating data in open-loop and closed-loop mode. The validity and effectiveness of the performance was verified in nominal and faulty conditions, in particular, by introducing a dead-band. Furthermore, performances of this electric actuator was compared with that of a conventional pneumatic actuator with positioner, coupled to the same valve, installed on the same plant line, and tested in equivalent experimental conditions.

In general terms, it has been confirmed that the electric actuator for control valve is a promising technology, and its performance are fully comparable - if not superior - to those of the pneumatic actuator. In particular, some simple performance indices assume similar numerical values, and also the time trends of the positional error and the limit cycles registered on polar diagram between valve input and output signals are similar.

1 Introduction

Generally speaking, monitoring and assessment of performance of control systems of industrial plants are important topics in process control. The deterioration in performance is, in fact, a fairly common phenomenon and manifests with sluggish or oscillating trends of control variables. Oscillations in control loops can cause many problems which affect normal operation of process plants. Typically, fluctuations increase variability of product quality, accelerate wear of equipment, move operating conditions away from optimality, and, in general, cause excessive or unnecessary consumption of energy and raw materials [1, 2].

Control valves are the most commonly used actuators in process industries. Unfortunately, in many cases valves not only contain static nonlinearity (e.g. saturation), but also dynamic nonlinearity including backlash, friction, and hysteresis. Dead-band due to backlash and mostly static friction (*stiction*) is a root source of the valve problems. A control valve with excessive dead-band may not even respond to small changes in control action.

As a result, these malfunctions would produce a sustained oscillation in the process variables, decrease the life of control valves, and generally, lead to inferior quality end products causing reduced profitability [3]. Oscillations in process variables induced by stiction, can be confused with other causes of malfunction, as incorrect controller tuning, presence of external disturbances, multi loop interaction and other valve internal problems. In addition, such type of nonlinear oscillations cannot be completely eliminated by controller detuning or by the action of digital positioners [4].

One of the main objectives of the collaboration between University of Pisa and CLUI AS, formerly CLUI EXERA, has been the development of a system for control loop performance monitoring. In the last years, different versions of this program, called *Plant Check-Up* (*PCU*) [5, 6], has allowed one to evaluate performances of basic control loops. In particular, tuning of controllers and the presence of friction in control valves have been evaluated. Recently, also transient operating conditions have been assessed, i.e., the cases of frequent changes of reference, as it happens in plants operating under real-time optimization [7].

Among other capabilities, the last version of the system allows the performance analysis of basic control loops equipped with control valve and electric actuator. In practice, the validity of the software has been recently verified in the analysis of performance of electrically actuated valves, which has laid the basis for the development of a new dedicated version of the program, containing logics of recognition of the specific causes of malfunction of electric actuators.
It has to be highlighted that:

I. the system *PCU* has been initially developed for control loops equipped with pneumatic valves and actuators, and traditional devices, that is, electro-pneumatic converter and communication 4-20 mA [5].

II. Subsequently, the system has been dedicated to smart pneumatic valves, equipped with positioner and Fieldbus communication, through the advanced version of the software, also known as PCU^{+} [4].

III. In a third step, a specific diagnosis for the transient phases and for loops with electric actuators has been developed, as the starting point for a version called PCU^{++}.

This paper describes some results of the comparative analysis of performance between pneumatic actuators and electric actuators, on the basis of extensive experimental activity on a pilot plant.

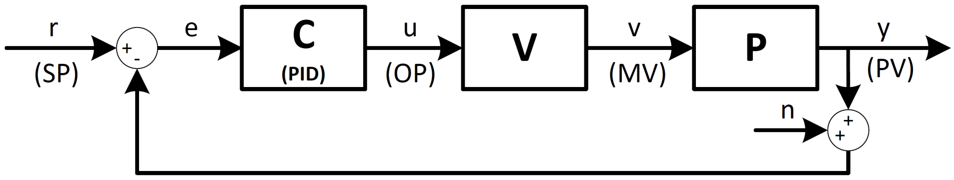


Figure 1: Feedback control loop (SISO type).

2 Background

2.1 Modeling a Control Loop

In a feedback control loop of SISO type (see Figure 1), $P(s)$ and $C(s)$ represent the transfer function of the process and of the PI(D) controller, respectively. Signals $r(t)$, $u(t)$ and $y(t)$ are the reference (set-point, *SP*), the control action (*OP*), and the process variable (*PV*), respectively. These three variables are typically measured for any control loop installed in a traditional industrial plant. On the contrary, the internal variable $v(t)$, corresponding to the position (*MV*) of the control valve $V(s)$, is available only in new generation plants.

A control loop characterized by a nonlinear phenomenon of friction in the valve can be described by a dynamic system of Hammerstein type, formed by a nonlinear block (V) followed by a linear element (P), as shown in Figure 2 [3]. The friction nonlinearity can be managed with good precision with some established models of the literature: for example, the data-driven models of Kano [8] and He [9].

The linear part of the system can be described in discrete time domain by means of a ARX model: $A(q)y_k = B(q)v_{k-t_d} + e_k$ where v_k and y_k are the process input and output, that is, MV and PV, respectively. $A(q)$ and $B(q)$ are polynomial in the "time shift" operator q (such that, $qv_k = v_{k+1}$), expressed by: $A(q) = 1 + a_1q^{-1} + a_2q^{-2} + ... + a_nq^{-n}$ and $B(q) = b_1q^{-1} + b_2q^{-2} + ... + b_mq^{-m}$, where (n,m) are the orders of the auto-regressive and exogenous term of the model, respectively. Furthermore, the signal e is assumed as white Gaussian noise and t_d is the time-delay of the process, and finally η (see Figure 2) is a bias variable representing an external disturbance, also nonstationary, which affects possibly the output of the process and can be estimated only through linear models of extended type.

In this paper, for the sake of simplicity, the linear dynamics is approximated by a continuous-time model of FOPTD type (first order plus time-delay), comprised by a static gain K, a time constant τ, and a time-delay θ. FOPTD model corresponds to a model ARX $(1,1)$ in discrete time. More details on possible Hammerstein systems, that is, combinations of linear and non-linear blocks, which describe a loop with control valve affected by friction can be found in [10, 11, 12].

In Kano friction model [8], the relationship between the output of the controller, i.e., the desired (*OP*), and the actual valve position (*MV*), is represented by a limit cycle of characteristic shape, and employs two simple data-driven parameters (S,J), as shown in Figure 3.

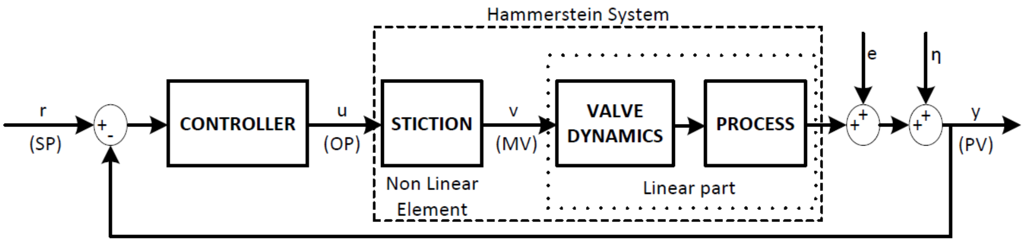


Figure 2: Hammerstein system: control valve (in friction) followed by the linear process within the control loop.

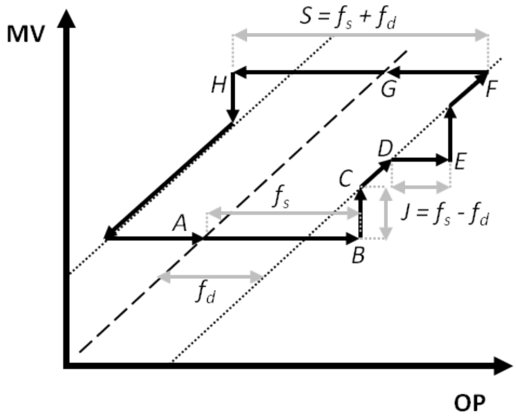


Figure 3: Modeling valve static friction (stiction). Limit cycle on MV(OP) diagram.

2.2 Electric Actuators

Within the collaboration between University of Pisa and CLUI AS, along with the development of the last version of the software *PCU*, a specific analysis of the performance of electric actuators for control valves in industrial feedback control loops has been carried out. In particular, this study has concerned the new electric quarter-turn actuator of *Rotork® CVA*, which has been installed in IdroLab, a pilot plant owned by ENEL and located at Livorno until the end of 2016.

As a premise, it should be noted that pneumatic actuators still represent the most commonly used actuation devices in the process industry, mainly because of the simple technology, good performance, and fast response. Nevertheless, in recent years, electric actuators, as a result of their enhanced features, are finding increasing applications in the area of process control. For example, the total order of industrial actuators from Italian customers is estimated around 235 million of Euro. The pneumatic actuators account for 60% of the total market, and the remaining 40% is divided between electric and hydraulic actuators [13].

Therefore, the electric actuators have become a popular way to automate all types of industrial valves, and recently also control valves. One of their primary advantages is the inherent flexibility of their embedded control systems both because of where such systems can be placed and because of the wide range of control system interfaces available [14]. Despite the new generation of electric control-valve actuators may not yet be suitable for all process applications, it can eliminate many problems of compressed air as a power medium. For example, electric actuators are ideal for many situations, in particular where users have experienced problems with air hoses (freezing, humidity and dust), frequent maintenance, lack of control precision, stick-slip behavior, and so on [15].

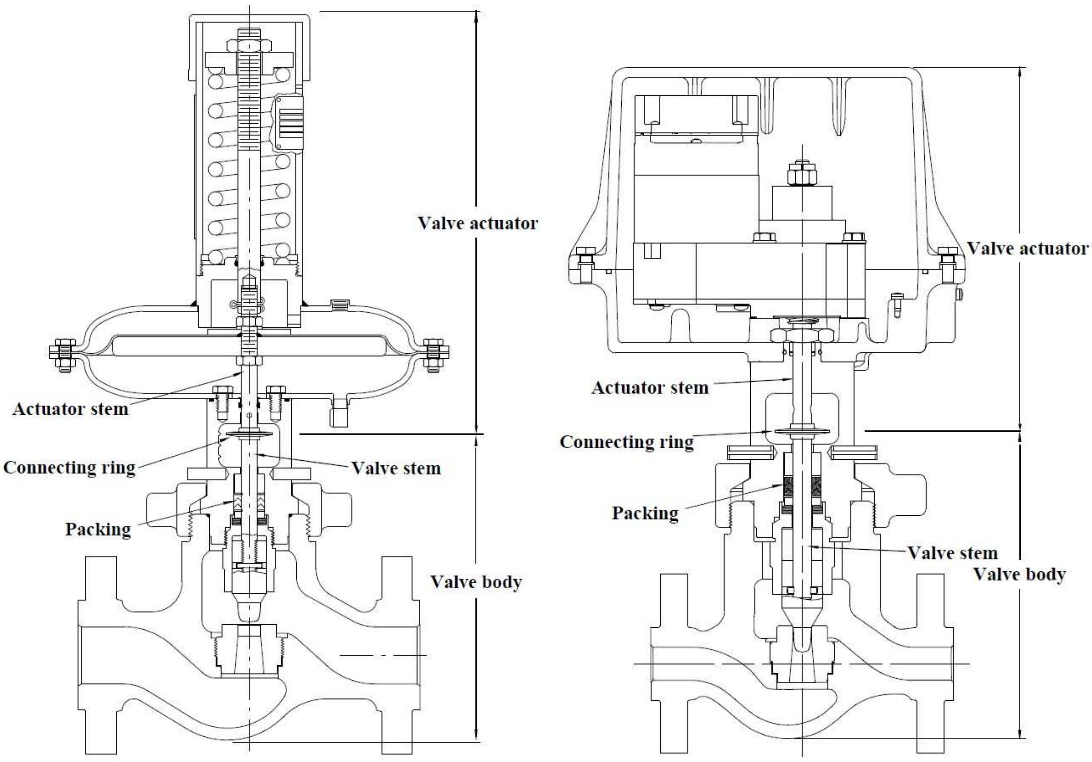
Anyway, some practical aspects, such as the degradation of the valve seat, an excessive tightening of the seal, and an expansion of metallic components due to high temperature operation, can cause malfunctions, and in particular, phenomena of wear and friction within a control valve regardless of the type of actuator [3]. In fact, pneumatic and electric valves differ only in the actuation system; while the valve body, subject to most of the friction forces, is absolutely the same, as shown in Figure 4.

Nevertheless, electric actuators are intrinsically less subject to friction phenomena with respect to pneumatic actuators. For example, since the compressed air acts like a spring, pneumatic control valve actuators do not often have the stiffness required for a precise process control. For example, consider a globe valve with a high degree of friction in its stem packing or a ball valve with a high degree of friction on its seat. In either case, this high static friction requires an excessive amount of air pressure in order to initiate movement in the valve. Once the valve moves, static friction is replaced by dynamic friction, which is invariably lower. This causes the resistance to the excessive air pressure to drop abruptly. The result is the valve runs away with itself and often overpasses the desired set-point, by causing a correction to be made which results in oscillation around the set-point, and then a limit cycle as the one shown in Figure 3. This problem can be eliminated with an electric actuator due to the higher stiffness and controllability of today's electric drive trains and the advent of sophisticated dual sensor technology [15].

2.3 Experimentation on a Pilot Plant

In the last two years, 12 different sets of data from the experimental plant of IdroLab were collected. This study has served to verify the validity of the logics of the current version of the system *PCU* for monitoring and assessing control loops, and to lay the basis for the development of a last version dedicated to electric actuators (*PCU* $^{++}$).
The control valve tested is V2 of the scheme of Figure 5a, a rotary valve with butterfly shutter. The actuator is of electric type of *Rotork*® class *CVA*, quarter-turn *CVQ-90°*, 1200 model (see Figures 5b and 5c) [16]. This electric actuator is equipped with several advanced features which help achieve a highly reliable performance. For example:

- Dual Sensor™ system, by utilizing two independent position sensors, can minimize backlash and positional errors;
- Brushless DC motor – a highly reliable brushless motor, which allows full continuous unrestricted modulation duty - S9;
- Simple, efficient geartrain – this simple yet durable high efficiency system, which is lubricated for life, is designed for arduous control valve duties.



(a) Pneumatic valve (b) Electric valve

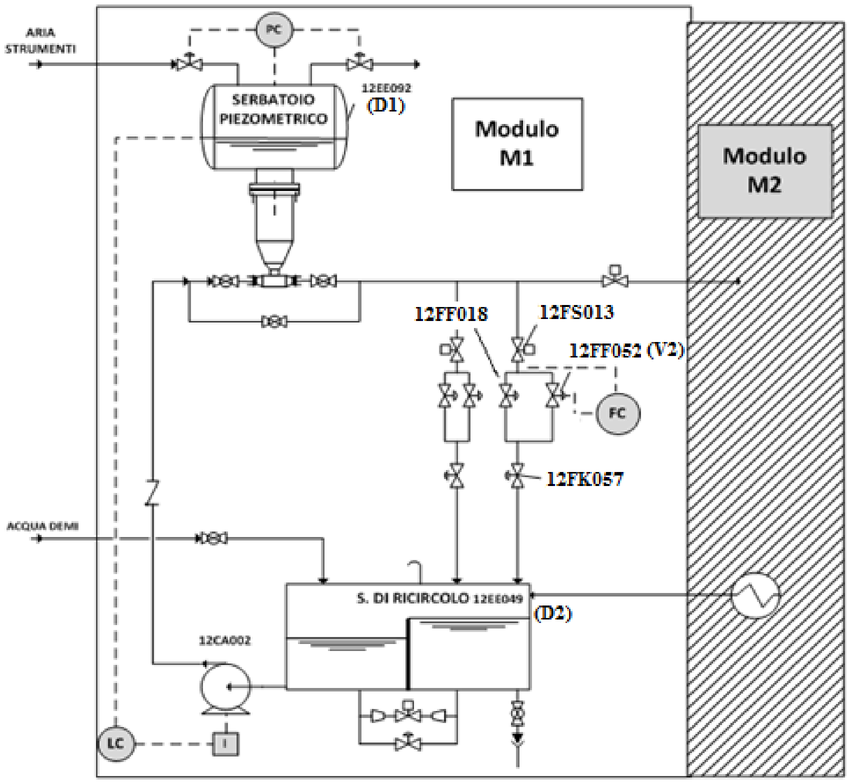
Figure 4: Example of configuration of the two different types of actuators installed on the same linear control valve.

- Double-sealing – *Rotork*'s Double-Sealing to IP68, provides protection in the most demanding environments.

The controlled variable (PV) is the water flow rate (expressed in l/s) that flows through the valve; the control action (OP) is the output signal ($0 - 100\%$) from the controller with PI algorithm; the sampling period is equal to 1 second. The actual position of the actuator (MV) is measured and controlled within the "smart" electric actuator (A in Figure 6) with a resolution of 0.1%. Note that Dual Sensor™ system of *Rotork*® employs two independent position sensors which help eliminate backlash and inertia effects in the gearing. These sensors are 12-bit rotary magnetic encoders, one on the motor output and the other near the output shaft of the actuator [16]. Therefore, the electric system is able to measure and control indirectly the position of the valve stem. On the contrary, the position of valve shutter V - that is, the actual opening of the valve (MV') - remains an internal variable which is not measurable.

It is finally noted that, being a flow control loop, the process dynamics to be controlled (P) coincides substantially with the dynamics of the control valve, which relates the valve opening with the flow rate.

Preliminarily to numerous tests in closed-loop mode, some tests were carried out with the external PI controller set in manual. The actuator position (OP) is imposed manually and its actual position (MV) is registered. These tests were carried out both in *nominal* conditions, i.e.,



(a) Simplified plant scheme.

(b) Label of the electric actuator. (c) Valve mounted in line.

Figure 5: IdroLab plant.

in the absence of any type of malfunction, either in the presence of a *dead-band* in the actuator.

Nominal conditions Figure 7a shows the ramps imposed to OP signal, oscillating from 0 to 100% of the operating range, the actual position of the actuator MV, and the corresponding flow rate PV, all obtained in *nominal* conditions. Figure 7b shows the limit cycles on diagram PV(MV), which basically represents the installed characteristic curve of the valve. In addition, Figure 7c shows - on the left - the limit cycles on PV(OP) diagram, and - on the right - the cycles on MV(OP) plot. It is observed the presence of a perfectly linear relationship between the required position and the actual position, throughout the operating range, which confirms the absence of malfunctions (i.e., nonlinearity) in the actuator.

Note also how the input (OP) and output (MV) signals do not coincide perfectly in every instant of time, but the actuator shows a small dynamics. On the basis of these two signals,

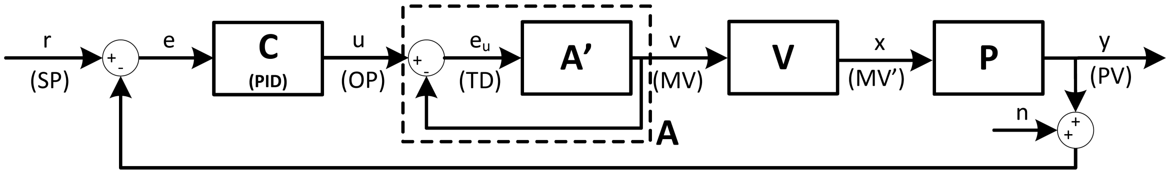
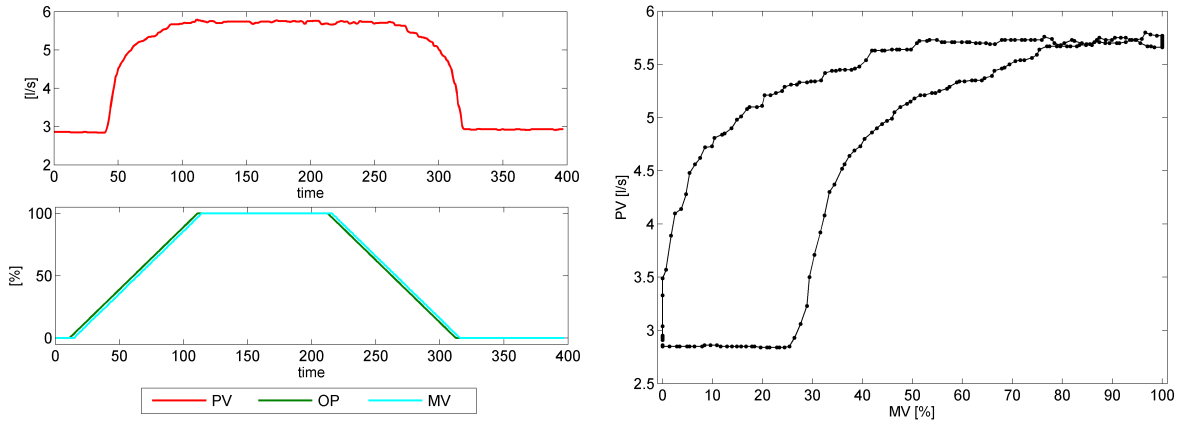
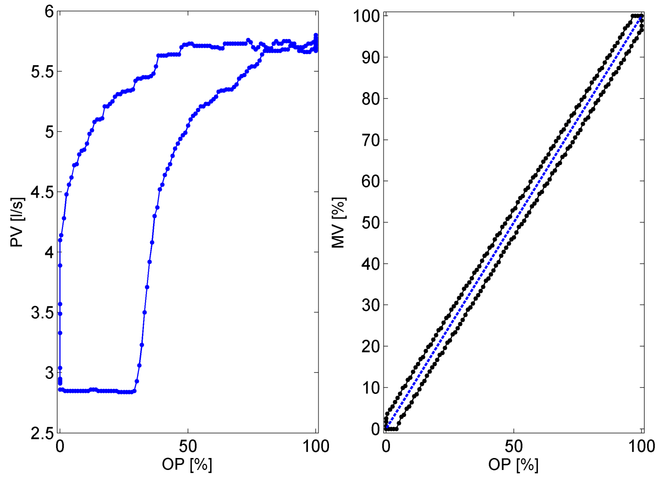


Figure 6: Control loop with “smart” electric actuator.



(a) Time trends in manual.

(b) Limit cycles on PV(MV) diagram.



(c) Limit cycles: left) PV(OP) diagram; right) MV(OP) diagram.

Figure 7: Example of test in open-loop operation; *nominal* case.

this dynamics is identified by means of a simple model of the FOPTD-type: $\hat{A}(s) = \frac{A'(s)}{1+A'(s)} = \frac{K}{\tau s+1}e^{-\theta s}$, where K is the gain, τ is the time constant, and θ is the time delay. Table 1 shows the parameters identified for two tests obtained in open-loop operation in *nominal* conditions.

The validity of identification results is quantified by a fitting index on MV signal (F_{MV}), with 100% as the maximum value. Note that it is possible to identify - rightly - congruent models for the two tests, which were carried out during two different weeks under the same conditions.

Presence of dead-band Subsequently, similar data are collected in the presence of a *dead-band* in the actuator. This phenomenon is introduced on purpose, by changing the corresponding parameter in the configuration software of the actuator of *Rotork*®. A dead-band $d = 5\%$ is

Table 1: Tests in open-loop mode in *nominal* conditions. Identified FOPTD models.

Test	$\hat{A}$	$F_{MV}\,[\%]$
1	$\dfrac{1.0002}{0.570\,s+1}e^{-1s}$	98.02
2	$\dfrac{0.9983}{0.698\,s+1}e^{-1s}$	97.63

set.

Figure 8a shows the limit cycles obtained on the MV(OP) plot by imposing triangular waves on the OP signal, oscillating from 0 to 100% of the operating range. In addition, Figure 8b shows the limit cycles obtained by imposing triangular waves oscillating between 20 and 80%, in the presence of the same nonlinearity. Figure 8c, shows the limit cycle on PV(MV) diagram by imposing triangular waves on the OP for the entire operating range ($0-100\%$); Finally, Figure 8d shows the same plot obtained by imposing triangular waves between 20 and 80%.

Altogether, by analyzing the limit cycles on the MV(OP) plot in the case of *dead-band*, it can be observed that the actuator shows a nonlinear behavior, which is particularly symmetrical, and which generates a *staircase* profile due to the series of movements of blocking and unblocking.

This phenomenon of *dead-band* in the actuator can be described in two different ways:

I : by a single nonlinear dynamic model (D);

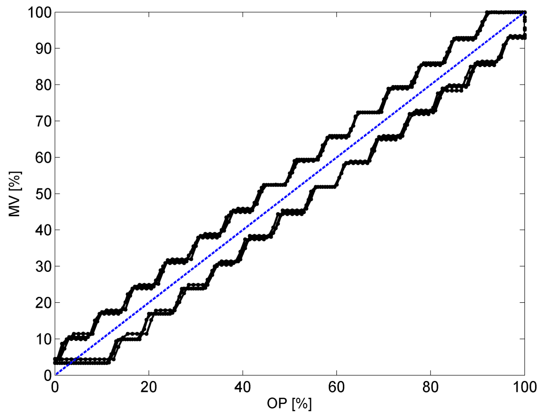
II : by a dynamic system of Hammerstein type, constituted by a nonlinear block (D') followed by a linear element (A'), as shown in Figure 9.

In both cases, the nonlinearity can be managed with reasonable accuracy by using empirical friction models of the literature (as Kano [8], and He [9] model), by noting that the dead-band can be assumed as a special case of friction. The linear dynamics A' can be approximated, as seen for the *nominal* case, by a model of FOPTD type.

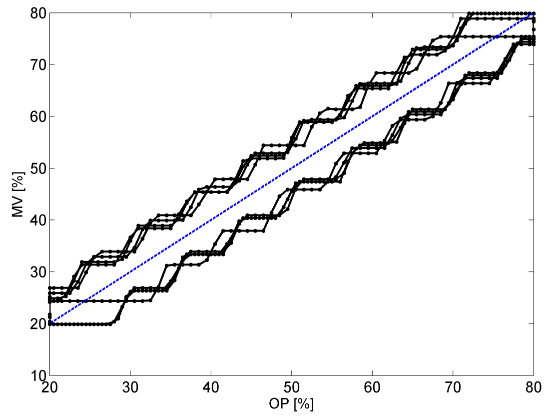
Details about the identification of tests in the presence of *dead-band*, and the results of tests in closed-loop mode are omitted for the sake of brevity.

3 Comparison between Pneumatic and Electric Actuator

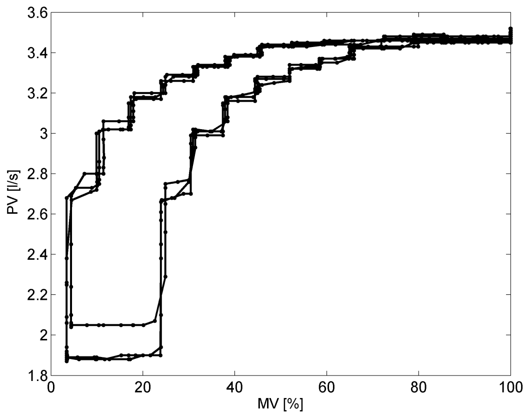
As said before, a major part of the activity of collaboration has concerned the comparison between the performance of a pneumatic actuator and those of an electric actuator applied to the same control valve. The valve under tests in IdroLab - V2 of the diagram of Figure 5a - is of rotary type with a butterfly shutter, installed on the recirculation line of diameter of 2”, which connects the piezometric tank (D1) to the atmospheric pressure tank (D2). The pneumatic actuator had a positioner of *Fisher Rosemount*® DVC5020f model (Figure 10a); the actuator of electric type is the *Rotork*® class *CVA*, type *CVQ-90°*, model 1200 (Figure 10b). In the sequel, results for tests carried out in open-loop and closed-loop mode are presented.



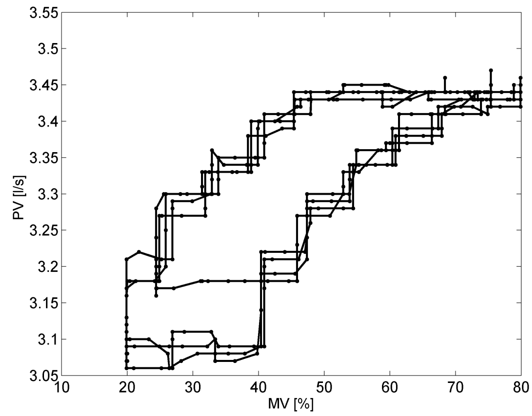
(a) MV(OP) diagram, range $0 - 100\%$



(b) MV(OP) diagram, range $20 - 80\%$



(c) PV(MV) diagram, range 0-100%



(d) PV(MV) diagram, range 20-80%

Figure 8: Example of test in open-loop operation; in the presence of *dead-band*.

3.1 Tests in Open-loop Mode

First, the performance of two different types of actuator are compared relatively to the open-loop operation, that is, in manual control, once they are installed on the same control valve. Recent data for the electric actuator were compared with some archive data for the pneumatic actuator. Table 2 summarizes the main features of the operating conditions under which the two tests were conducted. It can be noted that the two tests are characterized by rather similar conditions; therefore, they represent a set of comparable data.

The time trends of control action (OP), that is, the input signal imposed to the actuator, and the corresponding actual position of the valve (MV) are shown respectively in Figure 11a for the Test I with pneumatic actuator, and in Figure 11b for Test II with the electric actuator.

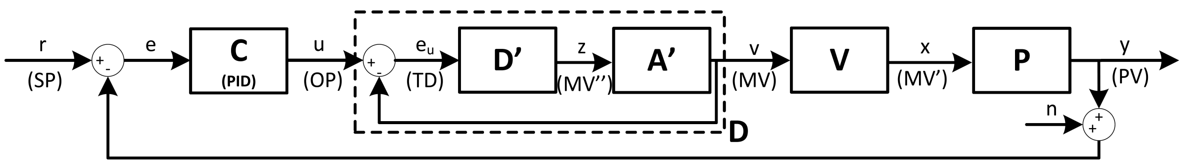


Figure 9: Control loop with "smart" electric actuator and *dead-band*.

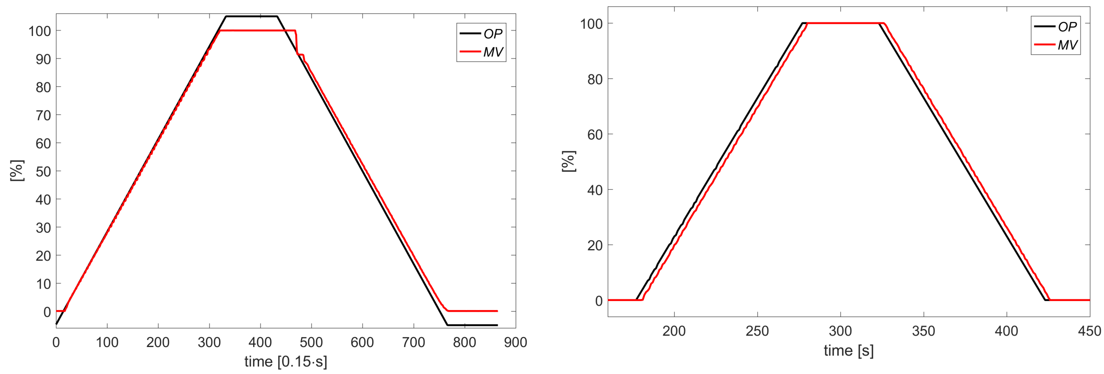
(a) Valve with pneumatic actuator. (b) Valve with electric actuator.

Figure 10: Valve under test in the IdroLab plant.

Table 2: Operating conditions for the two open-loop tests.

Parameter	u. of. m.	Pneumatic Actuator	Electric Actuator
Test		I	II
Test typology		manual ctrl.	manual ctrl.
Malfunction		none - nominal	none - nominal
PV: flow rate through valve 12FF052	[l/s]	0	0
Upstream valve 12FS013	[% opening]	0	0
Sampling period	[s]	0.15	1
Control resolution on MV	[%]	0.01	0.10

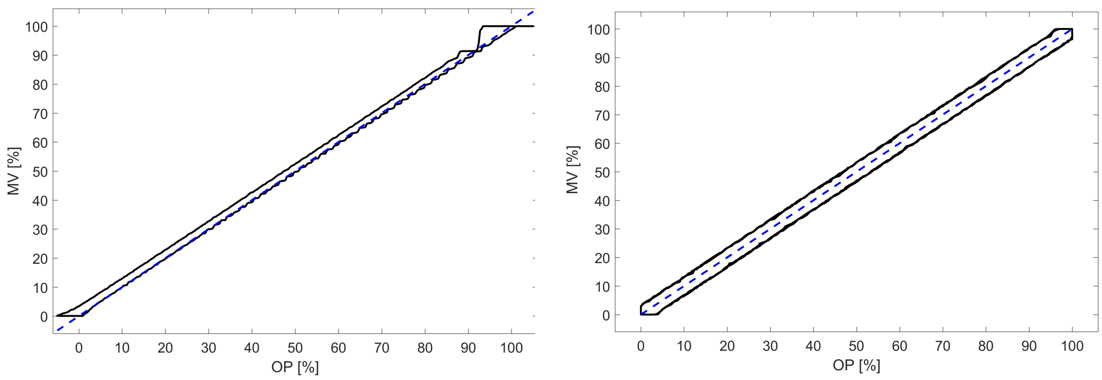
Figure 12 shows the polar diagrams MV(OP) for the two data sets. The relation between the desired (OP) and the actual valve position (MV) is substantially linear in both cases. Around the full-open and the full-closed position, when a change of direction of input signal occurs, two small horizontal segments can be identified, which correspond to a slight phenomenon of dead band. This nonlinear effect is particularly evident for the pneumatic actuator around the full-open position, where the positioner needs to impose more than 100% on OP signal in order to force the full-open position on MV, and in the close direction, where a dead band equal to about 10% of the valve stroke is detected. On the opposite, in the opening direction no significant dead-band is noted. For the electric actuator, a dead band around $4-5\%$ is detected, which is highly uniform in both directions. In addition, no positional errors is visible around extreme positions. These results confirm that the Dual Sensor™ system, mounted on the *Rotork*® electric actuator, can reduce backlash, hence, dead band, and positional errors.



(a) Test I: pneumatic actuator.

(b) Test II: electric actuator.

Figure 11: Time trends for tests in open-loop mode.



(a) Test A: pneumatic actuator.

(b) Test B: electric actuator.

Figure 12: MV(OP) diagram for tests in open-loop mode.

3.2 Test in Closed-loop Mode

Subsequently, the performance of the two different types of actuator have been compared in closed-loop operation, that is, in condition of automatic control, once they are installed on the same valve. Once again, recent data for the electric actuator were compared with archive data for the pneumatic actuator. Table 3 summarizes the main features of the operating conditions. It can be noted that the two tests are characterized by rather similar conditions. Therefore, they represent a set of comparable data. In particular, a similar sequence of stepwise changes has been imposed to the reference signal (set-point). The only significant differences concern the operating pressure of the piezometric tank (D1) and the tuning parameters chosen for the external PI controller. In the case of Test A, with the pneumatic actuator, the controller had a slower tuning than the case of Test B, with the electric actuator.

The time trends of flow rate (PV) in response to variations of the reference (SP), the corresponding control action (OP), and the valve position (MV) are shown, respectively, in Figure 13a for Test A with the pneumatic actuator, and in Figure 13b for Test B with the electric actuator, with a sampling period of 1 second. Note that good performance in set-point tracking are possible in both cases.

Table 3: Operating conditions for the two tests in closed-loop mode.

Parameter	u. of m.	Pneumatic actuator	Electric actuator
Test		A	B
Typology of test		automatic ctrl.	automatic ctrl.
Typology of control		LC and PC active	LC and PC active
Malfunction		none - nominal	none - nominal
Set-point level for tank 12EE092	[dm]	21.5	21.5
Set-point pressure for tank 12EE092 (D1)	[bar]	4	2
Upstream valve 12FS013	[% opening]	100	100
Downstream valve 12FK057	[% opening]	90	90
Set-point flow rate for valve 12FF052	[l/s]	3.0 $\leftrightarrow$ 4.5	3.0 $\leftrightarrow$ 4.5
Control resolution on MV	[%]	0.11	0.10
Tuning of PI controller	K_c [-]	3	1
	T_i [s]	60	2

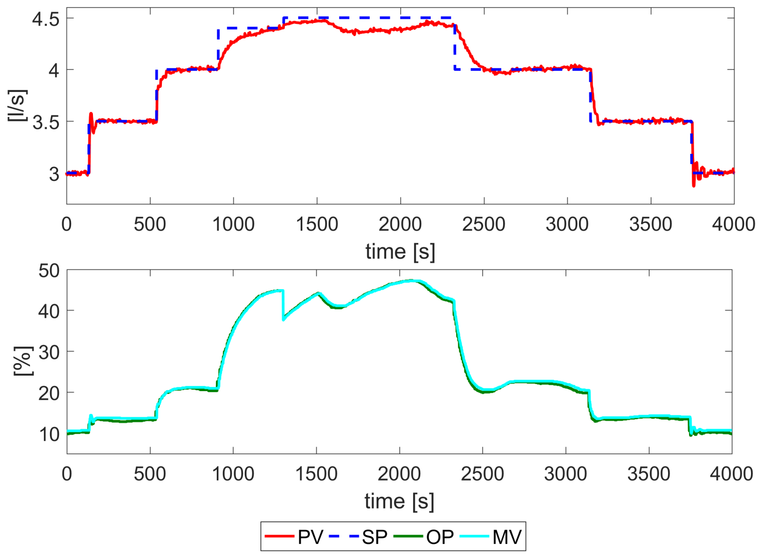
3.2.1 Analysis via PCU$^+$

Firstly, the performance of the two actuators are evaluated and compared by using the advanced version of the PCU software. The PCU^+, within the specific analysis module **Act_AIM**, employs six key performance indicators (KPI) based on simple metrics of the valve positional error, defined as *Travel Deviation*, $TD = MV - OP$. In detail:

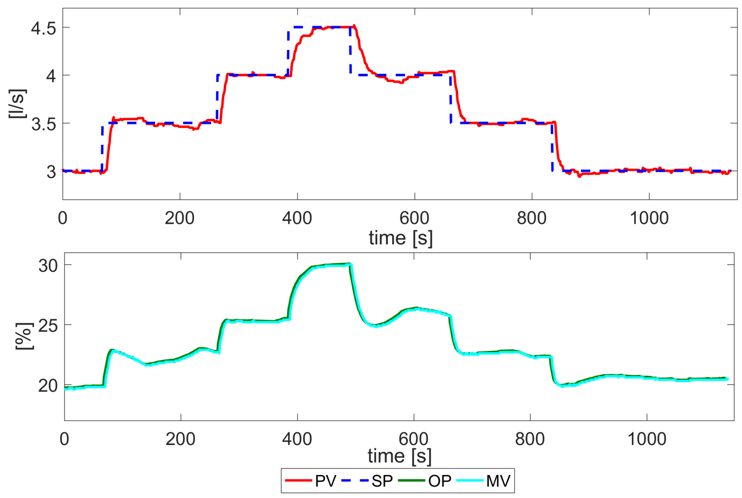
- ***I*_1**, *Significant Oscillation Index*: index of significant fluctuations, number of times in which a band of acceptability TD_{lim} is exceeded (normalized to 1 hour).
- ***I*_2**, *Percent Time Out*: percentage of time when TD is outside the band of acceptability.
- ***I*_3**, *Mean Travel Deviation*: average value of TD signal.
- ***I*_4**, *Integral Travel Deviation*: integral of TD signal (normalized to 1 hour).
- ***I*_5**, *Absolute Integral Deviation Travel*: integral of absolute value of TD (normalized to 1 hour).
- ***I*_6**, *Blockage Index*: number of movements of locking and unlocking of the valve, by excluding peaks due to changes of set-point (normalized to 1 hour).

These indices allow a quantitative assessment of different valve behaviors, distinguish between the nominal cases and those characterized by malfunctions. Note that the indices *I*_3, *I*_4 and *I*_5 are self-defined and independent from any auxiliary parameters. On the contrary, *I*_1 and *I*_2 are based on TD_{lim}, the band of acceptability for the oscillation of TD, which is set between $[-2\%;+2\%]$. The index *I*_6 depends on two secondary parameters in order to exclude peaks of TD caused by changes of set-point.

Table 4 shows the actuator indices, with their threshold values and the associated faults which can be diagnosed in control valves by the PCU. As detailed in [4], the system can diagnose three different types of faults: friction, air leakage, and malfunction of the electro-pneumatic converter (I/P), but without separating between these last two typologies.



(a) Test A: with pneumatic actuator.



(b) Test B: with electric actuator.

Figure 13: Time trends for tests in closed-loop operation.

Table 5 shows the results of the analysis carried out on the two tests of Table 3, by reporting the overall verdicts of the PCU, details of the numerical values and the status assumed by the performance indices ($I\_1 \div I\_6$). It is to be noted that in both cases, all the indices are below the respective threshold values and, consequently, none malfunction is identified. Therefore, the system emits a correct verdict: GOOD, that is, normal operation.

Figure 14 shows MV(OP) diagrams for the two data sets. The relation between the desired (OP) and the actual valve position (MV) is reasonably linear in both cases; only some small horizontal segments can be detected, in which the actuators deviate from ideal behavior and show slight phenomena of deadband. Note that electric actuator guarantees even smaller positional errors with respect to the pneumatic actuator. Note also that two different intervals of variation for OP and MV are required, due to the different settings of external PI controller. In the case of electric actuator, valve is subjected to a smaller variation of the position, between 20% and 30%, while the pneumatic actuator operates in a larger interval $10 \div 45\%$.

Table 4: Actuator indices: threshold values and corresponding malfunctions.

Index	I_i-low	I_i-high	Detectable malfunction
I_1	5	10	Friction & Air leakage & I/P Malfunction
I_2	3	6	Friction OR (Air leakage & I/P Malfunction)
I_3	$\pm$ 1	$\pm$ 2	Friction OR (Air leakage & I/P Malfunction)
I_4	$\pm$ 3000	$\pm$ 6000	Air leakage & I/P Malfunction
I_5	3000	6000	Air leakage & I/P Malfunction
I_6	5	12	Friction

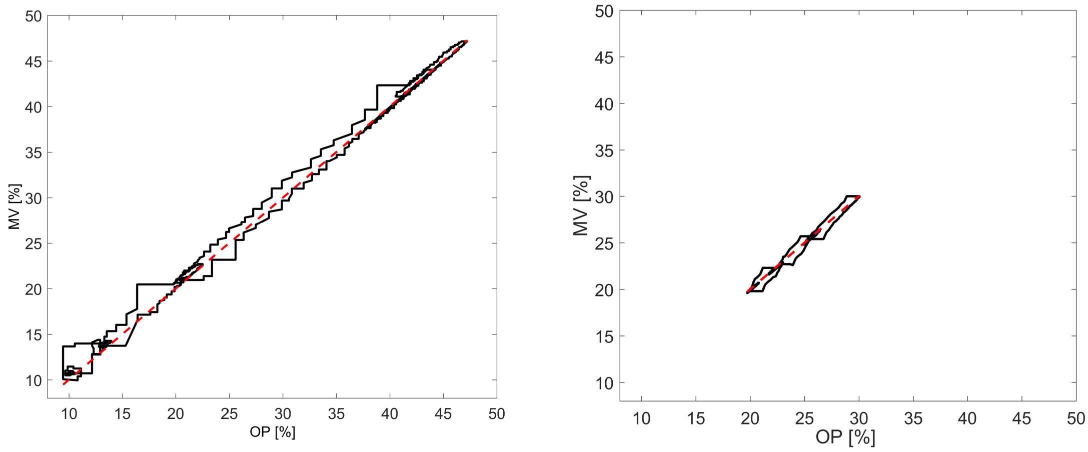
Table 5: Results of performance analysis via PCU^+.

Parameter		Pneumatic Actuator	Electric Actuator
Global verdict		GOOD	GOOD
I_1	value	0.0	0.0
	status	GOOD	GOOD
I_2	value	0.5249	0.0
	status	GOOD	GOOD
I_3	value	0.344	-0.098
	status	GOOD	GOOD
I_4	value	1237.4	-353.8
	status	GOOD	GOOD
I_5	value	1670.7	521.4
	status	GOOD	GOOD
I_6	value	2.70	0.0
	status	GOOD	GOOD

In addition, Figure 15 shows time trends of the travel deviation (TD) for the two data sets. In detail, by referring to the indices of Table 4, it can be observed that:

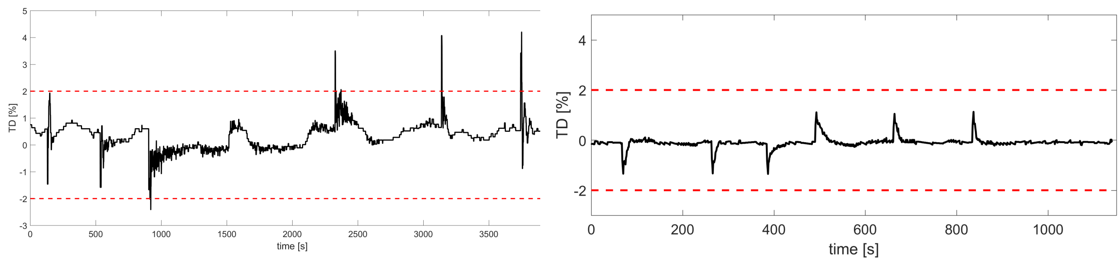
- both signals of TD lay within the acceptable band: $TD_{lim} = \pm 2$;
- no significant segment of data is outside the band: $I\_1 = 0$ in both cases;
- the time period in which TD is outside the band is negligible: $I\_2 < 0.6\%$ in both cases;
- the average value of TD is close to zero: $I\_3 \simeq 0\%$, in particular for the electric actuator;
- the integrals of errors on TD are limited: I_4 and I_5 are low;
- the number of movements of locking and unlocking (I_6) is low: in particular, zero for the case of the electric actuator.

Finally, from a qualitatively point of view, it can be observed an oscillatory behavior of TD for the pneumatic actuator and a much softer and damped trend for the electric actuator. This fact indicates a more aggressive behavior of the pneumatic positioner with respect to the control system mounted on the electric actuator. In fact, in correspondence of reference changes, the TD signal for the pneumatic actuator shows high and thin peaks beyond TD_{lim}, which are then



(a) Test A: with pneumatic actuator. (b) Test B: with electric actuator.

Figure 14: MV(OP) diagrams for two data-sets.



(a) Test A: with pneumatic actuator. (b) Test B: with electric actuator.

Figure 15: Time trend of TD for two data-sets.

followed by oscillations. On the opposite, the positional error for the electric actuator shows smaller and soft peaks, which subtend only apparently larger areas, since it holds $I\_5^{el} < I\_5^{pn}$.

3.2.2 Identification of Actuator Dynamics

Secondly, once the absence of malfunctions has been verified, a linear model for the dynamics of the two control loops in comparison is identified.

In both actuation systems, the actual valve position (MV) is measured and controlled internally by the actuator ($A = \frac{A'}{1+A'}$), as shown in Figure 16. To be precise, the positioner of the pneumatic actuator measures the position of the valve stem, while the electric actuator can directly measure and control only the position of the same actuator, and hence indirectly the position of the valve stem. However, in both cases, the position of the shutter of the valve V - that is, the actual opening of the valve (MV') - remains an internal variable which is not measurable. It is finally noted that, being a flow control loop, the process dynamics to be controlled P correlates the opening of the valve (MV') with the flow rate of water (PV), and the dynamics of valve shutter V can be considered almost instantaneous.

In particular, on the basis of measured signals MV and PV, a model of FOPTD-type for the whole process dynamics ($\hat{P} \approx V{\cdot}P$) can be identified. Furthermore, on the basis of OP and MV

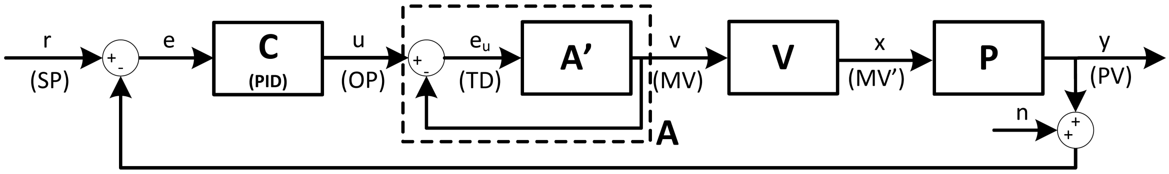


Figure 16: Scheme of control loop with “smart” actuator (pneumatic or electric).

Table 6: Models e parameters identified in the two tests in closed-loop operation.

	Actuator	$\hat{P}$	$\hat{A}$
Test A	Pneumatic	$\frac{0.033}{731.7s+1}e^{-1s}$	$\frac{0.9848}{7.349s+1}e^{-0s}$
Test B	Electric	$\frac{0.171}{25.5s+1}e^{-0s}$	$\frac{0.9996}{0.448s+1}e^{-2s}$

signals, for the dynamics of the two actuators other models of FOPTD-type ($\hat{A}$) are identified. All these models are summarized in Table 6.

The two process dynamics $\hat{P}$ are very different: in the case of Test A with the pneumatic actuator, the system is almost 30 times slower: $\tau_P^{el} \simeq 0.035\tau_P^{pn}$. Note also that for the two actuators, very similar models in terms of static gain are identified, $K_A^{el} \approx K_A^{pn} \simeq 1$, but different in terms of time-constant and delay. As a matter of fact, the electric actuator proves a faster dynamics than the pneumatic actuator by more than one order of magnitude: $\tau_A^{el} < 0.1\tau_A^{pn}$, but it suffers from a small time-delay equal to $\theta_A^{el} = 2$ seconds.

Figure 11 highlights the different dynamics of two actuators, by showing the trend of actual valve position (MV) in response to a unitary step variation of the position demand (OP). Note also that the model of the electric actuator $\hat{A}_{el}$ obtained in closed-loop mode is similar to those identified in open-loop operation shown in Table 1.

Finally, note that for the global system - actuator plus valve - the electric actuation solution proves to be much faster than the corresponding pneumatic.

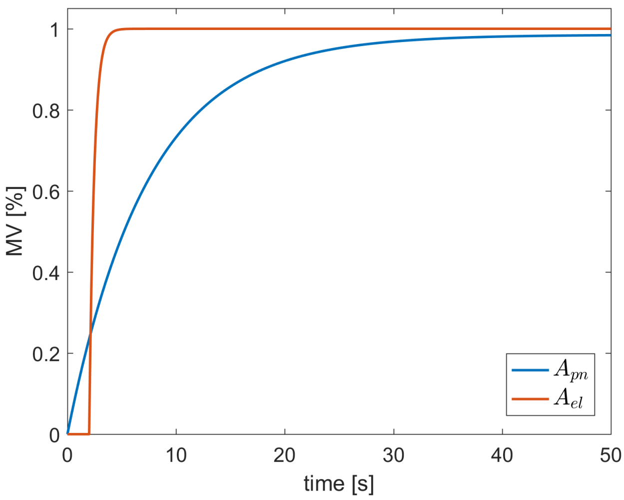


Figure 17: Comparison of step-test response for the identified dynamics of two actuators.

4 Conclusions

In general terms, on the basis of this brief comparative analysis between pneumatic and electric actuator, by using data collected in open-loop and closed-loop operation, it is possible to conclude that performance of electric actuator are fully comparable - if not superior - to those of the pneumatic actuator. In particular, the performance of the indices of PCU^{+} assume very similar values, and also the time trends of positional error (TD, travel deviation) and the limit cycles on the polar diagram MV(OP) are comparable.

These results confirm that the presence of several advanced features in the electric actuator of *Rotork®* helps achieve a highly reliable performance. In particular, the Dual Sensor™ system, by utilizing two independent position sensors, can minimize backlash and positional errors, as shown by Figures 11 and 12 for tests in open-loop operation and by Figures 13, 14, and 15 for tests in closed-loop operation.

In addition, it can also be said that the actual version of *PCU* program shows to be a valuable tool for the performance analysis of basic control loops with electric actuator. Anyway, it must be noted that the module for the actuator analysis, **Act_AIM** of *PCU*, and in particular the logic of verdicts emission and the threshold values of the indices, were calibrated for valves with pneumatic actuator and positioner.

Therefore, subsequent studies could concern:

1. a critical re-analysis of **Act_AIM** module of *PCU*, by verifying the verdicts obtained from different types of electric actuators, and with the possible revision of logics and recalibration of the threshold values.
2. the development of a new dedicated version of the program (PCU^{++}), which contains logics of automatic recognition of the specific causes of malfunction of electric actuators. For example, problems such as overheating and mechanical stresses may be diagnosed by recognizing anomalies in time trends of temperature and torque of the electric motor.

These activities will be possible by carrying out new experiments on the pilot plant IdroLab, now moved to Cecina (Livorno), by CLUI AS.

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