Comparative performance analysis of an electric actuator for control valves

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Experimentation on a Pilot Plant

Analysis of the performance of **electric actuator** for control valve

- within the collaboration between **University of Pisa** and **CLUI AS**
- along with the development of the last version of a software for **CLPM**

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New electric quarter-turn actuator
of **Rotork® CVA: CVQ-90° - 1200**

rotork®
Process Controls

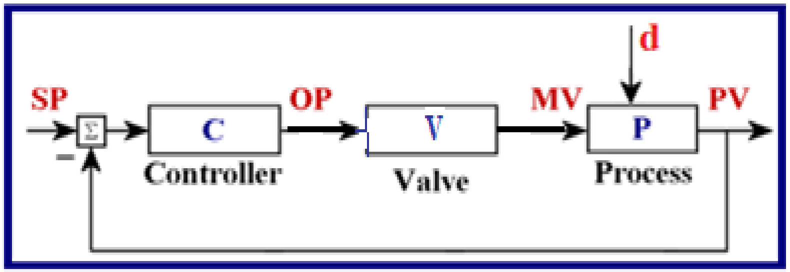
IdroLab: a pilot plant owned by ENEL
located at Livorno until the end of 2016

Outline

- Introduction:
    - ❑ Control Loop Performance Monitoring
    - ❑ Standard diagnosis vs. Advanced diagnosis
- Background:
    - ❑ Electric actuators vs. Pneumatic actuators
    - ❑ Malfunctions (friction) in control valves
    - ❑ Modeling a control valve
- Experimentation on the pilot plant:
    - ❑ Nominal conditions
    - ❑ Fault conditions
- Comparison between electric and pneumatic actuator:
    - ❑ Tests in open-loop & closed-loop mode
    - ❑ Performance analysis & dynamics identification
- Conclusions and further activities

Control Loop Performance Monitoring (CLPM)

Base Controller (PID): Feedback action

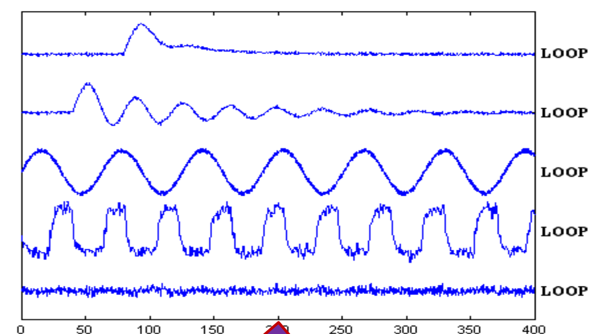


SP: set point
OP: controller output
MV: valve position (~ flow rate)
PV: controlled variable

Importance of Monitoring:
- Product quality
- Material and Energy savings
- Plant profit

Objective of Monitoring:
- Diagnosing sources of malfunction
- Suggesting ways of correction

Industrial relevant problems:
- High number of control loops
- Frequent anomalies and variables **oscillations**



Sources of Malfunction:
a) Incorrect tuning
b) Valve anomalies (*friction*):
c) External perturbations
d) Variables interactions

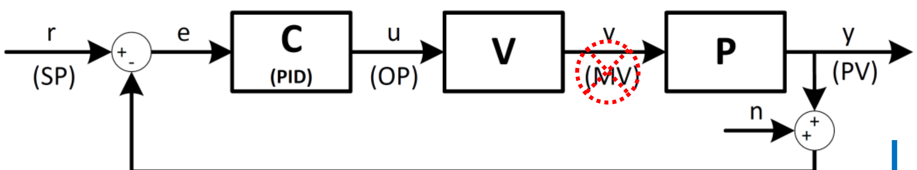
Specific Correction:
a) Controller Retuning
b) Valve Maintenance
c) Upstream Corrections
d) MIMO Controller

CLPM Software: PCU (@ CPC Lab)

Standard Diagnosis vs. Advanced Diagnosis

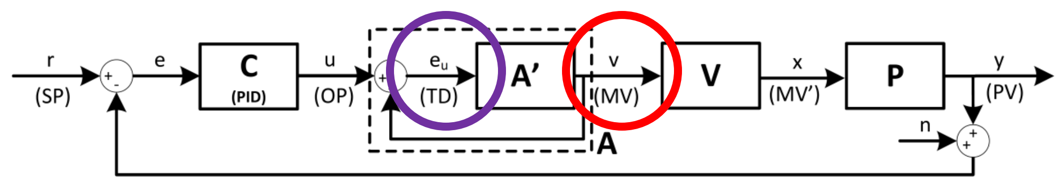
Standard Diagnosis

- For traditional industrial plants (*e.g., petrochemical*)
- Only 3 variables (measurements) available:
  - Set Point (SP)
  - Controlled Variable (PV)
  - Controller Output (OP)
- Valve Position (**MV**) is **not** available
- Signals transmitted in 4-20 mA current



Advanced Diagnosis

- In new-design plants (*e.g., power*)
- Use of intelligent instrumentation and smart valves
- Adoption of field bus communication
- Additional variables to acquire and analyze:
  - **MV** (Valve Position), **TD** (position error)



- MV allows better diagnosis of loop and valve problems:
  - **stiction** (static-friction) - most common cause of degradation
  - related problems: *dead band, hysteresis, backslash*
  - other faults for pneumatic valves: *changes in spring elasticity, membrane wear or rupture, leakage in the air supply system, I/P malfunction*

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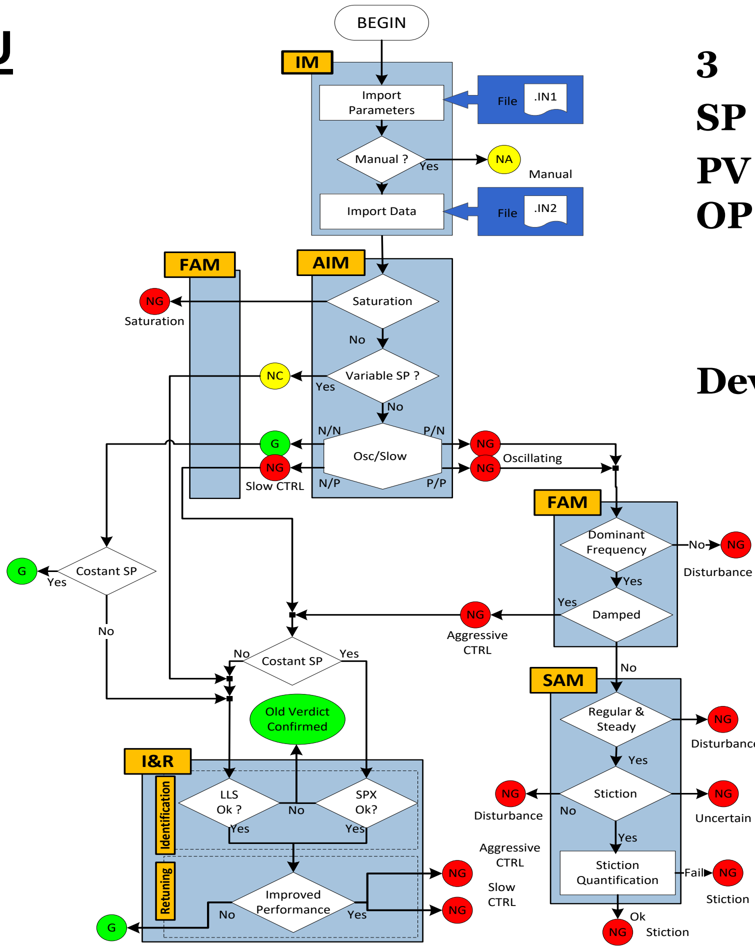
CLPM software: PCU systems

Installed in ENI, ENEL, CLUI
More than 1200 loops monitored …

Standard Diagnosis

PCU



3 N° variables

SP
PV
OP

4

SP
PV
OP
MV (TD)

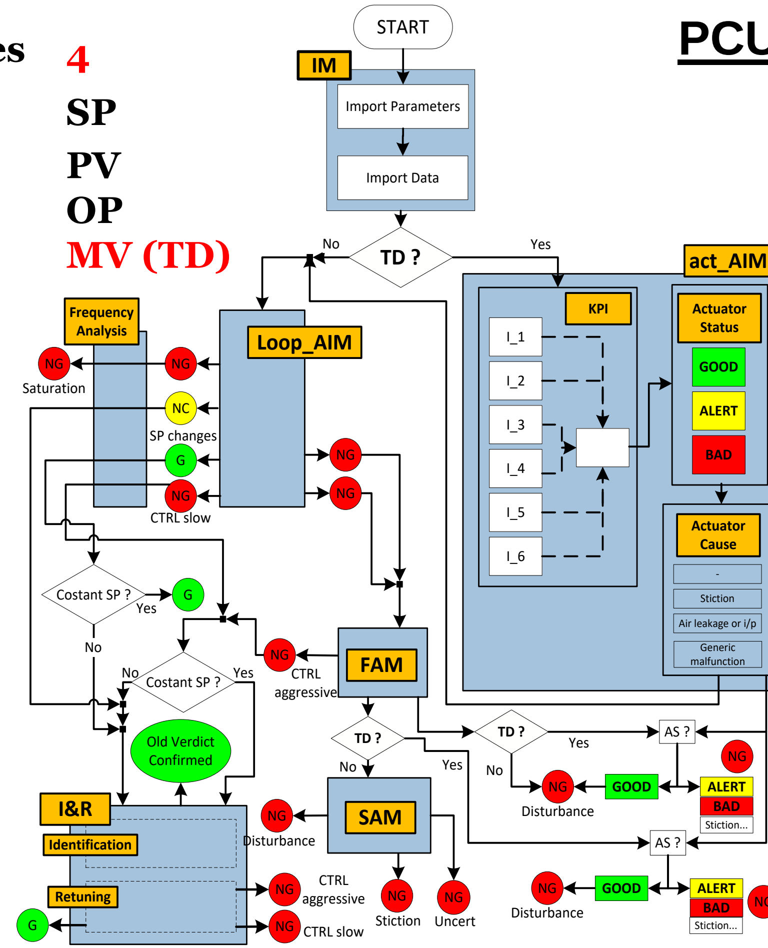
Developed in MATLAB

@

CPC Lab

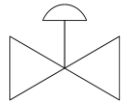
Advanced Diagnosis

PCU+



Pneumatic vs. Electric Control Valve actuators

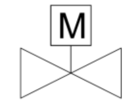
Pneumatic



➢ Still most commonly used in the process industry:

- simple technology
- good performance
- fast response

Electric



➢ Enhanced features

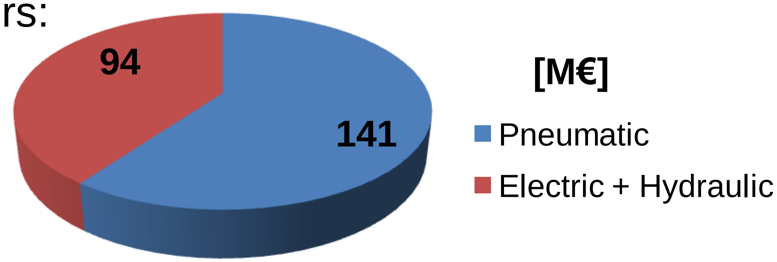
➢ Increasing applications in the area of process control

➢ Anyway, not yet suitable for all situations

Total order of industrial actuators from **Italian** customers:

estimated around **235** million of Euro [13].

- pneumatic actuators 60% of the total market
- electric + hydraulic actuators 40%



[13] U. Cé, Valvole e attuatori per l'industria di processo: l'indagine di Cogent sul mercato di valvole e attuatori, Automazione e Strumentazione 8, Nov–Dec (2016) 38–39.

Electric actuators

Advantages:

➢ Flexibility of their embedded control systems:

- easy location of various devices within the actuator
- wide range of interfaces available [14].

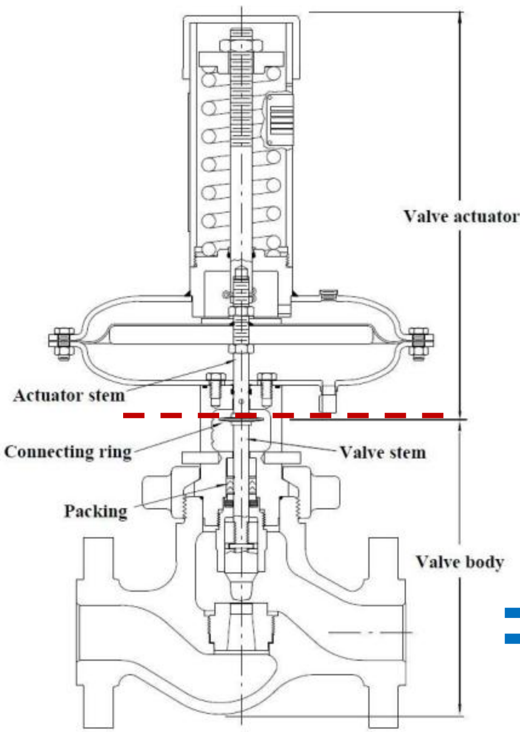
➢ can eliminate many problems of compressed air as a power medium;

➢ ideal for many situations, in particular, where users experienced problems with:

- air hoses: freezing, humidity, and dust
- frequent maintenance
- lack of control precision, stick-slip behavior [15].

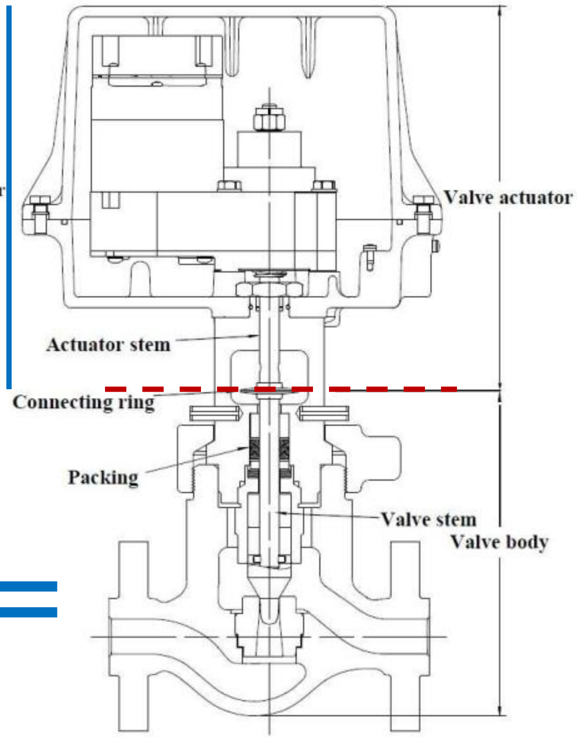
[14] R. D. Oaks, Valve Magazine 18 (2006) 48–54.
[15] C. Warnett – Rotork Controls Limited, Documentation on-line (2010).

<u>Malfunctions</u> in control valve actuators



Pneumatic

=



Electric

Practical drawbacks:

- degradation of the seat
- excessive tightening of the seal
- expansion of metallic components due to high temperature

Faults:

- wear and **friction**
- delays and position errors

for **both** type of actuator

… theoretically, but …

Pneumatic and Electric valves differ only in the actuation system

valve body: subject to most of the friction forces, is absolutely the same …

Friction in control valve actuators

Pneumatic control valve

- do not often have stiffness for a precise process control
- compressed air acts like a spring

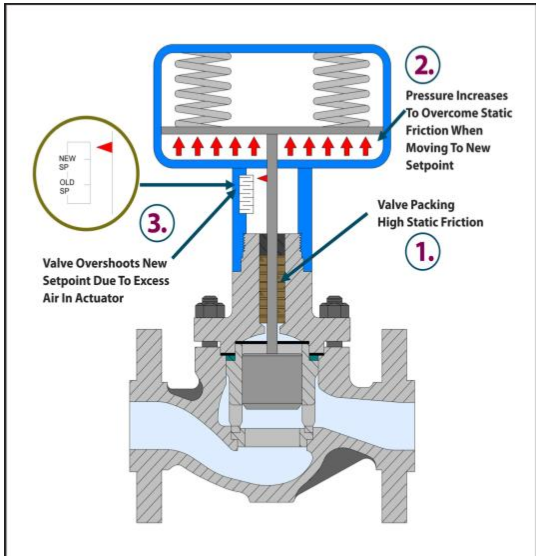
Static friction (stiction)

- ❑ requires an excessive amount of air pressure to initiate valve movement
- ❑ once the valve moves, stiction is replaced by dynamic friction, which is invariably lower
- ❑ resistance to the excessive air pressure drops abruptly
- ❑ the valve overpasses the desired set-point, and a correction is needed
- ❑ oscillations around the set-point and then limit cycles occur

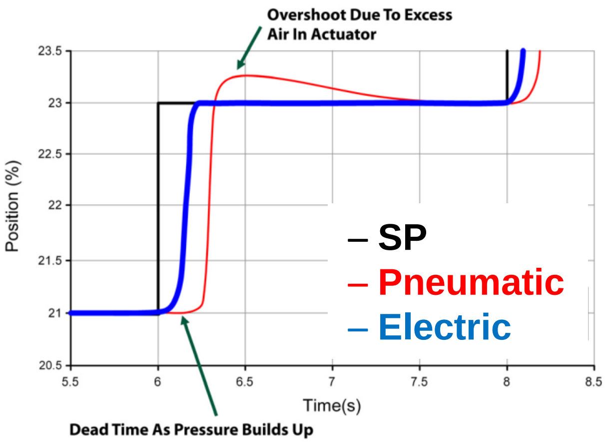
… practically !!!

Electric control valve

- **intrinsically less subject to friction phenomena**
- no overshoot to due excessive air
- higher stiffness and controllability due to:
  - modern electric drive trains
  - sophisticated dual sensor technology [15]



TYPICAL STICK SLIP ACTION ON A CONTROL VALVE



GRAPHIC DESCRIPTION OF STICK SLIP ACTION

[15] C. Warnett – Rotork Controls Limited, Documentation on-line (2010).

Modeling a pneumatic control valve with friction

OP: controller output

PV: controlled variable

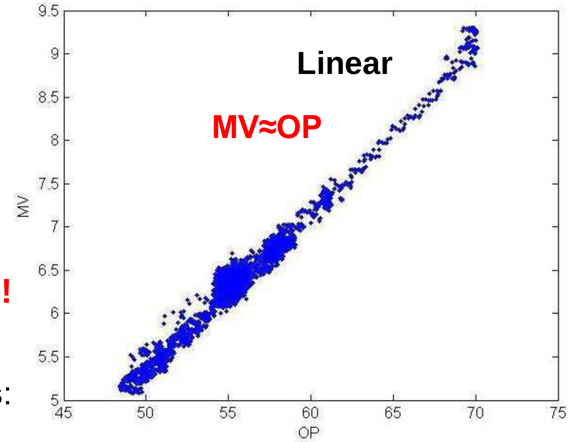
MV: valve position

→ flow trough valve

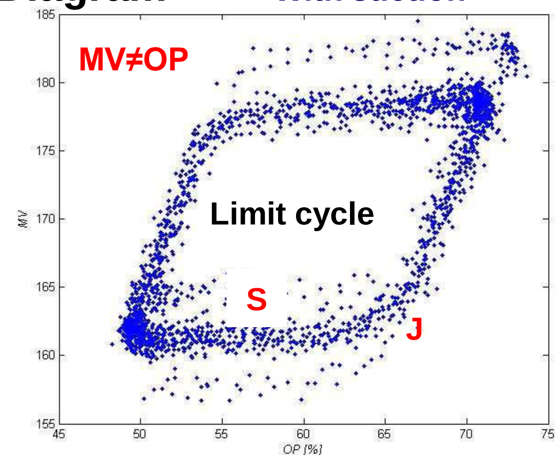
Normally not available !!!

MV(OP) Diagram

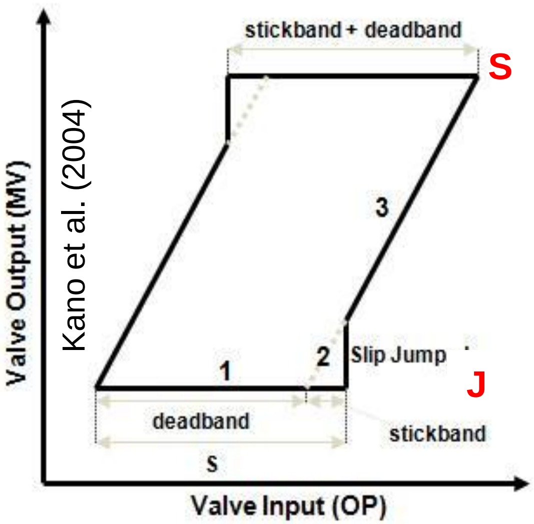
No stiction



With stiction



Kano model: data-driven with **2 parameters**:

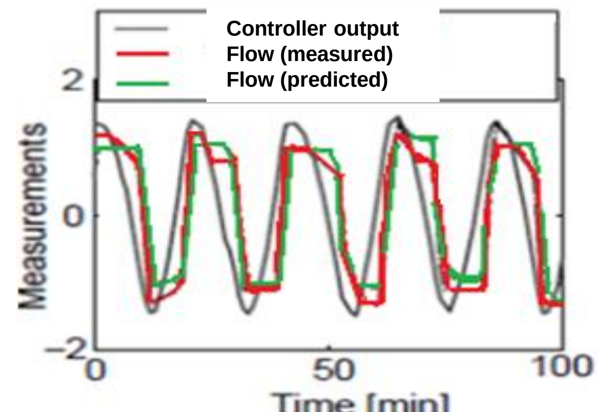


Signature of a sticky valve:

1. Block: MV is steady; valve does not move, owing to static friction

2. Jump: MV changes abruptly; the active force unblocks the valve

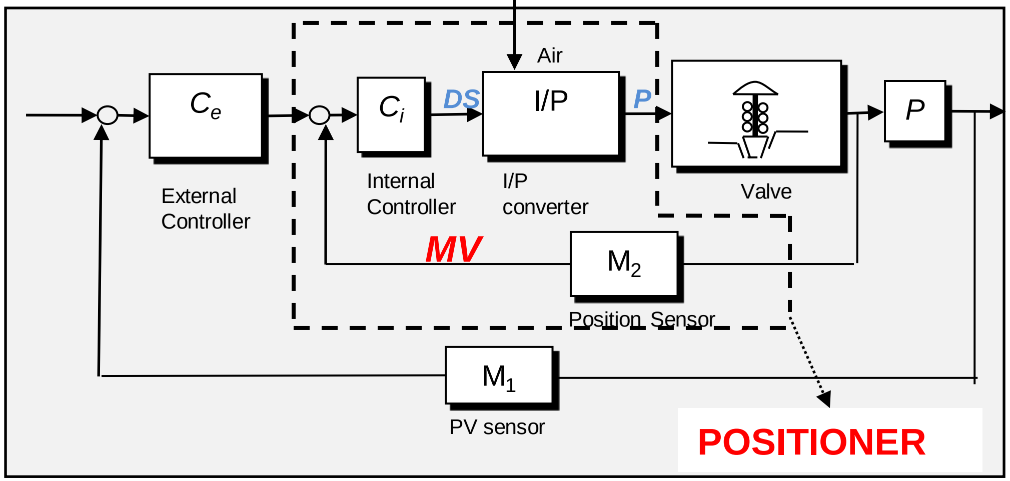
3. Motion: MV changes gradually.

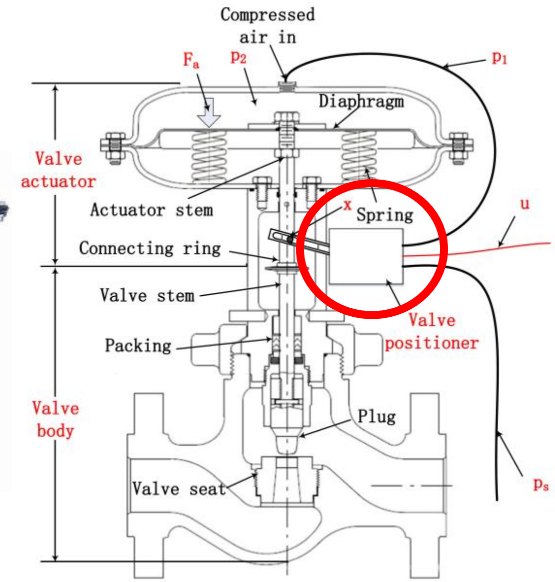


Accurate Model: reproduces properly industrial data trends

Smart pneumatic valves

Positioner: additional device which operates as an internal cascade element to control valve position





Objectives

- Force the correct position of valve stem
- Improve actuator performance
  speed up response, linearity,
  reduce hysteresis and deadband
- Modify characteristic curve of valve
- Improve performance in the presence of static friction

MV: valve position

DS: electric signal generated by internal controller *Ci*

P: pressure signal on valve membrane by I/P converter

NB: … but does NOT completely remove valve malfunctions

Experimentation on a Pilot Plant

Analyisis of the performance of **electric actuator** for control valve

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New electric quarter-turn actuator
of **Rotork® CVA: CVQ-90° - 1200**

IdroLab: a pilot plant owned by ENEL
located at Livorno until the end of 2016

- ➢ Experimentation on the pilot plant:
  - ❑ Nominal conditions
  - ❑ Fault conditions
- ➢ Comparison between electric and pneumatic actuator:
  - ❑ Tests in open-loop & closed-loop mode
  - ❑ Performance analysis & dynamics identification

Rotork® CVA: CVQ-90° - 1200

Electric control valve actuator

- installed on a rotary valve with butterfly shutter
- equipped with several **advanced features** [16]:
  - ***Dual Sensor™ system*** – two independent position sensors, minimizing backlash and positional errors
  - ***Brushless DC motor*** – a highly reliable brushless motor, allowing full continuous unrestricted modulation duty - S9
  - ***Gear train*** – simple and durable high efficiency system, lubricated for life, and designed for arduous control valve duties
  - ***Double-sealing*** – to IP68, providing protection in the most demanding environments.

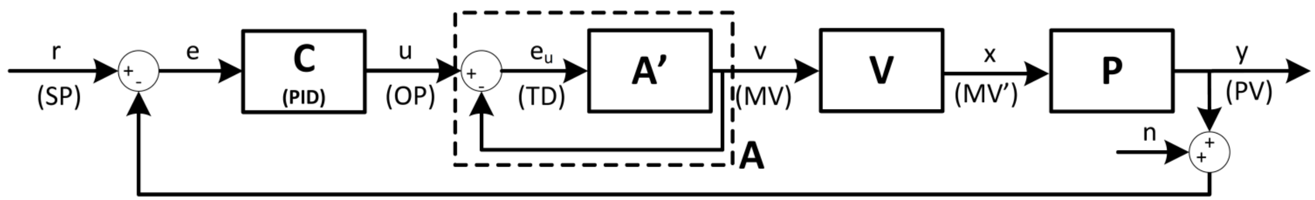
⇨ help achieve a highly reliable performance

[16] Rotork Controls Limited, CVA Range - Linear and Quarter-turn actuators to automate control valves, Documentation on-line (2008 – 2011).

The control loop

FC: flow control loop

- controlled variable (PV) — water flow rate (l/s) through the valve
- control action (OP) — output signal (0-100%) from controller **C** with PI algorithm
- actuator position (MV) — measured and controlled with a resolution of 0.1%
- **P ≈ V** — process dynamics **≈** valve dynamics : valve opening vs. flow rate



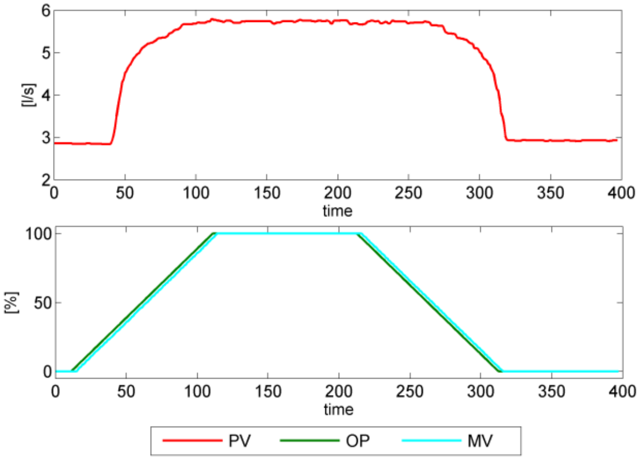
***Dual Sensor*™** system of Rotork®

- **two independent position sensors: 12-bit rotary magnetic encoders**
- one on the motor output, one near the output shaft of the actuator **A**
- helps eliminate backlash and inertia effects in the gearing
- enables to measure and control *indirectly* the valve opening

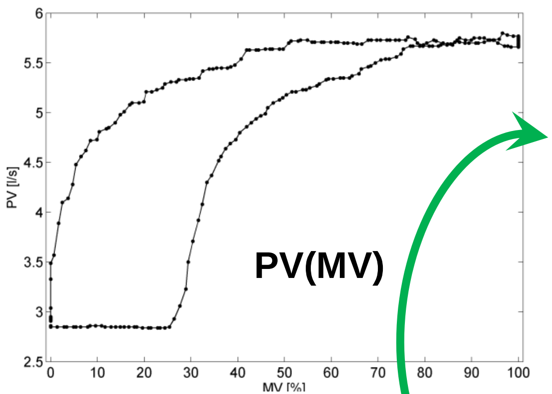
MV' position of valve shutter V - that is, the actual valve opening, is not measurable

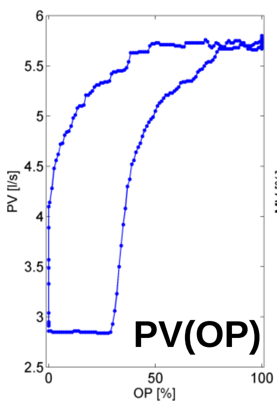
Preliminary tests: nominal conditions

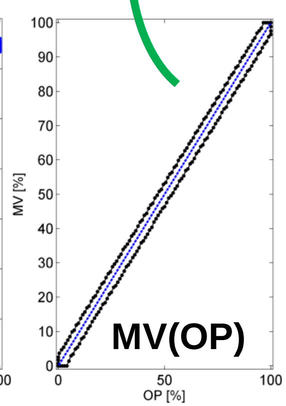
- external PI controller — excluded, in manual
- required actuator position (OP) — imposed
- actual actuator position (MV) — registered
- flow rate (PV) — registered



OP: series of ramps 0-100%







Relationship OP vs. MV

perfectly **linear**
throughout all the operating range

absence of malfunctions
(i.e., nonlinearity) are confirmed

Actuator dynamics

Identified FOPTD models

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

$$\hat{A} = \frac{A'}{1+A'} = \frac{K}{\tau s+1}e^{-\theta s}$$

Two comparable tests

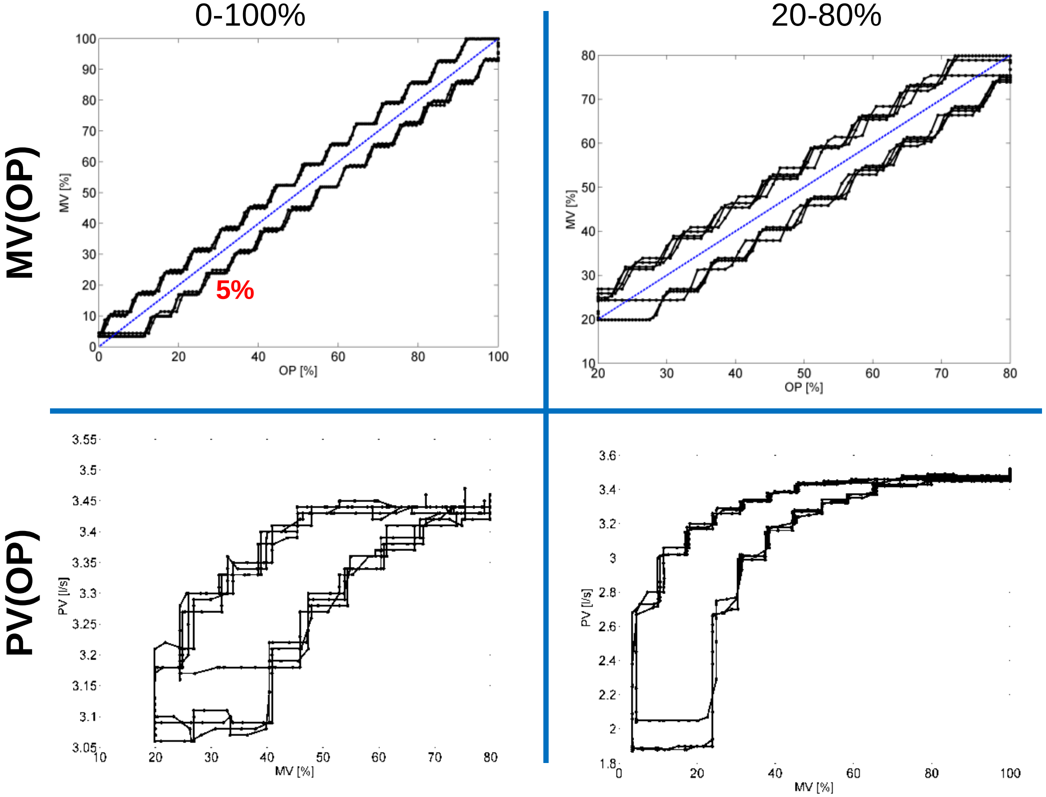
- ❑ similar parameters
- ❑ very fast dynamics
- ❑ very good data fitting (≈ 100%)

Preliminary tests: presence of dead-band

Malfunction is introduced on purpose: dead-band **d = 5%**

changing setting parameter in the configuration software of the actuator

Series of ramps on OP



Nonlinear behavior: ✓

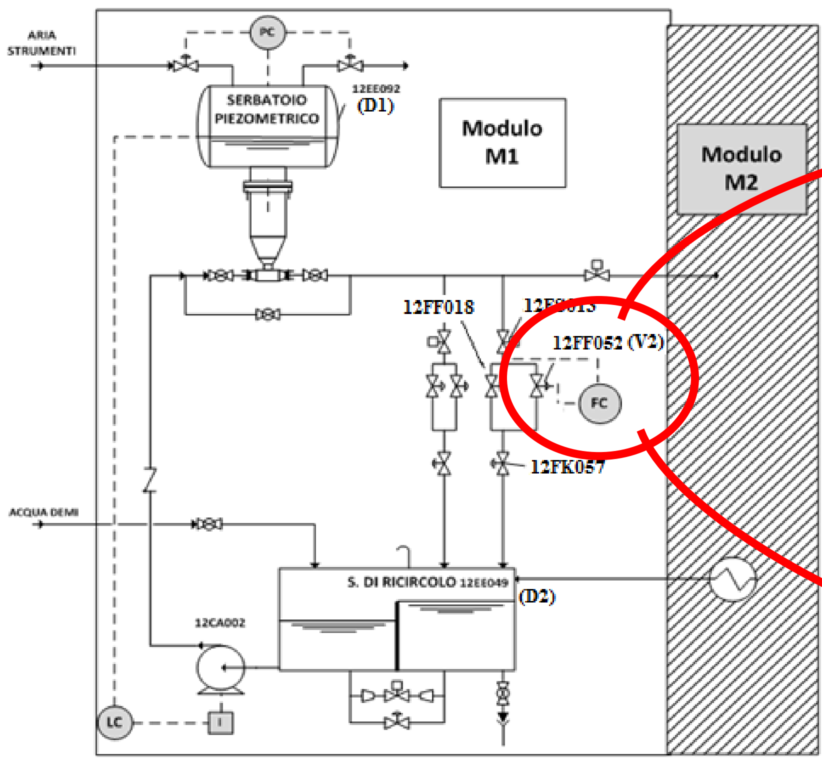
- ❑ very symmetrical
- ❑ staircase profile on MV(OP)
- ❑ series of moves: blocking and unblocking

Modeling and Identification

- ❑ very complex
- ❑ fair accuracy with empirical friction models
- ❑ note: dead-band as a special case of friction
- ❑ details omitted for the sake of brevity

Comparison between Pneumatic and Electric Actuator

IdroLab:



1. Pneumatic
Fisher Rosemount®
DVC5020f model

2. Electric
Rotork®
class CVA
type CVQ-90°
model 1200

Fair comparison:

- same control valve
- same control loop
- same operation conditions

2 Types of tests:

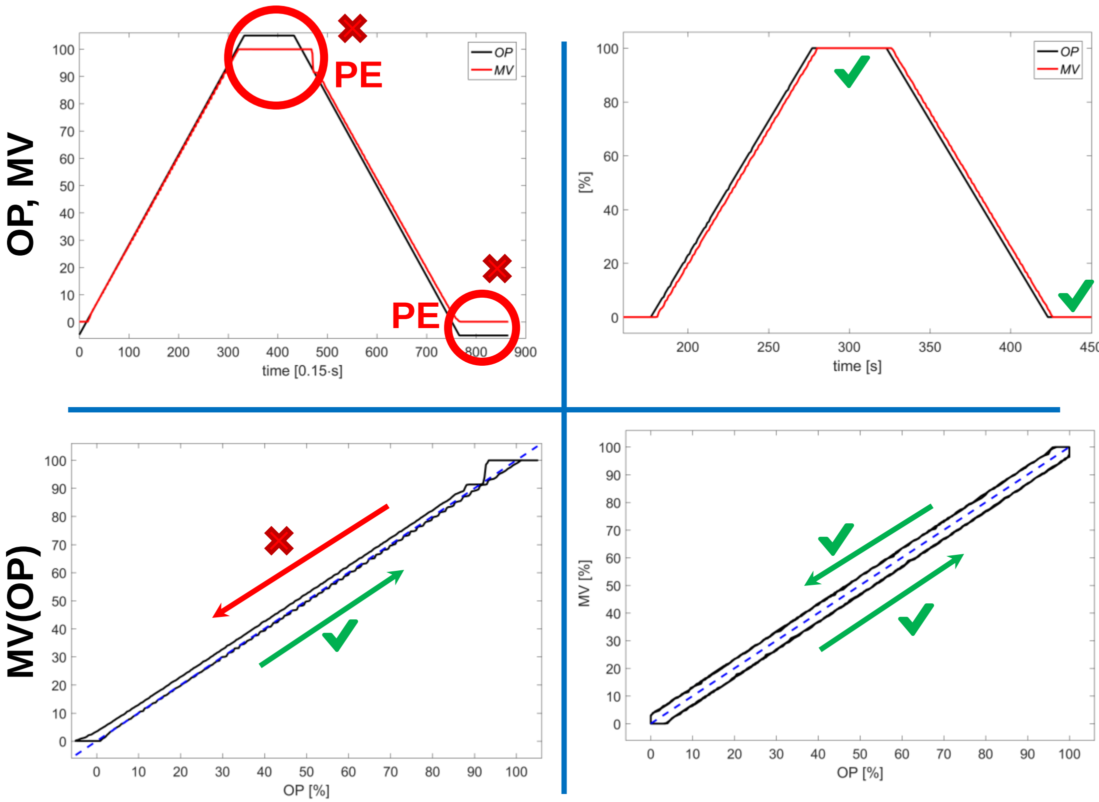
- ❑ open-loop mode
- ❑ closed-loop mode

2 Types of analysis:

- ❑ Performance via PCU^+
- ❑ dynamics identification

Tests in Open-loop Mode

Pneumatic **Electric**



MV(OP) plot: both ≈ linear, but …

OP: series of ramps 0-100%

Pneumatic actuator

- Position errors (**PE**): sign of dead band (**DB**) @ 0 and 100% position
  e.g.: nonlinear effect evident @ 100% position:
  OP > 100% to force MV = 100%
- asymmetry due to calibration limits:
  - in close direction: DB ≈ 10%
  - In open direction: no significant DB

Electric actuator

- dead band around 4-5%
- highly uniform in both directions
- no PE around extreme positions

confirmation !!!

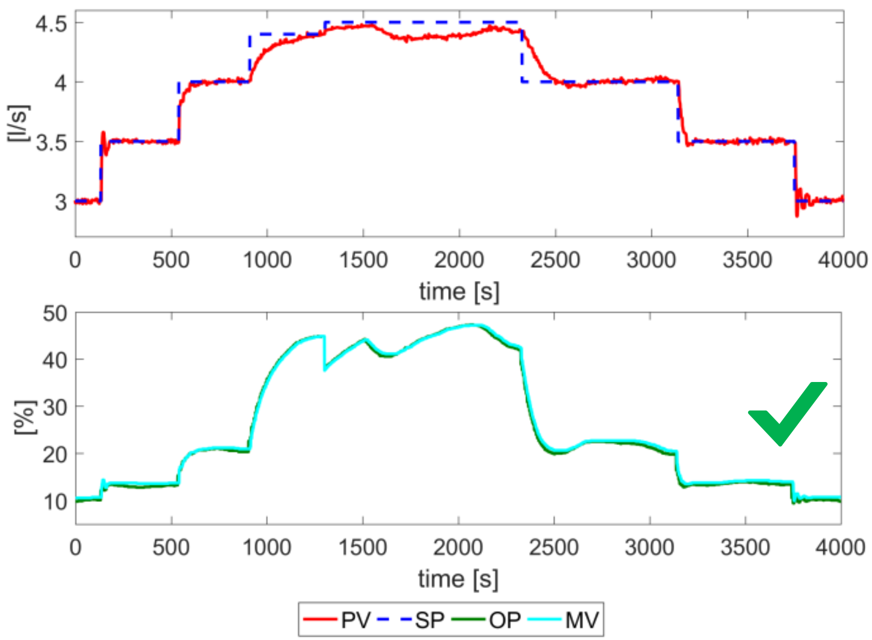
Dual Sensor™ system, on Rotork® EA can reduce
dead band and position errors

Tests in Closed-loop Mode

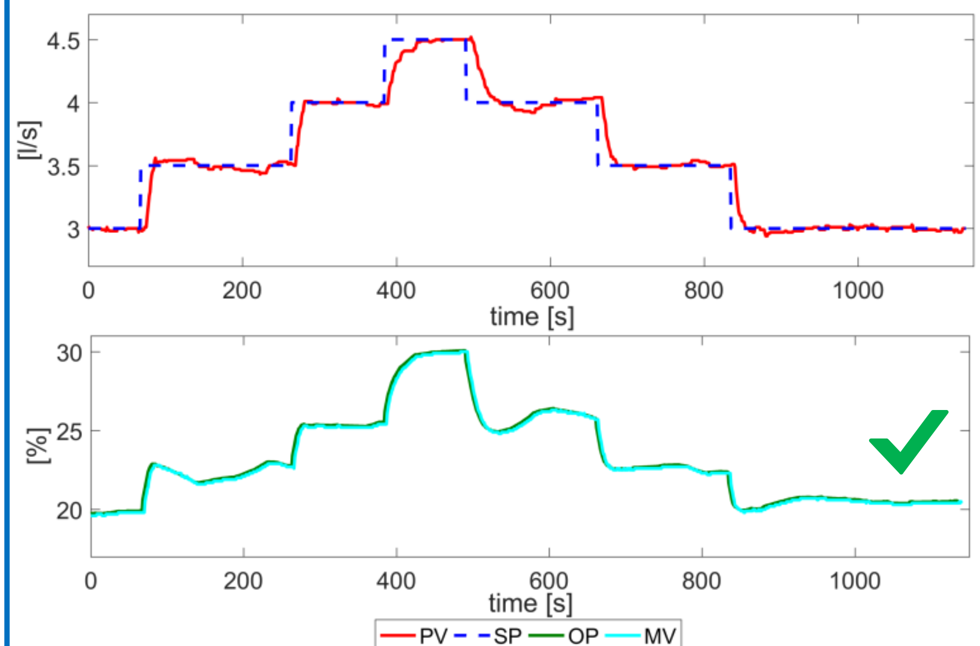
Time trends

Very similar sequence of stepwise changes imposed to the reference signal (set-point, SP)

Pneumatic



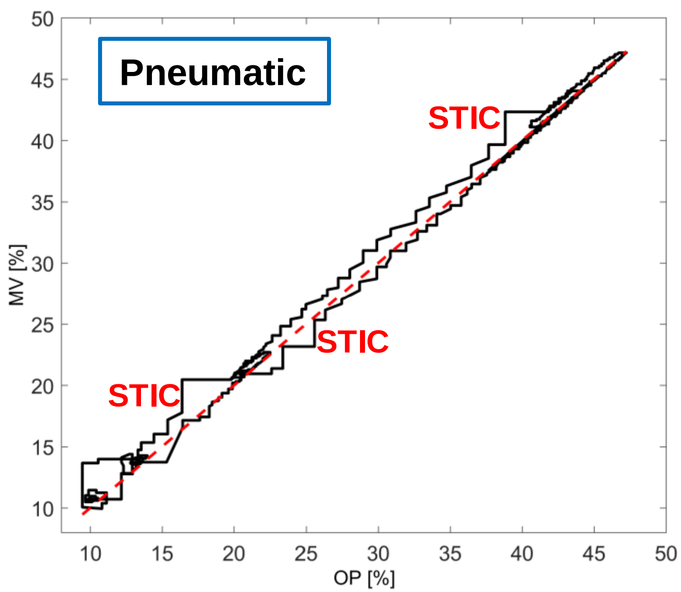
Electric



good performance in set-point tracking are possible for both actuator, but …

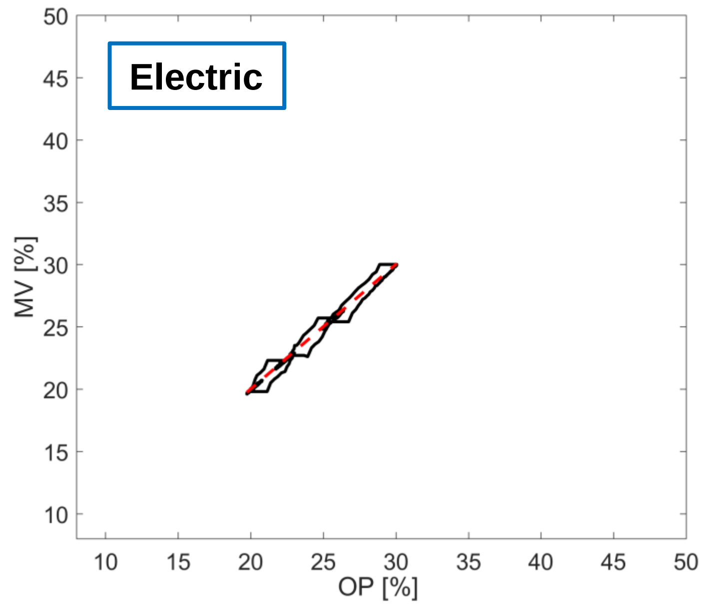
Tests in Closed-loop Mode

MV(OP) plots



- some deviations from ideal behavior
- presence of positional errors PE
  - ❑ segments of deadband (horizontal)
  - ❑ segments of friction (vertical): **STIC**
- larger intervals of variation for OP and MV *: 10-45%

* Also due to different controller tuning



- smaller positional errors
  - ❑ little segments of deadband
  - ❑ no segments of friction
- smaller interval of variation of the position: 20-30% *

Both are good,
But Electric is even better …

Performance Analysis via PCU+

Performance: evaluated and compared with the advanced version of PCU software (**PCU+**)

Six key performance indicators (**KPI**) based on simple metrics of the valve positional error, *Travel Deviation*, **TD = MV – OP**:

- **I_1**, *Significant Oscillation Index*: number of times in which a band of acceptability *TDlim* is exceeded (normalized to 1 h).
- **I_2**, *Percent Time Out*: percentage of time when TD is outside the band of acceptability **(TD_lim = ± 2)**
- **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 blocking and unblocking of the valve, by excluding peaks due to changes of set-point (normalized to 1 hour).

KPI allow:
- quantitative assessment of different valve behaviors
- distinction between nominal and fault cases

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Analysis via PCU+

Results of perfomance

Index		Pneumatic Actuator (PA)	Electric Actuator (EA)
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

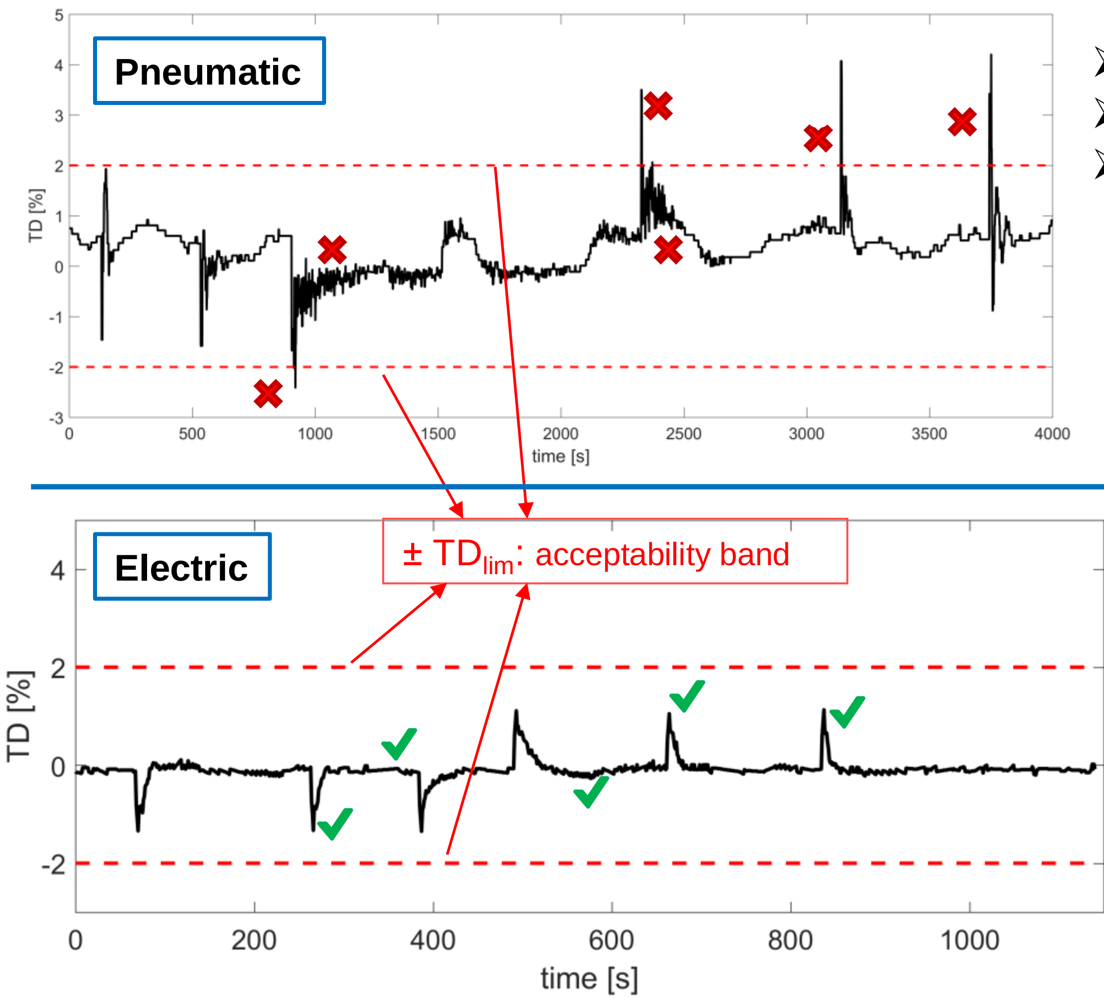
In both cases:

- all KPI indices are below the respective threshold values
- none malfunction is identified
- PCU system emits a correct verdict: **GOOD** that is, normal operation

- TD inside the acceptable band: TDlim = ±2
- no significant trespassing of the band: I_1 = 0
- time period TD outside the band is negligible: I_2 < 0.6%
- average value of TD close to zero: I_3 ≈ 0%, in particular for the **EA**
- integrals of errors on TD are limited: I_4 and I_5 are low
- number of movements of locking and unlocking (I_6) is low: in particular, zero for the EA

Both are good,
But EA is even better …

Analysis via PCU⁺ : positional error TD



Pneumatic:

- ➢ more aggressive behavior
- ➢ oscillatory trends
- ➢ in correspondence of SP changes:
  - high and thin peaks beyond TD_{lim}
  - then oscillations at high frequency

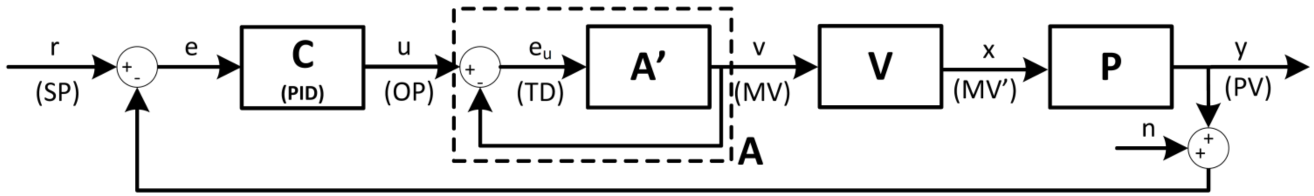
Electric:

- ➢ softer behavior
- ➢ more damped trends
- ➢ in correspondence of SP changes:
  - smaller and softer peaks
  - smaller integral areas of errors
  - note: $I\_5_{el} < I\_5_{pn}$

Both are good,
But EA is even better …

Identification of Actuator Dynamics

- Linear models for the dynamics of the control loops
- Absence of malfunctions (NL) has been verified



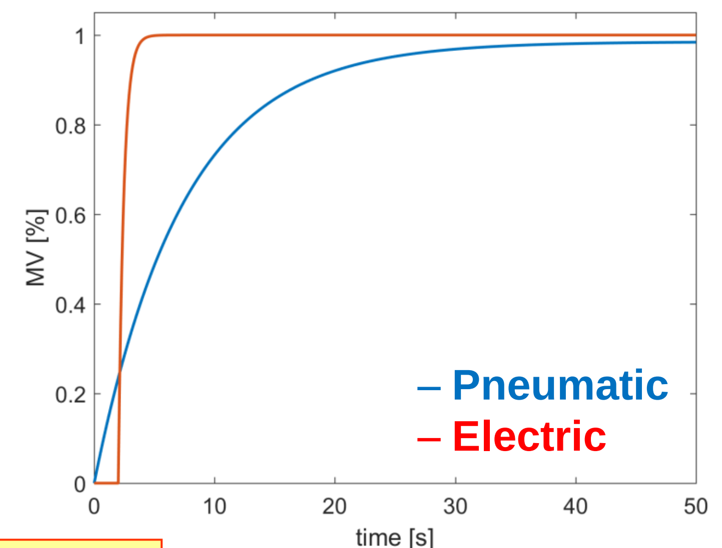
Identified FOPTD models

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

$$\hat{A} = \frac{A'}{1+A'} = \frac{K_a}{\tau_a s+1} e^{-\theta_a s}$$

$$\hat{P} = \frac{K_p}{\tau_p+1} e^{-\theta_p s}$$

Actuator dynamics: step-test response MV vs. OP



- Process dynamics **P**: very different:
  for **PA**: 30 times slower: $\tau_{pn}^P \approx 30\ \tau_{el}^P$
- Actuator dynamics **A**
  - similar in terms of static gain ***K*** (≈ 1)
  - different in terms of time-constant $\boldsymbol{\tau}$ and delay $\boldsymbol{\theta}$
    for **EA**: faster dynamics: $\tau_{el}^A < 0.1\ \tau_{pn}^A$
    - suffers from a small time-delay: θ_{el}^A = 2 sec
    - A_{el} obtained in CL mode is similar to those in OL mode

Global system: A + P
Electric solution much faster than pneumatic

Conclusions

- ➢ A comparative analysis between pneumatic and electric actuator has been performed.
- ➢ Data collected in open-loop and closed-loop operation has been employed.
- ➢ Performance of electric actuator are fully **comparable** - **or superior** - to those of the pneumatic actuator:
  - performance indices of PCU^{+} assume similar values;
  - time trends of positional error (TD, travel deviation) are comparable;
  - limit cycles on the polar diagram MV(OP) are close.
- ➢ The presence of several advanced features in the electric actuator of Rotork® helps achieve a reliable performance:
  - *Dual Sensor™ system*, with two independent position sensors, can minimize backlash and positional errors;
  - **confirmation** are obtained from results of experimental tests in OL and CL.
- ➢ Actual version of PCU proves to be a valuable tool for the performance analysis of basic control loops also with electric actuator.
- ➢ **NB**: PCU and in particular logic of verdicts emission and threshold values of the KPI, were calibrated for valves with pneumatic actuator and positioner.

Future Research

- A critical re-analysis of PCU:
  - verify verdicts obtained from different types of electric actuators;
  - possible revision of assessment logics and recalibration of threshold values.
- Development of a *dedicated* version of the program (**PCU^{++}**), with logics of recognition of the specific malfunction of electric actuators:
  - diagnosing problems such as *overheating* and *mechanical stresses;*
  - monitoring variables such as *temperature* and *torque* of the electric motor.
- All possible by carrying out new experiments on the pilot plant IdroLab: now moved to **Cecina** (Livorno), by **CLUI AS** at CPTM (*Consorzio Polo Tecnologico Magona*).

Thanks for your attention !!!

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Extra: Analysis via PCU$^+$

Actuator indices: threshold values and corresponding malfunctions

Index	Alert Level	Bad Level	Detectable Malfunction
I_1	5	10	Stiction & Leakage & I/P Malfunction
I_2	3	6	Stiction OR (Leakage & I/P Malfunction)
I_3	±1	±2	Stiction OR (Leakage & I/P Malfunction)
I_4	±3000	±6000	Leakage & I/P Malfunction
I_5	3000	6000	Leakage & I/P Malfunction
I_6	5	12	Stiction

NB:
KPI and threshold are general, but faults were conceived for pneumatic actuators !!!

3 causes of valve malfunction can be diagnosed:

- Stiction: without any doubt
- Air leakage or I/P malfunction: both together
- Generic Malfunction: includes all causes not directly recognizable, but responsible for actuator fault.