ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

AUTOMATIC AND ADAPTIVE TUNING OF PID CONTROLLERS FOR PRESSURE REDUCING VALVES IN WATER SUPPLY SYSTEMS

Anderson Quadros
André Murilo
Universidade Federal de Pernambuco - UFPE
anderson@compesa.com.br
andre.murilo@ufpe.br

Abstract. *The real water losses, primarily related to occurrence of leaks, compromise the conservation of water and energy resources and negatively impact the operating and financial performance of water utilities. This paper deals with the control of pressure in water supply systems through the use of Pressure Reducing Valves (PRV) as a final control element to reduce the real losses. The oscillations of the operating pressures in water distribution system, caused by changes in process dynamics and disturbances, are controlled by a PID control system with automatic tuning procedure. For important variations in these characteristics, which can generate significant effects on the dynamic behavior of the control system so that the linear feedback gains with constant coefficients are unable to reach the previously established performance specifications, an adaptive technique gain scheduling is also proposed. The simulation results showed the efficiency of this control strategy, held with the use of the mathematical models validated experimentally.*

Keywords: *PID control; automatic tuning; adaptive tuning; pressure reducing valves; water supply systems*

1 INTRODUCTION

The poor performance of Brazilian water companies reflects in indicators of water losses. According to (RECESA, 2008), Brazil has an average of 40.5% of water losses in their supply systems. The water losses include both real losses, which represent the portion not used due to leaks in the system, and the apparent losses, which correspond the water consumed and unregistered originated mainly by illegal connections and measurement errors. Approximately half of the water losses are associated with real losses and 70% to 90% of this occurs in the distribution network (PNCDA, 2003).
Considering the great influence exerted by the water pressure in the event of leaks, many companies are investing in the control of pressures in distribution networks. In order to facilitate the monitoring and the control activities, the networks commonly are split into District Metered Areas (DMA). This action is complemented with the use of Pressure Reducing Valves (PRV). Whereas that is impossible to eliminate demand changes from a network so it is important to control PRV appropriately to minimize the occurrence of water quality problems, a higher number of pipe bursts and premature wear of the pipe infrastructure (PRESCOTT; ULANICKI, 2008).

Thus, this paper proposes the application of a control system based on a PID controller (Proportional, Integral and Derivative), with an automatic tuning based on the Astrom-Hagglund procedure and an adaptive technique gain scheduling, to improve the performance of the PRV with the standard control loop. Moreover, it is also proposed a novel way to act in the PRV by means of a linear proportional valve.

The test network, similar to that presented in (PRESCOTT; ULANICKI, 2003), used to perform simulations and for the control system design is illustrated in Fig 1. The network comprises a fixed pressure source, two gate valves (v_1 and v_2), one PRV and four pipes. All elements were arranged in series. The control circuit, highlighted in red, consists of a fixed orifice, a needle valve, a control valve and pipes connecting these elements to PRV. The fixed pressure source can be obtained through a pumping or a reservation water system and the gate valves are used to simulate changes in the system operating conditions.

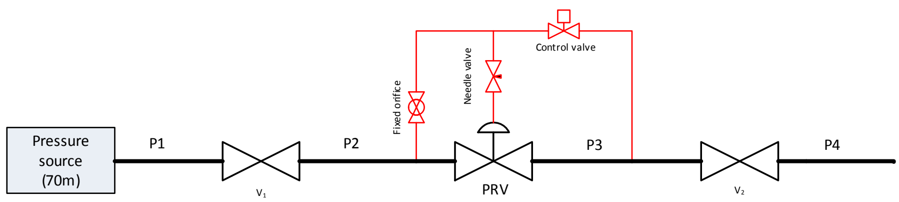


Figure 1: Test network layout.

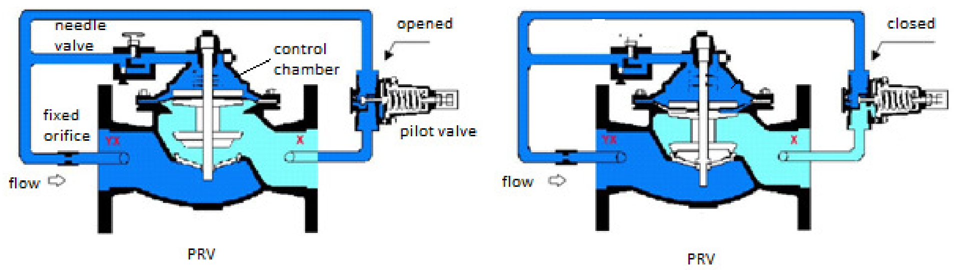
2 SYSTEM MODELS

In this section, the models and parameters used throughout the paper are presented. The PRV will be represented by simplified phenomenological and behavioral models developed by (Prescott; ULANICKI, 2003). Data from manufacturer's catalog (ASCOVAL, 2012) are used to represent the linear valve. The pipes will be represented by the rigid column model and the gate valves by the usual theory.

2.1 PRV Models

a. Behavioral Model

The behavioral model will be used to demonstrate the behavior of the network with the PRV in its standard control loop. In this configuration, without the action of automatic electronic controllers, the control valve shown in Fig. 1 is represented by a pilot valve. As can be seen in Fig. 2, the pilot valve allows setting the output pressure of the PRV by modulating the opening and closing caused by the action of the downstream pressure on this diaphragm, which permits or restricts the passage of the water from the control chamber to the downstream PRV.



Source: Adapted of RESTOR, 2003.

Figure 2: PRV standard control loop.

The equations of the behavioral model are showed below.

$$q_m = C_{vm}(x_m)\sqrt{p_m - p_j} \quad (1)$$

$$\dot{x}_m = \frac{q_3}{A_{cs}(x_m)} \quad (2)$$

$$q_3 = \begin{cases} \alpha_a(p_{sp} - p_j), se\ \dot{x}_m \geq 0 \\ \alpha_f(p_{sp} - p_j), se\ \dot{x}_m \leq 0 \end{cases} \quad (3)$$

Where q_m is the PRV flow, C_{vm} the PRV capacity (as a function of valve opening), x_m the opening of the PRV, p_m the PRV inlet head, p_j the PRV outlet head, q_3 the flow into or out of the control space (through a needle valve), A_{cs} the cross-sectional area of the control space (as a function of valve opening), α_a the setting of needle valve for PRV opening, α_f the setting of needle valve for PRV closing and p_{sp} the setpoint. The same parameters used in (PRESCOTT; ULANICKI, 2003) for the simulations were adopted for the opening and closing gains $\alpha_a = \alpha_f = 2.10^{-6}$.

b. Simplified Phenomenological Model

In order to demonstrate the behavior of the network with the action of PID controllers, the simplified phenomenological model will be used, which leads to the structure as shown in Fig. 3.

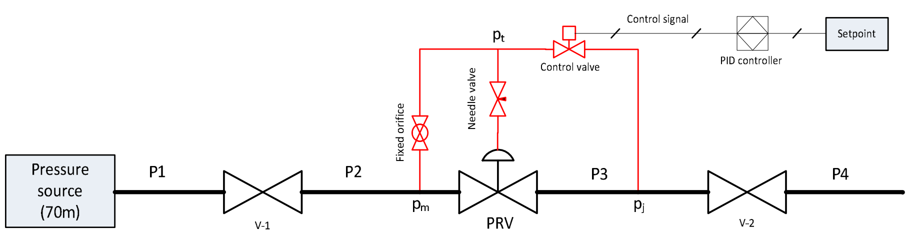
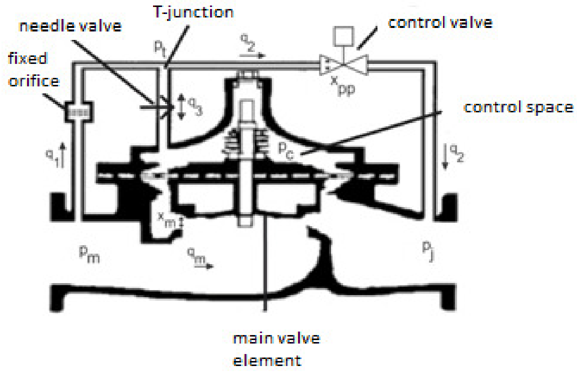


Figure 3: Test network with PID controller layout.

The use of this model is necessary since it takes into account pressures and flows present in the control circuit of the PRV and the influence of its control valve, as can be seen in Fig. 4.



Source: Adapted of PRESCOTT; ULANICKI, 2003.

Figure 4: PRV standard control loop.

The simplified phenomenological model is represented by the equations below.

$$\dot{x}_m = \frac{q_3}{A_{cs}(x_m)} \tag{4}$$

$$\rho g\left(p_m a_1 + p_j(a_2 - a_1) - p_c a_2\right) - m_m g + \frac{\rho {q_m}^2}{a_1} = 0 \tag{5}$$

$$k_{spr}\left(p_{sp} - x_p\right) - \rho g p_j a_d + m_p g = 0 \tag{6}$$

$$q_m = C_{vm}(x_m)\sqrt{p_m - p_j} \tag{7}$$

$$q_1 = C_{vfo}\sqrt{p_m - p_t} \tag{8}$$

$$q_2 = C_{vp}(x_p)\sqrt{p_t - p_j} \tag{9}$$

$$q_3 = C_{vnv}\sqrt{|p_c - p_t|}sgn(p_c - p_t) \tag{10}$$

$$q_1 + q_3 = q_2 \tag{11}$$

Where ρ = is the density of water, g = the acceleration due to gravity, a_1 = the area of the bottom of the main valve, a_2 = the area of the top of the main valve, m_m = the mass of the PRV, k_{spr} = the pilot valve spring constant, x_p = the opening of the pilot, a_d = the area of the pilot valve diaphragm, m_p = the mass of the pilot valve, q_1 = the fixed orifice flow, C_{vfo} = the fixed orifice capacity, p_t = the T-junction pressure, q_2 = the pilot flow, C_{vp} = the pilot valve capacity (as a function of valve opening), C_{vnv} = the needle valve capacity (as a function of valve opening), p_c = the control center pressure. Similar to that used in (PRESCOTT; ULANICKI, 2003), for the simulations with this model, were adopted the following parameters and variables: $a_1 = 0{,}0078\text{m}^2$, $a_2 = 0{,}0218\text{m}^2$, $a_d = 0{,}00196\text{m}^2$, m_m = 8kg, $C_{vnv} = 1.10^{-5}$, $C_{vfo} = 3.10^{-5}$, capacity and cross-sectional area of the control space of the PRV:

$$C_{vm}(x_m) = 0{,}02107 - 0{,}02962e^{-51{,}1322x_m} + 0{,}0109e^{-261x_m} - 0{,}00325e^{-683{,}17x_m} + 0{,}0009e^{-399{,}5x_m} \tag{12}$$

$$A_{cs}(x_m) = \frac{1}{3700(0{,}02732 - x_m)} \tag{13}$$

2.2 Linear Valve Model

This paper proposes a new control scheme comparing to the standard PRV mechanical structure. Existing solutions utilize pilot valves with diaphragm, with some sort of mechanical adjustment, solenoid valves type on/off or a combination thereof. This work will use an electric linear valve to reproduce the behavior of the pilot valve. The main reason to change such structure is to obtain a direct relationship between the control signal from the PID controller (valve opening) and the equations of PRV. Moreover, the implementation of the resulting control strategy becomes considerably easier since the control signal is applied directly in the linear valve, which is not possible with previous solutions. It is also believed that the use of linear valves increase the availability rate of the control system, since solutions on/off type often exhibit sealing problems due to friction of the valve with the suspended solids in the water.

In order to develop the model of the linear valve, a proportional solenoid valve model Posiflow, series G202 of the manufacturer ASCO® (ASCOVAL, 2012) was chosen as reference. The selected valve has process connection of ¼", internal orifice of 3.2mm and flow capacity (C_{vpp}) of 0.2808. The $C_{vpp}(x_{pp})$ of the linear valve is given by:

$$C_{vpp}(x_{pp}) = 0{,}2808x_{pp} \tag{14}$$

Where C_{vpp} is the linear valve capacity and x_{pp} the linear valve opening. In simulations of the control systems, this coefficient will be used in Eq. 9. The Eq. 6, which represents the behavior of the pilot valve, is not used.

2.3 Pipes and Gate Valves Models

To simulate the flow in the hydraulic network, which will be subject to small perturbations, it will be used the method of rigid column. This method models the transient behavior assuming that the propagation velocity of the disturbance to be infinite, which means that the whole system reacts instantly to any disturbance. With this assumption, each section of pipe is solved from the equation of mass oscillation. The nonlinear differential equation model of the motion of the rigid column is shown below.

$$\dot{q} = \frac{gA}{L}(p_m - p_j - f_{DW}\frac{L}{D}\frac{v^2}{2g}) \tag{15}$$

Where f_{DW} is the Darcy-Weisbach friction factor and v the velocity of water in the pipe. The Eq. 15, together with the continuity equation and boundary equations describe the dynamics of the transient flow with the rigid column model. The parameters of the pipes used in the simulations of the test network are shown in Tab. 1.

Table 1: Parameters of the pipes used in the simulations.

Pipe	Length (m)	Diameter (m)
P1	1.5	0.05
P2	4	0.1
P3	5	0.1
P4	6.6	0.1

The behavior of the gate valves will be represented by the standard theory.

$$q = ca\sqrt{2g(p_m - p_j)} \tag{16}$$

Where c is the discharge coefficient, a the cross-sectional area of orifice. In the simulations the parameter a has been set to $0{,}007854\text{m}^2$.

3 CONTROL SYSTEM

Control systems design with feedback based on PID controllers is considered as one of the most important control strategies. In the last seven decades, the PID controller has been the most important in control engineering. Studies show that more than 95% of control applications use this type of process controller (Åström, Hägglund, 1995). The high rate of the use of PID controllers in the industry can be explained by the fact that this type of control leading to satisfactory solutions, with respect to some parameter of performance, low cost and simplicity for implementation, operation and maintenance. According to (Åström, Hägglund, 1995), the standard PID control structure has the following form

$$e(t) = y_{sp}(t) - y(t) \tag{17}$$

$$u(t) = K(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}) = K_p e(t) + K_i\int_0^t e(\tau)d\tau + K_d\frac{de(t)}{dt} \tag{18}$$

Where $u(t)$ is the control signal, $e(t)$ the error signal, $y(t)$ the process value and $y_{sp}(t)$ the setpoint value. The control signal is formed by the sum of the proportional, integral and derivative terms. The proportional gain K, the integral time constant T_i, and the derivative time constant T_d are the controller parameters.

To obtain the parameters of the controller, it will be used in this paper the automatic tuning method of relay of Astrom-Hagglund and the adaptive method based on gain scheduling. To ensure better accuracy in the results, performance of the simulator and avoid overflow in the integrators, all simulations were performed in MATLAB®/Simulink® with a fixed sampling period of 0.01 s, on a standard personal computer with 32 bit/dual core 2 GHz processor and 2GB RAM memory.

To validate the results, it will be adopted a simulation scenario that will reproduce the typical behavior of a supply sector with residential and industrial consumers, characterized by a consumption profile formed by the adding of small and constant variations with a large variation in demand. To reproduce this behavior on the test network, it will be added a signal with small successive changes with another one with an important variation in the coefficient of discharge of the downstream gate valve. The small signal variations have mean of 0.03 and variance of 0.001. The other signal in the time interval [0 30s] has a constant value of 0.02, between 30s and 32s increases linearly to 0.04 and remains at this value until 120s. The coefficient signal applied to the downstream gate valve is shown in the Fig. 5.

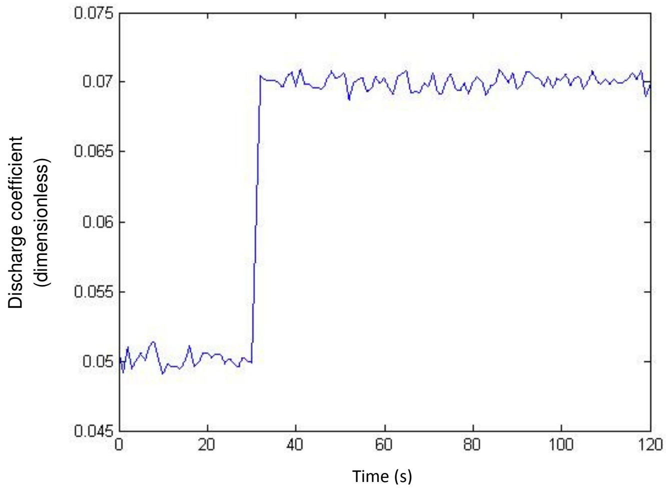


Figure 5: Opening profile applied in the downstream gate valve.

For the simulations, it will be used a discharge coefficient for the gate valve upstream of 0.15 and setpoint of 38.81 m. In the forthcoming sections it will be present the theoretical fundaments and the methodology developed to build the proposed control scheme.

3.1 PID Controller Automatic Tuning with the Astrom-Hagglund Relay Method

The relay method of Astrom and Hagglund involves the insertion of a relay in the place of the controller, and the amplitude thereof is adjusted until the forward error oscillations with amplitude and time constant obtaining the critical period T_{cr}. The Fig. 6 shows an example of the critical period (T_{cr} = 129.6s) obtained to first order process.

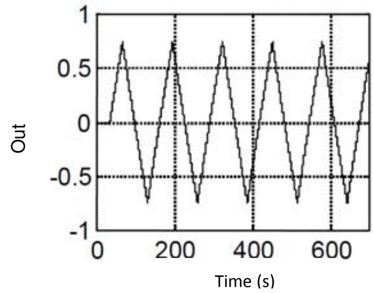


Figure 6: Example of critical period obtained to first order process.

If d is the amplitude of the relay, from the Fourier series expansion, the first harmonic of the output amplitude of the relay has $4d/\pi$. Considering a as the magnitude of the process value, the critical gain is calculated by the Eq. 17.

$$K_{CR} = \frac{4\mathrm{d}}{\pi\mathrm{a}} \quad (19)$$

The critical period can be determined by counting the time between zero-crossings of the system output. With K_{cr} and T_{cr} values, the phase margin will be adopted for determining the parameters of the PID controller (Astrom, Hagglund, 1983). In this case, the following relations should be used for calculating PID parameters.

$$K = K_{cr}\cos\emptyset_m \tag{20}$$

$$T_d = \frac{\tan\emptyset_m + \sqrt{\tan^2\emptyset_m + \frac{4}{\alpha}}}{2w_{cr}} \tag{21}$$

$$T_i = \alpha T_d \tag{22}$$

Where $\emptyset_m$ is the phase margin and α a constant which represents a correction factor for the calculation of the integral constant time. To perform the simulations in MatLab® it was used the Simulink® diagram as shown in Fig. 7.

To obtain the oscillations with period and amplitude constants, the amplitude of the relay (*d*) was increased up to 0.0003. With this value, the equations 17, 18, 19 and 20 were applied to obtain the PID controller parameters. The calculated parameters values, as well as the parameters used in the simulation of the network tests were: $K_p = 7{,}24.10^{-5}$, $K_i = 1{,}91.10^{-4}$, $K_d = 2{,}74.10^{-5}$, $\emptyset_m = 60°$, $\alpha = 1$.

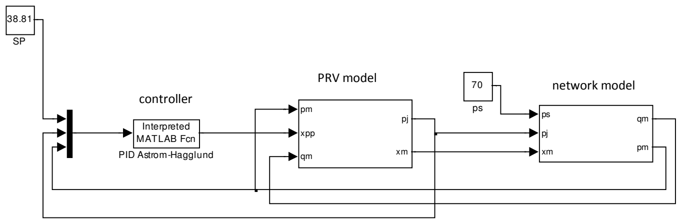


Figure 7: Simulation diagram of the system with Astrom-Hagglund tuning method.

3.2 PID Controller Adaptive Tuning with Gain Scheduling Method

Gain scheduling is an alternative often used for adaptive control method. This technique is applied to nonlinear time variants processes or in situations where large and well known variations occur in the operational conditions of the system, due to its ability to adapt to large changes in system dynamics. When used with a technique for automatic tuning, the technical implementation of the scheduling gain is greatly facilitated.

As can be seen in the flowchart of Fig. 8, before the start of the simulations is generated the parameter table of the controller. For this, the upper and lower limits and the steps of variation related to the variable to be scaled (downstream gate valve discharge coefficient) should be defined. For each algorithm step, an increment of the scaled variable is computed in order to calculate the controller parameters by the method of Astrom-Hagglund. The resulting values are stored in the table and this part of the algorithm keeps running until the limits are reached and the complete table with the parameters is obtained.

The second part of the algorithm consists in starting the simulations using the parameters stored in the table. For each sampling time, the discharge coefficient value is read and the best set of parameters that will be applied to the controller is selected in the table. The algorithm stops when the limits, which were computed in the previous step, are reached.

Considering the variations applied in downstream gate valve discharge coefficient valve, it will be adopted in the simulations the upper limit, lower limit and step variation of the scaled variable 0.045, 0.075 and 0.005 respectively. For each step of variation of the scaled variable, the PID controller parameters were calculated by the relay method of Astrom-Hagglund.

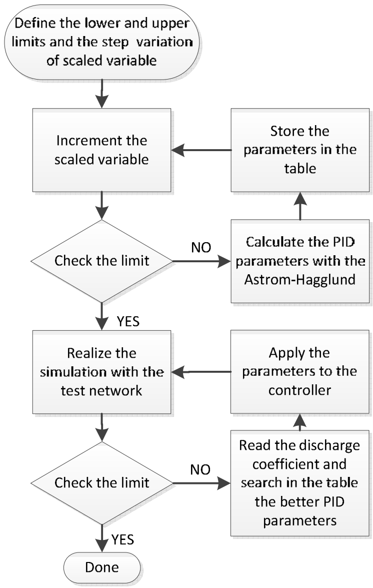


Figure 8: Flowchart to apply the gain scheduling method in the simulations.

In the simulations, a relay with amplitude 0.004, $\emptyset_{\mathrm{m}} = 60^{\mathrm{o}}$ and $\alpha = 0{,}3$ was used. The controller parameters obtained are shown in Fig. 9.

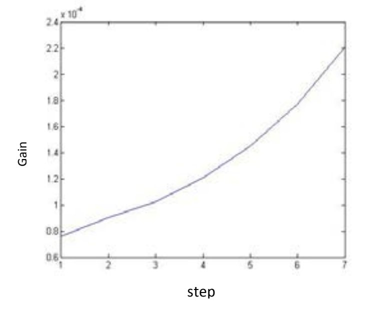
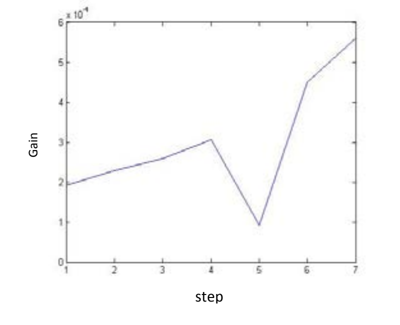
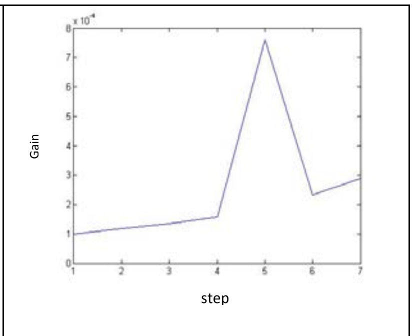
		
Proporcional Gain K_p	Integral Gain K_i	Derivative Gain K_d

Figure 9: PID gains calculated from the gain scheduling method.

4 RESULTS AND DISCUSSIONS

This section will present the results obtained from the simulations of the PRV controlled by the pilot valve, which is the existing solution, and the PID controllers tuned by the methods of Astrom-Hagglund and gain scheduling. To compare the efficiency of the above methods, the following performance indicators will be used:

- **Simulation time**: Represent the computational efficiency of the method.
- **Average**: Represent the average distance of the controlled signal (PRV downstream pressure) compared to the setpoint established.
- **Variance**: Represent the dispersion of the values obtained for the controlled signal, indicating the distance of these values in relation to the average.
- **Maximum**: Represent the maximum variation of the controlled signal.
- **Minimum**: Represent the minimum variation of the controlled signal.

4.1 Behavior of the PRV with pilot valve

The first scenario concerns the standard PRV solution using the pilot valve. As explained previously, the behavioral model was used to perform simulations. The PRV downstream pressure controlled by pilot valve is shown in Fig. 10.

ISSN 2176-5480

PRV downstream pressure (m) *versus* time (s)

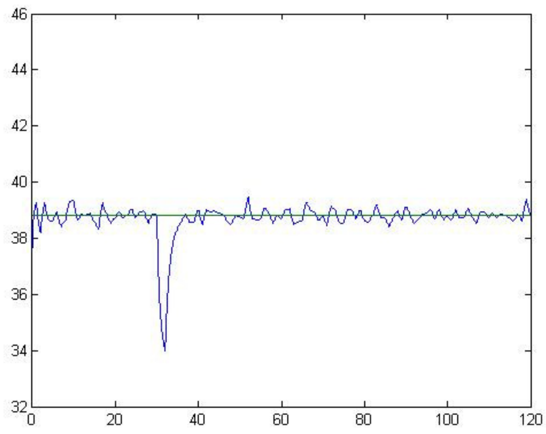


Figure 10: PRV downstream pressure profile obtained with the pilot valve.

The results obtained in this simulation are shown in the Tab. 2.

4.2 Behavior of the PRV with Astrom-Hagglund Automatic Tuning Method

The result obtained for the PRV downstream pressure controlled by PID controller with Astrom-Hagglund tuning method is shown in Fig. 9.

PRV downstream pressure (m) *versus* time (s)

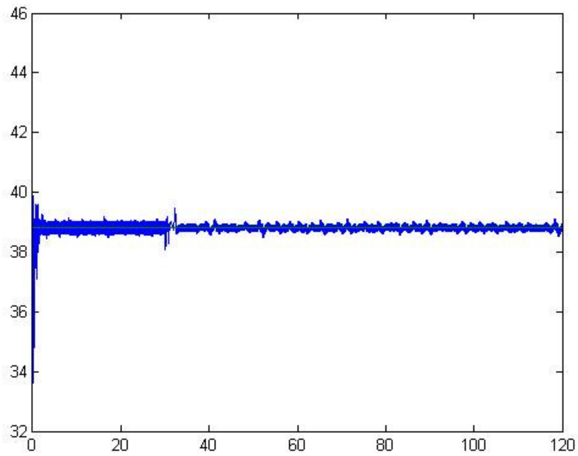


Figure 11: PRV downstream pressure profile obtained with the PID controller with Astrom-Hagglund method.

The results obtained in this simulation are shown in the Tab. 2. The Fig. 11 also shows that only after approximately 3s the system stabilizes around the setpoint. This fact can be explained by the influence of the models initials conditions settings in the system response during the first steps of the simulation. After this time, the system response occurs as established by the models. The values for the performance parameters obtained only for the interval [3s 120s] also are shown in the Tab. 2.

4.3 Behavior of the PRV with Gain Scheduling Tuning Method

The last scenario shows the simulation using the PID controller with gain scheduling tuning method. The result obtained for the PRV downstream pressure is presented in Fig. 12.

ISSN 2176-5480

PRV downstream pressure (m) *versus* time (s)

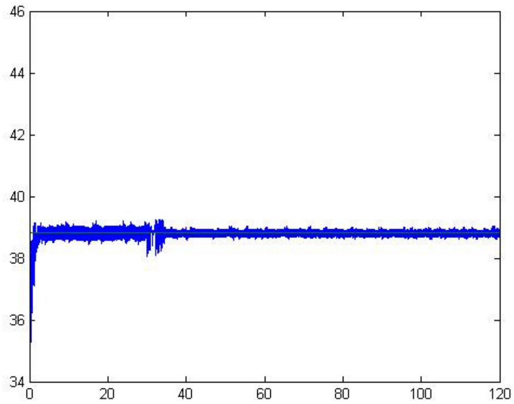


Figure 12: PRV downstream pressure profile obtained with the PID controller with gain scheduling method.

The results obtained in this simulation, for the intervals [0 120s] and [3 120s], are shown in the Tab. 2.

4.4 Summary and Comparisons

A summary of the results obtained from the simulations are presented in the Tab. 2.

Table 2: Summary of the results obtained in the simulations (setpoint = 38.81).

Performance parameters	PRV with pilot valve		Astrom-Hagglund		Gain Scheduling	
	[0 120s]	[3s 120s]	[0 120s]	[3s 120s]	[0 120s]	[3s 120s]
Simulation time	1.71	1.71	6.31	6.10	17.01	16.58
Average	38.7072	38.7072	38.8022	38.8106	38.7921	38.807
Variance	0.3511	0.3511	0.0586	0.0228	0.0595	0.0238
Maximum	44.9725	44.9725	44.9725	39.4552	44.9725	39.2556
Minimum	33.9803	33.9803	33.6359	38.0671	34.2158	38.0415

The results presented in the above table shown that all performance indicators of the PRV controlled by PID controllers were improved compared to the PRV with the pilot valve. Significant improvements were obtained for the reduction of the variance and the deviation from the average in relation to setpoint. The behavior of the peaks values also was improved, the maximum value was reduced and the minimum was incremented. It is worth noting that the reduction of the variance and the errors of the average and the maximum and minimum of the output signal, in relation to the setpoint, provide a positive impact in reducing the real losses, since the network will be subject to small variations in pressure, regardless of the system operating conditions.

Performance comparisons of the obtained results are shown in the Tab. 3. The value of the setpoint was used as reference. The average deviation in relation to setpoint presented by Astrom-Hagglund in the [3 120s] interval represents only 0.58% of the deviation obtained for the PRV with the pilot valve. Moreover, the peaks values were improved compared with the PRV with the pilot valve. In the worst result, the reduction was of 84% approximately.

The variance values obtained for the PRV with PID controllers were reduced approximately 94% in relation to PRV with the pilot.

Finally, it was verified that the performance of methods Astrom-Hagglund and gain scheduling were similar. The advantage of applying gain scheduling can be checked for larger variations in the operating conditions.

ISSN 2176-5480

Table 3: Comparisons of the results obtained in the simulations (setpoint = 38.81).

Performance parameters	PRV with pilot valve	Astrom-Hagglund		Gain scheduling	
	[0 120s]	[0 120s]	[3s 120s]	[0 120s]	[3s 120s]
Average deviation in relation to setpoint	0.26%	0.02%	0.0015%	0.046%	0.0078%
Maximum deviation in relation to setpoint	15.88%	15.88%	1.66%	15.88%	1.15%
Minimum deviation in relation to setpoint	12.44%	13.33%	1.91%	11.84%	1.98%

5 CONCLUSIONS

This paper presented the development of PID control systems, tuned by automatic and adaptive methods, applied to PRV to control pressures in water distribution networks. It was also proposed a new action form of the control system in the PRV, using linear valves. The fact of changing the hydraulic circuit control of the PRV, not only provides a direct relationship between the control signal and the equations of PRV, but also guarantees an easy implementation and robustness of the control system.

The simulation results demonstrated the effectiveness of the proposed methods. All performance indicators of the PRV controlled by PID controllers have been improved compared to the PRV with the pilot valve. It was also noted that this work represents an important improvement comparing to the work presented by (PRESCOTT; ULANICKI, 2008) concerning the action form and tuning of the PID controller, which showed better results in several performance parameters of the control system.

6 REFERENCES

ASCOVAL INDÚSTRIA E COMÉRCIO LTDA. Válvula solenoide proporcional posiflow. Catálogo do fabricante. Disponível em < http://www.ascoval.com.br/literatura/FluidControl/31B/catalogo/126_G202.pdf >. Acessado em: ago. 2012.

ASTROM, K.J; HAGGLUND, T. Automatic tuning of simple regulators with specifications on phase and amplitude margins. IFAC Workshop on Adaptive Systems in Control and Signal Processing, San Francisco, California, U.S.A., 1983.

ASTROM, K.J; HAGGLUND, T. PID controllers: theory, design and tuning. Instrument Society of America, 2ª ed. 1995. 343p.

LAMBERT A.; HIRNER W. Losses from water supply systems: standard terminology and recommended performance measures. International Water Association. The blue pages. London, 2000.

PNCDA - Programa Nacional de Combate ao Desperdício de Água. Documento de Apoio Técnico nº A2. Indicadores de perdas nos sistemas de abastecimento de água. Brasília, 2003. 80p.

PRESCOTT, S. L.; ULANICKI, B. Dynamic modeling of pressure reducing valves. Journal of hydraulic engineering – ASCE, Vol. 129, Nº 10, Out. 2003.

PRESCOTT, S. L.; ULANICKI, B. Improved control of pressure reducing valves in water distribution networks. Journal of hydraulic engineering – ASCE, Vol. 134, Nº 1, Jan. 2008.

RECESA - Rede de Capacitação e Extensão Tecnológica em Saneamento Ambiental. Núcleo Regional Nordeste – NURENE. Abastecimento de água: gerenciamento de perdas de água e energia elétrica em sistemas de abastecimento: nível 2 / Secretaria Nacional de Saneamento Ambiental. Salvador, 2008. 139p.

7 RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.