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APPLYING PID CONTROL STRATEGY FOR PREVENTING DAMAGE CAUSED BY WATER HAMMER EFFECT IN AN EXPERIMENTAL HYDRAULIC PUMPING SYSTEM

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Abstract. *In this paper, a detailed experimental study on the design, implementation and laboratory tests of a PID control for a hydraulic pumping system is presented. The PID controller has been designed using Poles Placement technique, a classical method for controller design. The PID control aims at regulating the pressure level of the hydraulic pumping system under an wide set of different operating conditions. The developed controller allows for performing advanced tests, including operation on higher pressure levels. Therefore, it contributes for improving the plant reliability as well as the operator safety against partial obstruction of pipe or against damage due to the Water Hammer effect on the hydraulic network, what is one of the main causes of permanent failure in hydraulic systems. The experimental tests shown the good performance of the proposed methodology.*

Keywords: *Hydraulic pumping system, Analog PID controller, Poles Placement technique, Water Hammer*

1. INTRODUCTION

A hydraulic pumping system is essentially composed by motor-pump set, pipes, fittings, valves, sensors, and reservoir. For activating the pump is used in three-phase induction motor, forming the motor-pump set. Three-phase motor-pump set is commanded by a frequency inverter and, by means of the inverter, the pump-motor is driven, starting the operating process. With the frequency inverter are generated adjustable voltages and frequency three-phase in order to control the speed and torque of the motor-pump set.

The operation of the process starts when the frequency inverter is triggered by the operator connecting the three-phase motor, the motor which drives the pump, starting the process of fluid transferring. In open loop any disturbance applied to the plant, gradual or abrupt, varies the level of pressure in the pipeline. For operation in closed loop mode, it is desired to adjust the level of pressure in the pipeline. For this, it's need performing the speed control of motor-pump set. According to (Franchi, 2008), for this purpose, an analog control voltage, between 0 and 10Vdc, it's used, and the rotation speed the motor is proportional the this value. This tension, adjusted by the control system, feeding one of the analog inputs of the frequency converter, allowing the control of the speed and consequently the pressure level adjustment.

In this paper, a real system was designed, and a process mathematics model suitable is obtained through using identification technique based in the system step response, and, after that, the model it's used in order to design a PID regulator controller, by using the Poles Placement technique (Landau and Zito, 2007). The controller objective is providing disturbance rejection capability, in order to preventing damage in the hydraulic system.

2. HYDRAULIC PUMPING SYSTEM

A hydraulic pumping bench system was designed with the purpose of simulating the behavior of a real hydraulic system, considering loss due local loads. In (Netto and Alvarez, 1977), it is considered that these losses are relatively important in case of short pipes with special parts such as curved pieces, registers, branch piece, all them responsible for more loss, beyond of the losses due the resistance due to fluid flow, which in this case are proposed very small.

The hydraulic pumping system was developed for application control techniques. The plant and the actuators, frequency inverter and motor-pump, are represented in the Fig. 1. For the tests of perturbation rejection, the tests referents to the obstruction will be performing by proportional valves in discharge plumbing see 6, in Fig. 1.

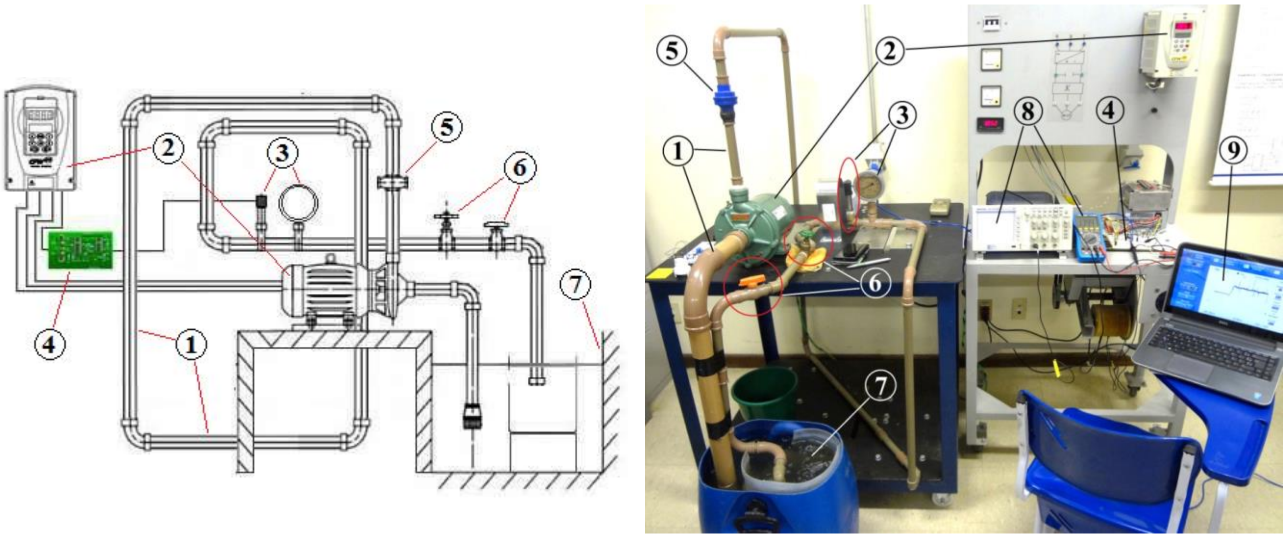

Figure 1. Hydraulic pumping system design (plant + actuator + controller)

Where:

1) Hydraulic plant - discharge piping and suction piping.
2) Actuators - frequency inverter and motor-pump.
3) Meter and sensor pressure - the sensor is responsible for recording the pressure data, converting it into an electric correspondent; while the meter is just a visual indication of pressure in the pipeline.
4) PID controller, which controls the level of pressure in the pipeline.
5) Check valve - it have function similar to the diode in electrical circuits, preventing reverse flow of water, and keeping the water column while the system is off.
6) Proportional valves, used to simulate faults as the gradual or abrupt blockage of water flow in piping.
7) Tank
8) Oscilloscope and multimeter for acquisition and measurement of the system data.
9) Computer Interface Human-Machine (HMI), for assessment of the system curves.

Based on (WEG, 2004), the converter was parameterized to receive the control signal at the analogic input AI2 (Analogic Input 2), which corresponds to the XC1 connector: 15 (V +) and XC1: 16 (0V), Fig. 2. As specified in the same reference, the operation range of this entry is 0 to +10V.

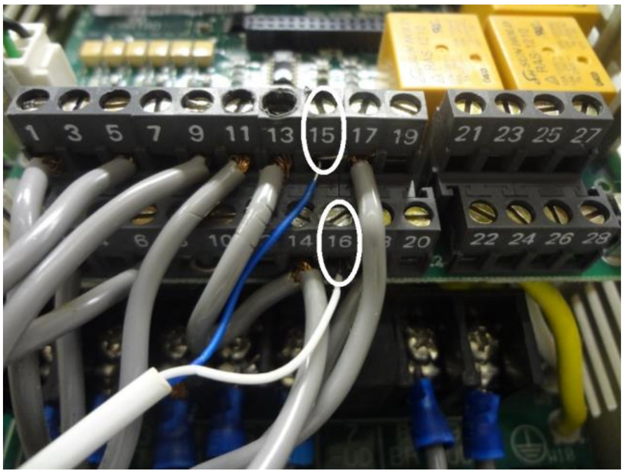

Figure 2. Connection of PID controller designed in the frequency inverter

Based in (WEG, 2004), the actuation via HMI, local command, was used to observe the dynamics of the system in open loop, and the actuation via digital input 1 DI1, remote command, to observe the dynamics of the system after the introduction of the analog PID controller, in closed loop. The parameters set for this purpose were the parameters P220, P221, P222 and P264 in (WEG, 2004).

3. HYDRAULIC PUMPING SYSTEM IDENTIFICATION

To identify the system dynamic, it's used technique based on system response to a step input, detailed in (Aguirre et al, 2007). Where it's shown that, to obtain dynamic models in systems with noisy response through step response method, it's necessary to introduce some assumptions and the realization of some tests to collects data.

3.1 Identification and acquiring system

As the objective is the pressure level control in the pipe, and the controller is an electronic circuit, then you need to associate the pressure variation in the pipe with a corresponding electrical quantity, in this case the voltage. As this purpose, a transducer pressure was used. For data acquisition, the pressure transducer is associated in series with a resistor, and both powered by a supply voltage of 12.0V, forming a voltage divider, Fig. 3. The resistance value is chosen to have 1.0V in output for each 5.0 m.w.c. (meter water column) (50.0 kPa) of pressure.

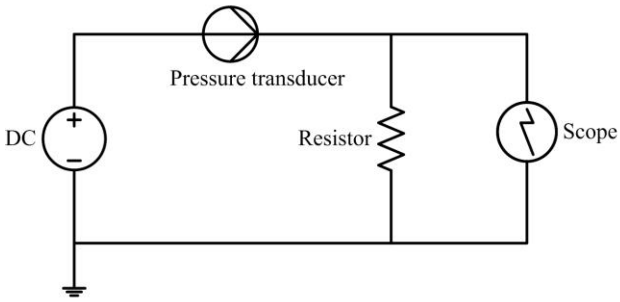

Figure 3. Circuit for data acquisition

Thus the variation in voltage captured by the oscilloscope on the resistor of 250Ω corresponds to the pressure variation experienced by the piping at a given time.

3.2 System identification tests in open loop

For a correct representation of the plant dynamics, it's necessary the system identification in open loop. The system diagram in open-loop is shown in Fig. 4.

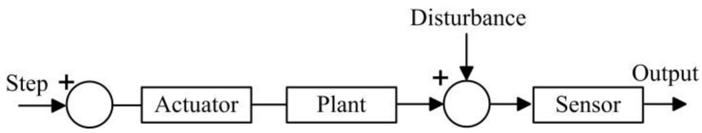

Figure 4. Diagram in blocks of open loop system

It was observed experimentally that, a non-minimum phase behavior was manifested in some operating conditions. It was decided to represent this dynamic like a transport delay, following the methodology proposed (Skogestad, 2003). In a simplified manner the system can be represented by a first order model with delay transport in the form:

$$H(s) = \frac{G_0}{Ts+1} e^{-\theta s}, \tag{1}$$

where: G_0 and T are the gain in open loop and the model time constant, respectively, and θ it's the transport delay.

According (Ogata, 1998), can be adopted as time constant (T), the time the system takes to reach the value of 63.2% of its steady state value, from of the time application of the step, that this case is T = 0.16 seconds. And the values of the gain and of the transport delay were, respectively, 0.69 and 0.15 seconds.

Transport delays are often encountered in dynamic systems, such as hydraulic systems (Aguirre et al., 2007). Thus, to define a mathematical model that represents $e^{-\theta s}$, it is proposed in (Aguirre, 2007), the representation of the transport delay as a reason of polynomials in *s*, using Padé approximation. Given the first-order function with transport delay was used the Half Rule, described in (Skogestad, 2003) and presented here, to obtain a transfer function of second order without transport delay as in Eq. (2) , and so reducing the mathematical efforts to PID controller design via Poles Placement technique.

$$H(s) = \frac{G_0}{(T_1 s + 1)(T_2 s + 1)}. \tag{2}$$

Considering that the original model with transport delay can be expressed in the form:

$$\frac{\prod\left(-T_{j0}^{inv} s + 1\right)}{\prod\left(\tau_{i0} s + 1\right)} e^{-\theta_0 s}, \tag{3}$$

where the τ_{i0} (time constant) are ordered according with their magnitudes, and $T_{j0}^{inv} > 0$ corresponds to the time constants of the non-minimum phase response. Thus, the relationship between T, G_0, T_1 and T_2 are the following:

$$T_2 = 2\theta, \tag{4}$$

$$T_1 = T - (T_2 / 2). \tag{5}$$

And the second order transfer function is as in (6)

$$H(s) = \frac{0.69}{(0.3s + 1)(0.01s + 1)}. \tag{6}$$

The real system response as well as the step response model identified after 10 measurements are show in Fig. 5.

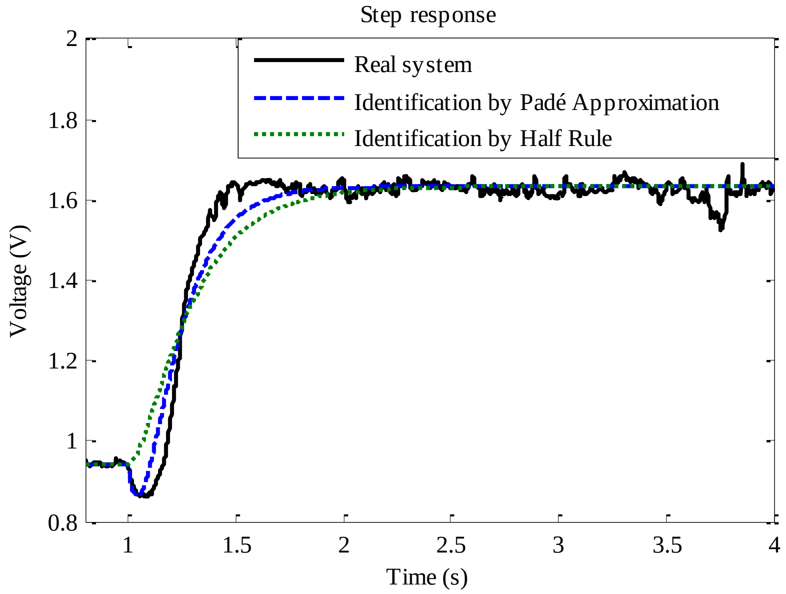

Figure 5. Step response of the identified systems

It can be seen in Fig. 5 that the value of voltage when system reached the steady state is around 1.63 volts, which corresponds the pressure of 5 m.w.c. in the pipe and a motor-pump speed around 3290 rpm.

4. PID CONTROLLER DESIGN AND IMPLEMENTATION

The Proportional-Integral-Derivative (PID) controller has the function of to control automatically a variable specific of a process. The PID controller eliminates the steady-state error through of its integral action, and anticipates the system behavior, through of this derivative action. The proportional action, in turn, causes the system reacts to the error immediately. Therefore any perturbation, or, reference variations, should be eliminated (Bazanella and da Silva Jr., 2005).

4.1 PID controller in the hydraulic pumbing system

The external analog PID controller designed to control the level of pressure in the piping, will send a voltage signal to the analogic input of the frequency converter in order to regulate the motor speed and keeping pressure in the pumping system in security levels.

For the PID controller design it is used the Poles Placement technique (Landau and Zito, 2007), this choice is justified for to be this a classical method of controller project, that in most often ensure good practice results, besides from the relative ease of development. The diagram in Fig. 6 shows the relation between the gains in a PID controller in the topology parallel.

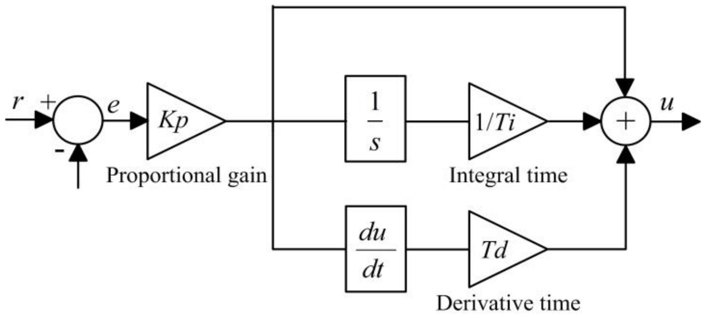

Figure 6. Diagram in block of the PID controller

The PID controller input is an electrical signal proportional to the difference between the pressure value adjusted in the controller, which corresponds to a pressure level in the pipeline (around 5.0 m.w.c), and the pressure value at any instant, this signal represent the error, *e*. As the controller is an electronic device, a pressure transducer is used to convert the mechanical variable, pressure, in a variable electrical signal.

In this way, when a disturbance is applied in the hydraulic system, a pressure variation will occur, and consequently, is generated a voltage correspondent the difference between the voltage for o new operating point, and the voltage specified in the controller reference, this difference generated a proportional control signal *u*, in the controller output, which will act into the actuators, changing the motor speed, and controlling the pressure level in the piping.

4.2 Computing the gains of the PID controller

Given the transfer function in (6), it's calculated the gains K_p, K_i and K_d of the analogic PID controller, whose structure is as below:

$$C(s) = \frac{K_i}{s} + K_d s + K_p, \tag{7}$$

According with (Ogata, 1998), the gains are:

$$K_p = \frac{20\xi^2 \omega_n{}^2 T_1 T_2 + \omega_n{}^2 T_1 T_2 - 1}{G_0} \tag{8}$$

$$K_i = \frac{10\xi\omega_n{}^3 T_1 T_2}{G_0} \tag{9}$$

$$K_d = \frac{12\xi\omega_n T_1 T_2 - T_1 - T_2}{G_0} \tag{10}$$

Where the gains are function of time constants T_1 and T_2, damping coefficient ξ, natural frequency ω_n, and gain in open loop. For the project will be considered an overshoot maximum equal the M_p = 10%, corresponding, to the value of damping coefficient of $\xi = 0.54$. Considering also the settling criterion of 2%, and a settling time of t_s = 0.45 seconds, the value of system natural frequency is $\omega_n = 16.46 rad/s$. And the gains utilized for the controller project using Poles Placement are approximately (Ogata, 1997):

K_p = 6.56, K_i =104.72, K_d = 0.0145.

4.3 Calculating the values of the electrical components to implement analogic PID controller in the serie structure

The relation between the gains proportional, integral and derivative are presented in (Ogata, 1998).

$$K_p = \frac{R_1C_1 + R_2C_2}{R_1C_2}, \tag{11}$$

$$K_i = \frac{1}{R_1C_2}, \tag{12}$$

$$K_d = R_2C_1. \tag{13}$$

Assigning a possible commercially value to the capacitor C_2, we have from (12)

$$R_1 = \frac{1}{K_iC_2}, \tag{14}$$

substituting R_2 of (13) into (11) is obtained C_1.

$$R_1C_1^{\,2} - K_pR_1C_2C_1 + K_dC_2 = 0, \tag{15}$$

and, thus, R_2 can be obtained directly from (13).

$$R_2 = \frac{K_d}{C_1}. \tag{16}$$

Thus, the component values for the gains by Poles Placement are:

$$C_2 = 0.8\mu F, \quad R_1 = 11.93k\Omega, \; R_2 = 2.848k\Omega, \; C_1 = 0.191\mu F.$$

The circuit of the analogic PID controller implemented is shown in Figure 7.

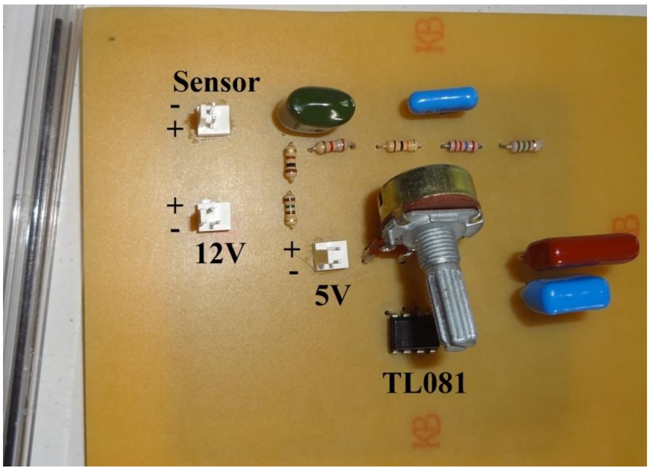

Figure 7. Developed analogic PID controller board.

5. EXPERIMENTAL RESULTS

Firstly will be analyzed the system behavior in open loop verifying the pressure variation with the gradual strangulation, until 80% of the flow. The same condition will be analyzed, when a PID controller is inserted for comparison of responses. In Fig. 8 the curve dashed represents the system response over action of the PID controller. It was observed that the PID controller was able to kept around of 5.0 m.w.c. the pressure level in the pipe, what was expected given specifications of PID controller project. It's important to mentioned that the control signal is represented in 1:10 scale, then the 1.0 Volt correspond to the real value of 10.0 Volts of voltage. The same occurred for following figures.

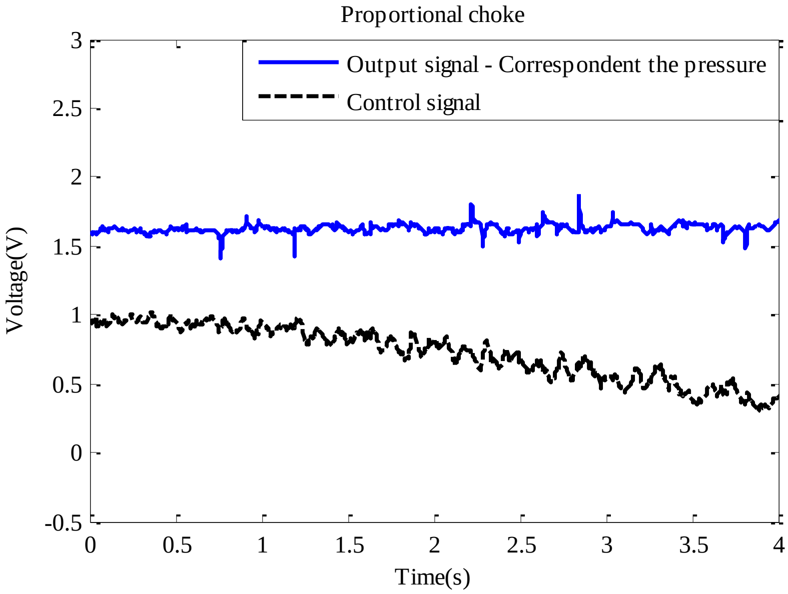

Figure 8. System response to a progressive strangulation in the pipe

To test the designed controller, disturbances were applied to hydraulic loop, firstly applied a choke of 50% in pipe, checking the disturbance rejection capacity of the control system to the Water Hammer.

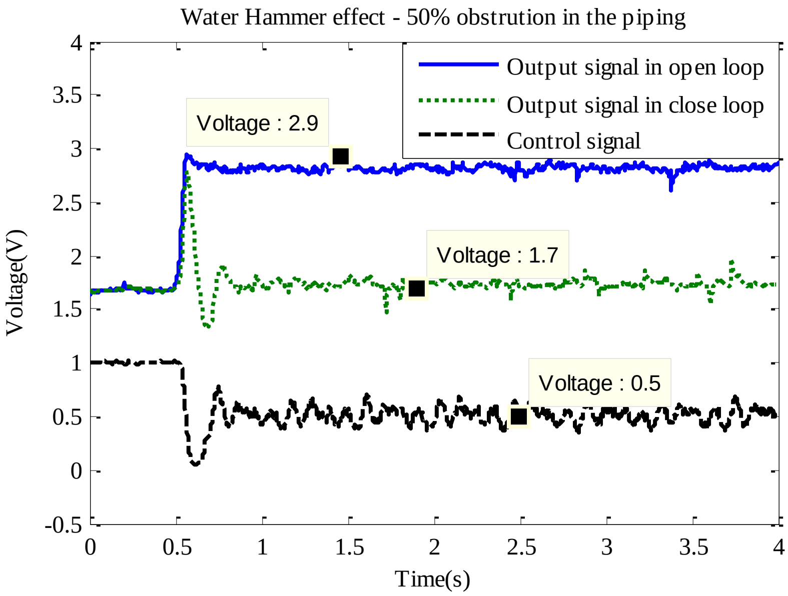

Figure 9. System response to a disturbance type step

It can be observed, in the Fig. 9, that the PID controller was able to eliminating the disturbance applied to pipe. The voltage around 1.70 volts showed that the pressure in the pipeline was maintained in safe levels for system operation. Now the test following emulates the Water Hammer with the sudden and full obstruction of the piping. This obstruction form is extremely detrimental for the whole hydraulic system, and mainly for pipe, causing cracks, and until complete destruction of the water network in more severe faults. This test, aiming at verify if the controller is able to protect the system, leading the hydraulic loop operate in pressure acceptable values, as showed in Fig. 10.

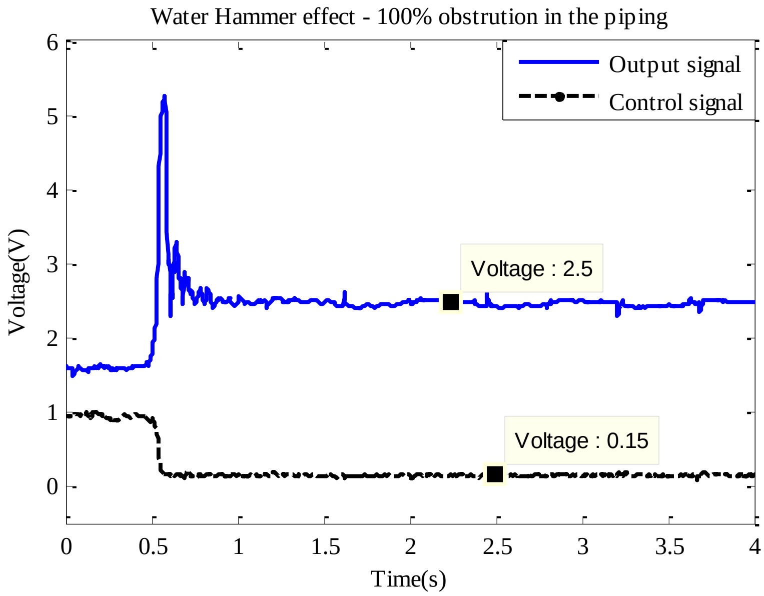

Figure 10. System response to a disturbance type step

The presented results confirm the improvement obtained on the system performance and safety. The PID controller rejected partly or totally the disturbance applied in the pipe, leading the system to operating in a safe pressure level. It's possible to observe in Fig. 10, that neither motor speed is set to zero (0 rpm), nor the pressure level is equal a 5.0 m.w.c.. The Water Hammer effects are very intense in the piping net, such that the controller doesn't rejected completely the disturbance, however the motor speed was kept small, around, 645 rpm, corresponding the 1.35 V in the control output, and the pressure level has been maintained around of 10 m.w.c., corresponding the 2.45 V in the identification resister, both observed in the Fig. 10.

6. ACKNOWLEDGEMENTS

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