Discrete Time LQG Controller for Speed Control in a Steam Turbine Coupled to DC Generator

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***Abstract*— This paper proposes a discrete-time Linear Quadratic Gaussian controller (LQG) for speed control in a steam turbine coupled to a DC generator. The goal is to keep the speed constant despite the changes of pressure in the steam pipeline and the field resistance of DC generator. In the first part, the mathematical model that describes the dynamic behavior of a steam turbine coupled to a DC generator and their parameters are calculated using an optimization algorithm. In the second part, the discrete LQG controller is designed to eliminate the influence of the disturbance in the output signal. Finally, in the last part the controller was implemented on a distributed control system (DCS), called Delta V (Emerson), and tested for different set points.**

Keywords- LQG Controller; steam turbine; distributed control system (DCS)

I. INTRODUCTION

Industrial steam turbines have many applications such as driving electric generators, small and large ship propellers, pumps and compressors. A steam turbine extracts thermal energy from pressurized steam to convert it into mechanical work using a shaft to drive an electrical generator. The steam turbine is a kind of heat engine that derives much of its improvement in thermodynamic efficiency through the use of multiple stages in the expansion of the steam, which results in a closer approach to the most efficient reversible process. An ideal steam turbine is considered an isentropic process or a constant entropy process, in which the entropy of the steam entering the turbine is equal to the entropy of the steam leaving the turbine, however, based on the steam turbine application, it's considered a typical isentropic efficiency ranges from 20% to 90%.

The interior of a turbine is composed of several sets of blades, commonly named buckets. One set of stationary blades is connected to the casing and one set of rotating blades is connected to the shaft. The efficiency of the turbine can vary depending on the size and configuration of the sets. This inner structure of the steam turbine allows it tasks that require high rotational speeds, even with widely fluctuating loads.

The mechanical speed control of the turbine, the governor, is essential, as turbines need to be run up slowly to prevent damage in some applications (such as the generation of alternating current electricity). Uncontrolled acceleration of the turbine rotor can lead to an overspeed, which causes the nozzle valves that control the flow of steam to the turbine to close. If this fails, the turbine may continue accelerating until the governor can break. Instead of that, an electronic controller and a control valve can be implemented to regulate the amount of steam that is going to the turbine. Some techniques for regulating the speed of shaft in a steam turbine are PID [1][2], FUZZY [3][4] and MPC [5][6].

This paper is structured as follows: in Section 2, dynamic models of steam turbine and DC generator are presented. Section 3 presents the design of the LQG control. In Section 4, the experimental validation of the control system is presented, and Section 5 resumes the conclusions of this research.

II. DYNAMIC MODEL

The dynamic model of the system relates the differential equations of the steam turbine and the separately excited Dc generator.

A. Steam turbine

In many cases, the steam turbine models are simplified, many intermediate variables are omitted and only map input variables to outputs as outlined in [7]. In these conditions, the input-output mathematical model (the transfer function) of a steam turbine and the expression for mechanical power developed by a turbine are based on the continuity equation:

$$\frac{\partial W}{\partial t} = V\frac{\partial \rho}{\partial t} = F_{in}(t) - F_{out}(t) \tag{1}$$

where W is the weight of steam in turbine $[kg]$; V – volume of turbine $[m^3]$; ρ – density of steam $[kg/m^3]$; F – steam mass flow rate $[kg/s]$; t – time $[sec.]$.

Assuming the flow out of the turbine to be proportional to pressure in the turbine:

$$F_{out} = P\frac{F_0}{P_0} \tag{2}$$

where P – pressure of steam in the turbine $[kPa]$; P_0 – rated pressure; F_0 – rated flow out of turbine. With constant temperature in the turbine:

$$\frac{\partial \rho}{\partial t} = \frac{\partial P}{\partial t}\frac{\partial \rho}{\partial P} \quad (3)$$

From (1)-(3), it results the differential equation:

$$F_{in}(t) - F_{out}(t) = V\frac{\partial P}{\partial t}\frac{\partial \rho}{\partial P} = V\frac{\partial \rho}{\partial P}\frac{P_0}{F_0}\frac{\partial F_{out}}{\partial t} = T_T\frac{\partial F_{out}}{\partial t} \quad (4)$$

$$T_T\frac{\partial F_{out}}{\partial t} + F_{out}(t) = F_{in}(t) \quad (5)$$

and, after a Laplace transform, the transfer function of a steam turbine unit:

$$\frac{F_{out}(s)}{F_{in}(s)} = \frac{1}{T_T s+1} \quad (6)$$

where $T_T = V\frac{P_0}{F_0}\frac{\partial \rho}{\partial P}$ is the time constant [seconds.]. The turbine torque is proportional to the steam flow rate:

$$T_m(t) = kF_{out}(t) \quad (7)$$

where k is a proportional constant. The change in density of steam respecting to pressure $(\partial\rho/\partial P)$ at a given temperature may be determined from tables. The steam flow $(F_{in}(t))$ is regulated by a proportional valve:

$$F_{in}(t) = k_p e^{-T_d s}u(t) \quad (8)$$

where k_p is a proportional constant, T_d is time delay [seconds] and $u(t)$ is percentage of valve opening.

B. Separately excited Dc generator

Separately excited DC generators are those whose field magnets are energized by some external DC source, such as a battery. The dynamic of this type of machines is represented by the following differential equations:

$$V_f(t) = R_f I_f(t) + L_f\frac{dI_f(t)}{dt} \quad (9)$$

$$K_v\omega(t) = (R_a + R_L)I_a(t) + L_a\frac{dI_a(t)}{dt} \quad (10)$$

$$T_m(t) = J\frac{d\omega(t)}{dt} + B_m\omega(t) + K_I I_f(t)I_a(t) \quad (11)$$

where V_f is the voltage applied to field coil, I_f is the current in field coil, R_f is the resistance in the field coil, L_f is the inductance of the field coil, K_v is the speed constant, ω is the shaft speed, R_a is the resistance in the armature coil, L_a is the inductance in the armature coil, I_a is the armature current, R_L is the load resistor connected to generator, T_m is the mechanical torque of the steam turbine, J is the inertia of shaft that joins the DC generator to the steam turbine, B_m is the viscous friction coefficient and K_I is the torque constant.

C. Parameters of the mathematical model

The following transfer function corresponds to the type Terry steam turbine coupled to a DC generator with a power of 1 kW:

$$\frac{T_m(s)}{u(s)} = \frac{k_p k e^{-T_d s}}{T_T s+1} \quad (12)$$

$$\frac{\omega(s)}{T_m(s)} = \frac{L_a s + R_T}{(Js+B_m)(L_a s+R_T)+K_v K_I I_{f\_ss}} \quad (13)$$

where R_T is the sum of the armature resistance and load resistance, $I_{f\_ss} = V_f/R_f$ is the current in the field coil in stable state. The following parameters are given by the technical sheet of the generator: $R_f = 367\,\Omega$, $L_f = 20.6\,H$, $R_a = 7.4\,\Omega$, $L_a = 11.38\,mH$, $R_L = 20.8\,\Omega$ y $V_f = 213$. To evaluate the unknown parameters of the model, an optimization algorithm was programmed, the algorithm is based on Sequential Quadratic Programming (SQP) method. The optimization function is the mean square error between experimental data and simulated data, for a control signal $u(t)$. Figure 1 shows the data used for optimization algorithm: generator speed (revolutions per minute - RPM) and percentage of valve opening. Table 1 presents the values obtained for each parameter.

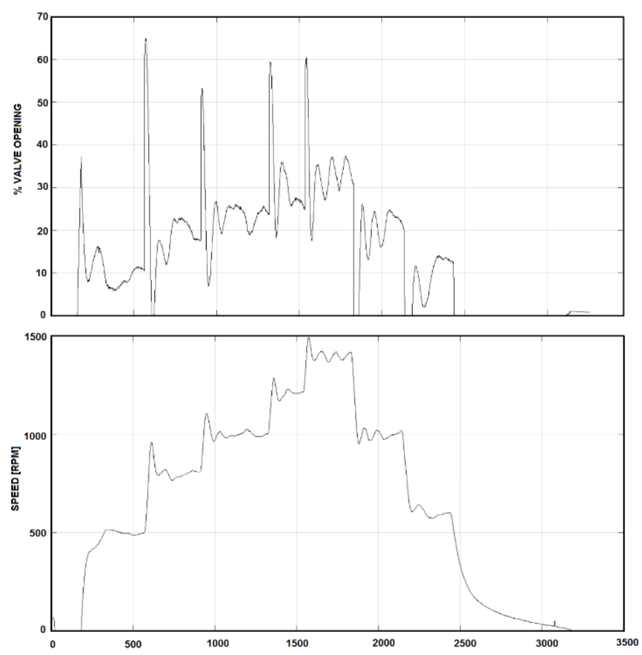

Figure 1. Experimental data. a) Percentage of valve opening, b) Generator speed

The transfer function of the system is:

$$\frac{\omega(s)}{T_m(s)} = \frac{(0.01879s+46.56)e^{-9s}}{0.02574s^3+63.8s^2+124.5s+1.036} \quad (14)$$

To simplify the model, the delay was approximated to a transfer function of first order (Pade approximation).

$$e^{-9s} = \frac{-s+2/9}{s+2/9} \quad (15)$$

TABLE I. PARAMETERS OF MATHEMATICAL MODEL

T_T	119.7 $[sg]$
$k_p k$	0.055031$[Nm/\%]$
T_d	9 $[sg]$
J	0.006015527721586 $[Kg \cdot m^2]$
K_i	0.843524807917543 $[N \cdot m/A^2]$
K_v	0.620330916257256 $[N \cdot m/A^2]$
B_m	0.000922377688340 $\left[\frac{N\cdot m}{rad/sg}\right]$

The model of the steam turbine coupled to DC generator was discretized with a sampling period of one second and represented in state space.

$$\begin{aligned} x(k+1) &= G_L x(k) + H_L u(k) \\ y(k) &= C_L x(k) \end{aligned} \quad (16)$$

where

$$G_L = \begin{bmatrix} -0.000117 & -0.004559 & -0.000102 & -0.000003 \\ 0.001424 & 0.055065 & -0.042968 & -0.001370 \\ 0.039239 & 1.519927 & 0.880884 & -0.003809 \\ 0.006815 & 0.264122 & 0.238425 & 0.999629 \end{bmatrix} \quad (17)$$

$$H_L = \begin{bmatrix} 0.000089 \\ 0.039239 \\ 0.109044 \\ 0.010605 \end{bmatrix} \quad (18)$$

$$C = [0 \quad -0.002851 \quad -1.766304 \quad 1.570189] \quad (19)$$

III. LINEAR QUADRATIC GAUSSIAN (LQG) CONTROLLER

For plants with no integrator, the basic principle of the design is to insert an integrator in the feedforward path between the error comparator and the plant [8], as shown in Figure 2.

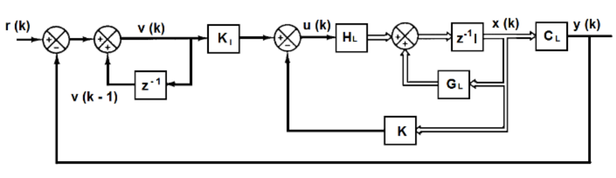

Figure 2. Block diagram of tracking system

Assume that a reference input (step function) is applied at $t = 0$ where t is the time [seconds]. Then, for $t > 0$, the system dynamic can be described by:

$$\begin{bmatrix} x(k+1) \\ v(k+1) \end{bmatrix} = \begin{bmatrix} G_L & 0 \\ -C_L G_L & 1 \end{bmatrix} \begin{bmatrix} x(k) \\ v(k) \end{bmatrix} + \begin{bmatrix} H_L \\ -C_L H_L \end{bmatrix} u(k) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r(k+1) \quad (20)$$

Remark that $r(k)$ is a step input, so we have $r(k) = r(k+1) = r$. When k approaches to infinity:

$$\begin{bmatrix} x(\infty) \\ v(\infty) \end{bmatrix} = \begin{bmatrix} G_L & 0 \\ -C_L G_L & 1 \end{bmatrix} \begin{bmatrix} x(\infty) \\ v(\infty) \end{bmatrix} + \begin{bmatrix} H_L \\ -C_L H_L \end{bmatrix} u(\infty) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r(\infty) \quad (21)$$

By subtracting (20) from (21), we obtain:

$$\begin{bmatrix} x_e(k+1) \\ v_e(k+1) \end{bmatrix} = \begin{bmatrix} G_L & 0 \\ -C_L G_L & 1 \end{bmatrix} \begin{bmatrix} x_e(k) \\ v_e(k) \end{bmatrix} + \begin{bmatrix} H_L \\ -C_L H_L \end{bmatrix} u_e(k) \quad (22)$$

where

$$x_e(k) = x(k) - x(\infty) \quad (23)$$
$$v_e(k) = v(k) - v(\infty) \quad (24)$$
$$u_e(k) = -\boldsymbol{K} x_e(k) + \boldsymbol{K_I} v_e(k) \quad (25)$$

Define a new $(n+1)$ th-order error vector $\xi(k)$ by:

$$\xi(k) = \begin{bmatrix} x_e(k) \\ v_e(k) \end{bmatrix} = (n+1) - vector \quad (26)$$

Then (22) becomes:

$$\xi(k+1) = \widehat{\boldsymbol{G}}\xi(k) + \widehat{\boldsymbol{H}} u_e(k) \quad (27)$$
$$u_e(k) = \widehat{\boldsymbol{K}}\xi(k) \quad (28)$$

where

$$\hat{G} = \begin{bmatrix} G_L & 0 \\ -C_L G_L & 1 \end{bmatrix} \quad \hat{H} = \begin{bmatrix} H_L \\ -C_L H_L \end{bmatrix} \quad \hat{K} = [K \quad -K_I] \quad (29)$$

The LQG regulator consists in an optimal state-feedback gain and a Kalman state estimator [9]. The first design step is to seek a state-feedback law that minimizes the cost function of regulation performance, (30), it is measured by a quadratic performance criterion with user-specified weighting matrices, Q and R, which define the trade-off between regulation performance and control effort, respectively. The gain matrix $\widehat{\boldsymbol{K}}$, to minimize the function J, is obtained by solving an algebraic Riccati equation.

$$J = \frac{1}{2}\sum_{k=0}^{\infty}(\xi^T Q \xi + u_e{}^T R u_e) \quad (30)$$

The next design step is to derive a state estimator using a Kalman filter because the optimal state feedback cannot be implemented without full state measurement. Since the Kalman filter is an optimal estimator when dealing with Gaussian white noise, it minimizes the asymptotic covariance of the estimation error. Mathematically, the Kalman state estimator can be expressed by (31), with two inputs, controls u(k) and measurements y(k). The gain matrix L of the Kalman filter is determined solving the Riccati algebraic equation.

$$\hat{x}(k+1) = G_L\hat{x}(k) + H_L u(k) + L(y(k) - C_L\hat{x}(k)) \quad (31)$$

The following values are assumed for the controller design: $Q = \mathrm{diag}(1, 1, 1, 8.5, 0.009)$ and $R = 5$. By solving the Riccati equation gives $\widehat{K}$ = [0.061111, 2.367096, 1.369298, 1.786684, -0.037269]. To design the observer, the variance of experimental data of the control signal and the generator speed are determined. The values are $Q_n = 176.9876$ and $R_n = 21225$, respectively. By solving the Riccati equation gives L = 10-8 [37.59397, -1129.21097, -51464.655, 1617969.98].

Figure 3 shows the block diagram of the control strategy. An anti-windup gain is implemented because integral term accumulates a significant error during the rise (windup), this creates a large overshoot, a slow settling time, and, sometimes, even instability in the speed response. A method used to compensate this phenomenon is tracking back calculation [10]. In the linear range, the error is integrated and the difference between the saturated and the unsaturated control signal is used to generate a feedback signal. This signal can control properly the integral state in the saturation range. It may seem advantageous to choose a very large value for the anti-windup gain K_a because the integrator can be limited quickly. If the anti-windup gain is big, a spurious error can cause input saturation and accidentally reset the integrator. For the design of the control system, it is assumed an anti-windup gain of $K_a = 10$. Evaluating closed loop response to a step input, it gets an overshoot of 2.22 % and a setting time of 130 seconds.

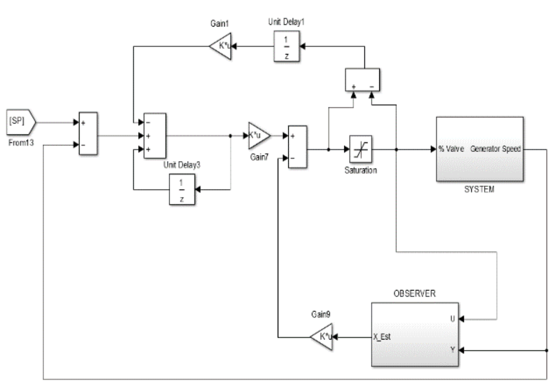

Figure 3. Block diagram of the control strategy

IV. RESULTS

The LQG controller is implemented in Delta V DCS. The pseudocode that depicts the operating principle of the algorithm is shown in Table 2, where the matrices G_L, H_L and C_L correspond to the state space representation of the mathematical model.

TABLE II. PSEUDOCODE LQG CONTROLLER

```
SP = Read Setpoint
PV = Read process value
en =  SP – PV
% Anti-windup gain
Vk = en + Vk_1 – Ka*Du
un = Ki*Vk – K*Xob_1
if un > Umax
   U = Umax
If un > Umin & U<Umax
   U = un
If un < Umin
   U = Umin
% Observer
Xob = (GL – L*CL)*Xob_1 + HL*U + L*PV
Vk_ 1 = Vk
Du = un - U
Xob_1 = Xob
```

The strategy of control is suitable for startup procedure and it can be applied for nominal work point (the range of speed is 0 RPM to 1500 RPM). Figure 4 shows the transient response of the generator speed and the signal control for different values of the reference signal. As seen in Figure 4, the signal that corresponds to generator speed, oscillates around the set point when steady state value is reached, this oscillations are due to changes of steam pressure in the pipeline as shown in Figure 5.

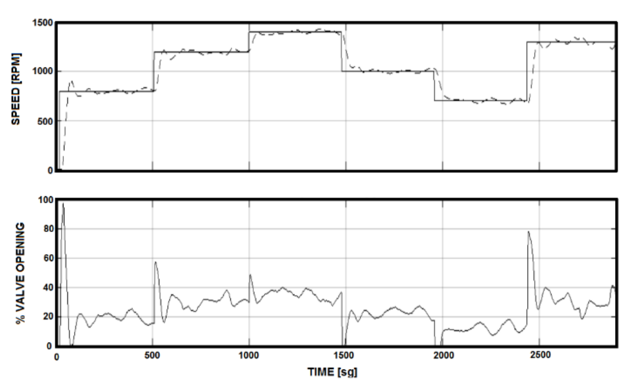

Figure 4. Transient response of LQG control. a) Speed generator b) Control signal

The transient response of the LQG controller is analyzed by making variations in the field resistance of the DC generator. By decreasing this parameter, the mechanical speed of the turbine increases, therefore, it is expected that the proportional valve should decrease its opening percentage. As seen in Figure 6, for a set point of 1000 RPM, at the 120 seconds, the field resistance is changed to 60 % over its nominal value and the controller stabilizes the signal in 70 seconds. At the 950 seconds, the resistance value is changed to 20 % over its nominal value and the signal stabilizes in 120 seconds. At the 1400 seconds, the resistance is set to its

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nominal value and the speed has a strong transient response, then the controller stabilizes the signal in 200 seconds.

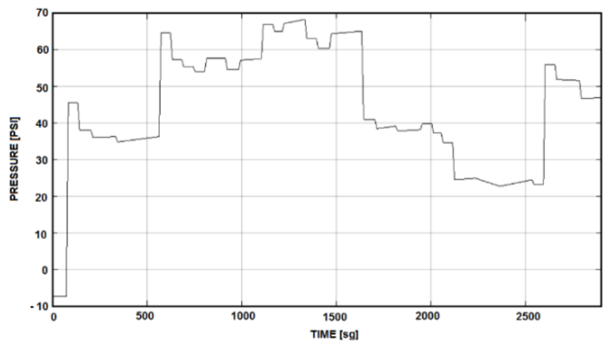

Figure 5. Steam pressure in pipeline

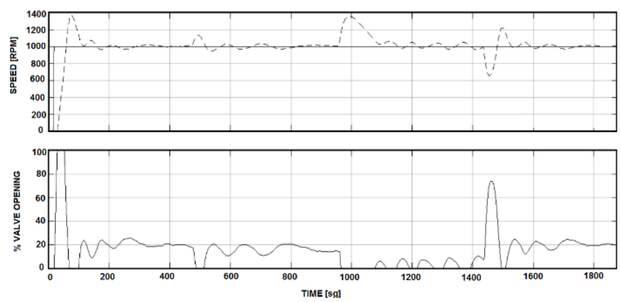

Figure 6. Transient response of the speed generator due to changes of field resistance in the generator

A proportional integral (PI) controller (32) was designed based on the dynamic model of steam turbine coupled to the DC generator. Figure 7 shows the transient response of generator speed and the control action, for the same speed range. The PI controller has a greater overshoot than the LQG control and the changes in the steam pressure in the pipeline considerably affect the speed around the reference point.

$$G_c(z) = 0.1188 + \frac{0.0012}{1-z^{-1}} \quad (32)$$

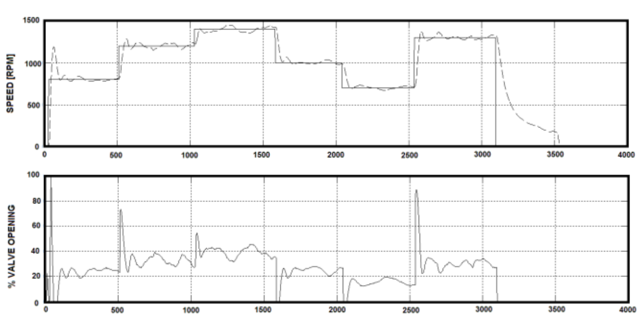

Figure 7. Transient response of PID control. a) Speed generator b) Control signal

V. Conclusion

In this paper, it was presented the design, test and comparison of two different control strategies applied to a steam turbine coupled to a DC generator. The dynamic model of the system was obtained using an optimization algorithm that is based on the quadratic sequential programming method. The turbine model was approached to a first order system with delay and the DC generator model was approached to a second order transfer function. Then, two control strategies were designed based on the dynamic model: PI control and LQG control. The obtained results show that the LQG controller has a better performance than the PI controller considering three main points: changing the set point, the transient response is quicker and smoother with the LQG controller; if the pressure changes in the steam line, the speed variations around the set point are smaller with the LQG controller; making changes in the value of the field resistance of the DC generator, results in oscillations in the speed, such oscillations are smaller with the LQG controller. For further research, it can develop a dynamic model that contemplates the thermal effects present in the elements inside the turbine and test other control strategies like fuzzy logic and predictive control.

References

[1] M. Ismail, "Adaptation of PID controller using AI technique for speed control of isolated steam turbine", Proc. IEEE Symp. Electronics, Communications and Computers (JEC-ECC), IEEE Press, March 2012, doi: 10.1109/JEC-ECC.2012.6186962.

[2] F. Wang, Z. Yao, W. Wang, J. Huo, X. Zhao, "Research on Steam Turbine Speed Fuzzy Self-Tuning PID Control during Island Formation", Proc. IEEE Symp. Electrical and Control Engineering (ICECE), IEEE Press, June 2010, doi: 10.1109/iCECE.2010.435.

[3] Q. Zhu, Y. Zhang, J. Zhang, "Design Of Fuzzy Neural Network Controller For Marine Steam Turbine System", Proc. IEEE Symp. Fourth International Conference on Natural Computation (ICNC'08), IEEE Press, Oct. 2008, doi: 10.1109/ICNC.2008.637.

[4] F. A. Alturki, A. B. Abdennour, "Neuro-fuzzy control of a steam boiler-turbine unit", Proc. IEEE Symp. International Conference on Control Applications, IEEE Press, Aug. 1999, doi: 10.1109/CCA.1999.801041.

[5] M. Kordestani, M. S. Khoshro; A. Mirzaee, "Predictive control of large steam turbines", Proc. IEEE Symp. Control Conference ASCC. IEEE Press, June. 2013, doi: 10.1109/ASCC.2013.6606366.

[6] M. Gyun; Y. Rok, Y. Joon, "Design of an adaptive predictive controller for steam generators", Proc. IEEE Symp. IEEE Transactions on Nuclear Science, IEEE Press, Feb. 2003, doi: 10.1109/TNS.2002.807854.

[7] M. Dulau, D. Bica. "Mathematical modelling and simulation of the behaviour of the steam turbine". The 7th International Conference Interdisciplinarity in Engineering (INTER-ENG), ScienceDirect, vol. 12, pp. 723–729, 2014, doi: 10.1016/j.protcy.2013.12.555.

[8] K. Ogata. "Sistemas de control en tiempo discrete". Ed. Pearson Educacion, ISBN 0-13-034281-5, pp. 596 – 609, 1995.

[9] R. Burns. "Advanced Control Engineering". Ed. Butterworth Heinemann, ISBN 0750651008, pp. 288 – 299, 2001

[10] X. Lan Li, J. Gyu Park, H. Beom Shin. "Comparison and evaluation of anti-windup PI Controllers", Journal of Power Electronics, vol. 11, January 2011, doi: 10.6113/JPE.2011.11.1.045.