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Methodology for the MDL Model Implementation of the Dinorwig Hydroelectric Plant

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ABSTRACT
Nowadays the importance of the Hydroelectric Plants (HP) lies on the energy production, generating from 30 to 60 percent of the energetic balance. As a result, the efficient exploitation is mainly the cause of the implementation of control algorithms that frequently need real time debugging. The HP that will be the studied is the Dinorwig plant, located on the north of Wales, United Kingdom.
In order to solve the problem, a new methodology has been foreseen, based on using as equals or emulate the HP through a differential equation of the mathematical model, at hardware level trough electronic devices.
***Keywords*-**Bilinear transform, Dinorwig, Hydroelectric Plant, Non-variant impulse method

I. Introduction

The importance of the hydroelectric plants lies on the energy production, generating from 30 to 60 percent of the energetic balance of most countries. Their efficient exploitation require the implementation of control algorithms that frequently need real time debugging.

The HP that is going to be studied is the Dinorwig Plant, located on north Wales, United Kingdom. It possess six 300 MW turbines and requires the implementation of several control systems, which entails the search for mechanisms that allow the realization of tests without affecting the function of the real system.

Exists a mathematical model of the HP that allows testing to a simulation level, being Simulink an efficient tool for that, however it represents a problem because does not allow real time simulation.

In order to solve that problem, a new methodology has been foreseen, based on trying to replicate or emulate the HP through a differential equation of the mathematical model at hardware level through electronic devices. The differential equation represents the relation between the input and output of the system on discrete time.

Unlike a simulation, which is pretended to represent the ideal operation of a system, the emulation will allow an imitation of the plant.
Due to the necessity of implement control algorithms, it is proposed an emulation of the HP, using as a main device an FPGA from Xilinx. The present work shows the methodology to follow for the implementation of the MDL model of the Dinorwig Hydroelectric Plant.

II. Dinorwig Hydroelectric Plant

In every industrial sector, the highly competitive markets force the companies to have optimal and reliable processes. On the electric supply sector, the market has been constantly changing the energy network, which is formed by producers and consumers. It is necessary to have a good real time balance between consume and production in order to insurance the quantity and the quality of the electric supply. Although, for business means, it is common to consider an adjustment on periods of 30 minutes, actually the demand varies on second fractions, giving as result that the stations that feed up the national network, get to function on diverse operating conditions to maintain the balance of the power. In addition, the current industry is facing an increase in energy demand of electricity supply at low cost and good quality, due to financial and reglamentary changes. That means improvement on velocity and correctness of response to perturbations on the charge to maintain the financial utility. In order to insurance the energy supply quality, voltage and frequency the values must be maintained between the required terms, such as the harmonic lows, minimum voltage depression and pikes. For the Great Britain national supply, where it is located the hydroelectric plant under study, the terms to meet on voltage and frequency are: 230 volts +10/-6% (residential) and 50 hertz +/- 0.5 Hz.

The hydroelectric plants are designed to be highly flexible on operation and capable of taking or giving up the charge quickly, resulting in extensive use for the frequency control of the electricity network and in the charge handling. Dinorwig is an electrical station located north Wales on the United Kingdom, has six reversible turbines of 300 MW, therefore is one of the biggest of his class on Europe and is used to provide auxiliary electric services to the british national network. The plant consists on a main tunnel that provides water from a superior lake to a collector.

The collector feeds six conduction tubes (penstocks) (Fig. 1)[1],[2].

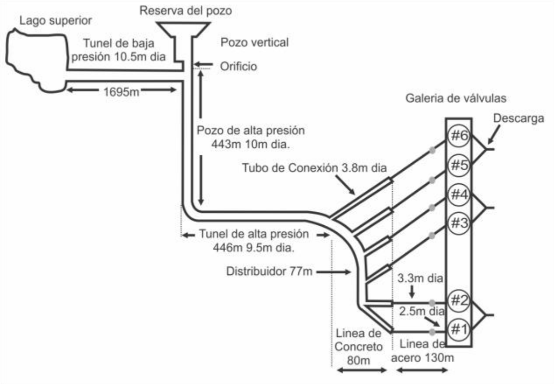

Fig. 1. Schematic diagram of the hydroelectric station (not on scale)

III. Hybrid Model

Dynamic hybrid systems are those systems that contain continuous and discrete components that can be found on the states, as the input and the output [3]. This type of systems has been modeled on different ways: as a state transition graph (with a continuous dynamic on every state), or as a set of differential equations, that include variables that can take continuous or discrete values.

3.1 Mixed Logical Dynamical Systems (MDL)

A way of modeling hybrid dynamic systems is through a mixed logical dynamical system. Eq. 1[4],[5].

$$\begin{aligned} X_{K+1} &= Ax_k + B_1u_k + B_2\delta_k + B_3Z_3 \\ Y_k &= Cx_k + B_1u_k + B_2\delta_k + B_3Z_3 \\ E_1x_k &+ E_2u_k + E_3\delta_k + E_4Z_3 \le g \end{aligned} \quad (1)$$

Where $x_k = [x_k^r \quad x_k^b], x_k^b \in \mathbb{R}^n$ is the continuum part of the state and $x_k^b \in \{0,1\}^{n_b}$ is the discrete part. Similarly $y_k = [y_k^r \quad y_k^b], y_k^r \in \mathbb{R}^m$ is the output continuum part and $y_k^b \in \{0,1\}^{m_b}$ the discrete part. Also $u_k = [u_k^r \quad u_k^b], u_k^r \in \mathbb{R}^l$ is the input continuum part and $u_k^b \in \{0,1\}^{l_b}$ the discrete part. Finally, $Z_k \in \mathbb{R}^{r_r}$ and $\delta_k \in \{0,1\}^{r_b}$ are auxiliary variables, and $A, B_1, B_2, B_3, C, D_1, D_2, D_3, E_1, E_2, E_3, E_4, g$ are the model parameters.

On the MDL systems the logical expressions of the discrete part of a hybrid system are expressed as equability restrictions or inequalities. That is to say, through the logical variables δ_1 and δ_2 that can take values 0 or 1, upper bounds M, lower bounds m, and/or positive ϵ tolerance, any logical expression can be converted into an equality or inequality, Ec. 2, Ec. 3, Ec. , Ec. 4 [6], [7].

$$\begin{aligned} L_1 \wedge L_2 \; es\; equivalete\; a\; \delta_1 + \delta_2 \ge 1 \\ L_1 \vee L_2 \; es\; equivalete\; a\; \delta_1 = 1, \delta_2 = 1 \end{aligned} \quad (2)$$

$$\delta_3 = \delta_1\delta_2 \; es\; equivalente\; a \begin{cases} -\delta_1 + \delta_2 \le 0 \\ -\delta_2 + \delta_3 \le 0 \\ \delta_1 + \delta_2 - \delta_3 \le 1 \end{cases} \quad (3)$$

$$y =$$

$$\delta f(x) \; es\; equivalente\; a \begin{cases} y \le M\delta \\ y \ge m\delta \\ y \le f(x) - m(1-\delta) \\ y \ge f(x) - M(1-\delta) \end{cases} \quad (4)$$

1. MDL Model from a HP Francis Turbine

The development of an emulation system of the Dinorwig hydroelectric plant begun taking the MDL mathematical model from a turbine or active unit $G_1(s)$, which consist on a transference function (TF) on the continuum S domain (Ec. 5) [8],[9].

$$G_1(s) = \frac{y(s)}{x(s)} = \frac{-2.358s+3.395}{0.076s^3+0.8204s^2+2.788s+3.031} \quad (5)$$

Because the TF is in the continuum domain, it is been made the programming of a script in MATLAB to convert it to discrete domain Z and obtain a TF through the non-variant impulse method (Eq. 6) and through the Tustin method or bilinear transform (Eq. 7)

$$\frac{y(z)}{x(z)} = \frac{-0.00294z+0.003116}{0.076z^3+0.1977z^2+0.04935} \quad (6)$$

$$\frac{y(z)}{x(z)} = \frac{-0.009792z^3-0.009212z^2+0.01095z+0.01037}{z^3-2.6z^2+2.25z-0.6487} \quad (7)$$

The programming of the TF was done in Simulink Eq. 5, Eq. 6 and Eq. 7 (Fig.2), to determine the solution of every TF, at one unitary stair.

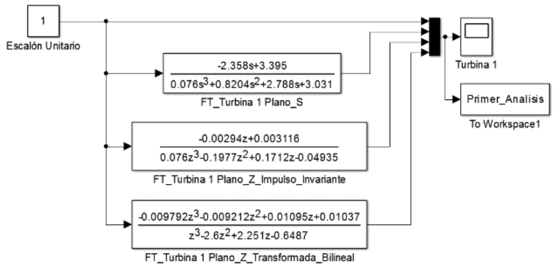

Fig. 2. Transference Functions on Simulink

Performing the first analysis in an arbitrary point where the answer to every method is stable, is possible to establish that the response amplitude of the non-variant impulse method is nearest than the amplitude of the bilinear transform to the original TF in the continuum S domain.

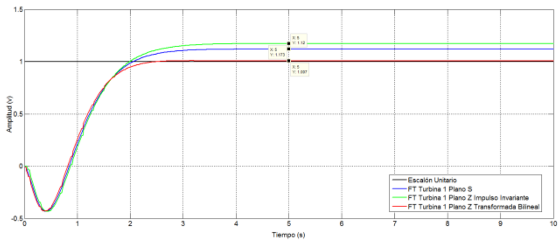

Fig 3. First analysis of the response of every method

In order to determine the behavior of each method in front of a change, it is been decided to narrow the coefficients of each TF by performing a rounding to four digits (Fig. 4).

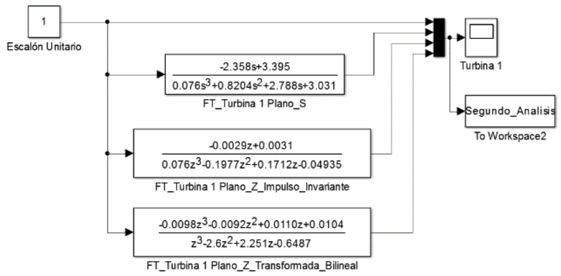

Fig. 4. Transfer Functions on Simulink with rounding.

Performing the second analysis at the same arbitrary point (Fig. 5), it is been determined that the non-variant impulse method considerably increases its amplitude compared with the bilinear transform, because of it, it is been decided to use the bilinear transform for the MLD mathematical model of the Hydroelectric Plant with two turbines.

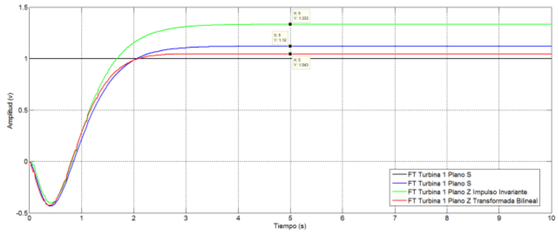

Fig. 5. Second analysis of the response of every method

IV. MDL Model Differential Equation

Given the transference function on the discrete domain Z (Ec. 7), a modification has been made to the exponents to obtain a transference function in terms of the negative exponents (Eq. 8).

$$\frac{G_1(z)}{I_n(z)} \frac{-0.009792-0.009212\,z^{-1}+0.01095\,z^{-2}+0.01037\,z^{-3}}{1-2.6z^{-1}+2.25z^{-2}-0.6487\,z^{-3}} \quad (8)$$

The output has been cleared [eq] to obtain the differential equation of one turbine MDL model (Eq. 9). A differential equation is a mathematical expression, that provides an answer based on the relation between the coefficients with the input and/or output of a system.

$$G_1(z)\ 0.009792 I_n(z) - 0.009212z^{-1}I_n(z)0.01095z^{-2}I_n(z) + 0.01037z^{-3}I_n(z) + 2.6z^{-1}G_1(z) - 2.251z^{-2}G_1(z) + 0.6487z^{-3}G_1(z) \quad (9)$$

Then, it is been made a block diagram of the differential equation (Fig. 6). The diagram permits to establish an analogy with the direct structure I of an infinite response to impulse digital filter (IIR). The structure is not canonical because of the need of six delays (Blocks z-1) to implement a third order TF.

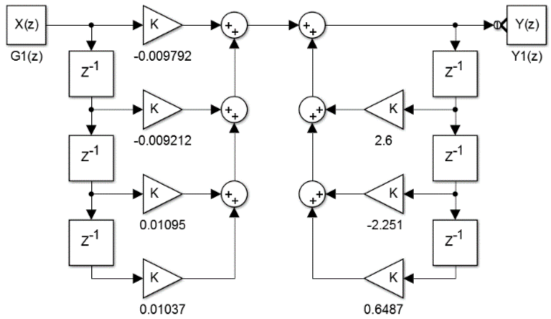

Fig. 6. TF on Direct Structure I

Therefore, a modification has been made to the delays blocks on the direct structure to obtain other non-canonical direct structure I (Fig. 7), that allows later some reduction.

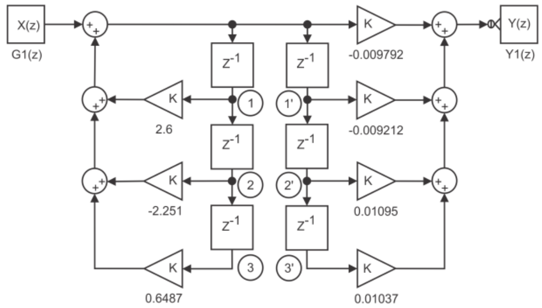

Fig. 7. Direct Structure Transpose I

The signal on the node 1 and 1' is the same, hence, the two first delays can be group in a single delay. The same way, signal on node 2 and 2' is the same, consequently the two next delays are group also. Following the same reasoning, is possible to group both delays of the lower part to finally obtain the direct canonical structure II (Fig. 8).

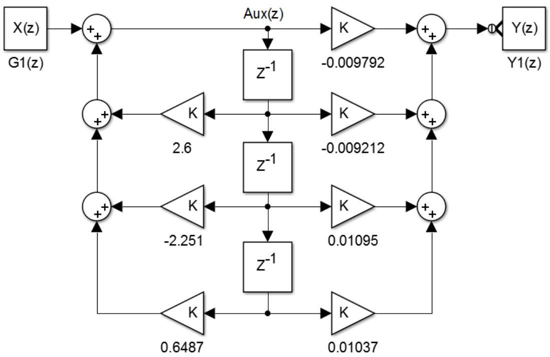

Fig. 8. TF on Direct Form II

The TF represented on the differential equation of the direct structure I (Ec. 9) and the differential equation (Ec. 10) correspondent to direct structure II, it will be used later to determine the resource consumption and select an appropriate FPGA.

$$\begin{gathered} Aux(z) = -0.009792I_n(n) - 0.009212z^{-1}Aux(z) + 0.0109z^{-2}Aux(z) + 0.01037z^{-3}Aux(z) \\ G_1(z) = Aux(z) + 2.6z^{-1}Aux(z) - 2.251z^{-2}Aux(z) + 0.6487z^{-3}Aux(z) \end{gathered} \quad (10)$$

Through a MATLAB script it is been made a desktop test on both differential equations. The desktop test is a numerical tool that allows verification, that an algorithm meets the specs with runs without executing it on a compiler. This procedure will allow to realize error debugging on the system implementation.

The desktop test of the TF of the direct structure I and the TF of the direct structure II, consist on 100 runs of a unitary stair input. It is been determined that the answer is the same (Fig. 9), due to the variation relays on the used resources.

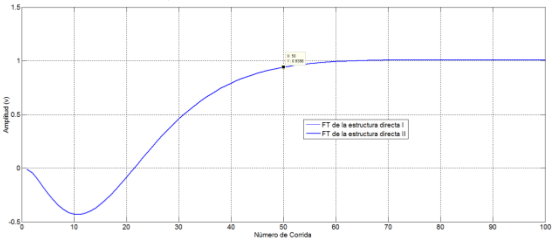

Fig. 9. Desktop test of the TF on direct form I and direct form II

V. Conclusion

The present work allowed to establish a methodology for the implementation of the Dinorwig Hydroelectric Plant MDL model. It is been established a procedure for the selection of a transform method from Plain S to Plan Z.

Likewise, a differential equation model has been obtained. It has been realized an analogy with an infinite response to impulse digital filter (IIR). Later, a modification on the delay blocks has been made to obtain the canonical structure. Finally it has been demonstrated that the procedure does not affect the response of the model regarding to the non-canonical structure.

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