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System identification applied to a single area electric power system under frequency response

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ABSTRACT

This research paper proposes a methodology to apply identification methods to find a simplified model of three different governors in a single area electric power system (SAEPS). A SAEPS with different governors-turbine is presented: a hydraulic turbine, a steam turbine and a steam reheat turbine. In this same investigation, an analytic reduction has been performed, a fifth order system was found analytically, thus a transfer function equivalent to the three different governor-turbine elements was obtained, this equivalent transfer function models the complete behavior of the three devices. Two systems identification (SI) algorithms have been proposed to apply them to this generic subspace state-space (N4SID) and generalized poisson moment functionals (GPMF) electrical system, these presented similar results. The results of the performance and simulation analysis exhibit that using the SI technique, fifth, fourth and third-order systems were obtained that graphically show a very small estimation error compared to the original signal, this fact could be check simulating the simplified models using the same input-output data. The results are presented in a table that shows a comparison of the model respond the fifth, fourth, third and second-order systems.

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1. INTRODUCTION

The electrical industry is constantly changing and evolves technologically every day, trying to find and improve the efficiency and reliability with which electrical energy is produced. So many modelling techniques and simulation tools have been used to implement the processes in the production of electric energy and make this faster and more precise. The main focus of the dynamics of the turbine governor is to present the initial response produced in the seconds just after a disturbance of this network [1]. In many papers different techniques have been applied to model and simplify the turbine governor, in several cases, they are intelligent controllers, adaptive controllers and proportional-integral-derivative (PID) controllers [2]-[4]. Although traditional PID controllers do not respond efficiently when there are nonlinearities in complex processes. A simplified model of an area with different generation is of great importance when conducting studies for frequency control and stability of the electrical system. Thus, it is possible to understand that, the frequency response is a primary aspect of the performance of the power system (PS) [5]-[7].

Obtaining a simplified model of the turbine governor is critical when PS stability studies are conducted and used primarily for frequency stability, voltage stability, transient angles, small-signal stability and control, several authors have generally conducted research and studies to model the turbine governor [8]-[12]. This research proposes a structure to apply systems identification (SI) methods to find a simplified model of three governors in a single area electric power system (SAEPS). This paper presents a SAEPS with different types of electrical generation that are: hydraulic turbine, steam turbine, and a steam reheat turbine. To do this, it will be necessary to perform an analytic reduction and find the minimum order of the system, this equivalent transfer function will model the complete behaviour of the three devices in parallel. Two SI algorithms that will be used to the generic electrical system have been proposed, these algorithms are called generalized poisson moment functionals (GPMF) and numeric algorithms for the subspace state-space (SS) SI (NS4SID), which will be explained later.

2. METHOD

The SI process is a method, art and science of structure mathematical models of dynamic systems taking the measures of the systems output and input signals [13]. The following describes the methodology needed to find a simplified model of a single area power control, where there may be N units with different kinds of governors. The process of SI, involves the following steps corresponding for the development of the proposed methodology are described: i) Step 1: The input-output variables of the set of N governors of an electric PS are selected, this will provide the corresponding input-output data set, some data processing is performed if necessary; ii) Step 2: To estimate, the SI takes the input and output data and applies the identification algorithm to find the system parameters that show a minimum error; iii) Step 3: To analyze the predicted models, the best way is to simulate in dedicated software, for this case Matlab Simulink will be used, applying the same input that was used to the original model and thus output is obtained; and iv) Step 4: For the validation of the parameters found by the identification algorithm, it is necessary to compare the output obtained from step 4, then calculate the estimation error to see the performance.

2.1. Simplified modelling

The procedure for modeling a system requires, take the measurements of output and input variables from the primal SAEPS in frequency or time domain and the model structure need to be selected: transfer function (TF) or SS. The SI uses the output and input measurement of the variables of a system to estimate the values of the adaptable parameters in a specify model frame. The measured data must adequately reflect the behavior of each system, since the obtaining of its parameters depends on this, in most cases, it depends on the amount of data. Therefore, it is requiered to apply in the frame of the candidate model an estimation methodology to obtein the value of the adjustable parameters, the next step would be to evaluate the estimated model by validation.

As referred to above, the motivation of this document is to discover an equivalent model of *n* SAEPS that can substitute the different kinds of a governor that the area contains. To demonstrate this technique, a SAEPS with three kinds of the governor are proposed, which are: the steam turbine, the Steam reheat turbine and the hydraulic turbine, Figure 1.

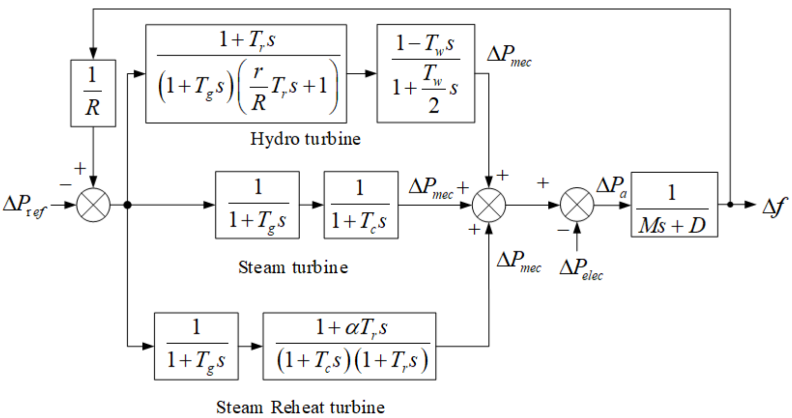


Figure 1.. SAEPS with a different generation source

2.2. Single area model description

Normally, an isolated electrical area, where a generating unit or a group of generating units is placed nearby to distribute electricity in the same area is called a SAEPS. There is no other generator unit that is far away, only the generating units present in that area are responsible for maintaining the desired frequency in normal and abnormal conditions [14]. The general generator-load dynamic relation between the frequency deviation (Δf) and the incremental mismatch power *(ΔPm−ΔPL)* is denoted as (1).

$$\Delta P_m(t) - \Delta P_L(t) = 2H\frac{d\Delta f(t)}{dt} + D\Delta f(t) \tag{1}$$

Where ΔPm the mechanical power change, ΔPL the load change, Δf is the frequency deviation, D is the load damping coefficient and M the inertia constant. Thus, the damping coefficient is in general defined as a per cent change in load for a one percent change in frequency. Hence, a value of one and a half for D imply that a one percent change in frequency give rise to a one and a half percent change in load. Applying the Laplace transformation, it is described as (2).

$$\Delta P_m(s) - \Delta P_L(s) = 2Hs\Delta f(s) + D\Delta f(s) \tag{2}$$

In general, low order models have been proposed for the representation of the dynamics of turbines and generators (Gt and Gg) for use in the frequency analysis of the PS and the control design. The slow and fast dynamics of the boiler system and the generator system are generally not included in the models used. The block diagram scheme of the speed controller and the turbine for the steam and hydraulic regulator units appropiate for the load frequency control analysis, is shows in Figure 2. Where R shows the regulation of the speed thanks to the action of the regulatoris and is the speed velocity characteristic [14], [15]. The TFs that are shown next to the governor-turbine schemes in Figure 2, are the equivalences and define the behaviour of these elements

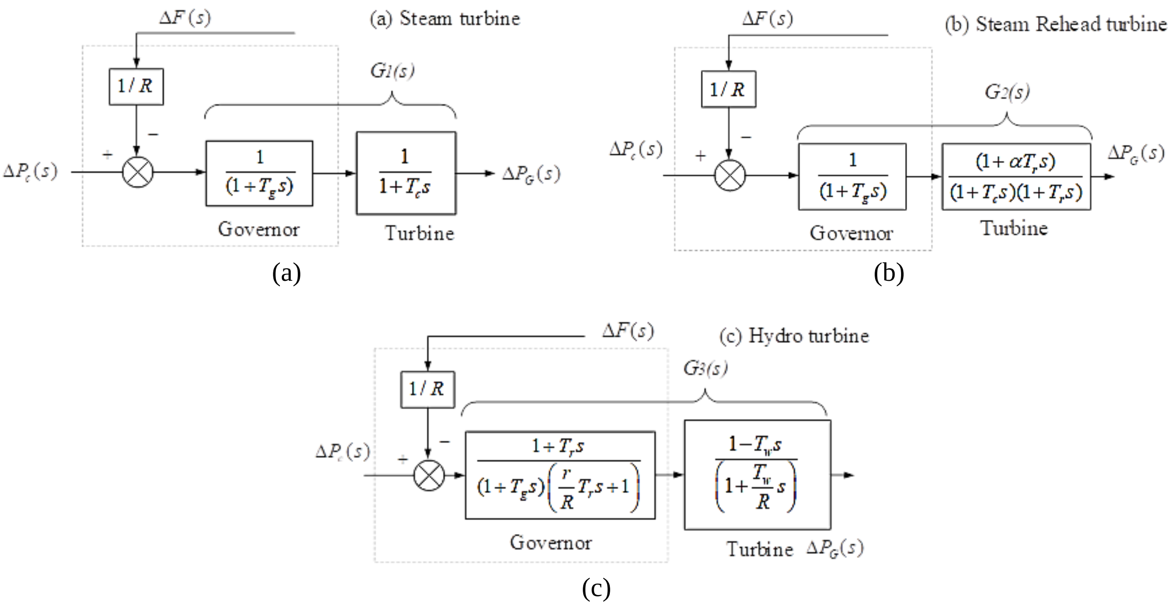


Figure 2. Different governors in a SAEPS: (a) steam turbine, (b) steam rehead turbine, and (c) hydro turbine

2.3. Analytical equivalent

In the (3) and (4), it can be observed that the three types of the governor can be reduced by mathematical operations, this is possible and relatively simple because, we are working with a singular area PS, this would not be so easy to be an *n* area PS. This is one of the reasons why a parameter estimation algorithm is proposed.

$$G_{ov} = G_1(s) + G_2(s) + G_3(s) \tag{3}$$

substituting:

$$G_{OV} = \frac{1}{(T_{\ c}s+1)(T_g s+1)} + \frac{T_r a s+1}{(T_{\ c}s+1)(T_g s+1)(T_r s+1)} - \frac{(T_r s+1)(T_w s-1)}{(T_{\ g}s+1)\left(\frac{T_w s}{2}\right)\left(\frac{T_r r s}{R}+1\right)} \quad (4)$$

The analytical result of the reduction is shown in (5), as can be seen, all the variables involved in the three governors were used, so that it results in a fifth-order TF.

$$G_{ov} = \frac{(\alpha_4 s^4+\alpha_3 s^3+\alpha_2 s^2+\alpha_1 s+\alpha_0 R)}{(\beta_5 s^5+\beta_4 s^4+\beta_3 s^3+\beta_2 s^2+\beta_1 s+\beta_0 R)} \quad (5)$$

where:

$$\alpha_4 = -2RT_cT_r^{\ 2}T_w$$
$$\alpha_3 = 2RT_cT_r^{\ 2} - 2RT_r^{\ 2}T_w + T_r^{\ 2}T_wr + T_r^{\ 2}T_war - 4RT_cT_rT_w$$
$$\alpha_2 = 2RT_r^{\ 2} + 2T_r^{\ 2}r + 4RT_cT_r - 2RT_cT_w - 3RT_rT_w + 2T_rT_wr + 2T_r^{\ 2}ar + RT_rT_wa$$
$$\alpha_1 = 2RT_c + 6RT_r + 4T_rr + 2RT_ra$$
$$\alpha_0 = 6$$
$$\beta_5 = T_cT_gT_r^{\ 2}T_wr$$
$$\beta_4 = 2T_cT_gT_r^{\ 2}r + T_cT_r^{\ 2}T_wr + T_gT_r^{\ 2}T_wr + RT_cT_gT_rT_w + T_cT_gT_rT_wr$$
$$\beta_3 = 2T_cT_r^{\ 2}r + 2T_gT_r^{\ 2}r + T_r^{\ 2}T_wr + 2RT_cT_gT_r + RT_cT_gT_w + RT_cT_rT_w + RT_gT_rT_w + 2T_cT_gT_rr + T_cT_rT_wr + T_gT_rT_wr$$
$$\beta_2 = 2T_r^{\ 2}r + 2RT_cT_g + 2RT_cT_r + 2RT_gT_r + RT_cT_w + RT_gT_w + RT_rT_w + 2T_cT_rr + 2T_gT_rr + T_rT_wr$$
$$\beta_1 = 2RT_c + 2RT_g + 2RT_r + RT_w + 2T_rr$$
$$\beta_0 = 2$$

Furthermore, the model can be reduced by replacing the values of each variable in the TFs of each type of governor, the Table 1 shows the parameter and the corresponding values. The values are substituted in (3) TF and, therefore, it is possible to obtain a reduced equivalent analytical model, in (6) presenting the necessary operation.

$$G(s) = \frac{1}{\left(\frac{s}{2}+1\right)\left(\frac{s}{10}+1\right)} + \frac{7s+1}{\left(\frac{s}{2}+1\right)\left(\frac{s}{10}+1\right)\left(\frac{266s}{5}+1\right)} + \frac{\frac{21s}{10}+1}{\left(\frac{s}{2}+1\right)\left(\frac{s}{10}+1\right)(7s+1)} \quad (6)$$

Must perform mathematical operations to reduce (6), so the result is a simplified expression which is seen in (7). Only a fourth-order TF is used to represent the complete system.

$$G_{OV_2} = \frac{53312s^2+12950s+300}{1862s^4+22645s^3+40857s^2+6080s+100} \quad (7)$$

The data used as input is the Δf and output the mechanical power *Pm*, are used in the identification algorithm to calculate the parameters for the simplified model of the three areas, the system order was determined by analytical mathematical reduction. The SI need it that the data identify the significant dynamics of the system [16], this can be achieved with a large amount of data, in this document, tests are made with different data groups.

Table 1. Parameter values for SAEPS

Parameters	Tg	Tc	Tr	α	Tw	R	r
Value	0.1	0.5	7	2.1	3	0.05	0.38

3. STRUCTURE OF THE SYSTEM IDENTIFICATION MODEL

A model structure establishes a mathematical association of the input and output variables that have unknown parameters [17]. In SI, the order of the system is known in many cases. The order is the only structural parameter, in a single input and single output system, on the other hand in multivariate systems, there can be different structural parameters [18]. These model structures can be the TFs with adjustable zeros and poles, the SS equations with unspecified system matrices and the non-linear parametrized functions. The process of identifying the system requires put forward a model structure and put on the estimation methods to define the numerical values of the parameters of the model.

To choose the model structure is viable to use one of the next approaches: The model must be able to use the measured data and be as simple as possible; in vectors, it is most appropriate, several mathematical structures are tested in the algorithm. This kind of modelling approach it is known black-box modelling. A determined structure is necessary for the model, but it does not know the numerical values of its parameters. It is also possible to illustrate the framework of the model in the form of a group of equations or SS system and to estimate the values of the parameters from a set of data. Thereby the focusing is also called gray box modeling. The following identification methods for parameter estimation have been used in this document.

3.1. Generalised poisson moment functionals (GPMF)

Currently there is an algorithm to estimate parameters that use a generalized PMF approach. This algorithm increases a vector of parameters by the size of the system order n terms related to the preliminary conditions. To estimate both terms: parameters and states, the observable phase variable form is used to represent the SS of a system. One of the advantages of this way of representing the observable phase variable is that the details that relate to the initial conditions in the parameter vector are the so-called initial states. Consequently, these states are estimated together with the parameters that the system has. Thus, each state vector at each instant of time afterwards is estimated at the same time as the parameters by recursively applying the initial states that were estimated [19]-[21].

3.2. Numeric algorithms for subspace state-space system identification (NS4SID)

The NS4SID formulated by Van Overschee and De Moor, perform calculations of parameterization of the model, resolving for the matrices A, B, and C. The algorithm is noniterative and does not be conditional on a priori parameterization. An advantage of this method is that avoids problems such as local minima, initial condition bias and always find a convergent system. The SI is funded on singular value decomposition and QR which guarantee that the estimated linear time-invariant model is stable. The system order is the only information required for the identification process [22]-[24].

3.3. Model parameters estimation

The SI make a stimate of model parameters by minimizing the error among the model output and the measured response. Thus, the output y_{model} of the linear model is represented by:

$$y_{model}(t) = T_f u(t) \tag{8}$$

where T_f is the trasnsfer function. Thereby to establish the T_f, the algoritm minimizes the difference between the measured output $y_{meas}(t)$ and the model output $y_{model}(t)$. A weighted norm of the error $e(t)$, is the minimization criterion, where:

$$e(t) = y_{meas}(t) - y_{model}(t) \tag{9}$$

$y_{mod\ el}(t)$ is one of the subsequent: Simulated response (predicted response of the model for a given input $u(t)$, $T_f u(t)$ of the model for a given input $u(t)$ and past measurements of output $y_{meas}(t-1), y_{meas}(t-2)$,…). Therefore, the error $e(t)$ is called prediction error or simulation error. The estimation algorithm fiting the parameters in the model structure T_f to achieve that the norm of this error is as small as achievable [25].

4. SIMULATION STUDIES AND RESULTS

This section shows the simulations and the results, the following case are proposed. Figure 3shows the input and output of the three-unit model; the sample time is 0.1 ms. The Δf is used as input because in this variable it is appropriate due to its nature sensitive to changes by power, and disturbances, the sum of the mechanical powers Pm was used as an output, because it represents the response of each of the governors. These inputs and outputs are shown for the experiment. An experiment using the algorithms N4SID and GPMF, expected to verify the system order that produces the smallest approach error. The experiments characteristics are defined in Table 2. Where ΔP_{elec} load power disturbance and ΔP_{ref} is a reference load power. The graphical results for each case of the experiment are shown in Figures 4 to 7. Each of these figures is a case where it is possible to observe measured and simulated model output and measured minus simulated output.

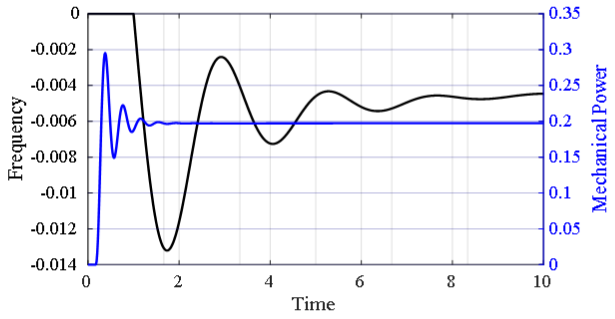
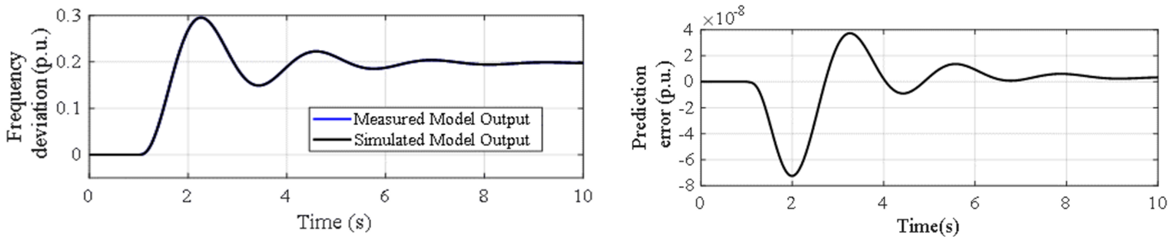


Figure 3. Frequency and mechanical power

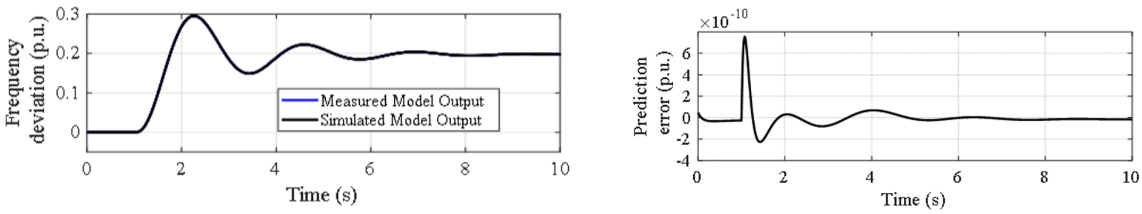
Table 2. Summary of experiment features

	Experiment		Experiment
Simulation time	60s	Time format	Continuous time
ΔP_{elec}	0.2	Initial condition Algorithm	Zero
ΔP_{ref}	0	Initial Method:	N4SID, GPMF
Estimation data	Time – domain	Data	600001
Staring time	0 s	First Case:	Fifth order
Sample time	0.0001	Second Case	Fourth order
Number of polos	5,4,3,2	Third Case	Third order
Number of Zeros	4,3,2,1	Fourth Case	Second order



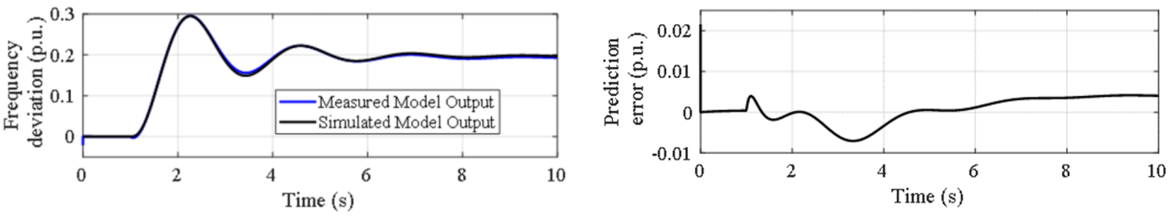
(a) (b)

Figure 4. Experiment first case: (a) measured and simulated model output and (b) measured minus simulated output



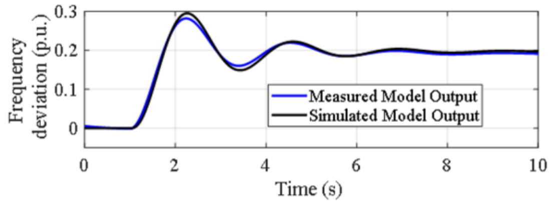
(a) (b)

Figure 5. Experiment second case: (a) measured and simulated model output and (b) measured minus simulated output

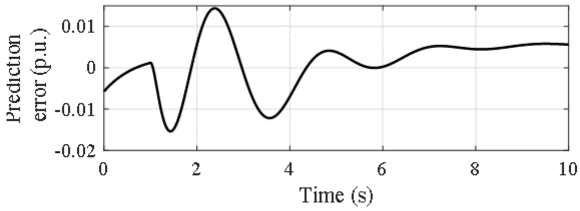


(a) (b)

Figure 6. Experiment third case: (a) measured and simulated model output and (b) measured minus simulated output



(a)



(b)

Figure 7. Experiment fourth case; (a) measured and simulated model output and (b) measured minus simulated output

4.1. Presentation of result

A system TF with a different order was proposed. The SI achieved the following TF parameters are represented in Table 3, is possible notice the result obtained from experiment, in this experiment is shown: the order of the System, the estimated values of each parameter depending on the order of the System, the fit to estimation data (FIT) and the final prediction error (FPE) for an estimated model. Analytically, the order of the System was calculated, based on the fifth-order system, when substituting numerical parameters, the order was reduced to 4. Experiment uses a complete signal with a sampling of 0.1ms, simulation time of 60 seconds, disturbance of 0.2 and Δ_{ref} is 0. It can be concluded that for experiment, case 1 (fifth-order), had the best performance in terms of FIT and FPE.

Table 3. Model parameter comparation

	Experiment 1				Model
Order	5	4	3	2	-
α_4	-6.504×10^{7}	-	-	-	-
α_3	-11.44×10^{12}	-0.02864	-	-	-
α_2	-2.288×10^{16}	-572.94	9.831×10^{5}	-	53312
α_1	-5.557×10^{15}	-139.1	-1.551×10^{7}	-44.71	12950
α_0	-1.287×10^{14}	-3.222	-1.655×10^{6}	-4.424	300
β_5	1	-	-	-	-
β_4	3.995×10^{13}	1	-	-	1862
β_3	4.859×10^{14}	12.16	1	-	22645
β_2	8.767×10^{14}	21.94	3.139×10^{5}	1	40857
β_1	1.305×10^{14}	3.265	5.188×10^{5}	1.458	6080
β_0	2.14×10^{12}	0.05371	3.06×10^{4}	0.08147	100
FIT	100%	100%	92.59%	90.06%	-
FPE	7.878×10^{-17}	1.491×10^{21}	5.523×10^{-6}	9.92925×10^{-6}	-

4.2. Results and discussion

In the structure that was implemented in this investigation, the parameter estimation technique used employs the use of different algorithms, here N4SID and GPMF were applied, the process performance was evaluated in an experiment. The results showed that the process is very precise when considering the order of the system obtained analytically. From the results obtained, it can be concluded that in order to identify the parameters of a model, it is appropriate to have a complete signal with a large database. The order of the proposed system is important, it can be concluded that the results of the experiment in terms of FIT and FPE, the best results were obtained with systems of fifth and fourth-order. For the estimation of the parameters, the performance of the method is exceptional, the N4SID and GPMF algorithms have had very similar results.

As can be seen from (7), only a fourth order TF is used to represent the complete system, mathematical operations were used to reduce to a minimum expression. As shown in the comparison of the model parameters in Table 3, the best prediction was presented in the order 4 and 5, it can be seen in the FIT to the simulation data and the FPE. It is possible to notice the result obtained from Figures 1 to 7, in these experiments the prediction error is shown, which is minimum for cases 1 and 2.

5. CONCLUSIONS

A 5th order system was found analytically. When replacing the real data of the system within the equations, a 4th order system was obtained. Using the SI technique, fifth and fourth-order systems were obtained that comply 100% with the approach to the original signal, this means that the input-output response is the same for these cases. The sampling time was very important; they were carried out with 0.01, 0.001 and finally 0.0001, which was used for having better results.

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