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CAPABILITIES OF MATLAB AND SIMULINK RELATED TO MODELLING OF POLISH POWER EXCHANGE

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The paper presents selected results of research on modelling a system of the POLISH Power Exchange in the MATLAB and Simulink environment. Modelling capabilities of various toolboxes and Matlab language were presented. Special attention was paid to identification modelling using System Identification Toolbox, neural modelling using Neural Network Toolbox and simulation modelling using Simulink. Research experiments were preformed based on the Day Ahead Market quotations. The obtained models of th type in SIT, an artificial neural network (ANN) in NNT and a block diagram in Simulink were subjected to comparative and sensitivity tests. Final results were interpreted.

Keywords: Artificial Neural Network, Identification, MATLAB and Simulink Environment, Polish Power Exchange, simulation, the Day Ahead Market

1. Introduction

MATLAB and Simulink offer numerous alternatives as regards modelling systems and processes, which involves using, i.a. Matlab language, and appropriate toolboxes (MATLAB and Simulink environment in version R2015b contains 83 toolboxes available for purchase for commercial uses (Source: MathWorks company [14]) such as, e.g. Simulink (SIM) – analytical and simulation modelling, etc., Neural Network Toolbox (NNT) – neural modelling, Control System Toolbox (CST) – control modelling, Fuzzy Logic Toolbox (FLT) – fuzzy modelling, Optimization Toolbox (OT) – evolutionary modelling, Mapping Toolbox (MT) – geographic modelling, Image Processing Toolbox (IPT) – image modelling, etc. articular attention was paid to identification, as well as neural and simulation modelling, which complement analytical modelling wherever it is not possible to establish phenomenological relationships or laws governing systems, processes or phenomena. Due to the fact that within the Towarowa Giełda Energii S.A. [Eng. Polish Power Exchange joint-stock company] (TGE S.A.) it is possible to distinguish a system of Power Exchange (TGE) where electrical power (ep) is purchased and sold as a commodity and TGE system development that involves changes in the structure and parameters of the system, numerical data for the Day Ahead Market (DAM), with quotations 24 or 48 hours prior to electrical power delivery were used to illustrate capabilities of selected toolboxes.

When modelling TGE from the DAM perspective, a few factors ought to be considered, which factors include the specificity of the electrical power market resulting from physical characteristics of the EP system operation, including the need to continuously balance supply and demand, yearly, weekly and daily seasonality, i.e. cyclical trends in hourly, daily, monthly, quarterly, yearly, etc. price fluctuations, price tendency to return to a mean value following trends, seasonality, sharp increases and decreases in prices caused by unpredictable events, e.g. failures in power plants, sudden reconfigurations of distribution network, unpredictable weather changes, discrete changes in demand for electrical energy and power, etc. Numerical data related to TGE functioning describe the following: as regards the inputs to the system – total supplied volume of electrical power in each hour of the 24-hour day [kWh], and as regards the outputs of the system – obtaining average price for electrical power sold in each hour of the 24-hour day [PLN/kWh].

Based on the numerical data, appropriate models of development were created in MATLAB and Simulink environment (Numerous other environments are also available, e.g. MATHEMATICA, STATISTICA, SAP, SAS, etc.) and such toolboxes oriented towards TGE system modelling as, i.a., System Identification Toolbox (identification modelling), Neural Network Toolbox (neural modelling) and Simulink (simulation modelling). MATLAB and Simulink environment includes toolboxes which are continuously developed and updated by and American company MathWorks. There is also a very useful environment for modelling systems, produced by a Polish company AITECH. This environment named SPHINX contains i.a. NEURONIX for modeling artificial neural networks and PC SHELL for modeling expert systems [6–13].

In the case of TGE, the aim of modelling is to obtain a model of development of a system of power exchange (PE), in which average prices of electrical power for each hour of the 24-hour day are input streams, and a total volume of electrical power supplied in each hour of the 24-hour day are output streams. Analysis of literature shows that there are no works available on using MATLAB and Simulink environment for modelling TGE development as a technical-economic system [1–5, 13]. On the other hand, one may observe a growing demand for TGE system modelling methods, especially, from the point of view of development of replacement block diagrams for testing sensitivity and for the purpose of simulation research, including forecasting research [6–8]. For the reasons mentioned above, TGE system (and TGE S.A. as a trade law entity) is of interest to both practice and science. However, results of analysis related to MATLAB and Simulink environment capabilities as regards selection of system development modelling methods have not been published so far. It not only applies to MATLAB and Simulink environment but also to the object of research in this work, namely TGE in the DAM area.

2. Modelling of systems in MATLAB and Simulink environment

The main aim of generally understood technical-economic systems modelling is simplification of complex reality that allows for finding laws governing the object, including technical and economic laws, and, creating a mathematical model of the system based on these laws. Therefore, in this respect, systems modelling process, called analytical modelling, comes down to determining mathematical dependencies between input and output quantities.

EP system modelling, in analytical respect, is an extremely complex task that requires broad knowledge of mathematics, economy, computer science, power sector, and even power policy of the State. Also, such factors as: fuel prices, trading emissions of greenhouse gases and characteristic features of power market, which include lack of possibility to store power, necessity to balance supply and consumption of power, a natural monopoly of major operators on the market, demand seasonality, etc. ought to be considered. Such approach as regards TGE does not bring the expected results. Generally, the obtained models are inadequate and do not reflect the reality. For these reasons, other methods of modelling are being sought, including methods of identification, neural and simulation modelling, etc. Identification modelling involves searching for a mathematical model of the system based on numerical values of input and output quantities, and neural modelling involves designing an artificial neural network (ANN) and teaching it a system model. Another approach towards modelling process is simulation modelling that involves using Simulink environment for creating replacement block diagrams of systems [8]. At present, due to huge amounts of data, modelling process ought to be preceded by cluster analysis, etc. that involves initial preparation of data for further processing.

The most important types of files available in MATLAB environment include: m-files (*.m), mex-files (np. *.dll) and mat-files (*.mat). There are two types of m-files in MATLAB environment, namely, script m-files (commands written in a file are all called by a single command) and function m-file (a program written in the Matlab language function form (it also contains commands). Mex-files (abbreviation from Matlab EXecutable) allow for compilation of programs written in C or Fortran in MATLAB environment (mex command in order to obtain a dynamically loading library – *.dll files). Other types of files useful for modelling are mat-files (*.mat) written to an ASCII text file with any name or to a binary file with *.mat extension as temporary or final results of calculations and files that contain figures – *.fig.

3. Identification modelling of TGE using SIT and CST

Identification of TGE system was performed in MATLAB and Simulink environment using numerical data available for the DAM [6-7]. 24 input values (one for each hour of the 24-hour day) related to the volume of supplied electrical power [kWh] and 24 output values related to the average value of electrical energy in each hour of the 24-hour day were assumed (fig. 1). Numerical data used for the purpose of identification related to individual hours of the 24-hour day in the period of 1st January 2013 to 31st December 2015 (730 training pairs; identification was performed for Multi Input Single Output (MISO) models for 24 input quantities and one output for hour 13.00-14.00 [15].

Different structures of models, i.e. with various degree of polynomials $A_j(q)$ and $B_i(q)$ were obtained for different values of parameters of arx discrete models (***na***, ***nb*** and ***nk*****).** In this way, as a result of performed identification experiments, 24 discrete parametric ARX models (AutoRegressive with Exogenous Input) of MISO type in the form of **th** matrix were obtained [9-13] in MATLAB and Simulink environment (fig. 2) with the structure presented below:

$$A_j(q)\cdot y_j(t) = B_i(q)\cdot u_i(t) + e_i(t), \tag{1}$$

where $A_j(q)$ and $B_i(q)$ are polynomials of the following form:

$$\begin{aligned} A_j(q) &= 1 + a_{j1}\cdot q^{-1} + a_{j2}\cdot q^{-2} + \ldots + a_{jna}\cdot q^{-na}, \\ B_i(q) &= b_{i0} + b_{i1}\cdot q^{-1} + b_{i2}\cdot q^{-2} + \ldots + b_{inb}\cdot q^{-nb-nk}, \end{aligned} \tag{2}$$

with:

$y_j(t)$ – j-th output variable (average price in j-th hour),
$u_i(t)$ – i-th input variable (total volume of electrical power in j-th hour),
$e_i(t)$ – sequence of values of i-th noise (white noise), q – time shift operator,

na, *nb*, *nk* – identification parameters, *na* – degree of a polynomial $A(q)$, *nb* – degree of a polynomial $B(q)$ and *nk* – time lag between the output and the input, respectively.

An example of a MISO model obtained for 24 inputs (volume of electrical power supplied in each hour of the 24-hour day) and for a single output in the form of average value of electrical power for hour 13.00-14.00 has arx44 form (fig. 2):

$$A_1(q)\cdot y_1(t)=\sum_{i=1}^{24} B_i(q)\cdot u_i(t)+e\ (t), \tag{3}$$

where:

$$A(q)=1-0.5969\cdot q^{-1}-0.08548\cdot q^{-2}-0.1389\cdot q^{-3}-0.04357\cdot q^{-4},$$

$$B1(q)=-0.008521\cdot q^{-1}-0.006249\cdot q^{-2}+0.01497\cdot q^{-3}-0.0148\cdot q^{-4},$$
$$B2(q)=-0.008521\cdot q^{-1}-0.006249\cdot q^{-2}+0.01497\cdot q^{-3}-0.0148\cdot q^{-4},$$

....

$$B24(q)=-0.06017\cdot q^{-1}-0.006569\cdot q^{-2}-0.02453\cdot q^{-3}+0.068\cdot q^{-4},$$

q – time shift operator.

As a result of identification the following were obtained: a polynomial $A(q)$ with the degree $na = 4$, a polynomial $B(q)$ with the degree $nb = 4$, and time lag between the output and the input – $nk = 1$. Thus, a parametric model has arx141 form. Control System Toolbox (CST) is coupled with SIT, as a vast library of programs that facilitate, i.a. modelling and analysis of control systems, including model transformations:

[A, B, C, D] = th2ss(th) – from parametric to state form,

[A, B, C, D] = tf2ss(l,m) – from rational to state form,

[l,m] = ss2tf(A,B,C,D) – from state to rational form,

[z,p,k] = tf2zp(l,m) – from rational to zero-pole form,

[l,m] = zp2tf(z,p,k) – from zero-pole to rational form,

[A, B, C, D] = zp2ss(z,p,k) – from zero-pole to state form,

[z,p.k] = ss2ap(A,B,C,D) – from state to zero-pole form.

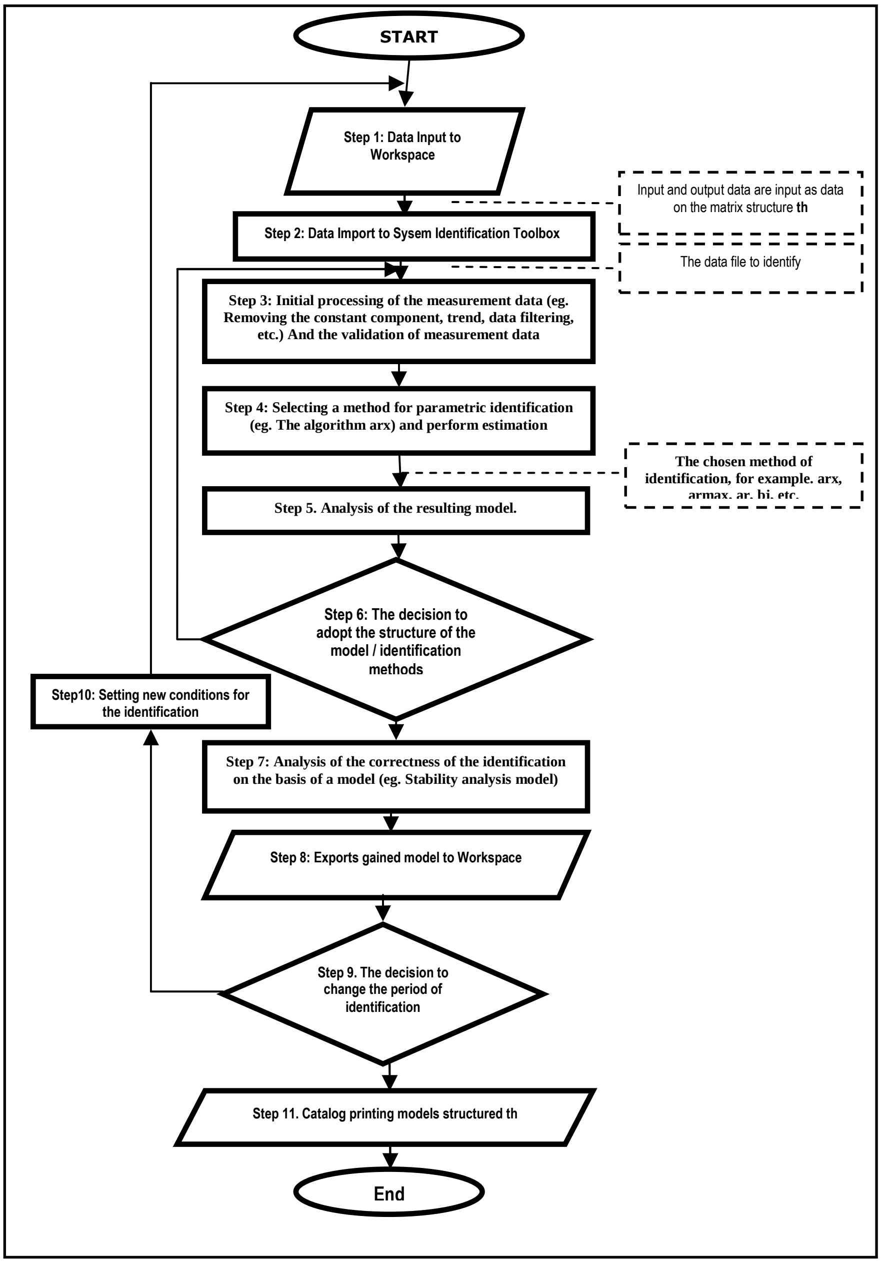

Figure 1. Block diagram of the process of parametric identification TGEE.
Symbols: th - a matrix of theta structure containing the results of identification. *Source*: [8]

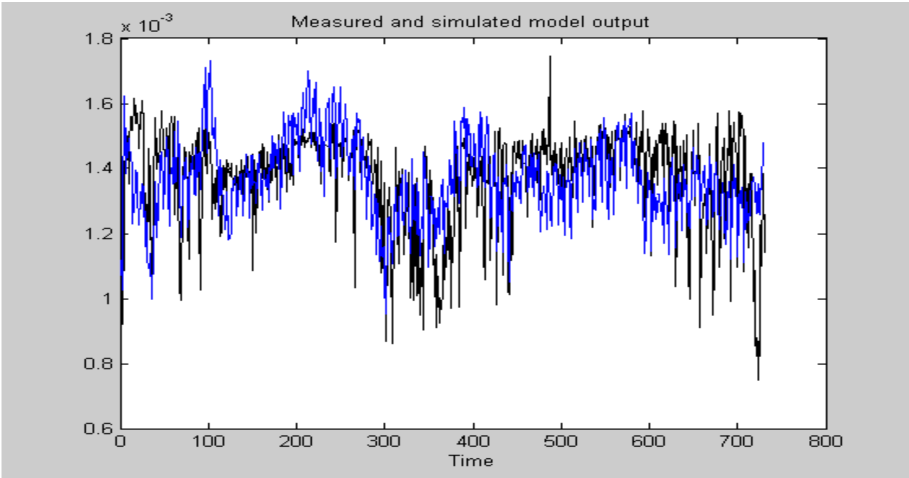

Figure 2. Graphs of the output quantity for the model and the system for hour 13-14 for a MISO model for data related to TGE, for the period of 1st January 2013 to 31st December 2014 (730 days). Denotations in the text. *Source*: Author's own compilation in MATLAB environment

Examples of the obtained models, based on th matrices of MISO models of TGE are presented in table 1. Each form may be discrete or continuous, which forms are obtained with the help of functions of the following types: d2c() or c2d().

Table 1. Examples of MISO models of TGE created for the DAM. Denotations in the text

Form	Name	Method of obtaining	Mathematical model
th	parametric	Identification in SIT	A(q)y(t)=B(q)u(t)+e(t)
th	parametric	th=ss2th(**A,B,C,D**)	A(q)y(t)=B(q)u(t)+e(t)
[**A**,**B**,**C**,**D**]	state	[**A,B,C,D**]=th2ss(th)	dx(t)/dt=Ax(t)+Bu(t) y(t)=Cx(t)+Du(t)
[**A**,**B**,**C**,**D**]	state	[**A,B,C,D**]==tf2ss(l,m)	dx(t)/dt=Ax(t)+Bu(t) y(t)=Cx(t)+Du(t)
[l,m]	rational	[l,m]=ss2tf(**A,B,C,D**)	l/m
[z,p,k]	zero-pole	[z,p,k]=tf2zp(l,m)	k(s-z)/(s-p)
[l,m]	rational	[l,m]=zp2tf(z,p,k)	l/m
[A,B,C,D]	state	[A,B,C,D]=zp2ss(z,p,k)	dx(t)/dt=Ax(t)+Bu(t) y(t)=Cx(t)+Du(t)
[z,p,k]	zero-pole	[z,p,k]=ss2ap(A,B,C,D)	k(s-z)/(s-p)

Source: Author's own compilation in CST

4. Neural modelling of TGE using NNT

Neural modelling was performed in MATLAB and Simulink environment using NNT. As a result of training process, an ANN as a model of TGE was obtained based on numerical data for the period of 1st 2013 – 31st December 2014 (2 years). Train, test and validation curves are presented in fig. 3, and provide the following information, i.a., the ANN learnt the TGE system model after only 4 epochs with the mean squared error (MSE) of 10^{-4}. Finally, the following model of TGE was obtained in the form presented below:

$$\mathbf{y}_i^k(\mathbf{t}) = f_i^k(\mathbf{net}_i),$$
$$\mathbf{net}_i^k = \sum_{i=1,\, j=1}^{i=n,\, j=m} w_{ij}^k u_j^k, \tag{4}$$

where:

u_i – i-th input of TGE model (volume of power in i-th hour),
y_i - i-th output of TGE model (average price of electrical power in i-th hour),
w_{ij} – weight between i-th input and j-th neuron of the next layer,
k – number of layer, i – number of output, j – number of input.

In the neural model described by dependence (4), one hidden layer with 24 neurons was designed. Thus, two weight matrices with dimensions 24 x 24, two bias vectors with dimensions 24 x 1, and the activation function tansig (sigmoidal function) were obtained both for the hidden layer and for the output layer. Trainlm algorithm was used to train the model. Prior to training, numerical data in the train and test file were normalized.

As fig. 3 shows, the process of training the ANN lasted a relatively short time. From epoch number thirteen, changes in weights were small, which indicates little additional learning of the ANN. After teaching the ANN the EPM model based on the above mentioned quotations on the DAM, a neural model was generated using gensim() function in the form of Simulink block, which was then used to build a block diagram in Simulink, for the purpose of simulation and sensitivity tests.

5. Simulation modelling of TGE using Simulink

In order to obtain a simulation model in Simulink, a block diagram was built, which diagram consisted of an identification model of MIMO type for hour 13-14 and a neural model of MIMO type. The two models were compared with each other and with real output data for hour 13-14. An example of a simulation model for hour 13-14 is presented in fig. 4.

MATLAB and Simulink environment proved user-friendly while performing simulation experiments that led to testing capabilities of the two models, the identification and the neural one. Comparison of average prices for hour 13-14 showed that the output from the neural model resembled the real TGE system more closely than the output from the identification model. Also, it is worth noting that MATLAB environment provides numerous methods of signal analysis, which involve using Signal Processing Toolbox and improvement of models, i.a., using Optimization Toolbox and evolutionary algorithms or Fuzzy Logic Toolbox and systems and fuzzy numbers.

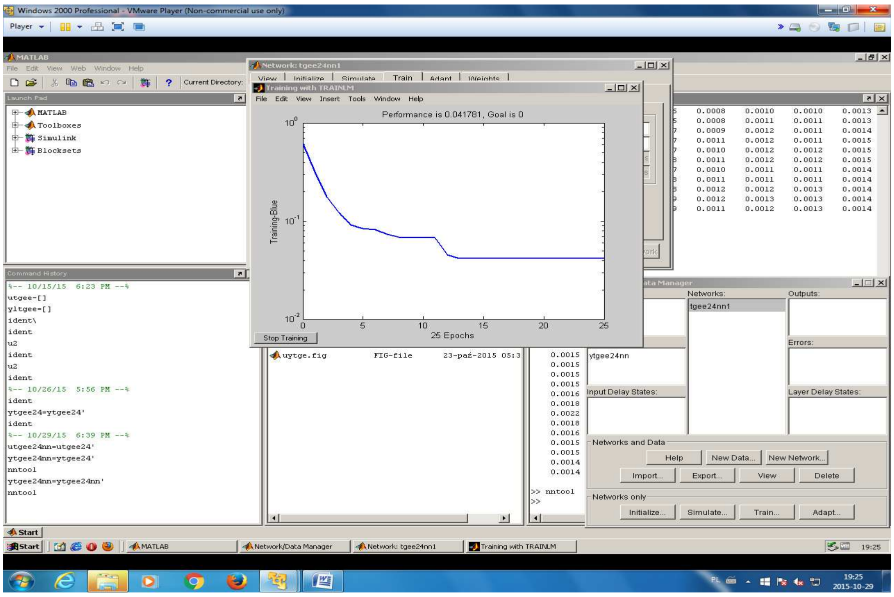

Figure 3. A training curve for the model of the TGE system for the DAM for the MIMO model. Denotations in the text

Source: Author's own compilation in MATLAB and Simulink environment

A simulation model was designed with the help of a block library in Simulink, and in particular, such blocks (S-functions) as:

From Workspace (reading data from workspace),
To Workspace (writing data to workspace),
Demux (extracting single elements from a signal vector),
SUM (add signals),
Gain (amplifying signals),
Transport Delay (signal delay),
Scope (displaying signals),
Math function (transposing matrices), etc.

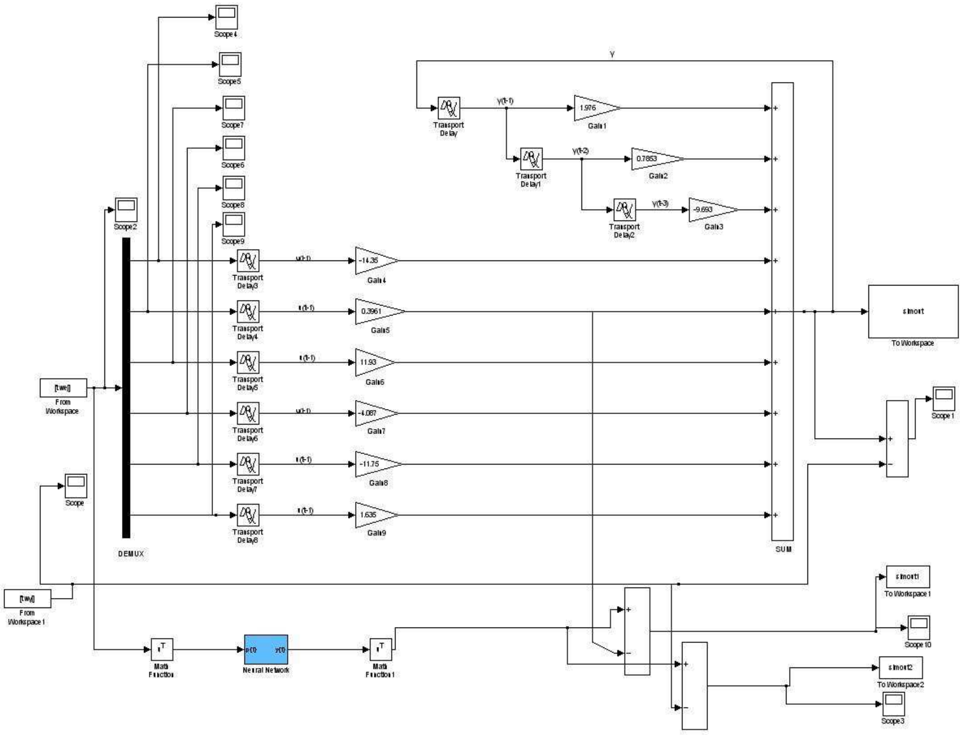

Figure 4. A simulation model of the TGE system for the DAM composed of, i.a., an identification model and a neural model. Denotations in the text. *Source*: author's own compilation in MATLAB and Simulink

6. Conclusions

The paper does not exhaust all capabilities of MATLAB and Simulink environment that are significant for modelling TGE for the numerical data for the DAM. However, it is worth noting that libraries of programs such as Simulink, System Identification Toolbox, Control System Toolbox, Neural Network Toolbox, Fuzzy Logic Toolbox, Mapping Toolbox, Optimization Toolbox, Signal Processing Toolbox, etc. mentioned in this paper, allow for obtaining models both by using phenomenological dependencies and laws governing processes, identification or teaching artificial neural networks models of the TGE system and analysing and testing sensitivity of models as well as using them for simulation research.

System Identification Toolbox proved a convenient tool, especially for performing parametric identification. The obtained models were susceptible to parameter improvement using evolutionary algorithms and Optimization Toolbox.

In turn, Neural Network Toolbox allows for creating various architecture types of an artificial neural network and subsequent teaching the network the model of the TGE system. As for fuzzy knowledge, Fuzzy Logic Toolbox may be used for the purpose of defuzzification and fuzzification of signals used for training of the ANN. Finally, Simulink allows for building block diagrams composed of, i.a., blocks of the identification model and the neural model, and their subsequent use for simulation research and for sensitivity tests of models.

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