Identification and interpretation of the development of the domestic electrical power system from the point of view unmanned manufactories

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In case of studying regularities in the development of the domestic electrical power system (DEPS) from the point of view of unmanned factories, it is not possible to develop a model using the modelling method. Therefore, identification of development was conducted using the arx method as well as the MATLAB environment and the System Identification Toolbox. For the designed research experiment, assuming one output variable and 14 input variables, MISO models were obtained in the form of matrices th. Th models were expressed in the form of models of development as a function of long time θ, and then, interpretation of its coefficients as basic elements of matrices th was conducted. The results of the analysis of model coefficients influence on the value of the output quantity $y_1(\theta)$ – the total achievable power output for power plants (maximum output) were presented. Studying regularities in the DEPS development was limited to studying the degree of changes in the internal organization of the system and changes in the level of control, and resulted in obtaining a catalogue of moving stationary models in state space (ss). For this purpose, th models were transformed into ss models, and then changes in long time θ of matrices **A** and **B** as well as their elements were studied. Ss model was written in the form of the model of state variables development, followed by the interpretation of its coefficients as basic elements of matrices **A** and **B**. Other state variables were also interpreted as elements of the DES development vector.

1. Identification of the DEPS system development

In order to perform identification of the domestic electrical Power system, appropriate data concerning fourteen input variables (u_1-u_{14}) and four output variables (y_1-y_4) for the years 1946-2007 with the structure of output variables presented in Table 1 and with the structure of input variables presented in Table 2 were collected [7]. Plots for input and output data were presented in Fig. 1 and in Fig. 2, respectively.

Identification of the DEPS system, for 30-year periods in the years 1946-2007, with the step equal one year was conducted in the MATLAB environment using the System Identification Toolbox (SIT). A catalogue of models for four MISO outputs [4, 6, 12] was obtained, such as models for all fourteen input variables and for the first output y_1 that represents the total achievable power output for power plants (maximum output). These 33 models were presented in Table 3

Years	Employment in Power plants (total) [persons]	Installed Power capacity in Power plants [MW]	Number of turbine sets [pcs]	Number of Power boilers (total) [pcs]	Number of transformers in Professional Power industry [pcs]	Number of substations [pcs]	Number of switches [pcs]	Length of overhead electric Power lines (all voltages in total) [km]	Length of cable line (with cable sernice lines) [km]	Hard coal consumption (total) [thousand tons]	Brown coal consumption (total) [thousand tons]	Gas fuels consumption (total) [thousand m^3]	Plants including liquid fuels in Professional Power (total) [TJ],	Import of electrical Power (total) [GWh]
	u_1	u_2	u_3	u_4	u_5	u_6	u_7	u_8	u_9	u_{10}	u_{11}	u_{12}	u_{13}	u_{14}
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
46	3000	2553	174	333	3224	24420	882	76000	7091	3550	190	15	176	21
…….	…….	………	…..	…….	……….	……….	……….	………..	…….	………	………	…………	……….	………
07	35096	35800	254	591	243000	359526	49500	759500	201500	45150	60200	1704800	35500	7752

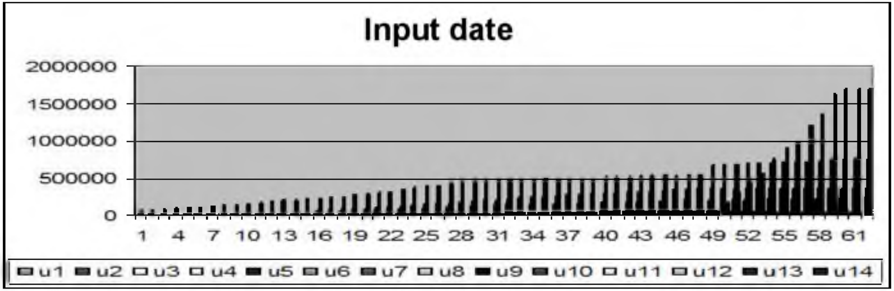

Fig. 1. Plot presenting input data of the DEPS system in the years 1946-2007 (X axis [years]), where values of 14 successive inputs are successive bars of the bar chart

(characteristics A(q)) and in Table 4 (characteristics B(q)). An example characteristic of the DEPS system, namely the arx133 type, obtained with the accuracy of 99.14% for the period of 1969-1998 was presented in Fig. 3.

Table 1. Structure of output variables for the identification of the DEPS

Years	Achievable power output (maximum output) for power plants (total) [MW]	Electrical power consumption (expenditure) (total) [GWh]	Electrical power export (total) [GWh]	Loss of electrical power in transmission networks (total) [GWh]
	y_1	y_2	y_3	y_4
1	16	17	18	19
1946	2004	8000	92	1517
…	…	…	…	…
2007	34877	162500	13110	26950

Table 2. Structure of input variables for the identification of the DEPS

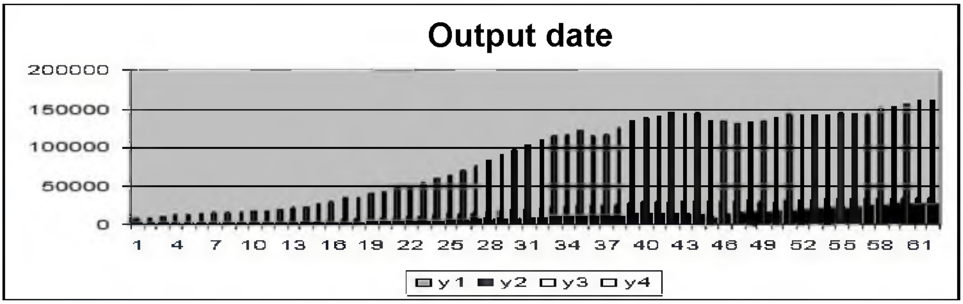

Fig. 2. Plot presenting output data of the DEPS system in the years 1946-2007 (X axis [years]), where values of 4 successive outputs are successive bars of the bar chart

The obtained results showed certain regularities in the DEPS system models, predominantly regularities concerning the structure of the model and the values and structure of parameters [6, 8-12]. Generally, in most periods, the model of the arx133 type prevailed, whose similarity to real data of the DEPS system equals 99.03%. Moreover, the values of parameters of models of arx 131 type for the assumed degree of accuracy did not generally differ.

On the other hand, identification conducted for the whole period of 61 years (1946-2007) generated a model of arx 133 type with the accuracy of 99.14% (Fig. 3).

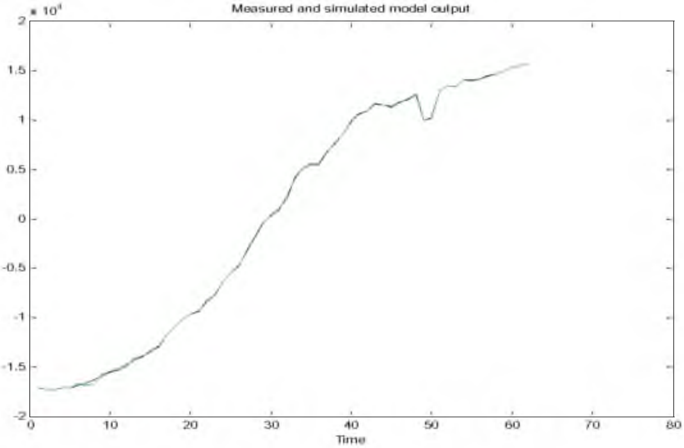

Fig. 3. Characteristic of the model arx133 of the DEPS system (99.14 compliance rate with the real system)

This comparison shows inaccuracy of methods used for forecasting the DEPS system development based on one dataset. Moreover, it is worth noting that only six model structures occur, namely, model arx131 (for periods: 1-4, 7-11, 14, 17-

19, 23, 25-26, 28-32), model arx135 (for periods: 3-4), model arx132 (for periods: 12, 15, 27), model arx134 (for periods 13, 22), model arx133 (for periods 16, 20, 24), model arx619 (for periods 33), i.e. six structural changes, which took place in the EES in the studied period of time, and within the scope of the experiment.

2. Selected results of the identification

An example of the generated structure of the model of the arx 133 type in the form of matrix th is as follows:

$$A(q)y(\theta)=B(q)u(\theta)+e(\theta) \tag{1}$$

where:

$$\begin{aligned}
&A(q)=1-0.1342\cdot q^{-1},\\
&B1(q)=-0.1342\cdot q^{-1}-0.05387\cdot q^{-2}-0.1443\cdot q^{-3},\\
&B2(q)=-0.1965\cdot q^{-1}-0.7748\cdot q^{-2}+0.3264\cdot q^{-3},\\
&B3(q)=-5.191\cdot q^{-1}+0.3683\cdot q^{-2}+29.52\cdot q^{-3},\\
&B4(q)=-14.5\cdot q^{-1}+9.715\cdot q^{-2}+14.17\cdot q^{-3},\\
&B5(q)=0.1554\cdot q^{-1}-0.05293\cdot q^{-2}+0.06803\cdot q^{-3},\\
&B6(q)=0.01335\cdot q^{-1}-0.02755\cdot q^{-2}+0.006739\cdot q^{-3},\\
&B7(q)=-0.05234\cdot q^{-1}-0.2766\cdot q^{-2}-0.6104\cdot q^{-3},\\
&B8(q)=-0.002718\cdot q^{-1}-0.007408\cdot q^{-2}+0.02639\cdot q^{-3},\\
&B9(q)=-0.03015\cdot q^{-1}+0.1073\cdot q^{-2}-0.02883\cdot q^{-3},\\
&B10(q)=0.08841\cdot q^{-1}+0.2976\cdot q^{-2}+0.1541\cdot q^{-3},\\
&B11(q)=0.131\cdot q^{-1}+0.06231\cdot q^{-2}-0.04736\cdot q^{-3},\\
&B12(q)=0.01546q^{-1}-0.009961q^{-2}-0.009608q^{-3},\\
&B13(q)=-0.02857\cdot q^{-1}-0.1287\cdot q^{-2}+0.2337\cdot q^{-3},\\
&B14(q)=-0.02198\cdot q^{-1}+0.3019\cdot q^{-2}+0.02655\cdot q^{-3}.
\end{aligned}$$

Matrix in the theta format used in the MATLAB environment is a matrix containing results of identification of the system model (theta format matrix). It contains all the information about the model, its structure and parameter estimators together with their estimation using covariance [8-10, 12]. Theta matrix has a strictly defined dimension, and each element of theta matrix contains a specified piece of information. The elements of the first row contain the following: estimators of parameter variance, sampling interval T (in the discussed case T= one year) and na = 1, nb = 3, nk = 3, etc. The second row contains the FPE index, year, month, day, minute and numeric code of the command, which was used to generate the particular model. The third row includes estimators of model parameters in the alphabetical order: a_1 , a_2 , ..., b_0 , b_1 , ...(zeros and ones at the beginning of the polynomial are disregarded). Rows from 4 to 3+n contain estimation of the covariance matrix.

By analyzing the equation (1), it can be observed that the current value of the output variable y_1 is influenced to the greatest extent by the output variables for the last year and input variables for the last three years, in some cases the influence is positive and in others - negative. Moreover, variable u_4 (the total number of power boilers) is influenced to the greatest extent by the past situation. Also, certain regularities may be observed in the models of the DEPS system, in particular, regularities regarding the scope of the structure of models and their parameters. Model of arx 131 type was the dominating model in most periods. This model is similar to the real data of the DEPS system, with the compliance rate of 99.03%. Moreover, these models did not differ in respect of the values of parameters (there occurred minor parametric changes of the system).

Therefore, the sought value of the total achievable power output of power plants (maximum output) [MW] e.g. in $\theta = 2010$ is influenced by the following quantities: the value of achievable power output for the previous year (θ-1, i.e. 2009) and all fourteen input variables for the last three years (θ-1, i.e. for 2009, θ-2, i.e. for 2008, θ-3, i.e. for 2007).

3. Interpretation of the DEPS development

Therefore, the sought model of the DEPS system (after the elimination of the time shift operator q^{-1}), is a model of the following form such as [1-2, 3, 5, 8-10]:

$$\begin{aligned}
y_1(\theta) = {} & 0.1342\cdot y_1(\theta-1) - 0.1342\cdot u_1(\theta-1) - 0.05387\cdot u_1(\theta-2) - 0.1443\cdot u_1(\theta-3) - 0.1965\cdot u_2(\theta-1) + \\
& -0.7748\cdot u_2(\theta-2) + 0.3264\cdot u_2(\theta-3) - 5.191\cdot u_3(\theta-1) + 0.3683\cdot u_3(\theta-2) + 29.52\cdot u_3(\theta-3) + \\
& -14.5\cdot u_4(\theta-1) + 9.715\cdot u_4(\theta-2) + 14.17 u_4(\theta-3) + 0.1554\cdot u_5(\theta-1) - 0.05293\cdot u_5(\theta-2) + \\
& +0.06803\cdot u_5(\theta-3) + 0.01335\cdot u_6(\theta-1) - 0.02755\cdot u_6(\theta-2) + 0.006739\cdot u_6(\theta-3) - 0.05234\cdot u_7(\theta-1) + \\
& -0.2766\cdot u_7(\theta-2) - 0.6104\cdot u_7(\theta-3) - 0.002718 u_8(\theta-1) - 0.007408\cdot u_8(\theta-2) + 0.02639\cdot u_8(\theta-3) + \\
& -0.03015\cdot u_9(\theta-1) + 0.1073\cdot u_9(\theta-2) - 0.02883\cdot u_9(\theta-3) + 0.08841\cdot u_{10}(\theta-1) + 0.2976\cdot u_{10}(\theta-2) + \\
& +0.1541\cdot u_{10}(\theta-3) + 0.131\cdot u_{11}(\theta-1) + 0.06231\cdot u_{11}(\theta-2) - 0.04736\cdot u_{11}(\theta-3) + 0.01546\cdot u_{12}(\theta-1) + \\
& -0.009961\cdot u_{12}(\theta-2) - 0.009608\cdot u_{12}(\theta-3) + -0.02857\cdot u_{13}(\theta-1) - 0.1287\cdot u_{13}(\theta-2) + 0.2337\cdot u_{13}(\theta-3) + \\
& -0.02198\cdot u_{14}(\theta-1) + 0.3019\cdot u_{14}(\theta-2) + 0.02655\cdot u_{14}(\theta-3) + e(\theta),
\end{aligned} \tag{2}$$

which allows to provide detailed interpretation of successive coefficient in the model:

a_1 - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to the achievable power output in year θ-1 [MW/MW],

b_{11} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to the number of people employed in power plants in year θ-1 [MW/person], by analogy b_{12} to year θ-2 and b_{13} to year θ-3,

b_{21} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to the installed power capacity in power plants in year θ-1 [MW/MW], by analogy b_{22} to year θ-2 and b_{23} to year θ-3,

b_{31} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to the number of turbine sets in year θ-1 [MW/pcs], by analogy b_{32} to year θ-2 and b_{33} to year θ-3,

b_{41} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to the number of power boilers in year θ-1 [MW/pcs], by analogy b_{42} to year θ-2 and b_{43} to year θ-3,

b_{51} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to the number of transformers in professional power industry in year θ-1 [MW/pcs], by analogy b_{52} to year θ-2 and b_{53} to year θ-3,

b_{61} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to the number of substations in year θ-1 [MW/pcs], by analogy b_{62} w to year θ-2 and b_{63} to year θ-3,

b_{71} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to the number of switches in year θ-1 [MW/pcs], by analogy b_{72} to year θ-2 and b_{73} to year θ-3,

b_{81} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to the length of overhead electric power lines (all voltages in total) in year θ-1 [MW/km], by analogy b_{82} to year θ-2 and b_{83} to year θ-3,

b_{91} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to the length of cable lines (with cable service lines) in year θ-1 [MW/km], by analogy b_{92} to year θ-2 and b_{93} to year θ-3,

b_{101} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to hard coal consumption (total) in year [MW/thousand tons], by analogy b_{102} to year θ-2 and b_{103} to year θ-3,

b_{111} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to brown coal consumption (total) in year θ-1 [MW/thousand tons], by analogy b_{112} to year θ-2 and b_{113} to year θ-3,

b_{121} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to liquid fuels consumption (total) in year θ-1 [MW/thousand tons], by analogy b_{122} to year θ-2 and b_{123} to year θ-3,

b_{131} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to consumption of other fuels in professional power plants including liquid fuels (total) in year θ-1 [MW/TJ], by analogy b_{132} to year θ-2 and b_{133} to year θ-3,

b_{141} - a coefficient that expresses the ratio of the achievable power output for power plants in year θ to the import of electrical power (total) in θ-1 [MW/GWh], by analogy b_{142} w to year θ-2 and b_{143} to year θ-3.

A similar method is used to determine and interpret the coefficients in MISO models for outputs y_2, y_3 and y_4, i.e. for the consumption (expenditure) of electrical Power (total) [GWh], export of electrical Power (total) [GWh], and loss of electrical power in transmission networks (total) [GWh]. The analysis of the model (2) implies that the value of the output variable $y_1(\theta)$ is positively influenced not only by the value of $y_1(\theta)$ for the previous period but also the values of output variables for the following periods: $u_2(\theta)$ in θ-3, $u_3(\theta)$ and $u_4(\theta)$ in θ-2, θ-3, $u_5(\theta)$ and $u_6(\theta)$ in θ-1, θ-3, $u_8(\theta)$ in θ-3, $u_9(\theta)$ in θ-2, $u_{10}(\theta)$ in θ-1, θ-2, θ-

3, $u_{11}(\theta)$ in θ-1, θ-2, $u_{12}(\theta)$ in θ-1, $u_{13}(\theta)$ in θ-3, $u_{14}(\theta)$ in θ-2, θ-3, and it is negatively influenced by the values of the input variable $u_1(\theta)$ in all three pervious periods, i.e. in θ-1, θ-2, θ-3, and the values of other input variables in other periods, excluding the variable j $u_{10}(\theta)$, i.e.: $u_2(\theta)$ in θ-1, θ-2, $u_3(\theta)$ and $u_4(\theta)$ in θ-1, $u_5(\theta)$ and $u_6(\theta)$ in θ-2, $u_8(\theta)$ in θ-1, θ-2, $u_9(\theta)$ in θ-1, θ-3, $u_{11}(\theta)$ in θ-3, $u_{12}(\theta)$ in θ-2, θ-3, $u_{13}(\theta)$ in θ-1, θ-2, $u_{14}(\theta)$ in θ-1.

Therefore, hard coal consumption in all periods of the studied period of the DEPS development was always connected with an increase in the total achievable power output - output variable $y_1(\theta)$, and the input variable $u_3(\theta)$ for period θ-3, expressing the number of turbine sets (coefficient b_{32} = 29.52 MW/pcs) had the greatest positive influence, and the input variable $u_6(\theta)$ for period θ-3, expressing the number of substations (coefficient b_{63} = 29.52 MW/pcs) had the least positive influence.

The greatest negative influence can be attributed to the input variable $u_4(\theta)$ for period θ-1, expressing the number of power boilers (coefficient b_{41} = -14.5 MW/pcs), and the least negative influence can be attributed to input variable $u_8(\theta)$ for period θ-1, expressing the length of overhead electric power lines (coefficient b_{81} = -0.002718 MW/km).

4. DEPS development in the state space

As a result of the transformation of the DEPS system model of the arx 133 type by means of identification using statistical data related to the DEPS system into ss model in the state space, the following form of state and output equations was obtained [7-10]:

$$
\begin{gathered}
\dot{x}_1 = 0.4884x_1 + x_2 - 0.0554x_5 + 0.04866x_7 + 0.05838x_9 - 11.9791x_{11} + 0.0169x_{13} + 0.0465x_{15} + \\
+ 0.0236x_{17} + 0.0089x_{19} - 0.1416x_{21} - 0.2164x_{23} - 0.0843x_{25} + 0.0153x_{27} + 0.2199x_{29} - 0.3297x_{31}, \\
\dot{x}_2 = -0.1004x_5 + 0.2477x_7 - 44.654x_9 + 12.8095x_{11} - 0.0589x_{13} - 0.0255x_{15} + 0.3572x_{17} - 0.013x_{19} + \\
+ 0.0078x_{21} - 0.0243x_{23} - 0.0415x_{25} - 0.0198x_{27} - 0.4983x_{29} + 0.0405x_{31}, \\
\dot{x}_3 = 0.0954x_5 + 0.6879x_7 + 10.2627x_9 + 19.6908x_{11} - 0.0274x_{13} - 0.0298x_{15} + 0.1703x_{17} + \\
0.0228x_{19} + 0.0782x_{21} - 0.1506x_{23} + 0.0341x_{25} + 0.0016x_{23} - 0.0843x_{27} - 0.6753x_{29} - 0.1886x_{31}, \\
\dot{x}_4 = u_1,\ \dot{x}_5 = x_4,\ \dot{x}_6 = u_2,\ \dot{x}_7 = x_7 + x_{22},\ \dot{x}_8 = u_3,\ \dot{x}_9 = x_8,\ \dot{x}_{10} = u_4,\ \dot{x}_{11} = x_{10} + x_{25},\ \dot{x}_{12} = u_5, \\
\dot{x}_{13} = x_{12} + x_{27},\ \dot{x}_{14} = u_6,\ \dot{x}_{15} = x_{14} + x_{29},\ \dot{x}_{16} = u_7,\ \dot{x}_{17} = x_{16},\ \dot{x}_{18} = u_8,\ \dot{x}_{19} = x_{18},\ \dot{x}_{20} = u_9, \\
\dot{x}_{21} = x_{20},\ \dot{x}_{22} = u_{10},\ \dot{x}_{23} = x_{22},\ \dot{x}_{24} = u_{11},\ \dot{x}_{25} = x_{24},\ \dot{x}_{26} = u_{12},\ \dot{x}_{27} = x_{26},\ \dot{x}_{28} = u_{13},\ \dot{x}_{29} = x_{28}, \\
\dot{x}_{30} = u_{14},\ \dot{x}_{31} = x_{30}, \\
y_1 = x_1.
\end{gathered}
\tag{3}
$$

This 31 state variables were obtained, with first three, i.e. x_1, x_2, x_3, being the most important. They may be interpreted as follows:

x_1 – state variable that expresses the achievable power output in power plants (total) [MW],

x_2 – state variable that expresses the yearly average rate of change in the achievable power of generators [MW/year],

x_3 – state variable expressing the amplified yearly average rate of change in the achievable power of generators [MW/year].

One may observe that some state variables only depend on input variables, and others do not depend directly on input variables. Moreover, values of elements of matrices **A** and **B** for state variables $x_4 - x_{31}$ are equal one. Also, it is worth noting that there are state variables which are derivatives of other state variables or integrals of other state variables. The output y_1 studied in the experiment depends directly on the state variable $x_{1,}$ which does not depend on any input variable.

The obtained model of the DEPS is a model of development and contains information concerning both parametric changes and structural changes that occurred in the years 1946-2007 [7]. An attempt to interpret the obtained 31 state variables for the continuous linear model, shows that successive state variables may be interpreted in the following way [4, 6-12]:

x_4 – state variable that expresses employment in power plants at the end of the year (total) [person],

x_5 – state variable that expresses working time of employed persons in short time (total) [person x day],

x_6 – state variable that expresses installed power capacity in power plants (total) [MW],

x_7 – state variable that expresses potential maximum electrical power that may be generated during the running time of installed generators [MWh],

x_8 – state variable that expresses the running time of turbine sets [number of turbine sets x h],

x_9 – state variable that expresses the total running time of turbine sets used, calculated in number of turbine sets and days as well as the time constant of the period of development - in years [(number of turbine sets x day) x year],

x_{10} – state variable that expresses the total running time of power boilers calculated in number of power boilers and days [number of power boilers x day],

x_{11} – state variable that expresses the total running time of the power kettles used, calculated in number of power boilers and days, with the time constant of the period of development calculated in years [(number of power boilers x day) x year],

x_{12} – state variable that expresses the running time of transformers used in professional power industry calculated in number of transformers and days [number of transformers x day],

x_{13} – state variable that expresses the running time of transformers used in professional power industry calculated in number of transformers and days, with the time constant of the period of development calculated in years [(number of transformers x day) x year],

x_{14} – state variable that expresses the running time of substations used, calculated in number of substations and days [number of substations x day],

x_{15} – state variable that expresses the running time of substations used, calculated in number of substations and days with the time constant of the period of development calculated in years [(number of substations x day) x year],

x_{16} – state variable that expresses the running time of switches used, calculated in number of substations and days [number of switches x day],

x_{17} – state variable that expresses the running time of switches used, calculated in number of switches and days, with the time constant of the period of development calculated in years [(number of switches x day) x year],

x_{18} – state variable that expresses the running time of overhead electric power lines, calculated in kilometres and days [km x day],

x_{19} – state variable that expresses the running time of overhead electric power lines, calculated in kilometres and days, with the time constant of the period of development calculated in years [(km x day) x year],

x_{20} – state variable that expresses the running time of cable lines, calculated in kilometres and days [km x day],

x_{21} – state variable that expresses the running time of cable lines, calculated in kilometres and days, with the time constant of the period of development calculated in years [(km x day) x year],

x_{22} – state variable that expresses the time of hard coal consumption in power stations calculated in tons and days [thousand tons x day],

x_{23} – state variable that expresses the time of hard coal consumption in power stations calculated in tons and days with the time constant of the period of development calculated in years [(thousand tons x day) x year],

x_{24} – – state variable that expresses the time of brown coal consumption in power stations calculated in tons and days [thousand tons x day],

x_{25} – state variable that expresses the time of brown coal consumption in power stations calculated in tons and days with the time constant of the period of development calculated in years [(thousand tons x day) x year],

x_{26} – state variable that expresses the time of liquid fuels consumption in power stations calculated in cubic metres and days [thousand m^3 x day],

x_{27} – state variable that expresses the time of liquid fuels consumption in power stations calculated in cubic metres and days with the time constant of the period of development calculated in years [(thousand m^3 x day) x year],

x_{28} – state variable that expresses the time of consumption of other fuels including liquid fuels, calculated in TJ and days [TJ x day],

x_{29} – state variable that expresses the time of consumption of other fuels including liquid fuels, calculated in TJ and days, with the time constant of the period of development calculated in years [(TJ x day) x year],

x_{30} – state variable that expresses the time of import of electrical power calculated in GWh and days [GWh x day],

x_{31} – state variable that expresses the time of import of electrical power calculated in GWh and days, with the time constant of the period of development calculated in years [(GWh x day) x year].

5. Assessment of the DEPS development

Due to the fact that the general case of the development assessment model includes the information on the system of development (inputs, outputs, state variables), a single criterion or multiple criteria of quality assessment, as well as an algorithm, which determines the value of the criterion of development quality assessment [1-2, 4-6, 8-12]. Hence, the quality of the development process, etc. may be presented as a difference of the assumed $\Delta y_0(K,\theta)$ and the real $\Delta y(K,\theta)$ output characteristic of the DEPS system. For a multidimensional case, this discrepancy can be written as a difference of two multidimensional vectors [6, 8-10]:

$$\overline{\Delta y}(\theta)) = \left|\overline{\Delta y_0} - \overline{\Delta y}\right|, \tag{4}$$

where: $\Delta y_0(K,\theta)$ – assumed output characteristic of the DEPS system, $\Delta y(K,\theta)$ - real output characteristic of the DEPS system, K – a set of parameters of the DEPS system, θ – long time (years, decades).

Assessment of the development of the DEPS system, like any wear and tear (exploitation) assessment of the system in the sense of renewal or use of the system; or assessment of the electrical power system functioning and operation are a natural consequence of identification research, and verification of the development model is followed by the assessment of research results obtained using the development model.

However, for the development problems, understood as structural and parametric changes of the DEPS system, and not as planning, predicting or programming the development, performing appropriate assessment experiments is connected with the necessity to generate numerous models of system development for specified periods of long time $\Delta\theta$, e.g. in the moving version with the step of one year [3, 6-10]. Due to the fact that the DEPS system is a control system, it is possible to obtain respective models of development in state space, and based on them, conduct credible assessment research, e.g. courses of eigenvalues (characteristic values), elements of matrices **A, B, C and D**, or the rank of matrices and the number of state variables.

Element a_{11} of matrix **A** expresses the degree of internal influence of the feedback on the values of changes in the state variable x_1 (fig. 4). Until period $\theta 15$ its value was negative (negative feedback), and then it changed into positive, reaching the maximum value in the periods θ25 to θ30. Element b_{11} of matrix **B** expresses the influence of the input variable u_1 on the value of state variable x_1 (fig. 5). Until period θ10 its value was equal zero, i.e. state variable x_1 expressing the total achievable power output of generators in power plants was not influenced by the input variable u_1, namely by the total employment in power plants.

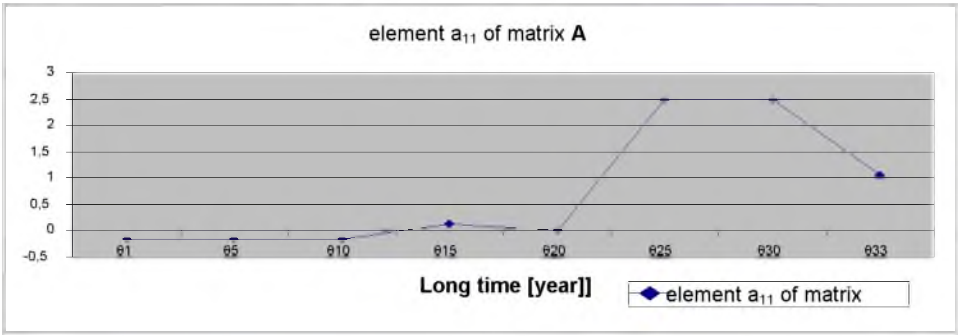

Fig. 4. Changes in the element a_{11} of matrix **A** n successive periods of the DEPS development

However, from period θ10 to θ20, the influence was positive (stimulating), and from period θ20 to θ33 negative (impeding).

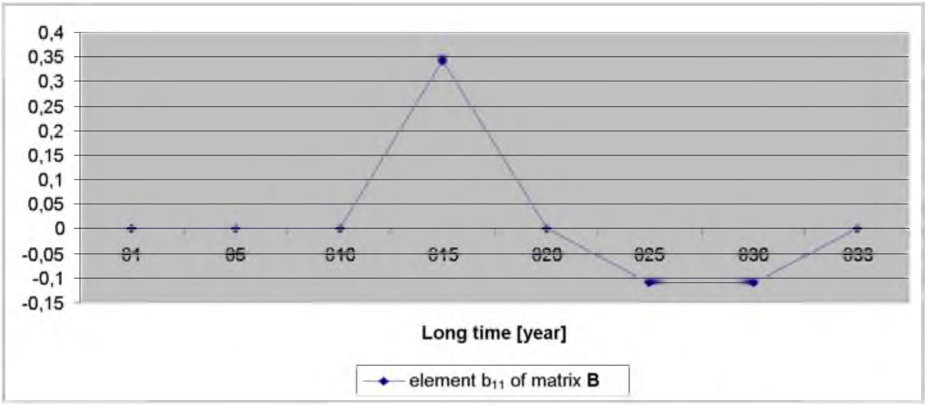

Fig. 5. Changes in the element b_{11} of matrix **B** in successive periods of the DEPS development

6. Designing the development of the DEPS

The technique of development programming seeks for both the model of development and laws of development, i.e. laws governing the changes in the model of development in long time θ [3, 6, 8-10, 12]. In the studied case, the model of development is e.g. a model of state variables defined by the following dependences (1), with parametric changes being connected with the changes in the values of elements of matrices **A**, **B**, **C**, **D**, present in state equations. Elements of matrix **A** are responsible for the degree of internal organization of the DEPS system, elements of matrix **B** are responsible for the connections between the DEPS system and the external environment using inputs (for the level of control), and elements of matrix **C** are responsible for the connections between the DEPS system and the external environment using outputs [4, 6, 8-10].

Structural changes are connected with the changes concerning the quantities and number of those quantities, as well as the ranks of matrices **A, B, C** and **D**, which is caused by including in the model new state variables, new inputs or outputs (or disregarding the existing ones), as a result of technological, organizational, etc. changes. Structural changes in the DEPS system development are caused by the changing number of elements and relations between those elements.

Analysis of changes in the elements of matrices in state variables equations demonstrates that the DEPS system as a developing system has a changeable structure, depends on long time θ, and is sensitive (susceptible) to changes of development parameters. In order to introduce structural changes, the occurrence of a new state variable $x_{32}(\theta)$, new system input, e.g. $u_{15}(\theta)$ or a new output, e.g. $y_2(\theta)$ may be assumed. Then, the following form of state equations may be obtained:

$$\dot{x}_1 = 0.4884x_1 + x_2 - 0.0554x_5 + 0.04866x_7 + 0.05838x_9 - 11.9791x_{11} + 0.0169x_{13} + 0.0465x_{15} + \\ + 0.0236x_{17} + 0.0089x_{19} - 0.1416x_{21} - 0.2164x_{23} - 0.0843x_{25} + 0.0153x_{27} + 0.2199x_{29} - 0.3297x_{31} + k_{132}x_{32},$$

$$\dot{x}_2 = -0.1004\,x_5 + 0.2477\,x_7 - 44.654\,x_9 + 12.8095\,x_{11} - 0.0589\,x_{13} - 0.0255\,x_{15} + 0.3572\,x_{17} - 0.013\,x_{19} + \\ + 0.0078\,x_{21} - 0.0243\,x_{23} - 0.0415\,x_{25} - 0.0198\,x_{27} - 0.4983\,x_{29} + 0.0405\,x_{31} + k_{232}\,x_{32},$$

$$\dot{x}_3 = 0.0954\,x_5 + 0.6879\,x_7 + 10.2627\,x_9 + 19.6908\,x_{11} - 0.0274\,x_{13} - 0.0298\,x_{15} + 0.1703\,x_{17} + 0.0228\,x_{19} \\ + 0.0782\,x_{21} - 0.1506\,x_{23} + 0.0341\,x_{25} + 0.0016\,x_{23} - 0.0843\,x_{27} - 0.6753\,x_{29} - 0.1886\,x_{31} + k_{332}\,x_{32},$$

$$\dot{x}_4 = m_{11}u_1,\ \dot{x}_5 = k_{44}x_4,\ \dot{x}_6 = k_{62}u_2,\ \dot{x}_7 = k_{77}x_7 + k_{722}x_{22},\ \dot{x}_8 = m_{83}u_3,\ \dot{x}_9 = k_{98}x_8, \tag{5.1}$$

$$\dot{x}_{10} = m_{104}u_4,\ \dot{x}_{11} = k_{1110}x_{10} + k_{1125}x_{25},\ \dot{x}_{12} = m_{125}u_5,\ \dot{x}_{13} = k_{1312}x_{12} + k_{1327}x_{27},\ \dot{x}_{14} = m_{146}u_6,$$

$$\dot{x}_{15} = k_{1514}x_{14} + k_{1529}x_{29},\ \dot{x}_{16} = m_{167}u_7,\ \dot{x}_{17} = k_{1716}x_{16},\ \dot{x}_{18} = m_{188}u_8,$$

$$\dot{x}_{19} = k_{1918}x_{18},\ \dot{x}_{20} = m_{209}u_9,\ \dot{x}_{21} = k_{2120}x_{20},\ \dot{x}_{22} = m_{2210}u_{10},\ \dot{x}_{23} = k_{2322}x_{22},$$

$$\dot{x}_{24} = m_{2411}u_{11},\ \dot{x}_{25} = k_{2524}x_{24},\ \dot{x}_{26} = m_{2612}u_{12},\ \dot{x}_{27} = k_{2726}x_{26},\ \dot{x}_{28} = m_{2813}u_{13},$$

$$\dot{x}_{29} = k_{2928}x_{28},\ \dot{x}_{30} = m_{3014}u_{14},\ \dot{x}_{31} = k_{3130}x_{30},\ \dot{x}_{32} = m_{3215}u_{15},$$

as well as the output equation:

$$\begin{aligned} y_1(\theta) &= x_1(\theta). + l_{12}\,x_2(\theta) + n_{115}\,u_{15}(\theta), \\ y_2(\theta) &= l_{21}\,x_1(\theta) + l_{22}\,x_2(\theta) + n_{15}\,u_{15}(\theta). \end{aligned} \tag{5.2}$$

Equations (5) show that, parametric changes will at least cause changes in the following parameters (elements of matrix A), namely: m_{ij}, k_{ij} in equation (5-1) and l_{ij}, n_{ij} in equation (5-2). Determination of value of these parameters involves estimation of the lower and upper limit of safe development of the DEPS system model, and defining safe development of the DEPS system.

Parameters m_{ij} are elements of matrix **A**, and parameters k_{ij} are elements of matrix **B**, while parameters l_{ij} are elements of matrix **C**, and parameters n_{ij} are elements of matrix **D,** tidied case concerns the change in the rank of matrices **A** and **B**. As for matrix **A** three parameters appear that require estimation and for matrix **B** - eight elements, which jointly gives 11 parameters, which are indispensable for writing state equation that require estimation (additional ones appear in connection with output equation).

Estimation of the level of safety of the DEPS system development may be based on the knowledge of the course of the changes in the values of elements of matrix A, called a matrix of internal organization of the process, in long time θ. Based on state equations (5), matrix **A** for the case of structural changes may be written as follows:

$$\mathbf{A} = \begin{bmatrix} -0.3295 & m_{11} \\ m_{21} & m_{22} \end{bmatrix}, \tag{6.1}$$

which leads to the following form of characteristic equation:

$$C(s) = s^2 + (0.395 - m_{22})s - (0.395 \cdot m_{22} + m_{11} \cdot m_{21}) = 0. \tag{6.2}$$

Therefore, structural development requires the estimation of safety margin of the DEPS system development, i.a. as regards specification of elements of matrix **A**, coefficients in the characteristic equation C(s), or roots of characteristic equation. In the discussed case, the values of the coefficient (6.2) are as follows: $a_2 = 1$, $a_1 = - m_{22} + 0.395$, $a_0 = - 0.395\ m_{22} + m_{11}\ m_{21}$. It appears that the method of Evans root lines, which presents both parametric changes (movement of roots along the existing lines) and structural changes (appearance or disappearance of root lines) is especially useful for research on the stability of the DEPS system [8-10].

7. Conclusions and directions of further research

The process of identification conducted for the identification experiment using the arx method, MISO model for 14 input variables and one output variable $y_1(\theta)$, expressing the total achievable power output in power plants resulted in the development of the model of the DEPS subsystem development in the form of matrix th, written in the function of long time θ. The obtained elements of the matrix th of the DEPS subsystem were interpreted, paying particular attention to the interpretation of the arx model coefficients. The results of the analysis of the model from the point of view of its elements sensitivity to changes in the coefficients of the model were presented.

The results of research on regularities in the DEPS development considering the degree of internal organization of the system and changes in the level of control were also presented. The transformation of th models into ss models allowed to study changes in matrices **A** and **B** and their elements in long time θ. Ss models were written in the form of models of development of state variables conditional on long time θ, which was followed by the interpretation of its coefficient as basic elements of matrices **A** and **B**. State variables, as elements of the DEPS system development vector were also interpreted.

Including further criteria of development such as development safety or development efficiency in the development assessment allows to assess the development of the electrical power system in long time θ, and thereby indicate warning signals to the DEPS development designers, planners and even strategists (it is important to emphasize that we mean the development assessment criterion, which is not a development optimization criterion).

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