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Research into the Sustainable Development Problem of Urban Electric Power Systems on the Basis of Cognitive Modeling Technology

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Abstract

Sustainable urban development has been one of the most burning problems encountered by the global community for the last two decades. Russian cities as well as cities all over the world are plagued by problems ensuing from considerable anthropogenic environmental footprint.

Since the industrial revolution, urban development has been inseparably intertwined with the evolution of power industry. Up until now urban impact on the environment has been significantly determined by the work of its electric power system.

Non-linear character of correlations between city energy system and social, economic and climatic factors as well as indefinite nature of these relations and difficulty of formal characterization of any arising tasks constitute an urgent need for working out modern analytical methods in this field. Given the inaccurate and insufficient nature of raw data input, development of fuzzy analysis and intricate systems and processes modeling methods, namely, those of fuzzy cognitive modeling and fuzzy logic inference, appear to be quite promising.

The paper is concerned with fuzzy cognitive model that serves as a basis for a comprehensive analysis of the sustainable development problem of city electric power systems taking into consideration subsequent specification of the system factors and their mutual influence.

Keywords: sustainable development, urban electric power system, fuzzy cognitive modeling

INTRODUCTION

Design of fuzzy cognitive model is aimed at assessment of sustainable development of city and urbanized area electric power systems. On the basis of this assessment, in turn, evaluation of the impact made by separate groups of factors on providing and maintaining overall power system stability and assessment of the system influence on certain characteristics (concepts) of the designed model can be carried out.

The suggested model is designed to conduct a general research into the problem of sustainable development of diverse power systems and can serve as a basis for consequent comprehensive analysis with proper consideration of system factors specification on a lower hierarchical level of this model.

FUZZY COGNITIVE MODEL FOR RESEARCH ON SUSTAINABLE DEVELEMENT OF URBAN POWER SYSTEMS

Fuzzy cognitive models for research on sustainable development of electric power systems in cities and urbanized areas are supposed to provide:

- formalized input of system-related factors of a power system as well as direct, indirect and aggregated influence of these factors on one another;
- implementation of a flexible mechanism of incorporating common characteristics of energy consumption for different types of cities and urbanized areas in case the model preserves an invariable structure (i.e. an aggregate of system-related factors and their interrelations);
- modeling of diverse situations in order to assess and identify different factors and any relations of mutual influence and coherence that may cause power system instability;
- character and extent to which various factors of the model influence one another directly or indirectly;
- coherence of factors in their impact on each other and on the model as a whole;
- dynamics modeling of changes in power system sustainable development alongside assessment of other system-related factors impact, energy consumption specifics as well as various actions on these changes.

Along with conducting preliminary research a thorough analysis of indices and criteria characterizing the main parameters of heat and energy supply to urbanized areas, cities and metropolises was carried out. On the basis of the research outcomes [1] and taking into account well-established assessment models of sustainable development indices commonly applied to city ratings [2], [3], [4], the following aggregated system factors groups corresponding to generalized concepts of the suggested fuzzy cognitive model were established:

- K_1 – *sustainability of urban electric power system* (a target system-related factor);
- K_2 – *capacity of urban power system infrastructure* (aggregated heat capacity, aggregated electric power capacity, length of an electrical network);
- K_3 – *population living standards* (hot water and heat provision, average income, tariffs on energy resources, energy consumption by households);

- K_4 – *industrial consumption of fuel and energy resources (FER)* (overall heat and power consumption, fuel consumption);
- K_5 – *specific FER consumption by households*;
- K_6 – *quality of the city eco-system* (area size of forests and water bodies, emissions and runoffs, solid household waste);
- K_7 – *rate of city development* (population growth, gross national product, new housing supply);
- K_8 – *measures aimed at increasing sustainability of the city power system* (introduction of energy-saving technologies, renewable sources of energy);
- K_9 – *infrastructure condition of the city power system* (condition of the heat and electric power networks).

Note. A group of system-related factors describing *general urban characteristics* (climate zone, population size, urban land area, relief, overall area of heated buildings) is left out in this model which enables its application to the research on sustainable development problem of power systems in diverse types of cities and urbanized areas.

A group of experts in the field of urban power systems assessed mutual influence of system-related factors on each other. Processing of expert assessments resulted in obtaining agreed values of direct influence relations between pair of concepts K_i and K_j from $\boldsymbol{K} = \{K_1, \ ..., \ K_N\}$.

These relations of influence in fuzzy cognitive model are depicted in Figure 1 in the form of directed arcs weighed by scales $w_{ij} \in [-1, \ 1]$. Value $w_{ij} = -1$ means a negative peak value whereas $w_{ij} = 1$ stands for positive peak value of the impact made by concept K_i on concept K_j, while value $w_{ij} = 0$ denotes absence of any direct influence of K_i on K_j.

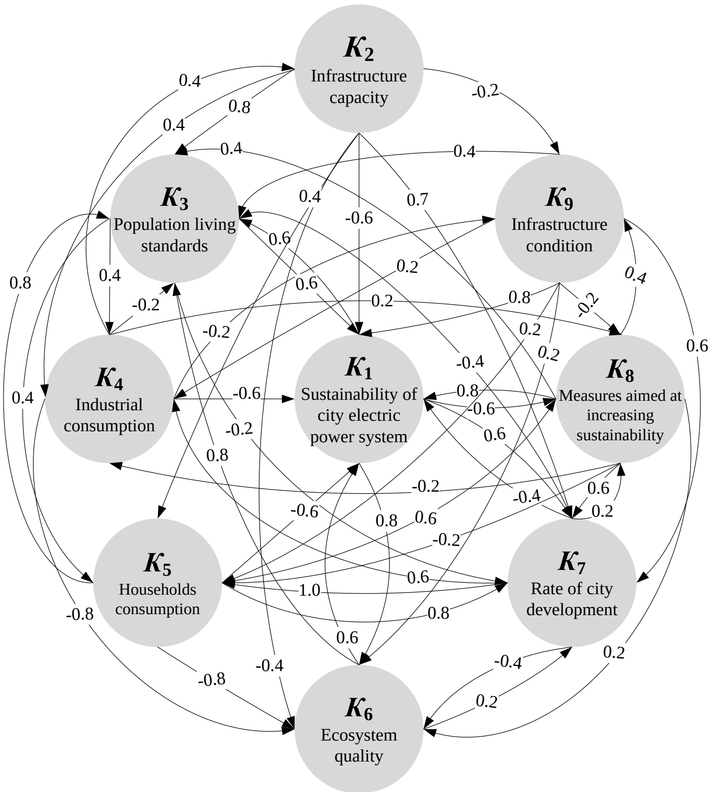

Figure 1: Structure of fuzzy cognitive model for the research on sustainable development problem of urban electric power systems

In case of positive influence $K_i \xrightarrow{w_{ij}} K_j$ and increase in value K_i value, K_j goes up whereas in case of decrease, on the contrary, it goes down. If value w_{ij} is negative, increase in value K_i will cause decrease in value K_j and vice versa. Apart from that, there can occur simultaneous direct influence of concepts pair on each other along with mismatch of w_{ij} and w_{ji}.

Scales values of direct impact between all concept pairs in the model can be conveniently depicted as a matrix of mutual influences:

$$\mathbf{W} = \begin{vmatrix} w_{11} & \dots & w_{1N} \\ \dots & \dots & \dots \\ w_{N1} & \dots & w_{NN} \end{vmatrix}.$$

This matrix is made up on the basis of processing results of data yielded in a corresponding expert survey. Obviously, values of impact relations between concepts will differ for various types of cities and urbanized areas. Meanwhile the structure of fuzzy cognitive model will remain intact.

ANALYSIS OF FUZZY COGNITIVE MODEL

Assessment of indirect influence of one concept on another considers aggregated effect of all ways among them. Thus, l way between K_i and K_j is described by:

$$K_i \xrightarrow{l} K_j : d_l = (K_i, K_{z_1^l}, ..., K_{z_1^l}, K_j), l = 1, ..., L,$$

where L – number of ways between concepts K_i and K_j.

As for the indirect influence of concept K_i on concept K_j itself, it is calculated as follows:

$$w_{ij} = \mathop{S}_{l=1}^{L}\left(\mathop{T}_{k\in d_l} w_{k,k+1}\right),$$

where T – t-norm (minimum operation or multiplication); S – s-norm (maximum operation).

Since the effect of weight between concepts can be either positive or negative, calculations are made separately (for positive and negative influences) with the subsequent combining of the yielded results. To perform this operation, the original matrix of interferences $\mathbf{W}$ is transformed into a matrix consisting only of positive elements $\mathbf{V} = \|v_{ij}\|_{2N\times 2N}$:

$$v_{2i-1,\,2j-1} = w_{ij} \;\; and \;\; v_{2i,\,2j} = w_{ij},\; if \;\; w_{ij} > 0;$$
$$v_{2i-1,\,2j-1} = -w_{ij} \;\; and \;\; v_{2i,\,2j} = -w_{ij},\; if \;\; w_{ij} < 0.$$

Transitive closure of matrix V of positive relations between concepts is carried out in order to ensure the consistency of mutual relations among concepts and correctness of subsequent calculations of the model *system parameters* (see below):

$$\hat{\mathbf{V}} = \mathbf{V} \vee \mathbf{V}^2 \vee \dots$$

where the degrees of matrices $\mathbf{V}, \mathbf{V}^2, ...$ are calculated using max-prod-composition:

$$\mathbf{V}^m = \mathbf{V}^{m-1} \circ \mathbf{V},\; v_{ik}^m = \max_j (v_{ik}^{m-1} \cdot v_{jk}),$$

while minimum operation is applied as operations "$\vee$" on matrices.

Note. In case the condition of transitive matrix $\mathbf{V}$ closure is defaulted, relations of inferences between model concepts need to be corrected. If the mismatched model adequately reflects the analyzed problem, it is considered to be unstable and results in further analysis of underlying causes of such a mismatch and in search for possibilities of bringing the modeled situation back to its stable condition.

Next, a modified matrix of inferences relations $\hat{\mathbf{W}} = \|(w_{ij}, \bar{w}_{ij})\|_{N\times N}$ between concepts of agreed fuzzy cognitive model is formed to the following rule:

$$w_{ij} = \max(v_{2i-1,\,2j-1}, v_{2i,\,2j}),\; \bar{w}_{ij} = \max(v_{2i-1,\,2j}, v_{2i,\,2j-1}).$$

Table 1 demonstrates a modified transitively closed matrix $\hat{\mathbf{W}}$ for fuzzy cognitive model depicted in Figure 1.

Table 1.

	K_1	**K_2**	**K_3**	**K_4**	**K_5**	**K_6**	**K_7**	**K_8**	**K_9**
K_1	0.48; –0.48	0.102; –0.096	0.64; –0.307	0.256; –0.24	0.256; –0.123	0.8; –0.384	0.205; –0.4	0.288; –0.6	0.115; –0.24
K_2	0.48; –0.6	0.168; –0.061	0.8; –0.384	0.42; –0.154	0.4; –0.154	0.384; –0.48	0.7; –0.192	0.36; –0.288	0.144; –0.2
K_3	0.6; –0.288	0.16; –0.058	0.384; –0.256	0.4; –0.144	0.4; –0.102	0.48; –0.32	0.32; –0.24	0.24; –0.36	0.096; –0.144
K_4	0.288; –0.6	0.4; –0.102	0.32; –0.64	0.168; –0.256	0.16; –0.256	0.23; –0.8	0.28; –0.205	0.36; –0.173	0.144; –0.2
K_5	0.48; –0.6	0.192; –0.102	0.8; –0.64	0.48; –0.256	0.32; –0.256	0.384; –0.8	0.8; –0.205	0.6; –0.288	0.24; –0.115
K_6	0.6; –0.288	0.128; –0.058	0.8; –0.205	0.32; –0.144	0.32; –0.082	0.48; –0.256	0.256; –0.24	0.192; –0.36	0.077; –0.144
K_7	0.192; –0.4	0.24; –0.064	0.192; –0.4	0.6; –0.16	0.096; –0.16	0.154; –0.48	0.168; –0.128	0.24; –0.115	0.096; –0.12
K_8	0.8; –0.384	0.144; –0.08	0.512; –0.246	0.36; –0.2	0.205; –0.2	0.64; –0.307	0.6; –0.32	0.23; –0.48	0.4; –0.192
K_9	0.8; –0.384	0.144; –0.077	0.512; –0.246	0.36; –0.192	0.205; –0.098	0.64; –0.307	0.6; –0.32	0.23; –0.48	0.4; –0.192

On the basis of matrix $\hat{\mathbf{W}}$ model system indices are calculated. The main indices are given in Table 2 [5].

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Table 2.

№ п/п	**The main system indices for fuzzy cognitive model**
1.	Consonance of impact made by concept K_i on concept K_j $$c_{ij} = \frac{\lvert w_{ij} + \bar{w}_{ij} \rvert}{\lvert w_{ij} \rvert + \lvert \bar{w}_{ij} \rvert}$$
2.	Mutual consonance of influence of concepts K_i and K_j $$\overleftrightarrow{c}_{ij} = \frac{\lvert (w_{ij} + w_{ji}) + (\bar{w}_{ij} + \bar{w}_{ji}) \rvert}{\lvert w_{ij} + w_{ji} \rvert + \lvert \bar{w}_{ij} + \bar{w}_{ji} \rvert}$$
3.	Influence of concept K_i on concept K_j $$p_{ij} = \mathrm{sign}(w_{ij} + \bar{w}_{ij}) \max(\lvert w_{ij} \rvert, \lvert \bar{w}_{ij} \rvert),$$ $$w_{ij} \neq \bar{w}_{ij}$$
4.	Mutual positive influence of concepts K_i and K_j $$\overleftrightarrow{p}_{ij} = \overleftrightarrow{p}_{ji} = (w_{ij} \, \mathrm{S} \, w_{ji}),$$ where S – operation of *s*-norm
5.	Mutual negative influence of concepts K_i and K_j $$\overleftrightarrow{n}_{ij} = \overleftrightarrow{n}_{ji} = -\lvert \bar{w}_{ij} \rvert \mathrm{S} \lvert \bar{w}_{ji} \rvert$$
6.	Consonance of influence of *i* concept on the system (map) $\vec{C}_i = \frac{1}{n} \sum_{j=1}^{n} c_{ij}$
7.	Consonance of the system influence on j concept $$\overleftarrow{C}_j = \frac{1}{n} \sum_{i=1}^{n} c_{ij}$$
8.	Influence of *i* concept on the system $$\vec{P}_i = \frac{1}{n} \sum_{j=1}^{n} p_{ij}$$
9.	Influence of the system on j concept $$\overleftarrow{P}_j = \frac{1}{n} \sum_{i=1}^{n} d_{ij}$$
10.	Mutual consonance of *i* concept and the system $$I_i^{SC} = (\vec{C}_i \, \mathrm{S} \, \overleftarrow{C}_i)$$

It is highly significant for comprehensive research into sustainable development of urban power systems to address the following issues of analysis on the basis of model system indices discussed in Table 2:

- analysis of sustainable development problem of urban energy system and identification of those concepts in the model that have major direct or indirect impact on it;
- assessment of direct and indirect influence of various concepts on each other as well as evaluation of the extent to which this influence is positive or negative on the basis of indices p_{ij}, $\overleftrightarrow{p}_{ij}$, $\overleftrightarrow{n}_{ij}$;
- assessment of the coherence degree between various concepts together with establishing consistency classes on the basis of indices c_{ij}, d_{ij}, $\overleftrightarrow{c}_{ij}$, $\overleftrightarrow{d}_{ij}$;
- assessment of how certain concepts affect stability of urban power system as a whole and how consistent or inconsistent this impact actually is on the basis of indices $\vec{P}_i$, $\vec{C}_i$, $\vec{D}_i$;
- evaluation of the impact made by urban power system stability on separate concepts and how consistent or inconsistent this impact is on the basis of indices $\overleftarrow{P}_j$, $\overleftarrow{C}_j$, $\overleftarrow{D}_j$.

The following conclusions can be drawn on the basis of an in-depth analysis of the yielded system indices in the suggested fuzzy cognitive map:

- the problem of sustainable development is most positively influenced (according to the degree of such impact) by:

measures aimed at increasing stability of the city power system (K_8); infrastructure condition of the city power system (K_9); quality of the city eco-system (K_6); population living standards (K_3). The most negative impact on this problem is made by industrial consumption of fuel and energy resources (K_4);

- the problem of urban power system development has strongest positive influence on (according to the degree of such impact): population living standards (K_3); rate of city development (K_7); industrial consumption of fuel and energy resources (FER) (K_4). In turn, this problem has a detrimental influence on infrastructure condition of the city power system (K_9);
- out of all concept pairs in the model the strongest positive mutual influence have the following pairs: $K_1 \leftrightarrow K_6$; $K_1 \leftrightarrow K_8$; $K_1 \leftrightarrow K_9$; $K_2 \leftrightarrow K_3$; $K_3 \leftrightarrow K_5$; $K_3 \leftrightarrow K_6$; $K_5 \leftrightarrow K_7$;
- out of all concept pairs in the model the strongest negative mutual influence have the following pairs: $K_4 \leftrightarrow K_6$ и $K_5 \leftrightarrow K_6$.

Modeling of changes in concept values in the dynamics can involve application of one of the value expressions given below, its choice is determined by specifics of the researched problem of sustainable development of a particular power system:

$$K_j(t+1) = \sum_{i=1}^{n} w_{ij}\, K_i(t),$$

$$\Delta K_j(t+1) = \sum_{i=1}^{n} w_{ij}\, \Delta K_i(t),$$

$$\Delta K_j(t+1) = \sum_{i=1}^{n} w_{ij}\, K_i(t),$$

where n – number of concepts that have direct influence on j concept; $K_i(t)$ and $\Delta K_i(t)$ – value and increment value of i concept at the moment t; $K_j(t+1)$ and $\Delta K_j(t+1)$ – value and increment value of j concept at the moment $(t + 1)$.

To prevent concept values from going beyond the specified range, non-linear function f that limits the resultant value of concept-receiver in [0, 1] or [–1, 1] can be applied, for example:

$$K_j(t+1) = f\left(\sum_{i=1}^{n} w_{ij} K_i(t)\right),$$

where a sigmoid function can be used as function f.

Modeling changes of value concepts in dynamics can be performed either under conditions of the situation self-development (without any external impact on the concept values) or under conditions of external influence on concept values at different moments of model time.

Achieving the primary goal of modeling system dynamics comes down to a sequence of the following actions:

Firstly, input of initial concept values of fuzzy cognitive model;

Secondly, launch of the modeling process in compliance with a selected expression of a change in concept values;

Thirdly, input of impacts on model concepts (change of values) at definite moments of the model time;

Fourthly, completion of modeling in case the selected criterion is met.

Modeling outcomes can be applied to determine: facts of exceeding criteria concept values by a particular moment of the model time; forecast values and change trends in values of various concepts; consequences assessment of direct and indirect external influences on concepts.

CONCLUSIONS

Fuzzy cognitive model is designed to conduct a generalized comprehensive research into the problem of sustainable development of urban electric power systems of different types. This model also serves as a basis for an in-depth analysis of this problem with due consideration of system factors specification and relations of mutual influence between them on lower hierarchical levels of this model.

The model provides a formalized presentation as well as proper consideration of overall characteristics of energy consumption for various types of cities and urbanized areas while the structure remains intact.

Solution of various research problems of diverse urban power systems sustainable development is demonstrated on the basis of the suggested fuzzy cognitive model. Among such problems there is dynamic modeling both under conditions of the situation self-development and under conditions of external impact on concept values at different moments of the model time.

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