Forecasting electric power consumption of technocenosis objects on the basis of values from transformed vector rank distribution

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Abstract. The article examines a technique for predicting the electric power consumption of technocenosis objects on the basis of the values of the transformed vector rank distribution. This technique includes the following stages: preparing data on electric power consumption, calculating an additional resource for technocenosis objects, forming transformed rank distribution and forecasting its values. The theoretical basis of the methodology was formed by the tenets of the theory of vector rank analysis, the methodology of functional rank analysis and the theory of mathematical statistics, as well as the concepts "technocenosis", "MC-cenosis" and "bifurcation". Its distinctive feature is the possibility to take into account the external control effect of a higher power system - MC-cenosis by adding or deducting an additional resource calculated using the system of transformed vector rank distributions. The additional resource is the difference between the values of the technocenosis located on the vector rank distribution of the higher MC-cenosis and the lower permissible value of the lower boundary of permissible values. The presented technique can be implemented in software and hardware complexes and situational centers for electric power consumption control in the area, energy system, transport network complex, large infrastructures and enterprises. The results will significantly supplement the methods of resource management for large infrastructure and energy facilities and form a resource consumption plan individually for each object.

1. Introduction
Forecasting issues have always played a key role in the management of a complex technical system. Nowadays along with the high rates of development of information technology, new methods of forecasting and planning of various types of resources are being elaborated. Using new software and modern hardware platforms, scientists and engineers create forecasting methods based on many different factors, elements of intelligent decision support, neural networks, machine learning, etc [1].

Today, there are quite a lot of scientific schools whose research is devoted to issues of forecasting the resources of complex technical systems, corporations and organizations in various fields. Among foreign scientists, the following ones can be highlighted: K. Nassirtoussi, L. Zhao, N. Ramakrishnan, G. Finnie, L. Anastasakis, C.-J. Huang, M. Liebmann et al.

The leading Russian scientists in the field of forecasting resources of various types are N.E. Golyandina, A. Yu. Shlemov, S.M. Ermakov, B.I. Makoklyuev, A.S. Poilzharov, A.A. Basov, Yu. E. Alla, S.V. Loktionov and others.
For several decades technocenosis methods of resource forecasting have been gaining popularity. Their implementation in the field of electric energy consumption management of technocenosis showed the best results in comparison with traditional forecasting methods. Major distribution in this scientific field was made by B.I. Kudrin, V.I. Gnatyuk, B.V. Zhiulin, V.V. Fufaev, D.V. Lutsenko and others. A distinctive feature of technocenosis forecasting methods is the possibility to apply the technique of rank analysis. This article presents a technique for forecasting the electric power consumption of technocenosis objects based on the transformed vector rank distribution [2].

2. The structure of the technique for forecasting the electric power consumption of technocenosis objects on the basis of the values from the transformed vector rank distribution

The theory of vector rank analysis is presented in detail in [3], including a method for managing the electric power consumption of technocenosis based on additional resource. One of the components of this method is the method for forecasting the electric power consumption of technocenosis objects based on the transformed vector rank distribution (Fig. 1).

At the first stage of the algorithm, a set of values for the electric power consumption of technocenosis objects $W_k = \{w_k^i\}_{i=1}^n$ and values on the electric power consumption of MC-cenosis objects $W_{mc} = \{w_{mc}^j\}_{j=1}^p$ are imported from the database. The algebraic formula of calculated set of values is presented through the following system:

$$\begin{align*}
W_k &= \{w_k^i\}_{i=1}^n = \{w_1^k, w_2^k, \ldots, w_n^k\}; \\
W_{mc} &= \{w_{mc}^j\}_{j=1}^p = \{w_1^{mc}, w_2^{mc}, \ldots, w_p^{mc}\}; \\
W_k \cup W_{mc} &\in VR.
\end{align*}$$

$W_k$ – set of values on the electrical power consumption of technocenosis objects;  
$W_{mc}$ – set of values on the electrical power consumption of macrocenesia;  
VR – vector rank space.

![Figure 1. The structure of the technique for forecasting electric power consumption of technocenosis objects on the basis of the transformed vector rank distribution.](image-url)
It should be noted that the MC-cenosis is understood as a “parent” intercon-nected set of technocenoses of a higher systematic level, possessing technocenosis properties, which includes the investigated technocenosis as a subordinate (MC-object) [13]. An example of MC-cenosis is the electrical engineering complex of the Russian Federation for any regional electrotechnical complex (REC). It includes a set of individual technocenoses such as electrical engineering complexes of its regions [4]. After the import, the vector rank distribution (VRS) is constructed based on the values of the set \( W_k \). The original distribution is shown in Figure 2.

Figure 2. Vector rank distribution of technocenosis.

After that, the stage of calculating the lower permissible values (LPV) for the VRD of the technocenosis is implemented. As a result of this stage, the following subset is formed:

\[
A^{nd}(\rho) \left\{ w_{1}^{N}, w_{2}^{N}, \ldots, w_{\rho}^{N} \right\}_{\rho=1}^{n}
\]

During are formed such as the approximation values of the initial VRD \( W_k \) and the approximation values of the lower boundary of the range of admissible values \( A^{nd}(t) \),

\[
W_k \approx \left\{ w_{i}^{N} \right\}_{i=1}^{n} \\
A^{nd}(\rho) \approx \left\{ a_{\rho}^{nd} \right\}_{\rho=1}^{n}
\]

\[
W_{pot}^{\rho} \approx \frac{W_{i}^{1}}{x_{i}^{p}} ;
A^{nd}(p) \approx \frac{A_{1}}{x_{p}^{a}}
\]

\[
A^{nd}(t) - \text{set of approximated values of lower boundary of admissible values;}
W_{pot}^{\rho} ; x_{i}^{p} - \text{parameters of approximated VRD of a set } W_k ;
A_{1} ; x_{p}^{a} - \text{parameters of approximated VRD of a set } A^{nd}(p).
\]

Figure 3 shows the graphical presentation of the approximation of the values of the original VRD, formed from the set \( W_k \) and the lower permissible values, formed from the set \( A^{nd}(p) \). At the next stage, the curvilinear integral of the second kind is calculated for the VRD constructed from the sets \( W_k \) and \( A^{nd}(p) \). In order to do this, they are represented as smooth arcs \( AB \) and \( A'B' \) belonging to the vector rank space [4].
In addition, it is assumed that along the lengths of the arcs $AB$ and $A'B'$ there is a two-dimensional vector field defined by the following vector functions:

$$\begin{align*}
F_i(x_j, w_j) &= \begin{pmatrix} f_i(x_j, w_j) \\ g_i(x_j, w_j) \end{pmatrix} \in AB; \\
F_j(x_j, w_j) &= \begin{pmatrix} f_j(x_j, w_j) \\ g_j(x_j, w_j) \end{pmatrix} \in A'B'.
\end{align*}$$

(3)

$f_i(x_j, w_j), g_i(x_j, w_j)$ – vector functions of two-dimensional vector field, distributed onto $AB$;

$f_j(x_j, w_j), g_j(x_j, w_j)$ – vector functions of two-dimensional vector field, distributed onto $A'B'$.

Then the curvilinear integrals of the second kind for $AB$, $A'B'$ can be calculated in the following way:

$$\begin{align*}
\int_{AB} f_i(x_j, w_j)dx + g_i(x_j, w_j)dw &= \lim_{n \to 0} \sum_{i=1}^{n} F_i(x_j, w_j) \cdot \left[ w_{i-1} - w_{i} \right], \\
\int_{A'B'} f_j(x_j, w_j)dx + g_j(x_j, w_j)dw &= \lim_{m \to 0} \sum_{j=1}^{m} F_j(x_j, w_j) \cdot \left[ w_{j-1} - w_{j} \right].
\end{align*}$$

(4)

Calculating the values of the curvilinear integrals in the system (4), it is possible to calculate the value of the Z1 energy-saving potential for technocenosis objects. Its value will be equal to the difference of these integrals:

$$Z1 = \int_{AB} f_i(x_j, w_j)dx + g_i(x_j, w_j)dw - \int_{A'B'} f_j(x_j, w_j)dx + g_j(x_j, w_j)dw.$$

(5)

The calculated value of the energy-saving potential enables to clarify parameters of the transformed VRD during the next stages. During the next stage algorithms of formation and approximation of VRD for MC-cenosis are implemented as well as for its lower boundary (Fig. 4).
Next, the value of the additional resource is calculated for the rank of the investigated VRD of MC-cenosis.

In fact, this is the difference between the values of electric power consumption, the studied object of the MC-cenosis and its lower permissible value of the lower limit of the LPV. Within the framework of vector rank analysis, this difference is determined by the vector rank norm (Fig. 5) and it is calculated using the following formula:

$$\Delta W^AD = W_j^{mc} - W_j^N; W_j^{mc}, W_j^N \in X_k$$  

(6)

$W_j^{mc}$ – i values of the electrical energy consumption for the object of MC-cenosis;

$W_j^N$ – j lower permissible value at the lower boundary of LPV for the object of MC-cenosis;

$X_k$ – value of rank topological measure for values of electrical power consumption of the object of MC-cenosis and lower permissible value.

At the next stage, an algorithm for forming the transformed VRD and forecasting its values is implemented. It includes the following stages: calculating the average value of the entropy of the technocenosis, determining the parameters of the transformed VRD such as the first point and the rank coefficient, and predicting the calculated values of the transformed VRD.

Mathematically, this algorithm can be described by the following system:

$$\left\{ W_k(x, \tau); W_{AD}(\tau) \right\} \xrightarrow{H_W^{BF}(\tau)} \left\{ W_k^{BF}(x, \tau) \right\}$$

$$\int_0^\infty W_k^{BF}(x, \tau)dx = \int_0^\infty W_k^{BF}(x, \tau)dx + W_{AD}(\tau)$$

$$\text{Force}\{H_W\} \xrightarrow{t=\tau} H_W^{BF}(\tau)$$

$$H_W(\tau) \approx -\sum_{j=1}^s \left( \frac{W_{\Delta j}(\tau)}{W_{\Delta}(\tau)} \times \ln \left( \frac{W_{\Delta j}(\tau)}{W_{\Delta}(\tau)} \right) \right)$$

(7)

$W_k(x, \tau)$ – VRD on electrical power consumption at the moment $\tau$ (x – rank topological measure);
\( W_k^{BF}(x, \tau) \) – corresponding bifurcational VRD on electrical power consumption at the moment \( \tau \);

\( W_{AD}(\tau) \) – additional resource at the moment \( \tau \) (measure which is turned into electrical energy consumption at the moment of bifurcation);

\( H_w^{BF}(\tau) \) – parametric bifurcational entropy of electrical energy consumption at the moment \( \tau \);

\( Forec{\{t\}} \) – process of forecasting (\( t \) – time);

\( W_\Lambda(\tau) \) – complex average value (according to the parameter of electrical energy consumption) taken in general at the moment \( \tau \);

\( W_{\Lambda j}(\tau) \) – corresponding average value, defined for a particular \( j \) functional group;

\( s \) – number of functional groups.

The first and the third expressions of the system (7) show that the stability of the VRD depends on the change in the entropy of rank norms during bifurcation of electrical power consumption. The concept of bifurcation of electric power consumption was introduced and proposed by Professor V.I. Gnatyuk and it represents a special period of the functioning of the technocenosis, during which its sustainable development is replaced by an unstable state. Then several new options for its development appear [4].

The second equation of system (7) enables to determine the total electric power consumption of the technocenosis at the bifurcation stage. The additional resource \( \Delta W_{AD} \) can be both negative and positive. It depends on the value of the electrical power consumption of the MC-cenosis.

The fourth expression is a general expression for determining the entropy of a technocenosis.

Since a two-parameter hyperbolic approximation form of the VRD is used, the system (7) can be significantly simplified

\[
\begin{align*}
\{W_{k1}, \beta^{IN}\} & \xrightarrow{H_w^{BF}} \{W_{k1}^{BF}, \beta^{BF}\}; \\
\{W_{rk}(x)\} & \boxtimes \{W_{rk1} \times x^{-\beta}\}; \\
n_{BF} &= \text{const}; \\
\text{Forec}\{W_{k1} \text{ or } \beta\} & \xrightarrow{H_w} W_{k1}^{BF} \text{ or } \beta^{BF}; \\
W_{k\Sigma} + W_{AD} &= \frac{W_{k1}^{BF}}{1 - \beta^{BF}} (n_{BF}^{1 - \beta^{BF}} - 1),
\end{align*}
\]

\( W_{k1}, \beta \) – parameters of approximated form of VRD of technocenosis;

\( W_{k1}^{BF}, \beta^{BF} \) – corresponding parameters of bifurcational VRD;

\( n_{BF} \) – number of objects in the technocenosis after the process of bifurcation;

\( W_{k\Sigma} \) – collective electrical energy consumption of technocenosis objects.

Thus, solving a simple system of equations presented in the fifth formula of system (7), it is possible to obtain the parameters of the transformed VRD such as the first point and the rank coefficient. Figure 5 shows the view of the VRD of technocenosis and the transformed VRD.
Thus, the calculated values of the transformed VRD are specified based on the additional resource $\Delta W^{AD}$ and become the initial data for forecasting.

3. Implementation of the technique for forecasting the electrical power consumption of technocenosis objects on the basis of the values from the transformed vector rank distribution

The implementation of the presented technique was carried out on the data on the electrical power consumption of the technocenosis (110 kV substations in the Kaliningrad area) and MC-cenosis (areas of the Russian Federation). The time interval was taken from 2015 to 2019 for every month.

The forecasting of electric power consumption at substations in the Kaliningrad area was implemented by three methods: the technocenosis method with a fixed first point, the technocenosis method without a fixed first point, and the forecasting method based on transformed vector rank distributions.

Two matrices were used as the initial data: initial transformed values of electric power consumption for a month for substations of the Kaliningrad area from 2015 to 2019.

The forecast accuracy was estimated according to two criteria: the average relative error and the absolute forecast error. The results are shown in Table 1.

### Table 1. Forecasting results.

|                     | The technocenosis method with a fixed first point | The technocenosis method without a fixed first point | The forecasting method based on transformed vector rank distributions |
|---------------------|--------------------------------------------------|---------------------------------------------------|---------------------------------------------------------------------|
|                     | 1st month | 2nd month | 3rd month | 1st month | 2nd month | 3rd month | 1st month | 2nd month | 3rd month |
| Average relative error, % | 9,6       | 10,1      | 9,8       | 6,3       | 5,8       | 7,1       | 4,1       | 4,8       | 5,1       |
| Absolute error for power grid overall kWh10^4 | 1,8       | 1,9       | 1,85      | 1,68      | 1,7       | 1,82      | 0,7       | 0,85      | 1,01      |

Figure 5. Additional resource for technocenosis objects.
As it can be seen from the Table 1, the values of the criteria in forecasting based on the matrix of transformed values of electric power consumption for substations in the Kaliningrad area are much better than those of the matrix of initial values [5].

Conclusion
The theoretical basis of the technique includes the scientific tenets of the theory of vector rank analysis, the methodology of functional rank analysis and the theory of mathematical statistics. When developing its algorithms, such key concepts as "technocenosis", "MC-cenosis" and "bifurcation" were used.

The implementation of the technique for forecasting the electric power consumption of technocenosis objects on the basis of the values of the transformed vector rank distribution enables to significantly define the plans for managing the resources of the power system.

The elaborated technique can be implemented in software and hardware complexes and situational centers for electric power consumption control in the region, energy system, transport network complex, large infrastructures and enterprises. The results of the technique will significantly supplement the methods of resource management for large infrastructure and energy facilities and form a resource consumption plan individually for each object.

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