Approach to calculation the parameters of emergency modes of electric grid using topological list

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Abstract. The article presents a method of representing the topology of the electrical grid on the basis of a topological list (T-list), including both structural and numerical information about the elements of the grid. The method of calculation of emergency operation modes parameters of power supply system (PSS) with T-list use, which can be used for calculation on the personal computer, is resulted. The considered approach allows optimizing computing resources at calculation of emergency operation modes of industrial enterprises PSS.

1. Introduction
Calculation of operation modes of power supply systems (PSS) of industrial enterprises is relevant today. Existing software packages allow estimating the parameters of power consumption without taking into account the technological features of the oil enterprises.

However, a comprehensive assessment of electrical and technological modes allows us to determine the most rational ways to improve energy efficiency and lifetime of equipment [1].

Very frequently one of the main problems encountered in the PSS of industrial facilities is the high territorial distribution of power consumption nodes [2], for this reason the parameters of emergency operation modes vary widely [3].

Verification of equipment for PSS of complex technological objects requires the calculation of a huge array of emergency operation modes parameters. This fact is compounded by the changing topology of PSS and the availability of large amounts of equipment [4].

In the described conditions, a relevant task is to develop an automated complex for assessing emergency operation modes of complex technological objects PSS [5]. This article discusses the proposals for the automation of calculations of emergency operation modes.

2. Methods of power supply system’s parameters calculation
One of the most convenient methods for calculating the parameters of electric power systems for software implementation is the method of nodal voltages [6]. The mathematical description of this method allows interpreting the PSS as a matrix-topological structure.

Within the implementation of the calculation module for estimates parameters of PSS was proposed an algorithm for obtaining a matrix-topological description of the object model, described in [7]. This algorithm allows obtaining a description of the matrix-topological structure by the topological list (T-list), which enables you to change the size of PSS [8] (table 1).
### Table 1. Template of topological list

| Branch | Nodes (Branch Start) | Nodes (Branch End) | Conductivity | Current Source | Electromotive Force Source |
|--------|----------------------|--------------------|--------------|----------------|---------------------------|
| 1      | s₁                  | e₁                | Yᵥ₁          | J₁            | Eᵍ₁                       |
| ...    | ...                 | ...               | ...          | ...           | ...                       |
| m      | sᵅ                  | eᵅ                | Yᵥᵅ          | Jᵅ            | Eᵍᵅ                       |

2.1. Methods of normal operation mode parameters calculation

Analysis of electric power mode includes the calculation of the of the normal operation mode parameters, obtained as a solution of the matrix equation:

\[ \begin{align*}
\begin{bmatrix} \mathbf{U} \\
\mathbf{M} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{Y}_v \\
\mathbf{1} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{J} \\
\mathbf{0} \end{bmatrix} & = \begin{bmatrix} \mathbf{Z} \\
\mathbf{0} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{E}_g \\
\mathbf{0} \end{bmatrix}
\end{align*} \quad (1)
\]

where \( \mathbf{Y}_v \) is a diagonal matrix, elements of which composed of vector conductivity \( Y_v \) elements from table 1, \( \mathbf{J} \) is a vector of current source, \( \mathbf{U} \) is a vector of nodal voltages, \( \mathbf{Z} \) is a matrix of nodal resistances, and \( \mathbf{M} \) is incidence matrix.

The T-list is based on the description of branches, so the result of solution (1) is more convenient to represent as a branch parameter – voltage drop vector:

\[ \begin{align*}
\begin{bmatrix} \mathbf{U} \\
\mathbf{M} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{Y}_v \\
\mathbf{1} \end{bmatrix} & = \begin{bmatrix} \mathbf{Z} \\
\mathbf{0} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{E}_g \\
\mathbf{0} \end{bmatrix}
\end{align*} \quad (2)
\]

where \( \mathbf{E}_g \) is a column vector of branch electromotive forces (EMF).

Then branch currents vector is calculated:

\[ \begin{align*}
\begin{bmatrix} \mathbf{I} \\
\mathbf{M} \end{bmatrix} & = \begin{bmatrix} \mathbf{Y}_v \\
\mathbf{1} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{U} \\
\mathbf{M} \end{bmatrix}
\end{align*} \quad (3)
\]

2.2. Methods of emergency operation mode parameters calculation

Calculation of emergency operation mode parameters in case of short circuit in k-node is performed by adding a branch to the T-list with conductivity \( y_k \rightarrow \infty \) (table 2). The conductivity in the short circuit node is recommended to be equal to \( y_k = 10^6\cdot10^8 \) S [9] depending on the base voltage level.

### Table 2. Template of T-list for calculating short circuit current

| Branch | Nodes (Branch Start) | Nodes (Branch End) | Conductivity | Source current | Source electromotive force (EMF) |
|--------|----------------------|--------------------|--------------|----------------|----------------------------------|
| 1      | s₁                  | e₁                | Yᵥ₁          | J₁            | Eᵍ₁                             |
| ...    | ...                 | ...               | ...          | ...           | ...                             |
| m      | sᵅ                  | eᵅ                | Yᵥᵅ          | Jᵅ            | Eᵍᵅ                             |
| m+1    | sᵅ+₁ = k            | eᵅ+₁ = 0          | Yᵥᵅ+₁ = yᵅ  | Jᵅ+₁ = 0      | Eᵍᵅ+₁ = 0                       |

Next step, the operation mode is calculated according to the equations (1)-(3). The required value is the current \( I_{m+1} \) of vector \( \mathbf{I} \).

The above method has a significant disadvantage, namely, the calculation of the short circuit currents in each of the \( n \)-nodes of the PSS requires the matrix inversion by \( n \)-times. The matrix inversion is the most computationally expensive operation, and the result of the inversion can be saved for future use.

3. Description of the proposed approach to the determination of short-circuit currents on the grid elements

The article proposes to save obtained by equation (1) the normal operation mode matrix of nodal resistances \( \mathbf{Z} \) in the computer memory for further use in order to reduce computational resources.
The method of adjusting operation modes parameters based on the Lemma about the inversion of the sum of matrices is known [10, 11]:

$$Z^\text{adj} = \left(Y^\text{adj}\right)^{-1} = \left(Y + y_{pr} \cdot \mathbf{m} \cdot \mathbf{m}^T\right)^{-1} = Y^{-1} - \left(y_{pr}^{-1} + \mathbf{m}^T \cdot Y^{-1} \cdot \mathbf{m}\right)^{-1} \cdot Y^{-1} \cdot \mathbf{m} \cdot \mathbf{m}^T \cdot Y^{-1} \quad (4)$$

where $Z^\text{adj}$, $Y^\text{adj}$ is the adjusted nodal resistances and conductivities matrices, respectively, $y_{pr}$ is the conductivity changes in between nodes $p$ and $r$, $\mathbf{m} = [0 \ldots ^{p-1} 1 \ldots ^{r-1} 0]^T$ is the vector-column of commutations between nodes $p$ and $r$ of dimension $n$.

Substituting $\alpha = \left(y_{pr}^{-1} + \mathbf{m}^T \cdot Z \cdot \mathbf{m}\right)^{-1}$ and equation (4) in equation (1), it obtained an expression for the adjusted nodal voltages vector:

$$\mathbf{U}^\text{adj} = \left(Y^\text{adj}\right)^{-1} \mathbf{j} = \mathbf{U} - \alpha \cdot Z \cdot \mathbf{m} \cdot \mathbf{m}^T \cdot \mathbf{U} \quad (5)$$

The vector-column of commutations for a short circuit in node $k$ emergency mode parameters calculation takes the form:

$$\mathbf{m} = [0 \ldots ^{k-2} 1 \ldots ^{n} 0]^T, \quad (6)$$

where $k$ is the sequence number of the node where the short circuit is calculated.

Given that the short-circuit node conductivity meaning tends to infinity ($y_{ij} \rightarrow \infty$), then:

$$\alpha = \left(\mathbf{m}^T \cdot Z \cdot \mathbf{m}\right)^{-1} = (Z)^{kk} \quad (7)$$

where $\alpha$ is a scalar value equals $(Z)^{kk}$ (the element of the nodal resistance matrix main diagonal).

It is worth noting that the vector-column of commutations contains only one nonzero element, therefore the element-by-element actions on the matrices should be revealed:

$$Z \cdot \mathbf{m} \cdot \mathbf{m}^T = \begin{bmatrix} 0 & \cdots & Z_{ik} & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & Z_{nk} & 0 \end{bmatrix} \Rightarrow Z \cdot \mathbf{m} \cdot \mathbf{m}^T \cdot \mathbf{U} = \begin{bmatrix} Z_{ik} \cdot U_i \\ Z_{ik} \cdot U_k \\ \vdots \\ Z_{nk} \cdot U_n \end{bmatrix} \quad (8)$$

Whereupon the expression for determining each element of the adjusted nodal voltages vector from equation (5) with (7) and (8) takes the form:

$$\mathbf{U}^\text{adj} = \begin{bmatrix} U_i - Z_{ik}^{-1} \cdot Z_{ik} \cdot U_k \end{bmatrix} \quad (9)$$

Similarly, an expression to calculate the adjusted voltage losses vector in the T-list can be written as:

$$\mathbf{U}^\text{adj} = \begin{bmatrix} U_i - Z_{ik}^{-1} \cdot Z_{ik} \cdot U_k - (U_e - Z_{ek}^{-1} \cdot Z_{ek} \cdot U_e) \end{bmatrix} = \begin{bmatrix} U_i - U_e + (Z_{ek} - Z_{ik}) \cdot Z_{ik}^{-1} \cdot U_k \end{bmatrix} \quad (10)$$

where $s$, $e$ are the node numbers of the beginning and end of the branch, respectively.

According to the values of the adjusted voltage losses vector, the adjusted branch current vector is determined by the equation (3).

4. Conclusion

Obviously, the approach for determining the of emergency operation modes parameters of PSS does not allow to explicitly assess the magnitude of the current in the short circuit node, however, when the equipment checking on thermal and electrodynamic stability requires currents through the elements, which corresponds to the branch currents in the calculated graph.

The greatest difficulty in the presented method is the inversion of the conductivity matrix when determining the nodal resistance matrix, but this stage of the calculation algorithm in the software implementation can be performed directly when the circuit is set [12].

The novelty of this work lies in using scalar operations instead of matrix inversion for emergency mode parameters calculation, which increases the system speed and expands the field of use of the convenient T-list structure.
It is assumed that the results of the work will be included in the training course of the new master's program “Conceptual Design and Engineering of Improving Energy Efficiency” for the training of engineering skills, scientific personnel and management personnel in the power industry, grid companies and related sectors [13].

Acknowledgments

Part of the conducted research was carried out with financial support from the Ministry of education and science of Russia within the framework of research projects carried out by teams of research centers and research laboratories (project 8.4157.2017/Research Part).

Research is also supported by educational and research grant 573879-EPP-1-2016-1-FR-EPPKA2-CBHE-JP by European program Erasmus+ (Project INSPIRE).

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