The Model of Propagation of the Own Electromagnetic Radiation of the HV Equipment on Substations

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The mathematical model of the power substation is proposed. The substation esteems as a set of the equipment elements which integrated common connections and electromagnetic field. Some capabilities of model represented by both electric networks and a discrete logical model demonstrated by non-directional graph. The model can be useful for solution of the problem of diagnostic of the high-voltage equipment.

Keywords : Substations, Electromagnetic radiation, Logic circuits

1. INTRODUCTION STATEMENT OF A PROBLEM

The technical condition of the high-voltage electrical power equipment is mostly determined by condition of its insulation. The method of the analysis of partial discharges (PD), as a primary electrophysical process describing the quality of its insulation of the equipment elements (e.e.) is considered to be one of the most perspective one[1,2]. The PD are accompanied by own electromagnetic radiation (e.m.r.) in on the broad band of frequencies. This radiation can obviously be found at the time of service e.e. in operational modes and registered by means of the electronic devices. The substations can be considered as a combination of the e.e., which separately have properties of technical condition (serviceability or fault).

It is necessary to note, that the electromagnetic field of the substation forms by all e.e. simultaneously. The main purpose of e.m.r. research on the substations consists in early warning about in changes in technical state of e.e. without interference in the operation.

The problem is to establish properties of each equipment component as source e.m.r. most authentically, on the basis of electromagnetic field observation in some terrain points on the substation.

The specific parameters of the e.m.r. are the results of measurements during diagnosing. There are the radiation energy, signal amplitudes, concrete values of spectrum lines etc.

The object of processing of the measurement results is an allocation of useful (from the point of view of diagnostics) signals based on spatial arrangement of the equipment and connecting circuit, estimation of their properties and, in the issue, estimation of the e.e. technical state.

2. CIRCUIT MODEL OF PROPERTIES OF THE E.M.R SOURCES AND OBSERVABLE SIGNALS

Let's consider the problem of generation and distribution of e.m.r. on the substations and formalize the associations between elements and observed reactions. All the e.m.r. sources on the substation are throught to be generated only with its equipment and in any point of the substation recorded e.m.r. is a linear additive function of its sources.

The real arrangement of the power equipment at the substation is showed in Fig. 1. High frequency signals are distributed both by wires and by air especially for neighboring elements of the equipment.

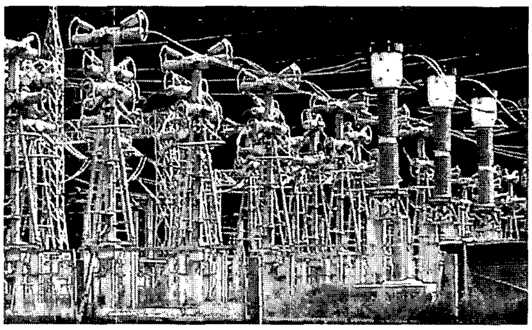

Fig. 1. Typical arrangement of the power equipment at the substation.

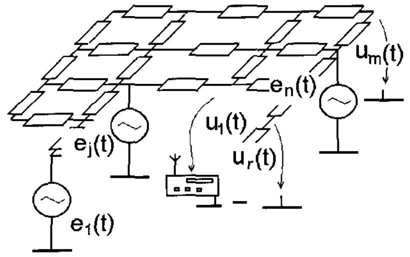

Fig. 2. Equivalent network as an electric circuit.

The generalized equivalent network as a circuit is shown in Fig. 2 and it corresponds to the above model.

There are:

$e_1(t)...e_s(t)$ - *s* e.m.r. sources,

$u_l(t)...u_m(t)$ - e.m.r voltages which are measured in *m* points of territory of the substations.

Connection between vectors of e.m.r. sources and measurements (**e(t)** = col $[e_1(t)...e_s(t)]$ and **u(t)** = col $[u_1(t)...u_m(t)]$) is described by an integral functional relation:

$$\boldsymbol{u(t) = F \{h(t), e(t)\}}, \quad (1)$$

where **h(t)** – is a matrix of transition functions, and **F** – is linear integral operator.

By going to spectral form representation of sources and measured voltages, we shall find in the matrix form:

$$U(j\omega) = \boldsymbol{K}(j\omega)\ \boldsymbol{E}(j\omega), \quad (2)$$

where **U**(jω) and **E**(jω) – are vectors of spectra of signals and sources, respectively, and **K**(jω) – is matrix of complex transmission factors of appropriate sizes.

The equivalent electrical circuit of substation can be seen on the Figure and the grid of impedances reflects objective parameters of electrical connections between equipment elements and the electro-physical characteristics of air, and propagation conditions e.m.r. due to different substation designs.

The determination of matrix elements **K**(jω) in theoretical aspect is described as the problem of diagnostics of multipole networks and is considered in the circuit theory in various modifications. From the practical point of view this task poses many problems.

Realization of experiments to estimate some characteristics of an equivalent electric network in the off-line mode is quite possible. Thus, special sources of e.m.r. (simulators) should be used and reactions in different points of the substation should be measured.

In the process of analyzing the propagation of their own e.m.r. on the substations it is possible to use categories, equivalent circuits, formulas and methods of the classic circuit theory.

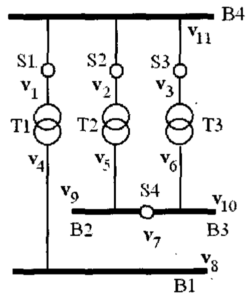

Fig. 3. One-linear substation scheme.

If to be limited only by power properties of signals, taking advantage of simpler ratio for modules of variables is possible:

$$U(\omega) = \boldsymbol{K}(\omega)\ \boldsymbol{E}(\omega),\ \omega \in \boldsymbol{\Omega}, \quad (3)$$

where **Ω** - set of frequencies for which the analysis is made.

The practical implementation and solving of mathematically correct relations (1, 2, 3) interferes with many factors handicapping the solution.

Besides there are serious problems, related to discrepancy of the information about the equivalent model parameters, measurement errors and availability of outside electromagnetic noises. It is possible to draw a conclusion that the construction of the model of propagation e.m.r. across the substation on the basis of the classic circuit theory is nonconstructive.

In this situation we should use more rough models, namely, methods performing logical representation of parameters of the electric network and parameters of signals.

The fragment o substation in Fig. 3 consists of three transformers, four cutout switches and a system of buses. The system of buses is not considered an independent source in this case/ it is a one-line map. But if earch high-voltage lead- in of three-phase transformer has a defect (source of radiation), we must take into consideration a complete three-phase electrical scheme.

The following for all elements v1, ..., v11 is schematized as: S1, S2, S3, S4 – cutout switches (e.e. v1, v2, v3, v7); T1, T2, T3 – transformers (e.e. v4, v5, v6): B1, B2, B3, B4 – buses (e.e. v8, v9, v10, v11).

3. LOGICAL MODEL OF PROPERTIES OF THE E.M.R SOURCES AND OBSERVABLE SIGNALS

In the analysis under review the spectrum is considered to be shown as a set of properties. Each property can either be present, or absent and this corresponds to 1 or 0 in logic calculus.

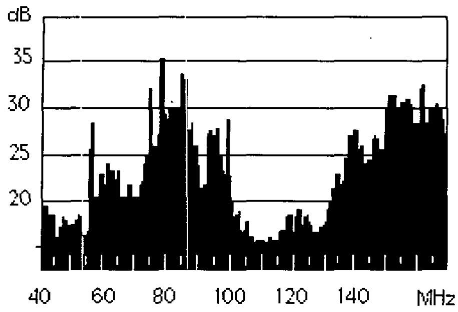

Fig. 4. A common spectrum of the signal.

In Fig. 4 a common spectrum of the signal measured on the substation is shown.

For example, in elementary case it is possible to consider that the properties of the spectrum are associated with spectral lines present or absent in some frequency subrange.

Logical description of the spectrum $\mathbf{E_L}(\omega)$ can be obtained from dissection set of frequencies on subsets $\{\Delta\omega_r\}$ and prescribing a threshold value $\underline{E}$. The overflow of threshold magnitude by values of the spectrum in some subsets corresponds to logic variable "1", and otherwise logic variable "0" is considered:

$$\mathbf{E}_{Li}(\Delta\omega_j) = \begin{cases} 1 \;\; \exists\, \omega \in \Delta\omega_j \;\; E_s(\omega) \geq \underline{E}, \\ 0 \;\; \forall\, \omega \in \Delta\omega_j \;\; E_s(\omega) < \underline{E}, \\ i = 1 \ldots s,\; r = 1 \ldots f \end{cases}$$

(For simplicity in the further analysis the index "L" of the logical matrix will be rejected).

So, the logical matrix of radiation sources **E**, in which columns correspond to sources and strings correspond to a set of properties of sources e.m.r. $\{\sigma_r\}$, $r = 1 \ldots n$, can be constructed. In the example the frequency subsets represent itself as properties of sources.

Let's associate nodes v1, ..., v7 for the above example the substation with sources e.m.r., and consider 8 prorerties of sources e.m.r. Here the prorerties of sources are set by a matrix **E**:

E =

1	0	1	0	0	0	0	1
1	1	0	0	0	0	0	0
1	0	0	1	0	0	0	1
0	0	0	1	0	1	0	0
0	1	0	0	1	0	0	0
0	0	1	0	0	0	0	0
1	0	0	0	1	0	1	0

Its columns correspond to properties, and strings correspond to sources. It is necessary to note that ideally identical columns in matrix **E** correspond to the same type of power equipment. However, in practice the behavior of power apparatus units usually has its own features reflected in elements of the matrix **E**.

Similarly we can use a matrix of measured properties of spectrum $\mathbf{U} = \{\mathbf{U}_{rj}\}$ $(r = 1 \ldots f, j = 1 \ldots m)$ where strings correspond to points of measurements and columns correspond to properties of observable signals.

4. LINK BETWEEN E.M.R. SOURCES AND THE MEASUREMENTS

A link between e.m.r. sources properties and properties of measured voltages can be written down (3) as

$$\boldsymbol{U}_r = \boldsymbol{K}_r \boldsymbol{E}_r, \quad (r = 1 \ldots n), \tag{4}$$

Here:

$\mathbf{E}_r = \text{col}\,[E_{ri}]$, $(i = 1 \ldots s)$ is a vector of the presence of property r in sources,

$\mathbf{U}_r = \text{col}\,[U_{rj}]$, $(j = 1 \ldots m)$ is a vector of presence of property r in registered signals,

$\mathbf{K}_r$ - is a matrix of transfer factors (influence) of property r.

The matrix **K** generally depends on a transmitted property r. For example, the e.m.r. transfer to the top or the bottom of the frequency range can differ noticeably.

The transmission factor **K** reflects real conditions of the signal distribution, including mutual geometrical arrangement of sources, observation point and enclosing constructions. The matrix of transmission factors can be presented as a logic matrix, with elements 0 and 1 too.

The mathematical model of the link between sources and measurements is constructed on the basis of a graph and can be used to expose and analyse the processes on the object of diagnosing the substation.

Let's enter a series of formal labels.

Let's designate set of all nodes by $\mathbf{V} = \{V_k\}$, $k = 1 \ldots v$. Set of nodes connected by branches form the graph $\mathbf{G} = \mathbf{G}(\mathrm{V})$.

The set of nodes is divided into 3 subsets:

$\mathbf{S} \subseteq \mathbf{V}$ – nodes associated with e.e. which are sources of e.m.r. ($|\mathbf{S}| = s$);

$\mathbf{P} \subseteq \mathbf{V}$ – nodes corresponding to sources of e.m.r. electric circuit substation;

$\mathbf{M} \subseteq \mathbf{V}$ – nodes associated with points of measurements of e.m.r. on the territory of substation.

Ways to distribute e.m.r. are associate with branches of the graph. Branches of the graph have a dual nature. Taking into account the specificity of an object, two ways of distribution of a signal are regarded.

First - due to direct electric connections (branches of the graph are formed on the basis of the electric circuit of connection of e.e.). These connections between e.e.

under specific operating conditions on substation depend on the substation circuit, they are known at the moment of carrying out experiments.

The second way of distribution of a signal - due to direct radiation of electromagnetic waves in ether elements of the equipment. In this case the basis for construction of branches of the graph serves as the analysis of the spatial - geometrical arrangement e.e. being as e.m.r. sources. Clearly, that connection between elements of each pair e.e. is symmetric, i.e. the signal can be distributed from any of pair elements to the second - in any direction.

Thus, some pairs nodes of the graph $(V_k, V_j) \in (\mathbf{P} \cup \mathbf{S}) \subseteq \mathbf{V}$ are connected by nondirectional branches, and this connection is expressed by the predicate:

$$\forall V_k \in (\mathbf{P} \cup \mathbf{S}),\ V_j \in (\mathbf{P} \cup \mathbf{S})\ \mathbf{G}(V_k, V_j, \theta), \qquad (5)$$

where θ is sign of nondirectional branch.

On the other hand, the branches of the graph associated with points of supervision $V_k \in \mathbf{M}$, have an obviously expressed orientation. It is clear, that e.m.r. signals can be distributed only from substation e.e. to the point of supervision; this point should not and cannot be in itself to of source e.m.r. on substation. (i.e. the measuring devices are located in corresponding substation places)

Nodes $V_k \in \mathbf{M}$

- are connected to other nodes directed branches,
- are connected only to nodes of set $(\mathbf{P} \cup \mathbf{S})$,
- are deadlock tops.

Similarly (1), it is expressed as:

$$\forall (V_k, V_j)\ V_k \in \mathbf{M},\ V_j \in [(\mathbf{P} \cup \mathbf{S}) \setminus \mathbf{M}],$$

$$\mathbf{G}(V_k, V_j, \eta) \wedge \mathbf{G}(V_j, V_k, \xi). \qquad (6)$$

Here η and ξ are signs of the end and beginning of the oriented branch, respectively.

It is clear that $\mathbf{S} \cap \mathbf{P} = \varnothing$, and for simplicity we shall put, that set $\mathbf{M}$ is not crossed with sets $\mathbf{S}$ and $\mathbf{P}$:

$$\mathbf{M} \cap (\mathbf{P} \cup \mathbf{S}) = \varnothing.$$

The process of construction of the graph consists of two stages. At the first stage the nodes and branches corresponding only power equipment are observed. The second stage is the adding the points of measurement.

In the simplest case we can speak about propagation of signals from neighboring sources and neglect of signals of the remote sources.

5. EXAMPLE OF THE GRAPH CONSTRUCTION

The graph $\mathbf{G(V)}$ for one-linear scheme is shown in Fig. 5. The nodes v_1 ... v_7 are sources of electromagnetic radiation. The branches that appropriate conductive electrical links between equipment elements are marked off by solid lines. Links for electromagnetic radiation are marked off by dash lines. We shall add still nodes - points of supervision $\{v_{12}, v_{13}, v_{14}\}$, directly not connected with unique e.e. Real supervision in these points is logic sum e.m.r. of several sources.

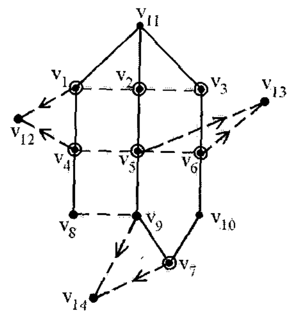

Fig. 5. Graph **G(V)**.

(If in the same simple electric circuit in Fig. 3 to present three phases separately the graph takes the essentially more complex form submitted in Fig. 6).

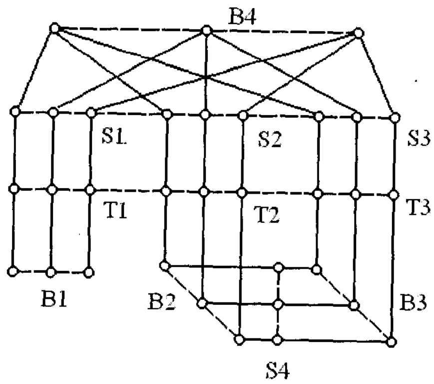

Fig. 6. Three-phase substation scheme.

6. THE MATRIX DESCRIPTION OF THE GRAPH

Let's as the primary matrix description of the graph enter into consideration the matrix of a nodes contiguity **D**. According to splitting $\mathbf{V} = \mathbf{S} \cup \mathbf{P} \cup \mathbf{M}$ matrix **D** we shall present in a block kind:

	$V_k \in \mathbf{S}$	$V_k \in \mathbf{P}$	$V_k \in \mathbf{M}$	
	$\mathbf{D}_{SS}$	$\mathbf{D}_{SP}$	$\mathbf{D}_{SM}$	$V_k \in \mathbf{S}$
D =	$\mathbf{D}_{PS}$	$\mathbf{D}_{PP}$	$\mathbf{D}_{PM}$	$V_k \in \mathbf{P}$
	0	**0**	**1**	$V_k \in \mathbf{M}$

(7)

The top left submatrix from 2x2 blocks corresponds to a nondirectional part of the graph. Since the orientation of branches is connected with nodes - points of supervision, elements of contiguity matrix $\mathbf{D} = \{d_{jk}\}$ represent 0 or 1 according to rules:

$$\begin{cases} \forall(V_k, V_j) \in (\mathbf{S} \cup \mathbf{P}) \quad \mathbf{G}(V_k, V_j, \theta) \Rightarrow d_{kj} = d_{jk} = 1; \\ \forall(V_k, V_j) \in (\mathbf{S} \cup \mathbf{P}) \quad \neg\mathbf{G}(V_k, V_j, \theta) \Rightarrow d_{kj} = d_{jk} = 0; \\ \forall V_k \in (\mathbf{S} \cup \mathbf{P})\, V_j \in \mathbf{M} \quad \mathbf{G}(V_k, V_j, \xi) \Rightarrow d_{kj} = 1; \\ \forall V_k \in \mathbf{M} \quad v_j \in \mathbf{V} \quad V_j \neq V_k \Rightarrow d_{kj} = 0 \\ \forall(V_k, V_k) \Rightarrow d_{kk} = 1 \end{cases} \tag{8}$$

For the example and as on partition (7) matrix **D** shows as:

D=

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1		1							1	1		
2	1	1	1		1						1			
3		1	1			1					1			
4	1			1	1			1				1		
5		1		1	1	1			1				1	
6			1		1	1				1			1	
7							1		1	1				1
8				1				1	1					
9					1		1	1	1					1
10						1	1			1				
11	1	1	1								1			
12												1		
13													1	
14														1

7. THE ANALYSIS OF THE SIGNAL DISTRIBUTION

In practice show that the individual e.m.r. signals generated by elements of the e.e. at distribution on substation are damped out. In this connection it is necessary to enter a measure of distance between corresponding nodes of the graph. Since this measure it is possible to accept length of a way between nodes of the graph and to consider, that a signal (or its some properties) are shown on distance from a source, not the greater of some set size.

From the graph theory it is known, that the matrix of quantity of the ways having length ℓ between nodes of the graph is set by a degree ℓ of the contiguity matrix (having zero along the main diagonal): $\mathbf{D}^{\ell}$. If on the main diagonal are located "1" (according to (7, 8)) matrix $\mathbf{D}^{\ell}$ gives information on the quantity of the ways between nodes having length of no more than ℓ. The matrix $\mathbf{D}^{\ell}$, calculated on the rules of the boolean arithmetics, will give a required matrix of ways of length of no more than ℓ:

$$(\mathbf{D})^{\ell} = \begin{array}{|c|c|c|} \hline \mathbf{D}^{\ell}_{SS} & \mathbf{D}^{\ell}_{SP} & \mathbf{D}^{\ell}_{SM} \\ \hline \mathbf{D}^{\ell}_{PS} & \mathbf{D}^{\ell}_{PP} & \mathbf{D}^{\ell}_{PM} \\ \hline \mathbf{0} & \mathbf{0} & \mathbf{1} \\ \hline \end{array} \tag{9}$$

As in the problem under consideration it is of interest of ways from nodes - sources in nodes - points of supervision, a matrix of influence $\mathbf{K}(\ell)$ when e.m.r.signal is distributed on of the graph to distance of no more than ℓ are of interest only, is the transposed right extreme submatrix of the first block line from expression (9):

$$K(\ell) = (D^{\ell}_{SM})^T.$$

In the specific case, when supervision of e.m.r. signals is possible in all nodes of the graph, we shall obtain $\mathbf{K}(\ell)$ from the first block – line of (9):

$$K(\ell) = \begin{array}{|c|c|c|} \hline \mathbf{D}^{\ell}_{SS} & \mathbf{D}^{\ell}_{SP} & \mathbf{D}^{\ell}_{SM} \\ \hline \end{array}^{T}$$

The matrix reflects the distance in the graph to which the properties of the spectrum are transmitted. So, if the properties of the spectrum are transmitted only to the next nodes, as the basis for construction of a matrix **K** it is possible to accept a matrix of an incidence of nodes.

There are cited matrixes **K**(1):

K(1) =

1	1	0	1	0	0	0
1	1	1	0	1	0	0
0	1	1	0	0	1	0
1	0	0	1	1	0	0
0	1	0	1	1	1	0
0	0	1	0	1	1	0
0	0	0	0	0	0	1
0	0	0	1	0	0	0
0	0	0	0	1	0	1
0	0	0	0	0	1	1
1	1	1	0	0	0	0
1	0	0	1	0	0	0
0	0	0	0	1	1	0
0	0	0	0	0	0	1

and **K**(2) as an example:

K(2) =

1	1	1	1	1	0	0
1	1	1	1	1	1	0
1	1	1	0	1	1	0
1	1	0	1	1	1	0
1	1	1	1	1	1	1
0	1	1	1	1	1	1
0	0	0	0	1	1	1
1	0	0	1	1	0	1
0	1	0	1	1	1	1
0	0	1	0	1	1	1
1	1	1	1	1	1	0
1	1	0	1	1	0	0
0	1	1	1	1	1	0
0	0	0	0	1	0	1

Then the following properties in nodes of measurements can be observed:

U(1)=K(1)E =

1	1	1	1	0	1	0	1
1	1	1	1	1	0	0	1
1	1	1	1	0	0	0	1
1	1	1	1	1	1	0	1
1	1	1	1	1	1	0	0
1	1	1	1	1	0	0	1
1	0	0	0	1	0	1	0
0	0	0	1	0	1	0	0
1	1	0	0	1	0	1	0
1	0	1	0	1	0	1	0
1	1	1	1	0	0	0	1
1	0	1	1	0	1	0	1
0	1	1	0	1	0	0	0
1	0	0	0	1	0	1	0

and

U(2)=K(2)E =

1	1	1	1	1	1	0	1
1	1	1	1	1	1	0	1
1	1	1	1	1	0	0	1
1	1	1	1	1	1	0	1
1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1
1	1	1	0	1	0	1	0
1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	0
1	1	1	1	1	0	1	1
1	1	1	1	1	1	0	1
1	1	1	1	1	1	0	1
1	1	1	1	1	1	0	1
1	1	0	0	1	0	1	0

8. PROBLEM OF DIAGNOSTICS OF THE SOURCES PROPERTIES

The inverse problem - diagnosis of properties of sources may be of interest. It not always can uniquely be resolved. Taking into account that the matrix of measurements **U** is evaluated under the formula we have:

$$U_{jr} = \bigvee_{i=1}^{s} (K_{ji} \,\&\, E_{ir}),$$

Let's deduce the following expression to analyze the inverse problem. It is to formulate 2 rules:

Rule 1 (0-analysis):

$$If\ (U_{jr} = 0 \,\&\, K_{ri} = 1) \Rightarrow E_{ir} = 0$$

Rule 2 (1-analysis):

If (for each j of l-neigborhood of source i, $U_{jr} = 1$) & (for each $k \neq i$ of l-neigborhood of source i, $U_{kr} = 0$) $\Rightarrow$ $E_{ir} = 1$

One example can be offered to illustrate the solution of the inverse problem. It's assumed, that as result of observations the matrix **U**(1) is obtained and for the given graph the matrix of transmission factors **K**(1) is known. Let's prepare an "empty" matrix $\mathbf{E}_{01}$ for the further analysis the elements of which having no concrete values yet. By applying the mentioned we can fractionally fill in this matrix with elements:

$\mathbf{E}_{01}$ =

1	0	1	X	0	0	0	1
X	1	0	X	0	0	0	0
X	X	X	X	0	0	0	1
0	0	0	X	0	1	0	0
0	1	0	0	1	0	0	0
0	0	1	0	0	0	0	0
1	0	0	0	1	0	1	0

And if we have matrix **U**(2) and **K**(2) then are obtained the result of diagnosis of the sources properties as follows:

$\mathbf{E}_{02}$ =

X	X	X	X	X	0	0	1
X	X	X	X	X	1	0	0
X	X	X	X	X	0	0	1
X	X	X	X	X	1	0	0
X	X	0	0	X	0	0	0
X	X	X	0	X	0	0	0
X	X	0	0	X	0	1	0

Here symbol "X" designates elements with uncertain values. The comparison of this matrix and a matrix **E**, which is used for construction of the illustration.

displays that the formal substitution of symbol "X" on "1" does not reduce in the complete solving of the problem. It is necessary to state there are still many problems in this field calling for further solution.

9. SUMMARY

In summary we can state the problems to be posed and solved on the basis of a circumscribed model.

First, these are the problems to detect individual properties of e.m.r. of sources, which on further monitoring will be a subject of special attention of serving staff.

Second, the problem to minimize the necessary points of measurements, sufficient enough to analyse all properties of signals is very important.

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