Implementation of inverse calculation method in diagnostics of digital electric substations

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Abstract. Diagnostics of the equipment of a substation is an important element of effective work of the machine-building industry in view of the fact that engineering plants need continuous and high-quality power supply. The article presents the solution for the accelerated analysis of the complex technical system equipment condition by the example of a digital substation. It is based on Boolean algebra and logic-numerical polynomic models. This approach can be applied to state estimation of the power equipment and digital devices of the substation.

1. Introduction

Precipitant development of modern information technologies, microprocessor equipment allows one to move to a new level of automation of electric substations – to digital substations. To accomplish this transition, a lot of research related to digital substations are performed [1-10].

The digital substation represents the complex technical system (TS) which is subject to an operating mode change, so, continuous monitoring of its condition is necessary. The change of a reliability status of the TS by an example of a digital substation is connected with the transition of the TS to a condition of refusal or with transition of the TS to a pre-failure condition. Accordingly, considering specificity of the technical system, the requirements for agility control are imposed to it.

The power equipment, used on the substation, is delivered by the companies which are engaged in the mechanical engineering area. An important question is obtaining information on the current state of such equipment during its operation for the purpose of its diagnostics because the main functions of the substation are assigned to this equipment. In addition, any machine-building plant needs uninterrupted power supply, therefore, there are high requirements to the reliability of the power supply.

An electrical power supply system of machine-building plants consists of supplying, distributive, transformer and converting substations, power line and current distributors of high and low voltage. The system of power supply should be reliable, convenient and safe in service and provide necessary quality of energy and uninterrupted electric power supply in normal and post-emergency conditions.

Thus, diagnostics of the power equipment and substations in general, which feed machine-building plants, is an important element of effective work of the machine-building branch.
2. Materials and methods

System of Boolean functions, tree of malfunctions, mathematical model operation on the basis of application of logical-numerical models.

3. Results and Discussion

For ensuring uninterrupted power supply, it is necessary to carry out the fast control of a condition of substations. One of the systems, necessary for the work of the digital substation, is an information system of monitoring (ISM), namely an SCADA-system. The structure of ISM includes the software (the interpreter of values of the TS controllable parameters into the values characterizing conditions of the TS), allowing one to carry out the analysis of a condition of the system.

Management of processes on the digital substation depends on the reaction time. If the reaction time of ISM and TS state change big in magnitude, this change can be missed by ISM (figure 1).

However, the time of reaction consists of several temporary intervals, such as time $t_1$ necessary for data collection, the time necessary for the analysis of this data $t_2$ and the time $t_3$ necessary for providing information characterizing a TS condition:

$$t_r = t_1 + t_2 + t_3.$$

But, with these time intervals, time $t_a$ for control action is also needed. Accordingly, the duration of a cycle of management of the TS is defined by the sum of times $t_r$ of the reaction and times $t_{ca}$ of realization of the control action.

For reduction of time $t_r$ of the reaction, it is necessary to reduce the time of the analysis of condition, $t_2$. As a part of ISM, there should be models and control methods of a condition of the TS. One of the methods of representation of models is creation of the logic functions (LF) of failures of the TS. For designation of working ability (1) or not working state (0) of each of $n$ TS elements, Boolean variables $x_i (i = 1, n)$ are used. Values of the function on each of sets of values of variables allow one to draw a conclusion what condition a TS is in.

Figure 1. The emergence of a dangerous condition.
One of standard methods of creation of such LF is the method of creation a technical system malfunctions tree. The tree of malfunctions comprises a set of the initiating events (a deviation of values of parameters from admissible values, refusals of the TS elements), expressed by Boolean variables, as well as the hierarchy of nodes, to each of which Boolean function is compared. By means of a tree of malfunctions, it is possible to track cause-effect relationship between simulating events. During creation of a tree of malfunction for the TS, having an essential quantity of elements, there are difficulties connected with a large number of communications between a TS elements.

Let us make the tree of malfunctions of the TS by the example of the digital substation represented in figure 2.

For the substation, following malfunctions are defined:
- Failure of the power equipment;
- Failure of networks of data transmission;
- Failure of the power equipment and data-communication network.

One of logic functions ‘AND’, ‘OR’, ‘CONDITION’, ‘EXCLUDING OR’ and ‘PRIORITY AND’ corresponds to each node of the malfunction tree. The nodes of the tree, being at the lowermost level of the hierarchy, correspond to the initiating events changing conditions of the TS which are entered by logical variables.

A Boolean function (BF) can be corresponded to each node of the malfunction tree. For each level of the tree of malfunctions of the TS a system of Boolean functions (SBF) can be associated. SBF is used for the description of processes of TS in a failure condition transition.

Following SBF correspond to tree of malfunctions represented in figure 2:

\[
\begin{align*}
\text{Level 1:} & \\
& f_{\text{failure11}} = x_1 \land x_2 \lor x_3, \\
& f_{\text{failure12}} = x_4 \land x_2 \lor x_6, \\
\end{align*}
\]
where $f_{\text{failure}ij}$ – BF of failure of the node $j$, located on the $i$ level of the tree of malfunctions considered by the TS;

$x_1 \ldots x_6$ – the Boolean variables describing existence of initiating events for transition considered by the TS under conditions of failure (value "0" of Boolean variable $x_i$ corresponds to lack of the initiating event, and values "1" corresponds to event existence), symbols $\wedge$, $\vee$ have designated operations of logic addition and multiplication.

However, in case of a large number of the initiating events and/or additional functions, malfunctions analysis of the TS assumes the creation of SBF of high complexity. The described fact testifies to complexity of SBF, storage and realization of BF corresponding to a logic structure of the tree of malfunctions that in turn reduces productivity of the information system of monitoring of the technical system.

Parallel processes of the modern TS causing necessity of simultaneous realization of several BF – i.e. SBF. The effective solution of this task is application of a logical-numerical polynom (LNP) [11] which allows creating SBF in one arithmetic expression.

Using expressions:

$$
\begin{align*}
    & x_1 \wedge x_2 = x_1 x_2, \\
    & x_1 \vee x_2 = x_1 + x_2 - x_1 x_2 ,
\end{align*}
$$

it is necessary to transform systems (1) and (2), using presented expressions:

**Level 1:**

$$
\begin{align*}
    f_{\text{failure}11}(x_1) &= x_1 x_2 + x_3 - x_1 x_2 x_3, \\
    f_{\text{failure}12}(x_1) &= x_4 x_2 + x_6 - x_4 x_5 x_6,
\end{align*}
$$

**Level 2:**

$$
\begin{align*}
    f_{\text{failure}21}(x_2) &= f_{\text{failure}11}(x_1), \\
    f_{\text{failure}22}(x_2) &= f_{\text{failure}12}(x_1), \\
    f_{\text{failure}23}(x_2) &= f_{\text{failure}11}(x_1) f_{\text{failure}12}(x_1).
\end{align*}
$$

Then, it is necessary to multiply level-by-level expressions on relative to them weighting factors: $2^0, 2^1, 2^2, \ldots, 2^{s-1}$ ($s$ – quantity of BF entering into SBF at each level):

**Level 1:**

$$
\begin{align*}
    f'_{\text{failure}11}(x_1) &= 2^0 (x_1 x_2 + x_3 - x_1 x_2 x_3), \\
    f'_{\text{failure}12}(x_1) &= 2^1 (x_4 x_2 + x_6 - x_4 x_5 x_6), \\
    f'_{\text{failure}21}(x_2) &= 2^0 f_{\text{failure}11}(x_1), \\
    f'_{\text{failure}22}(x_2) &= 2^1 f_{\text{failure}12}(x_1), \\
    f'_{\text{failure}23}(x_2) &= 2^2 f_{\text{failure}11}(x_1) f_{\text{failure}12}(x_1).
\end{align*}
$$

For receiving LNP $D(x_i)$ for each of the levels of the tree of malfunctions, summation of factors of an arithmetic polynom on each level is performed:

$$
\begin{align*}
    D_1(x_i) &= x_1 x_2 + x_3 - x_1 x_2 x_3 + 2 x_4 x_5 + 2 x_6 - 2 x_4 x_5 x_6, \\
    D_2(x_i) &= f_{\text{failure}11}(x_1) + 2 f_{\text{failure}12}(x_1) + 4 f_{\text{failure}11}(x_1) f_{\text{failure}12}(x_1).
\end{align*}
$$

Let’s consider following abnormal situation example.

The initiating events $x_1$ - transformer temperature increase; $x_2$ – the increase of the current proceeding through the transformer; $x_3$ - turn-to-turn short circuit; $x_4$ - duplicative stream supply on the information network; $x_5$ - overload of the information network; $x_6$ - time server malfunction.
Let’s simulate the situation as follows: \( x_1 = [0 0 1 1 0 1] \). Then, the values of polynom \( D_1(x_1) \) during substitution will be equal to \( D_1(x_1) = 3_{(10)} = 11_{(2)} \). Thus, values of polynom \( D_1(x_1) \) will allow us to write down value \( x_2 = [1 1] \). Then values of polynom \( D_2(x_2) \) during substitution it will be equal to \( D_2(x_2) = 7_{(10)} = 111_{(2)} \), then analyzing binary representation of the value of polynom \( D_2(x_2) \) it is possible to draw a conclusion that the emergence of three refusals will occur on the set of values of variables \( x_1 \). This conclusion can be traced graphically on a basis of figure 2.

4. Conclusion
Thus, the used mathematical support based on LNP, allowing to increase productivity of ISM-difficult TS by an example of the digital substation, as well as to estimate the current status of the equipment of the substation. This approach is effective, because the digital substation represents the system with big amount of elements and connections and the analysis of a condition of the digital substation is a critical time parameter. Providing the fastest analysis of a condition of the substation will allow to take actions on elimination of the arisen malfunctions and the fast restoration of power supply that is an important element of the machine-building area.

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