Digitalization for operational management of electric networks

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Abstract: - The article discusses digitalization issues for managing electrical networks and the basic principles of digitalization. Examples of digitalization are given, such as the allocation of events and their intelligent processing, analysis of emergencies, and the search for damage in branched electrical networks. The verification algorithm for current meters based on redundant measurements is considered.

Key-Words: - Digitalization.

Received: August 7, 2023. Revised: December 11, 2023. Accepted: February 19, 2024. Published: April 3, 2024.

1 Introduction

The task of digitalization (digital transformation) of energy is now extremely urgent. Unfortunately, despite the efforts made by specialists (see, for example, [1]), there is still no universally accepted formulation of this concept, and there are no "recipes" that allow you to plan digitalization actions, and evaluate the expected effect of these actions. Digitalization in modern conditions is closely related to the development of the Internet of Things [2], but the required nature of this connection is also not completely clear.

Let us formulate some general principles of digitalization for the problems of managing electric networks.

2 General Principles

1. Digitization should not be reduced to a simple conversion of all technological parameters into digital form. This transformation should give rise to conceptually new tasks, the solution of which gives a significant economic effect.

2. One should strive for the maximum (within reasonable limits) "revitalization" (telemechanization) of pieces of equipment that should act as elements of the Internet of Things.

3. Data transmission in digital systems should be organized at two levels:

-detailed level (relatively rare transmission);

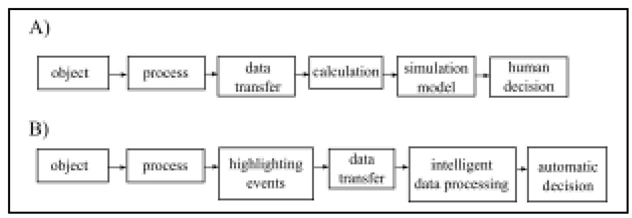
-express level (frequent transmission).

For a detailed level, all technologically significant parameters (processes) are subject to transfer, forming a digital simulation model of the control object [3].

For the express level, only new semantically significant information is transmitted in the form of information about events.

4. The selection of events from processes is the result of intelligent processing.

Thus, the meaning of the expression "intellectual connection" of the elements of digital systems is revealed.



The meaning of the above is explained by the structures depicted in Fig. 1.

Fig. 1. Data processing at various levels
A) detailed level, B) express level

3 Event Highlighting

From processes, it is necessary to select events. In many cases, such a selection is elementary. This refers to a change in the state of equipment and its elements. In particular, this applies to events of a change in the position of switching devices, to events of operation of relay protection devices, and to emergency automation (RPA).

In more complex cases of state, it is some (often predicative) function of the process of changing a parameter. For example, "violation of the limit" (this function is usually available in the arsenal of SCADA systems). There may be other predicates. It should be noted that, for example, the determination of the limits of operational parameters may require intelligent processing (as in the development of repair requests [4]).

In some cases, the event may be associated with the results of inspections (or tests) of equipment (for example, "oil leak").

4 Intelligent Event Processing

This processing is related to solving the tasks necessary in this particular application. Processed mainly information about events and conditions. For intelligent processing, it is advisable to use expert systems, which, in turn, need to specify a system of rules. Electric power is a technologically complex industry, therefore, for setting (and correcting) the rules, one should choose expert systems that provide a simple set of rules that are based on the operational experience of the corresponding expert experts [17-19]. Preference should be given to systems that use the natural language of specialists to formulate rules. As one of the possibilities, it is recommended to use the MIMIR instrumental expert system focused on the tasks of the electric power industry [5].

Thus, for instance, on the substation 500 kV of the Far-Eastern region was switched off by the action of gas protection of the 167 MVA/500/220 kV autotransformer. It was established with the chromatographic analysis by dissolved gas analysis (DGA) of transformer oil that the concentration of the dissolved gases exceeds boundary values several times[16]. The damage of the 4th turns of regulating winding was revealed with the internal inspection of autotransformer windings.

As a result, the internal inspection of autotransformer windings after emergency switching off revealed the damage and short-circuit of the fourth turns of regulating winding (fig. 2).

Fig. 2. Internal short-circuit of 167 MVA/500/220 kV autotransformer regulating windings.

It may be noted here that in existing and emerging digital systems and systems using the Internet of Things, insufficient attention is paid to intellectual processing. This is due to the relatively simple applications of the "pioneering" systems of this type. Anyone can come up with the rules for a coffee maker (a common example of a “smart home” in popular literature). And to formulate the rules for solving electric power problems, highly qualified specialists with significant operational experience are required. Moreover, the transfer of this experience to the rules of the expert system is a separate big problem.

The rules of the expert system are “packaged” in blocks (intelligent agents). The result of solving the problem can be the formation of messages (prompts) for users, the formation of new events, and the initiation of new intelligent agents.

Expert systems can be effectively used in practically important tasks of intelligent networks of energy enterprises:

- planning of repairs and operational regimen study of repair requests;
- analysis of emergencies in electric networks;
- restoration of electric networks after failures.

Below, we will consider in more detail the application of the methods described for some important control problems in electric networks [20,21]:

- analysis of emergencies;
- diagnosis of measuring channels of intelligent relay protection and automation based on redundant measurements;
- search for damage in branched electrical networks.

For the first of these tasks, the formulation of natural language rules will be considered, and for the third, a connection to the Internet of Things.

5 Analysis of Emergency Situations

The rules based on which the expert system for the analysis of emergencies operates are determined by the logic of the relay protection and automation operation. For example, if the protection of the power line is detected, the expert system determines which circuit breakers this protection is tripping on, and whether all previously turned-on circuit breakers from this set have been disconnected. For circuit breakers that have not shut down, the event “circuit breaker failure” is recorded and it is checked whether the operation of the CBD (circuit breaker failure backup device) of this circuit breaker has occurred, etc.

The emergency at the 500 kV electrical substation with damage and fire of a three-phase autotransformer group is shown in Fig. 3.

Fig. 3. The emergency at the 500 kV electrical substation with damage and fire of a three-phase autotransformer group.

Using special intelligent programs (reasoning programs) and based on technological instructions, it is possible to formulate advice texts on the actions of dispatching and operational personnel necessary in certain situations (and, above all, in emergency and pre-emergency situations) [6-12]. The texts of the reasoning programs are not given here, they are close to the descriptions given here.

Intelligent information processing is based on equipment conditions (for example, the positions of switches) and events - relay protection events [13,15].

An example of analysis and formation of advice:

--**Transformer protection tripping**

DZT Konka T-1 16 MVA

- transformer backup

trip of the residual current protection after the protection of the transformer

UROV Konka Konka B 110 T-1

- defective switch

Konka B 110 T-1

circuit breaker failure

--- TIP: Disable manually.

--- if the switch does not turn off, with the permission of the dispatcher

--- disconnect the line and bus disconnectors of this switch

--- with violation of security lock

Konka

No backup transformer

Transformer disabled by backup protection

- Protection triggered

UROV Konka Konka B 110 T-1

- Possible breaker malfunction

Konka B 110 T-1

Shutdown failure

At substation

Konka

The operation of the CBD is directly preceded by the protection of the transformer

DZT Konka T-1 16 MVA

Konka T-1 16 MVA

Tire repayment

Konka I secondary school 110

--- NOT ALL disconnect switches connected to this school are disconnected

--- the switch did not turn off

Konka B 110 T-1

Manual shutdown of a non-tripping circuit breaker

--- if the switch opens, then with the permission of the dispatcher

--- to test - by push to apply voltage to extinguished tires

- turn on the switch

Konka V-110 VL Revskaya

- upon successful testing of the secondary school

turn on the switches

Konka OV-110

Konka V110 VL Anchor

Konka T-1 10kV

TIP: Repair for inspection and repair.

- transformer

Konka T-1 16 MVA

- and switch

Konka B 110 T-1

When tripping transformer protections, it is necessary to determine if there are defective circuit breakers and what type of defect (failure, tightening) takes place (circuit breakers that have not been disconnected must be disconnected before testing voltage extinguished by disconnecting their circuit by disconnectors, and for “tightened” circuit breakers the circuit is disassembled after testing the tires). The fact of tightening can be logically set in the argument - the URO of the defective circuit breaker is triggered before it trips.

The described logical processing does not impose high requirements on computer performance.

6 Diagnostics of measuring channels of intelligent relay protection and automation based on redundant measurements

A well-known example of the development of an algorithm for intelligent relay protection devices for verification of data of measuring current transformers based on redundant measurements [9, 10, 11]. The approach proposed in this work expands the diagnostic capabilities through the use of an increased number of measurements, including redundant ones. The IEC 61850 standard, which is used for the digitalization of substations, assumes that any relay protection and automation device can have access to currents and voltages not only on its protected network section but also in other parts of the network since the relay protection system is located in a single information space implemented by the Ethernet network. This is also true for information on the state of switching devices.

In this approach, an incident matrix is constructed for the well-known network topology, which uniquely describes any given electrical circuit, indicating the connection of branches and nodes. The incident matrix is subsequently used to verify the accuracy of measurements by the first law of Kirchhoff.

For any circuit, the Kirchhoff equation holds for converging currents in the node:

$$A \cdot I = 0, \quad (1)$$

where A is the incident matrix, I is the current vector in the branches of the circuit, and 0 is the vector of the corresponding length (in this case m) with zero values.

Equality (1) can be used to determine the presence of an error (or errors) in current measurements. If the values of the vector I contain an error, then it will manifest itself in the discrepancy calculated by the formula:

$$G = A \cdot I . \qquad (2)$$

The error in the measurements is fixed by LG:

$$LG = \{ i , G_i > \varepsilon_0 \},$$

where ε_0 is the given value of the residual that determines the boundary of admissible values from the values of the flowing currents and the error of the measuring transformers. The discrepancy directly points to nodes whose sum of currents is nonzero.

From the analysis of *LG* array, it is already possible to determine the presence or absence of measurement errors. If the set of LG is not empty, then it is necessary to continue research to search for a specific meter that generates an error.

In [9], a technique is considered for determining the presence of erroneous current measurements using the example of the 5AN-Bridge circuit with switches in the transformer circuits and a repair jumper on the transformer side [12] (Fig . 4).

To formalize the description of the circuit topology, it is assumed that each branch contains no more than one switching device (disconnector or switch) and no more than one current-measuring transducer. It becomes necessary to introduce additional nodes (for example, 5 and 6), from which no more than two branches depart. Then, in the considered circuit, 11 nodes and 11 branches are detected. For further generalization, four additional branches are introduced, limited to only one node.

The incident matrix A uniquely describes the proposed scheme. The number of columns n of the matrix corresponds to the number of designated branches, the number of rows m to the number of nodes. Then each element of the matrix Ai, j takes the following values:

- 0 if node i and branch j are not connected;
- 1, if the current of branch j flows from node i ;
- -1 if the current of branch j flows into node i .

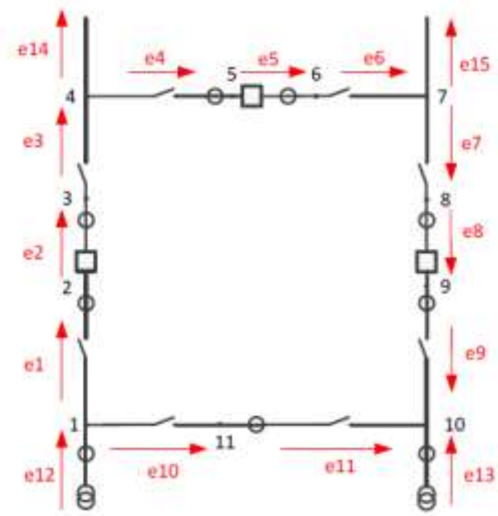


Fig.4. 5-AN-Bridge circuit

For the selected circuit in Fig . 4 incident matrix A has the following form:

$$A = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & -1 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Matrix A can be used to verify the correctness of measurements made at the protected object, for example, by the first law of Kirchhoff. For known values of branch currents Ij, the fulfillment of equality (1) means the correspondence of currents and a given network topology. Equality (1) is expediently used for complex values of the fundamental harmonic or instantaneous current values.

However, it is easy to notice that in the proposed 5AN-bridge circuit, only 9 currents are measured, which is less than the total number of branches equal to 15. It is impossible to use expression (1) to diagnose current information. Nevertheless, branch currents in which there is no measurement can be found from expression (1) by the first Kirchhoff law under the assumption that all measurements are correct. To do this, the current vector I must be divided into two subvectors: the vector of measured currents and the vector of calculated currents. As a result, two incident matrices are formed, bound currents with two groups.

Equation (2) follows from (1), as a result of which solution it is possible to obtain a matrix of rated currents, supplementing the matrix of known currents, and used to verify the correctness of measurements. Depending on various conditions, equation (2) may not have a unique solution. Then it is recommended that you obtain a least-squares solution. Checking the conformity of measurements consists of finding the residual

E = A * I, (3)

where I is a vector containing the measured and calculated values of currents.

The set LE = {i, εi > ε 0}, where ε 0 is the given value of the residual, indicates nodes in which the sum of the currents converging in the node is nonzero. Erroneous measurements are directly or indirectly related to these nodes. Perhaps further study of the electrical circuit to search for one or more erroneous currents.

The detection ability of the algorithm is analyzed with the assumption of one erroneous measurement in the circuit in Fig. 1. The results of his work are presented in Table 1. As you can see, there are cases when the method does not detect an error, but "compensates" it due to the calculated values of the currents. This occurs when measurements are insufficient to control all branches of the electrical circuit. Corresponding branches can be identified during the topological analysis at the preliminary stage, and special attention can be paid to the reliability of the measurement of coupled currents.

Table 1. Identification of measurement errors

Current in the branch	***Branch Characteristic***	***Current in the branch***	***Branch Characteristic***
e1	detectable	*e9*	detectable
e2	detectable	*e10*	detectable
e3	detectable	*e11*	detectable
e4	undetectable	*e12*	detectable
e5	undetectable	*e13*	detectable
e6	detectable	*e14*	detectable
e7	detectable	*e15*	detectable
e8	detectable		

7 Search for damage in branched electrical networks

The most important task is to find and eliminate damage to the operation of distributed branched electrical networks of 0.38 - 20 kV with overhead power lines. The technological and economic efficiency of the network enterprise depends on its successful and quick solution.

The traditional solution method is connected with the process of iterative (sequential) switching of disconnectors and inspection of network sections. In this case, it is necessary to combine the topological task of detecting a damaged area with the logistic task of organizing the movements of repair crews. The construction of an expert system for this traditional method is described in [7].

Consider the use of the Internet of Things technology for this task [14]. First of all, it is necessary to “revive” the disconnectors, providing a tele-signaling of their positions. Next, it is necessary to provide for the installation of pointers to the damaged area (UPA) not only at the branching points, as described in [7], but also for each section of the branched network. Since the UPA fixes the passage of a short circuit current at the site at the time of damage, the transmission of events of the type “UPU operation” to the data center allows you to immediately, without iterations, determine the damaged area of the network. Pointers equipped with television signals are produced by domestic industry [8]. Perhaps, with such an approach, it is advisable to constructively combine the pointers not with power transmission poles, as is usually done, but with disconnectors that limit the part of the network. The logical rules for determining the damaged area by the signals of disconnectors and pointers are elementary (no more complicated than the “coffee machine rules”).

Having determined the damaged area, it should be isolated (disconnected by disconnectors), inspected, identified the place of damage, and repair the damage. For this, we need people - repair crews (remote control of disconnectors in distribution networks is not provided for economic reasons).

It is necessary to determine which repair team to call (if there are several). This should be the free repair team closest to the site of damage. Finally, the optimal path for the repair team should be determined. An automatic call to the repair team is organized, and its route is determined.

Here, the task is similar to “Uberization” in well-known implementations of the Internet of Things.

The basis of the data here is the geographical maps to which the roads and the coordinates of the elements of the electric network (poles, disconnectors) are attached. The use of programs such as "Navigator" will give the necessary solution.

The effect of the above approach is obvious. The damage search time will be reduced, according to some sources, by 90% compared to the traditional method. Accordingly, the shortage of electricity due to accidents in distribution networks will be reduced.

The disconnection of a 220 kV overhead transmission line from a ground fire in the Middle Volga region is shown in Fig. 5.

Fig.5. Disconnection of a 220 kV overhead transmission line from a ground fire.

The costs of tele-signaling the position of the disconnectors in distribution networks and the installation of UPU with tele-signaling are relatively small.

8 Conclusion

Some principles of digitalization and integration with the Internet of Things for the problems of power grid management are formulated:

It is shown that the selection of events and the intellectual processing of information are necessary conditions for digitalization;

An example of solving the problem of emergency analysis is given; a digitalized software system can quickly give advice to the dispatching and operational staff;

The technique of determining the reliability of the currents received from the measuring transducers at the substation is described. In the process of solving, all unknown system currents are subject to determination. An example of applying the technique to the calculation of the 5AN-bridge circuit is presented.

For the important task of organizing a search for damage in branched consumer networks of power lines, an economical way to drastically reduce the time for troubleshooting is proposed.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

The authors are greatly acknowledged for supporting this study to Mr. Lyubarsky Yu.Ya. and his research of intelligent information systems and operational dispatch analysis. Cooperation of Universities and Innovation Development, Doctoral School project "Complex diagnostic modeling of technical parameters of power transformer-reactor electrical equipment condition", 2009, has made publishing of this article possible.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.