On the Mathematical Simulation of Digital Substation Technological Processes

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Abstract: This study addresses the mathematical simulation of technological processes based on different approaches. Phenomenological Models are observed. The mathematical model of the digital substation technological process based on petri nets is developed.

Key words: Mathematical simulation, digital substation, technological process, petri nets, Russia

INTRODUCTION

The basis of modern production technology are the systems with complex structural and functional organization. Generally, the objects of control in these systems are specific technological processes that represent a complex dynamic system, parts of which interact: the equipment, control and management facilities, auxiliary and transport devices, the processing tool or environments etc. Virtually any manufacturing process is represented in a plurality of actions, conditions and connections. The sequence of stages is usually described via the technological scheme, each element of which corresponds to a specific manufacturing process. The connections between the technological scheme elements reflect the material and energy flows that occur in the system. The system is characterized by the operation algorithm, aimed at achieving a specific goal (Malkov *et al.*, 2010).

Work not with the object (phenomenon, process) itself but its model in many cases makes it possible to investigate the properties and behavior in all situations relatively quickly and without significant material cost. Mathematical simulation in the field is the process of creating an abstract pattern in the form of a formal description of the object of research in terms of mathematics and operation of the model in order to obtain the necessary information on the actual or projected technological objects. Depending on the level of knowledge about the object of research model development may be based on different principles and procedures: the fundamental laws of nature, variational procedures, analogies, hierarchical chains etc. Often the construction of a model allowing to obtain meaningful

results requires the integrated use of various simulation techniques. A mandatory step in simulation is assessing the adequacy of the model-matching constructed formal description of the real object and formulated hypotheses based on research goals (Malkov *et al.*, 2010).

MATERIALS AND METHODS

There are various mathematical models of technological processes which are based on various methods for their implementation, for example, system models based on physical laws (Voronin *et al.*, 2010; Urakseev and Avdonina, 2009; Savenkova *et al.*, 2009). Only system models are actually applicable for many problems. However, in most cases these models are complex but there are other models that are simple in structure and reflect object behavior in the individual operating modes well.

Another type are phenomenological models that do not reflect hypotheses of the physical processes, one such approach to the mathematical modeling of the process is the use of numerical methods for approximating of a function, namely the Bessel polynom (Nazarova *et al.*, 2006) but this approach is very complex, demands a large number of calculations and can be used only within narrow limits to ensure accuracy.

One of adequate models to describe the cause-effect relations that occur in the process and submitted by multitude of actions and conditions, is a petri net (Harjono *et al.*, 2012; Sergeev *et al.*, 2011; Serrano *et al.*, 2006).

The flow-chart of the technological process described in terms of petri nets, expresses the composition and a certain sequence of operations. The

petri net is a two-part oriented graph. The positions correspond to the nods, depicted by circles and the transitions to the nods, depicted by dashes. Focused arcs connect positions and transitions, where in each arc is directed from the element of one set (of positions) to an element of another set (of transitions). The arc can not connect the elements of the same set. This approach makes it possible to determine which actions occur in the system which states preceded these actions which states the system forms after the action and which states can not be achieved at all. Objects of two types are present in the petri nets: dynamic-represented by markers inside the positions and static the nods of petri nets correspond to them. Status of the petri net at each current point in time is determined by the system of conditions. Markers are necessary to specify the conditions in petri nets. The initial state of the system is worked out by the initial marking.

The essence of this approach lies in the fact that petri nets allow us to describe both successive steps and multiple operations. Petri network operation appears as a change in marking-events which allows to assess the current state of the system by location markers, so that it is possible to evaluate the properties of interest in the initial petri net. That is performed when changing the marking a part of the technological process is evaluated. One of the most important features of petri nets is the concept of execution time for the entire technological process or its part thereof replaced with the cause-effect relationships between actions (transitions) in the network. This approach in view of its specificity not only diagrammatically tracks the current state of the system but also creates a mathematical model of the system using a matrix approach. However such an analysis does not provide characters, determining the state of the system.

Another approach to the mathematical simulation of the process is the use of Experimental Design Theory (EDT) (Zavrazhnov and Volosevich, 2010). The essence of this approach lies in the fact that the actual object is represented by a "black box" with multiple inputs and multiple outputs. The values affecting the input of the object are called factors. The output variable the data-out or response variable. There are three kinds of standard EDT tasks:

- The task of studying the mechanism of the phenomenon
- The task of screening experiment
- The task of optimization

In solving the first and second EDT tasks it is necessary to obtain a mathematical simulation of the object of study. The mathematical simulation is regarded as an equation connecting the response with the factors. For the experiment it is necessary to select response and factors and then, based on experimental results, mathematical simulation of the process is created. The mathematical simulation is a regression equation. The adequacy of this equation is verified by the Fisher test. Regression equations can be obtained both in coded form and in nominal values. Another, approach to the mathematical simulation that takes into account operation, interaction and other elements of the system is represent states of the system in the form of state graphs and transition intensities (Lezhenkina, 2008). Graph vertices are specific system states and the transitions are described by the transition intensity. Based on the graph of states and transition intensities a mathematical simulation in the form of the system of algebraic equations is formed. In fact, the mathematical simulation is a description of the system of transition probabilities from one state to another. Accordingly, the number of equations depends on the number of possible states of the system. In order to construct the regression model theory of experimental design is applied, where the factors are the intensity of the event streams. The adequacy of the resulting model is estimated based on the values of multiple regression coefficient and the dispersion of inadequacy. Then, using the obtained regression models it is possible to determine the coefficient of the technological process efficiency depending on the change of the event flow rate.

As mentioned above, the mathematical simulation is an important stage in the study and description of certain processes and phenomena. One of the important areas where it is necessary to create mathematical simulations is the electric power. The mathematical description is inherent to this area because it is often impossible to conduct actual experiments, for example, there are mathematical models to calculate the power grid mode, the application of various mathematical packages for physical simulation (Obukhov, 2014). However, these examples represent only a small part of the interest in this area because currently a lot of attention is paid to the issue of electrical substation transition to an innovative automation level-digital substation (Dubrov *et al.*, 2016a, b; Rybakov *et al.*, 2014; Drozdova *et al.*, 2016). Accordingly, the important issue is the creation of mathematical simulations for such substations.
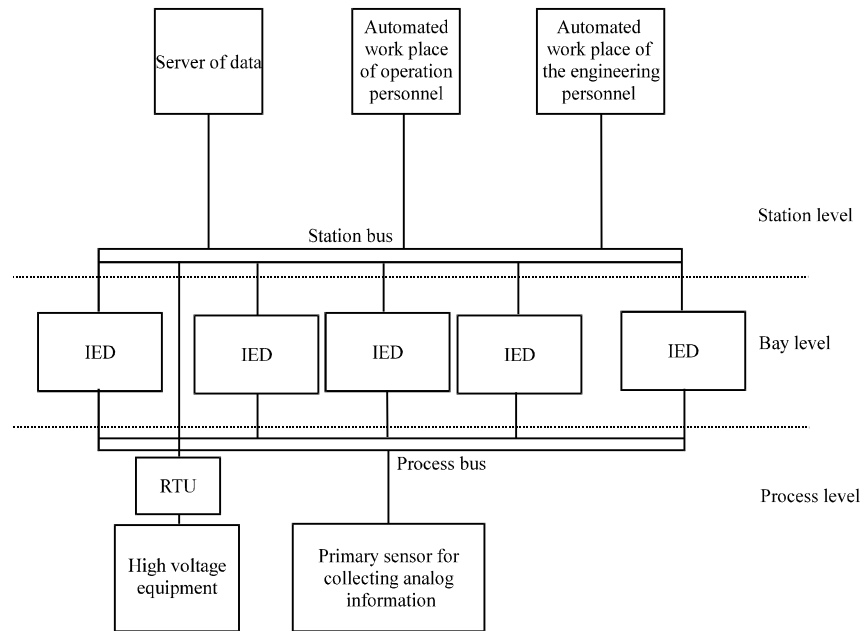
Fig.1: The stucture of the digital substation

Structure of the digital substation is shown in Fig. 1. Figure 1 uses the following keys; IED-Intelligent Electronic Device (relay protection, emergency control system, energy meter, etc.), AWS-automated workstation, RTU-remote terminal unit. The essence of digital substation work is not different from that of conventional substation. The main difference between digital substation and the latter is that the secondary circuits are in the form of digital communication channels.

RESULTS AND DISCUSSION

In fact, the work of the substation can be considered as a technological process which consists of three consecutive actions-reception, conversion and distribution of electricity. This sequence is conveniently represented in the form of petri net shown in Fig. 2. uses the following keys: P_1-P_3 there reception conversion and distribution of electricity; t_1, t_2-power transmission to the transformation and distribution, respectively. The presented petri net does not bear full information on the operation of the substation. For more information, you need to decompose each phase of the substation

Electric power reception step: Electric power reception depends on the incoming lines to the substation, respectively, if there is violation in the lines operation, the petri network shown in Fig. 3, this. Figure 3 uses the
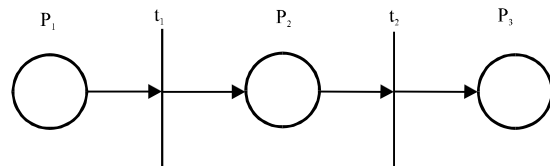

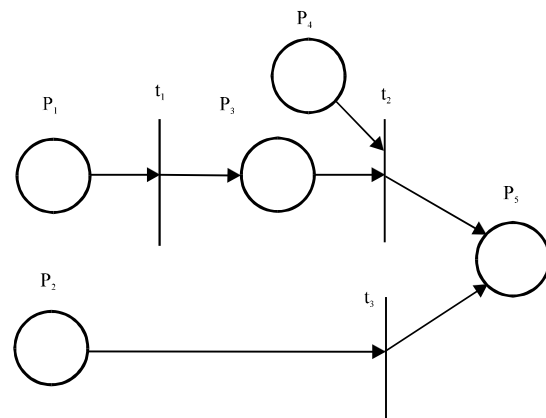Fig. 2: The technologica process of the substation

Fig. 3: Deco,position of electric power reception step

following keys: P_1-the power fail; P_2-normal operating mode; P_3-the power fail security; P_4-a dummy unit for t_2 transition block P_5-unit symbolizing the normal operation of the first stage; t_1-command issuing to the alarm; t_2-fixing the power fail; t_3-command issuing on normal operation. The operation of this stage is as follows: The
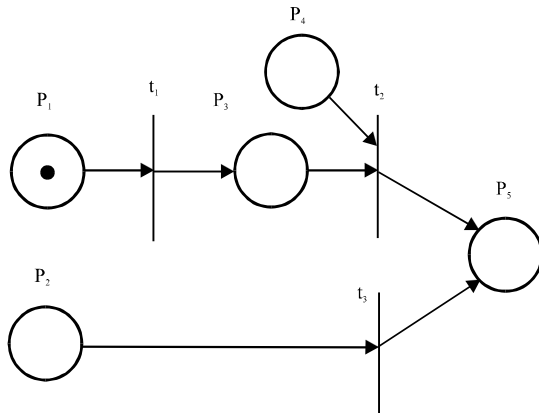
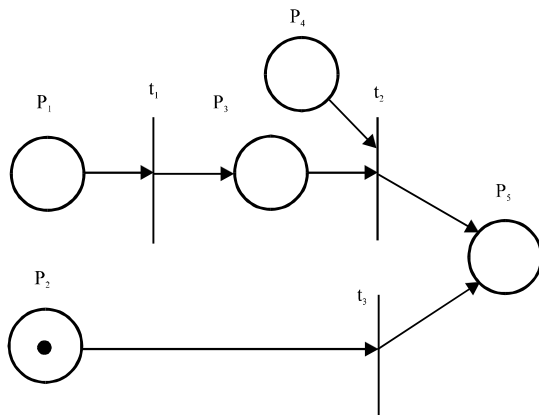Fig. 4: The initial petri net marking with damaged power line

Fig. 5: Initial marking petri net without breaking the power line

power lines are damaged, then the initial petri net marking will be as follows (Fig. 4) Thus the marking enters P_3 position and as a result will signal the power fail. Transition t_2 is not possible due to the absence of the marking in the position P_4; Receiving electric power is carried out without violations then the initial petri net marking will be as follows (Fig. 5). Thus, the marker enters P_5 position whereby the signal is applied to a normal mode operation of the first stage of the substation.

The stage of power conversion: Power conversion depends on the power of the transformer. Decomposition of the second phase of the substation is shown in Fig. 6. To simplify the scheme the petri net represents three types of disruption. Figure 6 uses the following keys: ■-the first mode of disturbance; ▲-the second mode of disturbance; ●-the third mode of disturbance; P_6-dummy unit; P_7-unit of the transformer operation

diagnostics; P_8-a dummy unit for transition block t_5; P_9-unit symbolizing the normal operation of the second stage; P_{10}-a dummy unit for transition block t_6; P_{11}-a dummy unit for transition block t_7; P_{12}-the end of the verification process for the first failure of the transformer; P_{13}-a dummy unit for transition block t_8; P_{14}-a dummy unit for transition block t_9; P_{15}-the end of the verification process for the second failure of the transformer; P_{16}-a dummy unit for transition block t_{10}; P_{17}-a unit for transition block t_{11}; P_{18}-the end of the verification process for the third failure of the transformer; P_{19}-the end of the verification process for all transformer failures; t_4-the transfer of command to diagnose hardware; t_5-the transfer of command on the lack of equipment failure; t_6-the transfer of command in the absence of fault and further diagnosis; t_7-the transfer of command of the presence of the first failure; t_8-the transfer of command of the absence of fault and further diagnosis; t_9-the transfer of command for the presence of the second failure; t_{10}-the transfer of command for the absence of fault and further diagnosis; t_{11}-the transfer of command for the presence of a third failure; t_{12}-the transfer of command for the completion of the diagnostic process.

The initial layout in Fig. 6 corresponds to the normal operation of the transformer. Obviously, the transition t_5 is only possible. In the future there will be a marking in the position P_9 and then the marking will move to the third stage. For example, as a result of the transformer diagnostic information is received that there are two disturbances (first and third). Then the initial network marking will be as follows (Fig. 7). It is clear from the initial marking, that t_7 transition is triggered, resulting in a standard marking is converted to a square, thus symbolizing the presence of the first type of disturbance. The purpose of this transformation is to give each violation a special marking. After triggering the transition t_7 label goes to the position P_{12} for further diagnosis and P_{19} position for fixing this type of violation. Then t_8 transition triggered due to the presence of the marker positions P_{13} and P_{15} in the marking switch position. Further actions on the third disturbance are identical to the first disturbance. As a result, the final position will have several markings insignia denoting the type of disturbance.

The stage of power distribution: Power distribution is dependent on the state of the output lines. Decomposition of the third phase of the substation corresponding to the normal mode of operation is shown in Fig. 8. uses the following keys: P_{20}-a violation
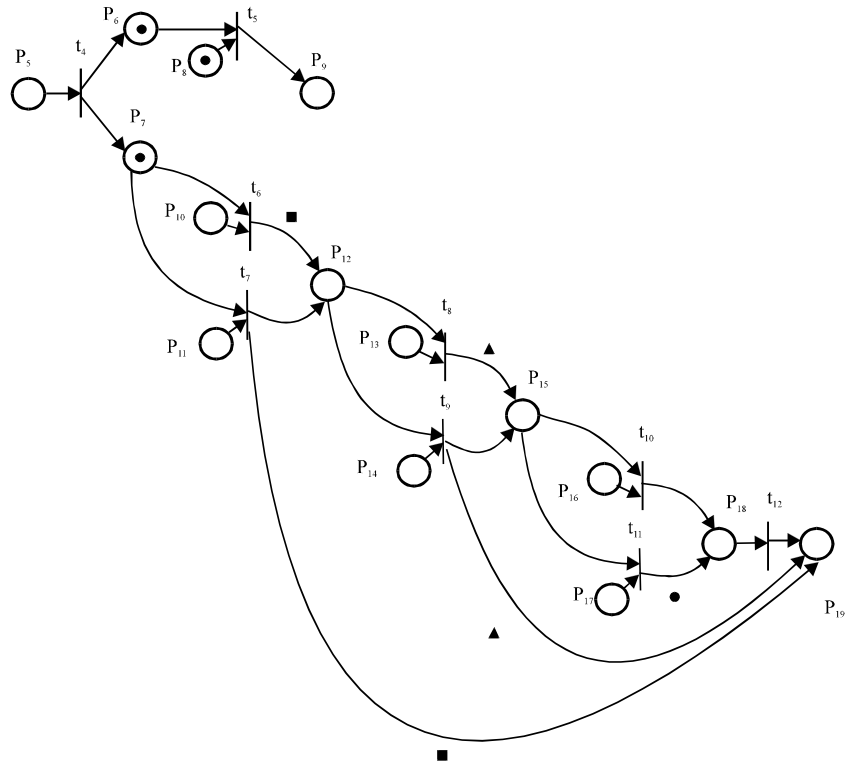
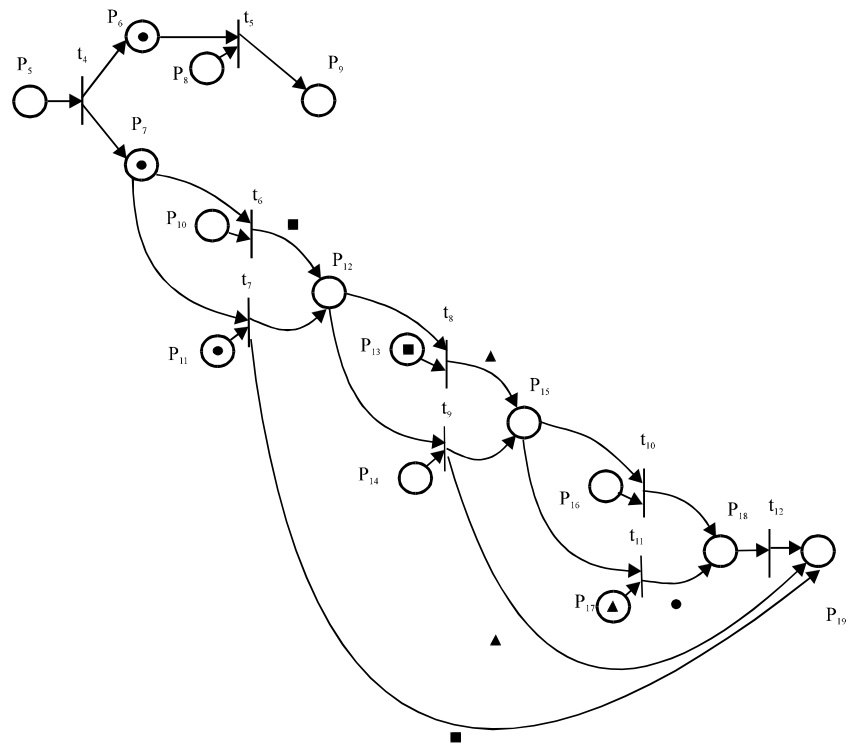Fig. 6: Decomposition of the second phase of the substation

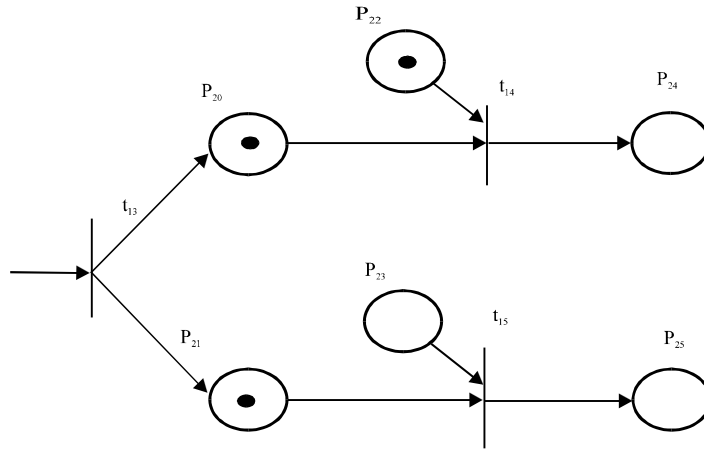Fig. 7: The initial Petri net marking the presece of the first and third disturbance
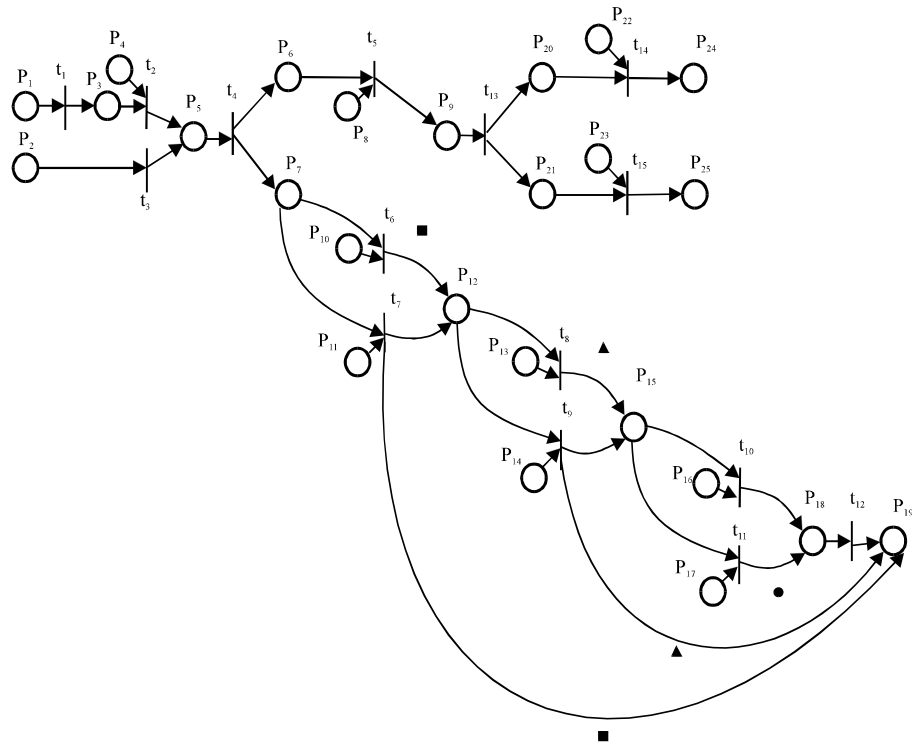
Fig. 8: Decomposition of the third phase of the substation

Fig. 9: Petri net describing the operation of the substation

at the output lines; P_{21}-normal operating mode; P_{22}-a dummy unit for transition block t_{14}; P_{23}-a dummy unit for transition block t_{15}; P_{24} recording of the information received on the poor condition and the end of examination; P_{25}-recording of the information received on normal functioning of the output lines and the end of examination; t_{13}-the transfer of command for information on the state of output lines; t_{14}-the transfer of command on violation of the output lines;

t_{15}-the transfer of command on normal functioning of the output lines. The functioning of the network is identical to the first stage. By combining each phase of operation the petri net will take the form shown in Fig. 9.

CONCLUSION

Thus, the developed petri net allows to analyze the substation as a process, namely the reception, conversion

and distribution of electricity. According to the given description of the substation functioning it is possible to estimate, at which stage of the substation there is a problem. In this particular case, diagnostic of the transformer is observed but on the basis of this approach it is possible to complicate the mathematical simulation for the diagnosis of other critical elements of the substation.

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