Advisor Information Control System for Tokamak Technological Equipment

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Abstract
This paper presents the results of designing a hardware and software suite of a control unit for Tokamak technological equipment (an experimental plant working in repetitively pulsed mode and intended for producing controlled thermonuclear fusion). In order to reduce time consumption for preparation activities, minimize errors of the operator when generating control commands and use the function of group complex preparation of a distributed park of technological aggregates, there has been solved a problem of automation of the equipment preparation to experiments via applying an advisor information control system. The solution to the problem is based on the application of the Petri-net machine, and the object under control at the informational level is described with a discrete model every state of which can be described by a Mealy machine. The control system software is completed and tested as a part of the control unit of КТМ plant (Kurchatov, the Republic of Kazakhstan), Viktoriya Т-15 plant, an impulse modulator complex, (Moscow) and others.

Keywords: control system, preparation, technological equipment, software.

INTRODUCTION
It is well known that one of perspective ways to produce energy in the future is controlled thermonuclear fusion (CTF) [1-3]. Modern CTF studies are actively developing [4]; the most significant results so far have been generated via Tokamak plants [5-7]. Successful completion of a physical experiment on Tokamak highly depends on the quality of preparation of technological and experimental equipment. Modernization of control systems of operating Tokamaks becomes a relevant objective in the context of a transfer of the scientific society to the new stage of CTF studies [4] or when new achievements appear in the area of hardware and software, and technological equipment. One of the examples is a modernization program for the Russian Tokamak from Kurchatovsky Institute National Research Center (Moscow) – T-15. Thus, the application of manual electrotechnical preparation of the T-15 plant can be substituted with a computerized distant setting of parameters of the technological equipment [8]. The aim of this is to improve the quality of preparation of technological aggregates before the experiment or achieve new work modes of the equipment, for example, the sources of electric power for additional plasma heating systems; plasma control systems; elements of information measuring system, etc.

Hardware and software systems of experiment automation (SEA) on Tokamak have significant features [9, 10] that are different from other plants, for example:

- Significant distribution and variety of equipment;
- Work in several modes with many stages of setting and testing;
- Different number of individual setting parameters for every unit;
- Different order of turning the equipment on and off, and the necessity to synchronize these processes in the process of an integrated launch of equipment;
- Physical parameters and algorithms of work in many cases are unique and could not be achieved earlier due to physical and technical limitations.

In the experiment mode of Tokamak’s operation, the preparation procedures with the help of a modern computerized control system are carried out according to the script [9] – a program of the experiment that can change before every experiment [8]. Procedures of preparation and launch of experiment script reproduction are impossible without an operator, i.e. these procedures cannot be carried out in a completely automatic mode (especially at the stage of system adjustment).

However, because of the complexity of the system, the process of interaction of the operator with it is complicated because of the lack of information about the state of multiple aggregates, the diversity of parameters and equipment setting operations, the complexity of algorithms for diagnosing failures, errors, and breakdowns. That is why relevancy arises for designing an advisor information control system (AICS) which would provide the operator with exhaustive information on the setting process and the state of the technological and experimental equipment, would not allow committing an error and would carry out a part of the preparation program automatically. The solution to this program is reviewed in this article.
**TASK DESCRIPTION**

Let’s review the control system of Viktoriya, the modernized impulse modulator complex, intended for electric power supply of additional plasma heating system of Tokamak Т-15. The existing modulator control system was designed 35 years ago and does not meet the current requirements of the planned informational control system of the plant to be modernized. The hardware-based technical solution for the modernization task is described in detail in [8].

In order to unify the control mechanism for various technological and experimental equipment, on Tokamaks, we apply controllers of technological aggregates (fig. 1) that ensure special interface of the target equipment setting: digital interfaces, analogue and discrete signals of control and management of the parameters and the state of the technological aggregate on the one hand, and support a unified command interface for all aggregates on the other hand.

![Diagram of high-voltage power system modulator: technological aggregate](image)

**Figure 1:** Schematic, simplified chart of the local system of manipulation on Tokamak technological equipment.

From the informational point of view, the controller of every aggregate of the system is in one of the nine discrete states:
- onLine – on, there is power connection, not configured;
- Config – configured;
- Init – experiment script parameters application initiated;
- PreSTART – ready to start;
- START – reproduction of the experiment script, collection of data;
- STOP – work stoppage;
- DataReady – data uploaded into database;
- offLine – off, the power can be disconnected;
- Terminate – holding mode;
- DataReady – data uploaded into database;

To operate the process of transition to these states, the operator at the workstation (fig. 1) performs the following operation commands:
- cmdOnLine – restart ECM, prepare for work;
- cmdSendConf – configure ECM and peripheral equipment;
- cmdInit – read the script, set the experiment parameters for the controlled equipment;
of designing an AICS is possible with the help of a Petri net which will allow diagnosing the process of parallel manipulation of discrete systems. AICS can be fulfilled as a program module (fig. 1), executed by means of the workstation operator and used in both modernized and re-designed plants of a Tokamak type.

The target plants to apply this system on are KTM (Kurchatov, the Republic of Kazakhstan), T-15 (Moscow) and other plants: FTU (Frascati, Italy), EAST (Hefei, China), etc.

SOLUTION OF THE TASK OF DESIGNING AN ADVISOR INFORMATION SYSTEM

The task that had been set was successfully accomplished. The solution is based on the research of the unified manipulated object presented as a discrete model, every state of which can be described by an abstract Mealy automaton (fig. 2): $A = (X , Y, S, f_0, f_y )$ where $X$ is the multitude of input signals of the system; $Y$ is the multitude of output signals of the system; $S$ is the multitude of states of the system; $f_0$ is the output function; $f_y$ is the transition function of the automaton from one state to another.

The event in this system happens at the command of the operator in the distance operation mode or when the parameter of the object change in the local operation mode. The object can initiate its transition itself when the appropriate favorable event occurs: the transition from Start to Stop – when experiment program is terminated; the transition from Terminate to offLine and online when the cycle is terminated, etc. It is also possible to skip a state (the controller did not indicate the state when executing the task). Thus, in the normal mode, the model is determined but in case of error, a likely transition to the state confirmation by the operator is possible (blocking of the automaton). Since the advent to the state $s(t)$ does not cause the immediate transition to the state $s(t+1)$ and requires the operator’s participation $x(t)$, as well as depends on the current state $s(t+1) = f_y (x(t), s(t))$ and $y(t) = f_y (x(t), s(t))$ when $s \in S$, $x \in X$. Considering $X = \{x_0 \ldots x_9\}$ where $x_0$ is no command, $x_1 \ldots x_9$ is commands in the list mentioned above, and $Y = (y_0, y_m) = (\{1\ldots 9\}, \{0\ldots 46\})$ where $y_n$ is an indicator of the state of the system and $y'_m$ is an indicator of the error, the model was described by a system of formulas (1):

$$f_y y_1 = \frac{x_2}{y_2, y_0} = \frac{2}{\{0,0\}}, f_y y_1 = \frac{x_8}{y_8, y_0} = \frac{8}{\{0,0\}}, f'_y y_1 = \frac{x_2, y_{0\ldots 9}}{y_{10\ldots 46}} = (10, \{0\ldots 46\})$$

$$f'_y y_1 = \frac{x_{y,1}}{y_{1\ldots 0}} = (0,1), f y_2 = \frac{x_3}{y_3, y_0} = \frac{3}{\{3,0\}}, f y_2 = \frac{x_8}{y_8, y_0} = \frac{8}{\{0,0\}}$$

Thus, the manipulated object can be described by a discrete model at the informational level. The solution to the set task of designing an AICS is possible with the help of a Petri net which will allow diagnosing the process of parallel manipulation of discrete systems. AICS can be fulfilled as a program module (fig. 1), executed by means of the workstation operator and used in both modernized and re-designed plants of a Tokamak type.

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To research the behavior of the model in the conditions of group operation it is necessary to build a Petri net. The results of the research will allow detecting dead-ends, lopping and net blocking, and then design an algorithm of safe group operation on technological aggregates. In accordance with cyclogram (fig. 2) and equations (1) we built a Petri net (fig. 3) presented as

\[
\begin{align*}
N & = (P, T, F, W, M_0) \\
\end{align*}
\]

where \((P, T, F)\) is the end net: \(P\) is the collective of the states of the system; \(T\) is the collective of the transitions from one state to another, and \(W : F \rightarrow N \setminus \{0\}\) and \(M_0 : P \rightarrow N\) are two functions called respectively the arc frequency and the initial markings \([11]\). The initial marking, in its turn, is a range of type \(M = (m_1, \ldots, m_n)\), in which \(m_i = M(p_i)\), where \(p_i\) is one of the positions of the net.

**Figure 2:** Orgraph of the discrete model of behavior of the technological aggregate command controller.

In the net (fig. 3), the functions of automation are not taken into account, and the following transitions are mentioned: \(t_1^\prime\), \(t_2^\prime\), etc, appearing as a result of a wrong operator’s command, \(t_1, t_2, \ldots\) – acceptable transitions of the net which transition to the initial state when error occurs. Not acceptable transitions marked with a cross must be compensated by AICS algorithms.

PowerOn trigger is activated, and the transition to \(t_6, t_2\) is initiated. The orgraph of the Petri net for automated control mode is introduced on the fig. 4, 5.

**Figure 3:** Petri net for the discrete model of states of an automated control system controller.

In the automated operator’s manipulation mode a shortened set of these commands can be fulfilled: 3-6, 9 (according to the list), i.e. the \(t_1, t_2, t_6, t_7^\prime, t_8^\prime\) transitions can be executed by the system automatically. The transitions \(t_5, t_4, t_5, t_7\) are AICS functions initiated by the operator’s commands, and \(t_9\) is a power triggering device of the controller. The same way \(t_5, t_7^\prime\) and \(t_5\) are sequences of automatically performed operations (response): when Stop command occurs, the transition to \(t_5, t_6\) and \(t_7\) is initiated; when Off-line command occurs, the transition to \(t_7^\prime, t_8^\prime\) and \(t_5\) is initiated (the PowerOff trigger is activated); when the On-line command occurs, the

**Figure 4:** Petri net of an automated system (mode of control over one aggregate).
Taking into account the operator’s command control and the absence of errors in the operation of the equipment, blocks and loops of the model (fig. 4) cannot occur. However, in the group manipulation mode (fig. 5) uncoordinated control is possible. This case can occur when choosing to operate aggregates which cannot be transitioned from initial informational state to that which the operator indicated. In this case, it is necessary to forbid the choice of such controllers, execute indication of the error and recommend other aggregates or transition some of the controllers to the state that is acceptable for group manipulation in manual mode.

ALGORITHMIC RESOURCING OF ADVISOR INFORMATIONAL CONTROL SYSTEM

Let’s review several algorithms fulfilled by the advisor informational control system. One of the important tasks that AICS needs to solve is the input of parameter values of the technological equipment. Since each controller is Master in the system of workstation controllers, it is necessary to enter a record into of value into the registers of the controller, control their application and changes in the local control mode (i.e. the value can be changed by the controller itself or by the command of an upstream system). In this regard, an algorithm has been developed (fig. 6) to enter parameter values of the technological equipment by the operator considering the application of the local control mode, the mode of parameters input by the command of an upstream system (from the script of the experiment) and with the control of application of the new value.

Figure 5: Petri net of an automated system (mode of group manipulation on aggregates).

Figure 6: Chart of the algorithm of the operator’s technological aggregate values input.
Let’s review the following AICS algorithm – an algorithm of normal termination of the controller’s operation. This algorithm executes the transition of a group of controllers by a cyclogram of states and transitions (fig. 2) into the informational Terminate state, then into Off-Line, and then normal auxiliary power disconnection. The algorithm (fig. 7) takes into account current state of each controller in the group, forms the sequence of commands permitted to be executed to each controller individually with control of their execution. When an error occurs in the operation of the controller or other factors that prevent the termination of work in normal mode occur, the controller is excluded from the control process, and the operator is notified about this.

Figure 7: Chart of the algorithm of normal termination of work of technological aggregate controllers.
Another important algorithm is the algorithm of executing operator’s commands. The algorithm takes into account the “Controller is busy” state, the cases of impermissibility of the command execution: the current state of the controller does not allow executing the operator’s command; errors in the operation of the manipulated object: ill-preparedness of the technological equipment, ill-preparedness of the measurement equipment, general error of the controller, loss of power network with the controller of the aggregate, mode of local control, etc.

In the case of appearance of any of the unfavorable factors for an aggregate controller of the chosen group, the control over this aggregate is removed, and the control for the rest of the aggregates is terminated by the algorithm.

SHORT SUMMARY OF A PROGRAM MODULE EFFECTUATING THE ADVISOR INFORMATIONAL CONTROL SYSTEM

The advisor informational system is effectuated as a program module in the IDE Trace Mode instrumental program system of SCADA level (AdAstrA Research Group Ltd., Moscow) and is carried out under the control of Runtime module Trace Mode RTM (fig. 1). We tested the system on the KTM plant (Kurchatov, the Republic of Kazakhstan), Viktoriya T-10 complex of impulse modulators and T-10 impulse high-voltage electric power system (Moscow).

The program module effectuating the AICS consists of 3 blocks that execute the following: calculate the marker of operator’s commands blockade; process commands of aggregate choice for manipulation; process commands of the operator to the aggregate. The module has the following inputs and outputs:

- **Loc** – mode of local control of the aggregate;
- **Err** – error in the work of the controller or aggregate;
- **Pow** – controller power status;
- **Ping** – state of net connection to the controller;
- **Block** – marker of manipulation blockade;
- **Sel** – commands of aggregate choice for manipulation;
- **Sel-2** – chosen aggregate permitted to be manipulated;
- **State** – informational state of the aggregate;
- **Com-o** – operator’s command to control the aggregate;
- **Com** – command to control the aggregate;
- **Exec** – status of command execution;
- **Indic** – aggregate state parameters indication.

Thus the operator fulfills the commands of aggregates choice for manipulation (Sel) and control commands (transition of aggregate into the new informational state, Com-o).

Elements of graphic interface of the user of the program effectuating AICS as part of the system for control over sources of impulse electric power of the T-15 plant, are introduced on fig. 8. With their help, the operator has a possibility to apply the whole set of control commands with the control over the set rules in accordance with the cyclogram (fig. 2).
Figure 8: Graphic interface of a software user performing AICS of Viktoriya complex of impulse modulators T-10 plant: a) control and input of modulator parameters; b) aggregate (modulators) control commands input in accordance with the cyclogram of states and transitions.

Fig. 8 (a) shows graphical forms allowing entering equipment parameter values; shows a cyclogram, elements of which allow transitioning of the group of chosen aggregates into a new state in accordance with the cyclogram (fig. 2); commands are processed by the algorithm (fig. 9). When pressing the Controller Disconnect button the algorithm is performed (fig. 7). Up to 22 aggregates can be chosen for group manipulation.

Figure 9: Chart of the AICS operator’s command execution algorithm.
CONCLUSION

Conducting modern studies on active plants designed decades ago is impossible without deep modernization. Modernization is usually accompanied by implementing modern computer technologies into the set of control systems for technological and experimental equipment. At the same time, using complex systems without specialized expert programs leads to errors of manipulation. The practice showed that in the mode of manual control, the number of errors committed by the operator was 25-30% of cases and was accompanied by the necessity to start the process of preparation again; as a result, the time for preparation of aggregates to the experiment increased, expensive equipment could work in extreme modes leading to breakage. Advisor informational control system excluded incorrect value input into the registers of the control cabinet controller of technological aggregates, allowed for automation of the procedures of reception, processing, and input of values received from an upstream system as a script of the experiment. The designed system excluded human errors of manipulation, significantly decreased the time for preparation for the experiment and time of staff training. The testing of the system on one of the modulators of Viktoriya complex (Kurchatovsky Institute R&D Center, Moscow) in 2014 and on a number of other complexes showed full working capacity, including of the program complex of the control unit and the advisor informational system in particular. The algorithms of preparation of the aggregate to the experiment are performed by the advisor informational system correctly. The correct start of execution of the experiment script by the command of the operator gave the possibility to perform the experiment program at high quality and receive the expected result of physical parameters measurement.

The validation of the system has also long been performed as part of the control unit of the KTM plant (~2000 tests). The tests have shown its complete working capacity and fitness (introduction act №452/03-14 dd. 12.04.2014).

REFERENCES