Functional status technological equipments modelling

G V Makarov, E V Tamarkina, M V Lyakhovets and A S Salamatin
Siberian State Industrial University, 42 Kirova street, Novokuznetsk, 654007, Russia
E-mail: gmakarov@nicsu.ru

Annotation. The paper deals with the modeling of the functional states of technological equipment that receive logical values “0” and “1” depending on the combination of input and output signals. The following functional states are possible: “Work”, “Ready”, “Not ready”, “Fault”. Model development these states and their minimization are possible by various methods, for example, with the help of Karnaugh maps, terminal machines, etc. The model variant for the simplest unit, obtained with the help of Karnaugh maps method, is presented. The application of this type of models is necessary for the typification of technological equipments, can be used to create logical control systems and integration into digital twins of complex production.

1. Introduction

It is accepted to describe the state of technological equipment by logical indicators, which can be divided into emergency and informing. Emergency indicators speak about equipment failure and impossibility of continuation (or the beginning) of work. Informing indicators serve for definition of a current condition of the equipment. Diagnostics of these indicators is carried out by system of local management on which information and operating functions are assigned. The logical control system should operatively estimate a condition of the equipment, form indicators, display the dispatcher and transfer in base for storage. In the event of an emergency indicator, the system must perform an algorithm of emergency stop or blocking the start. Informing indicators allow forming control actions to control the technological process.

The quality of logical control systems cannot be evaluated by the commonly used criteria of the theory of control – time of transients, stability, standard deviation, etc., as such notions are absent or do not make any sense for them.

The efficiency of a logical control system can be estimated by the time of reaction to emergency events, but mainly the direct relay protection of the launch equipment and additional protection devices are triggered. The system of logic management remains only to ascertain the fact, to generate the report and to deduce the corresponding warning to the operator - as it is done in modern automatic control systems at new designing and modernisation of existing [1-3].

In connection with the above, an indicator of the effectiveness of logical control systems (in addition, the correctness of the control algorithm and emergency interlocks) is the ratio of the number of diagnosed states to the total number of possible states of the unit or complex, which allow to quickly assess the situation, predict and prevent emergency states. In this case, the states can be “simple” (the presence / absence of a signal) and “composite” which depending on several logical or analog signals.

“Simple” states are the absence/presence of a signal, the simplest time conditions for the duration of triggering, acceleration or shutdown. “Complicated” states can be either in a specific unit or in a
group of jointly operating mechanisms, such as a shut-off valve pump in the inlet, flushing and downstream. Component states of one unit may include indirectly evaluated states such as “slamming”, overheating (when there is a continuous temperature measurement signal (or indirectly by thyristor temperature, by current evaluation of the drive temperature), the state of “heavy start”, scrolling of the conveyor belt or “atypical” device readings, which may indicate an incorrect process or a malfunction of the device. Important indications are also the values of drive currents, pulsations and other characteristics. In combination, these can indicate the condition of the bearings, the drive itself and the need for maintenance. You can find an example of this diagnosis in [4]. Thus, controlling changes in parameters, it is possible to indirectly assess the condition of the equipment, for example, statistical methods, wavelet analysis, neural networks, the method of precedents [5], type-representative situations, etc., can be used.

To take into account all these states in the diagnostic algorithms of the local logical control system is quite difficult both for a novice developer (because of small experience) and an experienced one (because of the “soap” of the eye, or employment by other, more global and complex tasks, because such a developer is first of all tasked with developing an approach, or “system architecture”). At occurrence of changes in conditions of functioning of the unit, in its control algorithm, or in system architecture there is a task of adaptation of typical control systems to the changed conditions which, as a rule, falls on beginning developers.

For qualitative diagnostics it is necessary to take into account a great number of states of different complexity, both quite clear and not quite obvious. As an alternative, it can be done relying on existing programs or by interviewing a more experienced developer. But it is rather difficult to form a correct algorithm of processing and diagnostics of such states at once. Thought modeling often does not allow you to take into account all the peculiarities. And emergency modification of systems during their commissioning (commissioning) is accompanied by stress, errors, it takes a lot of time and may lead to deterioration of technological equipment. In this regard, it is necessary to use simulation complexes for so-called virtual commissioning.

For effective application of the approach to modeling of states of technological equipment first of all it is necessary to have a formal mathematical description and classification of states of technological equipment in the language of mathematical logic, supplemented for systems of real time – mathematical model of the object. Thus the set of diagnosed states is unique for each developer and is the intellectual property.

2. Model development
Let us describe possible models of equipment states on the example of the simplest control circuit – lamp switching on.

As an example in Figure 1 there is a circuit diagram of the lamp power supply circuit, in which KL1 is the control relay, KL2 is the circuit diagnostic relay, EL is the lamp, QF is the protective automatic switch (voltage supply), CV is the voltage control. The given circuit reflects all possible sets of possible signals - input controllers, status signals and a feedback control signal.

Figure 2 shows the circuit diagram to control switching the lamp on and off, corresponding to the circuit in figure 1. The figure also shows the logic variables for the input (S1, S2, S3) and output (u) signals.

The functional status of the unit can be as follows: operation, ready for operation, not ready for operation and accident (F1 ... F4 respectively). For diagnostics, it is necessary to display not only the functional status of the unit, but also the causes.
The causes are determined by signals and reflect changes in the external environment in real time, i.e. they can appear and disappear, sometimes at high speeds. For fixing of the occurred event on the operator interface and storing in the base the processed logical variables, defined by signals or interrelation of signals – signs serve. The number of indications shall be sufficient to describe all the unique states of the system. For this purpose, it is necessary to have so many indications that the number of their \( N_p \) placements is greater than the number of signal placements. \( N_{(u+S)} \):

\[
N_{(u+S)} = 2^k = 2^4 = 16,
\]

where the number of signals \( k = k_{in} + k_{out} \).

**Figure 1.** Circuit diagram for the room lighting system.

| PLC (input)       | Variable |
|-------------------|----------|
| CV                | Presence of voltage at the input: \( s_1 \) |
| QF                | Safety automatics: \( s_2 \) |
| KL2               | Work of the lamp: \( s_3 \) |
| +24 VDC           |          |

| PLC (output)      | Variable |
|-------------------|----------|
| KL1               | Signal to switch on: \( u \) |
| 0 VDC             |          |

**Figure 2.** Circuit diagram of control.

The complete table of variants of combinations of logical input, output and variable functional states of the object looks like this (table 1).
Table 1. Summary table of input, output and variable states of the object.

| Signals                  | Indications                                                                 | Functional states |
|--------------------------|-----------------------------------------------------------------------------|-------------------|
| Signal to switch on      | There is no input voltage                                                  | Work             |
| Presence of voltage at the input | The automatic machine is off (safety automatics triggered).              | Ready            |
| Safety automatics        | Lamp on                                                                     | Not ready         |
| Work of the lamp         | Lamp does not switch on (contactor fault)                                  | Emergency         |
|                           | Lamp malfunction (or chain fault)                                          |                   |
| u                        | P_1, P_2, P_3, P_4, P_5                                                   |                   |
| 0                        | 0 0 0 0                                                                     |                   |
| 0                        | 0 0 1 0                                                                     |                   |
| 0                        | 0 1 1 0                                                                     |                   |
| 0                        | 1 0 0 0                                                                     |                   |
| 0                        | 1 1 0 1                                                                     |                   |
| 1                        | 0 0 0 0                                                                     |                   |
| 1                        | 1 1 0 0                                                                     |                   |
| 1                        | 1 1 1 0                                                                     |                   |
| 1                        | 1 1 1 0                                                                     |                   |
| 1                        | 1 1 1 0                                                                     |                   |
| 1                        | 1 1 1 0                                                                     |                   |

The methods of minimization for logical functions are well known – for example, the method of finite automata, Karnaugh maps, etc [6]. For a simple unit, each state can be visualized in the form of a Karnaugh map, after which we draw up tables of results, where u – inclusion KL1; S_1, S_2 and S_3 – states; F_1,2,3 – result. As an example, Figure 3 shows a Karnaugh map for the state of "Accident".

Figure 3. Karnaugh maps of the technological state of the “Crash”.

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Figure 3. Karnaugh maps of the technological state of the “Crash”.
Table 2 shows the function state models of $F_1 \ldots F_4$ in the language of logic algebra for all possible variants of signal placement and simplified expressions.

| Variable | Model                | Simplified model | Comment       |
|----------|----------------------|------------------|---------------|
| $F_1$    | $u \land s_1 \land s_2 \land s_3$ | $u \land s_1 \land s_2 \land \overline{s}_3$ | Work          |
| $F_2$    | $\overline{u} \land s_1 \land s_2 \land \overline{s}_3$ | $\overline{u} \land s_1 \land s_2 \land \overline{s}_3$ | Ready         |
| $F_3$    | $\overline{u} \land \overline{s}_1 \land \overline{s}_2 \land \overline{s}_3$ | $\overline{u} \land (\overline{s}_1 \lor \overline{s}_2) \land \overline{s}_3$ | Not ready     |
| $F_4$    | $\overline{u} \land \overline{s}_1 \land \overline{s}_2 \land \overline{s}_3$ | $u \land (\overline{s}_1 \lor \overline{s}_2 \lor \overline{s}_3) \lor u \land s_3$ | Emergency     |

3. Model simplification
Mathematical models in the language of logic are presented below.

$$F_1 = u \land s_1 \land s_2 \land s_3$$  \hspace{1cm} (1)
$$F_2 = \overline{u} \land s_1 \land s_2 \land \overline{s}_3$$  \hspace{1cm} (2)
$$F_3 = \begin{cases} 
\overline{u} \land \overline{s}_1 \land \overline{s}_2 \land \overline{s}_3 \\
\overline{u} \land s_1 \land s_2 \land \overline{s}_3 \\
\overline{u} \land s_1 \land s_2 \land s_3 \\
\overline{u} \land (\overline{s}_1 \lor \overline{s}_2) \land \overline{s}_3 \\
\overline{u} \land s_1 \land \overline{s}_2 \land \overline{s}_3 \\
\overline{u} \land s_1 \land \overline{s}_2 \land \overline{s}_3 \\
\overline{u} \land s_1 \land \overline{s}_2 \land \overline{s}_3 \\
\overline{u} \land s_1 \land \overline{s}_2 \land s_3 \\
\overline{u} \land s_1 \land \overline{s}_2 \land \overline{s}_3 \
\end{cases}$$  \hspace{1cm} (3)
Thus, the complete model of a control object that takes into account all its possible states is described by expressions (1)-(4). Based on this model, a logical control system is developed, which allows to control the diagnosis of an industrial unit. The table of indications for diagnostics looks as follows.

Table 3. Status Models (indications).

| Variable | Model | Type     | Comment                                      |
|----------|-------|----------|----------------------------------------------|
| $P_1$    | $\bar{s}_1$ | Emergency | There is no input voltage                   |
| $P_2$    | $\bar{s}_2$ | Emergency | The automatic machine is off (safety automatics triggered) |
| $P_3$    | $s_3$   | Informing | Lamp on                                      |
| $P_4$    | $\bar{u} \land s_3$ | Emergency | Lamp does not switch off (contactor fault) |
| $P_5$    | $u \land \bar{s}_3$ | Emergency | Lamp malfunction (or chain fault)           |

4. Conclusion
When logical expressions are minimized, models are obtained that describe different technological functions and types of units. On this basis it is possible to make classification of typical objects for which quite certain typical systems of logic control are suitable - for example, the simplest fan, the pump, the screen [7] or more difficult, as, for example, the electric drive of the lift [8] will be described by one and the same model. The received logical models of an object and control systems allow to apply methods of similarity of control systems [9] as they allow to consider joint characteristics of an object and system, taking into account system features. Such typification at designing allows to reduce time of working out of the software and debugging at a stage of introduction of the automated control system.

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