UDC 621.224 **doi: 10.20998/2411-3441.2021.2.02**

A. LYNNYK, M. CHERKASHENKO, N. FATIEIEVA, O. FATYEYEV, V. PONOMAROV

SYNTHESIS AND ANALYSIS OF CONTROL SCHEMES OF HYDROPNEUMATIC DRIVES

The method of analysis of circuits of hydropneumatic actuators is offered, which allows to detect and eliminate existing design errors, mainly related to the inconsistency of inputs operating between technological operations and "power struggle" on actuators, as well as the method of synthesis to obtain the scheme, which contains close to the minimum number of logical elements. A formalized method of analysis of control circuits of hydropneumatic actuators is proposed, which allows to detect and eliminate errors possible during synthesis. Equations of output functions and internal states of the system are written directly according to the scheme of the hydropneumatic drive by the method of standard positional structure and from the matrix of correspondences by the method of minimization. Error detection is carried out by determining the correctness of the graph of operations, analysis of the input sequence, the correctness of the matrix of correspondences and the corresponding system of equations. The efficiency of using the matrix of correspondences of M. Cherkashenko for the analysis of schemes is shown, the dimension of which does not depend on the number of inputs and outputs, but only on the number of transitions between technological operations. Further, it is not difficult to correct errors in the design and, if necessary, make appropriate adjustments to the scheme. When adjusting the scheme, the method of combining the functional and logical capabilities of the distribution equipment, as well as the modules built on it, was also used. The proposed method is an effective means of detecting errors, inaccuracies, performance checks, rational construction of circuits, and can be widely used by designers of control systems for hydropneumatic actuators, as well as university students in the study of methods of construction of circuits.

Keywords: hydropneumatic drive, scheme, synthesis, analysis, control system, technological equipment.

О. В. ЛИННИК, М. В. ЧЕРКАШЕНКО, Н. М. ФАТЄЄВА, О. М. ФАТЄЄВ, В. А. ПОНОМАРЬОВ

СИНТЕЗ І АНАЛІЗ СХЕМ УПРАВЛІННЯ ГІДРОПНЕВМОПРИВОДАМИ

Пропонується метод аналізу схем гідропневмоприводів, що дозволяє виявити і усунути наявні помилки при проектуванні, в основному, пов'язані з суперечливістю входів, що діють між технологічними операціями, і «силовою боротьбою» на виконавчих пристроях, а також метод синтезу, що дозволяє отримати схему, яка містить близьке до мінімального число логічних елементів. Пропонується формалізований метод аналізу схем систем управління гідропневмоприводів, що дозволяє виявити і усунути помилки, можливі при синтезі. Рівняння функцій виходів і внутрішніх станів системи виписуються безпосередньо за схемою гідропневмопривода при методі стандартної позиційної структури та з матриці вщідповідностей при методі мінімізації. Виявлення помилок здійснюється визначенням коректності графа операцій, аналізу вхідної послідовності, коректності матриці відповідностей і відповідної системи рівнянь. Показана ефективність використання для аналізу схем матриці відповідностей М. В. Черкашенко, розмірність якої не залежить від числа входів і виходів, а лише від числа переходів між технологічними операціями. Далі не складає труднощів виправлення помилок при проектуванні і, при необхідності, здійснення відповідного коригування схеми. При коригуванні схеми використано також метод поєднання функціональних і логічних можливостей розподільної апаратури, а також побудованих на ній модулів. Запропонований метод є ефективним засобом виявлення помилок, неточностей, перевірки працездатності, раціональної побудови схем, і може бути широко використаний проектувальниками систем управління гідропневмоприводів, а також студентами вузів при вивченні методів побудови схем.

Ключові слова: гідропневмопривод, схема, синтез, аналіз, система управління**,** технологічне обладнання.

А. В. ЛИННИК, М. В. ЧЕРКАШЕНКО, Н. Н. ФАТЕЕВА, А. Н. ФАТЕЕВ, В. А. ПОНОМАРЕВ

СИНТЕЗ И АНАЛИЗ СХЕМ УПРАВЛЕНИЯ ГИДРОПНЕВМОПРИВОДАМИ

Предлагается метод анализа схем гидропневмоприводов, позволяющий выявить и устранить имеющиеся ошибки при проектировании, в основном, связанные с противоречивостью входов, действующих между технологическими операциями, и «силовой борьбой» на исполнительных устройствах, а также метод синтеза, позволяющий получить схему, содержащую близкую к минимальному число логических элементов. Предлагается формализованный метод анализа схем систем управления гидропневмоприводами, позволяющий выявить и устранить ошибки, возможные при синтезе. Уравнения функций выходов и внутренних состояний системы выписываются непосредственно по схеме гидропневмопривода при методе стандартной позиционной структуры и из матрицы соответствий при методе минимизации. Выявление ошибок осуществляется определением корректности графа операций, анализа входной последовательности, корректности матрицы соответствий и соответствующей системы уравнений. Показана эффективность использования для анализа схем матрицы соответствий М. В. Черкашенко, размерность которой не зависит от числа входов и выходов, а только от числа переходов между технологическими операциями. Далее не составляет трудностей исправление ошибок при проектировании и, при необходимости, осуществления соответствующей корректировки схемы. При корректировке схемы использован метод сочетания функциональных и логических возможностей распределительной аппаратуры, а также построенных на ней модулей. Предлагаемый метод является эффективным средством выявления ошибок, неточностей, проверки работоспособности, рационального построения схем, и может быть широко использован проектировщиками систем управления гидропневмоприводов, а также студентами вузов при изучении методов построения схем.

Ключевые слова: гидропневмопривод, схема, синтез, анализ, система управления, технологическое оборудование.

Introduction. Analysis of previous work [1–8] related to the design of modern control systems for hydropneumatic drives, showed that the study and solution of many issues related to further improving the efficiency and quality of design of hydropneumatic units remain relevant today. When designing modern control systems for hydropneumatic drives of technological equipment, errors are possible, mainly related to the inconsistency of transitions between technological operations and "power struggle" on the working mechanisms. The problem of analysis solves the problems associated with the detection of errors in the design of hydropneumatic systems and their elimination at the stages of synthesis.

Analysis of the state of the issue. From the existing approaches to the synthesis of circuits of hydropneumatic drives can be divided into three, one of which (element) involves the expression of output signals through the input with sequential input of memory elements (ME), and the second – standard memory location of the device with simultaneous indication of time intervals (aggregate, using a command apparatus). The third, based on the symbiosis of the first two and proposed by professor M. Cherkashenko, combines the positive features of the two mentioned above.

The main advantage of the elemental approach is that the circuit obtained as a result of the design contains close to the minimum number of logical elements.

In general, the main disadvantages of the elemental approach are: consistent informal introduction of ME and placement of internal states; joint minimization of the system of logical equations of a large number of variables with the help of Carnot maps (which for control machines of large dimension becomes impossible even with the use of computers) or informal extension of sets that cause transitions from one technological operation to another.

The aggregate approach eliminates these shortcomings of the elemental approach due to the possibility of synthesizing the circuit of control machines (CM) from individual blocks, which simplifies its construction and reduces the design time. The main disadvantage of the aggregate approach is the redundancy of the structure, which complicates the scheme of CM.

This article proposes a formalized method of analysis of control circuits of hydropneumatic units, which allows to detect and eliminate errors possible during synthesis.

As a description of the control system, it is advisable to choose a graph of operations [9], which has known advantages over other formalized methods of description. Equations of output functions and internal states of the system are written directly according to the scheme of the hydropneumatic drive. Error detection is carried out by determining the correctness of the graph of operations, analysis of the input sequence, the correctness of the matrix of correspondences and the corresponding system of equations [10–12]. Further, it is not difficult to correct errors in the design and, if necessary, make appropriate adjustments to the scheme.

Consider the method of analysis on the example of the designed pneumatic control scheme of the pipe cutting machine.

Main part. Segments of pipes of different lengths with machined ends are very often used in technology. Processing is carried out by means of the power heads located on two parties of the special machine. The heads can be adjusted to different lengths of pipe sections. The manipulating system for feeding and removing workpieces can be relatively simply made by pneumatic means. The pipes are fed to the machine from the store, and the finished parts come from the machine back to the store. During machining, the parts are clamped and the tool performs the necessary movements. The tool will be fed evenly if you install a hydraulic brake cylinder (Fig. 1) in parallel with the working cylinder [13].

Pneumatic cylinders C1–C6 (outputs Z_1–Z_6) serve as executive devices (ED) of the pipe-cutting machine. Cylinder C1 (dispenser) opens and feeds the pipe to the supply lever, it is controlled by a limit switch (LS) X_3, then the dispenser 8 is closed (position is controlled by LS X_2). The rotary cylinder C2 lowers the pipe down to the machining position (the position is controlled by the LS X_5). The pipe clamp is performed by the clamping cylinders C3 and C4, which is controlled by LS X_7 and X_9. After clamping the pipe, the linear module cylinder C5 is turned on and the pipe is processed (position is controlled by LS X_{11}). After processing the pipe, the cylinder C5 returns to its original position (position is controlled by LS X_{10}). Then the pipe is unclamped by cylinders C3 and C4, which is controlled by LS X_6 and X_8. After unclamping the pipe, the ejector cylinder C6 is triggered (position is controlled by LS X_{13}). Then the ejector C6 and the rotary cylinder C2 return to their original position simultaneously (the position is controlled by LS X_{12} and X_4).

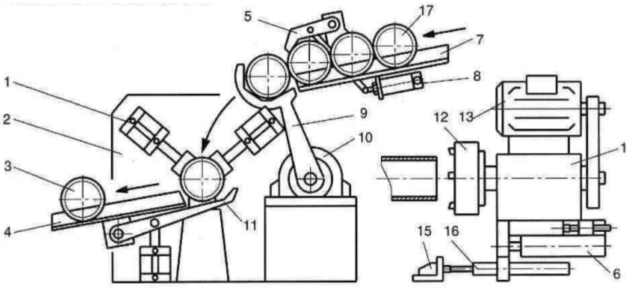


Fig. 1. Technological scheme of the pipe cutting machine:
1 – clamping cylinder (C3 and C4); 2 – machine bed;
3 – workpiece; 4 – conveyor to remove finished parts; 5 – cutter;
6 – linear module (C5); 7 – shop with billets of pipes;
8 – pneumatic cylinder (C1); 9 – feeding lever; 10 – rotary cylinder (C2); 11 – ejector (C6); 12 – tool head; 13 – electric motor; 14 – module "screw nut"; 15 – emphasis; 16 – brake hydraulic cylinder

The work cycle begins by pressing the start button $X_1 = 1$, and the dispenser C1 opens ($Z_1 = 1$), then the signal from the LS $X_3 = 1$ dispenser C1 closes ($\bar{Z}_1 = 1$), pressing at the end of the LS, the signal $X_2 = 1$ from which the pipe is lowered to processing position ($Z_2 = 1$). Next, the signal $X_5 = 1$ cylinders C3 and C4 perform a pipe clamp ($Z_3 = 1$ and $Z_4 = 1$). Then the signals $X_7 = 1$ and $X_9 = 1$ are processed pipe ($Z_5 = 1$). After processing the pipe, the cylinder C5 returns to its original position at the signal $X_{11} = 1$ ($\bar{Z}_5 = 1$). Next, the signal $X_{10} = 1$ cylinders C3 and C4 perform the expansion of the pipe ($\bar{Z}_3 = 1$ i $\bar{Z}_4 = 1$). On signals $X_6 = 1$ and $X_8 = 1$ the ejector C6 ($Z_6 = 1$) works. Next, at the signal $X_{13} = 1$, the cylinders C2 and C6 return to their original position ($\bar{Z}_2 = 1$ i $\bar{Z}_6 = 1$).

The purpose of the actuators, as well as their interaction with the input devices are shown in Table 1.

Formalization of the description of work of systems of hydro- or pneumatic drives of technological object allows to pass from the verbal description of work of system to the mathematical description necessary for realization of structural synthesis of the logical scheme of control system (CS).

Table 1 – Interaction of input and actuators

Output signals		Input signals	
Marking	Name	Starting position	The final position
Z_1	Dispenser	X_2	X_3
Z_2	Turn	X_4	X_5
Z_3, Z_4	Clamp/Squeezing	X_6, X_8	X_7, X_9
Z_5	Tool feed	X_{10}	X_{11}
Z_6	Ejector	X_{12}	X_{13}

Formalized description of the scheme is depicted as a graph of operations. A graph is a system of points called vertices and a system of lines connecting these points, called edges. An edge with a direction is called an arc. An arc that emerges from one vertex and enters it is called a loop. The graph of operations is used as a language to describe the operation of control systems for hydraulic and pneumatic drives. In this capacity, use an oriented graph, in which each edge connecting the two vertices is given a certain orientation relative to the vertices. Under the graph of operations means an oriented graph, the vertices of which correspond to the operations of the technological process, and its arcs – the transitions from one operation to another. Sequences of the form $Q_y \vdash Z_v$ are written on the arcs of the graph of operations (ie formulas of this type: if the condition Q_y is valid, then the condition Z_v is valid). Q_y is an input set of CS, containing the outputs of X_c nodes, the influence of X_b from manual controls, and others. The Q_y set transfers the CS from one operation to another. The output set of CM Z_v contains the inputs of nodes that have changed their values at this transition. The graph of transitions in the general case consists of contours, each of which corresponds to one program of work of CM. Based on the technical task, we construct an oriented graph of operations (Fig. 2), ie the vertices of the graph correspond to the number of technological operations, and the arcs of the graph correspond to the transitions from one operation to another.

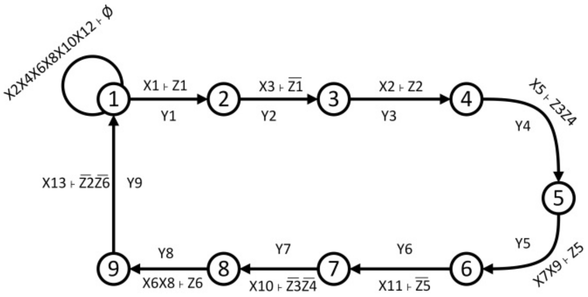


Fig. 2. Oriented graph of operations

The next stage of logical design after compiling a formalized description is no less important – structural synthesis.

The choice of the method of structural synthesis is determined by many factors, such as the complexity of the structure, the speed of the scheme, and others.

The principle of construction of schemes with use of standard positional structure is based on a method of construction of the scheme directly on the graph of operations. It uses a command-and-control method of construction. Moreover, the number of memory elements of the command apparatus is chosen to be equal to the number of vertices of the graph of operations. Thus, a single coding of the internal states of the system is performed, and the number of internal states coincides with the number of operations of the technological process. Functions of inclusion of ME $S = f(P, Y)$ depend on the corresponding input influence and on value of an exit of the previous ME:

$$S_i = p_i \cdot y_{i-1},$$

where S_i – the signal of the i-th ME; p_i – input set that transfers the system from one state to another in the i-th transition; y_{i-1} – the output of the memory item in the previous transition (i–1). The next transition after the last transition is the first.

For the automatic operation of the CS, the function of including the first ME will look like this:

$$S_1 = p_0 \cdot (X_1 + y_n),$$

where S_1 – signal to turn on the first ME; p_0 – input set from the actuators in the initial position; X_1 – input signal that includes the CS (usually the "START" button); y_n – output of the last ME.

For semi-automatic mode:

$$S_1 = p_0 \cdot X_1.$$

If there are two modes of operation of the CS – semi-automatic and automatic – the function of the first ME will look like this:

$$S_1 = p_0\,(X_1 + X_a\,y_n),$$

where X_a – signal from the operating mode switch corresponding to the automatic mode.

Output functions $Z = f(y)$ depend only on internal states and do not depend on input sets:

$$Z_m = y_i,$$

where Z_m – output function m.

So, functions on/off of memory elements: $S_1 = X_2X_4X_6X_8X_{10}X_{12} \cdot (X_1 + y_9)$; $R_1 = y_2$; $S_2 = X_3 \cdot y_1$; $R_2 = y_3$; $S_3 = X_2 \cdot y_2$; $R_3 = y_4$; $R_2 = y_3$; $S_4 = X_5 \cdot y_3$; $R_4 = y_5$; $S_5 = X_7X_9 \cdot y_4$; $R_5 = y_6$; $S_6 = X_{11} \cdot y_5$; $R_6 = y_7$; $S_7 = X_{10} \cdot y_6$; $R_7 = y_8$; $S_8 = X_6X_8 \cdot y_7$; $R_8 = y_9$; $S_9 = X_{13} \cdot y_8$; $R_9 = y_1$.

Functions of output signals: $Z_1 = y_1$; $\overline{Z}_1 = y_2$; $Z_2 = y_3$; $\overline{Z}_2 = y_9$; $Z_3 = y_4$; $\overline{Z}_3 = y_7$; $Z_4 = y_4$; $\overline{Z}_4 = y_7$; $Z_5 = y_5$; $\overline{Z}_5 = y_6$; $Z_6 = y_8$; $\overline{Z}_6 = y_9$.

The scheme, built directly on the graph of operations using a standard positional structure, is shown in Fig. 3.

Thus, using the graph and considering the transition 1/2, we include the first memory element with a signal X_1, and the output Z_1 – the signal y_1. And further, considering the transition 2/3, we turn on the signal X_3 of the second memory element, and the signal y_2 – the output, and so on.

To identify the possibility of untimely actuation of actuators and "power struggle" on actuators for systems of small complexity can be illustrated by embedding the graph of operations in the scan of an n-dimensional cube on the plane, and placing in the appropriate cells of the

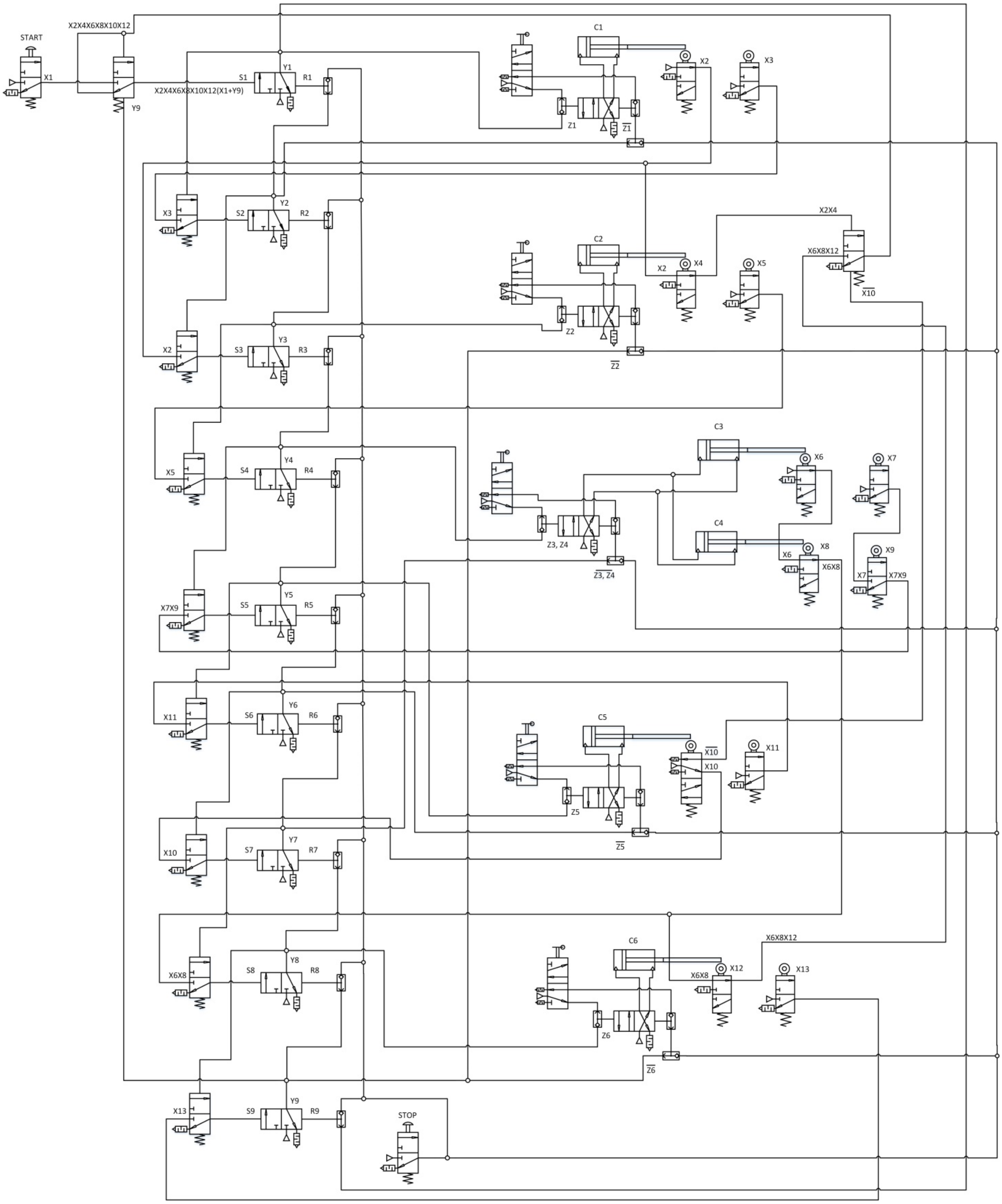


Fig. 3. Scheme control of the pneumatic drive of the pipe-cutting machine, which is synthesized using a standard positional structure

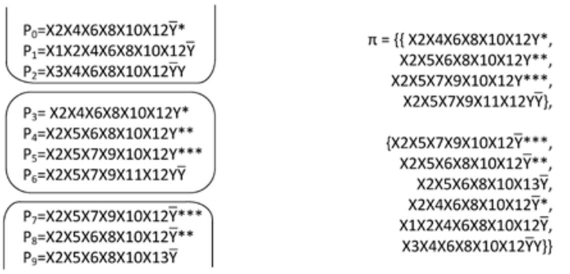
Carnot map vertices. The presence of two or more vertices in one cell indicates the ambiguity of two or more transitions, and, consequently, the need to introduce a memory element into the circuit [12].

For large-scale systems, the detection of any kind of contradictions in the scheme (if any) should be done by constructing a matrix of correspondences (MC), the dimension of which does not depend on the number of inputs and outputs, but only on the number of graphs of operations from the number of technological operations [10–12].

Method of minimization of the system of logical equations [10–12, 14, 15]. Let's analyze the input sequence of signals for the content of the same input sets.

If the input sequence contains the same sets, it is necessary to break it π into blocks that do not have the same input sets. The breakdown is carried out in a cycle from any set, taking into account that the same sets were not the last in the block. If the breakdown reveals two blocks, then one memory element is used with two outputs – direct and inverse ($y, \overline{y}$). In the absence of identical sets, a breakdown is not required. Next, we move on to minimizing logical equations based on the MC.

In this example, the input sequence has the form (see Fig. 4) and contains the same input sets (marked with asterisks – *, **, ***).



P_0=X2X4X6X8X10X12$\overline{Y}$*
P_1=X1X2X4X6X8X10X12$\overline{Y}$
P_2=X3X4X6X8X10X12$\overline{Y}$Y

P_3= X2X4X6X8X10X12Y*
P_4=X2X5X6X8X10X12Y**
P_5=X2X5X7X9X10X12Y***
P_6=X2X5X7X9X11X12Y$\overline{Y}$

P_7=X2X5X7X9X10X12$\overline{Y}$***
P_8=X2X5X6X8X10X12$\overline{Y}$**
P_9=X2X5X6X8X10X13$\overline{Y}$

π = {{ X2X4X6X8X10X12Y*,
X2X5X6X8X10X12Y**,
X2X5X7X9X10X12Y***,
X2X5X7X9X11X12Y$\overline{Y}$},

{X2X5X7X9X10X12$\overline{Y}$***,
X2X5X6X8X10X12$\overline{Y}$**,
X2X5X6X8X10X13$\overline{Y}$,
X2X4X6X8X10X12$\overline{Y}$*,
X1X2X4X6X8X10X12$\overline{Y}$,
X3X4X6X8X10X12$\overline{Y}$Y}}

Fig. 4. –Input sequence

Since the number of blocks $n = 2$, one memory element with two outputs is used – direct and inverse ($y, \overline{y}$), and the sets corresponding to these blocks are continued by signals of memory elements y and $\overline{y}$.

To obtain the minimum system of logical equations (SLE) it is necessary to perform a logical multiplication of signals that translate the system from one technological operation to another (according to customer requirements in this transition), the required minimum number of signals operating at the same transition. This makes it possible to prevent unexpected actuation signals of the ED, taking into account the outputs from the ME. This operation is called the extension of sets Q, which cause transitions, and perform it using a MC.

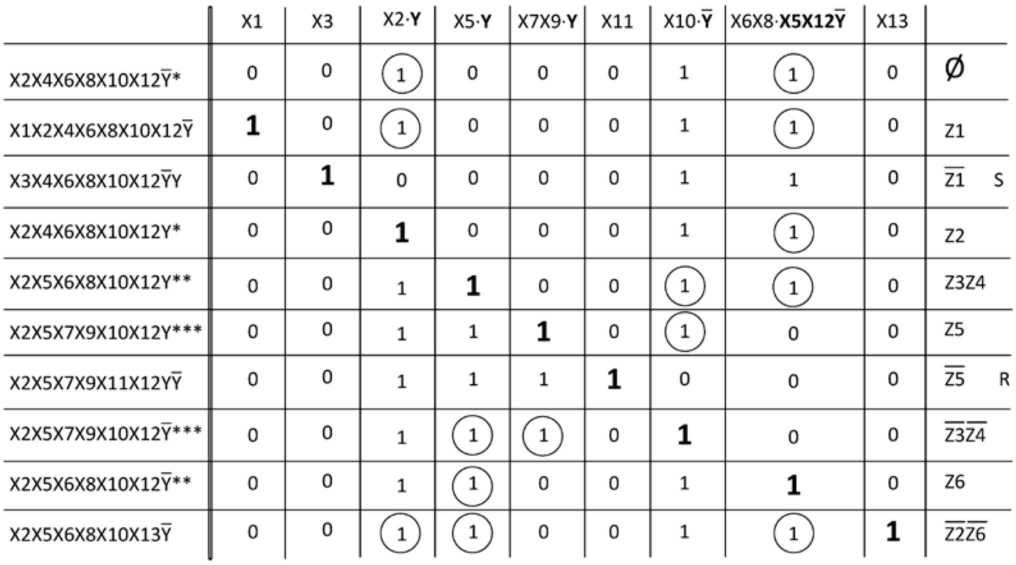
The use of a MC allows to synthesize a SLE regardless of the number of inputs and outputs, because the dimension of the MC is determined by the number of transitions of the control system. The rows of the MC to the sets P based on the signals y from the outputs of the memory elements, and the columns correspond to the signals that cause the transitions of the CM.

A unit is placed at the intersection of a row i and a column j if all the input signals corresponding to the column j are included in the input set that corresponds to the row i, otherwise it is set 0. Contradictory units are determined by the sequence of contradictory output signals and are circled. Units corresponding to transitions are denoted by "fat" units.

In the general case, to eliminate conflicting units, the signals of the scanned column should be extended by signals that are present at this transition (where the "fat" unit) and absent in the transition, where the "circled" unit. There may be several such signals, but you should strive for their minimum number. Preference is given to signals that occur in sets Q fewer times (this results in a minimum number of logic elements in the circuit). Let's make a matrix of correspondence with full input sets concerning the considered example (Table 2). For identical sets in columns we carry out initial extension by the corresponding signals from elements of storage ($y, \overline{y}$).

Consider a column X_1, there is only one "fat" unit, in the column X_{10} units that stand at the intersection with the rows $X_2X_5X_6X_8X_{10}X_{12}y$ and $X_2X_5X_7X_9X_{10}X_{12}y$, cause the appearance of the output signal of the CM Z_3 and Z_4. These units are contradictory and are distinguished by circles. To eliminate invalid units in the transition with a "fat" unit and set $X_2X_5X_7X_9X_{10}X_{12}\overline{y}$, it is necessary to find the minimum number of signals that are missing in the sets $X_2X_5X_6X_8X_{10}X_{12}y$ and $X_2X_5X_7X_9X_{10}X_{12}y$. The conjunction of the selected signals (for example $\overline{y}$) is extended X_{10} and, thus, the contradiction is eliminated. Signals of extension of sets from above in columns, owing to elimination of inadmissible units, are allocated in a fat font. Units that stand at the intersection of a row $X_3X_4X_6X_8X_{10}X_{12}\overline{y}\,y$ and a column $X_6X_8X_5X_{12}\overline{y}$, a row $x_2x_5x_7x_9x_{11}x_{12}y\,\overline{y}$ and a column X_7X_9y do not require removal because they disappear when the ME is switched.

Table 2 Correspondence matrix for automatic mode



	X1	X3	X2·**Y**	X5·**Y**	X7X9·**Y**	X11	X10·$\overline{\mathbf{Y}}$	X6X8·**X5X12$\overline{\mathbf{Y}}$**	X13	
X2X4X6X8X10X12$\overline{Y}$*	0	0	①	0	0	0	1	①	0	Ø
X1X2X4X6X8X10X12$\overline{Y}$	**1**	0	①	0	0	0	1	①	0	Z1
X3X4X6X8X10X12$\overline{Y}$Y	0	**1**	0	0	0	0	1	1	0	$\overline{Z1}$ S
X2X4X6X8X10X12Y*	0	0	**1**	0	0	0	1	①	0	Z2
X2X5X6X8X10X12Y**	0	0	1	**1**	0	0	①	①	0	Z3Z4
X2X5X7X9X10X12Y***	0	0	1	1	**1**	0	①	0	0	Z5
X2X5X7X9X11X12Y$\overline{Y}$	0	0	1	1	1	**1**	0	0	0	$\overline{Z5}$ R
X2X5X7X9X10X12$\overline{Y}$***	0	0	1	①	①	0	**1**	0	0	$\overline{Z3}\overline{Z4}$
X2X5X6X8X10X12$\overline{Y}$**	0	0	1	①	0	0	1	**1**	0	Z6
X2X5X6X8X10X13$\overline{Y}$	0	0	①	①	0	0	1	①	**1**	$\overline{Z2}\overline{Z6}$

The lengthening turns the circled units to zero and leads to the elimination of inconsistencies that cause malfunctioning of the ED. The logical equations for the inclusion of ED and ME are obtained in the assemblies of logical expressions written at the top of the MC, for the corresponding "fat" unit of the MC output.

Finally we have a system of logical equations: $S = X_3$; $R = X_{11}$; $Z_1 = X_1 + X_2X_4$; $\overline{Z}_1 = X_3$; $Z_2 = X_2y$; $\overline{Z}_2 = X_{13}$; $Z_3 = Z_4 = X_5y$; $\overline{Z}_3 = \overline{Z}_4 = X_{10}\overline{y}$; $Z_5 = X_7X_9y$; $\overline{Z}_5 = X_{11}$; $Z_6 = X_6X_8 \cdot X_5X_{12}\,\overline{y}$; $\overline{Z}_6 = X_{13}$.

It should be emphasized the need to be able to install the actuators and the memory element in the initial position, for which the scheme introduced the "Stop" button and four valves OR. In addition, the use of the "Start" button makes it possible to implement a semi-automatic mode of operation of the circuit. To get the automatic mode, you need to replace the start button with a toggle switch.

When adjusting the scheme, the method of combining the functional and logical capabilities of the distribution equipment, as well as the modules built on it was used [14, 15].

The final version of the adjusted scheme of the pipe-cutting machine taking into account all corrections is presented in Fig. 5.

Conclusions. Thus, the proposed method is an effective means of detecting errors, inaccuracies, verification, rational construction of circuits, and can be widely used by designers of control systems for hydropneumatic actuators, as well as university students in the study of methods of construction of circuits.

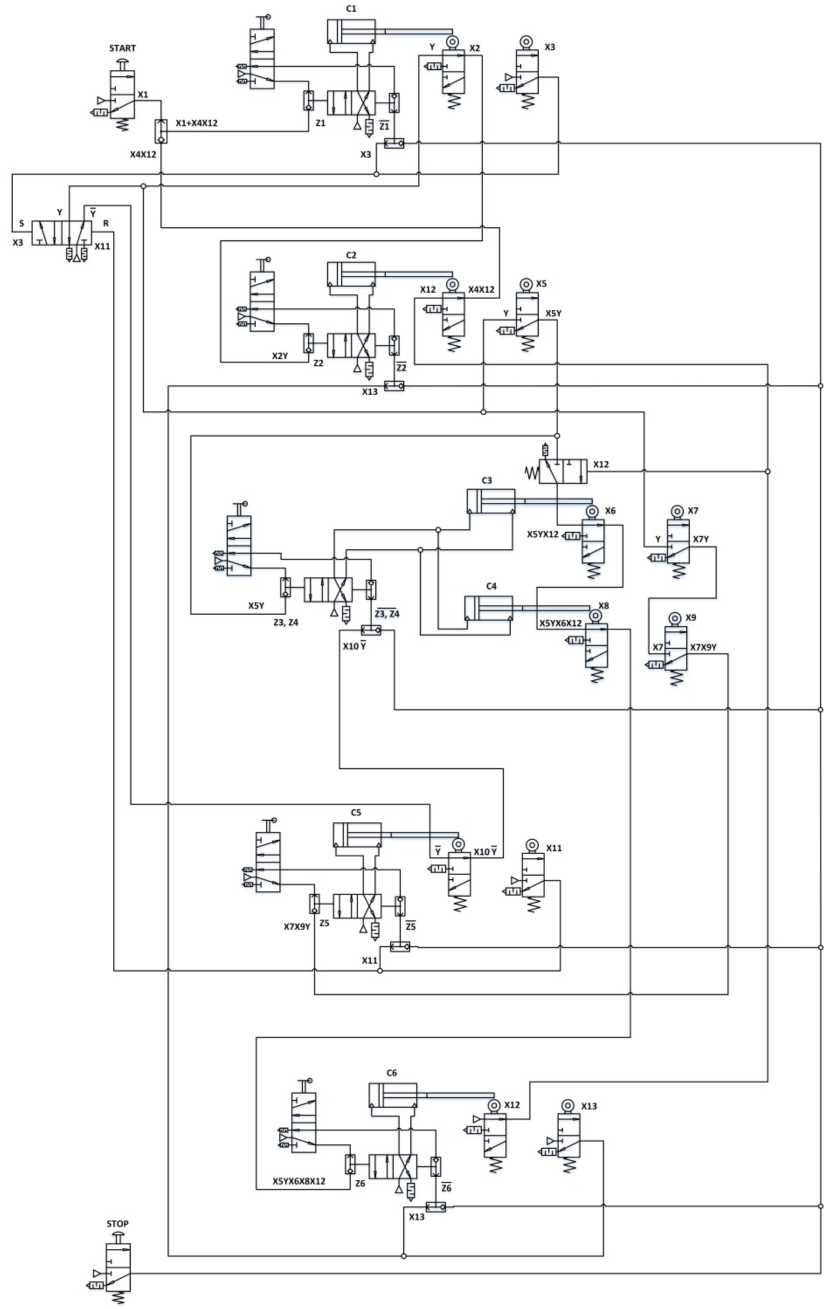


Fig. 5. Scheme control of the pneumatic drive of the pipe-cutting machine, which is synthesized by the method of minimization

References

1. Chai C. Research on PLC-Based Pneumatic Controlling System of Flying Splicer of Web-Fed Offset Presses. *The Open Mechanical Engineering Journal*. 2011. No. 5. P. 160–165.
2. Heikkilä M., Linjama M. Displacement Control of a Mobile Crane Using a Digital Hydraulic Power Management System. *Mechatronics – The Science of Intelligent Machines*. 2013. Vol. 23, issue 4. P. 452–461.
3. Rakova E., Hepke J., Weber J. Comparison of Methods for the Investigation on the Energetic Behaviour of Pneumatic Drives. *Proc. of the 9th International Fluid Power Conference. Modern Fluid Power – Challenges, Responsibilities, Markets. Vol. 1*. Aachen, 2014. P. 116–127.
4. Linjama M., Vilenius M. Improved Digital Hydraulic Tracking Control of Water Hydraulic Cylinder Drive. *International Journal of Fluid Power*. 2005. Vol. 6, no. 1. P. 29–39.
5. Губарев А. П., Левченко О. В. *Механотроника: от структуры системы к алгоритму управления*. Киев: НТУУ «КПИ», 2007. 180 с.
6. Аврунин Г. А., Грицай И. В., Кириченко И. Г., Мороз И. И., Щербак О. В. *Объемный гидропривод и гидропневмоавтоматика*. Харьков: ХНАДУ, 2008. 412 с.
7. Siivonen L., Linjama M., Huova M., Vilenius M. Jammed On/Off Valve Fault Compensation with Distributed Digital Valve System. *International Journal of Fluid Power*. 2009. Vol. 10, no. 2. P. 73–82.
8. Winkler B. A Hydraulic Micro-Positioning System for Industrial Mill Centers. *Proc. of the Mechatronics*. Linz, 2012.
9. Юдицкий С. А. К вопросу описания и синтеза дискретных систем промышленной автоматики. *Техническая кибернетика*. 1976. № 1. С. 131-141.
10. Cherkashenko M. et al. Synthesis of discrete control systems of industrial robots. *Automation and Remote Control*. 1981. Vol. 42, no. 5. P. 676–680.
11. Cherkashenko M. Universal devices for building pneumatic control circuits for industrial robots and automatic machines. *Soviet engineering research*. 1985. Vol. 5, no. 2. P. 29–31.
12. Черкашенко М. В. *Автоматизація проектування систем гідро- і пневмоприводів з дискретним управлінням*. Харків: НТУ «ХПІ», 2001. 182 с.
13. Хессе С. *Пневмоавтоматика: 99 примеров применения*. Фесто, 2000. 120 с.
14. Sokol Ye., Cherkashenko M. *Synthesis of control schemes for hydroficated automation objects*. Germany: GmbH & Co, 2018. 214 p.
15. Sokol Ye., Cherkashenko M. *Syntesis of control schemes of drives system*. Kharkiv: NTU "KhPI", 2018. 120 p.

References (transliterated)

1. Chai C. Research on PLC-Based Pneumatic Controlling System of Flying Splicer of Web-Fed Offset Presses. *The Open Mechanical Engineering Journal*. 2011, no. 5, pp. 160–165.
2. Heikkilä M., Linjama M. Displacement Control of a Mobile Crane Using a Digital Hydraulic Power Management System. *Mechatronics – The Science of Intelligent Machines*. 2013, vol. 23, issue 4, pp. 452–461.
3. Rakova E., Hepke J., Weber J. Comparison of Methods for the Investigation on the Energetic Behaviour of Pneumatic Drives. *Proc. of the 9th International Fluid Power Conference. Modern Fluid Power – Challenges, Responsibilities, Markets. Vol. 1*. Aachen, 2014, pp. 116–127.
4. Linjama M., Vilenius M. Improved Digital Hydraulic Tracking Control of Water Hydraulic Cylinder Drive. *International Journal of Fluid Power*. 2005, vol. 6, no. 1, pp. 29–39.
5. Gubarev A. P., Levchenko O. V. *Mekhanotronika: ot struktury sistemy k algoritmu upravleniya* [Mechanotronics: from system structure to control algorithm]. Kiev, NTUU "KPI" Publ., 2007. 180 p.
6. Avrunin G. A., Gritsay I. V., Kirichenko I. G., Moroz I. I., Shcherbak O. V. *Ob"emnyy gidroprivod i gidropnevmoavtomatika* [Volumetric hydraulic drive and hydropneumatic automation]. Kharkov, KhNADU Publ., 2008. 412 p.
7. Siivonen L., Linjama M., Huova M., Vilenius M. Jammed On/Off Valve Fault Compensation with Distributed Digital Valve System. *International Journal of Fluid Power*. 2009, vol. 10, no. 2, pp. 73–82.
8. Winkler B. A Hydraulic Micro-Positioning System for Industrial Mill Centers. *Proc. of the Mechatronics*. Linz, 2012.
9. Yuditskiy S. A. K voprosu opisaniya i sinteza diskretnykh sistem promyshlennoy avtomatiki [On the issue of description and synthesis of discrete industrial automation systems]. *Tekhnicheskaya kibernetika*. 1976, no. 1, pp. 131–141.
10. Cherkashenko M. et al. Synthesis of discrete control systems of industrial robots. *Automation and Remote Control*. 1981, vol. 42, no. 5, pp. 676–680.
11. Cherkashenko M. Universal devices for building pneumatic control circuits for industrial robots and automatic machines. *Soviet engineering research*. 1985, vol. 5, no. 2, pp. 29–31.
12. Cherkashenko M. V. *Avtomatyzatsiya proektuvannya system hidro- i pnevmopryvodiv z dyskretnym upravlinnyam* [Automation of design of systems of hydraulic and pneumatic actuators with discrete control]. Kharkiv, NTU "KhPI" Publ., 2001. 182 p.
13. Khesse S. *Pnevmoavtomatika: 99 primerov primeneniya* [Pneumatic automation: 99 application examples]. Festo, 2000. 120 p.
14. Sokol Ye., Cherkashenko M. *Synthesis of control schemes for hydroficated automation objects*. Germany, GmbH & Co Publ., 2018. 214 p.
15. Sokol Ye., Cherkashenko M. *Syntesis of control schemes of drives system*. Kharkiv, NTU "KhPI" Publ., 2018. 120 p.

Received 06.10.2021

Відомості про авторів / Сведения об авторах / About the Authors

Линник Олександр Васильович (***Линник Александр Васильевич***, ***Lynnyk Aleksandr***) – головний конструктор гідротурбін СКБ «Турбогідромаш» АТ «Українські енергетичні машини»; м. Харків, Україна; ORCID: https://orcid.org/0000-0002-6779-5528; e-mail: office@turboatom.com.ua

Черкашенко Михайло Володимирович (***Черкашенко Михаил Владимирович, Cherkashenko Mikhaylo***) – доктор технічних наук, професор, Національний технічний університет «Харківський політехнічний інститут», професор кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; ORCID: https://orcid.org/0000-0003-3908-7935; e-mail: mchertom@gmail.com

Фатєєва Надія Миколаївна (***Фатеева Надежда Николаевна, Fatieieva Nadezhda***) – кандидат технічних наук, доцент, Національний технічний університет «Харківський політехнічний інститут», доцент кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; ORCID: https://orcid.org/0000-0001-6955-5301; e-mail: nadin_yak@ukr.net

Фатєєв Олександр Миколайович (***Фатеев Александр Николаевич, Fatyeyev Aleksandr***) – кандидат технічних наук, Національний технічний університет «Харківський політехнічний інститут», доцент кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; ORCID: https://orcid.org/0000-0002-9212-4507; e-mail: fatyan1@ukr.net

Пономарьов Владислав Анатолійович (***Пономарев Владислав Анатольевич***, ***Ponomarov Vladyslav***) – Національний технічний університет «Харківський політехнічний інститут», аспірант кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; ORCID: https://orcid.org/0000-0001-8742-5615; e-mail: ponomaridze1@gmail.com