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Synthesis of ladder diagrams in the control of the transport line of rolling elements

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The article presents a synthesis of ladder diagrams in controlling any configuration of the conveyor path for delivering rolling elements to spiral storages in interoperative transport. The ladder diagram of the sequential control system sets the state of distributors to ensure a flow of parts to serve successive storages. The fundamental module of the ladder diagram is the memory block. The ladder diagram of the sequential control system was developed based on the sequence graph of filling the storages. A single or dual sensor system controls the filling status of spiral storages.

The rolling element displacement control sensors work together with appropriately designed systems to execute the delay of the rising and falling edge input signal. Time-delay relays, specifically the ON-delay Timer and OFF-delay Timer, were used in programming PLC controllers to implement control systems.

By using a two-level control of the filling level of the storages, it is possible to control the emptying status of the storages as a function of the technological time of removal of the items from the storage between the two control points.

The synthesis of ladder diagrams in control and their verification was conducted using the computer program FluidSim by Festo.

Key words: ladder diagrams, delay execution systems, synthesis and verification of sequential systems

1. Introduction

In the production of rolling elements, the transport path can be constructed using various devices such as conveyor feeders, manipulators, element storage, machining equipment, etc. Each of these devices can be controlled by computer software, which is responsible for ensuring the safety and efficiency of the pro-

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duction process. In this type of production, special machine tools with a high degree of automation are used to tool the components. Activities such as supplying components to workstations, applying products for machining, etc., result in increased worker utilisation, and which can be performed much more quickly by a unit of equipment configured in a mass handling system.

An essential component of the transport system is software that allows for monitoring the entire production process. This software enables employees to quickly respond to any breakdowns and optimize the entire process in real-time. Automating the transport path results in significant cost savings for manufacturers by increasing production efficiency while reducing transportation costs for processed elements. However, it is important to remember that production processes vary widely and require an individualized approach. From this perspective, collaboration between the manufacturer and an automation designer is crucial. The automation of the inter-operational transport route increases the productivity of machine tools almost to the maximum and reduces the costs associated with the transport of workpieces.

In the design of automation devices for technological processes, one of the most significant aspects is the analysis and synthesis of the device's conceptual diagram [1,2].

Automation devices can contain both combinational and sequential circuits. In sequential circuits [3], the current state of the outputs depends not only on the current state of the inputs but also on the sequence of previous input states. In combinational circuits [4], the current state of the outputs depends only on the current state of the inputs.

Synchronous sequential circuits involve a clock signal, unlike asynchronous sequential circuits. In asynchronous sequential circuits, input signals continuously interact directly with the internal state of the circuit. In this case, every input change causes an immediate (considering signal propagation time through the circuit) response from the circuit [5].

In general, synthesizing synchronous circuits is easier than synthesizing asynchronous circuits, where there is no clock signal [6].

Designing sequential circuits using the conventional method of state transition and output tables is straightforward when the number of inputs and internal states is not large.

For more complex circuits with a greater number of inputs and internal states (for circuits with more than three inputs and eight internal states), the design becomes more cumbersome, and synthesis algorithms become more complicated.

This leads to a reduced chance of achieving an optimal solution [7].

The monograph [8] presents an algorithmic approach to the synthesis of asynchronous sequential circuits.

The ladder diagram language [9] is very popular among PLC controller programmers. The algorithmic method of designing sequential circuits minimizes mathematical complexity in circuit analysis and allows for quickly obtaining a program in the form of ladder diagrams.

The popularity of the ladder diagram language stems from its ease of understanding due to its similarity to relay contact diagrams [10].

Ladder diagrams also enable the execution of more complex operations, such as arithmetic and timing operations. A control scheme in this language consists of symbols placed in circuits resembling a relay ladder diagram. This language allows the construction of control systems based on logical relationships derived from Boolean algebra [7].

The synthesis of electro-pneumatic sequential circuits using logic elements is presented in the article [11], while the use of programmable controllers is discussed in [12, 13].

The synthesis of a sequential system for the transport line for delivering rolling elements to machining storages is presented in the literature [14].

The selection of the transport routes is carried out through distributors consisting of actuators working together with two-state valves [15, 16]. In continuous control systems for actuator positioning, proportional valves are commonly employed [17, 18]. Precise control of actuator position is made possible using digital position transducers [19].

Selected examples of control system design using electropneumatic components and devices are presented in the literature [20, 21]. In control systems, the accuracy of positioning of executive elements is significant [22, 23]. An analysis of accuracy in signal processing is presented in the literature [24–26].

The article presents a synthesis of ladder diagrams in controlling any configuration of the conveyor path for delivering rolling elements to spiral storages in interoperative transport. The analysis is based on the schematic of the rolling element delivery line to warehouses presented in Fig. 1, which is a segment of the generalized configuration of the transport line section [14].

The transport line can be configured in any way using the appropriate connection of distributors R.

Using the vertical elevator PP, rolling elements are transported to a certain height and, utilizing the force of gravity and the properties of rolling elements, they are directed through distributors R to machining machines cooperating with spiral warehouses M.

It should be emphasized that the number of M storages is greater than the number of R distributors by one, i.e., for $R = X$, $M = X + 1$. For the synthesis, the number of storages M=8 and the number of distributors $R = 7$ was considered.

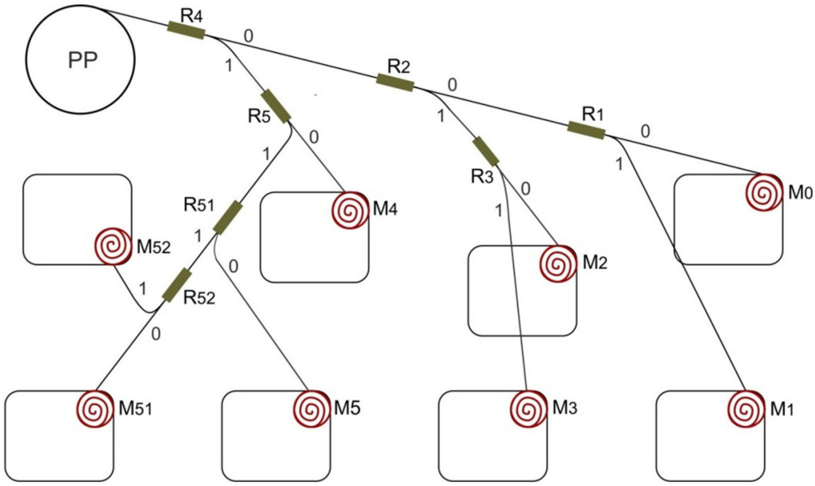

Figure 1: Diagram of the transport line under study: PP – vertical lift, R – distributors of transport routes, M – spiral storages; M = 8, R = 7

The aim of the article is to solve the problem of automatic delivery of bearing rings to machining stations using ladder diagrams in the control system. The ring feeder places elements on the rail busbars. The routing of the busbar, where a selected machining station connects with the storages through the feeder, is determined by appropriate control of the distributors in the adopted transport configuration. Signals from the storage filling sensors influence the choice of the transport path.

Based on the diagram of the analysed transport line, the state of individual distributors is determined depending on signals coming from the storage filling sensors.

The choice of transport route depends on the signals coming from the storage fill level sensors. Table 1 shows the status of setting up the R distributors to provide a flow of workpieces to the selected storage.

To ensure the flow of elements to a selected storage, the automation system must be configured appropriately. For example, distributors R4, R5, and R51 must be set to state 1, i.e., "on," while R52 should be in state 0, i.e., "off," to ensure the delivery of elements to storage M51. The status of the storages can be controlled by single-point or two-point sensors, with sensors for monitoring moving rolling elements cooperating with appropriate delay circuits.

The article presents developed measurement and control systems using ladder diagrams for use in the automation of interoperative transport of rolling elements.

Systems for implementing delay of input signal rising and falling edges were designed to work with sensors for monitoring moving elements. Time-delay re-

Table 1: The state of the R distributors to ensure the flow of workpieces to appropriate spiral storages M

	R1	R2	R3	R4	R5	R51	R52
M0	0	0	–	0	–	–	–
M1	1	0	–	0	–	–	–
M2	–	1	0	0	–	–	–
M3	–	1	1	0	–	–	–
M4	–	–	–	1	0	–	–
M5	–	–	–	1	1	0	–
M51	–	–	–	1	1	1	0
M52	–	–	–	1	1	1	1

lays, specifically ON-delay Timers and OFF-delay Timers used in PLC programming, were employed for control system implementation. Inductive or capacitive proximity sensors are used as presence sensors for rolling elements [27, 28].

The developed method for designing the control system for transporting rolling elements allows for a rapid creation of the system in the form of electrical ladder diagrams. This form of the system corresponds to the programming language known as the ladder diagrams language, which has gained popularity among PLC programmers.

To describe a mass service system, three key parameters need to be determined: the arrival rate, the service rate, and the method for managing the order of arrivals in the queue [29]. If the arrival flow follows a Poisson distribution, the service intensity is described by an exponential distribution, and the queue maintains a FIFO (First In First Out) discipline, the operation of such a system can be expressed using the system utilization factor (ρ) [30], also known as the Erlang formula:

$$\rho = \lambda / s\mu,$$

where: s – the number of service positions; $\lambda = 1/t_\lambda$ and t_λ is the average time interval between consecutive arrivals flowing into the system during the period under review; $\mu = 1/t_\mu$ and t_μ is the average service time for a single arrival during the period under review.

If the system utilization factor satisfies the condition of system stability: $0 \leqslant \rho < 1$ then the queue problem does not exist (the system is stable).

In the designed control system, storage handling is single-station. By selecting the appropriate service efficiency, the system ensures the proper handling time for the storage.

2. Single-sensor control transducer for the filling state of the spiral storage of rolling elements

At the output of the sensor controlling the level of filling of the spiral storage, pulses generated by moving rolling elements are produced.

A change in the sensor's signal state results in a pulse rise or fall. In Fig. 2, pulses generated by the moving ring during the filling phase (range A) and pulses generated by the moving ring during the emptying phase of the storage (range B) are shown.

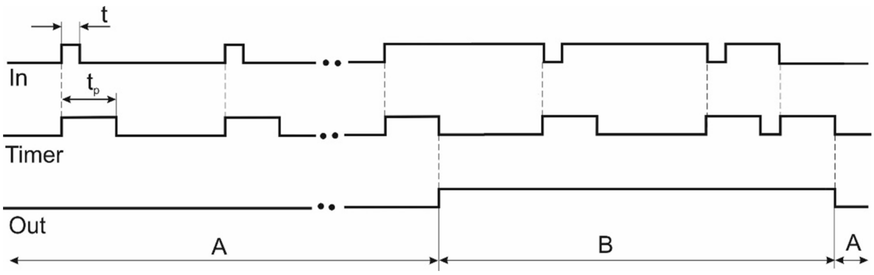

Figure 2: General operating principle of the transducer

To eliminate short-term changes in the sensor state, a converter circuit was developed, in which an appropriate delay circuit is used in conjunction with the storage level sensor.

The general operating principle of the transducer is presented in Fig. 2.

This is a circuit that implements both leading and trailing edge delay of the input signal, as shown in Fig. 3. The circuit utilizes time-delay relays commonly used in PLC programming.

The ON-delay Timer (TON) relay sets the output Q to "1" (ON – activated) after a specified delay time has elapsed. Timing begins after a change in the state of the input signal at IN from "0" to "1". A change in the state of the input signal at IN from "1" to "0" during the timing process cancels the timing, and it immediately returns the output Q to the state "0".

The OFF-delay Timer (TOF) resets the output Q to the state "0" (OFF – turned off) after the specified delay time has elapsed. Timing begins after a change in the state of the input signal at IN from "1" to "0". A change in the state of the input signal from "1" to "0" during the timing process cancels the timing, and the output Q remains in the state "1".

The system does not react to short pulses, shorter than the set delay time of the rising edge of the input signal (signal head), and shorter than the set delay time of the falling edge of the input signal (signal rear).

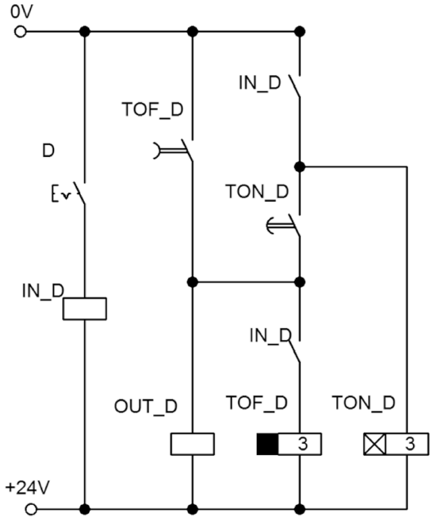

Figure 3: Circuit for implementing the leading and trailing edge delay of the input signal

The leading edge delay of the signal D from the storage control sensor M was achieved using the TON_D relay, which activates the OUT_D relay, while the trailing edge delay of the signal D from the storage control sensor M was achieved using the TOF_D relay.

The activation signal of the OUT_D relay (logic 1) reflects the presence of rolling elements in the storage, while deactivating the OUT_relay (logic 0) reflects the absence of rolling elements in the storage control sensor area.

The operation of the circuit from Fig. 3 is explained by the timing diagram presented in Fig. 4.

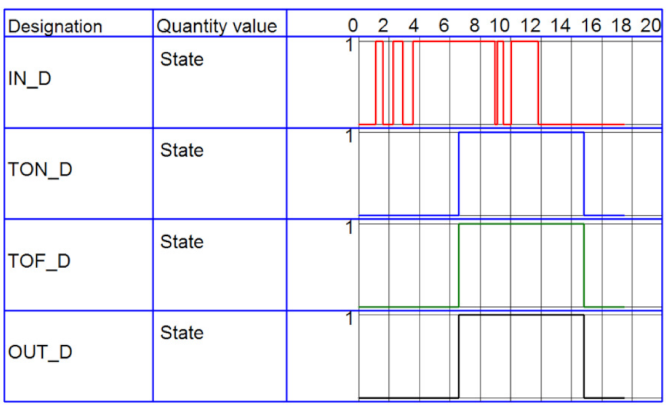

Figure 4: Timing diagram of the single-sensor control system

The rise and fall delay time of the input signal is determined in the process considering the speed of movement of the components in the rolling element control sensor zone.

3. Two-sensor spiral storage control system for rolling elements

Considering the developed single-sensor control system for the filling state of the spiral storage of rolling elements, a control system for the filling state of the storage using two control sensors was developed, as shown in Fig. 5. In the spiral storage, a lower ring position sensor D and an upper ring position sensor G were used. Each sensor is associated with a signal delay circuit for rising and falling edges of the input signal. These systems are identical to the systems discussed in item 2, and shown in Figs. 3 and 4.

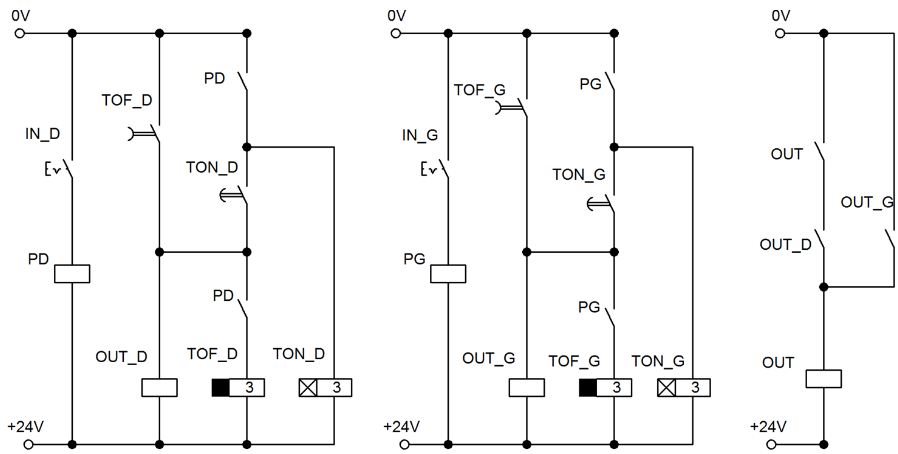

Figure 5: Two-sensor spiral storage control system for rolling elements

The essence of the developed system consists in linking two sensors: D and G, cooperating with the head and rear delay systems of the input signal, with a corresponding memory system.

The memory circuit implements a ladder diagram in which the relay OUT performs the function

$$(\mathrm{OUTOUT\_D} + \mathrm{OUT\_G}),$$

When the storage is unfilled, the output signal of the OUT memory circuit is in a low state (logic state 0). In the case of filling the storage to the lower-level D, the output signal of the delaying circuit OUT_D is in a high state (logic state 1), and the output signal of the memory circuit OUT remains in a low state.

In the case of filling the storage to the upper-level G, the output signal of the delaying circuit OUT_G is in a high state, causing the output signal of the memory circuit OUT to be in a high state as well.

In the case of emptying the storage in the technological process, the first change occurs in the state of the upper-level G sensor of the storage (the OUT_G signal changes from a high to a low level). The state of the OUT signal of the memory circuit is still high. Further emptying of the storage below the level of the lower-level D sensor of the storage causes a change in the signal of the delay circuit OUT_D to a low state.

There is then a change in the state of the memory circuit, thereby changing the OUT signal to a low state, which is signalled as a storage requirement for elements.

The exact operation of the designed system is illustrated by the cyclogram shown in Fig. 6.

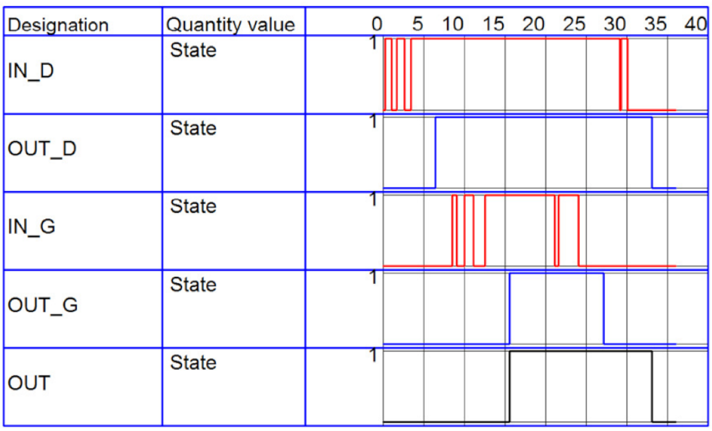

Figure 6: Cyclogram of the operation of the two-sensor rolling element spiral storage state control system

4. Minimised two-sensor spiral storage control system for rolling elements

Figure 7 shows the two-sensor control system for monitoring the storage's fill level, which works in conjunction with a single delay circuit for the rising and falling edge of the input signal and a logic function implementation circuit $P = (\neg IN\_D + \neg OUT)$ and $IN\_T = (\neg P + IN\_G)$. The IN_T output of this system is connected to the input of the rising and falling edge delay system.

The delay circuit for the rising and falling edge of the input signal is identical to the circuit discussed in item 2 and shown in Fig. 3.

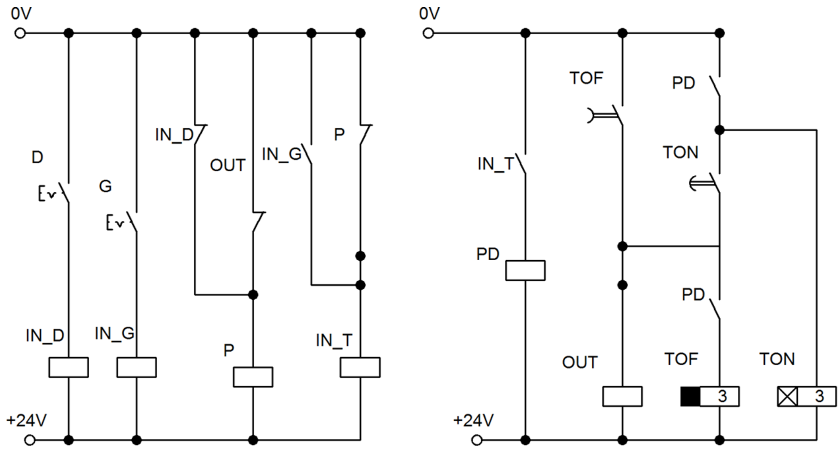

Figure 7: Minimised two-sensor spiral storage control system for rolling elements

The cyclogram presented in Fig. 8 accurately illustrates the operation of the designed minimized dual-sensor control system for the spiral storage of rolling elements.

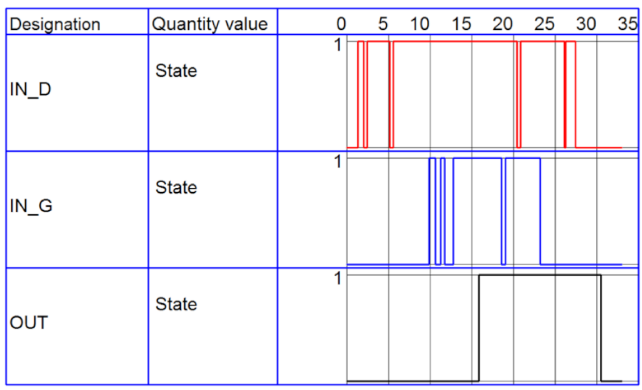

Figure 8: Cyclogram of the minimized dual sensor point control system for the spiral storage of rolling elements

5. Synthesis of ladder diagrams of a control system for the supply of rolling elements to a spiral storage

In the analysed transport line, the sequence of filling spiral storages is assumed to be from M0 to M52, as depicted in the sequence filling graph in Fig. 9.

Each storage M is assigned a memory state k, which is obtained by dividing the graph radially.

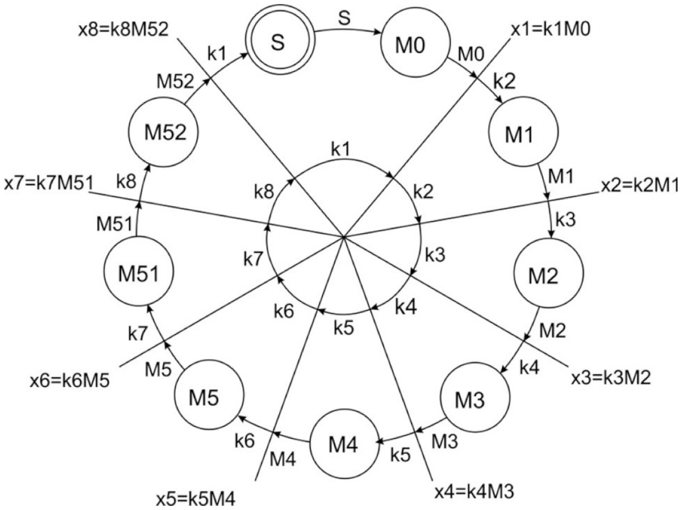

Figure 9: Graph of storage filling sequence

At the division line, signals xn are defined to determine the transition to the next state kn (the filling status of a storage in state kn enables the transition to the filling of the next unfilled storage).

The arrangement of ladder diagrams for delivering rolling elements to the spiral storage is developed based on the sequence filling graph as shown in Fig. 9.

The essential module of the control system is the memory block.

The graph shows in which memory state the sequential storage filling system is in when filling the detail storage. This is illustrated in Table 2. The memory is in a high state for the filled storage. The selection of the next storage is possible in the next memory high state (logical state 1), i.e., in the wandering memory high state.

Table 2: Sequence of storage filling depending on memory status

	k1	k2	k3	k4	k5	k6	k7	k8
M0	**1**	0	0	0	0	0	0	0
M1	0	**1**	0	0	0	0	0	0
M2	0	0	**1**	0	0	0	0	0
M3	0	0	0	**1**	0	0	0	0
M4	0	0	0	0	**1**	0	0	0
M5	0	0	0	0	0	**1**	0	0
M51	0	0	0	0	0	0	**1**	0
M52	0	0	0	0	0	0	0	**1**

The arrangement of ladder diagrams for sequential control of filling the storages is presented in Fig. 10. It was developed using distributors to ensure the flow

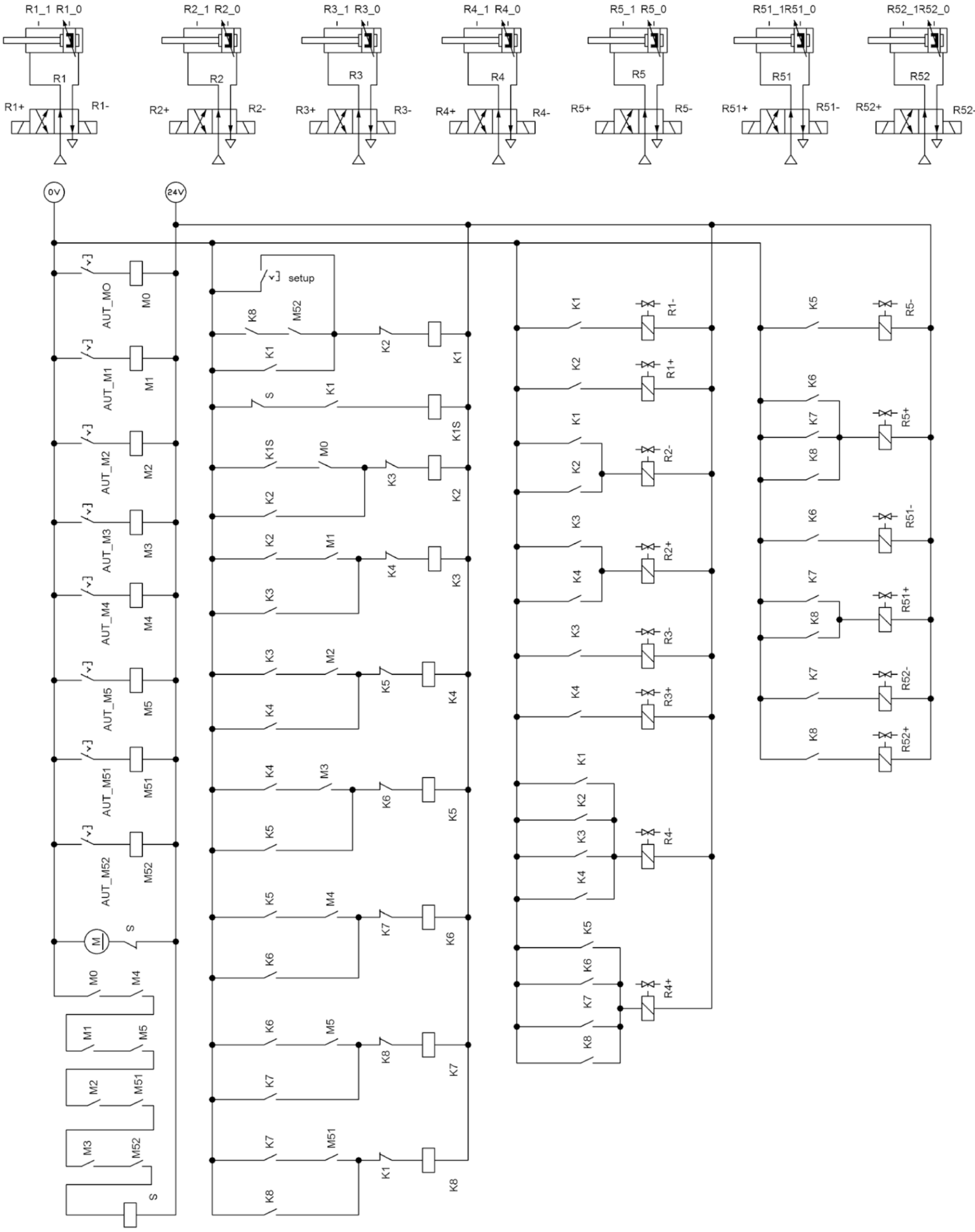

Figure 10: Arrangement of ladder diagrams for sequential control of filling the spiral storages for rolling elements

of details to the respective storages M. The state of the distributors is shown in Table 1.

In the ladder diagram system for controlling the filling of spiral storages for rolling elements, the following components can be identified:

- single or dual sensor control systems for filling storages M0–M52;
- memory system k1–k8 in the form of ladder diagrams;
- ladder diagram control system for distributing the R1–R52 flow stream to storages M0–M52.

The memory ladder diagrams are implemented using relays k1–k8 controlled by signals x1–x8. Generating the next state of memory clears the previous state. Signals M0–M52 represent signals from control sensors that work in conjunction with delay systems, reflecting the state of the storages.

Flow distributors for elements (R1–R52) are controlled by ladder diagrams that perform summation functions, as per Table 1. Distributors not involved in the flow setting for filling the currently selected storage are in the setting from the previous flow setting – it is uneconomical to overdrive them to the zero position.

In addition to selecting successive memory states, the storage filling control system is responsible for switching the vertical feeder on or off and stopping the cycle in state k1, according to the relation $S = k1[(M0) + (M1) + (M2) + (M3) + (M4) + (M5) + (M51) + (M52)]$.

Figure 11 shows an example of the simulation state of the developed sequential storage filling ladder diagram system.

In Fig. 11, the system is shown during simulation. The system is in k7 memory state. According to Table 2, the M51 storage is being filled. In this case, distributors R4, R5, and R51 are activated (set to state 1), while distributor R52 is deactivated (state 0). This corresponds to the state of the distributors, ensuring the flow of rolling elements into storage M51, as presented in Table 1.

The selected simulation cycle diagram for the ladder diagram system controlling the sequential filling of spiral storages for rolling elements in the analysed configuration of the transport line is shown in Fig. 12.

The following phases can be described in the cyclogram of the ladder diagram system for sequential filling of spiral storages for rolling elements in the analysed configuration of the transport line:

1. The vertical conveyor of rolling elements is activated when the storage is empty.
2. Initially, storages M1, M3, M4, and M5 are filled, while the others, M0, M2, M51, and M52, are empty.

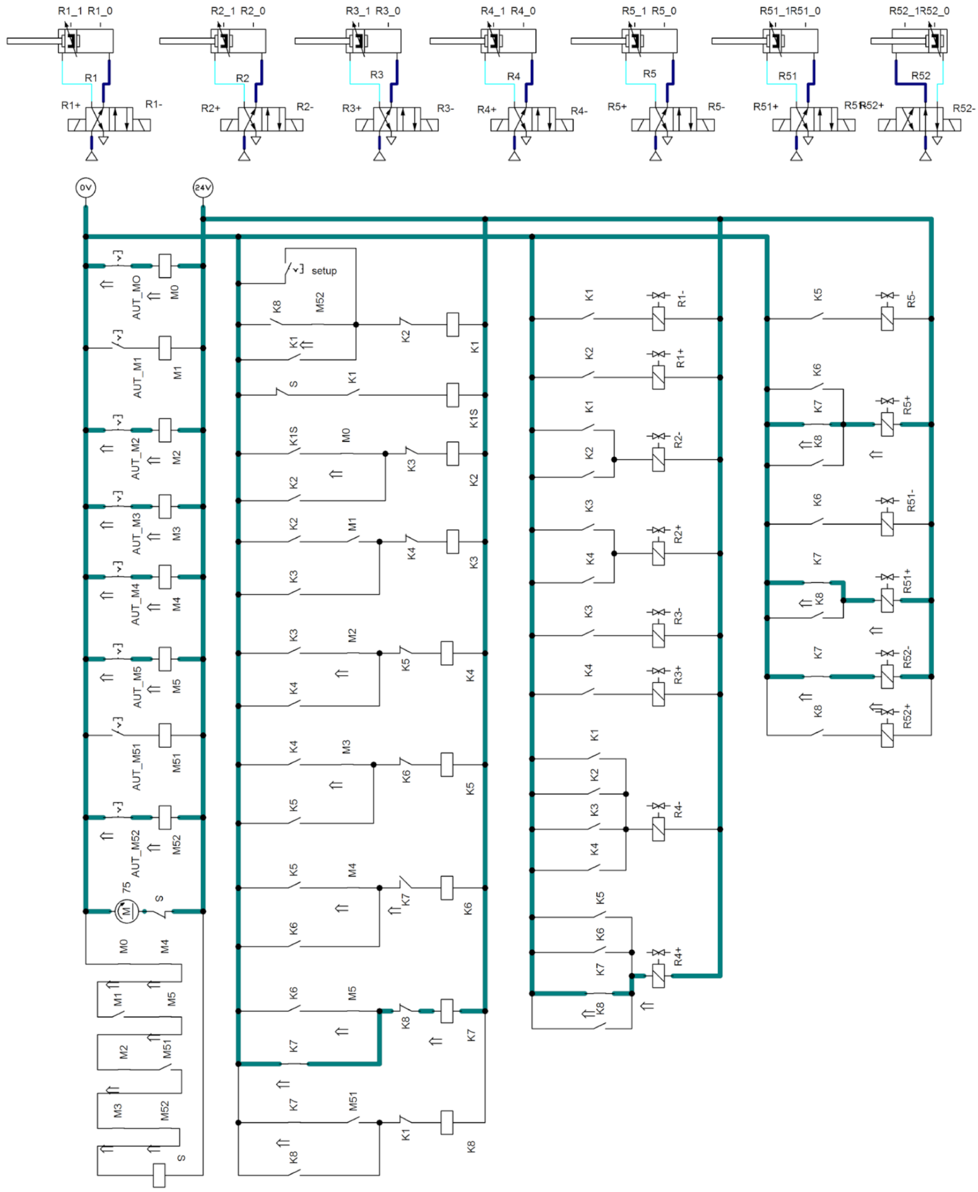

Figure 11: Example simulation of the sequential control system for filling spiral storages for rolling elements

3. When the control system is started, rolling elements are delivered to the first empty storage unit, in this case, M0; The flow of rolling elements to storage M0 is controlled by distributors R1, R2, and R4, which are in the off state (logic state 0).

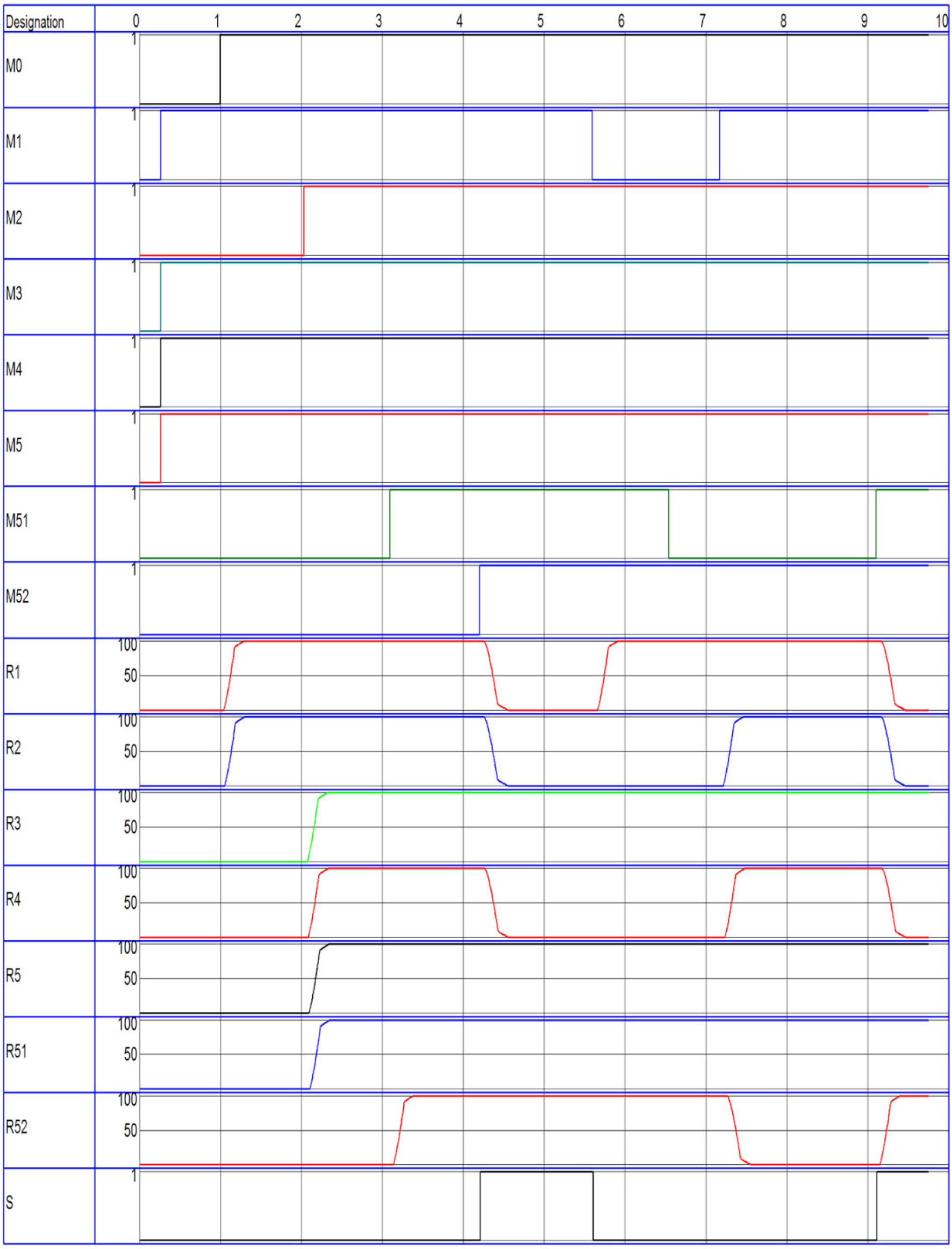

Figure 12: Cyclogram of ladder diagrams for sequential control of filling the spiral storages for rolling elements

4. In the following sequence, after filling storage M0 (logic state 1), storage M2 is filled with distributor R2 activated (set to logic state 1) and distributors R3 and R4 deactivated (logic state 0).
5. Filling storage M2 (logic state 1) triggers the filling of storage M51, with distributors R4, R5, and R51 activated (set to logic state 1) and distributor R52 deactivated (logic state 0).
6. After filling storage M51 (logic state 1), storage M52 is filled, with distributors R4, R5, R51, and R52 all activated (set to logic state 1).
7. After filling storage M52, all storages are in a filled state. The vertical conveyor of rolling elements is turned off, relay S is activated (logic state 1), and it waits for the request from a storage unit in need of workpieces.
8. The next storage unit to be filled is M1. In this case, distributors R2 are activated (logic state 1), and distributor R2 and R4 are deactivated (logic state 0). The vertical conveyor of rolling elements is also activated.
9. After filling storage M1 (logic state 1), the next one in line is storage M51. In this state, distributors R4, R5, and R51 are all activated (set to logic state 1), while distributor R52 is deactivated (logic state 0).
10. After filling storage M51 (logic state 1), the vertical conveyor of rolling elements is turned off.
11. The empty storages are sequentially serviced in the order from M0 to M52.

6. Conclusions

The research on the designed ladder diagram control system for the transport of rolling elements allows us to conclude that:

1. The ladder diagram systems have been designed for controlling production lines in interoperative transport, particularly in the manufacturing of rolling bearing components, especially inner and outer rings of bearings.
2. The developed method for synthesizing asynchronous systems is fast and enables the creation of ladder diagram systems for any configuration of the transport path in interoperative transport.
3. The use of sensors in conjunction with delay circuits for input signal rising and falling edges allows for a clear determination of the presence or absence of elements within the sensor's detection zone, thereby increasing the overall system's reliability.

4. The time delays in the system's interaction with the sensor are determined based on the speed at which elements move within the sensor's detection zone.
5. Ladder diagram systems can be applied not only in the automation of rolling element production but also in other industrial sectors where the control of element transport is necessary.
6. The developed method of designing systems based on ladder diagrams is relatively easy to grasp for experienced PLC programmers, which accelerates the process of creating new control systems.

Future research will aim to develop methods and principles for creating control modules for transport paths that deliver elements to storage units in interoperative transport using electronic systems.

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