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# MECHATRONIC CONTROL SYSTEMS
# FOR HYDROMECHANICAL TRANSMISSIONS

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## INTRODUCTION

The mechatronic electronic-hydraulic control systems (MCS) of hydromechanical transmissions (HMT) belong to the number of new and at the same time the most complicated automotive systems. But it has become evident by this time, that one of the main requirements that they have to meet is reliability and, first of all, safety in exploitation. This can be explained by the fact that in spite of very high reliability of any concrete model, such failures inevitably sometimes occur in the scope of mass production systems. Failures that cause self-arbitrary gearshifts are very dangerous. Failures that cause the loss of manoeuvrability are inadmissible and require that beforehand measures should be taken for its prevention (i.e. parring). As the analysis of patents of leading world automotive companies shows, this is recognized by practically all known HMT designers. In many patents it is shown beforehand what can possibly happen in case of failure of concrete electromagnet or valve (see [1], [2] ets.). "Limp home" regime already becomes almost obligatory (see, for example, patent GM for HMT WT [3]).

The difficulties of MCS' hydraulic scheme choosing are caused by the requirement to have "separation" property. This property means, that it must prevent simultaneously engaging friction devices in unforeseen (and, naturally, in prohibited) combinations. It is at this stage that intuition necessary because theoretical methods of the synthesis of the system with such properties are absent.

But within recent years such MCS have appeared, in which such requirements are not met. These are mainly MCS for high-power HMT such as Allison WT series or Caterpillar for quarry trucks.

So, today we can talk of a kind of "philosophy" of MCS scheme choosing: to avoid dangerous failures on the level of the hydraulics or to rely on the electronics. The decision has to be made by the systems designer.

In this paper the approach to this philosophical problem is based on two principal ideas. First of all, from the point of view of theory, the methods of synthesis of control systems are necessary as well as the transmissions synthesis methods. Secondly, safety level and expenses for its providing (i.e. complexity of the design) depend on the degree of responsibility of the vehicle. And there are many cases when the complexity and the price are not as important as thesafety.

In our paper [4] it is shown that the behaviour of MCS at failure modes fully depends on the structure of its hydraulic scheme. A method of analysis of the behaviour with the help of the graph of refusals has been worked out. It is shown there, that depending on connection schemes of the elements the safety of MCS changes from satisfactory to inadmissible. The number of possible variants of the scheme is so large, that as a rule the optimal one can not be found intuitively.

So, hydraulic scheme also influences the electronic parts structure. It determines the number of outputs and the order of their work, the peculiarities of gearshift quality etc. Namely that links hydraulic and electronic parts into a uniform mechatronic system.

The method of synthesis of electrohydraulic scheme of the automatic transmission controls is developed in this paper. It is based on the theory of analysis and synthesis of dis-

crete logical devices, that is well known in technical cybernetics, in combination with the use of the methods of safety providing, offered in our paper [4].

## 1. SETTING OF THE TASK OF THE SYNTHESIS OF HYDRAULIC SCHEME

One of main tasks of MCS is to organize gearshift process. This means that control elements (CEs) of HMT — friction clutches and brakes must be engaged in combinations that correspond to the engagement of certain stages and may not be engaged in unforeseen or prohibited combinations. In a generalized form such system is shown on fig.1. There 1 and 0 are inputs for feed and drain, that connect the scheme with hydraulic pump and sump. Then, $x_1...x_k$ are control inputs that receive signals from electric or hydraulic manual control device or from electronic or hydraulic automatic control device. Outputs $y_1...y_m$ are connected with m hydraulic cylinders of HMT CEs (not shown).
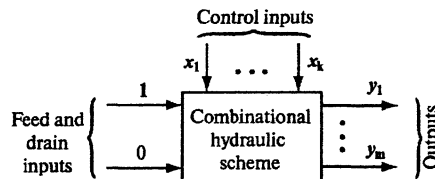


Fig. 1. Generalized form of MCS' hydraulic system
in the form of combinational scheme

If we denote the presence or absence of signals on the inputs $x_1...x_k$ and of pressures on the outputs $y_1...y_m$ by 1 and 0, then the scheme on fig. 1 may be considered as the discrete device with binary signals. Then that scheme corresponds to a well known cybernetic device — finite automaton. It changes discrete information and have finite volume of the memory. Scheme on fig. 1 represents a particular case of finite automaton — the scheme without the memory that is known under the name of combinational (switching) scheme. In most cases hydraulic schemes of MCS belong to this one, though systems with hydraulic memory also are known. See, for example, HMT Allison DP8000, 9000.

So, the task of the synthesis of electro-hydraulic scheme is equivalent to the synthesis of combinations circuit, that commutates m outputs with inputs 1 or 0 in dependence on the combinations of signals on inputs $x_1...x_k$. This is one of classical tasks of technical cybernetics.

The theory of combinational schemes is based on the apparatus of mathematical logic (boolean algebra) and the theory of sets. There is a large number of complicated methods of analysis and synthesis of combinational schemes and finite automatons.

Boolean (or logical, binary) variables (arguments) are the magnitudes, that may have only two meanings (for example, YES, NO or 1, 0).

Boolean function $f(x_1,...x_n)$ is the function that also may have only two meanings (1 and 0). The set of combinations of arguments that give meaning 1 of the function y, is named «the set of combinations».

One of the ways to set a boolean function is a so-called state (or truth) table. In the table all combinations of arguments and according to them the meanings of the function are indicated. For example, table 1 sets arbitrary function $y = f(x_1, x_2, x_3)$. The number of its possible meanings is equal to the number of combinations of binary arguments, i.e. $2^3 = 8$. Then its set contains 8 combinations, and table 1 has 8 lines. The function have meaning 1 at input combinations # 2, 4, 5, 7 and meaning 0 at rest combinations.

The simplest hydraulic logical element is a two-way two-position hydraulic distributing valve (fig. 2, a) or «flowing element». In dependence on mutual positions of inlet and outlet hydraulic lines and of the spool, with its help logical operations «repeating» (YES) and

«negation» (NO) can be made. Fig. 2, b,c,d shows its electrical analogue (normally open or closed contact) and images in logical and hydraulic schemes

Table 1

| № | $x_1$ | $x_2$ | $x_3$ | $f(x_1, x_2, x_3)$ |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 1 | 1 |
| 3 | 0 | 1 | 0 | 0 |
| 4 | 0 | 1 | 1 | 1 |
| 5 | 1 | 0 | 0 | 1 |
| 6 | 1 | 0 | 1 | 0 |
| 7 | 1 | 1 | 0 | 1 |
| 8 | 1 | 1 | 1 | 0 |

## 2. LOGICAL OPERATIONS IN COMBINATIONAL SCHEMES AND THEIR HYDRAULIC IMPLEMENTATION
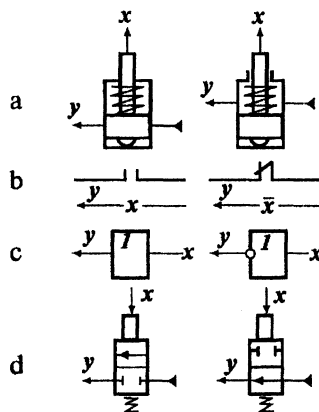


Fig. 2. Simple hydraulic logical element

If the conductivity of hydraulic circuit is denoted by y, then for fig. 2, a we have the logical function y = x (operation YES) and y = $\overline{X}$ (operation NO). So, by means of functions of type y = $(x_1 ... x_k)$ the structure and the state of hydraulic logical scheme can be worked out. Because of this they are named as conductivity functions or simply as structural formulas.

If the system of structural formulas is obtained by any way, then its transformation and the simplification (minimization) may be done with the help of the laws of boolean algebra. One flowing element shown on fig. 2 corresponds to every letter in formulas, and one their connection to every logical operation sign. For example fig. 3 shows structural (a) and hydraulic (b) schemes for logical function
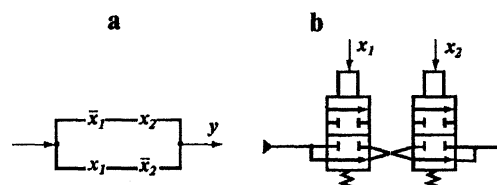
$$y = \left( x_1 \& \overline{x}_2 \right) V \left( \overline{x}_1 \& x_2 \right)$$



Fig. 3. Structural and hydraulic schemes for the function $y = \left( x_1 \& \overline{x}_2 \right) V \left( \overline{x}_1 \& x_2 \right)$

Symbols & and V correspond to functions AND and OR. The simple form of writing function AND – the symbol of algebraic multiplification. Then the simple expression is

$$y = \left( x_1 \bar{x}_2 \right) V \left( \bar{x}_1 x_2 \right).$$

So, by means of flowing elements logical operations AND, OR, NO may be implemented. It is known, that these functions form a functionally full set. With its help any other logical functions may be obtained (and, in principle, any combinational schemes).

Some more complicated elements are of an interest for HMT. These are two-position spool type valves shown on fig.4. The first of them (see arrangement (a) and scheme (b)) gives boolean functions for four variables, and the second (c, d) — two functions for five variables. It must be noted that the first of them gives functions AND, OR, NO, i.e. with its help all logical operations may be obtained.
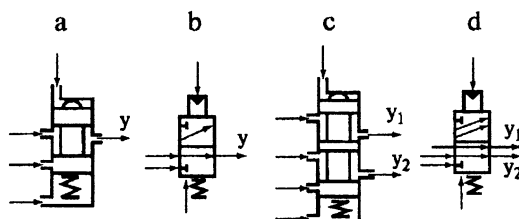


Fig. 4. Two-position spool type hydraulic valves

The difference of hydraulic schemes from electrical is that for switching them off hydraulic devices must be connected with drain. At the same time in electrical circuit its breaking is enough. Because of this hydraulic schemes always must be "two-wire" (see inputs 1 and 0 on fig.1).

Different methods of obtaining the schemes of hydraulic cylinders switching off are known. In our case only one of them is possible: the connection of every of HMT cylinder with drain by means of a special circuit that is always open when pressure circuit to this cylinder is closed. Then conductivity of such a circuit must be switched to the pressure one. Then, its structural formula is the inverted formula of the pressure circuit. For example, if we have the scheme shown on fig.3, then the formula of drain circuit for it may be obtained with the help of boolean algebra laws as

$$\bar{y} = \overline{\left( \bar{x}_1 x_2 \right) V \left( x_1 \bar{x}_2 \right)} = \left( x_1 V \bar{x}_2 \right) \left( \bar{x}_1 V x_2 \right).$$

## 3. ABSTRACT AND STRUCTURAL SYNTHESIS OF COMBINATIONAL HYDRAULIC SCHEME

Let us consider the synthesis of the scheme for HMT 4+1 with five CE a, b, c, d, e, that are engaged in next combinations: I — acd, II — abc, III — ace, IV — ade, R — bce, N — e. Let us denote the conductivities of pressure circuits with the same letters as the CE, the conductivities of drain circuits by the same letters with sign of operation NO and the control signals — by letters x with indexes according to numbers of stages. Let us suggest that only one control signal engages any gear. Then, according to the known method for synthesis of abstract combinational schemes, we can write the next system of structural formulas:

$$a = x_1 V x_2 V x_3 V x_4 \qquad \bar{a} = \bar{x}_1 \bar{x}_2 \bar{x}_3 \bar{x}_4$$

$$b = x_2 V x_R \qquad \bar{b} = \bar{x}_2 \bar{x}_R$$

$$c = x_2 V x_R \qquad \bar{c} = \bar{x}_2 \bar{x}_3 \bar{x}_R$$

$$d = x_1 V x_4 \qquad \bar{d} = \bar{x}_1 \bar{x}_4$$

$$e = x_3 V x_4 V x_R \qquad \bar{e} = \bar{x}_3 \bar{x}_4 \bar{x}_R.$$

With the help of that system of functions structural scheme of the hydraulic system may be built as depicted above. But it is obviously not optimal because it has a big number of the valves (it is equal to the number of variables $x_i$ : $Sx_1 = 5$). At the same time a minimal number of valves (and, according, the number of electrical magnets or electro-hydraulic pilot valves in modern MCS) is obtained by the relation

$$n+1 \leq 2^k$$

where n is the number of gears and "k" is the number of control inputs.

Now let us see the example of the synthesis of an abstract scheme for HMT with the next set of CE combinations: I — ab, II — ac, III — ad, IV — cd, N — a. For this HMT k=3 is enough ($2^3$ =8 > 5). This set is presented by means of the table 2 in the ordering sequence, that is used for combinational schemes. But such table has only working combinations of CE. Their whole number is equal $2^4 = 16$. All of them are presented in table 3, which has 16 lines. In the last column working and prohibited combinations (combinations, in which the number of engaged CEs is more than two) are marked. Question marks are placed for combinations with unknown properties such as bd and bc (lines 6 and 7) that are similar to working ones.

Table 2

| № | a | b | c | d | Gear | Note |
|---|---|---|---|---|------|------|
| 1 | 1 | 0 | 0 | 0 | N | 9 |
| 2 | 1 | 1 | 0 | 0 | I | 13 |
| 3 | 1 | 0 | 1 | 0 | II | 11 |
| 4 | 1 | 0 | 0 | 1 | III | 10 |
| 5 | 0 | 0 | 1 | 1 | IV | 4 |

In table 4 all possible combinations of three control signals (k=3) are given in ordered sequence.

Furthermore, it is necessary for the synthesis to choose what input combinations will correspond to the HMT stages, i.e. to join the tables 3 and 4. This is multivariant creative procedure that in result will give quest system of boolean functions. Working out such a system is schematically shown on fig. 5. There continuous lines depict pressure circuits with conductivity functions $y_1,...,y_m$ that connects m hydraulic cylinders with pressure input 1, and dotted lines — drain circuits with inverted conductivity functions

Table 5 is obtained by means of attaching table 2 to table 4 with combining the lines with the same numbers. The rest three free lines of the table 4 are filled in table 5 arbitrary (the numbers in brackets) so that in these lines CE (a) is engaged and the rest CEs are disengaged. So, this procedure is the synthesis of a truth table for the system. With its help the system of structural formulas may be obtained as explained above with help of fig.5. Then minimization of that system is executed with the help of apparatus of algebra of logic. For exam ple, for CE (b) we have from table 5: $y_2 = \bar{x}_1\bar{x}_2x_3$. If in state 6 (line 6) its state does not matter for the HMT, then 1 may be written in this line instead of 0, and then $y_2$ will be

$$y_2 = \bar{x}_1\bar{x}_2x_3 \vee x_1\bar{x}_2\bar{x}_3 = \bar{x}_2x_3\left(\bar{x}_1 \vee x_1\right) = \bar{x}_2x_3 \ ,$$

i.e. the function $y_2$ is simplified. But now in the state 6 CEs (a,b) are engaged. This corresponds to I gear instead of the neutral. This fact requires analysis. Therefore, these procedures show that the synthesis of truth table is a complicated task connected with the analy-

sis of a great number of factors. Namely in this stage the properties connected with the safety are created as it is described in our paper [4].

Table 3

| № | a | b | c | d | Note |
|---|---|---|---|---|------|
| 1 | 0 | 0 | 0 | 0 | ? |
| 2 | 0 | 0 | 0 | 1 | ? |
| 3 | 0 | 0 | 1 | 0 | ? |
| 4 | 0 | 0 | 1 | 1 | IV gear |
| 5 | 0 | 1 | 0 | 0 | ? |
| 6 | 0 | 1 | 0 | 1 | ? |
| 7 | 0 | 1 | 1 | 0 | ? |
| 8 | 0 | 1 | 1 | 1 | Prohibited |
| 9 | 1 | 0 | 0 | 0 | Neutral |
| 10 | 1 | 0 | 0 | 1 | III gear |
| 11 | 1 | 0 | 1 | 0 | II gear |
| 12 | 1 | 0 | 1 | 1 | Prohibited |
| 13 | 1 | 1 | 0 | 0 | I gear |
| 14 | 1 | 1 | 0 | 1 | Prohibited |
| 15 | 1 | 1 | 1 | 0 | >> |
| 16 | 1 | 1 | 1 | 1 | >> |

Table 4

| № | $x_1$ | $x_2$ | $x_3$ |
|---|-------|-------|-------|
| 1 | 0 | 0 | 0 |
| 2 | 0 | 0 | 1 |
| 3 | 0 | 1 | 0 |
| 4 | 0 | 1 | 1 |
| 5 | 1 | 0 | 0 |
| 6 | 1 | 0 | 1 |
| 7 | 1 | 1 | 0 |
| 8 | 1 | 1 | 1 |
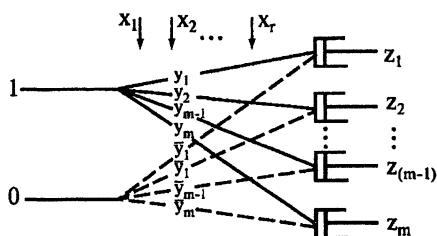


Fig. 5. The scheme of the system of boolean functions

Table 5

| № | $x_1$ | $x_2$ | $x_3$ | $y_1$ (a) | $y_2$ (b) | $y_3$ (c) | $y_4$ (d) | Gear |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | N |
| 2 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | I |
| 3 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | II |
| 4 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | III |
| 5 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | IV |
| 6 | 1 | 0 | 1 | (1) | (0) | (0) | (0) | N |
| 7 | 1 | 1 | 0 | (1) | (0) | (0) | (0) | N |
| 8 | 1 | 1 | 1 | (1) | (0) | (0) | (0) | N |

It is shown above how the structural scheme can be simplified with the use of existing methods of minimization of boolean functions. But there are considerable difficulties concerning this type of systems. The main of them is that with the help of manual methods only parallel-sequential schemes may be achieved, and more economical bridge-type schemes can not be built. Moreover, for mechanical engineers and motorists it is difficult to study them.

Taking into account everything mentioned above we worked out a formalized engineering method of synthesis that does not require special knowledge of the theory of logical devices. It is based on the use of graph-analytical canonic method of synthesis of switching circuits [6]. Boolean function of k arguments is set in the form of a standard table like the table 4. For example, it may be the function that is set by table 6. On the base of this table the canonical table is being built, and that scheme graphically coincides with known so called scheme of a tree. Its construction is shown on fig. 6, a. The numbers from the column of meanings of function y from table 6 are vertically written there. Graph in the form of tree is attached to these numbers from the left. This graph has all apexes numbered by a certain way. At the top of the groups of apexes the indexes of arguments are shown. That is called the canonical table.

Every apex of that table with two downhill segments forms a "bunch". The picture of the bunch is shown on fig. 7,a, where a, b, c — the numbers of apexes, x — argument.

Such a bunch performs boolean function (fig. 7,b)

$$c = a\overline{x} \lor bx .$$

Its implementation is structural scheme with one switching contact (fig. 7, c) or generalized logical node (fig. 7, d), or scheme with elementary logical operators (fig. 7, e). The implementation of the bunch in the form of hydraulic scheme with the help of three-way distributing valve and of separate flowing element is shown on fig. 7, f, j.

Table 6

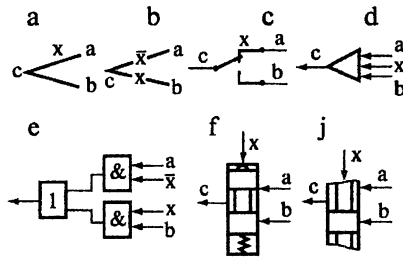| № | $x_1$ | $x_2$ | $x_3$ | y |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 1 | 1 |
| 3 | 0 | 1 | 0 | 1 |
| 4 | 0 | 1 | 1 | 1 |
| 5 | 1 | 0 | 0 | 0 |
| 6 | 1 | 0 | 1 | 1 |
| 7 | 1 | 1 | 0 | 1 |
| 8 | 1 | 1 | 1 | 0 |

Fig. 7. The "bunch" of canonical table and its implementation

Replacing apexes in canonical table fig.6, a by images of valve shown on fig. 7, f, or of flowing element of fig. 7, j gives a principal hydraulic scheme in the «logical» form (with separate valves shown on fig. 7, f) or in «contact» form (with groups of flowing elements united in spools of multiway valves). The segments connecting apexes are replaced by hydraulic lines. These operations are shown on fig. 6, c, d, where the structural and the hydraulic schemes corresponding to table 6 are shown.

This method also allows to avoid the procedures of finding inverse functions for the drain circuit and its constructing. For this, while skipping theoretical evidence, we do the next. Segments with zero numbers are not skipped but are connected with zero input of the scheme that corresponds to a drain. As a result, final structural and hydraulic schemes shown on figs 8, a, b are found for hydraulic control system for one separate hydraulic cylinder that is set by the table 6.
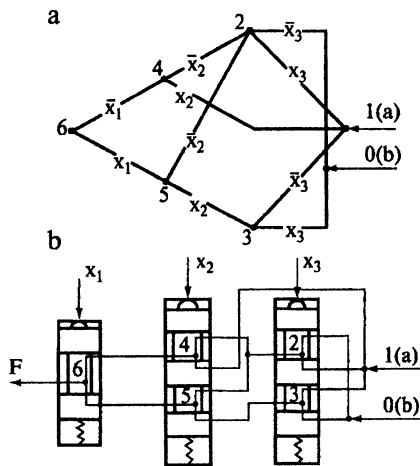


Fig. 8. Hydraulic scheme with inverse pressure and drain circuits

The synthesis method shown above may be easily used to construct a scheme with some outputs as on the fig. 5, that take place in HMT. In this case, all m columns of meanings of outputs must be written out into one vertical row. Separate graph (tree) is attached to every column, analogous to fig.6,a. Then through–numeration of all apexes along vertical rows beginning from right and further to the left must be done. If truth table was fully filled, then next bunches numeration in first (right) row is possible:
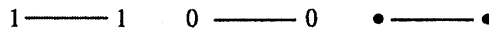


If not all positions in column are filled, then the following cases are possible:
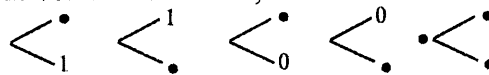


The points denote free positions of truth table. Then to simplify the scheme we can write the same number as at the other segment instead of the point. The view of the bunch will be:
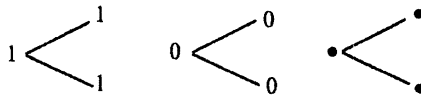
Such bunches may be changed by the segments

1———1    0 ——— 0    •——•

Such simplification leads to skipping corresponding argument in the boolean function and therefore it demands attentive analysis.

The numbers used for simplification must be included into the table. This ends its filling.

It must be noted that we do not show the example of procedure of synthesis of full scheme for HMT with m hydraulic cylinders because it needs much more space than a paper sheet.

We see that the method is represented in the formalized (tabular) form and does not require knowledge of discrete devices theory. It provides an opportunity of complex analysis of all possible combinations of on and off states of electromagnets, pilot (computer controlled) hydraulic valves, relay (executive) spool valves, clutches' hydraulic cylinders. As a result of elimination of combinations mentioned truth table of HMT control system is obtained. By means of truth table the required scheme may be built.

CONCLUSION

Hereby the proposed method of synthesis of control systems is adequate to the methods of HMT synthesis. It gives to the designers an effective tool that permits to analyse different variants of schemes and to obtain an "ideal" scheme from the point of view of safety and liveness. At the same time it gives the possibility to predict consequences of any possible simplifications, if they are necessary. Analysis of transmissions and their mechatronic control systems and patents of world companies shows that the problems concerning the analysis of failures, their prevention by means of design methods and providing the possibility of vehicle motion after failure ("limp home" regime) becomes ever more important. The proposed method provides an effective solving of these problems.

**Literature.** 1. Hydraulic control apparatus for automatic transmission. US Patent N 5 919 108. (Aisin Seiki K.K.). 2. Control apparatus for hydraulically operated vehicular transmission. US Patent N 6 024 663 (Honda Giken Kogyo K.K.). 3. Logic valving for a transmission control. US Patent № 4 827 806, May 9, 1989. (General Motors Corp). 4. L.Krasnevski, M.Vysotski, V.Boikov. The safety of mechatronic control systems for hydromechanical transmissions. SAE Tech. Pap. Ser. 1999-01-1049. 5. L.Krasnevski. Control of vehicles' multispeed hydromechanical transmissions. – Minsk, Nauka i Technica, 1990. – 256 p. (Russian). 6. Bloh A. Sh. The synthesis of switching schemes. – Minsk, Nauka i Technica, 1966. — 200 p. (Russian).

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## ИНТЕГРАЦИЯ НАУЧНО-ИССЛЕДОВАТЕЛЬСКОЙ РАБОТЫ И УЧЕБНОГО ПРОЦЕССА В ВУЗЕ

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