A power shift electro-hydraulic-controlled system of a seven-speed automatic transmission designed by the logic method

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Abstract. Aiming at a self-designed seven-speed planetary gear automatic transmission, the electro-hydraulic-controlled system of power shift is designed by logic method. First of all, according to the transmission diagrams and the working condition of each gear shift element, design the connection condition of the shift valves of each forward gears and the reverse gear in turn, and write out the corresponding logical equations. Then, on this basis, carry out the interlock and failure analysis, and complete the diagram of the power shift electro-hydraulic-controlled system. Finally, according to the designed electro-hydraulic-controlled system and shift valve control status table, logical equations are verified. The results show that the function of the system is realized by using the logic combination of six two-position three-way electro-hydraulic-controlled shift valves and one manual control valve, and the design of the power shift electro-hydraulic-controlled system can be carried out clearly, efficiently and accurately.

1. Introduction
The planetary gear automatic transmission has its advantages of compact structure and smooth shifting, therefore, it has become the focus of research and development of major automobile enterprises [1]. The design of power shift electro-hydraulic-controlled system is one of the core work of automatic transmission design [2-3]. The conventional methods like trial and reference to similar design have certain blindness [4-5]. What’s worse, the design result isn’t often the optimal value, which is difficult to meet the design requirements of complex hydraulic system. When the power shift automatic transmission realizes the normal operation of different gears, it controls the movement of the hydraulic valve spool in the shift valve through the on or off power of the shift valves. While the moving of the hydraulic valve spool makes the shift valve in different working positions, the corresponding oil circuit is connected or closed, and the combination and separation of the corresponding shift elements are realized. Different gear lever positions and different gears require a combination of several shift elements and the separation of other shift elements. It can be seen that the design of the electro-hydraulic-controlled system of the automatic transmission is essentially a logical problem. Aiming at a self-designed seven-speed automatic transmission, under the principle of shift design, this paper uses the logic method to design the shift structure of power shift electro-hydraulic-controlled system, then analyzes its interlock and actual effect, and finally uses logical equations to verify the correctness of each shift.

2. Design principle of logic method
The combination or separation of shift elements has two values, and different gears can be achieved through the combination of several shift valves. The two-position three-way electro-hydraulic-controlled shift valve is shown in Figure 1. "Z" on the left is the control end of shift valve, the spring
end is on the right, and the corresponding oil circuits are Y, X₁ and X₂. When the shift valve is energized, the shift valve is on the left position; when the shift valve is switched off, the shift valve is on the right position under the action of the spring. The corresponding logical equation can be expressed as:

\[ Y = ZX_2 + ZX_1 \]  

During the design process of the power shift electro-hydraulic-controlled system, some basic design criteria shall be followed:

Principle 1: achieve basic gears. The designed electro-hydraulic-controlled system can separate or combine the corresponding actuator according to the position of each gear lever and each gear in the working diagram of the shift elements.

Principle 2: no movement interference or shifting action. The designed electro-hydraulic-controlled system cannot interfere with the components in the planetary row. Take one component like the sun gear, the planet frame or the gear ring in the planetary row as an example. If the clutch and brake are arranged on the component, these two shifting components cannot be combined at the same time. In order to ensure the smoothness of gear shifting and to reduce the impact of gear shifting, the phenomenon of gear skipping should not occur in the design process, such as directly gear changing from the 1st gear to the 3rd gear or to the 4th gear.

Principle 3: invalidation protection function. In the designed electro-hydraulic-controlled system, if some or all of the shift valves cannot work, the electro-hydraulic-controlled system should be able to maintain a certain gear to ensure that the automobile can travel a certain distance to the automobile-repair enterprise.

3. Transmission structure and working principle of the seven-speed automatic transmission

Figure 2 is the structural diagram of a seven-speed planetary gear automatic transmission designed in reference [6], which includes three planetary gear rows and six shift actuators. The corresponding connection relationship is shown in the Figure 2. Table 1 is the working state of corresponding shift elements in different gear lever positions and different gears. It can be seen that each gear consists of 2 combined shift elements and 4 separated shift elements. Gear R can be controlled by the manual valve alone. Among the seven gears of gear D, the adjacent gears are all reserved for the combination of one shift element, and one shift element is added for the combination and one for separation at the same time.
Table 1. Working state of each shift element.

| Gear lever positions | Gear | Shift elements |
|----------------------|------|----------------|
|                      |      | C₁  | C₂  | C₃  | C₄  | B₁  | B₂  |
| 1                    | ●    |     |     |     |     |     |     |
| 2                    | ●    |     |     |     |     |     |     |
| 3                    | ●    |     |     |     |     |     |     |
| D                    | ●    | ●    |     |     |     |     |     |
| 4                    | ●    |     | ●    |     |     |     |     |
| 5                    | ●    |     |     | ●    |     |     |     |
| 6                    | ●    |     |     |     | ●    |     |     |
| 7                    | ●    |     |     |     |     | ●    |     |
| R                    | R    |     |     |     |     |     |     |

4. Design of the hydraulic system

4.1. Design analysis of different gears

It can be seen from the working state of shift elements of each gear in Table 1 that gear R can directly oil C₄ and B₂ through the manual valve instead of the shift valve, so that the two shift elements can be combined to realize gear R. In the position of gear lever D, each gear is a combination of two shift elements. C₁ is combined from the 1ˢᵗ to the 5ᵗʰ gear, and the corresponding gear is realized by changing the combination of another shift element; C₂ is combined from the 5ᵗʰ to the 7ᵗʰ gear, and the corresponding gear is realized by changing the combination of another shift element, too. The 5ᵗʰ to the 6ᵗʰ gear is a shift point, which keeps C₂ unchanged and both C₁ and C₄ changed. Set the oil return port as "E" and the system oil pressure connection port as "P", and design from D₁.

Gear D₁ (C₁, B₂) and gear D₂ (C₁, B₁): according to the above analysis, C₁ is combined in the first five gears, and there is a transformation between C₁ and C₄ from the 5ᵗʰ gear to the 6ᵗʰ gear. Therefore, a two-position three-way electro-hydraulic-controlled shift valve H₁ is designed to realize the separation and combination between C₁ and C₄, as shown in Figure 3; the transformation between B₂ and B₁ can be realized by a two-position three-way electro-hydraulic-controlled shift valve H₂, as shown in Figure 4.

The hydraulic logical equations are as shown in equations (2) and (3). When the shift valve H₁ is switched off, the valve is on the right position, and P is connected with C₁, so that the shift element C₁ is combined. When the shift valve H₁ is energized, the valve is on the left position, and the system oil pressure P is connected with P₁ which is considered as the input oil pressure of C₄. When the shift valve H₂ is switched off, the valve is on the right position, and P is connected with B₂, so that the shift element B₂ is combined to achieve gear D₁. When the shift valve H₂ is energized, the valve is on the left position, and the system oil pressure P is connected with P₂ which is considered as the input oil pressure of B₁.

\[
P = Z₁P₁ + Z₂C₁ \quad (2)
\]

\[
P = Z₂P₂ + Z₁B₂ \quad (3)
\]

Gear D₃ (C₁, C₃): on the basis of the 2ⁿᵈ gear, C₁ remains combination unchanged in the 3ʳᵈ gear. B₁ is separated and C₃ is combined, so a two-position three-way electro-hydraulic-controlled shift valve H₃ is designed to realize the separation and combination between B₁ and C₃, as shown in Figure 5. The hydraulic logical equation is shown in equation (4). When the shift valve H₃ is switched off, the valve
is on the right position, and P2 is connected with B1, so that the shift element B1 is combined to realize gear D2. When the shift valve H3 is energized, the valve is on the left position, and P2 is connected with P3, which is considered as the input oil pressure of C3.

\[ P_2 = Z_1 P_3 + \overline{Z}_1 B_1 \]  

(4)

Figure 5. shift valve H3.  
Figure 6. shift valve H4.

Gear D4 (C1, C4): on the basis of the 3rd gear, C1 remains combination unchanged in the 4th gear. C3 is separated and C4 is combined, so a two-position three-way electro-hydraulic-controlled shift valve H4 is designed to realize the separation and combination between C3 and C4, as shown in Figure 6. The hydraulic logical equation is shown in equation (5). When the shift valve H4 is switched off, the valve is on the right position, and P3 is connected with C3, so that the shift element C3 is combined to realize gear D3. When the shift valve H4 is energized, the valve is on the left position, and P3 is connected with P4, which is considered as the input oil pressure of C4.

\[ P_3 = Z_1 P_4 + \overline{Z}_1 C_3 \]  

(5)

Gear D5 (C1, C2): on the basis of the 4th gear, C1 remains combination unchanged in the 5th gear. C4 is separated and C2 is combined, so a two-position three-way electro-hydraulic-controlled shift valve H5 is designed to realize the separation and combination between C4 and C2, as shown in Figure 7. The hydraulic logical equation is shown in equation (6). When the shift valve H5 is switched off, the valve is on the right position, and P4 is connected with C4, so that the shift element C4 is combined to realize gear D4. When the shift valve H5 is energized, the valve is on the left position, and P4 is connected with P2, so that the shift element C2 is combined to realize gear D5.

\[ P_4 = Z_4 C_2 + \overline{Z}_4 C_4 \]  

(6)

Figure 7. shift valve H5.  
Figure 8. shift valve H6.

Gear D6 (C2, C4) and gear D7 (C2, B1): on the basis of the 5th gear, C2 remains combination unchanged in the 6th gear. C1 is separated and C4 is combined, so a two-position three-way electro-hydraulic-controlled shift valve H6 is designed to realize the separation and combination between C1 and C4, as shown in Figure 8. The hydraulic logical equation is shown in equation (7). When the shift valve H6 is switched off, the valve is on the right position, and P1 is connected with C4, so that the shift element C4 is combined to realize gear D6. When the shift valve H6 is energized, the valve is on the left position, and P1 is connected with B1, so that the shift element B1 is combined to realize gear D7.

\[ P_1 = Z_6 B_1 + \overline{Z}_6 C_4 \]  

(7)

4.2. Interlock and failure analysis

Interlock analysis: it can be seen from Figure 2 that C2 and C3 cannot be combined at the same time, because they cannot be connected to the same planetary row component P2-R3 at different speeds. C2 (or C3) and B2 cannot be combined at the same time, because component P2-R3 cannot input and brake at the same time. C4 and B1 cannot be combined at the same time, because components R2 cannot input
and brake at the same time. From the control logic of shift valves H1 to H6 from Figure 3 to Figure 8, the input oil circuit of one latter shift valve is on the basis of the power of the former one, so the six shift valves are interlocked. The combination and separation of the shift elements mentioned above will not interfere with each other and can meet the requirements of interlock.

Failure analysis: gear R does not pass through the shift valve, so there is no possibility of shift valve failure. For the lever position D, if all shift valves fail to work, C1 and B2 will be combined, and the transmission will operate in gear D1. The premise of normal operation of H6 is that H1 is powered on. If any one or several shift valves from H1 to H5 fail to work, the subsequent shift valves will fail successively. For example, H1, H2 and H3 work normally while H4 does not, then there is no hydraulic oil passing through H5, and the transmission will operate in gear D3.

Through the above analysis, the designed power shift electro-hydraulic-controlled system is shown in Figure 9.

4.3. Verification analysis
According to the analysis in Section 4.1, the corresponding shift valve controlling status is shown in Table 2.

| Gear lever positions | Gear | H1 | H2 | H3 | H4 | H5 | H6 |
|----------------------|------|----|----|----|----|----|----|
| 1                    | off  | off|    |    |    |    |    |
| 2                    | off  | on |    |    |    |    |    |
| 3                    | off  | on | on |    |    |    |    |
| D                    | 4    | off| on | on | off|    |    |
| 5                    | off  | on | on | on | on |    |    |
| 6                    | on   | on | on | on | on | off|    |
| 7                    | on   | on | on | on | on | on | on |
| R                    | R    |    |    |    |    |    |    |

Figure 9. Diagram of the power shift electro-hydraulic-controlled system.
According to Table 2 and equation (2) to (7), it is analyzed as follows. Position R is directly combined with the shift element controlled by the manual valve. Position D is powered on and powered off by the corresponding shift valve H1 to H6 in Table 1 to achieve the corresponding gears, specifically as follows:

In gear D1, H1 and H2 are powered off. From logical equations (2) and (3), \( P = \overline{Z}_1C_1 \) and \( P = \overline{Z}_2B_2 \) can be calculated, and C1 and C3 are combined.

In gear D2, H1 and H3 are powered off, and H2 is powered on. From logical equations (2) to (4), \( P = \overline{Z}_1C_1 \), \( P = Z_2P_2 \) and \( P = \overline{Z}_3B_1 \) can be calculated, and C1 and B1 are combined.

In gear D3, H1 and H4 are powered off, and H2 and H3 are powered on. From logical equations (2) to (5), \( P = \overline{Z}_1C_1 \), \( P = Z_2P_2 \), \( P_2 = Z_3P_3 \) and \( P_3 = \overline{Z}_4C_1 \) can be calculated, and C1 and C3 are combined.

In gear D4, H2, H3 and H4 are powered on, and H1 and H5 are powered off. From logical equations (2) to (6), \( P = \overline{Z}_1C_1 \), \( P = Z_2P_2 \), \( P_2 = Z_3P_3 \), \( P_3 = Z_4P_4 \) and \( P_4 = \overline{Z}_5C_4 \) can be calculated, and C1 and C4 are combined.

In gear D5, H1 is powered off, and H2, H3 H4 and H5 are powered on. From logical equations (2) to (6), \( P = \overline{Z}_1C_1 \), \( P = Z_2P_2 \), \( P_2 = Z_3P_3 \), \( P_3 = Z_4P_4 \) and \( P_4 = Z_5C_4 \) can be calculated, and C1 and C2 are combined.

In gear D6, H1, H2, H3, H4 and H5 are powered on, and H6 is powered off. From logical equations (2) to (7), \( P = Z_1P_1 \), \( P = Z_2P_2 \), \( P_2 = Z_3P_3 \), \( P_3 = Z_4P_4 \), \( P_4 = Z_5C_2 \) and \( P_1 = \overline{Z}_6C_4 \) can be calculated, and C2 and C4 are combined.

In gear D7, H1, H2, H3, H4, H5 and H6 are all powered on. From logical equations (2) to (7), \( P = Z_1P_1 \), \( P = Z_2P_2 \), \( P_2 = Z_3P_3 \), \( P_3 = Z_4P_4 \), \( P_4 = Z_5C_2 \) and \( P_1 = Z_6B_1 \) can be calculated, and C2 and B1 are combined.

The result of logical equations is completely consistent with the working state of each shift element in Table 1, which verifies the correctness of the design of electro-hydraulic-controlled system by logic method.

5. Conclusion
In view of the self-designed seven-speed planetary gear automatic transmission, the power shift electro-hydraulic-controlled system is designed by logic method. Based on the analysis of transmission structure and shift elements, the shift valves and logical equations are designed for different gears in turn, and the interlock and failure analysis are carried out. The final control system is a logical combination containing six two-position three-way electro-hydraulic-controlled shift valves and one manual control valve. At the same time, the logical equations are used to verify the system function, so as to achieve the purpose of self-test design. The whole design process goes through design, analysis, verification and other links, which belongs to a "closed-loop" design process. In the case that the transmission structure diagrams and the working status of each shift element are known, the design of the power shift electro-hydraulic-controlled system can be carried out clearly, efficiently and accurately.

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