Investigation of power split schemes for modern hybrid cars transmissions

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Abstract. The modes of operation of the transmissions for hybrid cars are studied in this work, using planetary gears for connecting the internal combustion engine (ICE) and the electric machines (motor-generators). The peculiarities of the two-stream variants with an electric branch – a closing block consisting of two electric machines is analysed. This achieves a stepless gear change and an increase in overall efficiency with respect to the efficiency of electrical machines. The theoretical formulation is based on the dependences between the losses of a two-stream circuit, which proves that this increase is a function of the relative share of power transmitted through the electrical branch. The characteristics of typical two-stream circuits with input differential and output differential with one mechanical and one electrical branch are determined. The aim is to evaluate not only the change in the total efficiency, but also the kinematic gear ratio and the ratio of the torques and their ranges for the whole circuit, as a function of the parameters of the electrical branch. The development of the schemes in order to improve their performance in different operating conditions is considered, which allows for combining the variants and modes of operation – serial hybrid and parallel hybrid in two variants, at low speed and high speed. Analytical and graphical methods are used to analyse and illustrate the results, which are more visual and suitable for composite planetary gears with more units. It is expected that cars with such transmissions will have better dynamics compared to conventional automatic transmissions and lower energy consumption or do less damage to the atmosphere, as a result of the optimal combination of the operating modes and dimensions of ICE and electric machines.

1. Introduction

Electric machines – motors and generators in combination with planetary gears are known in transport engineering as electromechanical transmissions and in the past were used mainly in tractors and locomotives [1]. When all the power for driving the transport or traction machine is transmitted from the internal combustion engine (ICE) through the electric machines, a stepless change of the gear ratio is achieved in a sufficiently wide range, but undesirable losses occur due to the double conversion of the energy – from mechanical to electrical and vice versa. With planetary gears the total power flow is separated into two or smaller parallel flow – mechanical and electrical. According to the power ratio, an increase in efficiency and preservation of the stepless change in the gear ratio of the transmission as a whole is achieved. In addition, it is possible to use smaller electrical machines, due to the lower power transmitted through the electrical branch. Generally it is considered that this solution has the disadvantage of greater complexity and smaller gear range. However, since electric machines are
reversible (rotating in different directions) and multi-mode (the same machine works both as a motor and as a generator) it is possible to achieve a larger range.

Recently, such schemes have also gained popularity in hybrid drives for passenger cars [2]. In connection with the trends for the transition of the car fleet to electric propulsion, modern high-speed electric motor-generator units (MGU) with very small relative mass and dimensions and advanced control and regulation systems are being developed. As a result, higher values of the efficiency and a more appropriate mechanical characteristics required for a transport machine engine are achieved, close to the ideal hyperbola. However, the use of further extending the range of gear ratio changes by the mechanical part is not superfluous and has a beneficial effect on the entire drive system [3].

The aim of the present study is to show the kinematic and force dependences of two-stream electromechanical transmissions and to evaluate the impact of the parameters of the mechanical and electrical branch on the performance of the whole system, to illustrate the connections between the individual units of the system and to investigate the possibilities of given scheme for realization of optimal operating modes. This will make it possible to increase the efficiency of energy conversions and use the results to create an adequate strategy for the management of internal combustion engine and electrical machinery.

2. Determining the features of electromechanical power split transmissions

In hybrid cars, there is a wide variety of ways to connect the internal combustion engine, the electric machines and drive wheels [4]. They are classified and analyzed in the specialized literature according to the number of electrical machines, the number of planetary rows, the number of used clutches and brakes, with which achieve to different modes of operation and more [5]. Power split systems can be basically of three types – single split, double split and a combination of the first two options.

2.1. Analytical method for determining the parameters of power split transmissions with electric branch

The idea of the two-stream transmissions is to increase their total efficiency ($\eta$) compared to the efficiency of the continuously variable part. In this case, that is possible if the efficiency of the mechanical branch ($\eta_M$) is higher than the efficiency of the electric branch ($\eta_E$) and the relative share of the power diverted through the electric branch ($\varepsilon$) is a positive number smaller than one (efficiency theorem: if $0 < \varepsilon < 1$ and $\eta_M > \eta_E$, to $\eta > \eta_E$). This is proven by the dependences shown below.

Figure 1. Flow scheme for single power split transmission.

Figure 1 shows the power transmitted through the mechanical branch ($P_M$) and through the electrical branch and the corresponding losses, taken into account by the efficiency coefficients of the mechanical and the electrical part. The mechanical power at the input of the electrical branch is marked with $P_{E1}$, and at the output of the electrical branch – with $P_{E2}$. The electric power that is exchanged between the two electric machines is denoted by $P_E$. The relationship between them is expressed by the efficiency of the electric machine $E_1$ ($\eta_{E1}$), the electric machine $E_2$ ($\eta_{E2}$) and the whole electrical branch ($\eta_E = \eta_{E1} \eta_{E2}$). The relative share of mechanical power diverted to electrical machines is denoted by $\varepsilon = P_{E1}/P'$ and the relative share of electric power – by $\varepsilon_E = P_E/P'$. 
Equation (1) is derived by expressing the output power \( P'' \) through the input power \( P' \) as the sum of the input powers of the two branches. To prove the theorem, the simplified variant of the equation \( (1') \) is used [6].

\[
\eta = \varepsilon \eta_E + \left(1 - \varepsilon / \eta_E \right) \eta_M. \tag{1}
\]

\[
\eta = \eta_M - (\eta_M - \eta_E) \varepsilon. \tag{1'}
\]

It shows that the smaller the relative share \( \varepsilon \), the greater the increase in total efficiency. For example, if we accept the efficiency of the mechanical branch to be of the order of 0.98 and of the electrical branch to be of the order of 0.72 (for one machine 0.85 together with the control), then the total efficiency will be above 0.9 if the relative share \( \varepsilon \) is below 30%. It should also be borne in mind that the efficiency of electrical machines depends on their operating mode.

The basic equation of the kinematics of the planetary mechanisms and the relations between the torques are used to determine the transforming properties of the two-flow scheme. Figure 2 shows the principal kinematic schemes of the two types of power split gearboxes with simple division.

\[
i = \omega'' / \omega', \quad K = T'' / T';
\]

\[
i_E = \omega_2 / \omega_1, \quad K_E = T_2 / T_1.
\]

The parameters of the planetary mechanisms are also required, for which the designations are accepted: "R" – for the ring gear-wheel, "S" – for the sun gear-wheel and "C" – for the planetary gears carrier and for the torques respectively – \( T_R, T_S \) and \( T_C \). The ratio of the number of teeth of the ring wheel \( (Z_R) \) to the number of teeth of the sun wheel \( (Z_S) \), which is a positive number greater than one, is a characteristic design parameter for each planetary set and is denoted by \( \alpha = Z_R / Z_S \). Friction losses in gear pairs are reported approximately with an efficiency of gear pair with external gearing \( (\eta_{EX}) \) and an efficiency of gear pair with internal gearing \( (\eta_{IN}) \), which can be represented by a total mechanical efficiency \( (\eta_0 = \eta_{EX} \eta_{IN}) \), internal to the planetary set. It is usually accepted for external gearing \( \eta_{EX} = \)
0.97 and for internal – \( \eta_N = 0.985 \). However, the manufacture quality of the gear wheels and the size of torque transmitted must be taken into account, which significantly affects these values.

For the scheme in figure 2 (a) the following dependencies are valid:

- By using the basic equation of kinematics for a simple planetary set
  \[
  \omega_S + \alpha \omega_R = (1 + \alpha) \omega_C \quad \rightarrow \quad \omega_1 + \alpha \omega' = (1 + \alpha) \omega'' ,
  \]
  and by dividing each member in it by \( \omega'' \) or \( \omega_2 \) (since \( \omega'' = \omega_2 \)) using equation (2) and equation (3) the required relationship between the kinematic ratios and parameter alpha is obtained:
  \[
  i = \frac{\alpha}{1 + \alpha - 1/i_E};
  \]

- By using the equilibrium condition of the torques of the three external units of the planetary set
  \[
  T_C = T_R + T_S = T' + T_1 .
  \]
  the internal relationship between the torques of the sun wheel and ring wheel
  \[
  T_S = \frac{1}{\alpha} \eta_0 T_R .
  \]
  and equations (3), the torques of the electrical machines and the carrier by the torque of the input can be expressed as follows:
  \[
  T_1 = T' \eta_0 / \alpha ; \quad T_2 = T' \eta_0 K_E / \alpha ; \quad T_C = T'(1 + \eta_0 / \alpha) .
  \]

On the other hand, for the output torque is valid
  \[
  T'' = T_C + T_2 .
  \]
  The dependence for the torque ratio (2) is obtained by substituting (8) in the expression (9) for \( T'' \):
  \[
  K = 1 + \eta_0 (1 + K_E) / \alpha .
  \]

For the internal connection between the torques of the sun wheel and of the ring wheel of the planetary mechanism another case is also possible
  \[
  T_R = \alpha \eta_0 T_S \quad \rightarrow \quad T' = \alpha \eta_0 T_1 ,
  \]
  when in the relative movement (at conditionally stationary carrier) the driving unit is the sun wheel, and the driven one is the ring wheel – in case of reversing or forwarding with high speed. This is determined by the directions of forces and velocities in the units by constructing plans of forces and velocities [7]. In this case, instead of equation (10), equation (10') is obtained through similar calculations:
  \[
  K = 1 + (1 + K_E) / \alpha \eta_0 .
  \]

For the scheme in figure 2 (b) similar dependences are used, taking into account the differences of the connections between the electric machines and the external units of the planetary mechanism and the characteristic feature \( \omega' = \omega_2 \):

- By dividing each member in equation (4) by \( \omega' \) or \( \omega_2 \) in this case for the kinematic gear ratio (2) is valid:
  \[
  i = (i_E + \alpha) / (1 + \alpha);\]

- And to determine the dependence of the torque ratios (2), the torques of the input and output by the torque of the electric machine \( E_2 \) are expressed by using equations (3), (6) and (7):
  \[
  T_C = T_S + T_R \quad \rightarrow \quad T'' = T_2 + T_2 \alpha / \eta_0 = T_2(1 + \alpha / \eta_0);\]
For modes, where the sun wheel is driving and the ring wheel is driven – by equation (3), (6) and (7'):

\[ K = \frac{1 + \alpha/\eta_0}{1/K_E + \alpha/\eta_0} \]  

Equations (5), (10), (10') and (11), (14), (14') can be used to estimate the change in the converting properties and efficiency (\( \eta = K \dot{\alpha} \)) of the power split transmission as a whole as a function of the change in the electrical part (EVT) parameters and the planetary mechanism parameter for different operating modes.

2.2. **Graphical method for visual representation of the connections between the elements of the power split transmission with double power separation**

In order to improve the use of electric machines at high speeds of the car, the division of the input power flow into two mechanical and one electric branch is applied [8]. Two planetary sets are used, connected according to the kinematic schemes in figure 3 and figure 4, which show one possible way for the flow of the streams.

![Figure 3](image1.png)

**Figure 3.** Scheme of a hybrid transmission with double power split and speed plan at two operating modes.

![Figure 4](image2.png)

**Figure 4.** Schematic diagram of the flows in double separation.
Figure 3 shows also a graphical representation of the input (ICE) and output speeds of the entire drive system and of the individual units of the mechanism (electrical machines) as straight lines. On each unit (gear wheel or carrier) corresponds a straight line with a certain slope. Since the linear velocities of the units \((v)\) are plotted on a certain scale along the x-axis of the velocity plan, and the radii \((r)\) are plotted on the y-axis, the slope of the straight lines \((\theta)\) relative to the x-axis shows visually the angular velocity of their respective units: \(\omega = v/r = \cot \theta\). This presentation is more convenient when the mechanisms have more units and makes it possible to estimate the change in the gear ratio \(i_g = \omega'/\omega''\) by comparing the angular velocities (slope of the lines) of the input and output unit. Different operating modes achieved as a result of changes in the speed of rotation of the internal combustion engine or the electric machines can also be compared. Two modes with the same ICE speed are given for illustration – in the first case it refers to the state of the system when all units rotate at angular speeds other than zero (most common case), and in the second – when the brake is applied and the speed of the electric machine \(E_1\) is zero \((\theta=90^\circ)\). When starting, the speed of the exit is initially zero and this forces the two electric machines to rotate in different directions \((\theta_1<90^\circ\) and \(\theta_2<90^\circ)\) because they are connected respectively to the ring wheel and the sun wheel on planetary set \(P_2\), and its carrier is stationary. Then the power through the electrical branch is the greatest. When accelerating, the output speed gradually increases and this leads to a decrease in absolute value of the angular velocities of electric machines at the same mode of ICE. This also implies a gradual reduction of the power, transmitted through the electrical branch, at acceleration of the car and an increase in the efficiency of the transmission as a whole – equation (1).

When the electric machine \(E_1\) reduces its speed to zero, the brake \(Br\) is applied automatically, which allows the movement to continue either only with the ICE (Conventional with gear ratio \(i_g = 1 + 1/\alpha_1\)), when the electric machine \(E_2\) is switched off, or only with electric machine \(E_2\) (Electric 1 with gear ratio \(i_g = 1 + \alpha_2\)) – with disconnected clutch \(Cl\) and ICE. When the brake and clutch are on, it is also possible to charge the battery from an electric machine \(E_2\), when it works as a generator and is driven by the ICE, or by the kinetic energy of the car when braking (Regeneration with the clutch disengaged).

Starting can be done either in two-stream mode (clutch on) with the largest share of electrical power, or only with an electric machine \(E_2\) (brake included), if there is sufficient battery power – for example in urban traffic conditions. Several more modes are possible:

- Parallel hybrid 1, the electric machine \(E_2\) works as a motor together with the ICE;
- Parallel hybrid 2, both electric machines operate in motor mode with mechanical differential connection together with the ICE, with brake off;
- Electric 2, with two electric machines, connected differentially by planetary set \(P_2\) at brake off.

The described operating modes are systematized in table 1.

When the brake is applied, the mechanical constant gear ratio is determined by applying equation (4) for the respective planetary set \((P_1\) and/or \(P_2\)), which is active, or for both and taking into account which unit is input, which is output and which is stationary.

### Table 1. Modes of operation of the transmission with double separation of the mechanical flow.

| Mode                     | Cl | Br | ICE | \(E_1\) | \(E_2\) | Batt | Gear ratio |
|--------------------------|----|----|-----|---------|---------|------|------------|
| Conventional             | On | On | On  | Off     | Off     | Off  | 1 + 1/\(\alpha_1\) |
| Charging by ICE          | On | On | On  | Off     | G       | On + | \((1 + 1/\alpha_1)/(1 + \alpha_2)\) |
| Parallel hybrid 1        | On | On | On  | Off     | M       | On - | ICE: 1 + 1/\(\alpha_1\); \(E_2\): 1 + \(\alpha_2\) |
| Parallel hybrid 2        | On | Off| On  | M       | M       | On - | variable |
| Regeneration             | Off| On | Off | Off     | G       | On + | 1/(1 + \(\alpha_2\)) |
| Electrical 1             | Off| On | Off | Off     | M       | On - | 1 + \(\alpha_2\) |
| Electrical 2             | Off| Off| Off | M       | M       | On - | variable |
| Double power split       | On | Off| On  | G/M     | M/G     | Off  | variable |

Battery status: On + charge; On – discharge
3. Characteristics of combined power split transmissions

The dual power split mode allows for optimal use of electric machines with almost twice smaller power compared to the single power split mode but in a narrower speed range shifted to high speeds. For example, when using internal combustion power in the range of 50 to 250 kW, the required power of electrical machines in single separation is in the range of 40 to 160 kW, and in double separation – from 50 to 80 kW, but at higher internal combustion power – from 150 to 250 kW. Therefore, it is appropriate to combine the two variants of power split schemes. Such hybrid drive systems that allow for operation on both schemes are called Two-Mode Hybrid [9]. Figure 5 shows an example of such a transmission with three planetary sets, two electric machines, two brakes and two clutches.

Table 2 shows the possible modes that are provided by the scheme for different combinations of turn on clutches and brakes.

![Figure 5. Kinematic scheme of Two-Mode Hybrid.](image)

With this scheme, two stepless ranges are achieved, which cover the entire required working range of gear and in principle correspond to the single and double power separation. Stepless ranges are suitable for low and high speed starting and acceleration modes, and fixed gear ratios (Conventional mode with four mechanical gears) can be used when driving in established mode to avoid losses in electrical machines.

| Mode            | Cl₁ | Cl₂ | Br₁ | Br₂ | ICE | E₁   | E₂   | Gear ratio | Value |
|-----------------|-----|-----|-----|-----|-----|------|------|------------|-------|
| Simple power split (1) | Off | Off | Off | On  | On  | G/M  | M/G  | variable   | ∞ ± 1.7 |
| Fixed gear 1    | On  | Off | Off | On  | Off | G/M  | M/G  | Off        | 1 + α₃   |
|                 |     |     |     |     |     |      |      | 1.7        | 3.69   |
| Fixed gear 2    | Off | On  | Off | On  | Off | Off  | G/M  | variable   | 1.7÷0.5 |
| Double power split (2) | Off | On  | Off | Off | On  | On   | G/M  | variable   | 1.7÷0.5 |
| Fixed gear 3    | On  | Off | Off | Off | On  | Off  | G/M  | variable   | 1.7÷0.5 |
|                 |     |     |     |     |     |      |      | 1          | 0.74   |
| Fixed gear 4    | Off | On  | On  | On  | Off | Off  | G/M  | variable   | 1/(1 + α₃)| 0.27   |
| Electrical      | Off | Off | Off | Off | Off | G    | M    | variable   | 1/(1 + α₃)| 0.74   |
| Regenerative braking | Off | Off | Off | Off | Off | Off  | G    | variable   | 1/(1 + α₃)| 0.27   |

The gear ratios are expressed as functions of the parameters (α) of the active planetary sets by applying equation (4). For example for gear ratio 2:

\[
P_3 \rightarrow \omega_S + \alpha_3 \omega = (1 + \alpha_3) \omega' = \omega_S = (1 + \alpha_3) \omega''; \tag{15}
\]

\[
P_2 \rightarrow (1 + \alpha_3) \omega'' + \alpha_2 \omega_R = (1 + \alpha_2) \omega'' = \omega_R = \omega''(\alpha_2 - \alpha_3) / \alpha_2; \tag{16}
\]

\[
P_1 \rightarrow \omega''(\alpha_2 - \alpha_3) / \alpha_2 + \alpha_1 \omega = (1 + \alpha_1) \omega'' \rightarrow i_2 = \omega' / \omega'' = 1 + \alpha_3 / \alpha_1 \alpha_2. \tag{17}
\]
These capabilities of the scheme, as well as the reduced size of electric machines, make it suitable not only for passenger cars but also for trucks [10].

A similar solution, which uses only a single power split, but with two stepless ranges, is shown in figure 6 (a). These ranges are realized by an additional Ravigneaux mechanism, connected in series in the electric stream, and two brakes, with which the ranges are switched [11]. The aim is to expand the range of the whole system, while reducing the size of the electric machines to be built into the transmission, without significantly increasing its mass and dimensions.

The Ravigneaux mechanism is often used in conventional automatic transmissions and is a unified unit. It allows for the use of three different planetary sets combined in one block. The first is ordinary \((R, Pl_2, S_2)\), the second consists of two sun wheels and two sets of successively engaged planetary wheels on a common carrier \((S_2, Pl_2, Pl_1, S_1)\) and the third – of a ring wheel, two sets of successively engaged planetary wheels of common carrier and small sun wheel \((R, Pl_2, Pl_1, S_1)\). In this case, only the first two planetary rows are used, for which also applies equation (4) when determining the gear ratios. A peculiarity of the second planetary set is that in the calculations the large sun wheel can be regarded as a fictitious ring wheel. Then the parameter \(a_2\) equals \(Z_{S_2}/Z_{S_1}\), and in the equation instead of \(\omega_r\), \(\omega_{S_2}\) is used and instead of \(\omega_S\), \(\omega_{S_1}\) is used. Nevertheless, the signs in the equation are preserved, because instead of one external and one internal gearing, there are three external gearing.

When the brake \(Br_1\) is applied, the following is obtained:

\[
\omega_{S_1} + a_2 \omega_{S_2} = (1 + a_2)\omega_C \rightarrow 0 + \omega_2 / \omega_2' = 1 + 1/a_2. \tag{18}
\]

The other range is achieved by applying brake \(Br_2\) and disabling brake \(Br_1\), when the first planetary set is active. The gear ratio in the electrical branch is obtained by analogous calculations:

\[
\omega_2 / \omega_2' = 1 + a_1. \tag{19}
\]

In this case, the following operating modes are possible, systematized in table 3.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Kinematic schemes of power split with single division and additional possibilities.}
\end{figure}

\begin{table}[h]
\centering
\caption{Modes of operation of the scheme of figure 6 (a).}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Mode & \(Br_1\) & \(Br_2\) & ICE & \(E_1\) & \(E_2\) & Gear ratio \\
\hline
Power split 1 (EVT at low driving speed) & Off & On & On & G/M & M/G & variable \\
Power split 2 (EVT at high driving speed) & On & Off & On & G/M & M/G & variable \\
Electrical 1 & Off & On & Off & Off & M & \(1 + a_1\) \\
Electrical 2 & On & Off & Off & Off & M & \(1 + 1/a_2\) \\
Regenerative braking 1 & Off & On & Off & Off & G & \(1/(1 + a_1)\) \\
Regenerative braking 2 & On & Off & Off & Off & G & \(1/(1 + 1/a_2)\) \\
\hline
\end{tabular}
\end{table}
The scheme in figure 6 (b) provides further expansion of the range of autonomous vehicle movement by ICE, when the battery charge is exhausted (E-REV, Extended-Range Electric Vehicle). This corresponds in principle to a serial hybrid, but smaller electric machines are used, as they are mainly designed to work in the electrical branch of the power split transmission on a simple split scheme (Output split) [12]. To increase the acceleration when driving only with electric machines, the power of both machines \( E_1 \) and \( E_2 \), differentially connected by the planetary set, can be used, while in economical movement only \( E_2 \) is used. These modes are achieved by two clutches and one brake (table 4).

### Table 4. Operating modes of the scheme of figure 6 (b).

| Mode                  | Cl_1 | Cl_2 | Br | ICE | E_1 | E_2 | Gear ratio |
|-----------------------|------|------|----|-----|-----|-----|------------|
| Electrical 1          | Off  | Off  | On | Off | Off | M   | \( \omega_2/\omega'_2 = -(1 + \alpha)i_A \) |
| Electrical 2          | Off  | On   | Off| Off | M   | M   | variable   |
| Serial hybrid         | On   | Off  | On | On  | G   | M   | variable   |
| Power split           | On   | Off  | On | G/M | M   | G   | variable   |
| Regenerative braking  | Off  | Off  | On | Off | G   |     | \( \omega''/\omega_2 = -1/(1 + \alpha)i_A \) |

### 4. Conclusion

The proposed methodology makes it possible to obtain the characteristics of power-split schemes \((i, K)\) as functions of the characteristics of the electric branch \((i_E, K_E)\) and the planetary mechanism \((\alpha, \eta_0)\). They can easily be used to calculate the degree of impact of each parameter on the total efficiency, on the range of gear ratio change and on the operating modes of the ICE and the electrical machines. The proposed graphical method can be used to study and visualize the changes in the angular velocities of the individual elements of the system – input (ICE), output, \( E_1 \) and \( E_2 \) and the resulting ratios between them (gear ratios) in different operating modes.

In this way, the possibilities of power split schemes for realization of different stepped and stepless ranges of gear ratio change and for expansion of the range of operation with high efficiency can be explored. The methodology allows for experimentation with different combinations of circuits, which provide not only an optimal combination of single and double separation, but also additional simpler drive options – only with internal combustion engines, only with electric machines and regenerative braking.

The research shows that with power split transmissions a combination of the optimal modes of the machines and the use of the mechanical characteristics in the necessary range can be achieved through appropriate control. Depending on the operating modes, it is expedient to reduce the relative share of the electric power at lower values of efficiency in the electric branch and vice versa.

The present work can also be used to develop simulation models corresponding to different control strategies for hybrid drives in order to optimize them according to different criteria.

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