Dynamics study of an automobile equipped with a hybrid powertrain system compared with the classic one

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Abstract. Cars with hybrid powertrain substantially reduce the fuel consumption and the environmental pollution, especially at medium and low speeds, because they use mostly electrical propulsion. The paper presents the mathematical calculation for working regimes of a car with parallel hybrid powertrain system, mathematical model which permits calculation of the propulsion power and torque, as well as the power and mechanical couple at the electrical generator. Dynamics performances for a car with a parallel hybrid powertrain system are presented and compared with the dynamics performances of the same car equipped only with the same gasoline internal combustion engine and without hybrid system. From the point of view of performances, hybrid-powered cars can achieve higher accelerations and traction forces than classic cars during autonomy of electric system, due to the propulsion with this system.

1. Introduction

Automobile equipped with hybrid powertrain system reduce fuel consumption and environmental pollution, especially at low speeds because it mostly use electric propulsion. At present there are several constructive variants for the hybrid propulsion of vehicles. Based on the basic, serial, parallel or mixed versions, combined variants are also built, each of which has both advantages and disadvantages [2], [6], [8], [9]. A variant for a parallel type transmission for a hybrid car is shown in Figure 1, [2], [3], [4]. This hybrid transmission uses one electrical engine which works as an electrical engine (E.E) or electrical generator (E.G), depending on the working conditions of transmission. The hybrid transmission includes two planetary mechanisms, MP1 and MP2. The solar wheels of MP1 and MP2 are coupled at the same shaft of the electrical engine. The hybrid transmission includes two clutches A1 and A2 and two belt brakes F1 and F2 which are used to achieve the different operating modes specified in the table bellow.

The hybrid transmission system meets the following five operating modes:

- the propulsion only with electrical engine (E.E);
- the propulsion using electrical engine (E.E) and internal combustion engine (I.C.E);
- the propulsion with internal combustion engine only and the transmission as a continuously variable transmission;
- the propulsion with internal combustion engine only and with the electrical engine working as electrical generator (E.G) for the recharge of the storage battery;
- the brake conditions with electrical engine working as electrical generator.
In Table 1, [2], [3], are presented all the specified working operating modes with their regimes.
Is specified the brake which is in function and the clutch which is coupled for each operating mode.

Table 1. Working operating modes for the parallel hybrid powertrain system

| Working operating modes     | Clutches and brakes | Working conditions of electrical engine |
|-----------------------------|---------------------|------------------------------------------|
|                             | Clutch A1 | Clutch A2 | Brake F1 | Brake F2 | Engine |
| Propulsion with E.E        | M        | Not Coupled | Not Coupled | Activated | Not Activated |
|                             |          |            |          |          | Engine |
| Propulsion with E.E and I.C.E | P1      | Coupled | Not Coupled | Activated | Not Activated |
|                             |          |            |          |          | Engine |
|                             | P2      | Not Coupled | Coupled | Activated | Not Activated |
|                             |          |            |          |          | Engine |
|                             | P3      | Coupled | Coupled | Not Activated | Not Activated |
|                             |          |            |          |          | Engine |
| Propulsion with I.C.E      | E1      | Coupled | Not Coupled | Activated | Not Activated |
|                             |          |            |          |          | Free rotation |
|                             | E2      | Not Coupled | Coupled | Activated | Not Activated |
|                             |          |            |          |          | Free rotation |
|                             | E3      | Coupled | Coupled | Not Activated | Not Activated |
|                             |          |            |          |          | Free rotation |
|                             | E4      | Not Coupled | Coupled | Not Activated | Activated |
|                             |          |            |          |          | Stopped |
| Propulsion with I.C.E and working of E.E such as E.G | EC1 | Coupled | Not Coupled | Activated | Not Activated |
|                             |          |            |          |          | Generator |
|                             | EC2 | Not Coupled | Coupled | Activated | Not Activated |
|                             |          |            |          |          | Generator |
|                             | EC3 | Coupled | Coupled | Not Activated | Not Activated |
|                             |          |            |          |          | Generator |
|                             | EC4 | Not Coupled | Coupled | Not Activated | Not Activated |
|                             |          |            |          |          | Generator |
| Recovery of kinetic energy during braking periods and working of E.E such as E.G | R1 | Not Coupled | Not Coupled | Activated | Not Activated |
|                             |          |            |          |          | Generator |
|                             | R2 | Coupled | Not Coupled | Activated | Not Activated |
|                             |          |            |          |          | Generator |
|                             | R3 | Not Coupled | Coupled | Activated | Not Activated |
|                             |          |            |          |          | Generator |
|                             | R4 | Coupled | Coupled | Not Activated | Not Activated |
|                             |          |            |          |          | Generator |

2. Mathematical model for a car with parallel hybrid propulsion and transmission system

The mathematical model of the parallel hybrid propulsion system and the simulations made and presented in this work are personal achievements and are not found in the writings of other authors.

As known, the ratio of transmission between two main shafts (i and j) in relation to the third (k) which is mobile:

\[ i_{ij}^k = \pm \frac{\omega_j - \omega_k}{\omega_j - \omega_k} \]  

(1)

If we consider the third (k) fixed results:
\[ i^{k}_{ij} = \pm \frac{\omega_i}{\omega_j} = \pm \frac{z_j}{z_i} \]  

(2)

Where: \( z_j \) the number of teeth for the toothed wheel on the ‘j’ shaft; \( z_i \) the number of teeth for the toothed wheel on the ‘i’ shaft; \( \pm \) represents the inside gear and outside gear;

![Diagram of Parallel Hybrid Transmission](image)

**Figure 1.** Parallel hybrid transmission

C.E.—internal combustion engine; E.E.—electrical engine; E.G.—electrical generator; MP1, MP2—planetary gear; A1, A2—clutches; F1, F2—brakes.

For the parallel hybrid transmission presented above, for the two planetary gear we write:

\[ \omega_7 - \omega_2 = \frac{z_3}{z_7} (\omega_3 - \omega_2) \]  

(3)

\[ \omega_7 - \omega_2 = -\frac{z_1}{z_7} (\omega_1 - \omega_2) \]  

(4)

\[ \omega_6 - \omega_3 = \frac{z_4}{z_6} (\omega_4 - \omega_3) \]  

(5)

\[ \omega_6 - \omega_3 = -\frac{z_1}{z_6} (\omega_1 - \omega_3) \]  

(6)

For the parallel hybrid transmission, presented in figure 1, for the two planetary mechanism we can write:

\[ \omega_1 - \omega_2 \left(1 + \frac{z_3}{z_i}\right) + \omega_3 \cdot \frac{z_3}{z_i} = 0 \]  

(7)
\[ \omega_1 - \omega_2 \left( I + \frac{z_4}{z_1} \right) + \omega_4 \cdot \frac{z_4}{z_1} = 0 \]  
\hspace{1cm} (8)

Where: \( \omega_1 \) - the angular speed of the central wheels of MP1 and MP2; \( \omega_2 \) - the angular speed of the satellite shaft of MP1; \( \omega_3 \) - the angular speed of the satellite shaft of MP2; \( \omega_4 \) - the angular speed of the gearwheel with inner gear of MP2; 1- the main shaft of the planetary mechanisms; 2- the satellite shaft of MP1; 3- output shaft; 4- gearwheel with internal gear of MP2; 5- input shaft; 6,7- gearwheels of satellites;

The relations (7) and (8) permit the calculations of two angular speeds when the others two are known. For the steady working conditions, the couples and powers at 1, 2, 3, 4 shafts verify the relations:

\[ \sum_{i=1}^{4} M_i = 0; \]  
\hspace{1cm} (9)

If we eliminate \( M_3 \) between equations (9) and using expressions (7) and (8), it results:

\[ M_1 \cdot \frac{z_4}{z_1} + M_2 \cdot \frac{z_4}{z_1 + z_3} - M_4 = 0 \]  
\hspace{1cm} (10)

By eliminating \( M_4 \) between equations (9) and using expressions (7) and (8), it results:

\[ M_1 \cdot \left( I + \frac{z_4}{z_1} \right) + M_2 \cdot \frac{z_1 + z_3 + z_4}{z_1 + z_3} + M_3 = 0 \]  
\hspace{1cm} (11)

The mathematical relations (10) and (11) permit the calculation of the couples at 1, 2, 3 and 4 shafts depending on the ratio \( z_3 / z_1 \) and \( z_4 / z_1 \) if two of these couples are known. Furthermore, the mathematical calculations [2] are presented for some of the significant working conditions of propulsion.

The most representative operating modes shown in Table 1 for parallel hybrid powertrain are:

2.1. The propulsion only with the electrical engine (E.E) – mode M

For propulsion, only the electrical engine through planetary mechanism MP2 is used, while MP1 is in free rotation. Only belt brake F1 is activated.

Using the conditions \( \omega_4 = 0 \) in equations (7) and (8) and \( M_2 = 0 \) in equations (10) and (11), it results:

\[ \omega_1 = \omega_{E,E} = \left( 1 + \frac{z_4}{z_1} \right) \cdot \omega_3 \]  
\hspace{1cm} (12)

and

\[ \omega_2 = \left( \frac{1 + \frac{z_4}{z_1} + \frac{z_4}{z_1}}{1 + \frac{z_4}{z_1}} \right) \cdot \omega_3 \]  
\hspace{1cm} (13)

\[ M_4 = M_1 \cdot \frac{z_4}{z_1} = \frac{z_4}{z_1} \cdot M_{E,E} \]  
\hspace{1cm} (14)

and
The sign “-” of couple M3 in equation (15) means that M3 has an opposite sign than the couple M1 of the electrical engine which is considered positive.

The power of propulsion of the outlet shaft of parallel hybrid system is:

\[ P_3 = \omega_3 \cdot |M_3| = \omega_3 \cdot \left(1 + \frac{z_4}{z_1}\right) \cdot M_{E,E} \]  

(16)

If the ratios \( z_4/z_1 \) and \( z_3/z_1 \) are known, couple M_{E,E} and the angular speed \( \omega_3 \) are calculated on the basis of speed and ratio of the transmission located after the parallel hybrid system, we can calculate the other parameters using the equations above.

2.2. The propulsion using the electrical engine (E.E.) and the internal combustion engine (I.C.E.) – mode P1

Clutch A1 is coupled and brake F1 is activated. E.E and I.C.E. achieve together the propulsion through the planetary mechanisms MP2 and MP1 rotates freely.

Using the condition \( \omega_4 = 0 \) in equations (7) and (8) it results:

\[ \omega_1 = \omega_{E,E} = \omega_{I,C,E} = \left(1 + \frac{z_4}{z_1}\right) \cdot \omega_3 \]  

(17)

and

\[ \omega_2 = \frac{\left(1 + \frac{z_1}{z_4} + \frac{z_4}{z_1}\right)}{1 + \frac{z_4}{z_1}} \cdot \omega_3 \]  

(18)

Using equations (10) and (11) it results:

\[ M_4 = M_1 \cdot \frac{z_4}{z_1} = \left(M_{E,E} + M_{I,C,E}\right) \cdot \frac{z_4}{z_1} \]  

(19)

\[ M_3 = -M_1 \cdot \left(1 + \frac{z_4}{z_1}\right) = -(M_{E,E} + M_{I,C,E}) \cdot \left(1 + \frac{z_4}{z_1}\right) \]  

(20)

The power of propulsion of the outlet shaft of parallel hybrid system is:

\[ P_3 = \omega_3 \cdot \left(M_{E,E} + M_{I,C,E}\right) \cdot \left(1 + \frac{z_4}{z_1}\right) \]  

(21)

If the ratios \( z_4/z_1 \) and \( z_3/z_1 \) and the couples M_{E,E} and the M_{I,C,E} are known, the angular speed \( \omega_3 \) is calculated on the basis of the speed and ratio of the transmission located after the parallel hybrid system, the other parameters will be calculated using the mathematical relations above.

2.3. The propulsion using the electrical engine (E.E.) and the internal combustion engine (I.C.E.) – mode P2

Clutch A2 is coupled and brake F1 is activated. E.E and I.C.E. achieve together the propulsion through the planetary mechanisms MP2 and MP1.
Using the condition $\omega_4 = 0$ in equations (7) and (8) it results:

$$\omega_1 = \omega_{E.E.} = \left(1 + \frac{z_4}{z_1}\right) \cdot \omega_3$$

(22)

and

$$\omega_2 = \omega_{I.C.E.} = \frac{1 + \frac{z_3}{z_1} + \frac{z_4}{z_1}}{\left(1 + \frac{z_3}{z_1}\right)} \cdot \omega_3$$

(23)

Using equations (10) and (11) it results:

$$M_3 = M_1 \cdot \frac{z_4}{z_1} + M_2 \cdot \frac{z_4}{z_1 + z_3} = M_{E.E.} \cdot \frac{z_4}{z_1} + M_{I.C.E.} \cdot \frac{z_4}{z_1 + z_3}$$

(24)

$$M_3 = -M_1 \cdot \left(1 + \frac{z_4}{z_1}\right) - M_2 \cdot \frac{z_4 + z_3 + z_4}{z_1 + z_3} = -M_{E.E.} \left(1 + \frac{z_4}{z_1}\right) - M_{I.C.E.} \left(1 + \frac{z_4}{z_1 + z_3}\right)$$

(25)

The power of propulsion of the outlet shaft of parallel hybrid system is:

$$P_3 = \omega_3 \cdot |M_3| = \omega_3 \cdot M_{E.E.} \cdot \left(1 + \frac{z_4}{z_1}\right) + \omega_3 \cdot M_{I.C.E.} \cdot \left(1 + \frac{z_4}{z_1 + z_3}\right)$$

(26)

If the ratios $z_4/z_1$ and $z_3/z_1$ and the couples $M_{E.E.}$ and the $M_{I.C.E.}$ are known, the angular speed $\omega_3$ is calculated on the basis of the speed and ratio of the transmission located after the parallel hybrid system, the other parameters will be calculated using the mathematical relations above.

2.4. The propulsion using only the internal combustion engine (I.C.E) – mode E1

The couple $M_{E.E.} = 0$, because the electrical engine is not fed with voltage and is in free rotation. The mathematical relations are:

$$\omega_3 = \omega_{I.C.E.} = \left(1 + \frac{z_4}{z_1}\right) \cdot \omega_3$$

(27)

and

$$\omega_2 = \frac{1 + \frac{z_3}{z_1} + \frac{z_4}{z_1}}{\left(1 + \frac{z_3}{z_1}\right)} \cdot \omega_3$$

(28)

$$M_4 = M_1 \cdot \frac{z_4}{z_1} = M_{I.C.E.} \cdot \frac{z_4}{z_1}$$

(29)

and

$$M_3 = -M_1 \left(1 + \frac{z_4}{z_1}\right) = -M_{I.C.E.} \left(1 + \frac{z_4}{z_1}\right)$$

(30)
The power of propulsion of the outlet shaft of parallel hybrid system is:

\[
P_3 = \omega_3 \cdot |M_3| = \omega_3 \cdot M_{i.c.e.} \cdot \left(1 + \frac{z_4}{z_1}\right)
\]  

(31)

2.5. The propulsion using with internal combustion engine and loading the storage battery – mode EC1

The clutch A1 is coupled and belt brake F1 is activated. The electrical generator consumes a part of mechanical energy delivered by the internal combustion engine for charging batteries and power the electricity consumers. The mathematical relations are those which we established at mode P1, but with a negative couple at the electrical generator.

\[
\omega_1 = \omega_{E.G.} = \left(1 + \frac{z_4}{z_1}\right) \cdot \omega_3
\]  

(32)

and

\[
\omega_2 = \omega_{i.c.e.} = \frac{\left(1 + \frac{z_3}{z_1} + \frac{z_4}{z_1}\right)}{\left(1 + \frac{z_3}{z_1}\right)} \cdot \omega_3
\]  

(33)

\[M_4 = M_1 \cdot \frac{z_4}{z_1} = \left(M_{i.c.e.} - M_{E.G.}\right) \cdot \frac{z_4}{z_1}
\]  

(34)

\[M_3 = -M_1 \cdot \left(1 + \frac{z_4}{z_1}\right) = -\left(1 + \frac{z_4}{z_1}\right) \cdot \left(M_{i.c.e.} - M_{E.G.}\right)
\]  

(35)

The power of propulsion of the outlet shaft of parallel hybrid system is:

\[
P_3 = \omega_3 \cdot |M_3| = \omega_3 \left(1 + \frac{z_4}{z_1}\right) \left(M_{i.c.e.} - M_{E.G.}\right)
\]  

(36)

The mechanical power used up by the electrical generator is:

\[P_{E.G.} = \omega_1 \cdot M_{E.G.}
\]  

(37)

where the \(M_{E.G.}\) results from relation (35):

\[M_{E.G.} = M_{i.c.e.} + M_3 \left(1 + \frac{z_4}{z_1}\right)
\]  

(38)

The couple \(M_3\) results from the following equation on the basis of the air resistance at speed \(V\):

\[M_3 = \frac{G \left(f \cos \alpha + \sin \alpha\right)}{\eta_i \cdot i_u \cdot r_s} \cdot r_s + \frac{k \cdot A \cdot V^2}{13 \cdot \eta_i \cdot i_u \cdot r_f}
\]  

(39)

Where: \(k\) -- frontal aerodynamic coefficient; \(V[\text{km/h}]\) – speed of the car; \(f\) -- the resistance coefficient for the rolling of wheels; \(G\) -- the total weight of the vehicle; \(A\) -- the maximum transversal surface of car; \(i_u\) -- gear ratio of power transmission after parallel hybrid system; \(r_s\) -- the dynamic radius of
wheels; \( \alpha \) -- the angle of the road measured by the horizontal surface (angle of road in slope); \( \eta_{pr} \) -- the efficiency of powertrain after parallel hybrid system;

2.6. The recovery of energy during the braking periods – mode R1

The brake F1 is activated; using the planetary gear MP2, the kinetic energy during the braking periods is recovered by the electrical generator into electrical energy which is used to load the storage battery. Using the condition \( \omega_4 = 0 \) in relations (7) and (8) and \( M_2 = 0 \) in relation (11) it results:

\[
\omega_1 = \omega_{E,G} = \left(1 + \frac{z_4}{z_1}\right) \cdot \omega_4 \quad \text{and} \quad \omega_2 = \left(1 + \frac{z_3 + z_4}{z_1}\right) \cdot \omega_4
\]

\[
M_1 = M_3 \cdot \left(1 + \frac{z_4}{z_1}\right) = -\left(1 + \frac{z_4}{z_1}\right) \cdot M_{E,G} \Rightarrow M_{E,G} = \frac{M_3}{1 + \frac{z_4}{z_1}}
\]

The mechanical power used by the electrical generator is:

\[
P_{E,G} = \omega_1 \cdot M_{E,G}
\]

The couple \( M_3 \) results from the same (39) relation on the basis of the air resistance at speed \( V \) and it is introduced with ‘-’ sign in relation (41).

If the ratios \( z_4/z_1 \) and \( z_3/z_1 \) are known and the angular speed \( \omega_3 \) is calculated on the basis of speed and ratio of the transmission located after the parallel hybrid system, the other parameters will be calculated using the equations above.

3. Numerical simulation for dynamics of a car with parallel hybrid propulsion and transmission system

For the numerical simulation of the regimes M, P1, E1 (see Table 1) a car with only front axle powered, with the following features was considered:

| \( G_{\text{car}} \) (total car weight) | 16500 [N] |
| \( V_{\text{max}} \) (maximum speed on horizontal and rectilinear road with hybrid powertrain combined, electrical and classical) | 190 [km/h] |
| \( V_{\text{max} \ E} \) (maximum speed with electric propulsion) | 80 [km/h] |
| \( n_{E,E} \) (maximum rotation speed of electric engine) | 4000 [rpm] |
| \( U_{\text{nom}} \) (rated DC voltage) | 220 [V] |
| \( P_{E,E} \) (maximum power of the electric engine) | 18 [kW] |
| \( P_{I,C,E} \) (maximum power of the spark engine) | 65 [kW] |

The car considered has the hybrid parallel powertrain system presented and a classic transmission with manual gearbox with six ratios for going forward: 2.9, 2.2, 1.7, 1.2, 0.9, 0.7 and final drive 4.9 ratio. At the same time, \( z_4/z_1 \) and \( z_3/z_1 \) ratios were considered equal to 1.4.

Based on the calculation, the following values were obtained for electrical propulsion only: the functioning time of 1 hour, at an average speed of 50 [km/h] and maximum possible speed of about 80 [km/h]. Operate only on the electric propulsion power, requires a power of about 18 [kW] which is realised by 18 li-ion batteries with 100 [Ah] each of them.
Figure 2 represents the traction forces obtained in the case of pure electric traction. It can be seen that the maximum speed that can be reached is 80 [km/h] and is obtained in the 4th gear. Under the same conditions (only electric propulsion), figure 3 represents the propulsion powers to the powertrain wheels.

**Figure 2.** The propulsion forces for working operating mode M

**Figure 3.** The power on wheels for working operating mode M
Where: \( F_{tr1,2,3,4} \) – M – the driving wheels propulsion force for the first four gears, for working operating mode M (propulsion only with E.E.); \( P_{r1,2,3,4} \) – M – the driving wheels propulsion power for the first four gears, for working operating mode M; \( F_{rez-mix} \) – the total resistance for running on the horizontal road. Figure 4 and 5 represents the traction forces respectively the propulsion powers to the driving wheels with a maximum car speed about 190 [km/h].

**Figure 4.** The propulsion forces for working operating mode P1

**Figure 5.** The power on wheels for working operating mode P1

Where: \( F_{tr1,6} \) – P1 – the driving wheels propulsion force for all six gears, for working operating mode P1 (propulsion with E.E and I.C.E.); \( P_{r1,6} \) – P1 – the driving wheels propulsion power for all six gears,
for working operating mode P1; $F_{rez-P1}$ – the total resistance for running on the horizontal road.

**Figure 6.** The propulsion forces for working operating modes M, P1, E1

**Figure 7.** The power on wheels for working operating modes M, P1, E1

Figure 6 and 7 represents the traction forces respectively the propulsion powers to the driving wheels, obtained under the following operating conditions:

- driving in the first 3 gears, using only the electric propulsion, means the M mode.
- driving in the 4th, 5th and 6th gears, using the combine propulsion (namely, the electric one to which the thermal engine is added), means the P1 mode, respectively using only the
propulsion generated by the thermal engine, means the mode E1 of the mathematical algorithm.

Where: \(F_{r1,3-M}, F_{r4,6-P1}\), E1—the driving wheels propulsion force for 1, 2, 3 gears for working in M mode and for 4, 5, 6 gears for working in P1. E1 modes; \(P_{r1,3-M}, P_{r4,6-P1}\), E1—the driving wheels propulsion power for 1, 2, 3 gears for working in mode M respectively for 4, 5, 6 gears for working in P1, E1 modes; \(F_{rez-ori}, P_{rez}\) – the total force and power resistance for running on the horizontal road.

In the case of combined traction, the maximum speed is 190 km/h and in the case of classical traction it is only 170 km/h. An important aspect to point out is that for any one of the 4th gear or 5th or 6th gear is used in the combine propulsion (that is to say, the electric one to which the propulsion generated by the thermal engine is added), the maximum traction force obtained in each gear is about 60% higher than the maximum traction force obtained in the same gear in the case of conventional traction (propulsion generated only by the thermal engine).

These increased traction forces generated by the hybrid powertrain system gives hybrid vehicles an increased acceleration. This is only true when the batteries have enough energy and they do not need to be charged using energy from the thermal engine, in which case the electric engine goes into the electric generator mode.

4. Conclusion

Cars with hybrid powertrain substantially reduce the fuel consumption and the environmental pollution, especially at medium and low speeds, because they mostly use electric propulsion. The hybrid powertrain working conditions, which are specific to each hybrid drive powertrain variant, can be grouped from the point of view of the control, automation and optimisation of hybrid powertrain.

From the point of view of their performance, hybrid-powered vehicles can achieve higher accelerations than classic vehicles, thanks to the propulsion of the electric system, during its autonomy.

In the case of parallel hybrid powertrain presented, traction forces were by about 60% higher than in conventional traction and the vehicles also reach higher maximum driving speeds.

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