

Design of electromechanical system for parallel hybrid electric vehicle

A. Beshta, A. Balakhontsev, A. Albu

State higher educational institution "National Mining University"

ABSTRACT: The article deals with design of configuration and control system for hybrid electric vehicle of parallel topology. The demands for powertrain are formulated. It is shown that speed-torque characteristics of the internal combustion engine and the electric drive must be adjusted to provide best efficiency under parallel operation. Mathematical description and simulation of internal combustion engine are given. Measures for fuel economy are proposed.

1 INTRODUCTION

Hybrid electric vehicles (HEVs) are being developed and manufactured by almost every automobile company. Their benefits are well known: lower fuel consumption and thus less emission, higher dynamic performances. Nevertheless high initial cost of such vehicles and immature infrastructure restrict application of these vehicles among average customers.

There is an ongoing project at the National Mining University (Dnepropetrovsk, Ukraine) dedicated to development of low-cost solution to retrofit conventional vehicle into hybrid one. Similar ideas were investigated by several researchers and engineers, like Bharat Forge and KPIT Cummins Infosystems LTD alliance which even announced that a special retrofit kit would be available on the market by 2011. The solution we pursue is to equip a front-wheel drive vehicle with additional electric drive installed onto the rear axle. The rear wheels can be equipped with hub motors, which requires less mechanical transformations and saves space but is more expensive, or the axle can be transformed to be driven from single electric motor. The latter solution despite its complexity is obviously cheaper and thus our target.

Since both motors are mechanically coupled via the road, we are dealing with parallel configuration of hybrid electric vehicle. Such configuration is known to provide better power/weight ratio for the vehicle. The electric motor can be of less power than the internal combustion engine, it can be used only as an auxiliary drive to fill dips in engine's speed/torque characteristic and to transform mechanical energy into electrical during braking. Despite all advantages of parallel topology the main obstacle is simultaneous operation of internal combustion engine and electric motor. In this article we shall discuss issues of parallel operation and consider the structure of control system for electric drive of parallel hybrid vehicle.

2 TOPOLOGY OF VEHICLE DRIVETRAIN AND ITS CONTROL SYSTEM

Let us consider the scheme of hybrid electric vehicle's powertrain shown in Fig. 1. The system contains components of power transmission: electric motor, internal combustion engine (ICE), torque coupler; and control modules for ICE and electric motor and the whole vehicle (Bogdanov 2009).

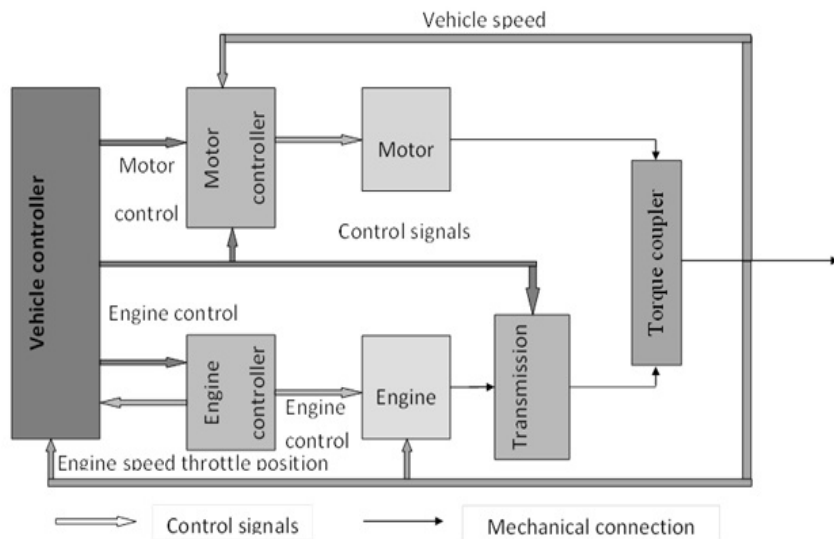


Figure 1. Conceptual architecture of a hybrid electric drive train.

The control system has two levels. The higher-level module is designed to manage overall vehicle by means of producing and distributing commands between lower-level control modules – ICE control module and electric motor control module. The control signals are formed according to certain control strategy which aims to fuel efficiency or dynamic performances. The reference signal is power demand from the driver, feedbacks include signals from the engine, motor and transmission.

In parallel configuration the total driving effort is produced by both primary source, which is internal combustion engine, and electric motor.

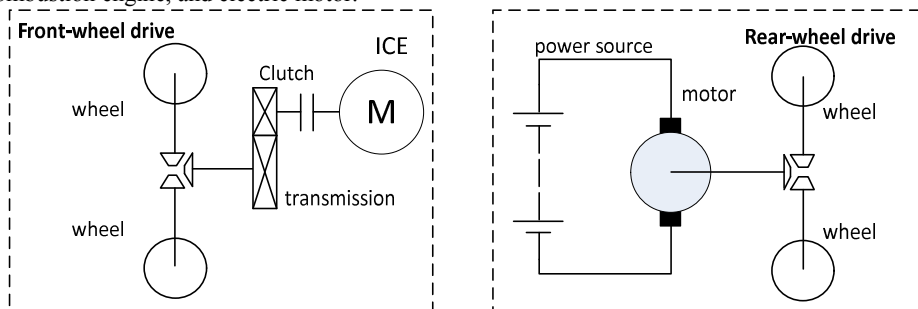


Figure 2. Configuration of parallel HEV drivetrain.

The torque coupling device that unites power flows from the engine and the motor is the factor that differs parallel configuration from the series one (Ehsani & Gao 2010). This element may or may not be present as a separate device. In our case the road itself is a torque coupler.

The interconnection of the engine and the motor via the road surface can be described mathematically as integration of the sum of torques, as it is shown in Fig.3.

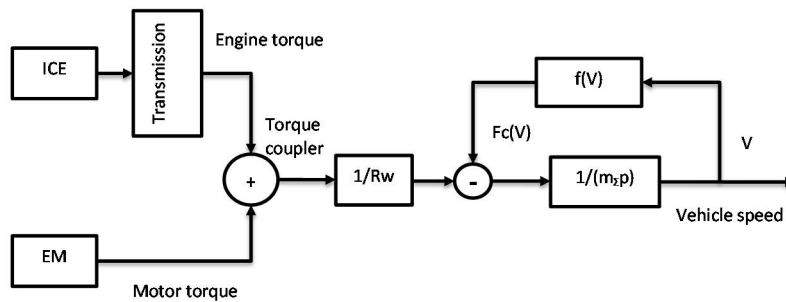


Figure 3. Mathematical representation of a torque coupling.

The rigid mechanical connection of the engine and the motor means that their speeds will always be maintained at certain ratio. Or, if reduced to wheel shafts, speeds of the engine and the motor will always be equal. The resulting speed-torque characteristic is obtained by summation of corresponding torques at certain speed levels.

Meanwhile there is always a danger of combining two motors with different speed-torque characteristics for parallel operation. The speed-torques characteristics always have different stiffness and/or no-load speeds. The motor with stiffer curve takes bigger part of the torque and can be overloaded. In worst cases when one of the motors has less value of no-load speed, it can be driven by its “partner” into the braking mode (Kolb & Kolb 2006).

An internal combustion engine is basically a torque source, it has soft speed-torque characteristic and little overload capacity. This being so, special measures must be taken for proper distribution of driving efforts between the motors and particularly to prevent operation of one of them in braking mode. It can be implemented by limitation of maximal speed reference for electric drive as it is shown in Fig. 4.

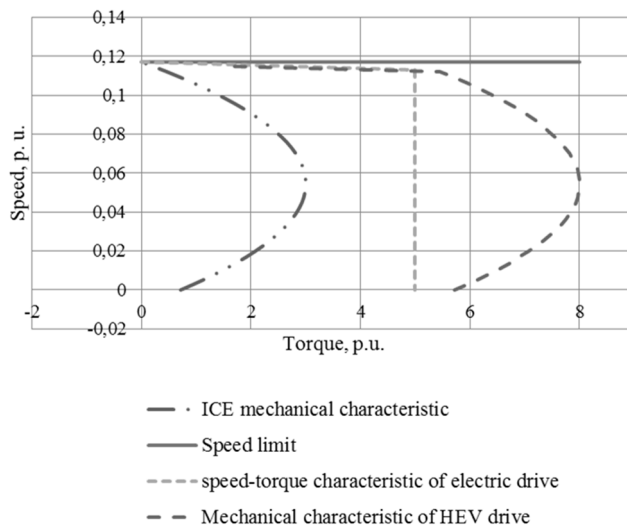


Figure 4. Necessary shape of electric drive speed-torque characteristic.

Thus the speed-torque characteristic of electric part of the drivetrain must be absolute by soft in the range of speeds up to the value of no-load speed of the engine. Then it transforms into typical stiff characteristic of electric drive.

The maximum speed threshold must be a function of reduced to wheels value of ICE no-load speed. The latter value, in turn, depends on throttle position and current gear ratio. The higher the gear the greater the

speed limit and the less is the current limit. At low gears the current is limited by natural overload capacity of the motor, at higher gears the motor produces less torque due to field weakening.

The key point in successful operation of parallel HEV is estimation of internal combustion engine's speed-torque characteristic. The position of operating point on this characteristic must be continuously tracked. The electric drive being more flexible and faster element can adapt to current conditions and drive the powertrain into point with higher performances.

Let us consider the performances of internal combustion engines.

3 DESCRIPTION OF INTERNAL COMBUSTION ENGINE

Interesting enough that first mechanically driven vehicles were electric ones. Performances of both types of engines – internal combustion and electric ones were improved with time and now they have roughly equal specific power. ICEs are known to have many disadvantages: high noise, bad speed-torque characteristic with dips, low overload capacity, and, of course, low efficiency and harmful emissions. Internal combustion engines got their chance only because of availability of hydrocarbon fuels and sufficient drive range they could provide at the dawn of automobile industry.

Nevertheless combustion engines in automotive applications will prevail in the near future. Let us consider mathematical description of the internal combustion engine. This will help when developing control algorithms for electric part of the HEV.

The model of ICE can be derived from mathematical description of processes within the engine. The model contains two blocks: one describes gas dynamics and the other describes mechanical part (Lamberson 2008).

The air flow rate in the manifold system m_a is a function of pressure in p_m and throttle position θ :

$$m_a' = f(\theta) \cdot g(p_m) \quad (1)$$

Each of the given elements can be presented as

$$f(\theta) = k_{th0} + k_{th1} \cdot \theta + k_{th2} \cdot \theta^2 + k_{th3} \cdot \theta^3 \quad (2)$$

$$g(p_m) = \begin{cases} 1, & p_m \leq 0.5 \cdot p_{atm} \\ \frac{2}{p_{atm}} \cdot \sqrt{p_{atm} \cdot p_m - p_m^2}, & p_m > 0.5 \cdot p_{atm} \end{cases} \quad (3)$$

where $k_{th0..3}$ – equation constants; θ – throttle position; p_{atm} – atmospheric pressure; p_m – manifold pressure.

The gas dynamics inside the intake system is described by first order differential equation:

$$p_m' = \frac{R \cdot T_m}{V_m} \cdot (m_{ai}' - m_{ao}') \quad (4)$$

where R – gas constant; V_m – manifold volume; T_m – gas temperature in the manifold system.

The mass flow rate of the air going to combustion chambers from the manifold m_{ao} is a function of manifold pressure p_m and engine speed:

$$m_{ao}' = k_{mo0} + k_{mo1} \cdot n \cdot p_m + k_{mo2} \cdot n \cdot p_m^2 + k_{mo3} \cdot n^2 \cdot p_m \quad (5)$$

where $k_{mo0..3}$ – equation constants; n – engine speed.

The crankshaft dynamics is described by the equation

$$J \cdot n' = T_{eng} - T_l \quad (6)$$

where T_{eng} – engine torque; T_l – load torque; J – engine inertia.

There is an empirical function for the engine torque

$$T_{eng} = k_{e0} + k_{e1} \cdot m_a + k_{e2} \cdot (AFR) + k_{e3} \cdot (AFR)^2 + k_{e4} \cdot \sigma + k_{e5} \cdot \sigma^2 + k_{e6} \cdot n + k_{e7} \cdot n^2 + k_{e8} \cdot n \cdot \sigma + k_{e9} \cdot \sigma \cdot m_a + k_{e10} \cdot \sigma^2 \cdot m_a \quad (7)$$

where $k_{e\theta \dots 10}$ – equation constants; m_a – mass of the air in the chamber; AFR – air-to-fuel ratio; σ – ignition advance.

The variable m_a represents air flow to the chambers during the intake. The intake takes place within first π radians of four crankshaft cycles. Thus the value of m_a may be obtained by integration of airflow from the manifold with zeroing it by the end of each cycle. To simplify representation of the engine, this process can be described as delay element (Khan, Spurgeony & Pulestonz, 2008).

An integrator with variable zeroing time can be approximately described as

$$m_a = \frac{m_{a0} \cdot \pi}{n} \quad (8)$$

where m_a – intake airflow; m_{a0} – output airflow; n – crankshaft speed.

The structure of internal combustion engine mathematical model is given in Fig. 5.

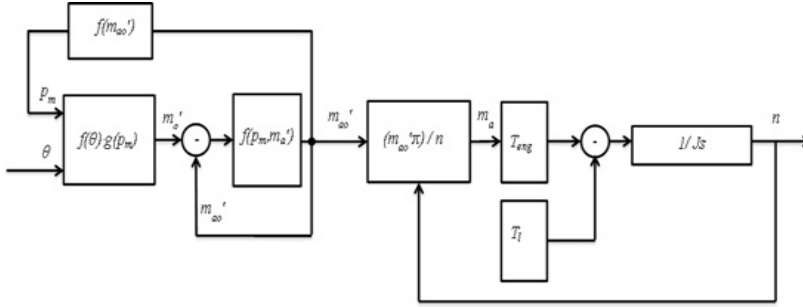


Figure 5. The structure of mathematical model of internal combustion engine.

The structure obtained can be used for design of control algorithms and simulation of vehicle dynamics. For preliminary configuration of HEV's components it can be useful to consider the resulting speed-torque characteristics of the internal combustion engine. The simulation of typical ICE installed in mid-class sedan gives the family of characteristics shown in Fig. 6.

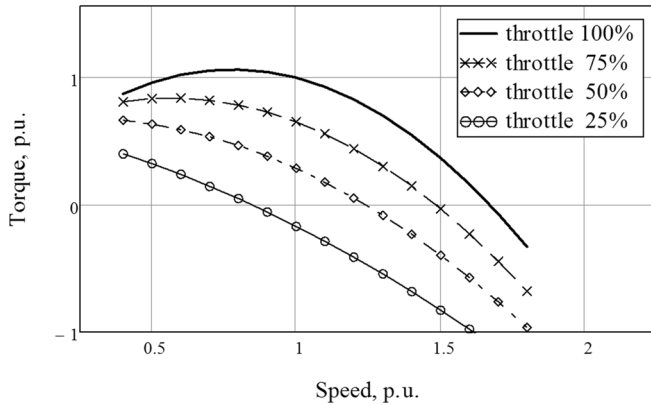


Figure 6. Speed-torque characteristics of internal combustion engine (in per units).

The family of characteristics is built for several positions of throttle, expressed in percents.

The obtained curves may be described by empirical equations such as

$$T(\omega, \theta) = k(\omega) \cdot T[\omega + \Delta\omega(\theta)] - \Delta T(\theta) \quad (9)$$

where $k(\omega)$, $\Delta\omega(\theta)$ and $\Delta T(\theta)$ – equation constants that are function of crankshaft speed and throttle position.

The key dependence is described by polynomial function such as

$$T(\omega) = -1.33 \cdot \omega^2 + 2.07 \cdot \omega + 0.251. \quad (10)$$

Coefficients in the equation given were obtained for the engine of ZAZ Sens vehicle – low cost Ukrainian sedan.

4 SIMULATIONS AND FURTHER STUDIES

The above given mathematical descriptions were used in the complex model of parallel HEV. For electric drive, a simple cascade multiloop structure was implemented. The only distinctive feature in electrical part of the model was variable saturation of speed controller. The saturation function was set to coincide with no-load speed of ICE.

Figure 7 shows standalone operation of the ICE and Figure 8 shows transients in the vehicle during its acceleration on the first gear.

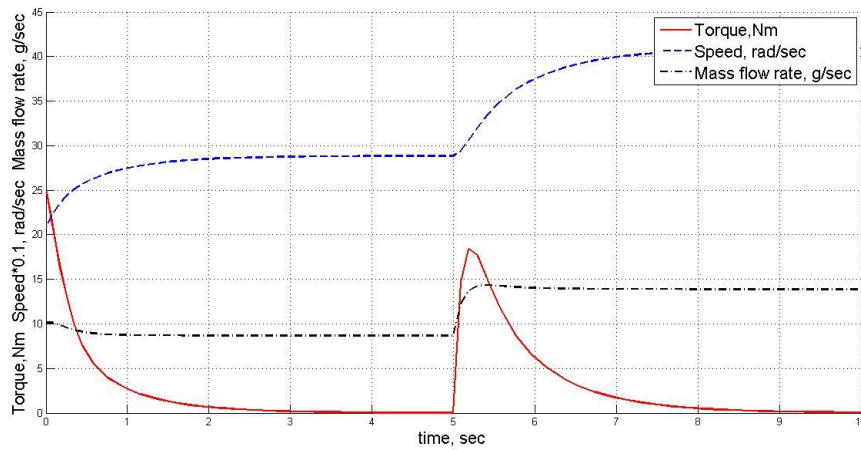


Figure 7. Simulation of internal combustion engine.

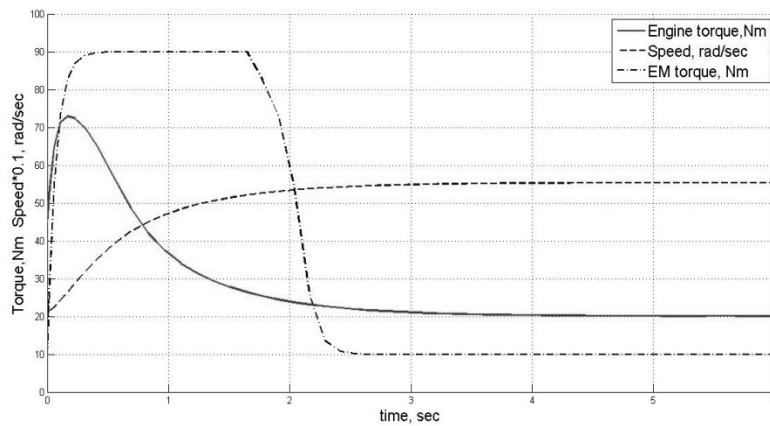


Figure 8. Transients in parallel HEV.

Opening the throttle causes the increase of the airflow, rise of engine torque and speed. Figure 8 shows efficient simultaneous operation of the ICE and the motor – neither of them produces braking torque.

So, the models given above can serve the basis for development of control strategies. The efforts should be directed onto optimization of operating modes of internal combustion engine while meeting demands for vehicle dynamics. Operation efficiency implies providing necessary torque by electric motor when ICE has unstable operation and driving the engine operating point into areas with highest possible efficiency (Ehsani & Gao 2010).

Simultaneous operation is especially important during the initial phase of acceleration when ICE works unstable and with poor efficiency. At this stage the electric motor can even be overloaded to the limit of its capacity.

During continuous drive at cruise speed, as a rule, the power demand for the powertrain lies far below optimal operating point. In this case the so called “thermostat” or “on/off control strategy” may be applied for fuel economy. It implies periodic switching between two states: 1) operation in pure electric mode, when energy is supplied from the battery; 2) ICE delivers energy for traction and for battery charging.

Capturing braking energy is a main source of fuel economy. In the braking mode, the electric motor operates as generator, delivering at least part of the energy to the battery.

5 CONCLUSIONS

Parallel configuration of hybrid electric vehicles will keep providing the best performance/cost ratio in the near-term future. The electric part of the drivetrain is flexible and fast enough to drive the internal combustion engine to the necessary operating point while meeting demands for tractive effort. The key issue in control of electric drive is correct distribution of torques between the engine and the motor. To do so, it is necessary to limit maximum speed of electric motor. The threshold should depend on instantaneous value of no-load speed of the engine reduced to the wheels. It, in turn, depends on current gear and throttle position.

The model of the internal combustion engine can be used for research of vehicle dynamics and developments of electric drive control system.

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