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Mathematical modeling of the electric drive train of the sports car

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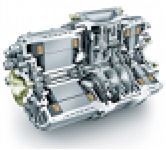

The present electric vehicles are using for the propulsion an electric motor with single stage reduction gearbox. A question is that it is suitable to use a multi-speed transmission unit. For this reason it is appropriate to analyze possible impacts of the multi-speed transmission application in electric vehicle. This paper describes a simulation model and results of an electric vehicle's powertrain with five speed transmission unit. Also shows the impact of the electric motor's dynamic loads during the gear shift process.

Introduction

The powertrain of the electric vehicle consists, as in the vehicle with internal combustion engine, of the motor, gearbox or transmission mechanism, driving shafts and differential with the final drive. Depending on the purpose and the vehicle structure, is also based its arrangement of the components and overall conception of the powertrain.

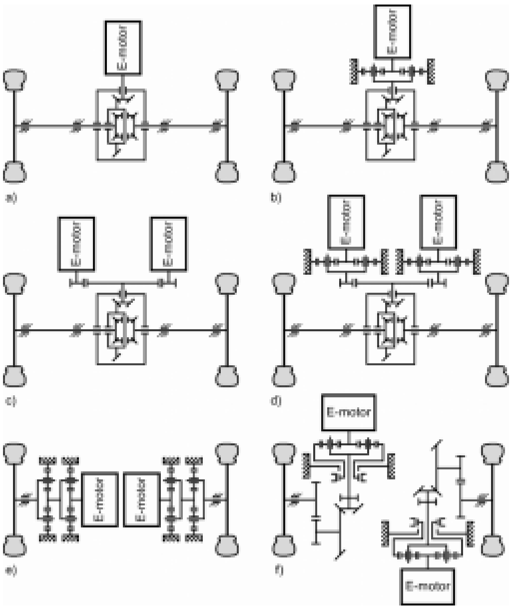

Fig.1 Conceptions of the electric propulsion systems [2] a. Direct central motor; b. central motor with planetary gear set; c. tandem motors with summarising gear; d. tandem motors with planetary gear set and summarising gear; e. wheel hub drive with planetary gear set; f. "in-hull drive" with selector gearbox

Commonly used is the conception with direct central motor for the front or rear axle drive. Alternative solutions to of electric drive systems can be divided into multiple concepts according to Fig. 1. Compared to propulsion systems of vehicles with internal combustion engine, electric propulsion system has usually a single stage reduction gear, and it’s much simpler. Therefore, there is no use of friction clutch and shifting elements.

Using the multi-speed transmissions brings many benefits. In the internal combustion engines are required for the operation of the engine speed in the best performance range with the highest torque parameters and also for the reaching some maximum speed (for example on the highway), which is typically in the range between 2500 – 4500 rpm, as can be seen on Fig.2. On the other hand, the electric traction motor reaching the maximum torque at zero rpm, and also have a much wider working range.

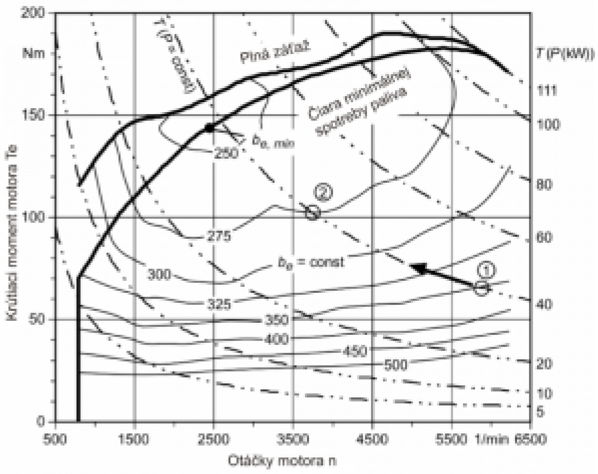

Fig.2 Engine map (“onion diagram”) with specific fuel consumption

However, the efficiency of electric motors changes at different speeds, as you can see on the Fig.2. As can be seen on the graph, in the area with the maximal torque of traction motor is the maximum value of efficiency between 70 – 80 %. It is possible to keep the electric motor rpm in the highest efficiency area, which is advantage for many reasons. The most important advantage is the lowered energy consumption from the batteries of the electric vehicle, which can be proofed by the simulations.

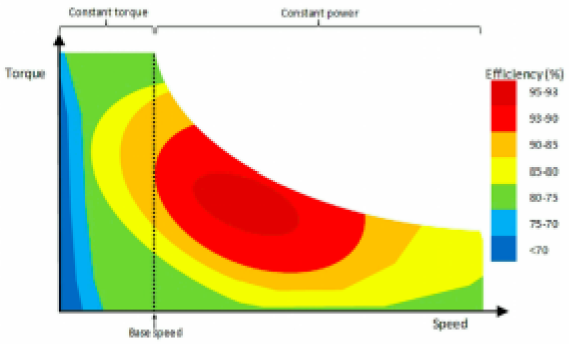

Fig. 3 Electric motor torque characteristics with efficiency map [3]

Other advantages of the multi-speed transmissions can be improving of the driving dynamics of the electric vehicle (climbing performance, highway drive).

Transmission mechanisms of the current electric vehicles

Present car manufacturers are aimed on the reducing losses of the electric vehicle drive train. With this aim is associated the optimization of the rotating parts of the drive system to minimize the adverse effects of the dynamic forces and moments on the overall operational and service life of the components. Significant impact on the dynamic parameters of the vehicle powertrain has transmission mechanism. The most common transmissions in vehicles with conventional power train with ICE with internal combustion engines are these:

- Mechanical speed gearbox
- Transmission with continuously variable gear ratio (planetary, dual clutch)

In vehicles with electric drive train is still the most widely used single-stage reduction gear, which the final drive with differential is part of its. One example is the reduction gear from GKN Driveline. This is a one-stage reduction gear with two pairs of spur gears with helical teeth and with bevel gear differential.

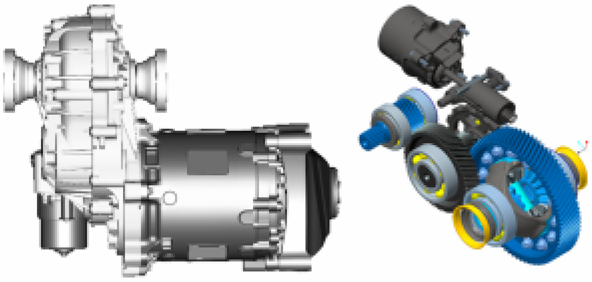

Fig. 4 Single-stage reduction gear GKN Driveline eTransmission [4]

The gearbox is designed to drive the front axle with single electric motor situated transverse to the vehicle. To ensure the vehicle during standing electronically managed parking pawl used is. Shafts with helical gears are located on the ball bearings. Parameters of shafts and gears are optimized for maximum input torque of 200 Nm. The manufacturer also provides balance of the relevant parameters to achieve:

- reduced noise levels
- increase efficiency
- increase of the service life of mechanical drive train

Antonov PLC Company developed for electric vehicles with electric central three gear automated transmission. It is a continuously variable gear ratio transmission. This is especially advantage for electric vehicles, which achieves a high torque from the zero rpm. This system has significantly effect on shifting gear elements. This means that a specific transmission can change gears under dynamic loads.

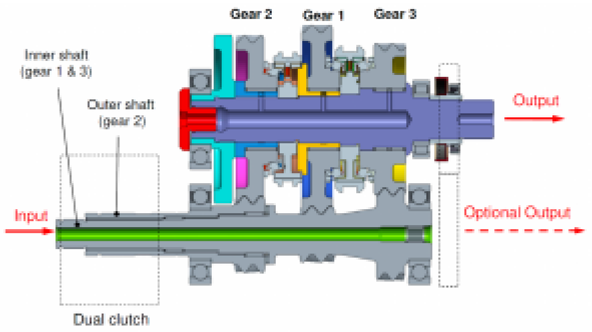

Fig. 5 Cross-section of the Antonov three gear automated transmission [5]

Shifting under dynamic loads is applied two fold multi-plate clutch. This clutch captures the torsional vibrations in the drive mechanism due to the high viscosity fluid. It follows, that acts as a damper of the torsional vibrations of the drivetrain mechanism. Another possible solution of the electric powertrain is the ACTIVeDRIVE Schaeffler system. This system works on the principle of active electronic differential. The system consists of two propulsion units on the front and rear axle. It is four wheel drive system.

The drive unit of this system consists of active differential, drive traction electric motor, planetary reduction gear, which consists of the final drive, planetary differential, superimposing stage and electric motor that controls the value of the speed and torque on the driven wheels of the vehicle, when vehicle is cornering or the vehicle is in the unstable condition (due wheel slip, on an unpaved surface). Generally is a Torque Vectoring system, which this system is the self-controlled all-wheel drive system, which extends in a given situation in real time.

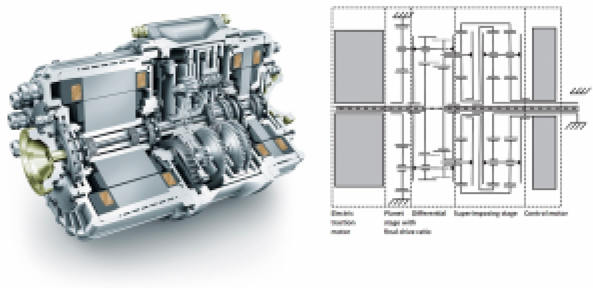

Fig. 6 Schaeffler ACTIVeDRIVE system of the active drive axles with electronic differential [6]

The selection and descripotion of the simulated vehicle

The first step for building of the model is the selection of the simulated vehicle. The simulated vehicle is Porsche model 996 Carrera 4, on which the conventional internal combustion engine with all wheels drive is replaced by electric motor. The powertrain components layout is designed and drawn in CAD software environment CATIA® V5 (Fig. 7).

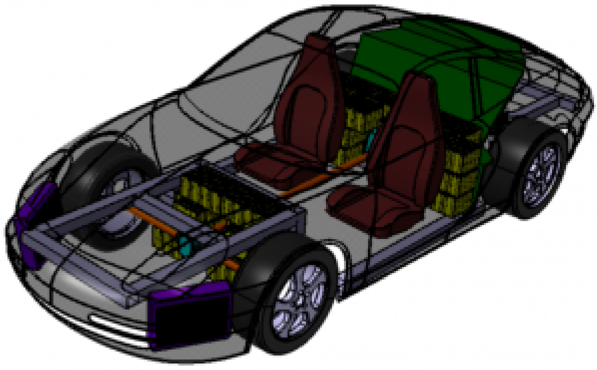

Fig. 7 CAD model of the simulated vehicle

For the building of mathematical-physical model was retained the original conception of powertrain, which is driving aggregate with the transmission located above the rear axle, and driven is the rear wheels (Fig. 8). It's typical components configuration for the Porsche vehicles. It advantages for example is very good traction and driving performance, simple braking system without pressure regulation between front and rear axle, and short torque flow from motor to drive wheels.

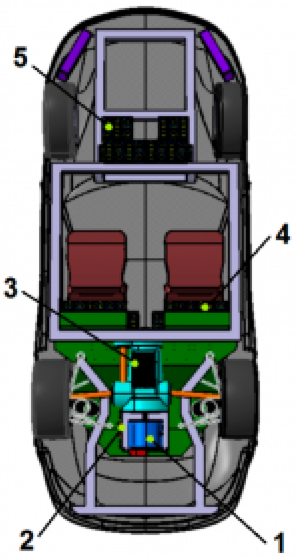

Fig. 8 Components layout of the simulated vehicle:

1 – Electric motor, 2 – DC/AC converter, 3 – automatic transmission with differential, 4 – rear battery pack, 5 – front battery pack

As can be seen on the Fig. 8, for the vehicle propulsion is an electric motor UQM145 with specific peak torque characteristics (Pos.1 on Fig.8). The motor's torque is transformed in the original ZF five speed automatic transmissions with final gear with differential. As an energy source a Li-FePO4 battery is used. For the transformation the current from DC batteries to AC electric motor an UQM inverter is used.

Building the mechanical model in Matlab Simulink® environment

The simulation model of the electric vehicle is built based on the chosen conception. This paper describes mainly the mechanical part of the model and the model parts, which needed are for the simulation process.

The electric motor subsystem

The main component of the simulation model is the electric motor subsystem. The base of this subsystem is an Ideal torque source, which generates the torque for the mechanical drive system. Input for this source is a Look-up table output based on the torque characteristics of the UQM motor and the accelerator pedal position.

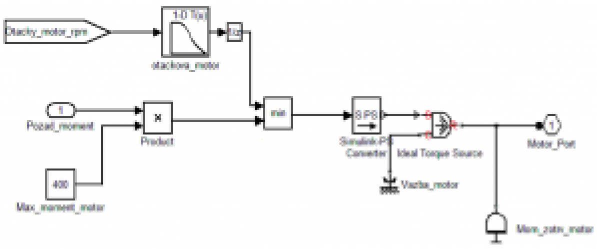

Fig. 9 Detailed view on the motor subsystem in Simulink

From the input torque signal and from the Rotational motion sensor is calculated the mechanical power according to equation

$$P_{mech} = T_{mot}\omega_{mot}[kW] \tag{1}$$

where P_{mech} is an mechanical power, T_{mot} is a motor torque and ω_{mot} is an electric motor angular velocity. To achieve the electrical power needed from the batteries, the mechanical power has to be multiplied by efficiency from the electric motor efficiency map (Fig. 10). The electrical power is then calculated according to equation

$$P_{el} = P_{mech}\eta_{mot}[kW] \tag{2}$$

where P_{el} is an electric power, P_{mot} is a mechanical motor power and η_{mot} is an efficiency of electric motor.

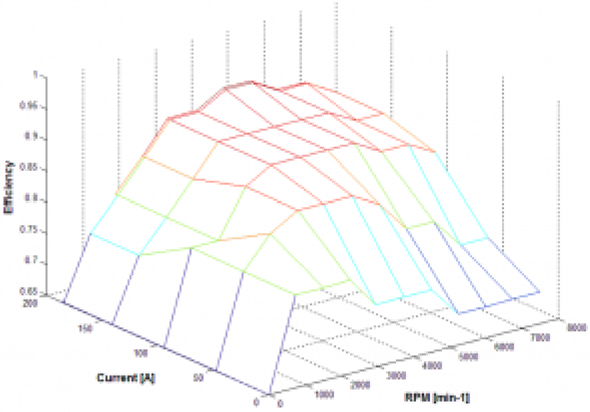

Fig. 10 Electric motor efficiency map

For the generating of efficiency the value of electric current is needed. Since the electric motor is a three-phase permanent magnet motor, the value of the voltage is constant. This implies, that the current equation is as follows

$$I_{mot} = \frac{P_{el}}{U_{mot}}[A] \tag{3}$$

where P_{el} is an electric power, U_{mot} is a motor voltage and I_{mot} is the electric current of the electric motor. For the generating of the efficiency value is a 2D Look-up table element used. Input variables is current and RPM of the motor (Fig. 11).

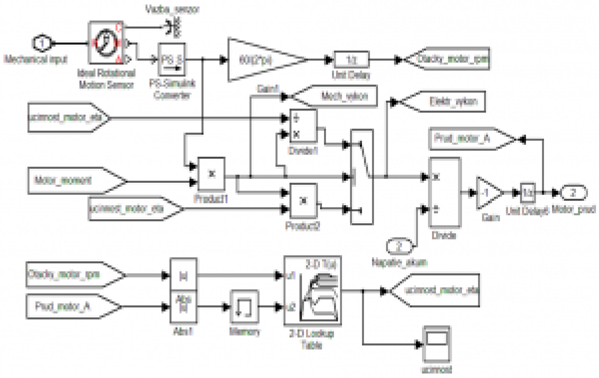

Fig. 11 Relations for calculating electric current, mechanical and electrical power of the electric vehicle powertrain

The automatic driver subsystem

For the most precise simulation is an automatic driver subsystem needed. In this subsystem are some Simulink blocks, which calculating the demanded acceleration pedal position and also brake pedal position for following the chosen driving cycle (Fig.12).

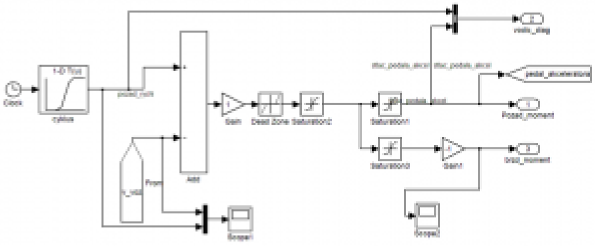

Fig. 12 Automatic driver Simulink subsystem

The vehicle mass and wheel dynamics subsystem

The basic subsystem for the mechanical components simulation is vehicle mass and wheel subsystem (Fig.13), where the basic mass and dimension parameters of the vehicle defined are. For the higher precision is simulated a four wheel model with defined inertias on each wheel.

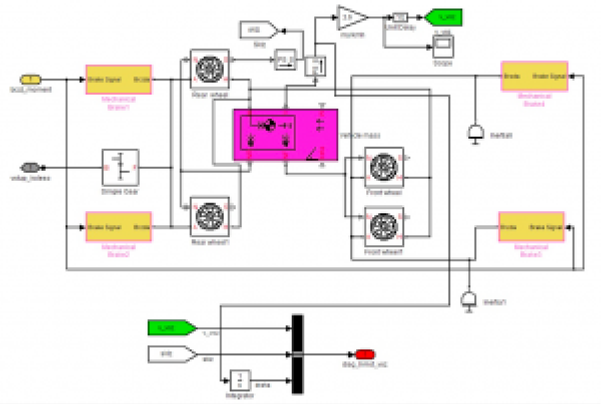

Fig. 13 Physical model of the vehicle mass and wheels

From the vehicle mass Simulink block, the vehicle speed is obtained for subsystems. For every wheel block is modeled a Mechanical brake subsystem with mechanical friction clutch block, which is controlled by generated brake signal from the automatic vehicle driver subsystem.

The five speed automatic transmission subsystem

This subsystem presents a physical model of the transmission of the simulated vehicle. This subsystem consists from mechanical rotational elements. As a transmission elements the planetary gear sets (PGS) blocks used are (Fig. 14).

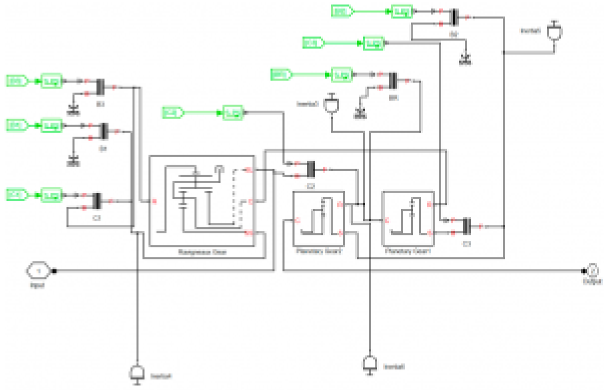

Fig. 14 Physical model of a rotating parts of a transmission

Every PGS block has an internal gear ratio and efficiency of power transmission defined. For change the gear ratio and gear shift a Friction clutch elements are used. These shifting elements are in the Fig. 14 marked as B or C. The B is the brake marking and C is the Clutch marking. The each shifting element is actuated by pressure which is controlled by transmission controller with the shifting algorithm. On every mechanical rotational line an inertia with specific value defined is. The entire model is built by all subsystems and it presents the electric vehicle powertrain (Fig. 15)

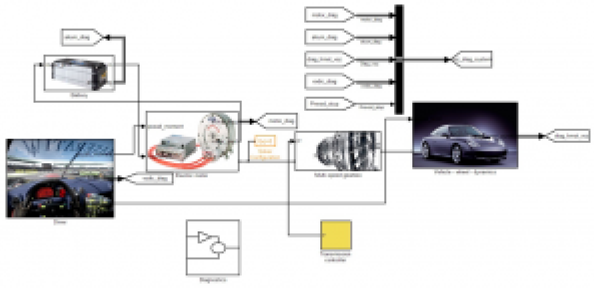

Fig. 15 The Simulink model of electric vehicle powertrain

Simulation results

The results of the simulations are time courses of physical parameters. The first parameter is desired speed compared to reached speed. Another parameters are Accelerator pedal position, electric motors RPM, traveled path, battery State of charge (SOC) and selected gear of the automatic transmission during the driving cycle (Fig. 16).

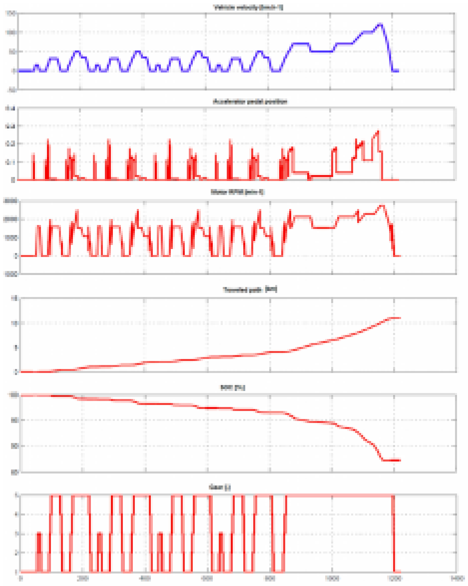

Fig. 16 The result parameters of the simulation

It also was found, that the parameters of Friction clutches are very important to set precisely and it’s appropriate to use a Torsional Spring-Damper Simulink block for eliminate the torsional vibrations.

Conclusion

This simulation model is fully parametric, whereby it is possible observe the impact of using an electric propulsion system for the transmission elements rotating parts during the dynamic loads, and at multiple input values. Simulation revealed, that a critical node of a mechanical model the shifting elements are. Advantage of this simulation may be the output parameters usage (mechanical power, torque, angular velocity) whose value is changing at depending on the time, and it application for the strength calculation of the rotating parts in an appropriate CAE or FEM software.

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