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Challenges of an electronically distributed all wheel drive on basis of a "retrofit" full hybrid 4WD solution

Rainer Schruth[1], Germano Sandoni[1], Wolfgang Kriegler[1]

[1] MAGNA STEYR Fahrzeugtechnik AG & Co KG, Liebenauer Hauptstraße 317, 8041, Graz, Austria
E-mail: rainer.schruth@magnasteyr.com

Abstract

One important task of electrification of vehicle powertrain is the functional integration of all new systems in respect of the performance, comfort and emission restrictions. In this particular case, starting from a mass produced vehicle platform in the small vehicle segment, the requirement was to keep the originally installed powertrain largely unchanged, but on the other hand enabling hybrid operating functions such as boosting and recuperating and additionally providing some torque vectoring features, under all relevant driving situations. The paper describes and explains the possibilities and limitations of an electrically supported four wheel drive system: first in simulation by use of a mathematical model and then, the experiences gained in the actual development of a prototype car, will be reported. A special focus will be put on the methodology of the development of a model based hybrid controller.

Keywords – Hybrid, all-wheel-drive, rear axle module, hybrid control unit, operating strategy, retrofit solution

1. Introduction

Nowadays modern car powertrain research is oriented in developing alternative drivetrain systems, aimed at saving resources and reducing emissions. A key role in the modern development of a vehicles is played by the design of mechanics combined with electric and electronic hardware as well as software. Hybrid powertrain systems combine standard combustion engines with electrical motors, in order to optimize the consumption and to allow improvements in driving dynamics. The main advantage of a hybrid structure is that, with the help of the electric motors, the internal combustion engine (ICE) is torque compensated and it is brought to the optimal functional working point, which minimizes the consumption/ emission (see [7]). Other advantages are the high comfort obtained through the electrical launch and the high efficiency in traffic with the use of the start/stop mode of the ICE.

Moreover there is the possibility of recuperating energy during braking. With a hybrid driveline also the car performance can be increased: an electrical boost can improve acceleration, handling and the gear shifting can be done without torque lack, simply delivering torque on the electric front axle etc. All these advantages normally are able to compensate the higher costs of the hybrid vehicles, the increased weight and the higher space requirements by the hybrid transmission [1].

Especially in this complex area of optimization parameters, it is very important to work with an flexible and efficient electronic control system for the hybrid driveline, with particular attention to the software architecture. For this in MAGNA STEYR the development of the hybrid software are focused on the modularity and reusability of the software components (like in [7]). All the main physical components of this hybrid system have been modeled by using a graphical technique, named power-oriented graphs (POG). By keeping "coupled" the variables which are "conjugate" with respect to power flow, this graphical technique provides block dynamic models which, usually, are intuitive and easy to use. For a more detailed description of the POG graphical technique, please refer to [9] and [10].

The effectiveness of the control strategy has been tested in simulation, using the presented POG nonlinear model, and results have been compared with the real data obtained on a demonstration vehicle.

This paper is organized as follows: at first, a project (demonstration vehicle) for the application example is presented. After that, the challenges for this kind of hybridization are shown (section 3) and the hybrid powertrain is described in detail (section 4). In section 5 the general proposed software architecture is presented together with. the hybrid functionality of the system. The POG dynamic model of the driveline is described in section 6. Simulations comparison and experimental results, that validate the control strategy can be found in section 7.

2. Project Background

Exemplified for the hybridization issues stands a project of an A-segment vehicle with electronically distributed all-wheel-drive. This project is part of Hi-CEPS (Highly Integrated Combustion Electric Propulsion System), an European Commission (EC) funded project, in which MAGNA STEYR and MAGNA POWERTRAIN are participating (see [3]).

One of the targets in this project is the integration of the hybrid components, without significant changes to a base vehicle, to achieve a low cost hybridization solution. For this purpose a modular concept has been developed, which can be easily adapted to different vehicle architectures and customer (OEM) requirements. Additional to a considerable consumption reduction the hybrid vehicle should have a considerable performance increase in terms of acceleration and drivability.

In order to implement these intentions, the car is hybridized by a distributed power split electric four wheel drive powertrain and equipped with an electric rear axle.

Figure 1: Hybrid demonstration vehicle for a "retrofit" 4WD solution: **compact**city**hybrid**e4WD made by MAGNA STEYR

For the demonstrator vehicle a standard FIAT Panda 1,2l gasoline, as available on the market, was chosen (see Figure 1) and used in the project with a completely unchanged internal combustion engine. A belt-driven high voltage starter-alternator is added to the front drive unit to realize start-stop functionality and charge the battery (by load shifting). The standard belt drive is adapted to fit the hybrid requirements.

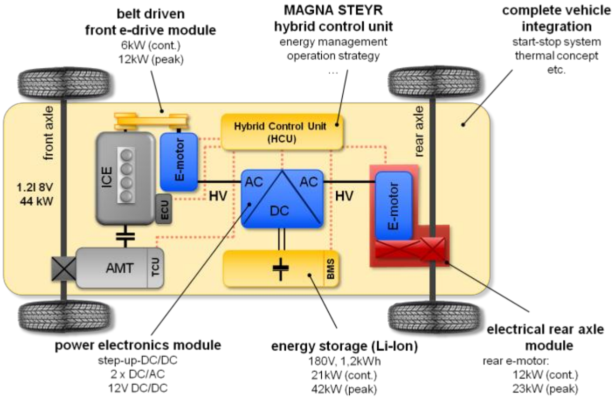

Figure 2: Vehicle architecture of the hybrid demonstrator **compact**city**hybrid**e4WD

The new developed rear axle module consists of a 12 kW electric motor (23 kW peak) coupled with a gear box with a fixed transmission ratio. With a maximum speed of 12,000 rpm the fixed gear ratio can be set to 8 or 12 in the same housing and is optimized with respect to weight, efficiency and NVH (noise, vibration and harshness) aspects. Technical design aspects for this concept are explained in [2].

The MAGNA POWERTRAIN rear axle module is used for boosting and recuperation ("through the road") without mechanical coupling to the rest of the powertrain. The MAGNA STEYR drivetrain control system allows four wheel drive functionality for vehicle start situations and traction improvement. This part is explained more in detail in this paper.

The electric motors in front and in the rear have the same outer diameter. Therefore the power is scalable depending on its length. The power electronics, including all converters (two times DC/AC, 12 V DC/DC and step-up-DC/DC) in one single water cooled housing, is adaptable to the different requirements of the three hybrid vehicles of the Hi-CEPS project (see [3]).

The energy storage unit, a MAGNA Li-Ion power battery, is highly integrated in the FIAT Panda rear end (out of the crash area): the battery housing is developed as part of the vehicle body without changes on the vehicle platform parts. The vehicle architecture and technical details can be seen in Figure 2. The installation situation of the electric rear axle drive module (eRAD) is shown in Figure 3.

Figure 3: Package of the electric rear axle drive module, consisting of the electric motor, the gear box and the rear frame

Because of the modular structure of the powertrain control system (including energy management, thermal management etc.) as well as the scalable hardware components, the hybridization concept can be used in all vehicles of the A to the C segment. It allows very flexible and scalable designs and additional a high level of integration in existing vehicle platforms. Thus marginal modification work is necessary for an industrialization solution to hybridize small mass produced vehicles.

With the same modular software structure MAGNA STEYR realized very different hybrid electric vehicle (HEV) and electric vehicle (EV) concepts like HySUV™ and Mila EV (described in [4]). The hybrid control unit module (HCU) describes with the generic software programming an implementation concept which is in its basic structure cost-efficiently adaptable for all HEVs and EVs.

3. Challenges of an Overall Hybrid Integration

In the mentioned project a very complex hybrid system is implemented. Both axles are equipped with additional electrical motors and all different hybrid modes in every permutation can be realized:

- ICE: coupling to the front axle
- Front e-motor: for load shifting (up and down) and boosting
- Rear e-motor: boosting and recuperating

With this configuration also an electrical distributed all-wheel-drive can be implemented. For the realization the HCU of MAGNA STEYR is used in that way as explained in the following sections. The challenges are to manage the detection of different driving demands, different environment conditions as well as slacks in the physical system.

With the knowledge of these requirements the different driving situations are implemented with the best strategy to reach all targets in terms of consumption, drivability comfort and performance improvements.

Several decision are necessary for:

- Boost (rear or front)
- Brake (with or without recuperation)
- All-wheel-drive activation
- Driveaway (without jerking)
- Driveaway uphill
- Recuperation (through the road on different surface conditions)

The main target is to control this prototype hybrid system in order to increase the fuel economy to a significant value. Therefore the control algorithms and software control strategies of different alternative propulsion systems should be taken and adapted, considering the project target setting of ability for industrialization.

In order to control the hybrid vehicle functionality, the main functional software tasks are the following:

- Driver request calculation for traction control
- Energy management
- Torque coordinator
- Belt drive system
- Rear axle system
- Energy storage status
- Auxiliary management

The following steps are the integration of the engine start maneuvers and the functionalities for electric and serial driving. After these functionalities are established and the system behavior is validated the parallel hybrid mode and standard driving mode are to be implemented. Validation will be finished when the system application on the test track has been carried out. A main problem of a hybrid system is given by the transition between different operation modes like engine start and stop, parallel, serial hybrid and electric maneuverings.

Due to the presence of oscillations in the high voltage traction system, high power transients and amplitudes appears on the real system. To investigate this transient behavior also with a focus on noise, vibration and harshness (NVH) and electromagnetic compatibility (EMC) issues, a very flexible model is necessary.

4. Hybrid Powertrain Description

The physical arrangement of the considered hybrid powertrain is shown Figure 4. The electric motor EM2 is added at the front engine belt as starter/alternator instead of the conventional starter without modifying the longitudinal driveline topology. On the rear axle the additional electrical motor EM1 is responsible for the traction. A detailed explanation of the high voltage power net topology is described in [6].

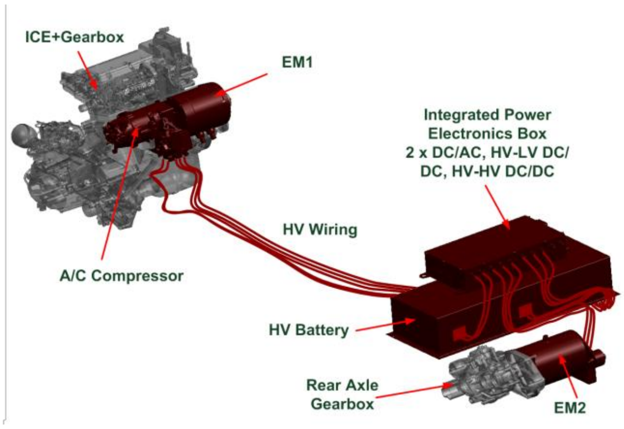

Figure 4: Component arrangement of the hybrid driveline

The basic functional principles of the hybrid powertrain are shown in Figure 5.

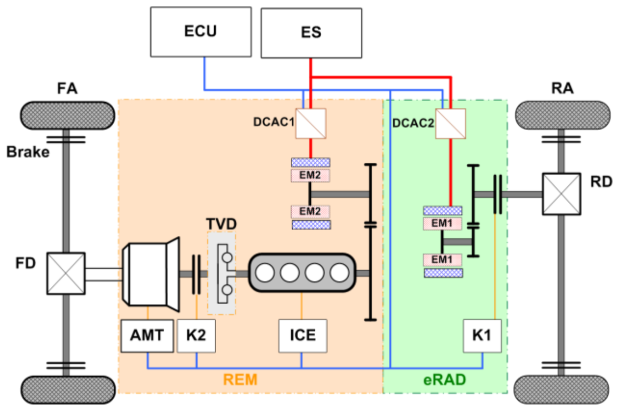

Figure 5: Hybrid powertrain schematization

The two electric motors EM1 and EM2 are connected to the rear axle (RA) and to the front axle (FA). For the rear axle the torque flows from electrical motor EM1 through the clutch K1 to the rear differential (RD). On the other hand the ICE and the EM2 are bringing the torque through the torsion vibrator damper (TVD), the clutch K2, the automated manual transmission (AMT) gearbox and the front differential (FD) towards the front wheels. This corresponds to the parallel hybrid configuration where the maximum efficiency of the vehicle is achievable. Through the two converters DCAC1 and DCAC2 it is possible to get/store energy from/towards the energy storage system (ES). The serial hybrid configuration is obtained by keeping the clutch K2 opened and the clutch K1 closed. So the electrical motor EM1 brings torque to the rear wheels, passing through the differential RD. Simultaneously the ICE and the EM2 are used as generator for loading the battery system ES. The proposed hybrid powertrain configuration is very flexible: due to the presence of the two clutches K1, K2, and both the electrical motors can be used to drive torque towards the ground.

The overall hybrid system is real time controlled through a rapid prototyping electronic control unit (ECU). In Figure 5 it is possible to distinguish already two important functional software modules, the range extender module (REM) and the electric rear axle drive module (eRAD).

5. Software Architecture Concept

The functional control software architecture, shown in Figure 6, has to bring and keep the hybrid transmission into the optimal working point in every driving situation.

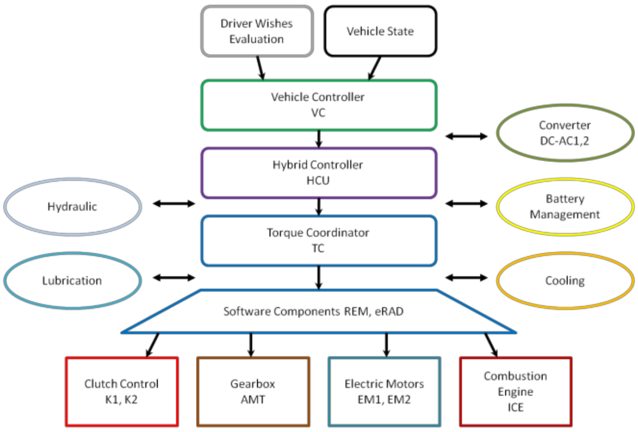

Figure 6: Functional software architecture for hybrid transmission and energy management

The drivers wishes, coming from the gas pedal, the brake pedal, the gear level and the steering wheel position are combined with the dynamic state of the vehicle (velocity, yaw rate, slip angle, etc.) and evaluated in the vehicle controller module (VC). This VC module is designed to optimize the traction and to translate the driver wishes in torque on the front respectively rear axles, in consideration of the availability of the request torque. The requested torques at the axles are passed to the hybrid control unit module (HCU). The HCU decides how to divide the torques between the different components EM1, EM2, ICE and calculates the actual gear as well as the transmitted torques through the clutches K1 and K2. These decisions are made on the basis of global efficiency, thermal condition, charge of the battery, comfort and the dynamic state.

The four wheels drive functionality is also implemented in this module. The main goal of the torque coordinator module (TC) is to handle and control the transient behaviors (e.g. launch and gear shift) and to apply the pseudo stationary HCU requested torques/gear directly to the different components. The different software components are shown in Figure 7. They have been designed to control the gearbox, the electric motors EM1, EM2 and the internal combustion engine, in such a way that the reference signals of the torque coordinator are followed as fast as possible. In the same figure it is possible to distinguish, that the "position" of the functional software (FS), with a defined interface software (IS), is resulting almost independent from the hybrid powertrain structure of the vehicle.

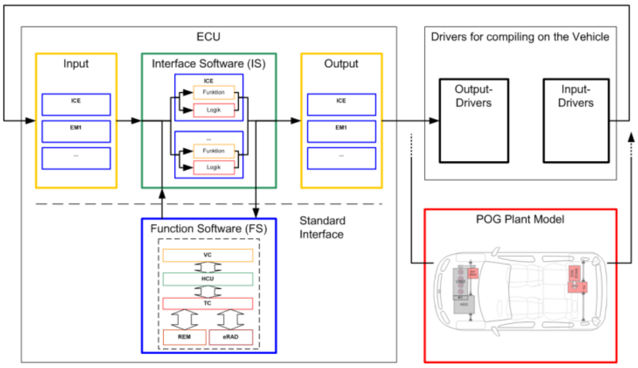

Figure 7: Global modular control software structure for hybrid transmission

In Figure 7 and Figure 8 is also shown the possibility to realize an easy interchange between the POG plant simulation model and the input sensors and output actuators to/from the real vehicle.

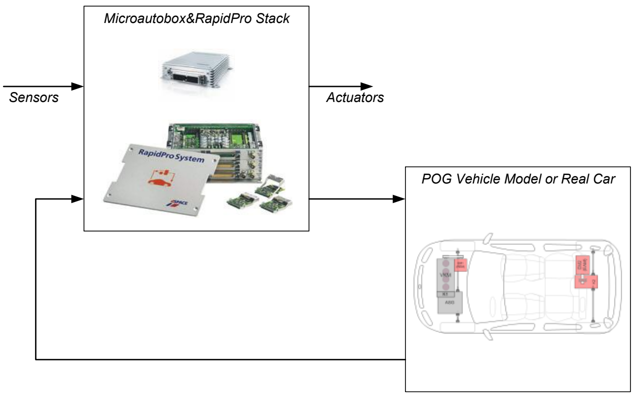

Figure 8: Electronic control for hybrid transmission

In this way it is possible to execute hardware in the loop (HIL) functional verification tests also without the availability of a physical car. In next section the detailed POG model of the proposed hybrid driveline will be described in details.

6. Power Oriented Graphs Model of the Hybrid Drivetrain

6.1 Basic Concept of POG Modeling Technique

The "Power-Oriented Graphs" are "signal flow graphs" combined with a particular "modular" structure essentially based on the two blocks shown in Figure 9. The basic characteristic of this modular structure is the direct correspondence between pairs of system variables and real power flows: the product of the two variables involved in each dashed line of the graph has the physical meaning of "power flowing through the section".

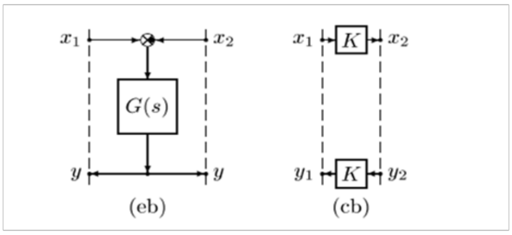

Figure 9: Graphic representation of the "basic" POG blocks: elaboration block (eb) and connection block (cb)

The two basic blocks shown in Figure 9 are named "elaboration block" and "connection block". There is no restriction on the choice of variables x and y other than the fact that the product x*y must have the physical meaning of a "power". The elaboration and connection blocks are suitable for representing both scalar and vectorial systems. While the elaboration block can store and dissipate energy (i.e. springs, masses and dampers), the connection block can only "transform" the energy, that is, transform the system variables from one type of energy-field to another (i.e. any type of gear reduction). Main characteristics of the POG technique are: a direct correspondence between the POG blocks and the real parts of the system; the POG schemes can be easily transformed, both graphically and mathematically; the state space mathematical model of a system can be "directly" obtained from the corresponding POG representation.

6.2 POG Model of the demonstration vehicle

As easy example of the POG schemes we can consider the longitudinal vehicle dynamic of Figure 10.

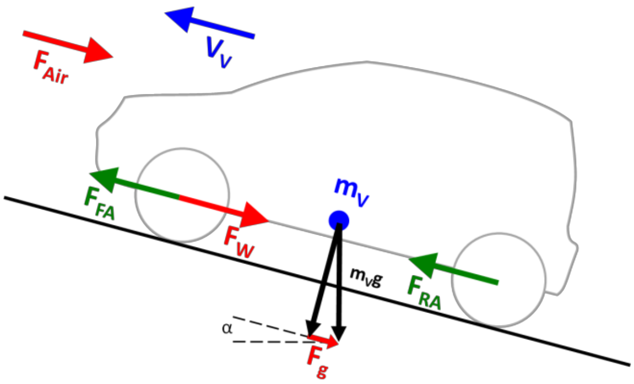

Figure 10: Longitudinal vehicle dynamics

The dynamic equation of the vehicle dynamics is:

$$m_V \frac{dv_V}{dt} = F_{FA} + F_{RA} - d_w v_V - c_W A v_V^2 - m_V g \sin(\alpha)$$

Where m_V is the mass and v_V the velocity of the vehicle, F_{FA}, F_{RA} are the forces at the ground coming from the electric motors and ICE on the front, respectively the rear axle, d_W is the rolling friction linear coefficient of the tires. c_W is the coefficient of penetration of the air in the lateral section A of the vehicle, g is the gravity accelerations and α is the slope of the street.

The same dynamic equation can be easily represented with a graphical block diagram in Figure 11.

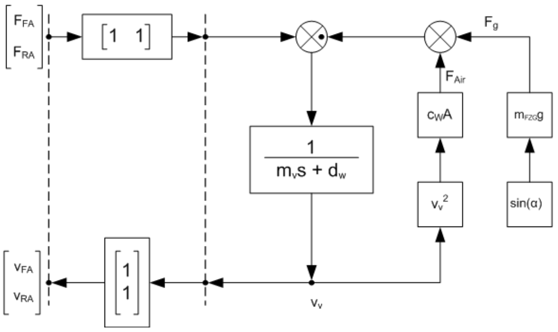

Figure 11: POG model of the longitudinal vehicle dynamics

This mathematical model is possible to "translate" in a very easy way into the Matlab/Simulink simulation model. In the same way the whole electric drivetrain can be modeled and easily simulated as shown in Figure 13 for the range extender module. For a more detailed description of the whole modeling technique please refer to [5], [10].

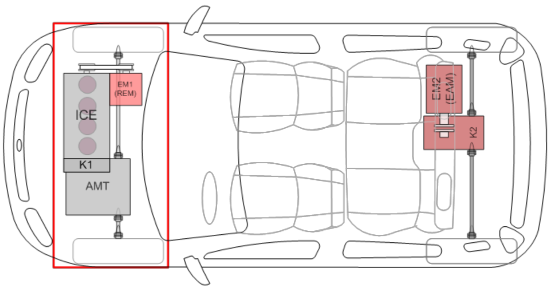

Figure 12: Range extender module in the vehicle corresponding to the REM POG model

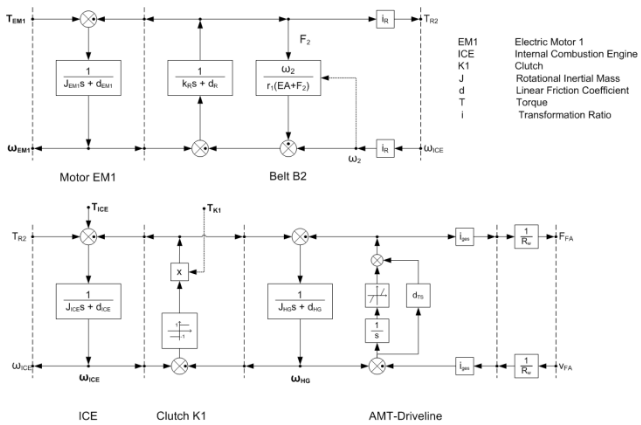

Figure 13: POG model of the range extender module

In order to precisely identify the parameters of the POG model, different tests have been executed: in particular a cost down test and a gear shifting test. In that way the whole hybrid functionalities can be tested first in simulation and then on the real vehicle.

7. Simulations Results Comparison

In Figure 14 and Figure 15 some comparisons between simulation and measurement results are shown.

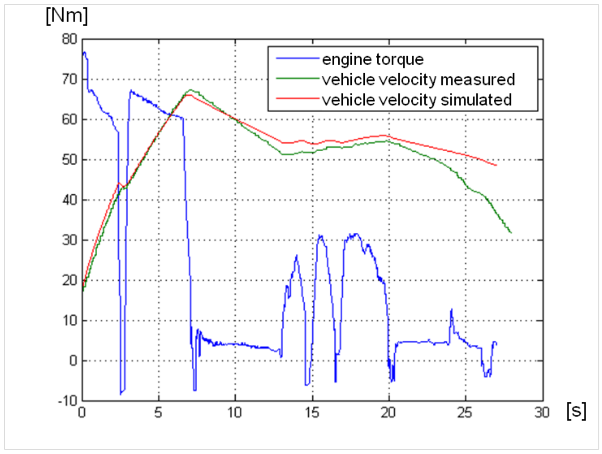

Figure 14: Comparison between the real measured vehicle velocity (green) and the simulated velocity (red) under the same input torque at the ICE

In this figure it is possible to see the behavior of the input engine torque coming from the driver gas pedal. The HCU is interpreting the driver intention and the state of the battery. With this information the HCU is delivering torque to the ICE and/or the electric motors. It is also choosing the optimal gear of the AMT in order to keep the minimum consumption and at the maximum efficiency. The simulations correspond to an acceleration of the vehicle with two upshift points and a roll down at almost constant speed. Both figures clearly show that the simulation results are very similar to real values measured on the system. The small differences are caused by the difficult identification of the friction parameters.

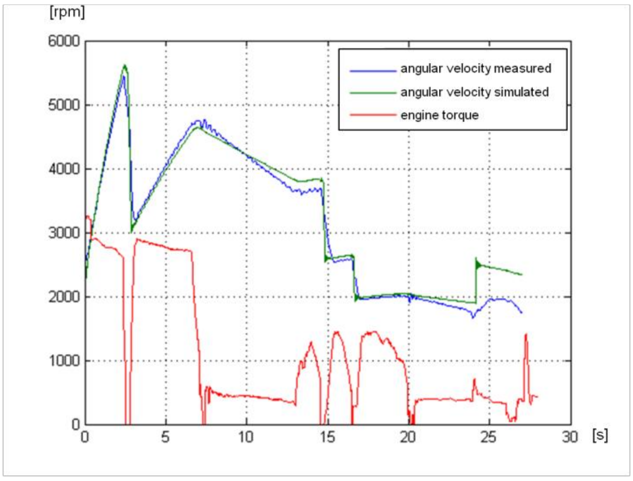

Figure 15: Comparison between the real measured ICE velocity (green) and the simulated velocity (red) during a gear shift

8. Summary and Conclusions

Hybrid vehicles have been already for some years on the market with the target of reducing fuel consumption and emissions. An innovative four wheel drive hybrid drivetrain was developed in MAGNA STEYR with the additional aim to improve performances and drivability comfort. In this paper the process for developing and integrating a full hybrid solution in terms of hardware and software on a standard production vehicle has been presented. The implementation of the presented hybrid powertrain topology, allowed MAGNA STEYR to develop a full modular integrated unit, that covers a wide range of driving possibilities: parallel, serial-hybrid, pure electric mode etc. This solution is suitable for various platforms of vehicle and classes. In particular the modular control software has been developed in Matlab/Simulink, tested in simulation with the POG modeling technique and then implemented in a dSPACE rapid prototyping hardware. The realization of a prototype demonstration vehicle with the model based oriented technique shows the capability for the complete vehicle integration in a serial production process. In that kind the presented development describes a very beneficial "retrofit" solution for mass produced vehicles.

9. Acknowledgements

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11. Authors

Rainer Schruth, Dipl.-Ing. in Electrical Engineering at RWTH Aachen. International work experiences in different automotive companies. Since 2006 MAGNA STEYR Engineering Center Graz, Department of Advanced Development. Responsible for research activities of complete vehicle development projects in the innovation field of sustainable powertrain concepts. Project leader of EU funded project Hi-CEPS. Head of Alternative Propulsion Systems Group. *rainer.schruth@magnasteyr.com*

Germano Sandoni, Ph.D. in Automatic Control, 2002 at Technical University of Modena and Reggio Emilia in collaboration with automotive company. University assistant from 2000 till 2003. Since 2004 employee in MAGNA STEYR Engineering Center Graz, Software Development. Responsible for the control of different hydraulic and electric actuators in hybrid and conventional drivelines. Took part in different advanced powertrain development projects. Eleven international publications. *germano.sandoni@magnasteyr.com*

Wolfgang Kriegler, Dipl.-Ing., studied mechanical engineering with special focus on internal combustion engine technology at the Technical University of Vienna. In his former positions he gained comprehensive experiences in the development of ICEs and in the field of hybrid and electric powertrains. Since 2009 head of MAGNA STEYR advanced technology development and responsible for innovative product development in the area of sustainable powertrain concepts, virtual product development and production process, innovative vehicle concepts, lightweight construction and electronic technologies. *wolfgang.kriegler@magnasteyr.com*