Drivability improvements obtained using a mild hybrid electrical system on a vehicle equipped with a manual gearbox

Ștefan Saragea*, Gheorghe Frățilă, Gabriel Badea

1 PhD Student, Automotive Engineering Department, Politehnica University of Bucharest, Bucharest RO-060042, Romania
2 Professor, Automotive Engineering Department, Politehnica University of Bucharest, Bucharest RO-060042, Romania

*Corresponding author’s e-mail: stefansaragea@gmail.com

Abstract. In order to fulfil the latest and future emission standards, all vehicles will need to be equipped with hybrid powertrains or advanced depollution systems. For low cost and entry level range of vehicles, in order to keep the production costs low, the simplest choice of hybridization is the mild-hybrid system with integrated starter-generator (ISG). This paper contains a model of a mild-hybrid electric vehicle equipped with a manual gearbox with focus on the drivability performance of the powertrain. The goal of this paper is to find out the drivability performances of a hybrid vehicle by simulation and to show the improvements compared to a similar vehicle equipped with a conventional powertrain.

1. Introduction

In order to reduce CO₂ emissions for the passenger vehicles, the latest European Union regulations [1] (EC regulation 443/2009) sets a target of 95 g CO₂/km for the average emissions of the new car fleet for each car manufacturer starting with the year 2021.

In order to fulfill the emission target, manufacturers are required to reduce the fuel consumption of their vehicles. One of the solution for reducing the fuel consumption is the hybridization of the vehicles. The simplest way of hybridization is the mild-hybrid system with Integrated Starter Generators (ISG).

The current forecast [2] shows that the mild hybrid vehicle global market share will reach 15% by 2030, compared to a decrease of market share for the conventional ICE vehicles to 47% by 2030 (from a market share of 78% in 2020 – figure 1).
2. Simulation model presentation

The model of the 48V mild hybrid electric vehicle was simulated using LMS Imagine.Lab AMESim program [3]. The simulation contains a B-class vehicle equipped with a 6 speed manual gearbox, 48V electric motor (Integrated starter generator) and 1 liter (998 cm³) petrol internal combustion engine (ICE).

![AMESim model of a mild-hybrid electric vehicle equipped with a 6 speed Manual Gearbox](image)

Fig. 2. AMESim model of a mild-hybrid electric vehicle equipped with a 6 speed Manual Transmission
The main components of the model are the following:

- **Internal combustion engine (ICE)** – The inputs for the engine model are torque structure and the engine load. The torque structure and losses are similar to a turbocharged 998 cm³ engine with 3 cylinders. The output of the engine are the torque transmitted to gearbox and exhaust gasses.
- **Gearbox and clutch (GB)** – the clutch and gearbox were modeled in order to simulate the clutch, gearbox and driveshaft torque oscillations during clutch closing.
- **Engine control unit (ECU)** - the engine control unit is used in order to set the source of the torque distributed to the drive wheels between the ICE and EM. The inputs for the ECU are: driver acceleration, braking and clutch command, battery state of charge, current and voltage, gearbox ratio and ICE speed. The output from the ECU are: ICE and EM load control.
- **Electric motor (EM)** – the EM model is a simple model with the following inputs: battery voltage, load control from ECU and temperature. The output is the torque produced by the motor. The electric motor parameters are presented in Table 1.

### Table 1. Electric motor parameters

| Nr. | Item               | Value          |
|-----|--------------------|----------------|
| 1   | Maximum Output Torque | 40 Nm          |
| 2   | Mechanical power   | 14 kW          |
| 3   | Speed              | 20,000 rpm     |

- **Battery** – the battery model is a simple Lithium-Ion battery model with the following outputs: battery current and voltage and state of charge. The battery parameters are presented in Table 2.

### Table 2. Battery parameters [4]

| Nr. | Item                    | Value          |
|-----|-------------------------|----------------|
| 1   | Capacity                | 6 Ah           |
| 2   | Operating Voltage       | 24-54 V        |
| 3   | Configuration           | 14 series / 1 parallel |
| 4   | Weight                  | 7kg            |
| 5   | State of charge range   | 30-80 %        |
| 6   | Usable energy           | 138 Wh         |
| 7   | Dimensions              | 304 x 92 x 180 mm |

The selected battery has compact dimensions, in order to integrate the battery in the body of the car without major modifications of the car body.

- **Car body** - this sub model is a simple model of a vehicle load used to calculate the longitudinal acceleration, velocity and displacement of the car body. The input parameters for this model are the vehicle mass, the aerodynamic coefficient, the frontal area and the air density.

### 3. Simulation results

One of the main disadvantage of downsized engines with reduced displacement and 3 cylinders is the need of heavy flywheel in order to reduce the engine vibrations transmitted to vehicle body. Due to the heavy flywheel, the engine inertia is high and the engine speed derivative in no load conditions is low compared to similar performance non-downsized engines.
In Figure 3 is presented a gear change from 2nd to 3rd gear with medium engine load. As can be seen, due to engine high inertia, the engine speed derivative is low (600 rpm/s). During the closing phase of the clutch, the engine speed is forced down to the primary shaft speed for the 3rd gear. This behavior causes high engine speed (Engine speed) and torque oscillations in the drivetrain which in turn causes high longitudinal acceleration oscillations to the car body. The maximum longitudinal acceleration oscillation is 2.5 m/s² (Longitudinal acceleration), this value causes discomfort for passengers during gear changes.

In case of the mild hybrid vehicles equipped with ISG, during the gear change, the engine speed derivative can be increased to 1000 rpm/s by increasing the engine load with the ISG. In this case, when the clutch is closed, the engine speed (Engine speed EM) is closer to the primary shaft speed and the maximum car body longitudinal oscillation is 0.9 m/s² (Longitudinal acceleration), compared to a maximum longitudinal acceleration of 2.5 m/s² for the vehicle without ISG.

A shift strategy with internal combustion engine speed control can be implemented in order to improve comfort during gear shifts. This strategy is similar with the strategy presented in a paper before [5].
Figure 4. Engine speed control strategy during gear shifts

The input for the engine speed control is the engine speed, the vehicle speed, the gear ratios and the clutch pedal position. With these inputs, the engine speed set point during gear shift is calculated. The calculated engine speed, the fuel injection and the body throttle are inputs for engine speed control using a PID regulator. The output of this strategy is the speed of the ICE which should be equal to the speed of the input shaft of the gearbox when the clutch is closed in order to produce a seamless gear shift.

Figure 5. Gear shift strategy with internal combustion engine speed control

In figure 5 is presented the gear shift strategy with the internal combustion engine speed control during gear shift. In order to cover different types of drivers, with different shifting times, the internal combustion engine speed (black signal) is maintained at the speed of the gearbox input shaft (green signal) using a PID regulator in order to follow the engine speed shift set point (red signal). In order to reduce the fuel consumption and to reduce the exhaust gases, during the gear shift, when the clutch is pressed, the engine speed is controlled by the electric motor (ISG).

Another improvement obtained using an ISG on a vehicle is the dynamic performance of the vehicle. The ISG can provide assistance power to the ICE when high engine load is requested by the driver, for example in an overtaking maneuver.
Figure 6. Vehicle acceleration in 4th gear from 60 km/h

In figure 6 is presented an overtaking maneuver, a vehicle acceleration from 60 km/h in 4th gear for a conventional vehicle and a mild-hybrid vehicle equipped with ISG. For the conventional vehicle equipped with only an ICE, the speed (Vehicle speed) of 80 km/h is reached in 7 seconds and the maximum torque (ICE Torque) of 170 Nm is obtained in 3.4 seconds after the acceleration pedal is pressed, due to the delay of increasing pressure in the turbocharger and intake manifold. For the mild hybrid vehicle equipped with ISG, the speed (Vehicle speed EM) of 80 km/h is reached in 4.5 seconds (2.5 seconds faster compared to conventional ICE time) and the ICE maximum torque of 170 Nm is obtained after 0.5 seconds (compared to 3.5 seconds with conventional ICE). This improvement on crankshaft torque is possible due to assistance from the ISG. A maximum of 80 Nm (EM Torque) at crankshaft can be produced by the ISG for a short amount of time (about 1.5 to 2 seconds), after this time, the ISG can still assist the ICE continuously with 40 Nm. The maximum torque produced by the mild hybrid vehicle powertrain (ICE + EM Torque) is 210 Nm (compared to 170 Nm for conventional ICE vehicle), achieved after 3.5 seconds. The response time of the mild hybrid powertrain can be further improved by using an electrically assisted turbocharger (e-turbocharger), which reduces the time needed for increasing pressure in the compressor and intake manifold.

4. Conclusion
In this paper are presented the drivability improvements using a mild hybrid electric vehicle using a 48V Integrated Starter Generator with focus on gear shifts and vehicle performance during acceleration. Using the Integrated Starter Generator, the internal combustion engine speed can be controlled during gear shifts in order to match the internal combustion engine speed with the gearbox input shaft speed. The results show improvement in longitudinal acceleration oscillations after the clutch is closed and also reduced acceleration times during overtaking maneuvers.

Other improvements obtained using mild hybrid electrical powertrains are reduced vehicle emissions, improved thermal comfort for passenger (possibility to equip vehicle with electrical AC compressor which can provide AC when the engine is stopped in start&stop mode and electrical cabin heaters during cold weather), electrical vacuum pump in order to improve braking performance without ICE torque consumption and engine oil heating in order to achieve maximum ICE performance faster during cold weather.
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Acknowledgments
This work has been funded by the European Social Fund from the Sectoral Operational Programme Human Capital 2014-2020, through the Financial Agreement with the title "Scholarships for entrepreneurial education among doctoral students and postdoctoral researchers (Be Antreprenor!)", Contract no. 51680/09.07.2019 - SMIS code: 124539.