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Software strategy for internal combustion engine and electric motor control on a hybrid electric vehicle equipped with belt starter generator and automated manual transmission

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Abstract. In order to fulfil the latest EU emission standards, the average amount of CO_2 emissions for each vehicle sold has to be reduced to avoid fines for manufacturers. One of the simplest and cheapest ways of hybridization is the belt starter generator (BSG), which makes it suitable for an entry-level range of vehicles. This paper presents a software strategy developed for internal combustion engine (ICE) and belt starter generator (BSG) control on a vehicle equipped with automated manual transmission and also the drivability, comfort and emission performances improvements expected by using this strategy.

1. Introduction

In order to fulfil the latest EU emission standards, the average amount of CO_2 emissions for each vehicle sold has to be reduced to avoid fines for manufacturers. The latest European Union regulations (EC regulation 443/2009) sets a target of 95 g CO_2/km for the average emissions of the new car fleet for each car manufacturer starting with the year 2021.

In figure 1 is presented the average CO_2 emissions for vehicles sold in European Union for each manufacturer. As can be seen from the average of CO_2 emissions, all manufacturers are above the 95 g CO_2/km, and further improvements in ICE efficiency and increasing the level of hybridization is needed to achieve the target.

One of the simplest and cheapest ways of hybridization is the belt starter generator (BSG), which makes it suitable for an entry-level range of vehicles.

The software strategy presented in this paper is developed for both hybrid vehicles equipped with an internal combustion engine (ICE) and belt starter generator (BSG) with manual or automated-manual gearboxes, and also for conventional vehicles equipped only with ICE.

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Man	R	Specific emissions target	Average CO2 emissions
BMW GROUP pool	1,003,404	140.8	125.6
DAIMLER AG pool	985,163	139.7	136.7
FCA-TESLA pool	984,048	129	115.7
FORD-WERKE GMBH pool	978,961	133.7	130.8
HONDA MOTOR EUROPE LTD pool	116,980	130.8	125
HYUNDAI pool	552,340	128.9	124.2
KIA pool	497,564	128.7	122.8
MG-SAIC pool	14,102	140.1	124
MITSUBISHI MOTORS pool	139,438	133.2	115.6
PSA-OPEL pool	2,507,547	125.7	113.9
RENAULT pool	1,653,093	126.3	118.1
SUZUKI pool	254,016	123.1	120.6
TATA MOTORS JAGUAR LAND ROVER pool	214,955	178	157.6
TOYOTA-MAZDA pool	1,035,435	129	108
VW GROUP PC pool	3,722,198	133.2	123.9
NISSAN INTERNATIONAL SA	391,479	130.5	114.3
VOLVO CAR CORPORATION	326,205	148.3	131.9

Figure 1. Average CO_2 emission of each manufacturer for vehicles sold in Europe in 2019 [1]

2. Strategy presentation

The strategy was constructed using LMS Imagine.Lab AMESim program [2].

The software strategy was developed to be used for both conventional vehicles (ICE only) and hybrid vehicles equipped with an internal combustion engine (ICE) and belt starter generator (BSG) with manual or automated-manual gearboxes.

The strategy was divided into 4 parts:

2.1. Strategy activation

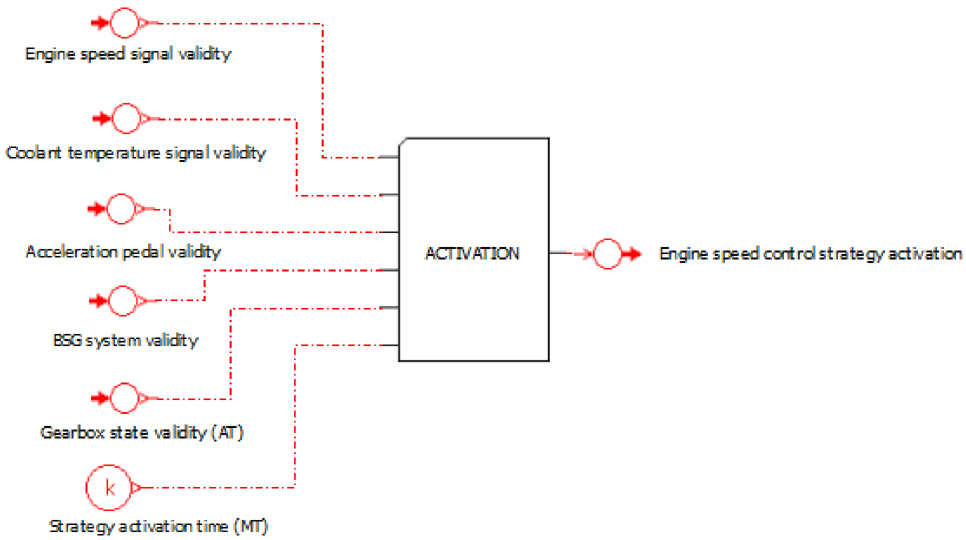

Figure 2. Strategy activation conditions.

In figure 2 are presented the conditions for the activation of the internal combustion engine (ICE) speed control during gear shifts. To have a smooth operation of ICE, the strategy will be activated only if all the following signals are valid:

- Engine speed signal – the engine speed is the main parameter of the strategy
- Coolant temperature – the coolant temperature is needed because the parameters of the strategy can be calibrated in the function of coolant temperature value. The coolant temperature has an impact on engine torque loses (ICE friction torque) which is an important factor in strategy functionality (conventional vehicles, ICE only)
- Acceleration pedal position – the acceleration pedal position is needed to calculate the engine speed setpoint during a gear shift. For low acceleration pedal positions, a smoother engine speed evolution can be used and for high acceleration pedal positions, faster engine speed decreasing must be achieved.
- BSG system – for vehicles equipped with BSG, the BSG is the main system that controls the ICE engine speed evolution during a gear shift.
- Gearbox state – for vehicles equipped with Automatic Manual Transmission, the shifting time is necessary for engine speed setpoint during gear shift calculation.

For a vehicle equipped with a manual gearbox (MT), the duration of the strategy activation can be set to avoid an engine speed hook if the driver stays with the clutch pedal pressed (sailing). The duration of the strategy activation can be set in the function of acceleration pedal position before strategy activation and selected gear.

The validity of the input signals is generated by the ICE control unit using self-diagnosis for each of the presented sensors. If one of the input signals is not valid (for example sensor malfunction, not plausible signal), the strategy will not be activated. In the case of vehicles equipped with Automated Manual Transmission, the gearshift will work on a backup strategy.

2.2. *Engine speed setpoint during gear shift*

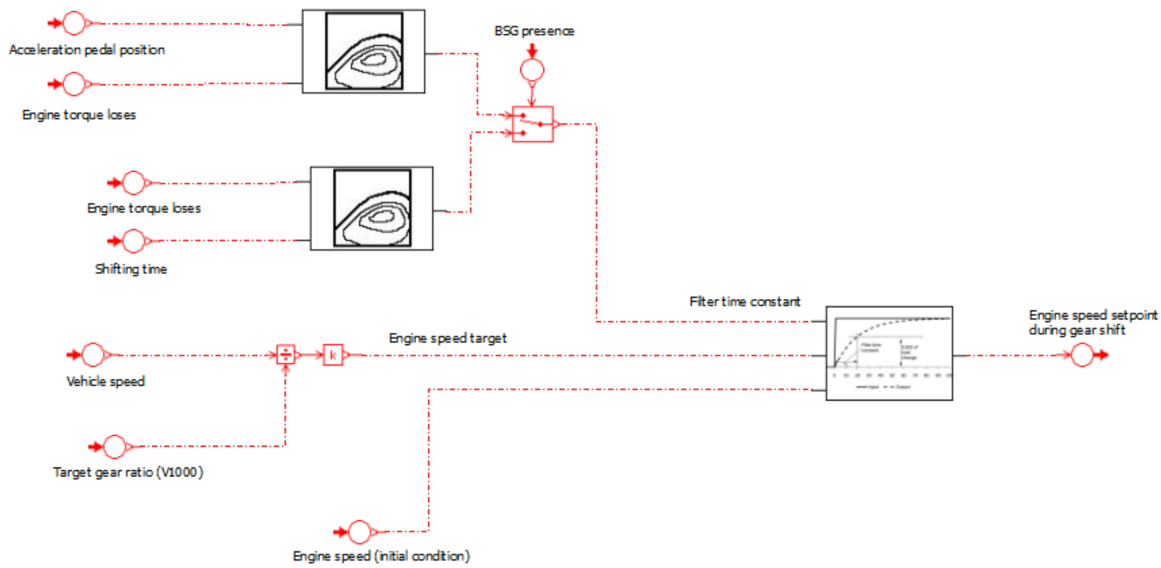

Figure 3. Engine speed setpoint during gear shift calculation.

In figure 3 is presented the engine speed setpoint calculation during a gear shift. The initial condition is the engine speed at which the strategy is activated. The target engine speed is calculated from the vehicle speed and the target gear ratio (V1000 - vehicle speed at 1000 min^{-1}). The engine speed setpoint transition is made using a calibrated filter (first-order filter). The filter time constant is calculated in function of vehicle type:

- for mild hybrid vehicles (ICE + BSG), the filter can be calibrated in the function of engine torque loses and acceleration pedal position. For low acceleration pedal position, for smoother gear shifts, the filter can be increased to achieve smoother gear shifts. For the high acceleration pedal position, the filter can be reduced to achieve faster gear shifts to increase vehicle performance.
- for conventional vehicles (only ICE), the filter can be calibrated in the function of engine torque loses and shifting time.

2.3. PI regulator

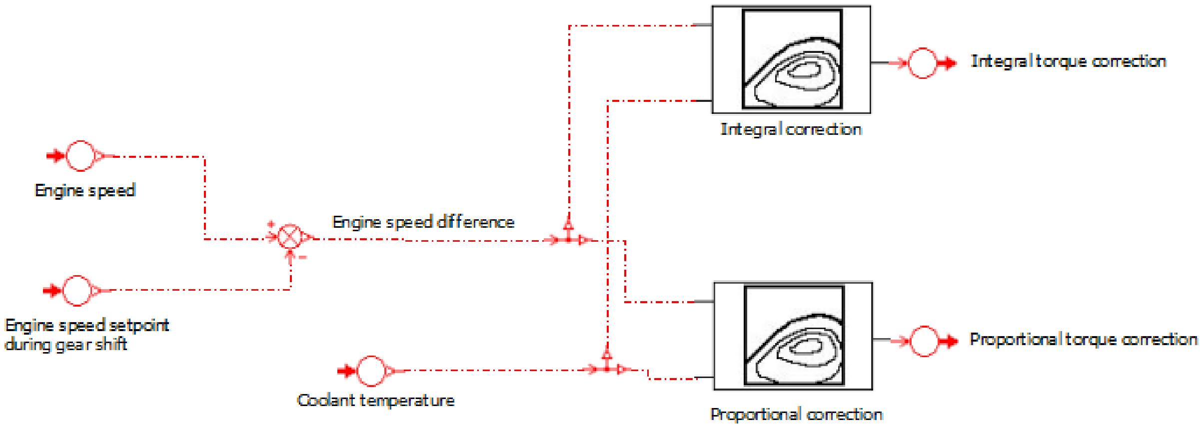

Figure 4. PI regulator.

In figure 4 is presented the PI regulator used to control the engine speed during a gear shift.

When the strategy is activated, the engine speed is compared to the engine speed setpoint (presented in 2.2). In function of the engine speed difference and the coolant temperature, the proportional and integral correction factors are calibrated to achieve smooth engine speed evolution during a gear shift. The proportional and integral correction factors will be calibrated as follows: in case of low coolant temperature, the factors will be lowered due to combustion low quality and high engine friction. Regarding the engine speed difference, the factors will be increased in coherence with the engine speed difference.

2.4. Torque correction

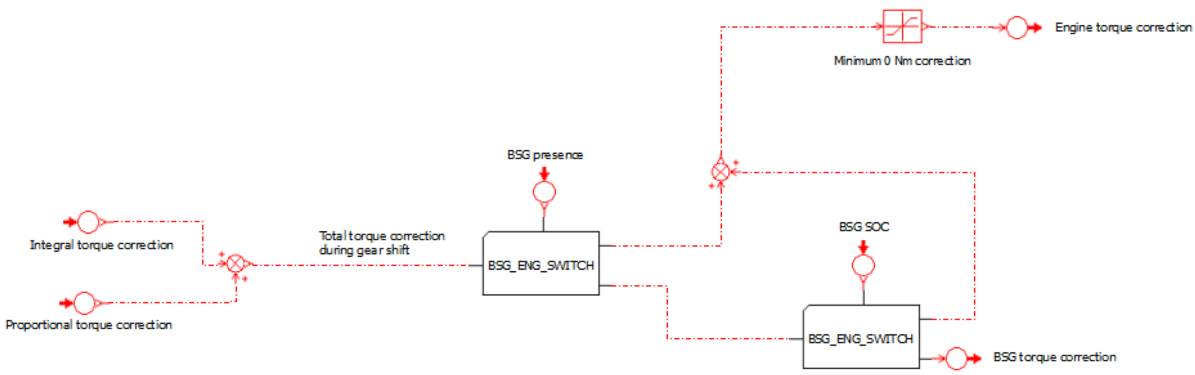

Figure 5. Torque correction.

In figure 5 is presented the torque correction calculation. The proportional and integral corrections are combined and in the function of the vehicle, the type is sent to ICE or BSG.

- For Mild hybrid vehicles equipped with BSG, the torque calculated during gear shift is sent to the BSG. In the case of positive torque, the BSG acts as an electrical motor and increases internal combustion engine speed. In the case of negative torque, the BSG acts as a generator and decreases internal combustion engine speed to follow the engine speed setpoint. In case of the low state of charge (SOC) for the battery, the BSG is deactivated from the strategy and the engine speed is controlled by the ICE only.
- For ICE vehicles (conventional vehicles), the torque correction is limited only to positive torque. The negative torque is not considered because in the case of low engine speeds if high negative torque is requested, there is a risk of engine stall. The disadvantage of using only the positive torque is that in the case of ICE with high inertia and low torque consumption (auxiliary torque loses, friction torque loses and pumping torque loses), the engine speed decrease is low (500-600 min^{-1}) [3] and to achieve smooth gear shift, the shifting time must be increased. For manual transmission applications or in the case of AMT at high engine load (shifting time is reduced to a minimum), a software strategy improvement can be considered, increase the load on the alternator or activate the air conditioning compressor during gear shift to increase the engine brake.

3. Expected results

The main improvement expected using this strategy is smoother vehicle longitudinal acceleration during a gear shift.

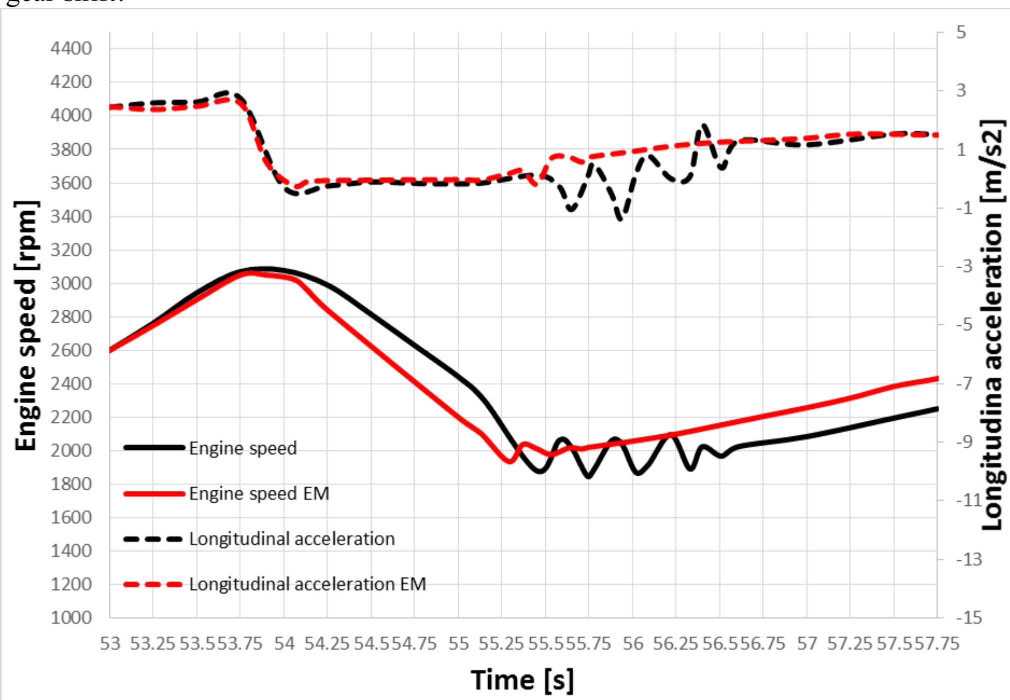

Figure 6. Engine speed and longitudinal acceleration variation during gear change from 2nd to 3rd gear. [3]

In figure 6 are presented the improvements expected to be obtained using the software strategy presented above during gearshifts for mild hybrid vehicles equipped with a belt starter generator (BSG). Using the BSG to control the ICE speed during gearshifts, the maximum car body longitudinal oscillation was 0.9 m/s^2 (Longitudinal acceleration), compared to a maximum longitudinal acceleration of 2.5 m/s^2 for the vehicle without ISG and engine speed control strategy during gear shift from 2nd to 3rd gear.

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For conventional vehicles (only ICE), as presented in a previous paper [4], by controlling the engine speed during the gear shift, the longitudinal acceleration oscillation was reduced by 50%, from 3 m/s^2 to about 1.5 m/s^2.

4. Conclusion

This paper is presented a software strategy used to control the internal combustion engine speed during gear shift to synchronize the ICE speed to the input shaft of the gearbox. The strategy was developed to be used for mild hybrid vehicles equipped with Belt Starter Generators (BSG), for conventional vehicles (ICE only) and also for vehicles equipped with manual transmissions and automated manual transmissions (AMT).

By using the mild-hybrid system with BSG, the vehicle CO_2 emissions can be reduced by up to 20% [5,6]. A reduction of 20% in CO_2 emissions can lead to the emission target (95 g CO_2/km in 2021) fulfilment for most manufacturers, compared to 2019 average CO_2 emissions (presented in Figure 1).

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