48 Volt Hybrid with e-drive features - Excellent fuel efficiency and drivability

Abstract

In this paper a propulsion concept is presented that targets the market between 48 volt starter generator systems and high voltage hybrid systems. In order to enable both CO₂ savings and good drivability, in a holistic approach, a high power density gasoline engine has been combined with a 48 volt P2-hybrid system. An optimized operating strategy enables a decrease in CO₂ emission. The P2 system is in particular characterized by an axially-parallel arranged E-machine that is connected with the powertrain and an air conditioning compressor via a poly-V belt drive. The opportunity to offer an electrically powered air conditioning without additional costs and moreover purely electric driving at low vehicle velocity are two of the most attractive functions of this P2 hybrid electric vehicle. With the e-drive option in particular the basis for automated/autonomous parking is set also with standard manual transmissions. Finally, similar to a starter generator system, the capability of a comfortable and fast engine start with the 48 volt E-machine is provided as a key functionality by the presented system. Various maneuvers are discussed and compared in a standard drive cycle with regards to functionality and drivability.

1. Introduction

Since the combustion engine has already reached a very high level of technical sophistication and further efficiency improvement potential is more and more limited, it is widely accepted that the electrification of the automotive powertrain will be necessary to comply with the future requirements on CO₂ and noxious gas emissions. The range of potentially conceivable and already existing hybridization concepts encompasses systems from enhanced 12 volt on-board power net via 48 volt mild hybrid electric vehicles (mHEV) to extremely high-performance ‘high-voltage (HV) HEV’. A comparison in [1] between the different hybridization concepts reveals that 48 volt mHEV systems combine a very cost efficient technology with a considerably high CO₂ reduction in standard drive cycles as well as under on-road driving conditions. The Gasoline Technology Car 1 (GTC1) – basing on a Ford Focus – was presented in 2014 as a highly integrated vehicle concept [2]. It is essentially a 48 volt starter generator system (P0 mHEV) with manual transmission and an automatic clutch that supports a ‘coasting’ functionality. For the Gasoline Technology Car 2 (GTC2) vehicle which will be presented here, the development partners set themselves the challenge to maximize the overall powertrain
efficiency by using an optimized gasoline engine and installing an improved 48 volt hybrid system. At the same time new functions with additional customer benefits have been implemented at limited integration effort and cost. Comparable to its predecessor, the GTC1, a Ford Focus is used for demonstrating the GTC2 concept. In this vehicle, however, the 48 volt hybrid system is in a P2 arrangement enabling a maximum recuperation and electric driving. The CO₂ potential of the chosen technology has been determined by simulation [1], 85 g/km (NEDC) for the GTC2 vehicle are targeted and under validation. In the WLTP with the presented concept a CO₂ reduction of 10% can be achieved.

2. System Architecture

The so-called P2 hybrid architecture was chosen for the GTC2 with the electric traction machine and the additional K0 clutch being installed between the internal combustion engine (ICE) and the transmission (Figure 1). Hence drag losses in hybrid states such as recuperation, coasting (rolling with open powertrain), sailing (driving electrically at constant speed) and pure electric driving are eliminated (Figure 2).

Special aspects of the chosen configuration are on one hand the integration of the 48 volt electric machine and furthermore of the standard mechanical climate compressor in an axial-parallel configuration. Adding an electric in lieu of a conventional coolant pump it is thus possible to discard the conventional front end accessory drive. On the other hand, a manual transmission car was selected to demonstrate the feasibility of a hybrid concept which avoids the additional on-cost of an automated transmission system.

The combustion engine is the Ford 1.0L EcoBoost three cylinder gasoline engine modified with a higher compression ratio (CR=12.0) in combination with a ‘late intake valve closing’ concept. It is enhanced by an accordingly matched RAAX turbocharger [1], a 200 bar fuel pressure injection system, an electrically heated catalyst (EHC, brand name EMICAT) and an engine control unit coordinating the entire powertrain. To counteract the problem of knocking but also to further increase part load engine efficiency, the intake cam event length is significantly increased (Late Intake Valve Closing (LIVC)). A further key engine component is the RAAX turbocharger with a low inertia radial-axial turbine, which generates high boost pressure and fast pressure build up even at low engine speeds. At the same time, with high gas flow rate at the rated power point, the exhaust gas back pressure does not increase as strongly as it does with a standard turbocharger.

To comply with the emission legislation requirements and to maximize CO₂ savings, an electrically heated catalyst (EHC) is selected as ideal partner for a P2 hybrid system with its frequent engine shut downs. The implemented EHC is a metal foil catalyst with an operating voltage of 48 volt. It can be heated up rapidly with an electric power of 4 kW to its light off temperature required for effective feed gas conversion.

From installation point of view, the centerpiece of the P2 system is a compact ‘hybrid module’ which is integrated between the internal combustion engine (ICE) and the manual transmission meeting the package requirements of an east-west installation. It comprises of a housing, a drive clutch (K1) and a decoupling clutch (K0), a belt drive system with decoupling tensioner, an electric machine with integrated power electronics and a conventional mechanical climate compressor. The E-machine is connected with an effective transmission ratio of 2.7 to the driveline. Both clutches K1 and K0 are designed as normally
closed friction clutches and are controlled by corresponding clutch actuators along with a dedicated clutch control software.

![System architecture of the 48 volt P2 hybrid vehicle ‘GTC2’](image)

The K1 in slip control mode is able to support automatic launch procedures and creeping of the vehicle. The K0 can modulate the combustion engine re-start by controlling the crank torque. The clutch automation allows this manual transmission vehicle to be driven either as a ‘three pedal’ or a ‘two pedal’ variant. The three pedal ‘clutch-by-wire (CbW)’ vehicle variant comprises a clutch pedal including a pedal force simulator. The clutch can be actuated fully electronically by the control software or, in a conventional manner, by the driver. For the two pedal variant with ‘electronic clutch management (ECM)’ no clutch pedal is required. Instead, the driver’s intention to change gears is detected by sensors at the gear lever and gearshift dome.

The electric machine is carried over from the Continental modular system for belt starter generators and consists of a water-cooled induction machine with integrated power electronics (inverter). Both the electric machine and inverter are cooled via the low-temperature intercooler water circuit. As required for a P2 hybrid vehicle a small electrical water pump enables electric machine operation when the ICE is shut down. The 48 volt power net which supplies the E-machine and the EHC uses a 48 volt Li-ion battery with a capacity of 460 Wh as energy storage. The air-cooled 48 volt battery is mounted in the trunk of the vehicle. The connection to the 12 volt power net is realized by a DC/DC-converter which is capable to bi-directionally transfer electric power with a continuous power of 3 kW between the two power nets.

To realize a simple and inherently safe serial braking (i.e. separation of electrical recuperation and mechanical friction braking), the vehicle is fitted with an ‘mGap’ brake booster. In combination with a brake pedal travel sensor this system utilizes the mechanical
lash in the brake booster to control the recuperation. The initial pedal travel within the lash is interpreted and triggers the degree of electrical recuperation. Only when the driver presses the pedal further the friction brakes are engaged additionally while braking. In order to have sufficient brake vacuum available during the engine-off phases the mechanical vacuum pump at the engine is replaced by an electric one.

The thermal management system of the combustion engine is implemented as combination of an electrical water pump with a thermal management module [1]. This approach allows not only a continuously controlled ICE coolant flow but, additionally, an on demand adjusted cooling of sub-circuits. In this way various cooling scenarios like ‘no flow’, ‘selective cooling’ (e.g. cylinder head only) or full coolant flow through the entire combustion engine and radiator can be implemented.

Another key subsystem is the high level ‘hybrid operation strategy’, which is executed by the engine control unit. It is implemented in a model-based manner and controls the entire hybrid powertrain.

As shown in Figure 2 the GTC2 is principally able to operate in all hybrid modes which are known from high-voltage hybrid vehicles. In particular it is possible to drive purely electrically which can be used to perform electric creeping and launch (in combination with ECM) as well as to maintain constant vehicle speed up to 50 kph (‘sailing’). Another advantageous feature of the axial-parallel configuration is the option to drive the climate compressor either conventionally by the combustion engine, by the inertia of the vehicle or by the E-machine when the K0 or both clutches are open. The latter configuration enables the functionality of a dedicated electric climate compressor, i.e. cooling the vehicle when the engine is shut down, avoiding the on-cost of an electric AC compressor.

Along with essential vehicle data the driver is always informed about the actual hybrid mode by an interactive human–machine interface using the capabilities of a tablet computer.
3. Drivability in Regensburg City Cycle analyzed by AVL DRIVE

The final customer acceptance of the unique GTC2 concept, namely a P2-hybrid based on 48 volt technology in combination with a manual transmission, can only be achieved by demonstrating the ‘on-road drivability’. As a reference route, the so-called Regensburg City Cycle (RCC, Figure 3) was chosen as representative low loaded on-road drive cycle (RCC distance 32,5 km, average velocity 28,5 kph, average traction power: 7,2 kW; for comparison WLTP: 23,25 km, 46,6 kph, 11,2 kW; NEDC: 11 km, 34 kph, 5 kW).

A break down into the different driving modes shows that the GTC2 drives only for approx. 50% of the RCC distance with the fired ICE [3] which is an essential feature of a P2 hybrid electric vehicle to save fuel. It is hence obvious that the ‘engine off’ drive maneuvers and especially the subsequent re-start determines vastly the driver's perception of this mild hybridized vehicle concept. The standard tool AVL DRIVE has been utilized to objectively assess the drivability of the GTC2 with the RCC as reference route. The target was to demonstrate the potential of the chosen mild hybrid concept.
One feature of AVL DRIVE is the possibility to compare the test vehicle to benchmark vehicle data for a selected vehicle class (here: Ford Focus class, light blue shaded area of Figure 4). This reference to existing mass production vehicles provides a valuable indication of the test vehicle capabilities and maturity. It should be noted that the GTC2 has to be considered as demonstrator vehicle with still some potential for further improvement and optimization in all areas.

The overall drivability rating (Figure 4) is a weighted average of the plotted category ratings (best rating 10). These ratings are based on a weighted average score for individual drive maneuvers during the RCC (indicated by the circles). These are automatically detected, processed and evaluated by AVL DRIVE. With the score of seven the AVL DRIVE rating of the most important drive conditions indicates that the GTC2 will well meet most driver expectations regarding the drivability. Since the GTC2 is currently operating with unmodified powertrain mounts further improvement of the AVL DRIVE ‘vibrations’ and ‘engine shut-off’ ratings can be expected if the engine mounts are adapted to the hybridized powertrain weight and inertia change.

4. Re-start capability and vehicle re-acceleration

As already outlined above, the implementation of frequent engine shut-downs to improve fuel efficiency with a P2-hybrid vehicle makes it necessary to have a quick and comfortable engine re-start capability. It has been stated in [1] and [3] that re-starts can be accomplished out of coasting and eDrive in a quite acceptable way. Using the 48 volt E-machine it is possible to start accelerating the vehicle using the combustion engine within 600 ms to 800 ms when the transmission input shaft is in the range of 1500 rpm.

The standard ‘sequential start’ is applied to start the ICE out of eDrive [1]: the driveline (clutch K1) is opened, the E-machine is connected to the ICE (clutch K0), the ICE is started, synchronized and finally the driveline is closed again (clutch K1). One drawback of this ‘sequential start’ procedure is that besides the above mentioned hesitation the driver may
perceive a short torque disruption during which the driveline is open and no torque can be provided to the wheels.

This is the most critical drive maneuver for the P2 hybrid and can be significantly improved by implementing the so-called ‘slip re-start’ strategy (Figure 5) which avoids the opening of the driveline. While speeding up the E-machine at peak power the clutches K0 and K1 are set in a coordinated slipping condition. Via the slipping of K0 the ICE cranking is engaged while surplus E-machine torque is provided to the wheels via the K1. In order to provide traction torque from the E-machine to the wheels it is necessary to control that the hybrid module speed continuously exceeds the transmission input shaft speed. This procedure leads to a quick re-acceleration of the vehicle at best NVH performance (no pinion starter noise).

![Figure 5: ‘Slip re-start’ from eDrive](image)

### 5. Driving comfort during hybrid mode changes

Apart from the transition dynamics between the different hybrid modes as they are described in section 4, the driving comfort of these changes is a key factor for driver acceptance. The sensitivity of drivers against irregularities is particularly high if the vehicle acceleration is close to zero. Hence the transition from ‘coasting’ to ‘recuperation’ is a key drive situation and is discussed further in detail below.
Figure 6: Transition from hybrid mode ‘Coasting’ to ‘Recuperation’. Synchronization is performed by either controlling the clutch K1 only (left) or by engaging the E-machine along with the clutch K1 (‘Active Synchronization’, right).

The transition (‘coasting’ to ‘recuperation’) is triggered by a slight pressing of the brake pedal. At a vehicle speed of about 50 kph in 3rd gear, Figure 6 shows this mode change performed with two strategies. The measured vehicle deceleration shown on the two top charts is a sensitive measure for any excitation of the driveline which can be perceived by the driver as (small) jerk (see top left chart of Figure 6). Thereby the driver demanded vehicle deceleration is achieved to a large extend by the negative torque of the electric machine whereas the friction brake torque employment stays small.

During the coasting phase the clutch K1 is open and the hybrid module rotational speed is at or close to stop (Figure 6, begin of measurement). To change to recuperation mode it is necessary to accelerate the hybrid module along with the belt drive and the E-machine to the transmission input shaft speed and to close K1 subsequently. Finally the E-machine applies a negative torque to decelerate the vehicle, hence recuperating kinetic energy.

In the example shown on the left side of Figure 6, the synchronization was carried out by closing the clutch K1 in a controlled way only. Since the vehicle is rolling freely during coasting, due to the inertia of the hybrid module, it is hardly possible to avoid a small jerk while closing the K1. This excitation becomes clearly visible on the vehicle acceleration signal (figure 6, top left chart). To improve the driving comfort and enhance driver acceptance an alternative synchronization procedure, the ‘active synchronization’ shown on the right hand diagrams, was applied. Here the electric machine is used to actively
accelerate the hybrid module to synchronous speed prior to closing the clutch K1. As it is clearly indicated by the acceleration signal no jerk exceeding the noise level typical for a vehicle in motion can be recorded or even be perceived by the driver resulting in a perfect NVH behavior.

6. eDrive on Regensburg City Cycle

A typical use case to benefit from the pure electric driving capabilities of the 48 volt P2-system is city driving, in particular in 30 kph zones. Figure 7 shows the drive strategy of the GTC2 while driving in a 30 kph zone that is part of the Regensburg City Cycle. The characteristic speed profile of this section with a total length of 760 m is shown in the bottom chart. The top chart outlines the torque which is applied by the internal combustion engine ('Torque ENG') and the electric machine ('Torque EM'), respectively.

![Graph showing drive strategy and torque](image)

*Figure 7: GTC2 driving in a 30 kph zone being part of the RCC.*

In this example the ICE is used for the initial launch and acceleration phase as well as for one intermediate acceleration, exceeding the E-machine performance, which is e.g. typical to overtake a bicycle. In total, the ICE is operating for only about 15% of the time. For the remainder of the section the ICE is switched off and disconnected from the driveline; i.e. during 85% of the time the driveline is either open and the vehicle is coasting or the electric machine is used for ‘eDrive’ (maintaining speed or slight acceleration) as well as to reduce the vehicle speed by regenerative braking (‘recuperation’).
Obviously, this example shows that the eDrive capability of this P2-hybrid, although limited in power and duration as restricted by 48 volt technology, is a valuable feature which can be used during city driving at low speeds. It enables to follow the traffic flow without major restrictions while, at the same time, inefficient operating points of the combustion engine are avoided. With the currently installed components, the described eDrive manoeuvres are available up to speeds of around 50 kph. The planned future upgrade to a more powerful E-machine and 48 volt battery will expand the usable eDrive range to most city areas, in particular to 50 kph zones.

7. Conclusion and outlook

The presented 48 volt P2 hybrid system in an axial-parallel configuration demonstrates a high fuel reduction potential by avoiding the drag losses of the internal combustion engine during ‘eDrive’, ‘Recuperation’ and ‘Coasting’. The drivability of this hybrid system is remarkably high and, for many aspects, already now on the level of production cars. The engine re-start and powertrain re-engagement strategy is on comparable high or better level as realized by 48 volt P0 hybrids with start stop coasting. It has been demonstrated that this enables operating strategies for very comfortable and quick transitions when either starting the combustion engine and accelerating the vehicle or when connecting the E-machine and recuperating the kinetic energy. In both cases irregularities such as torque disruption or jerks can be minimized leading to superior drivability and comfort of the GTC2 demonstrator vehicle.

In addition pure electrical driving can be experienced in particular during city driving (e.g. 30 kph zones). This includes as well automated electric parking maneuvers that will be fully supported by the feature of electrical creeping, even though this 48 volt mild hybrid vehicle concept is equipped with (but not limited to) a manual transmission. Another pure electric function is the capability to operate the air conditioner with recuperated energy using the 48 volt E-machine. This ‘Cool Welcome’ feature can be triggered remotely.

As a next step a two pedal variant (without clutch pedal) of the vehicle will be built up allowing for a new level of drive comfort and exploring the full potential of the GTC2, in particular in combination with an E-machine with higher power ratings. Finally a connected energy management will optimize the fuel efficiency under on-road conditions by taking into account the planned route, the traffic situation and the individual profile of the driver.
References

[1] Wagner, U., Rauch M.; Eckl T. ; Schaeffler AG Weber, C.; Springer M.; Schamel, A. Dr. ; Ford Werke GmbH Cologne Maiwald, O. Dr.; Knorr, T.; Lauer S. Dr. ; Continental Automotive GmbH
48V P2 hybrid vehicle with an optimized combustion engine – Fuel economy and costs at their best combined with enhanced driving behavior
37th Vienna International Motor Symposium, 2016.

Hubraumreduzierter Verbrennungsmotor und 48 V Eco Drive – Ein integrierter Ansatz zur ganzheitlichen Effizienzsteigerung des Antriebsstrangs [downsized gasoline engine and 48 V Eco Drive – an integrated approach to improve the overall propulsion system efficiency]
35th Vienna International Motor Symposium, 2014.

Drivability and 48 Volt Hybrids – Opportunities beyond CO₂ Reduction