ANALYSIS OF HYBRID DRIVETRAIN POWER MANAGEMENT STRATEGIES IN THE VIEW OF DUAL USE APPLICATIONS

dr. ir. Joeri VAN MIERLO, dr. ir. Peter VAN DEN BOSSCHE,
prof. dr. ir. Gaston MAGGETTO
VRIJE UNIVERSITEIT BRUSSEL
BELGIUM
jvmierlo@vub.ac.be
pvdbos@vub.ac.be

Abstract

Hybrid electric vehicles HEV combine electric and other drive systems, such as internal combustion engines, gas turbines and fuel cells. Hybrid electric vehicles merge the zero pollution and high efficiency benefits of electric traction with the high fuel energy density benefits of an energy source or thermal engine.

Different concepts of the hybrid drivetrain topology (physical layout) can be examined. A drivetrain layout simply consists of hardware components hooked up electrically and mechanically, with nothing telling them what to do or when to do it. The control strategy brings the components together as a system and provides the intelligence that makes the components work together.

This paper will describe different possible control strategies that can be implemented in hybrid electric drivetrains. A non-exhaustive list will be established of possibilities applicable on series (SHEV), parallel (PHEV) and combined hybrid vehicles (CHEV), Some examples: optimal operating point or line, time deviation limits, operational conditions, State of Charge (SoC) and vehicle operation criteria, minimum APU ON-time, relative power distribution, APU power in function of traction power, minimum efficiency loss, power consumption by auxiliary equipment, etc.

It is clearly that many different solutions are possible to control the powerflow in a hybrid drivetrain. To minimise both common testing, time and development cost, a software tool can facilitate engineers in evaluating current vehicle technologies and can help them with the selection and matching of energy storage devices, hybrid powertrain layouts and vehicle energy management.

All the strategies are implemented in the software tool Vehicle Simulation Programme (VSP) and hence can be compared [1,2]. The results of this assessment will be highlighted, with a particular consideration for the specific aspects of dual use application of the technologies

1 Powerflow Control Algorithms

The flexibility in design of hybrid vehicles comes from the ability of the powerflow strategy to control how much power is flowing to or from each component. This way, the components can be integrated with a control strategy to achieve the optimal design for a given set of design constraints.

There are many, often conflicting, objectives desirable for hybrid electric vehicles [3]:

- Maximised fuel economy;
- Minimised emissions;
- Minimised propulsion system cost;
- Acceptable performance (acceleration, noise, range, handling, etc.)
- Auxiliary load demands.

A hybrid drivetrain is a complex system in which APU power set-point, battery charging/discharging profile, DC-bus voltage, etc, will influence the consumption and emissions of the vehicle. The combination of the effect of all these parameters can best be evaluated with the help of a powerful simulation tool.

To minimise the consumption and emissions it is not only important to select an appropriate drivetrain topology, but next to the individual component efficiency, the development of the powerflow control algorithm is mainly decisive to optimise the global drivetrain energy efficiency. This furthermore closely relates to the vehicle application (type of drive cycle).

The following sections will describe different possible control strategies to be implemented in hybrid electric drivetrains.

2 Series Hybrid Electric Vehicle Control Algorithms [4]

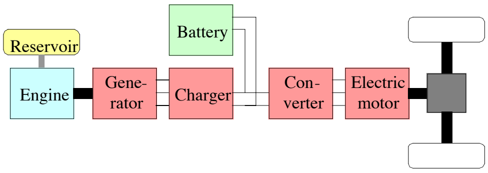

Figure 1
Series Hybrid

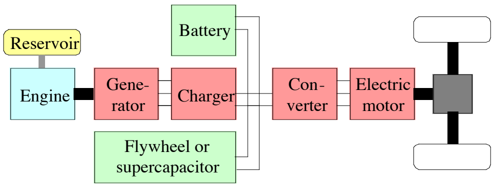

Figure 2
Series Hybrid with Peak Power Unit

Goal

a. ***Range extender***. With a small rate of hybridisation the APU is used to extend the range of the electric vehicle. However the autonomy is still depending on the capacity of the battery. The battery will discharge less quickly than without a range extender; nevertheless the APU power is usually not sufficient to maintain the battery state of charge. This type is also called a ‘battery depleting hybrid’ [5] where the state of charge of the traction battery at the end of a service day or driving cycle is lower than at the beginning. The batteries thus have to be recharged from an external source (electricity grid).

b. ***Continuous mode***. With this implementation the APU will have a bigger rated power compared to the APU of the range extender. It is the purpose to operate the APU continuously. The state of charge of the traction battery at the end of the service day or trip is mostly equal to that at the beginning. (The state of charge of the battery at any given time will of course be variable.) This drivetrain is mostly of the ‘non-depleting’ or ‘charge-sustaining’ hybrid type. The solution allows a smaller energy content of the battery due to the fact that it is only in charge of the peak power requirements.

c. ***Intermittent mode.*** In this category the vehicle is able to operate with the APU switched off in certain parts of the drive cycle, e.g. for stealth mission or silent watch duties. The APU must be powerful enough to be able to recharge the battery in the episode in which it is operating. The battery must be sufficiently large to secure the pure electric driving phase. Several APU-operating strategies for this working mode can be taken into consideration.

Delivered Power

a. ***Constant.*** When the APU is in use it will deliver a constant power corresponding to a certain setpoint (see further).

b. ***Discrete*** (manual or automatic). In this case the APU power can only be set on predefined values. The selection can be carried out by either the driver (who can have an idea of the type of driving trip he will perform) or automatically by a microprocessor. This working mode allows selecting the APU power in function of the demanded battery power without having much dynamic fluctuations of the engine. A maximum output power can be chosen in the case of need for fast charging of the battery or high power demand from auxiliary loads.

c. ***Continuously variable***. This option allows changing the APU power continuously. E.g. the generator-engine group can charge the battery at its maximum charging power and at the same time deliver the required traction power. The dynamic operation of the engine however is a serious drawback of this solution (higher emission and fuel consumption).

Set Point

The necessity to choose a setpoint is a typical action needed for an engine-generator group.

a. ***Optimal operating point***. One can choose to operate the engine in an optimal working point. The torque and rotational velocity corresponding to the lowest fuel consumption (in g/kWh) can be chosen to define this point. It can also correspond to the lowest NO_x-emission or SO_2-emission. The optimal emission point can be different from the optimal consumption operating point. This optimal operating point can also be a compromise between fuel consumption and emissions.

b. ***Optimal operating line***. When a generator has to deliver different power levels, the engine rotational velocity can be chosen for each power level corresponding to the lowest emissions or fuel consumption or a combination of both.

c. ***Deviation allowed between limits***. One can choose to operate the engine only in a certain velocity span. Most engines have an operating area (in torque and velocity plane) in which the fuel efficiency remains rather good.

d. ***Maximum deviation speed***. When the engine's working point has to change, the deviation in function of time can be restricted, to avoid fast engine fluctuations and hence to minimise engine dynamics.

e. ***Constant speed, variable torque***. Another approach consists in keeping the engine speed constant (no additional inertia torque) and allowing to change its output torque in function of the required generator power.

Strategy

The APU power can be selected in function of different parameters and requirements, like:

a. ***Battery voltage***. Independently of what strategy is used the battery voltage should be kept within its safety operating limits. Otherwise the battery can be damaged (inversion of polarisation, abundant gassing, etc).

b. ***Mission-dependent parameters***. One of the main advantages of hybrid electric vehicles is the ability to drive pure electric, with low emissions and a low thermal and acoustic signatures, allowing for stealth missions and silent watch operation. Furthermore, the demand of power by auxiliary systems (communication systems, electric weapons, electric armor, etc.) may influence the usage of the APU.

c. ***State of Charge (SoC)***. The state of charge of the battery can be an important parameter to regulate the generator. The state of charge may not be too low to have enough battery power left for acceleration. To allow maximum regeneration of braking energy the battery should not be completely charged. When the SoC reaches a maximum level the APU should be switched off or operated in idle mode. The APU should be switched on when exceeding a low SoC limit. Additionally when a critical SoC low limit is reached the APU power can be increased to its maximum level to charge the battery as fast as possible.

   Figure 3 illustrates an example in which the APU will deliver full power (in the example 24 kW) when the SoC is lower than 50 %. Above 70 % the APU will be disengaged. Between both SoC levels the APU power is a linear relation of the SoC.

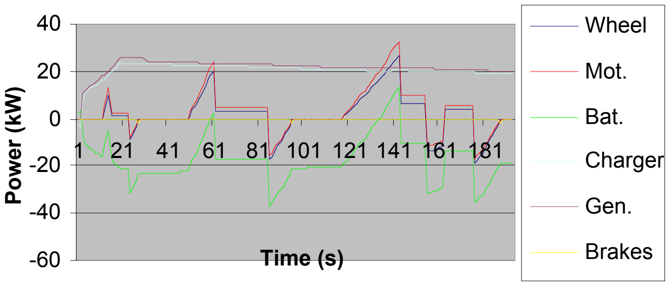

Figure 3
SHEV - APU Power in Function of SoC

In this example the start SoC is chosen at 50% and the battery capacity is selected very small to see the characteristic within a short simulation time.

d. ***State of Charge deviation*** [6]. In the same philosophy of previous paragraph the engine power setpoint can be chosen in function of a desired SoC deviation. Two deviation levels can be chosen. A recommended level that describes how fast the SoC may decrease. This value is closely related to the maximum range of the hybrid electric vehicle. If this is chosen equal zero, the range is defined by the content of the fuel tank. Otherwise the SoC will decrease until the battery is empty (battery depleting type). A second maximum deviation level can be chosen. If the SoC deviation is higher than this maximum limit the APU power level should be as high as possible. If the SoC deviation is between the recommended and the maximum limit the engine power can be selected according its lowest consumption. Furthermore if the SoC deviation is slower than the recommended level than the engine can be switched off or set to idle mode.

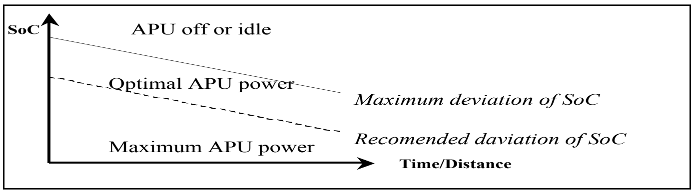

Figure 4
State of Charge Deviation Criterion

e. ***State of charge and vehicle velocity combination***. The APU should be switched on when the vehicle speed exceeds a certain limit. This vehicle speed corresponds with a certain required power and hence energy consumption. This speed level can be adjustable in function of the state of charge described with the equation (1).

$$v = v_s\left(1-\alpha\frac{SoC_{high}-SoC}{SoC_{high}-SoC_{low}}\right) \tag{1}$$

f. ***Minimum ON time***. Frequent switching on and off the engine will result in additional consumption and emissions. To avoid this, a minimum APU on-time can be imposed.

g. ***Relative distribution***. The previous strategies describe whenever the APU should be switched ON or OFF. One can also chose to relatively split-up the required traction power between the APU and the battery. E.g. the first delivers 70 % of the power and the latter 30 %. The APU can only provide power and hence all braking power can only be recuperated by the battery.

Figure 5 shows a model in which the APU delivers 30 % of the required driving power, except during braking. At this moment all braking energy is regenerated into the battery and the APU is switched off.

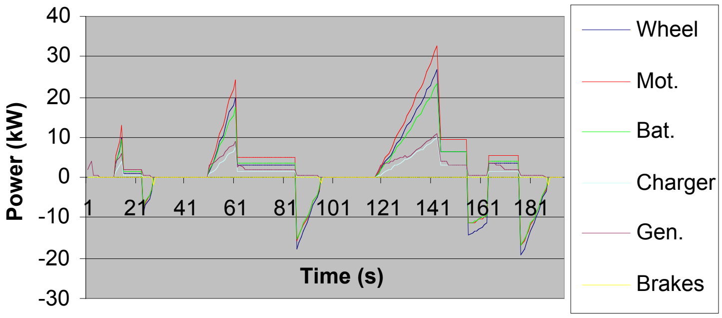

Figure 5
SHEV - Relative Power Distribution

h. ***Required traction power***. The maximum allowed charging power of a battery is in most cases much lower than the maximum discharge power. If the APU is only allowed to deliver a constant power, this power will be used for driving and battery charging together. In this case the maximum value of the APU power must be limited to the maximum battery charging power (at standstill all APU power goes to the battery). Another solution is modulating the APU power in function of the required traction power. Hence the battery can be charged at its maximum charging power level. The battery does not act as peak power unit anymore; the APU will deliver them. Power requirements are an important design parameter for the battery of a hybrid electric vehicle opposite to energy requirements. During braking, additional to the constant charging power(e.g. 7 kW), the brake energy is also regenerated into the battery. Figure 6 illustrates this strategy.

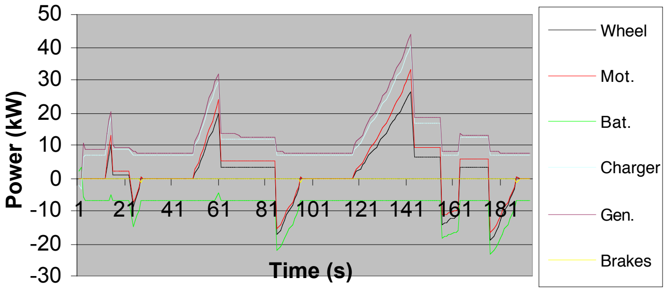

Figure 6
SHEV - Constant Battery Charging

i. ***History***. Previous discussion clearly shows that the pros and contras of a certain strategy should be evaluated. Operating the engine in its working point corresponding to its lowest fuel consumption can be at first sight very promising. This can be conflicting with battery charging constraints (charging/discharging losses). On the contrary, allowing a fluctuation of APU power will lead to additional inertia torques and fuel consumption. However one can choose to allow a slow changing of the APU operating point in function of the delivered energy. While driving at constant speed a lower APU power should be required. When driving a very demanding drive cycle the APU power should increase slowly. A microprocessor can integrate the required traction power and modulate the APU power in function of this parameter or similar one can establish a linear relation between APU power and SoC.

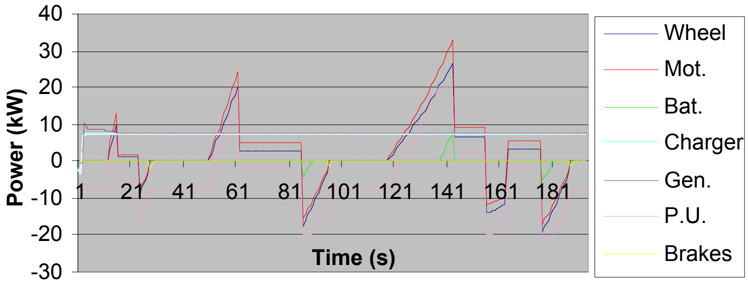

Figure 7
SHEV - With Flywheel

j. ***Additional peak power unit***. In a following example the SHEV is equipped with a flywheel. In Figure 7 (above) the APU delivers 7 kW continuously. The flywheel (P.U. or Power Unit) provides all peak powers. When the flywheel reaches its maximum deliverable power, the battery will deliver the remainder of traction power.

3 Parallel Hybrid Electric Vehicle Control Algorithms

The parallel hybrid electric vehicle can operate in several modes: electric only, engine only and dual power source or hybrid mode [7]. The electric motor can also operate as a generator during braking. Compared to a conventional vehicle the parallel electric drivetrain has the main advantage that it is able to regenerate the braking energy. This implies that during braking all braking torque will be delivered by the electric motor and the engine needs to be disengaged.

Moreover the parallel solution allows using the electric motor as starter motor. Even the alternator can be omitted and a DC/DC convertor can be used to supply auxiliaries via the main traction battery.

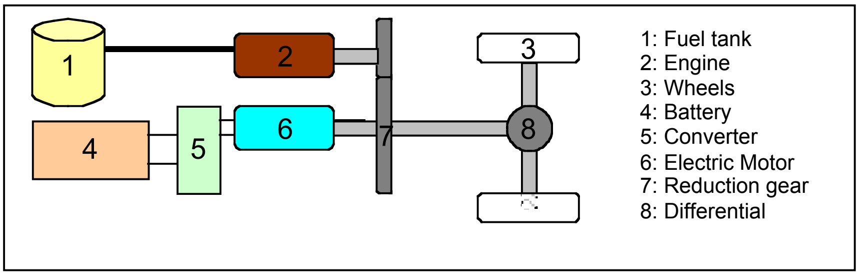

Figure 8
Parallel Drivetrain with Torque Addition

The same approach of the powerflow strategy for the series hybrid drivetrain as described above is applicable for the parallel hybrid drivetrain too. Only the ‘Set Point’ is different due to the fact that the engine is mechanically connected to the wheels. There is one degree of freedom less compared to the series hybrid vehicle. Indeed in most parallel hybrid vehicles the engine is mechanically connected to the wheels via a gearwheel, resulting in an engine speed proportional to the vehicle velocity. The number of power control algorithms in parallel hybrid vehicles is thus smaller than one can find for the series hybrid vehicle, where engine speed and torque can be controlled independently from the traction effort.

The gearwheel used in the PHEV can be described by equation (2) (torque addition) as well as the linear relation between the velocities (equation (3)).

$$T_8 = \frac{T_6}{\eta_6} + \frac{x_2 \cdot T_2}{\eta_2} \tag{2}$$

$$\omega_8 = \omega_6 = \omega_2 / x_2 \tag{3}$$

With :

- T: torque
- η_6: efficiency of gear connecting motor with differential
- η_2: efficiency of gear connecting engine with differential
- ω: rotational speed
- x: transmission ratio

Equation (2) shows the possibility to control the engine torque via the electric motor, independent from the required traction torque. Several approaches are possible. Five of them are explained below:

Relative Distribution

The required driving torque is proportionally split up; e.g. the engine delivers 70 % of the traction torque and the electric motor 30 %. This relative contribution of each motor can be kept constant during the whole drive cycle. This approach in itself has little benefits.

Constant Torque

One could consider keeping the torque value of the engine constant. This torque value can be chosen in function of the engine's highest efficiency and/or lowest emissions. The electric motor must deliver the remaining part of the required torque. Hence the electric motor is in charge of the vehicle dynamics.

The engine will deliver a constant base torque. Furthermore the engine can be declutched when its velocity drops under a certain limits or exceeds a maximum value. In this way the engine working point can be kept within an operating range corresponding with low fuel consumption. When declutching the engine one has the possibility to completely switch off the engine or to operate it at idle speed.

Minimum Efficiency Loss

This third approach is a more intelligent one. Hence it is possible to operate the engine on its optimal working line corresponding with low fuel consumption. The transmission ratio and the input velocity define indeed the engine velocity. One can define a power division to minimise the efficiency loss for the entire vehicle. This covers the total efficiency loss for all of the individual vehicle components. The most dominant loss will be the engine loss. The total efficiency loss can depend on the respective driving condition [8]. Calculating for each time step of a reference speed cycle the best operating point, with the lowest drivetrain losses, will not necessarily result in the lowest total fuel consumption, because battery charging and discharging are not taken into account. This charging-discharging profile is time and speed cycle dependent. Time integration can partially solve this problem, but provides only a solution for the considered reference speed cycle.

In Function of SoC(P_{APU}(SoC))

This criterion takes the state of charge into account. Hence the influence of the driving cycle is considered in an indirect way. When the speed cycle is a very demanding one, which means that the battery SoC is decreasing very fast, the engine power level should be enlarged to compensate this energy consumption. At the contrary, when driving a very moderate cycle, e.g. cruising at 50km/h, the engine will provide the traction power and probably it will charge the battery at the same time. At this moment the engine power level can be decreased.

Figure 9 is a simulation result of an ECE cycle. When the SoC is lower than 50 % the engine delivers all required traction power. Above 70 % all traction power is delivered by the electric motor (Mot-mech). In this graph the engine (Gear-ICE) delivers about 55 % of the required driving power (Wheel). If the speed cycle is much longer, the dependency of the engine power on the SoC is better demonstrated.

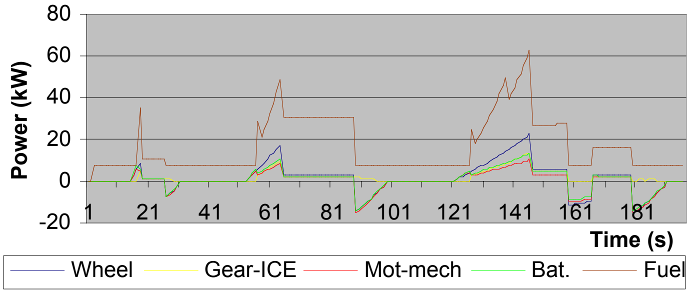

Figure 9
PHEV – ECE - P_{ICE} in Function of SoC

Figure 10 shows the same PHEV driving at constant speed. The SoC drops from 57 % to 50 %. The contribution of the engine to the driving power increases, while the electric motor and battery have to deliver a reduced amount of power.

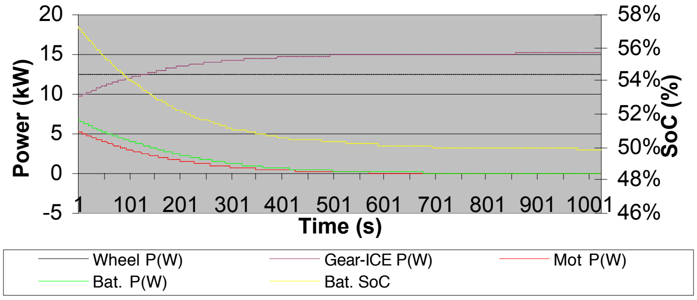

Figure 10
PHEV – Cte. Speed – P_{ICE} in Function of SoC

In Function of SoC bis (Switch$_{APU}$(SoC))

The use of the state of charge as control parameter can be slightly different than in the case of the series hybrid vehicle. When the battery SoC is low, the engine can provide the driving torque and an additional torque to recharge the battery via the electric motor. When the SoC is high the electric motor only launches the vehicle [9].

Combining some of these considerations can result in an example where the control strategy uses the electric motor for additional power when needed. This can be done in a variety of ways [10]:

a. The electric motor can be used for all driving torque below a certain minimum vehicle speed (e.g. 10 km/h).
b. The electric motor is used for torque assist if the required torque is greater than the maximum producable by the engine at the engine's operating speed.
c. The electric motor charges the batteries by regenerative braking.
d. When the engine is running inefficiently at the required engine torque at a given speed, the engine is shut off and the electric motor will produce the required torque.
e. When the battery SOC is low, the engine will provide excess torque, which will be used by the electric motor to charge the battery.

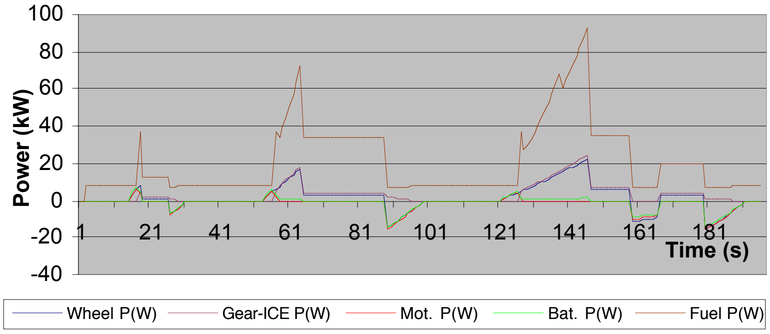

Figure 11
PHEV – ECE – Electric-Assist

In the following strategy the engine is in charge of all driving power (if the vehicle's speed is higher than 10 km/h and the vehicle is not braking). Figure 11 demonstrates this *electric-assist* strategy. In this case the engine is able to deliver all driving power.

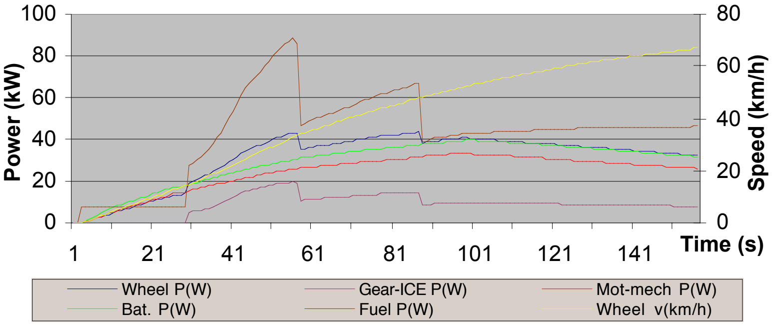

Figure 12
PHEV – Acceleration Test – Electric-Assist

In Figure 12 an acceleration test is simulated. In this case the engine delivers maximum power. Additionally the electric motor will deliver the lacking part of the driving power. In this maximum acceleration test this corresponds with the maximum motor power. Hence the acceleration is defined by engine and motor power together.

4 Combined Hybrid Electric Vehicle Control Algorithms

By introducing a planetary gear connected to a generator in the parallel hybrid configuration one gets a combined drivetrain with one degree of freedom more. This drivetrain has consequently a lot of possibilities to control the powerflow and to minimise this way the energy consumption.

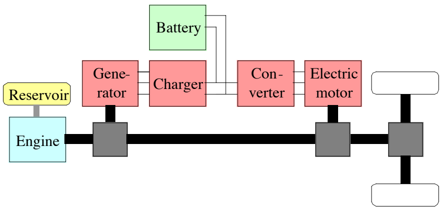

Figure 13
Combined Hybrid

The planetary gear and a torque splitter allow to control the speed as well as the torque of the engine. The next equations demonstrate the possibility to regulate the speed of the carrier (C) by changing the sun (S) speed independently of the ring (R) speed [11]. A detailed description of the functionality of this planetary gear in a combined hybrid drivetrain can be found in [12].

$$(1+\rho)\cdot\omega_C = \rho\cdot\omega_S + \omega_R \tag{4}$$

$$T_C = \frac{(1+\rho)}{\eta_S\cdot\rho}\cdot T_S = \frac{(1+\rho)}{\eta_R}\cdot T_R \tag{5}$$

With :

- T: torque
- η_S: efficiency from sun to carrier
- η_R: efficiency from ring to carrier
- ω: rotational speed
- ρ: planetary gear ratio (= nr. of sun gear teeth / nr. of ring gear teeth)

Constant Working Point

One could consider keeping the torque value of the engine constant, like it is described in the previous paragraph. Furthermore due to the planetary gear the engine velocity can be modulated with the help of the generator (see equation (4)). Consequently both torque and speed of the engine can be freely chosen independently from the driving requirements. The engine working point can be selected corresponding to its lowest consumption. Hence the drivetrain is controlled like it is generally done in a series hybrid vehicle: the engine delivers the average driving power; the acceleration peaks are covered by the electric motor; the battery is used as the energy buffer. Different to the series configuration is the fact that the engine power is mechanically coupled to the wheels. If this average power is higher than the required value, the remaining part is transmitted through the generator and possibly through the motor to recharge the battery.

Figure 14 illustrates the different velocities of some of the components. When vehicle speed increases, the generator velocity is decreased to keep the engine speed constant

In Figure 15 the torque values are displayed. Due to inertia of the planetary gear and the engine, the resulting engine torque shows a minor fluctuation.

Figure 16 shows the corresponding power levels. At stand still all engine power flows via the generator into the battery. During the first seconds of the acceleration phase, a part of the engine power goes to the wheels. The remaining engine power flows through the generator. A fraction of this generator power is used by the electric motor, another part still charges the battery.

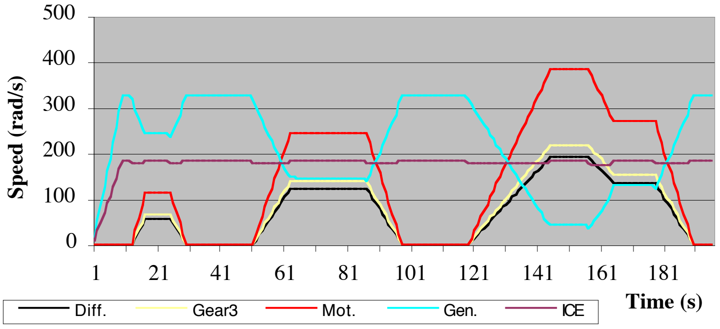

Figure 14
Velocity in CHEV

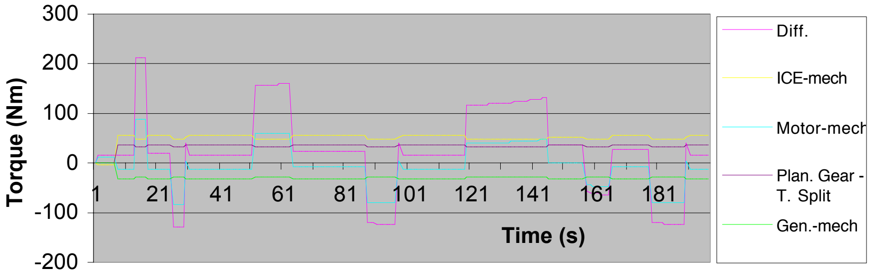

Figure 15
CHEV – Constant Working Point – Torque

At a certain time (16 s), additional battery power is required to accelerate the vehicle further on. This is due to the fact that the higher the vehicle speed at one hand the higher the required driving power and at the other hand the lower the generator power. If in the example the vehicle would exceed 55 km/h, the generator power is inversed and hence battery power flows through the generator as well as through the electric motor. In this mode, engine, generator and electric motor drive the wheels.

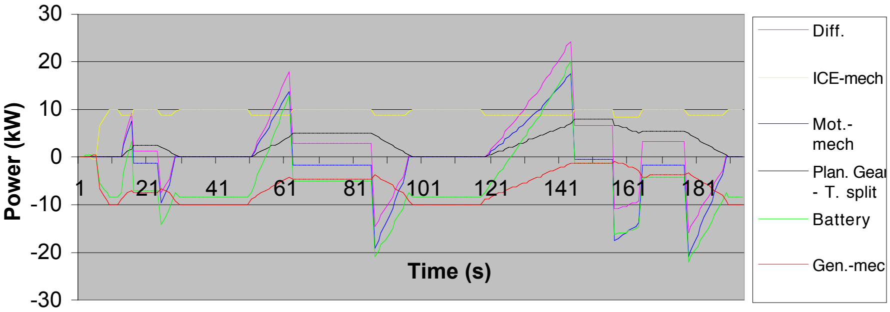

Figure 16
CHEV – Constant Working Point – Power

Although the engine operates in its most efficient working point, this control strategy does not automatically imply a low energy consumption of the total drivetrain. Indeed, a constant engine power results in frequent charging and discharging the battery, with high power levels. Moreover, in the drivetrain the power from the engine can flow via the planetary gear, through the generator and back through the motor to finally reach the differential, instead of going directly to the differential (see Figure 13). This strategy can also imply the necessity of a larger generator nominal power and battery capacity.

Overall Lowest Power Loss Minimalisation

Another approach considers operating the engine on its optimal working line, which describes the relation between engine torque and speed corresponding with the lowest fuel consumption. The speed of the engine can be adjusted in correlation with the required torque, by varying the generator speed. The torque can be controlled corresponding equation (2). The power distribution can be defined in function of the overall lowest power losses. This covers the total efficiency loss for all vehicle components. The total efficiency loss depends on the respective driving condition [8]. To define this power distribution a simulation programme is required. With the help of this simulation programme one has to find, for each required wheel torque and speed value of the considered reference cycle, the best power distribution according to the lowest total efficiency loss (power to battery and wheels compared to engine power).

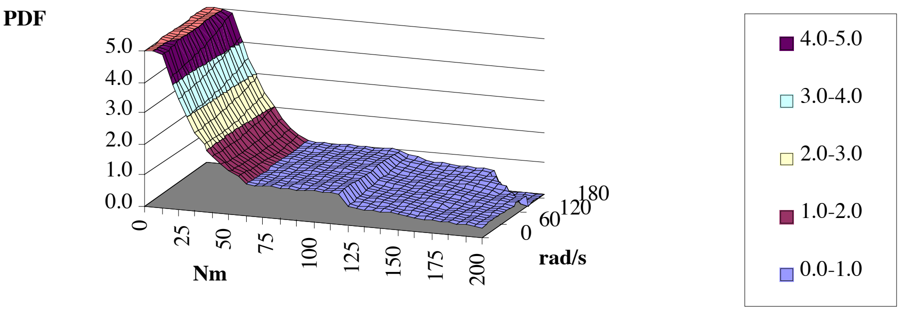

Figure 17
Power Distribution Factor of an Optimized CHEV Power Management

Figure 17 illustrates an example. The power distribution is here described as a Power Distribution factor (PDF) used in the simulation model of the Torque Splitter gear. One can recognize at low torque levels a very high PDF to impose a high enough torque at engine side. At this moment a part of the engine power is used to drive the vehicle and another part to charge the battery. For medium torque levels this PDF equals one. This means that the engine directly delivers all the traction power. At higher torque levels the engine as well as the electric motor is contributing in the power demand.

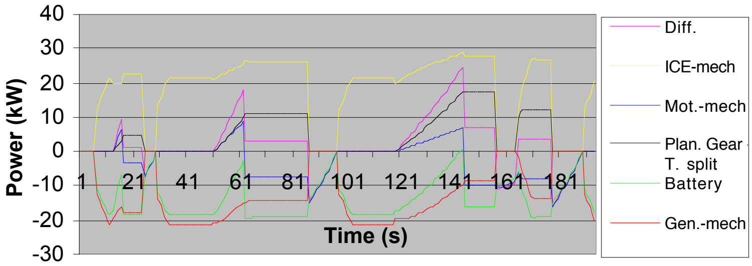

Figure 18
CHEV – Minimum Losses – Power

For the operating points which require a low power level (e.g. at low constant speed), the engine efficiency will be in any case unfavourable. This can be solved by

- Operating the engine only above a certain engine power level.
- Locking the generator at low required power (all engine power flows directly to the differential).

During braking no torque should go to the planetary gear, but all braking energy should be regenerated directly via the motor to the battery.

Figure 18 shows the simulation result in which the Torque Splitter imposes a torque at the planetary gear corresponding to the minimum overall drivetrain losses.

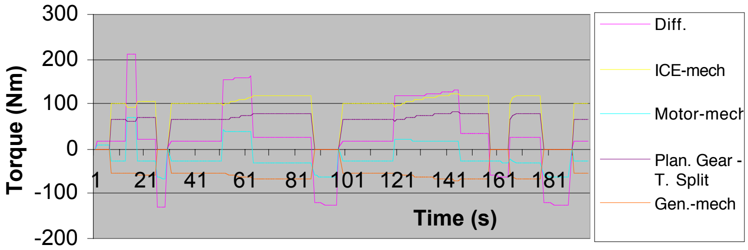

Figure 19
CHEV – Minimum Losses – Torque

Calculating for each time step of a reference speed cycle the best operating point, with the lowest drivetrain losses, will not necessarily result in the lowest total fuel consumption, because battery charging and discharging is still not taken into account. This charging-discharging profile is time and speed cycle dependent.

Maintaining Battery SoC

If the battery size is chosen rather small, to minimise vehicle weight, previous strategies cannot be implemented completely. Indeed, the battery SoC can decrease very fast in function of the drive cycle. To maintain the battery SoC level, it can be required to impose a power demand for battery charging. In this strategy the battery will provide energy when high vehicle acceleration is necessary or when a very low driving power is required. In the first case engine and motor will drive the wheels together. In the second case the engine is switched off and the electric motor is in charge of the driving force. When a moderate driving power is required, the engine will drive the wheels and will also charge the battery via the generator with a charging power in function of the SoC. This control strategy is implemented in the Toyota Prius [13].

5 Comparison

A case study is worked out to compare different drivetrain topologies, with the same body and chassis as of a 2,7 ton van. All hybrid drivetrains have a 30 kW asynchronous traction motor and a 1900 cc / 68 kW diesel engine that can be used to drive the vehicle or to drive the 65 kW alternator of the APU. The battery is a 310,8 V / 60 Ah NiCd battery.

Previous described drivetrain power management strategies are evaluated and compared [14]. Those with the minimum fuel consumption are used for further comparison.

SHEV:

- The size, weight and operating of the engine of a SHEV should be chosen in such a way that its most efficient working point corresponds with the average driving power (in city traffic) of the considered vehicle.
- Continuous operating the APU at this most efficient operating point will result in the lowest vehicle fuel consumption, especially when an efficient battery with a high power density is used.
- If necessary the APU power can be reduced during braking to benefit from maximum energy regeneration.

PHEV:

- Operate engine only in its most efficient working area:
    - Above 10km/h the engine may deliver all driving power.
    - An automatic gear should keep the engine between efficient operating limits.
    - When braking or stand still the engine is switched off.
- The electric motor is used when driving slower than 10km/h, while braking and for high accelerations.

CHEV:

- Manifold power path are possible in this complex hybrid drive train. An optimisation function should define the power distribution between electric motor and planetary gear (ICE) to minimize overall drivetrain losses.
- The generator speed should be chosen to optimize, via the planetary gear, the engine speed in function of the required engine torque.
- Lock the engine at low requested load (e.g. vehicle speed lower than 10 km/h), during braking (maximum regeneration of braking energy via the electric motor).

Acceleration Performance

With the help of the simulation programme the different drivetrains are compared on the bases of an acceleration test. Figure 20 illustrates the results. The results are function of the maximum power characteristics of the considered components and cannot be generalized.

The BEV and SHEV have the same acceleration performance since their acceleration power is determined by the maximum rating of the electric traction motor.

The DEV should have the same speeding up time, but the generator and engine power limit the acceleration, since there is no battery.

The PHEV has an improved acceleration performance due to the fact that the engine as well as the motor contributes to the acceleration torque.

Although the engine in the CHEV is scaled down with 70 % compared to the ICV and PHEV, the CHEV has the fasted acceleration. To clarify this result it is necessary to have a closer look at the power distribution in this complex drivetrain.

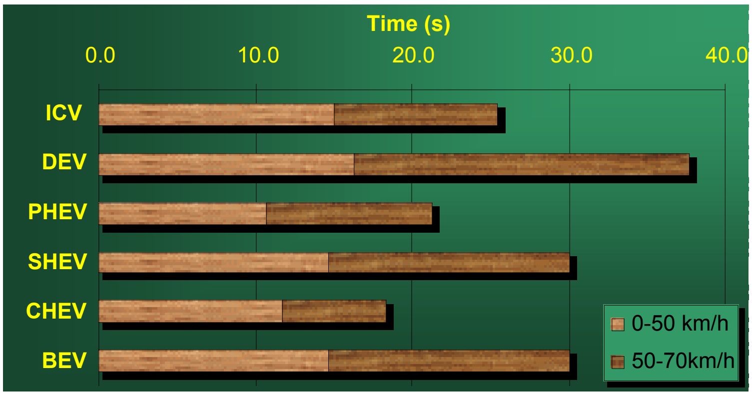

Figure 20
Acceleration Comparison

As can be seen in Figure 21, the first seconds (vehicle speed is inferior to 10 km/h) the CHEV operates in electric mode. Subsequently the engine contributes to the acceleration power in function of the overall minimum loss criteria. Between 5 and 20 seconds the main part of the engine power flows directly via the planetary gear to the wheels. The remaining engine power goes through the generator and via the motor, to drive the wheels as well. After 20 seconds the generator power is inversed. The battery power is split-up between generator and traction motor and both electric drives (motor and generator), as well as the engine contribute to the acceleration wheel power.

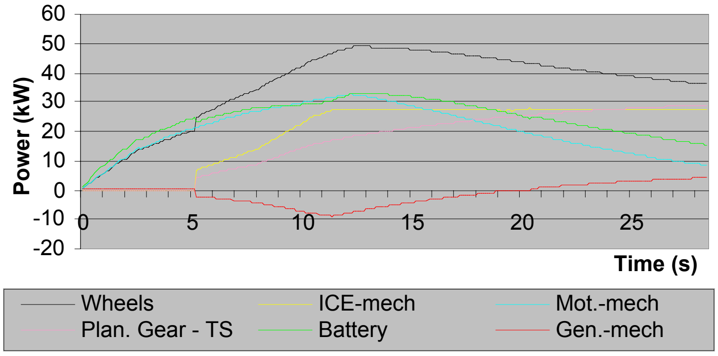

Figure 21
Power in CHEV – Acceleration Test

General Comparison

Figure 22 illustrates the primary energy consumption of the different drivetrains with a total static weight ranging from 1,7 to 2,7 ton.

The simulation results are based on:

- Driving five times the Dutch Urban Bus cycle.
- No component integration work or drivetrain component optimisation.
- End-charge of electric drivetrain is included.

In Figure 22 the blue-yellow line represents the Internal Combustion Vehicle (ICV) reference energy consumption. The top of the purple stroke corresponds with the energy consumption of this vehicle with a total weight of 2,7 ton and the bottom with 1,7 ton.

This reference is compared with the Diesel-Electric (DEV), the Parallel Hybrid Electric (PHEV), Series Hybrid Electric (SHEV), Combined Hybrid Electric (CHEV) and Battery Electric Vehicle (BEV). The latter is charged in Europe (EU), Denmark (DK) and Norway (N) [15

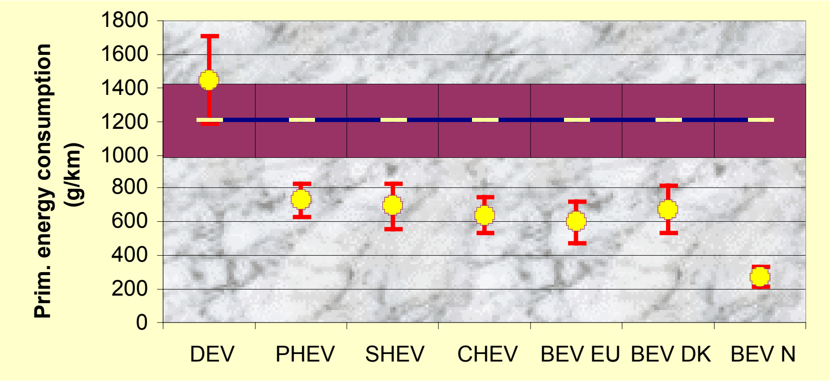

Figure 22
Primary Energy Consumption of Different Types of Drivetrains With a Total Static Weight Ranging from 1,7 to 2,7 Ton

The results give a confident indication of the potential energy reduction of battery and hybrid electric vehicles.

- ✓ In general the case study indicates the possibility to reduce energy consumption, when using hybrid or battery electric vehicles, with more than 40 % in comparison with conventional thermal vehicles.
- ✓ The comparison between the hybrid vehicles shows a benefit for the combined hybrid. However the choice of power management strategy is more decisive to the energy consumption than the drivetrain topology itself. This later should be chosen in function of the market segment, cost, etc.
- ✓ The battery electric vehicle gives the similar results as the hybrid vehicles. However power generation efficiency influences these results very much.
- ✓ At the contrary the diesel-electric drivetrain demonstrates a suboptimal energy management. Its main advantages are rather the performance and flexibility of the electric drive train and the availability of on-board electricity supply.

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