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Emmanuel Vinot, R. Trigui, B. Kabalan. Rule-based energy management of hybrid electric vehicles focus on load following strategy. Reference Module in Materials Science and Materials Engineering, Elsevier, 2022, 10.1016/B978-0-12-821204-2.00080-5 . hal-03842775

HAL Id: hal-03842775

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Submitted on 7 Nov 2022

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Rule-Based Energy Management of Hybrid Electric Vehicles Focus on Load Following Strategy

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Abstract

This chapter deals with the rule-based Energy Management Strategy (EMS) used for Hybrid Electric Vehicles (HEVs). Different methods are presented, with a special focus on the load following strategy. The choice of the system operations is presented for battery charge sustaining and charge depleting operations. A parallel hybrid architecture is chosen as a first example. The case of a Power-Split Hybrid architecture is also developed presenting the management of the engine operations. The energy management in a hybrid vehicle with hybrid electric storage system (Battery plus Ultra Capacitor) is also detailed.

Keywords: Energy management, Hybrid Electric Vehicle, Rule based management, Charge sustaining, Charge depleting.

1. Power system energy management

Energy management plays a paramount role in every multi-sources power system from electricity grid to hybrid vehicles (Roboam (2012)). Since two or more power sources are present in such system, several energy paths exist. The supervision of the energy flow is called the energy management of the system. Its role is to decide which sources are involved and how much power they supply (or absorb) at each time step. This choice depends on the instantaneously required energy and on other criteria (state of stored energy in bi-directional sources for example). It also has to respect the constraints on the system and on the components (for example min/max power, torque or current ...) and could try to minimize (or at least improve) some objectives as the global energy consumption or the greenhouse gas emissions.

Rule based methods are commonly used to achieve this task. They can be based for example on frequency approach or power demand approach. However, to be efficient, these rules become complex and should be tuned or directly derived from optimal (or sub-optimal) energy management strategies.

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In this chapter, we will focus on the case of Hybrid Electric Vehicles (HEVs) and simple rule-based energy management. The hybridization of a vehicle is a general concept achieved as soon as there is more than one sources of energy. Generally, unidirectional energy sources (gasoline, fuel cell, gas ...) are coupled with at least one bi-directional energy source (battery, ultra-capacitor UC, pneumatic storage ...). The concept is not only applied to ground vehicle, it is also used on other types of vehicles (train, boat ...).

This chapter deals with ground vehicles propelled by one engine (gasoline or diesel) and using one or two reversible sources (battery and UC) as main energy storage sources. However, the principle presented in the following section should generally be adapted to other energy sources and other types of vehicle.

The EMS of such vehicles are precisely defined in the previous chapter of this encyclopedia (Energy Management Strategies for HEVs: Introduction and Positioning). It presents the different EMS methods (Rule based, optimization based ...) and their classification.

Ground HEVs generally present a simple system as it is often composed of one main mechanical energy consumer (the vehicle itself) and two energy sources, with at least one bi-directional energy source. Figure 1 presents a general HEV architecture with one engine and one energy storage system (battery). An electrical energy consumer is often added to model the auxiliaries consumption. It represents the power demand of the accessories, including the air cooling system, when there is an electric compressor. For simplicity, it will be neglected in this chapter but can be easily considered by adding a requested power to the main consumer (in our cases: the vehicle). The mechanical and electrical connection between the motors; Internal Combustion Engine (ICE) and Electrical Machine (EM) can be of different types. This leads to different families of hybrid architectures (parallel, series, Power-Split...) see for example Guzzella and Sciarretta (2013). These connections can be composed of Planetary-Gear (PG), Gear-Boxes (GB), Final Gear (FG) ...

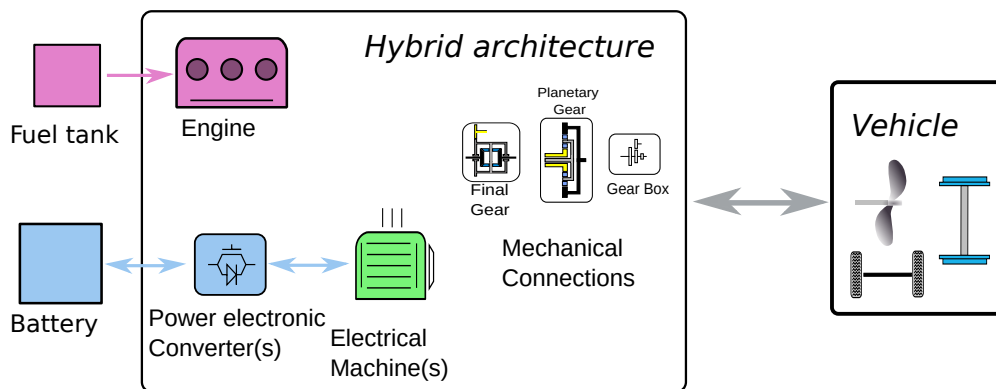


Figure 1: Hybrid electric vehicle architecture with two sources

In the cases of HEVs the energy management will address the following points:

- Choice of the operating modes of the vehicle : pure electric, or hybrid mode and the energy paths between the components (battery charge or discharge when engine ON,

sec.3.1).

- Managing the state of charge of the battery; charge sustaining (sec.3) or charge depleting modes (sec.4).
- Choice of the gearbox ratio if relevant.
- Choice of the engine operation point in a Power-Split Hybrid Electric Vehicle (PSHEV, sec.3.2).

The energy management rules make an instantaneous choice of the energy paths, however they have to respect long terms state of charge objectives. If the battery cannot be plugged to the grid, the vehicle operates in Charge Sustaining (CS) mode. The battery SoC (State of Charge) fluctuates around a pre-chosen SoC and globally, only chemical energy (coming from fuel) is used. If the vehicle can be plugged to the grid (Plug in Hybrid Electric Vehicle: PHEV) it is operated in Charge Depleting (CD) mode until a SoC limit. Hence a part of the energy comes from the grid reducing the fuel consumption.

The objectives of this chapter are to present in a simple way the concept of Rule based EMS. More Specifically we will focus on Load Following Strategy developed for the first HEVs. It existed for many decades but is still used as it is a simple method, easy to implement in HEVs, well-known and presenting good performances.

In this chapter a short presentation of the Rule Based EMS principle based on the example of a parallel hybrid Vehicle is proposed (sec. 2). The cases of charge sustaining operation will then be treated presenting simple rule based energy management in CS mode (sec. 3.1) for a parallel architecture and then its modification for Power-Split architecture (sec. 3.2) to manage the choice of engine operation. A more complex case, with two energy storage sources is then presented to provide an example of energy management with three sources HEVs (sec. 3.3). Finally, the charge depleting operations are discussed (sec. 4) presenting the basic rules to manage the decreases of the SoC along the travel.

2. Rule Based EMS and energy flow : case of Parallel hybrid Vehicle

As in every system where multiple energy sources are involved, energy management rules are mandatory in hybrid vehicles (Hofman et al. (2007)). They do the power and energy path choices in the vehicle, respecting the constraints of battery charge or discharge. As an example, the possible energy paths are presented fig.2 in the case of a parallel hybrid architecture with two clutches. In such an architecture the Engine (ICE) and the Electrical Machine (EM) are mechanically connected to the wheels. The EM is connected directly to the engine or by means of a coupling device (CPL). A first clutches (C1) allow to decouple the engine from the wheels in electrical operation. A Gear box (GB) is required, as in conventional vehicles to adapt the ICE speed depending on the wheel speed. A Second clutch C2 (if open) allows the EM to start the engine. GB is connected to the wheels by means of a Final Gear (FG) and differential device (DIFF). The Electrical machine is connected to an Inverter (INV), Which is linked to the Battery (BATT).

Different parallel architectures exist depending on the place of the electrical machine, and other hybrid architectures also exist such as Power-Split architecture (sec.3.2). For more information on the different hybrid architecture see for example Guzzella and Sciarretta (2013).

Several energy paths are possible in Parallel HEVs (and in HEVs in general). When the vehicle operates in electric mode, the power flows downstream from battery to the wheel (traction) or upstream from the wheel to the battery (regenerative braking). In hybrid mode, the engine and the EM provide power (orange and cyan arrow). Those powers are added in the coupling device and flow to the wheel (blue arrow). The electric flow can be positive (from the battery to the wheel: boost mode). It can also be negative, from the engine to the battery. A pure ICE flow, from the ICE to the wheels, can also be imagined with no electric flow. The energy management laws are thus in charge of choosing the directions and the values of these flows to provide the required power to the vehicle and the battery and generate the high level set-points to the component close loop controllers (set points of EM and ICE torque ...).

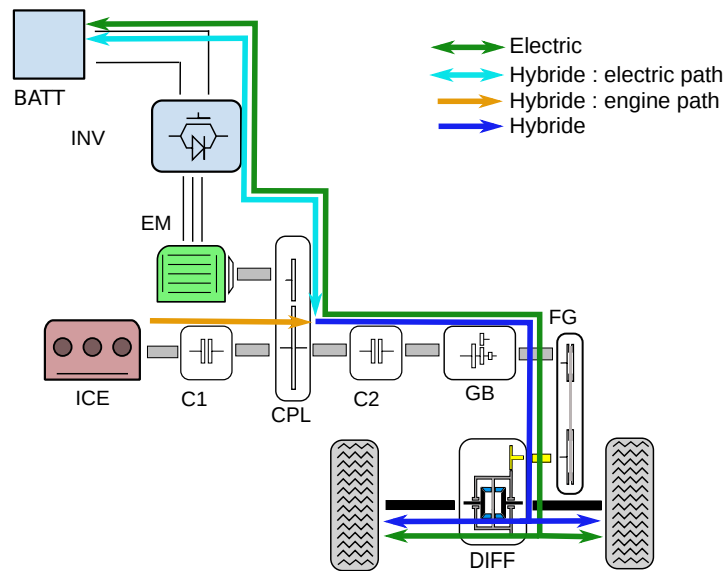


Figure 2: Energy path in hybrid parallel architecture

These laws can be classified in two types : online (can be implemented directly in the vehicle computer unit) and off-line (need the knowledge of the entire speed profile), thus cannot be implemented directly online (for more complete classification of HEVs energy management see chapter: "Energy Management Strategies: Introduction and Positioning"). In this chapter, we focus only on simple online energy management laws and their principles.

In this type of energy management, we currently find methods based on simple rules (sec. 3 and 4) (Kimura et al. (1999); Akli et al. (2007); Mayet et al. (2014); Vinot et al. (2008); Poline (2018)).

These rules are sometimes optimized offline by tuning some parameters (power threshold

for example) (Bertram et al. (2011); Buerger et al. (2010)). Complex rules are also developed based on offline pre-calculation on an optimal process as Stochastic dynamic programming (Leroy et al. (2012)). Fuzzy logic energy management (Singh et al. (2021)) or "Equivalent Consumption Management Strategy" (Li and Jiao (2019))) are also more and more developed. A lead of development of these laws now concerns predictive energy management laws based on the knowledge of future driving conditions (speed, traffic slopes ...) (Liu et al. (2021)). Neural networks (often linked with charge depleting operation) and predictive energy management are also a recent lead of development (Zhou et al. (2021)). For more information on these topics see other chapter and refer to chapter: Energy Management Strategies: Introduction and Positioning.

These laws tend to respect a predefined SoC objective (as explained in this chapter) but they also can try to improve other objectives. A compromise between fuel consumption and pollutants emission can be one of these objectives, improved by delaying or favoring the engine start at the beginning of the cycle avoiding catalyst pipe cold operations. The reduction of battery aging could also be an objective by reducing current or thermal stress (Pham et al. (2014)).

In the following, we mainly focus on simple but efficient rules managing only the battery state of charge in charge sustaining or charge depleting mode.

3. Charge sustaining case

The charge sustaining energy management is used in non plug-in hybrid vehicles. In this case, the only source of energy is the chemical energy contained in the fuel tank. The battery size is generally small in such vehicles (less than 5kWh). The battery SoC globally fluctuates around a preferred value as it will be generally of no interest to charge or discharge it too much (except for example in mountain use conditions). The relatively small SoC window evolution improves the life span of the battery avoiding high and low SoC. This section presents simple rule based energy management to choose the vehicle operation (sec. 3.1) and the engine operation in case of Power-Splitt HEV vehicles (sec. 3.2). Section 3.3 deals with the case of HEVs with Hybrid Storage System (HSS).

3.1. Simple rules for operation mode choice

3.1.1. General presentation

In charge sustaining, the operating modes of the system and the battery operation (charge or discharge) can be managed with simple rules. The management presented in the following is highly derived from the one of the Toyota Hybrid System, at least those used in the Prius II (Vinot et al. (2008); Kimura et al. (1999)) and is commonly called power following strategy or load following strategy (LFS).

3.1.2. System Management

A LFS is presented in the following. Simple decision rules and the principle of the Energy Management deciding to start or not the Engine are described. In this rule based management, the flowchart of decision principles is presented in figure 3 and is only based

on two characteristics. A first curve (fig. 4) will fix the choice of electric or hybrid mode (engine ON/OFF), a second (fig. 5) provides the power required by the battery depending on its SoC. Using the curve (fig.5), the required power by the battery P_{batreq} is easily assessed depending on its state of charge.

On the first curve (choice of operating mode characteristic, fig.4), a threshold $P_{startICE}$ is determined using the curve, depending on the battery SoC. The required power P_{req} is then evaluated summing the battery required power and the power requested by the driver to propel the vehicle. This power is evaluated knowing the driver's action on the throttle, which is transformed into a required torque (T_{req}) on the wheel shaft and multiplied by the rotation speed to provide a required power:

$$P_{req} = T_{req} \cdot \Omega_{wheel} + P_{batreq} \quad (1)$$

If this value (P_{req}) is higher than $P_{startICE}$ the engine is started otherwise the powertrain will be operated in electric mode. In this case, the battery provides the necessary required power to propel the vehicle.

If the engine is started ($P_{req} > P_{startICE}$), the variables $hyb1/0 = 1$ and $elec1/0 = 0$ (fig. 3) and the required torque on the ICE is determined knowing its rotational speed (which can be measured or deduced from the wheel speed and gear ratio).

If the engine is OFF ($P_{req} < P_{startICE}$), the variables $hyb1/0 = 0$ and $elec1/0 = 1$, and the required torque on EM is assessed using its rotational speed (measured or known using the total gear ratio from wheel to EM). The power provided by the battery is then disconnected from the required one (P_{batt_req}).

For example, considering a $SoC = 60\%$, and a required mechanical power $T_{req} \cdot \Omega_{wheel} = 10kW$. The battery required power is $P_{batt_req} = -1kW$ (5) corresponding to a battery recharge. The total required power is then of $P_{req} = 11kW$ when the threshold $P_{startICE}$ to start the engine is evaluated using fig.4 and is equal to $10kW$ (for $SoC = 60\%$). In this case; $P_{req} > P_{startICE}$ thus the powertrain will operate in hybrid mode and the energy management law will tend to recharge the battery.

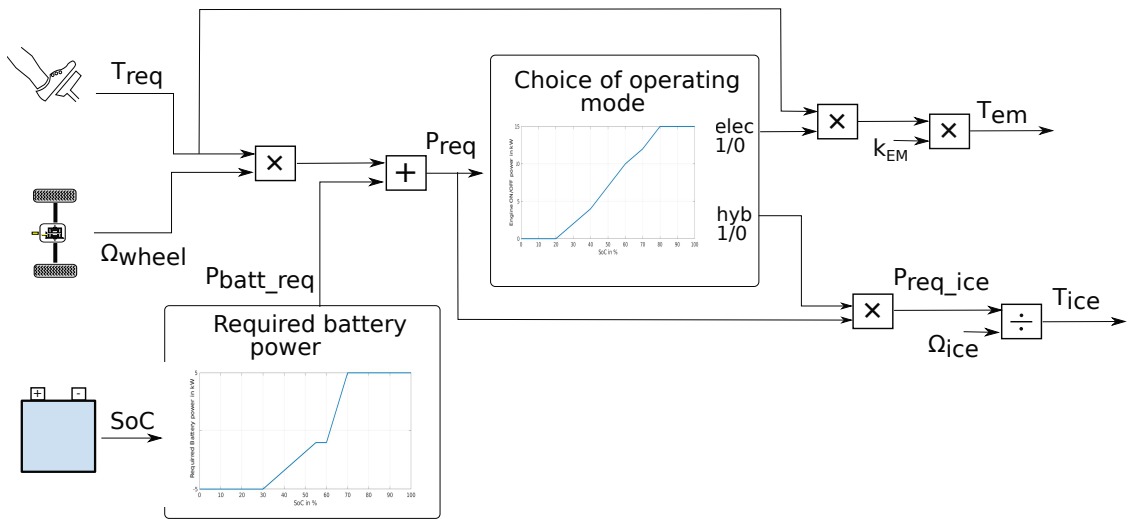


Figure 3: Rule based management in HEV vehicle

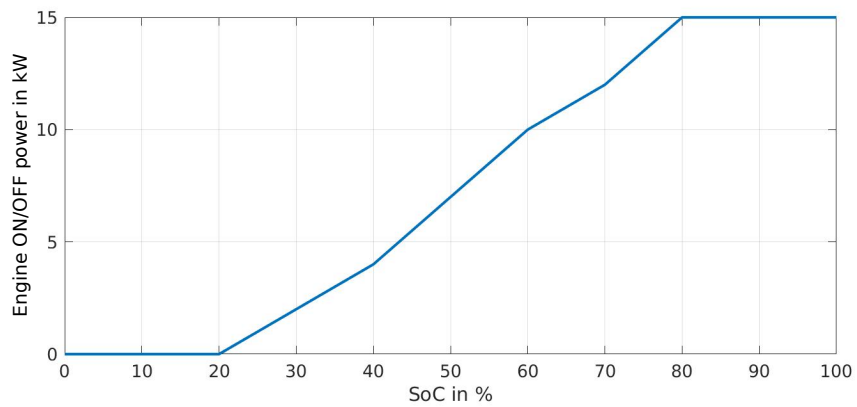


Figure 4: Choice of operating mode characteristic

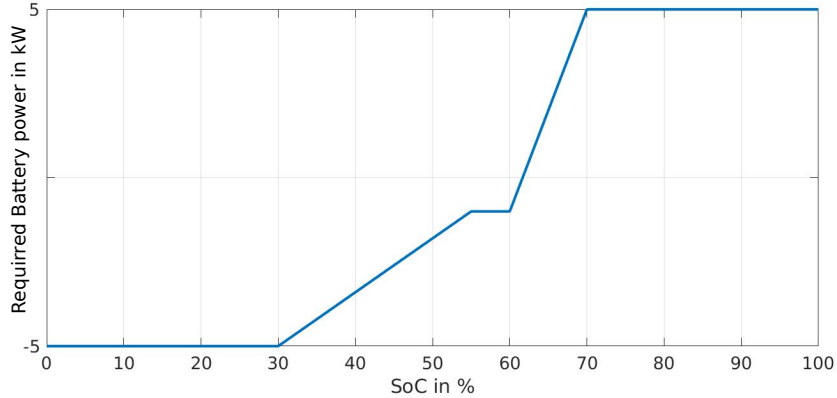


Figure 5: Required battery power curve

3.1.3. Application and discussion

With these two simple rules, the vehicle energy management (fig. 3) fixes the system operation and guarantees a charge sustaining mode. This can be seen in figure 6 where the state of charge of a vehicle (Toyota Prius II) is simulated with this energy management on the NEDC driving cycle for three initial SoC. It is clear that this management law tends to keep the SoC around a value of 56 %. If the starting SoC is around this value, the vehicle is globally operated with near zero battery energy balance (only fuel is consumed along the cycle). Starting at high SoC value, the battery is globally discharged and the engine is not too much used (fig. 6) especially during the first three hundred seconds. On the contrary, starting at really low SoC, the engine is highly used and is never OFF (including regenerative braking phases) during these three hundred seconds. This behavior is explained by the shape of the two curves (fig. 4 and 5). When the SoC is low, the engine will be started for low required power P_{req} and the battery request to be recharged with relatively high power (below 40 % SoC). On the other hand, for high SoC, the threshold to start the engine is high and the battery required power is negative (discharge cases). The hybrid mode is thus not much used favoring the electric mode (battery discharge except in regenerative braking) and hybrid mode with battery providing power to the wheel. These energy management rules tend to "naturally" bring the SoC around a value where the required power is around zero. Note that, due to the losses in the system (not taken into account in eq. 1) the SoC tends to a value with a small negative battery recharge requirement. For vehicle operation measurement and validation on this law in a real case (SoC, engine torque and speed, fuel consumption) one can refer to (Vinot et al. (2008)).

Supplementary rules are often added for the vehicle operations at high speed or when the engine and tail pipe are cold. At speeds higher than a certain threshold, the engine can be kept ON, even if in idle operation, favoring vehicle dynamic and driving comfort. In cold start conditions, the engine start can be favored in order to warm the catalyist converter to oxide the pollutants with a good efficiency.

Concerning the ON/OFF engine choice, to avoid oscillations between hybrid and electric

mode, the use of one curve is not enough. If the same characteristic is used to start or stop the engine a risk of oscillations between the two modes is high if the required power varies around the engine ON/OFF threshold. A simple way to solve this problem could be the addition of a minimum time spend in hybrid mode forcing the engine to be ON a minimum of time. Another solution could be to have a different threshold to stop the engine. A hysteresis should then be added on the engine ON/OFF laws (sec. 4).

These rules can be applied to any type of hybrid architecture (parallel, power-split, series ...). In those with a gearbox, the gear shifting is done automatically. The gear choice can be based on the engine speed and possibly on the required torque. This globally tends to fix the engine operating point in a good efficiency area. For power-split (PSHEV), another curve is used to manage the engine operation choice as it can be made in a continuous manner (section 3.2).

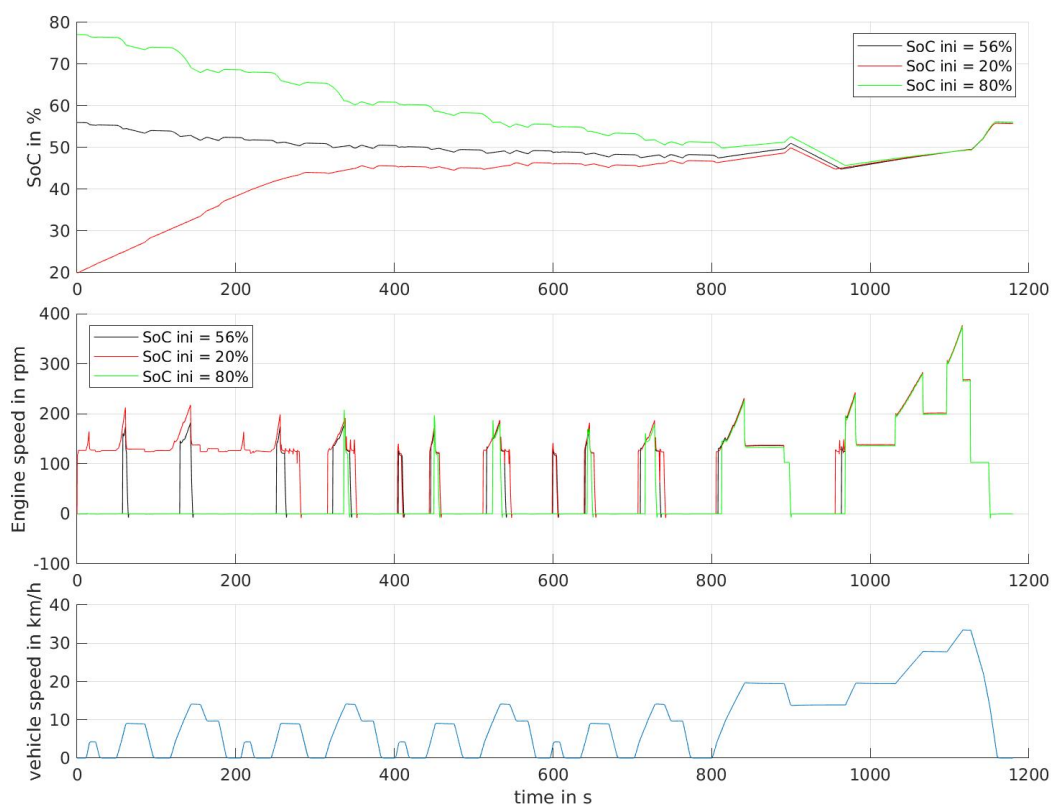


Figure 6: SoC evolution and engine speed along NEDC cycle

3.2. Power Split Hybrid Electric Vehicle Cases

3.2.1. General presentation

Among the hybrid vehicle architectures, the power-split hybrid electric vehicles (PSHEVs) have been proven to be among the most efficient. Several PSHEV architectures exist. The

Toyota hybrid system (THS) based on planetary gear is the most known (fig. 7). Opel uses another system based on planetary gear in the Ampera (Vinot (2016)). Finally, PSHEV architectures with Electrical Variable Transmission (EVT) are currently studied in laboratories (Hoeijmakers and Ferreira (2006); Verbelen et al. (2020)) but are not commercialized yet.

In the THS, the architecture is composed of one engine two EMs and one PG. The engine is linked to the Planet Carrier and EM2 to the Sun gear. The ring is connected to the wheels and EM1. No gearbox is needed as PG and EM2 allow the adaptation of engine speed on a continuous manner. For a complete explanation of the THS and its operating modes see for example Vinot et al. (2008); Guzzella and Sciarretta (2013).

By splitting the engine power in a combined serial and parallel way and decoupling the engine and wheel speeds, such architectures allow a fuel consumption reduction which can reach 40% in urban driving conditions compared to a conventional vehicle. A degree of freedom is added to the management of the powertrain. For a required engine power, the operating point of the engine can be chosen quite independently of the other parameters of the system (vehicle speed ...) along a given power hyperbole (fig. 8).

3.2.2. Engine operation Management

To manage the engine operation (fig. 10), a rule is added to the two previous rules presented in (sec. 3). A preferred engine operation curve is then often used (in cyan fig.8) to fix the engine torque and speed. It is predefined to match the best specific fuel consumption area (best efficiency). The operating point is then the intersection between this curve and the hyperbole of required power. Once the engine operating point is chosen, and knowing the wheel speed and required torque, the operation point of the others components (Planetary gear, Electric machines ...) can be deduced and the closed control generated (see for more details Vinot et al. (2014); Chen et al. (2009)).

3.2.3. Simulation Results

An example of the engine operation is presented in figure 9 on the WLTP cycle for a simulated Prius-II vehicle. It is clear on the figure that the engine operation points (in blue on the figure) mainly concentrate around the predefined engine operating curves (except in dynamic phases).

Load following rule based energy management (LFS) has been presented in the charge sustaining cases (sec. 3.1.2). The used curve can be simpler (uses constant threshold for example, see sec. 4) or more complex (Kim and Peng (2007); Romaus et al. (2010); Liu and Peng (2008)). Their shape could be optimized to improve the fuel consumption (see for example Vinot and Trigui (2013)). Other parameters could also be managed and particularly the DC bus voltage when a DC-DC converter is used between the battery and the inverters (for more details refer to Verbelen et al. (2020)).

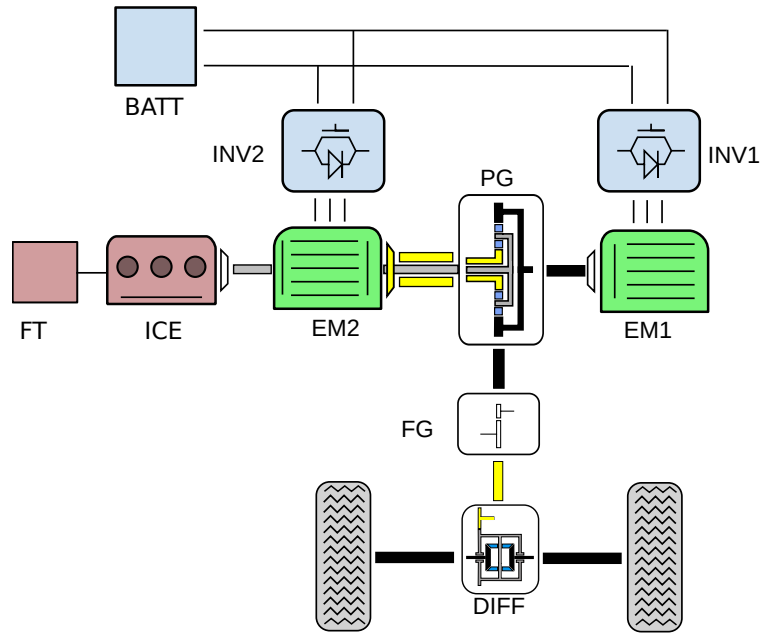


Figure 7: Toyota Hybrid System

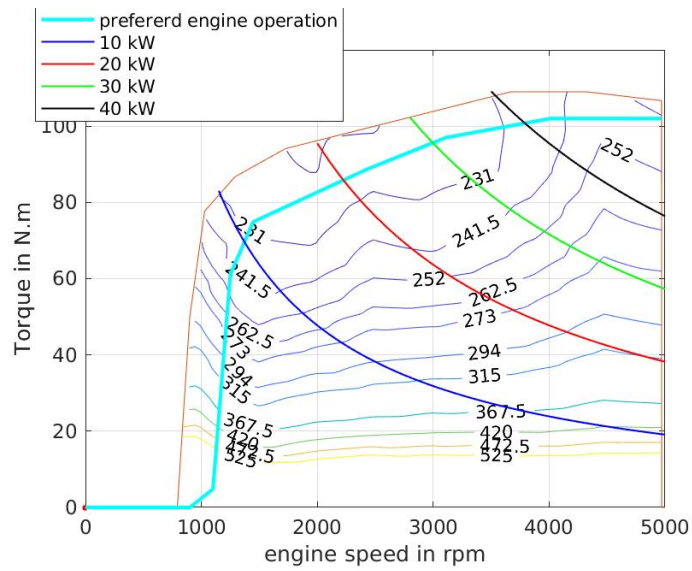


Figure 8: Engine specific fuel consumption maps in g/kWh with engine preferred operation

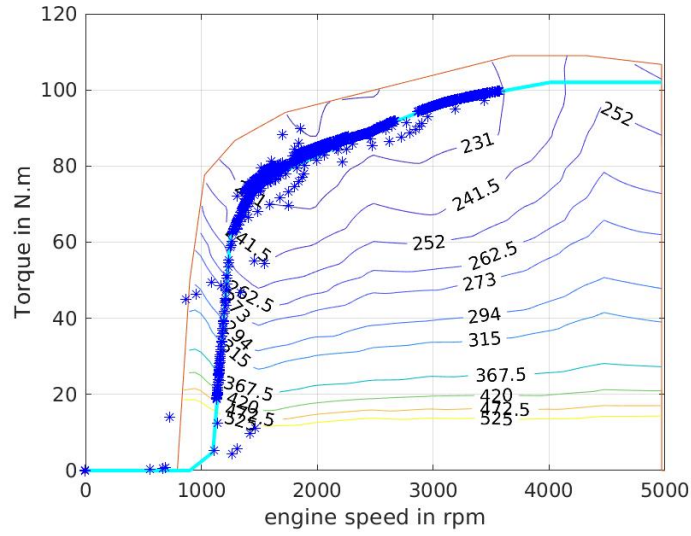


Figure 9: Engine Operation on WLTP cycle
 $(P_{req} > P_{startICE})$

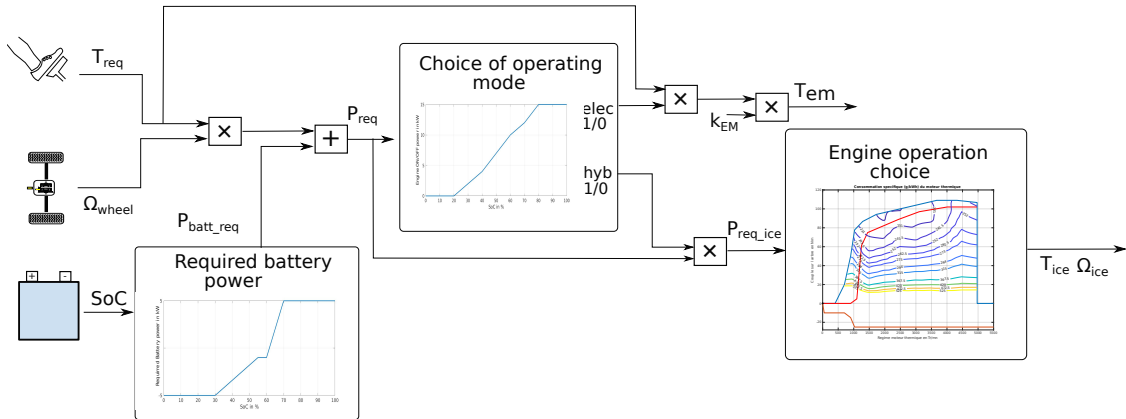


Figure 10: Rule based management in PSHEV vehicle

3.3. Case of hybrid vehicle with hybrid storage system

3.3.1. General presentation

In order to reduce the stress on the battery or to increase the capability of the storage system to better handle the power peaks, one can imagine to use hybrid storage systems (Vinot and Trigui (2013); Trovao et al. (2014); Castaings et al. (2016)). Such systems will commonly associate two sources with different characteristics; one mainly oriented on energy capacity and one able to absorb high peaks of power with small storage energy capability.

The association of a battery and an ultra-capacitor (UC) is probably the most studied hybrid storage system. In such a system, the energy management has an additional role: it has to manage the electrical power sharing between the battery and the ultra-capacitor.

An example of such architecture is presented in figure 11, where a DCDC converter is connected to the UC bus to adapt its voltage to those on the battery. The choice of the number and place of DCDC converter can be different. DCDC converters can be placed on the DC bus (before the inverter) or connected to the battery (Allègre et al. (2013); Castaings (2016)).

To manage such a vehicle, the rules presented in section 3 can be applied with a supplementary law to manage the power sharing between the battery and the UC. This can be managed in a relatively simple manner using frequency based principle. The high frequency electrical power is affected to the UC and the low frequency to the battery. For that, a first order filter could be added to the required electrical power (fig. 12).

In electric mode, the required electric power P_{req_elec} is deduced from the required torque T_{req} . In hybrid mode, a required battery power P_{req_batt} is added to the necessary power to drive the vehicle. The engine has to provide the sum of these two powers P_{req_ice} .

In both modes, a first order low pass filter with a cut-off frequency f_c is used on P_{req_elec} to compute the battery target power P_{targ_batt} . Taking into account the available UC power, the UC is then used to provide the difference between P_{targ_batt} and P_{req_elec} . If the desired UC power exceeds the available UC power (maximum/minimum current and/or voltage), the battery is used to provide the necessary additional power to fulfill P_{req_elec} . Overall, with this strategy the battery satisfies the mean required power while high frequency power peaks are provided by the UC. Moreover, if P_{req_batt} is correctly tuned, the charge sustaining mode is guaranteed for the battery even if the battery does not provide exactly its required power.

However, due to the losses in the systems, this management does not guarantee the State of charge sustaining of UC. In order to avoid long-term supercapacitors discharge, an adaptive controller can be added based on different techniques such as PI controller (Hussain et al. (2019)), fuzzy logic (Snoussi et al. (2018)), Linear quadratic regulation (Sadeq and Wai (2020)).

3.3.2. Simulation Results

Applying such rules for the energy management on a parallel hybrid architecture, figure 13 presents the battery and UC current and the battery SoC that can be obtained along a NEDC cycle for two different values of cutting frequency f_c (0.06 Hz and 0.0005 Hz). This figure highlights the effect of the cut-off frequency of the first order filter on the battery current. The battery current peak and the corresponding battery current stress are drastically reduced when the cut-off frequency is small (0.0005 vs. 0.06 Hz). The overall strategy does not change so much. The electric mode is mostly used in the first 800 s of the cycle and for the rest of the cycle the engine is used to charge the battery to achieve charge sustaining operation over the cycle. For more details (parameters of the use cases and deeper explanation see (Vinot and Trigui (2013))).

The rule based management laws in cases of hybrid architectures were presented in the

previous sections. The case of power split functionality was treated in section 3.2. The management of hybrid electric vehicle with hybrid storage system was presented in section 3.3. All these rules and laws are applied in the charge sustaining case. The case of plug-in vehicle and the battery discharge management (charge depleting) are presented in the following section.

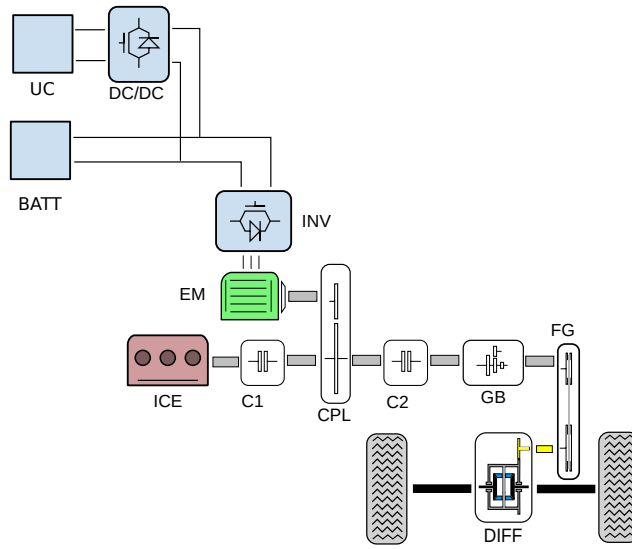


Figure 11: Hybrid parallel architecture with battery and UC

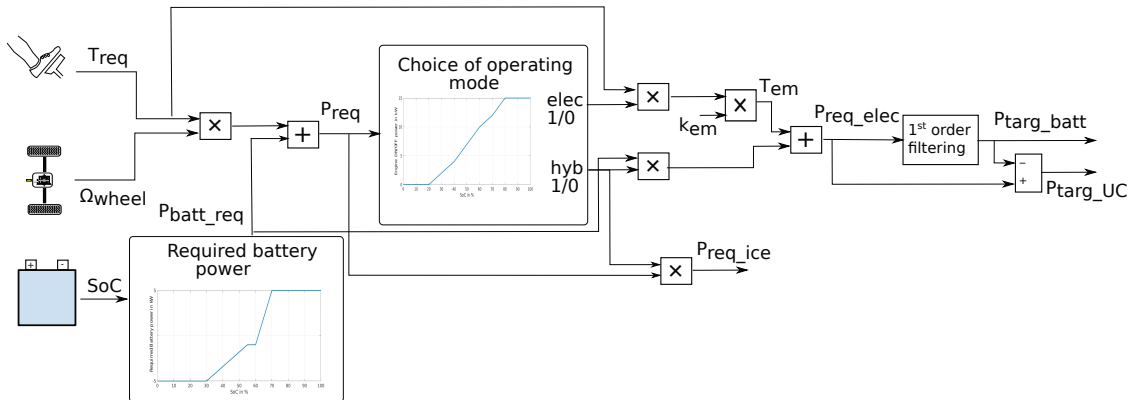


Figure 12: Rule based management in HEV vehicle with hybrid storage system

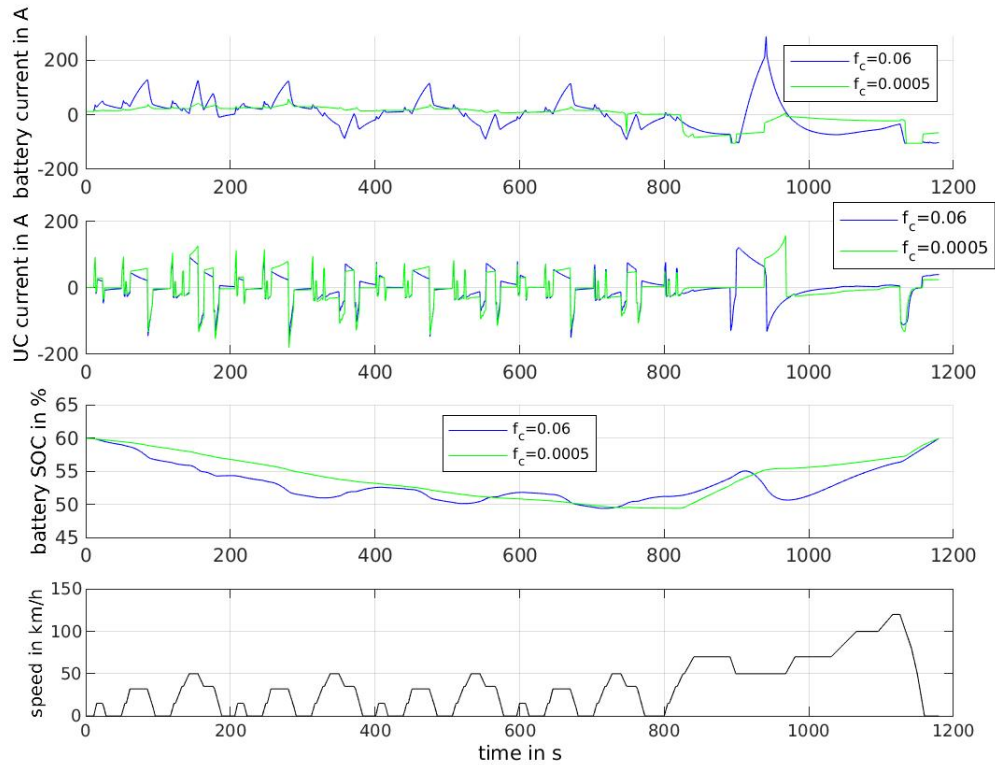


Figure 13: Battery and UC current and battery SoC for two cutting frequencies

4. Charge depleting case

Currently more and more vehicles are of Plug-in type. Compared to a non-plug-in hybrid vehicle, the external battery recharge capability of PHEVs adds a degree of freedom to increase the electrical consumption share and reduce the fuel consumption. The battery discharge strategy along travel becomes then another point to be addressed by the energy management law.

4.1. General principle

In a plug-in vehicle, the battery has to be discharged in order to replace a part of the fuel energy consumption by electrical energy consumption. The on-board computer unit has thus another parameter to manage: the global discharge of the battery. Three different modes of energy management can be defined (fig.14).

- A pure electrical mode. Only the battery provides energy to the wheels and the accessories. It needs a battery and electrical machine(s) with enough power (tens of kw).

- A blended mode. The vehicle is managed in hybrid mode. The engine is ON or OFF depending on rules, which can be close to those on charge sustaining mode, but aims to discharge progressively the battery.
- The charge sustaining mode. Generally triggered when a low battery SoC is reached and which can be managed as previously presented (sec.3).

The pure electric mode and blended mode can be present or not depending on the strategy adopted and on the size of the battery. Some manufacturers choose for example to switch directly from pure electric mode to charge sustaining mode.

The switching choice between these modes can be done in a simple manner as presented in (fig.14) by progressively discharging the battery until charge sustaining operation. In this case the SoC is the main parameter of decision. However more and more predictive energy management strategies are studied for PHEVs and try to use the complete or at least partial knowledge of the future driving mission. Depending on this knowledge, the choice of the operating mode can be modified. As an example, if urban conditions will follow highway conditions, a charge sustaining mode can be chosen in prevision of pure electric mode in urban conditions.

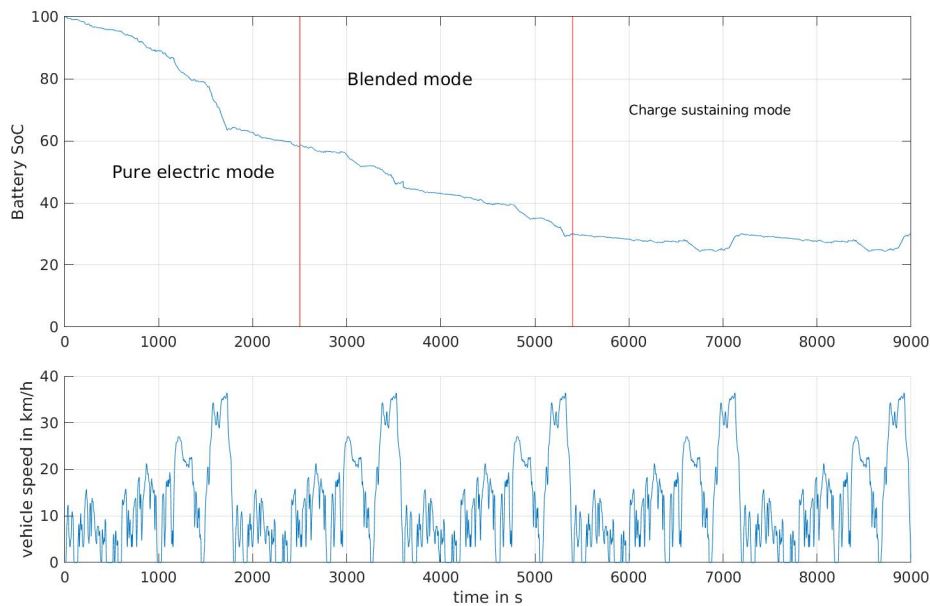


Figure 14: SoC evolution in PHEV vehicle

4.2. Example of rule based energy management for PHEV

As explained before three main modes are generally used for rule based energy management of PHEV, namely electric mode (EL), hybrid mode where the ICE is on (called

also blended mode, BL) and charge sustaining mode (CS). In the present example the mode selection is based on SoC thresholds.

Generally the PHEV charged at 100% of SoC begins with all electric mode. Some strategies suggest to use this mode until the minimum SoC corresponding to charge sustaining mode enabling (SoC_CS). In this case the blended mode is never selected (only for the cases where electric drive power is lower than the required power). This kind of strategy is basic and allows to maximize the electricity use whatever the trip distance and duration are. However when the trip is long, it leads to intensive use of the CS mode which is not the most efficient for a PHEV.

In the presented method here, we suggest to use appropriate SoC_BL as a threshold to enable Blended mode. The variation of this threshold makes it possible to adapt the use of the battery during the trip and thus to have long or short blended mode (we can decide in the opposite of the former case to enable the Blended mode from the beginning of the trip and never select the EL mode).

In all cases when the CS mode is selected, one can use a charge sustaining strategy using load following strategy (LFS) like explained in section 3.

For the Blended mode, simple rules could be adapted from the LFS strategy.

- When the power demand is higher than a constant threshold (P_h) and lower than the optimal ICE power, the ICE is ON and provides the requested power. Therefore, unlike in CS mode, the battery is not recharged in this case so that globally (in the BL mode) its charge continue to deplete.
- When the power demand is higher than the optimal ICE power, the ICE is ON and provides its optimal power. The battery provides the difference between the required power and the ICE optimal power.
- When the power demand is lower than a constant threshold (P_l), the ICE is OFF. The margin between P_h and P_l provides a hysteresis band to prevent modes oscillation.
- When the power demand is negative (vehicle deceleration/braking) the ICE is OFF (electric mode) and regenerative braking is maximized.

These rules have been implemented in a parallel PHEV model and tested on a succession of six driving cycle of extra-urban road type. The vehicle characteristics and the thresholds used are summarized in table 1. Simulation results (15) show the succession of the modes selection according to the SoC planed thresholds. The expected behavior of the SoC and the ICE vs EM use (Torques graph) is in accordance with the strategy. When varying the parameter values of the rule based EMS, the fuel consumption of the PHEV could be different for the same SoC variation along the use. This leads to the idea of a possible optimization of these values that could be done by simulation considering a representative use of the vehicle that includes different types of driving cycles.

Variable	Value/threshold
Vehicle mass	1350 kg
Electric power	60 kW
ICE power	80 kW
SoC_BL	40%
SoC_CS	20 %
P_l	18 kW
P_h	24 kW

Table 1: Vehicle characteristics and thresholds

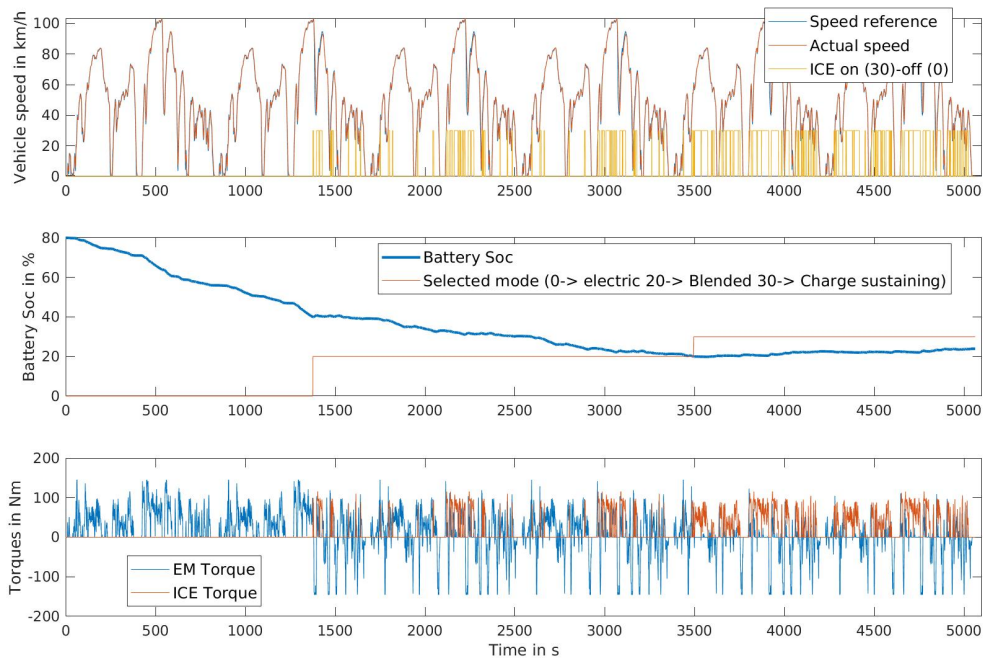


Figure 15: Energy management in CD operations

5. Conclusion

Due to the presence of more than one energy source and energy path in Hybrid Electric Vehicles (HEVs), an energy management strategy (EMS) is required. The objective of this chapter is to present in a simple way the well-known Rule-based EMS and how they are implemented in different cases of HEVs. For this, the general problem of energy management in HEVs is first explained: the instantaneous decisions to make, the state constraints to respect, and the objectives to optimize, if any. In the second section, this problem was explained in the case of a parallel HEV. After this, the application of rule-based EMS in charge sustaining operation is done for 3 examples: a parallel architecture, a Power-split architecture and a 3 sources HEV with hybrid energy storage system. For each example, the rules are described and the simulation results of the system operation are shown. Finally, rule-based EMS are applied in the case of charge depleting operation (plug-in hybrid vehicle). The simulation results and the vehicle operation are presented. It is clear that different parameterization of the rules leads to different results, which emphasizes the importance of optimizing these rules.

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