FEV Parallel Mode Strategy

Peter Janssen MSc.
Dipl.-Ing Glenn Haverkort
FEV Motorentechnik

As the automotive industry has to react to the global concern about climate change related to CO2 emissions and also driven by the rapid increase of the crude oil prices, alternatives to reduce the fuel consumption and reduce the emissions are being explored. One alternative is a hybrid power train, combining the internal combustion engine (ICE) with an electric machine (EM).

The control of such a system typically realized with a hybrid control unit (HCU). FEV has developed modular software for HCU and TCU controls. One of the main components in this software structure is the State of charge (SOC) management and torque distribution of a parallel hybrid driveline. This paper describes FEV’s parallel hybrid software as used in various finished and ongoing hybrid development programs.

The test object vehicle is a 4 cylinder 2.2l diesel powertrain with FEV E-Booster. The base driveline is a conventional 6 speed AT transmission. By replacing the torque converter with a planetary gear set and an electric Motor a mild or full hybrid vehicle is realized. The overall package length of the transmission remains unchanged. This means that the driveline has a high carry over content from the base driveline and the powertrain installation remains unchanged.

In this way a parallel hybrid vehicle is realized which shows the following features:
- High launch performance
- Regenerative Braking
- Boosting by E-Motor
- Charging by E-Motor
- Start / Stop
- Electric Driving (optional)

Figure 1: Example Vehicle with FEV E-Booster
The vehicle control in this vehicle is realized in a master-slave control unit arrangement. The Hybrid control unit HCU calculates the driver requested torque, the target gear (i.e. engine speed) and the desired torque of Internal Combustion Engine (ICE) and electric Motor (EM). The ECU, MCU and TCU are slaves which realize the commanded torque or speed by the HCU.

One of the most important factors in any hybrid driveline is the battery system. Generally, the battery deteriorates more rapidly with higher depth of discharge (DOD). For the parallel mode software this means that high SOC sweeps should be avoided as much as possible. On the other hand the driver should not notice the time dependant behaviour of the drivetrain.

Requirements for the parallel mode:
- Function module structure according to the FEV Standard requirements
- Easy and discrete to calibrate, easy to understand
- Good Drive ability
  - Noticeable part should be reproducible
  - Always fulfill driver demand
- Consider battery lifetime i.e. avoid high SOC sweeps
- Power limitation for battery overload protection
- Robustness against SOC deviations caused by battery adaptations
- Must cover all parallel conditions
- Cooperate with TopExpert calibration tools
- Compatible with Targetlink for production code
- Applicable for all parallel hybrid concepts:
  - Parallel mild hybrid systems with crankshaft EM
  - Electric torque converter mild hybrid system
  - Electric torque converter full hybrid system (with electric drive)

*Figure 2: Battery and SOC requirements*
During normal operation the Battery Control Unit (BCU) will calculate a SOC dependant on its measured signals and a battery model. On some operating points the battery system is able to adapt its calculated SOC to the real battery condition. Since one of the key input signals for the parallel mode strategy is the SOC, such a battery adaptation can lead to an operating point shift. If this occurs during a certification cycle, e.g. NEDC the system loses reproducibility.

For this reason some OEM choose to have a special certification mode for a hybrid vehicle. With FEV’s parallel approach using calibratable operating windows the system becomes less sensitive to minor SOC deviations. This allows the parallel hybrid vehicle to omit the certification mode.

**Figure 3: SOC adaptation during an NEDC cycle**

The parallel mode software is embedded in the standardized FEV software structure. This structure was developed to allow a high modularity and flexibility and at the same time have a compact structure with limited bus usage. The structure perfectly fits to an automated code generation process. The clearly defined interfaces allow a high flexibility as well as the ability to test, develop and compile software modules individually.

The parallel mode strategy is divided into several sub functions. During each program task the scheduler decides which sub-function is currently active and remains in this function until the next function is needed (e.g. normal mode to overboost).

During normal operation mode (roughly between 50 and 70% SOC) the hybrid system will try to minimize the use of the EM as much as possible. During recuperation charging will be done in any SOC condition until 90%. At a lower, but not critically low SOC the Parallel software will charge during part load condition. If the battery level is critically low a minimal charging will always take place. During overboost the charging will be limited to a level to compensate the
boardnet. In conditions of high SOC, e.g., after a long downhill driving, there will be an electric boost even at small torque requests.

In some occasions, especially in Diesel hybrid powertrains, an additional short term boosting mode can be activated. This mode can boost before the maximum engine torque is exploited for emission reasons. This Emission boost allows an optimization of, e.g., the NOx vs Fuel economy trade off for diesel powertrains.

![Figure 4: Parallel hybrid states](image)

The desired torque split is calculated as described below. From the torque distribution the target engine torque is generated. The difference between actual engine torque and driver request is sent to the EM. If the driver requested torque is equal or less than the maximum torque of the ICE, than the ICE will be the single torque source. If during transient conditions the engine can not follow the drivers request (e.g., turbo lag) this is compensated by the EM. Since these are short term effects the negative influence on fuel consumption is small. The driveability however is improved very much by this measure.
Figure 5: ICE and EM Torque calculation

The threshold for exceeding in the maximum ICE torque i.e. overboost mode can be calibrated separately. During economy mode the overboost is only activated at kickdown. By the transient torque compensation a significant improvement of driveability is achieved with a minimum usage of boost power i.e. very good overall real life fuel economy.

During sports mode the driver requested torque (pedal map) is more aggressive and overboost is used more frequently. This mode ensures highest performance, but will lead to an increase in fuel consumption.

With a parallel hybrid system the overall effort in finding the optimum setpoints in the n-dimensional variability’s of the system is rather complex. For the parallel hybrid system calibration offline tools were developed to ensure rapid high quality calibration results. For this purpose the Shift Analyser from FEV tool environment Top Expert® was extended by a hybrid load/boost calibration mode. For general visualization additional views were added.
Figure 6: Hybrid system calibration sequence.

First an offline calibration is generated. With the Shift analyzer the interaction of vehicle driving resistance, driver torque request, parallel mode and shift strategy is calculated and displayed.

In multiple views, dependant on gear, speed, SOC, uphill/downhill etc. Each operating point can be selected, displayed and checked. By this offline calibration the pedal map, shift lines and torque distribution manager can be pre-calibrated. Multiple views allow shift hunting, driver request and performance verification. With the generated parameter set an offline simulation can be carried out to quantify the impact of the calibration on e.g. performance and fuel economy.

In a second step the cycle to be optimized is driven and the required parameters are measured. The measurement is displayed and visualized in different views (e.g. display of operating points in the engine NOx and BFSC maps. Each operating point can directly be linked to a time stamp and displayed in Shift Analyser. Since only xCU data are used this optimization process is valid for any cycle. Generally it can be recommended to optimize NEDC and real world cycles like e.g. Aachen City, Overland and Highway. This calibration approach allows an optimization for any parameter or a direct trade-off optimization. In this diesel application the trade-off of NOx vs. fuel consumption could be optimized. The overall NOx level was kept at the same level as the conventional base vehicle with 6AT transmission, thus maximizing the fuel economy potential. An overall fuel consumption improvement of 20% was achieved.

During the calibration and optimization process several key attributes can be noticed:

- The lower the hybrid activity, the better the overall fuel economy (optimization parameter: minimizing the sum of the high voltage Current \( I (As) \))
- By the transient torque compensation a further reduction in engine speed (downspeeding) can be achieved with at the same time an improvement of driveability.
- Torque reduction by the EM avoids Emission peaks and has a slight positive influence on fuel economy as well (charging during peaks).

Conclusion:
- A modular Parallel mode software compatible with FEV’s modular software structure was realized
- Driveability targets achieved:
  - Driver demand always met i.e. high low end torque, no turbo lag
  - Smart interaction with driving strategy
  - Excellent reproducibility
- Fuel economy in cycle and real world:
  - Minimizing I for best fuel economy
  - Easy to calibrate
  - Discrete calibratable for all operating points
- Useage of Top Expert® calibration tools for minimizing calibration loops
- Battery constraints and limitations are considered