

Maneuver-Based Analysis of Starting-Systems and Starting-Strategies for the Internal Combustion Engine in Full Hybrid Electric Vehicles

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ABSTRACT

The requirement of the start of the internal combustion engine (ICE) not only at vehicle standstill is new for full hybrid electric vehicles in comparison to conventional vehicles. However, the customer will not accept any deterioration with respect to dynamics and comfort. ICE-starting-systems and -strategies have to be designed to meet those demands.

Within this research, a method was developed which allows a reproducible maneuver-based analysis of ICE-starts. In the first step, a maneuver catalogue including a customer-oriented maneuver program with appropriate analysis criteria was defined. Afterwards, the maneuvers were implemented and verified in a special test bench environment. Based on the method, two sample hybrid vehicles were benchmarked according to the maneuver catalogue.

The benchmarking results demonstrate important dependencies between the criteria-based assessment of ICE-starts and the embedded ICE-starting-system and -strategy. Those findings led to recommendations regarding the selection of suitable starting-systems and the design of the starting-strategy.

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INTRODUCTION

Full hybrid electric vehicles provide the opportunity of pure electric driving. Nevertheless, under certain circumstances a start of the internal combustion engine (ICE-start) is required. The main causes are the exceedance of the power of the electric system and a low state of charge (SOC). The ICE-start influences vehicle dynamics, comfort and efficiency and thus it is highly relevant for customers. For an optimal ICE-start from a customer's point of view, the selection of a starting-system and the combination with a suitable starting-strategy are crucial.

This article results from a research cooperation between IPEK - Institute of Product Engineering at Karlsruhe Institute of Technology (KIT) and the BMW Group. As an example, it introduces a customer-oriented, maneuver-based analysis of ICE-starts in different driving situations. For this purpose,

critical maneuvers with a high customer relevance were defined in the first step together with respective analysis criteria for the ICE-start. The maneuvers were implemented and verified using the development and validation environment of the IPEK-Acoustic-Roller-Test-Bench (IPEK-ARTB). On this basis, a method for a reproducible analysis of ICE-starts was successfully developed and deployed for sample vehicles. The focus was set on the influence of ICE-starts on the vehicle longitudinal dynamics.

As a result, effects of the chosen starting-system and starting-strategy are presented. Furthermore, relevant parameters of the starting strategy are outlined. Recommendations for the selection of ICE-starting-systems and ICE-starting-strategies can finally be derived based on the results.

ICE-STARTING-SYSTEMS AND -STRATEGIES

The ICE-starting-system is defined as the "entirety of technical components in a hybrid powertrain, which are needed to start and connect the internal combustion engine as well as to subsequently distribute the torque between the powertrain aggregates [1]. The starting-system is thus a part of the powertrain topology [2]. Basically two kinds of ICE-starting-systems are distinguished, the external-controlled and the self-controlled start. The external-controlled start uses an external torque, e.g. provided by a starter motor (SM), a belt-driven starter generator (BDSG), an integrated starter generator or a starting clutch (SC). Through the SC, the crank shaft is connected to the powertrain and thus it is accelerated. The self-controlled start means a direct engine start through ignition. In this case an external impulsion of the crank shaft is not required. Combinations of different ICE-starting-systems are possible, of course. Detailed descriptions, advantages and disadvantages of the starting-systems can be gathered from the following references [1,3,4,5].

The terminology "ICE-starting-strategy" hasn't been defined comprehensively so far. According to the definition of the operation strategy of a hybrid vehicle in [2], the ICE-starting-strategy is conceived as the control of the components of the ICE-starting-system depending on the driver's demand, restrictions, environmental conditions and optimization target values. On this basis, different starting-situations are to be distinguished, e.g.:

- ICE-start because of the driver's demand: exceedance of the power of the electric system by actuating the accelerator pedal (power-initiated ICE-start)
- ICE-start because of restrictions: low SOC (SOC-initiated ICE-start)
- ICE-start because of environmental conditions: battery heating with ICE at low ambient temperatures

The driver's expectations regarding the ICE-start highly depend on the situation. During a power-initiated ICE-start, the longitudinal dynamics are perceived as most important. On the contrary, during a SOC-initiated ICE-start, the focus must be set on driving comfort [1,6]. These requirements have to be reflected in the optimization target values of the ICE-starting-strategy.

In addition, two levels of the starting-strategy have to be distinguished. To meet the driver's demands in every situation, the starting-strategy can use appropriate components of the whole starting-system. If it offers alternatives for the ICE-start, e.g. starter motor and starting clutch, the starting-strategy must choose them according to the actual driving situation. This

decision represents the first level of the ICE-starting-strategy. In the second level, the sequential activation and control of the involved components is determined and the starting process is described.

MANEUVER-BASED ANALYSIS OF ICE-STARTS

The research target was to develop a method which allows besides others a standardized analysis and assessment of ICE-starts. Based on the method, influences of the starting-system and starting-strategy on the assessment of ICE-starts can be determined. Finally, recommendations for the selection of starting-systems and the situation specific design of the starting-strategy can be derived. In this article, the implementation of the method is illustrated exemplarily for the analysis of vehicle longitudinal dynamics during a power-initiated ICE-start in parallel hybrid electric vehicles. However, it can easily be transferred and applied to other starting-situations and powertrain topologies. Initially, relevant driving maneuvers with appropriate analysis criteria were defined. Afterwards, the maneuvers were implemented at the IPEK-ARTB and verified in comparison to road test measurements.

Derivation of Maneuvers and Criteria for the Analysis of Vehicle Longitudinal Dynamics During Power-Initiated ICE-Starts

A power-initiated ICE-start is caused if the driver demands more power via the accelerator pedal than the electric powertrain system provides. The origin for all maneuvers analyzing the dynamics of the ICE-start is thus a pure electric driving. Based on this electric operation, the ICE-start has to be triggered through an additional demand of power by a quick actuation of the accelerator pedal. To avoid a SOC-initiated ICE-start, the SOC should be charged high enough at the beginning of the maneuver. By varying the initial electric driving operation or the actuation of the accelerator pedal during the power-initiated ICE-start, different test cases can be created. For the initial electric driving operation two maneuvers are distinguished here: Firstly a power-initiated ICE-start based on electric driving with a constant velocity and secondly a power-initiated ICE-start based on electric acceleration. In both cases the ICE-start is initiated through a kick-down of the accelerator pedal, because this should demand the highest vehicle dynamics.

The procedure of the first maneuver is quite easy. The vehicle is accelerated electrically to a desired velocity. As soon as this speed is reached and maintained constantly for a certain time, the ICE-start is triggered through a kick-down. For the second maneuver, a critical case with respect to vehicle longitudinal dynamics is to be developed. Particularly, the time gap

between the initiation of the ICE-start and the torque transfer to the ICE due to the speed-up of the engine, the synchronization and the connection to the powertrain has to be considered. The impact of this time gap on longitudinal dynamics is especially negative, if the driver already operates the vehicle very close to the limit of the electric power and suddenly demands even more power. As the electric powertrain system is already operated at its limit, the driver demand cannot be fulfilled until the torque is transferred to the combustion engine. Meanwhile, the acceleration won't show any reaction or will even decrease in extreme cases. To cover this critical case in a driving maneuver, the maximum electric power range has to be determined at first. The respective maneuver has already been developed and verified [7].

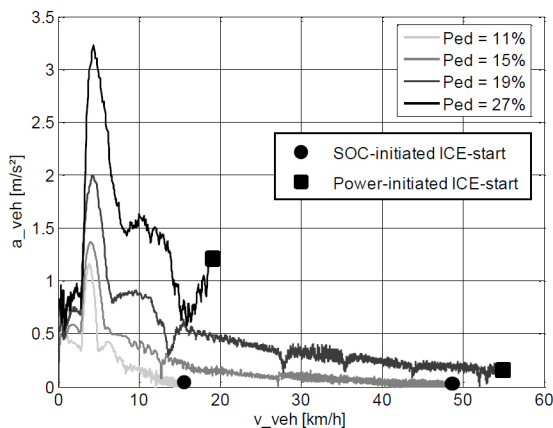


Figure 1. Electric a-v-curves of a hybrid electric vehicle [7]

Figure 1 illustrates the electric power range of a hybrid vehicle. The curves show the electric vehicle acceleration (a_{veh}) over the vehicle velocity (v_{veh}) and are thus called electric a-v-curves. To identify these a-v-curves, an accelerator pedal step (Ped) was executed for each curve beginning at vehicle standstill. For smaller steps, the power limit of the electric system is not reached. After a certain time of constant electric driving, a SOC-initiated ICE-start occurs (black circles). If the accelerator pedal tip-in is increased up to 19% and more, looking at the vehicle analyzed in figure 1, a power-initiated ICE-start occurs during the acceleration (black squares). Memorizing this maximal electric velocity (v_{max_el}) at the black squares from the pre-maneuver, the main maneuver for the analysis of ICE-starts based on electrical acceleration can be implemented. In the main-maneuver, an accelerator pedal tip-in is executed as well, but 1 km/h before reaching the memorized velocity, an ICE-start is initiated through a kick-down. For the two upper a-v-curves in figure 1, the kick-down would be carried out at 18 km/h, respectively at 53 km/h. Thus, the desired critical case for the analysis of ICE-starts based on electric acceleration is established. The sequence for this maneuver is demonstrated in figure 2.

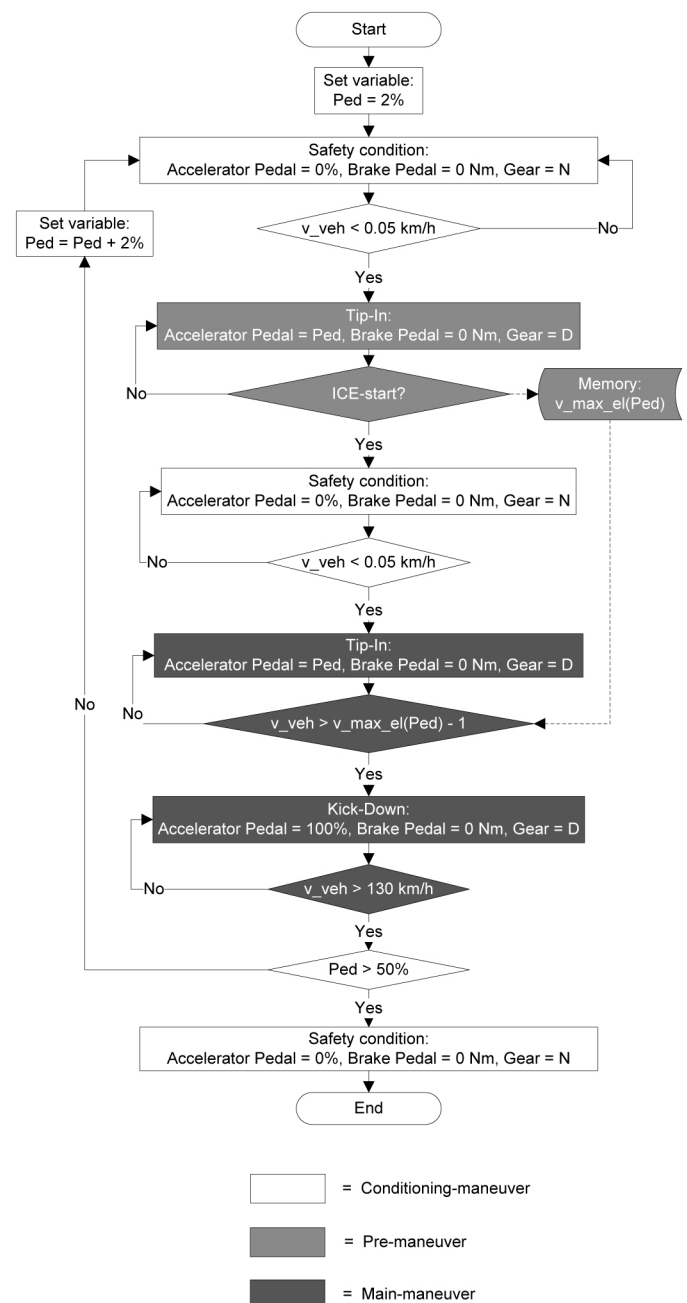


Figure 2. Maneuver sequence for the analysis of a power-initiated ICE-start based on electric acceleration

Figure 3 exemplarily shows the measurement of an ICE-start of a vehicle with P2 hybrid topology. The maneuver is about the ICE-start based on electric acceleration at 53 km/h according to the upper a-v-curve of figure 1. Figure 2 also exposes the objective criteria developed for the analysis of vehicle dynamics during a power-initiated ICE-start. These are valid for both maneuvers presented and guarantee the comparability of different measurements.