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COMPARATIVE BATTERY EFFICIENCY ANALYSIS FOR HYBRID ELECTRIC VEHICLES BASED ON MATLAB MODELLING

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Abstract

The present paper introduces a new comparative analysis method that is applied on different hev battery types, with the scope of enhancing the energy efficiency. The research is based on matlab modeling and hardware in the loop approach. The study considers a set of critical parameters that influence the system performance. The added value is given by the comparative overview as a result of the applied analysis. This method identifies also the set of parameter values needed for a better performance that can be afterwards considered in developing future battery types. A set of 4 case studies are proposed and the efficiency of the analysis method is proven through a series of simulation results. The motivation of the research is given by the fact that the battery is one of the most important components in hybrid electric vehicles architecture. A good understanding of different battery behavior helps in using the best suited battery system for a certain architecture resulting in a better control strategy, better energy efficiency and better costs. The advantage of this method is that the battery performance can be assessed in an early stage of development. The results contribute to the practical need of developing new battery control systems at higher quality standards.

Keywords: Battery model, hev, hil, matlab environment

Introduction

The battery is one of the essential and most crucial parts in hybrid electric vehicles (hev). A successful operation of a hev requires an intelligent battery management that operates the battery at the best compromise between high efficiency and low stress. Accurate and reliable knowledge about the state of the battery and its parameters is very important for a good battery management (Bohlen, 2013).

Developing affordable batteries which offer long driving range is the biggest challenge to increasing sales of plug-in electric vehicles. Batteries for hybrid electric vehicles and full electric vehicles differ substantially from traditional lead-acid batteries used in classical vehicles. They are heavier, larger, more expensive and have safety considerations that require the use of electronically controlled cooling systems (Canis, 2013).

Batteries are a form of energy storage. They store and release energy through electrochemical processes. All battery technologies have two fundamental characteristics which affect battery design, performance and durability. Power density is the amount of energy that can be delivered in a given period of time, affecting how fast the vehicle accelerates and energy density, which is the capacity to store energy, affecting the range a vehicle can travel (Canis, 2013).

The lead acid battery has been the standard battery technology over most of the last century but because of its low energy density it is poorly suited for electric vehicles. A set of lead-acid batteries placed in a hybrid or electric vehicle would add too much weight and would take up too much space (Canis, 2013). Considering these aspects, new types of batteries are developed aiming for a higher power and a higher energy density. Due to their greater energy density and a lower weight nickel metal-hydride (nimh) batteries became the choice for early hybrid vehicles. Lead acid batteries were not totally excluded from hybrid electric vehicles since they have their own contribution. The nimh batteries provide power to the electric motor, while lead-acid battery provides power for different starting functions and ignition. Lithium-ion battery, with its continuous improvement of technology and performance, has slowly become the first choice for hybrid and electric vehicles over the last years. These vehicles require batteries with high power, fast charge capability and long life (Wencheng, 2010). Li-ion batteries offer high energy and power densities.

This paper makes a complex analysis of a hybrid electric vehicle architecture focusing on the battery behavior in terms of energy efficiency. For a good understanding four battery models are used and compared in order to understand the impact of each one in hybrid architectures. The battery models are parameterized to represent most popular types of rechargeable batteries used in hev: lead-acid, lithium-ion, nickel-cadmium, nickel-metal-hydride. The battery parameters are extracted from data sheets for a real representation (Help Simulink, 2011). Since the battery is one of the essential and most crucial parts in hev a good understanding of the battery performance can bring a very high improvement in terms of technical efficiency and economical aspects. The software control can be improved in order to address some lacks in physical performance discovered during simulation and testing. The present paper contributes to the practical need of having better energy management in hybrid and electric vehicles. Valuable simulation results with real time testing based on models suitable for hardware in the loop have a high value added mainly because they are available in a shorter time and with a lower cost.

Case study

The model block diagram used in simulation is shown in figure 1 (Hybrid-electric vehicle model, 2010). It consists of a block for control simulation, one for engine simulation, a power split device and a block dedicated to the electrical part of the architecture. This electric part is most relevant for this paper since it focuses in simulating the motor and generator, the dcdc converter and the four battery models which are the scope of the research. Also the vehicle dynamics are considered and parameterized during the driving cycle, but they are not detailed in this paper, since these will be the subject for further research activities.

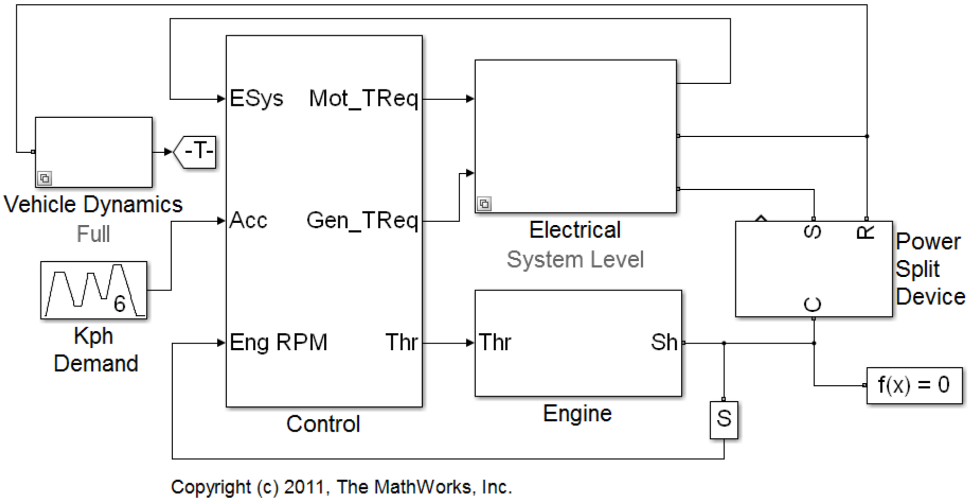


Figure 1. Model block diagram

The analysis method used in this paper is applied on a driving cycle that is considered to be the most relevant while assessing the energy efficiency in a hybrid electric vehicle. It consists of several accelerations and deceleration over a short period of time. These trigger the transition between internal combustion engine (ice) and electric motor several times over the driving cycle. The acceleration and deceleration factors are derived from my previous researches and are used for consistency as being considered to improve the energy efficiency during the driving cycle. The demanded speed values are specified in a parameter file and the outcome with the actual speed during the driving cycle is presented in figure 2.

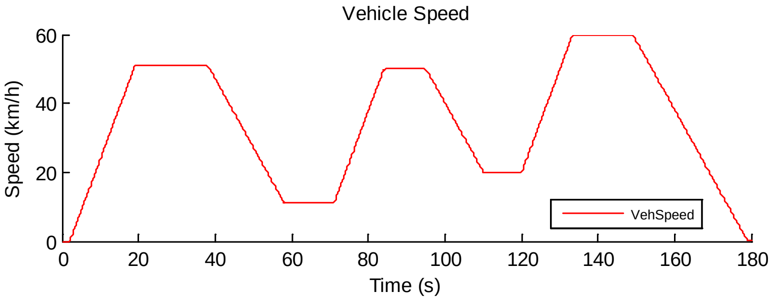
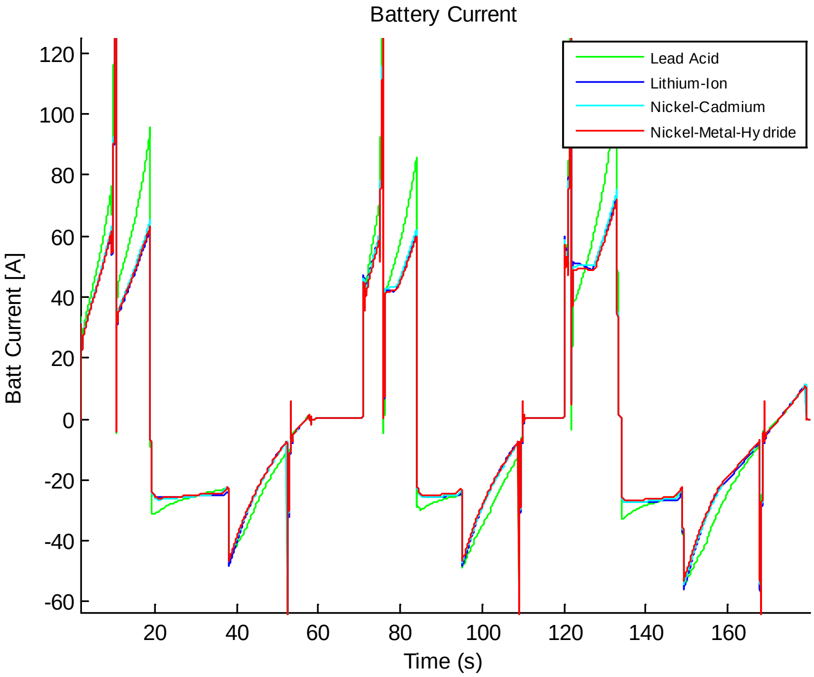


Figure 2. Driving cycle under analysis

The vehicle is frequent accelerated and decelerated during driving over a short period of time simulating one of the most demanding scenarios for hybrid electric vehicles (hev). This type of driving cycle requires the battery to power during acceleration, and recovers energy in deceleration and breaking. This requires that the battery has a good performance of pulse charge and discharge (Wencheng, 2010).

Over the same driving cycle 4 case studies are performed, each one dedicated to a certain battery model: lead acid, lithium-ion, nickel-cadmium, and nickel-metal-hydride. Simulation results for each case study are presented in this paper in order to create a performance overview for each of the battery types based on certain parameters: battery current, battery voltage, battery power, dcdc converter input current, dcdc converter output current, battery temperature, fuel consumption. The assessment is done from technical performance perspective and each parameter is crosschecked over the four battery models. The analysis approach presented in this paper improves the comparative understanding for different battery types modeled in each one of the case studies. The simulation results for the behavior of the battery current over the driving cycle for all 4 battery models, overlapped, ipresented in figure 3.



Fgure 3. Battery current over the driving cycle

It is visible that the battery current for three of the simulation results (li-ion, nicd, and nimh) follow the same path, excepting one (lead acid) which deviates to a certain degree comparing to the others. A higher deviation is visible during the acceleration period, in motor mode, where the lead acid battery current has a higher value. A difference is also visible during deceleration and breaking, in generator mode, where the response of the lead acid battery has a delay. This type of battery has a slightly different behavior than the other three modeled battery types, mainly because of the higher demand of current and because of delay in response. Also the different acceleration and deceleration factors have impact on the current value with a higher impact on the current behavior for the lead acid battery.

The behavior of the battery voltage over the driving cycle under analysis is presented in figure 4. The required voltage value during vehicle operation is different over the 4 case studies. Again the value for the lead acid battery exceeds the spectrum of the other group of battery types.

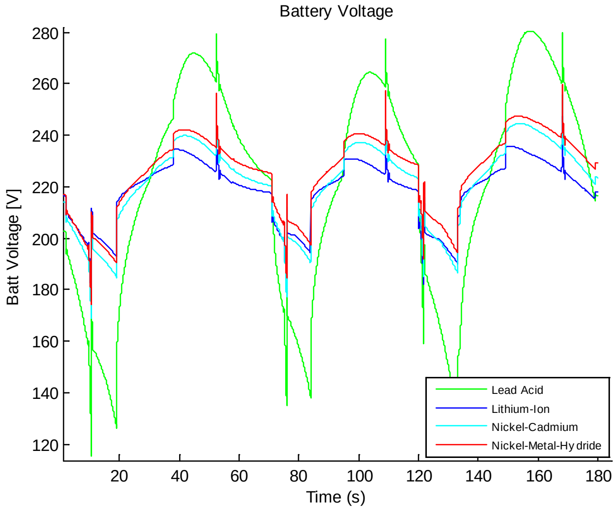


Figure 4. Battery voltage over the driving cycle

Lead acid battery voltage has a different behavior over the acceleration period, deceleration period and breaking. The other battery types: lithium-ion, nickel-cadmium and nickel-metal-hydride follow a similar path. There is a higher difference in these last three types during deceleration and breaking. During motor mode the performance is very similar to the conclusions above.

Battery power, as a result of the simulation models is represented in figure 5. All four test cases show similar results over the acceleration period. Over deceleration, in generator mode, there is a slower response in case of the lead acid battery. The same behavior path is followed also while assessing the battery power over all the battery models under test. Lithium-ion, nickel-cadmium, and nickel-metal-hydride models have very similar values and lead-acid model is slightly different from the other group from energy performance point of view. This difference is visible either on the acceleration or deceleration period, depending on the analyzed parameter. The paper proposes an analysis model that takes in consideration a set of relevant parameters for the battery performance in hybrid and electric vehicles. A comparative analysis is performed to determine the battery type with the higher energy efficiency. This analysis method determines through these simulation results that a battery energy efficiency performance assessment can be developed using matlab hil models. The contribution to the research and development in the field of hybrid and electric vehicles is significant from the perspective of time efficiency and cost. Using this type of analysis saves time and costs, and in the same time offers a better comparative understanding about actual and future battery technology for this type of vehicles.

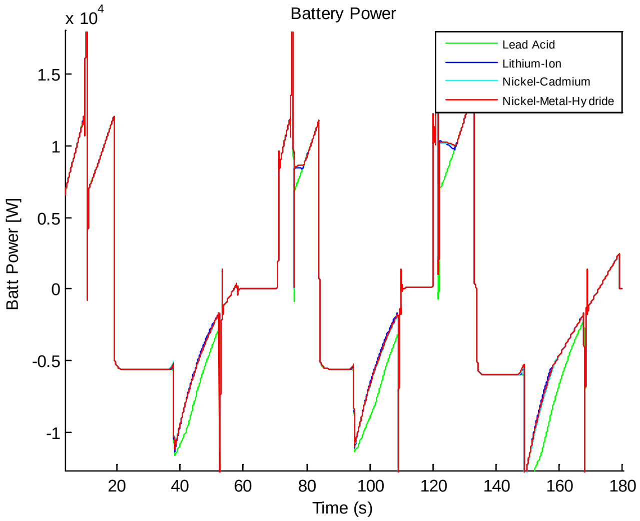


Figure 5. Battery power over the driving cycle

Two additional parameters under analysis in this paper are the input current into the dcdc converter and the output current from the dcdc converter. These currents are again assessed for all the four battery models developed for each case study. The results from the simulations are presented in figure 6 and figure 7, respectively.

The dcdc input current, visible in figure 6, has similar values over the driving cycle for all four case studies, with an exception for the lead acid model. The difference is visible over the acceleration and deceleration period. The difference becomes smaller in case of the dcdc output current. The dcdc output current presents a delay in response only during the deceleration period.

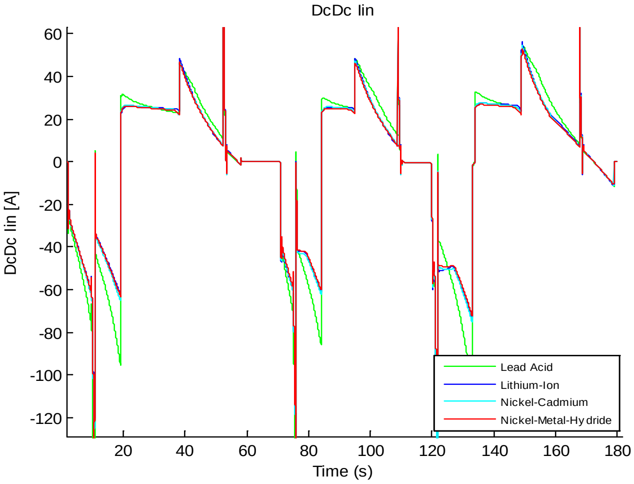


Figure 6. Dcdc input current over the driving cycle

For the battery power and dcdc output current all four battery models have a similar behavior with an exception on the deceleration period. This period is a critical one since it is responsible with the battery charging in generator mode. Any small improvement at this level can have a huge impact on the vehicle performance over the battery lifecycle. From figure 6 and 7 it is again visible that lithium-ion, nickel-cadmium and nickel-metal-hydride batteries have better performance than the lead acid batteries in high power application for hybrid electric vehicles.

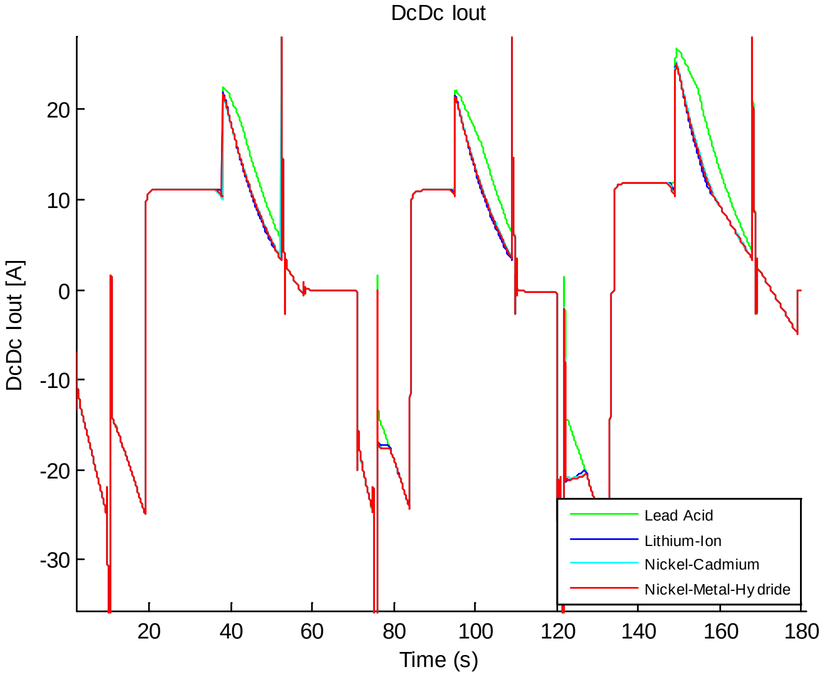


Figure 7. Dcdc output current over the driving cycle

Another important aspect is the battery temperature. This paper is focused also on this topic. Each case study corresponding to the analyzed battery types has also a battery temperature model implemented. The results of the temperature assessment of each battery model are presented in figure 8. The temperature evolution over the driving cycle is overlapped with the vehicle speed value for a better overview. The temperature of the lead acid battery reaches higher values over the driving cycle comparing to the other battery types. Also from the temperature perspective lithium-ion, nickel-cadmium, and nickel-metal-hydride have better performance than the lead acid batteries in high power application for hybrid electric vehicles.

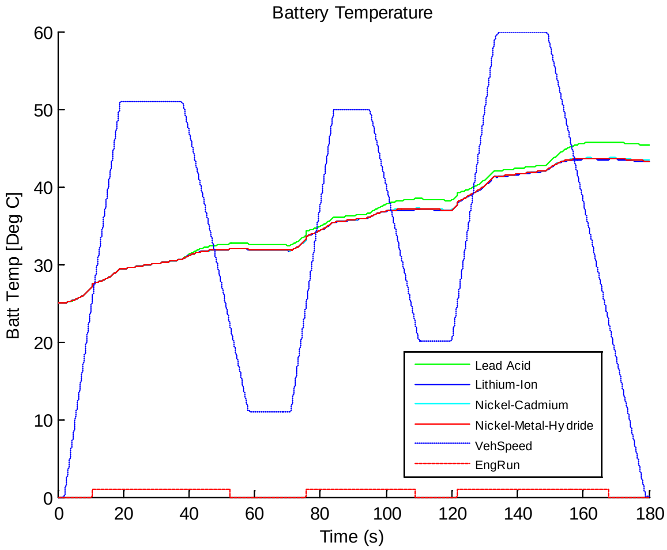


Figure 8. Battery temperature over the driving cycle

In case of hybrid vehicles the energy efficiency can be classified in electric battery efficiency and in fuel efficiency. The battery charges in generator mode while decelerating and breaking. The battery efficiency is directly proportional with the fuel efficiency. If the battery efficiency is high, then this will implicitly result in high fuel efficiency. For this kind of vehicles the fuel efficiency is visible and important to the end user. A fuel consumption model was considered in this paper to assess the estimated fuel consumption for every battery type under analysis over the four case studies. The analysis results are presented in figure 9. In line with the previous results listed in this paper it is visible that the fuel consumption of the architecture with lead acid battery is slightly higher than the other architectures with lithium-ion, nickel-cadmium, and nickel-metal-hydride batteries. Based on the differences between the mean values of the fuel consumption for each battery type it is visible that the fuel consumption of the vehicle powered with lead acid battery is higher with 0.19 l/100 km over the specific driving cycle. The “min” and “max” dotted green lines represent the minimum and maximum values of the fuel consumption for the vehicle that is equipped with a lead acid battery. The “min” and “max” dotted blue lines represent the minimum and maximum values of the fuel consumption for the vehicle that is equipped with a lithium ion battery. Lithium ion was considered as reference because lithium-ion, nickel-cadmium and nickel-metal-hydride battery types have very similar impact on the fuel consumption, as presented in figure 9.

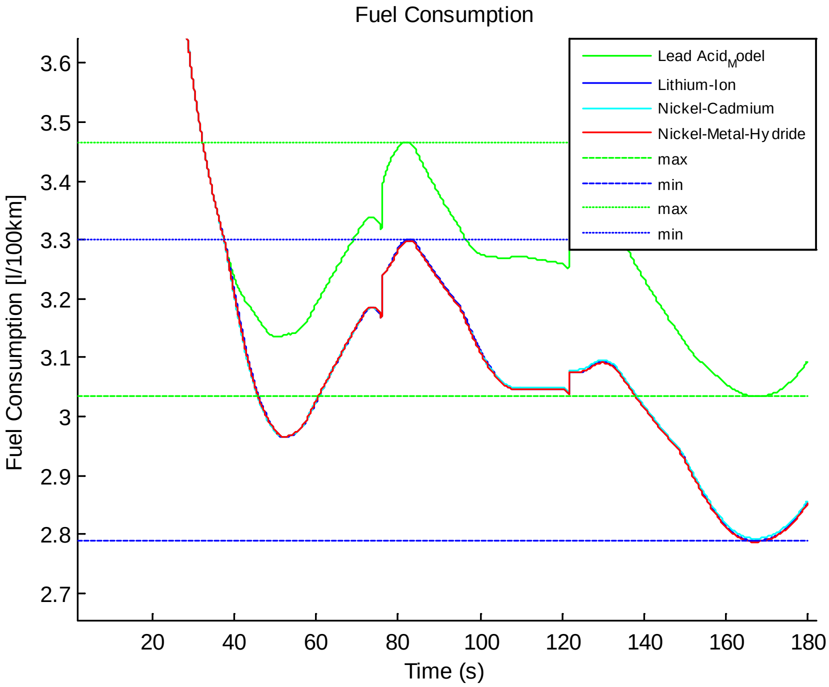


Figure 9. Fuel consumption over the driving cycle

Actual market status

For high voltage functions in hybrid electric vehicles the lithium-ion (li-ion) and nickel-metal-hydride (nimh) systems are up to now the storage batteries of choice for automakers. Not so, for the starting lightning and ignition functions (sli) where lead acid batteries are clearly the necessary choice (lead-acid battery consortium, 2013). Actual market status is visible in table 1. There is still room for improvement in this area and with every step the world is closer to a much more environmental friendly automotive fleet.

Table 1. Battery systems in hev 2013 us (hybridcars) (lead-acid battery consortium, 2013)

Vehicle	High voltage battery	Sli battery
Toyota prius	201.6 nimh	12 volt lead-acid
Toyota camry hybrid	244.8 volt nimh	12 volt lead-acid
Ford fusion hybrid	300 volt li-ion	12 volt lead-acid
Toyota prius c hybrid	201.6 volt nimh	12 volt lead-acid
Ford c-max hybrid	300 volt li-ion	12 volt lead-acid
Toyota prius v hybrid	201.6 volt nimh	12 volt lead-acid
Hyundai sonata hybrid	270 volt li-ion	12 volt lead-acid
Toyota avalon hybrid	244.8 volt nimh	12 volt lead-acid
Chevrolet malibu-eco	130 volt li-ion	12 volt lead-acid
Kia optima hybrid	270 volt li-ion	12 volt lead-acid

Conclusion

This paper offers a comparative analysis for different battery types like lithium-ion, nickel-cadmium, nickel-metal-hydride and lead acid. The study underlines the differences between lead acid battery type and the other types listed above. The analysis also shows that lithium-ion, nickel-cadmium and nickel-metal-hydride have very similar characteristics. The assessment is done purely from technical perspective in order to identify the performance of each type. Additional motivation to use a specific type, like cost of production, market availability, environmental impact are not considered, this being subject to further research. The usage of this method offers a good overview of the actual situation in the field of research and also can be used to identify the needs of future improvements of the analyzed parameters. This analysis method can be used in the future to compare newly developed battery types with the already existing ones. Following the same analysis path, virtual battery types can be developed, parameterized and used as reference for new real life batteries. The scope of this analysis method in combination with the matlab model is to assure a simulation platform that can be easily configured in order to simulate, analyze and compare already existing, or prototype battery types for further improvements in the field of hev vehicles. The goal of this research is to contribute to the practical need of improving the energy efficiency of the hybrid electric vehicles.

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