Assessment of high voltage battery parameters in the hybrid electric vehicle

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Abstract. The article presents the reasons why the hybrid powertrain in cars was developed. It shows how to make a better use of the internal combustion engine so that the energy in fuel be transformed into mechanical energy to the drive of a car with a greater efficiency. The article also shows the possibilities of better energy management by the recovery of the car’s kinetic energy during braking and not using it during the stopover. Such an energy management requires both energy’s accumulation and returning depending on the state of motion in which the car is located. The high-voltage (HV) battery is used to accumulate energy, whereas electrical machines and electronic circuits transforming electric current, are used to convert it. All elements mentioned generate energy losses. The balance of the energy’s gain and losses in connection with the energy’s generation and conversion is also included in the article. The HV battery plays a particular role here, as the efficiency of the entire hybrid powertrain depends on it. Therefore, the research which extended the basic diagnostic of this very important element has been carried out. The diagnostic tester enables to read some data concerning the HV battery, but they are not complete and do not allow to fully assess the condition of the HV battery. The research which has been carried out and its results extend the available diagnostic. The carried out test has concerned the battery of a 13-year-old car Toyota Prius II. The car has turned out to be efficient, and its initial capacity decreased by 18%.

1. Introduction

Hybrid powertrain in cars has been created for two main reasons. Firstly, to reduce fuel consumption, especially in the urban traffic conditions. Secondly, to reduce the emission of toxic compounds to the environment. The internal combustion engine is the main source of energy in the hybrid powertrain. If used properly, in conjunction with an electric motor it can meet two prime criteria concerning the hybrid powertrain. The internal combustion engines achieve the highest efficiency in converting energy in fuel into mechanical energy at the level of about 40%. Spark Ignition engines have slightly lower efficiency, whereas the efficiency of the Diesel engines is a bit higher. However, because of the emission of particulates in exhaust gases, the Diesel engines have not been accepted as a source of energy in the hybrid powertrain.

The efficiency of the internal combustion engine depends on the point of its operation (rotational speed and load). The internal combustion engines achieve the highest efficiency within the scope of medium rotational speeds and loads. The same operating conditions foster the smallest emission of toxic components in the exhaust gases. Unfortunately, in the typical drive train, the internal combustion engine often operates beyond the scope of the maximum efficiency, what significantly contributes to the decrease in the efficiency of the drive train. In numerous cases, the efficiency is
lower than 10%, including in the moment of starting and during warming up of the engine, drive in a traffic jam, etc. In the same operating conditions, the internal combustion engine emits the excessive amounts of toxic compounds.

The essence of the hybrid powertrain is the use of the internal combustion engine only within the scope of the rotational speeds and loads being in line with the highest efficiency. There are many cases in which the excess energy occurs in the drive train of the car. The mechanical energy which has not been used to the drive of a car is transformed into the electric one and accumulated in the battery. If the drive system lacks energy from the internal combustion engine, then the energy accumulated in the battery is used. Moreover, due to the use of the internal combustion engine in a limited scope of rotational speed, it is possible to readjust the timing in a manner that makes the efficiency of the engine greater. The timing phases in the Prius model has been changed in such a manner that the operation of the internal combustion engine proceeds according to the Atkinson cycle. As a consequence, the SI engine has achieved the efficiency to 41% which is not possible in Diesel engines operating in accordance with Otto cycle.

The action of the internal combustion engine at idle running, e.g. when the car is standing at the intersection with traffic lights or moves at a speed of several kilometers per hour in a traffic jam, is replaced with the action of the electric drive. The electric drive does not consume energy when standing, e.g. at the intersection. When the vehicle is in a traffic jam, it consumes only as much electrical energy as this move requires.

Moving a car in traffic requires the multiple braking and speed-up. In the typical drive system, the kinetic energy of the car during the braking process is irretrievably consumed as a result of the engine braking (overcoming the mechanical resistance and load exchange) and/or in the brake system (transformed into heat). In the hybrid powertrain, while braking a car, the energy from its wheels accelerates the electrical machine (operating as a generator) that transforms it into the electrical energy. After the conversion into direct current (unidirectional), it is accumulated in the battery. The typical braking system in a hybrid car is used only when the energy received by the electrical machine does not provide the desirable deceleration of a car. The cases mentioned occur both in the event of the strong and rapid braking and when the battery is fully charged. The energy accumulated in the battery during braking is used with regard to the drive of a car, not only during soft acceleration and driving with low speeds, but also to support the internal combustion engine during rapid acceleration of a car.

As far as the traffic situations are concerned, the car repeatedly overcomes hills and sheer turnings. In a conventional drive system, the engine braking occurs during braking, and the energy is lost to overcome the engine’s mechanical resistance. In the hybrid powertrain, the braking energy of the car is transformed into the electrical energy and accumulated in the battery. When overcoming hills, the energy accumulated in the battery is used to power the electric motor which supports the internal combustion engine.

According to the assumption, the hybrid powertrain guarantees better energy management which is generated from fuel. In certain situations, the excess energy is accumulated in the battery. However, there are situations when it uses this energy to drive a car. The HV battery plays a very important role in this drive. Therefore, its efficiency should be high so that the profit from using the hybrid powertrain be visible in the form of lower fuel consumption.

Hybrid powertrain operation was described in [1-6].

2. The gain and loss of the energy in the hybrid powertrain

Hybrid powertrain in cars is to reduce the fuel consumption. As in the case of all other devices, they also generate energy losses – mainly in the form of heat. Therefore, the difference between the gain of the additional energy resulting from the use of the hybrid system and the losses generated by this system must be positive and clearly visible.

The Figure 1 shows the gains and losses of the energy, concerning car's drive in the hybrid powertrain. In both conventional and hybrid system, the energy comes from the combustion of fuel in
the internal combustion engine. However, in the hybrid system, more energy is obtained from combustion of the same amount of fuel. It is connected with obtaining additional mechanical energy on the engine shaft what happens as a result of its optimal operation (optimal scope of rotational speed and load) and its optimization to the specific operating conditions. This additional energy, if not necessary to the drive of a car, is transformed into the electrical energy and accumulated in the HV battery. The process of conversion and accumulation takes place in three devices. The first one is the electrical machine that operates as a generator. It generates three-phased alternative current. The efficiency of the electrical machines is quite high. It depends on their structure and size, what is important it reaches values above 90%. The second device is the electron rectifier which transforms the three-phase alternative current into unidirectional current in order to power the HV battery. The efficiency of the electron rectifiers operating in the systems with a voltage of several hundred Volts is very high – almost 100%. The next element is the HV battery, in which the electrical energy is accumulated. The battery is the electrochemical device whose efficiency and stability depends on the way of its usage. So that the battery in the hybrid powertrain operates properly, the separate controller watches it. As a result, even after many years of use, the batteries remain efficient and capacious.

The energy losses in the mentioned hybrid powertrain devices must be smaller than the additional energy gained in the internal combustion engine operating only in the conditions for optimal efficiency. Then, the transformation of the mechanical energy into electrical energy, accumulation in the battery and retransformation into the mechanical one will achieve a desirable effect, i.e. a decreases the fuel consumption.

The additional increase of arising from the usage of the hybrid powertrain regardless of the operation of the internal combustion engine, makes the energy recovery in the moment of braking and during turnings from hills possible.

**Figure 1.** Distribution of energy in the hybrid powertrain
All cases, in which the efficiency of the hybrid powertrain improves, are associated with the energy accumulation in the battery. Therefore, the efficiency of the battery has a distinct impact on the efficiency of the entire hybrid powertrain.

3. Assessment of the HV battery efficiency

The battery efficiency is the ratio of energy absorbed from the battery in the process of full discharge to the energy supplied in the process of full charging.

The battery charging always takes place at a higher voltage than discharging, which is understandable and requires the direction of current. Hence the energy supplied to the battery will be higher than the one absorbed. The difference of these energies releases in the form of heat on the internal resistance. However, the authors of this publication are not looking for such a difference in energy. Interesting is the efficiency of the battery assessed by the current, i.e. the ratio of Ah (Ampere-hours) absorbed during the process of discharge to Ah supplied in the process of charging.

The HV battery should have a long service life. One must follow several rules in order to ensure it. It should be neither discharged below a certain limit value, nor charged above a certain limit value. Limit values are set for a given type of battery cells. The second very important element is the operating temperature. It is controlled by means of several sensors (often 3 for the battery + 1 for the cooling air). The rise of temperature is the result of the heat released on the internal resistance of the battery cells as a result of the current flow. The direction of the current, i.e. charging or discharging, does not have an influence on the generated heat.

In order to fulfil the aforementioned rules, the battery is supervised by the controller. It analyses the voltage on individual battery blocks, power and temperature in three areas, controls fans, as well as sends information to the hybrid powertrain controller about the level of the battery charge. The hybrid powertrain controller, on the basis of the information concerning the level of the battery charge, determines which drive source is to be used and whether the battery should be charged or discharged.

Battery packs in hybrid vehicles, as well as in other traction applications, are always equipped with a Battery Management System (BMS). The BMS consists of hardware and software for battery management including, among others, algorithms determining battery states.

State-of-charge (SOC) estimation is one of the most important issues in battery applications. Precise SOC estimation of the battery power can avoid unpredicted system interruption and prevent the batteries from being over-charged and over-discharged, which may cause permanent damage to the internal structure of batteries.

State-of-charge is the percentage of actually stored amount of charge compared with full charge [7]:

\[
SOC = \frac{\text{actual amount of charge}}{\text{total amount of charge}} \times 100\%
\] (1)

Many SOC estimation methods have been proposed in the literature [7-12]. In this paper an ampere hour counting method (Coulomb counting method) was applied. It is the most common technique for estimating a battery SOC by integrating the current from a battery. This estimation method is good for tracking the rapid changes of SOC [8, 12]. If an initial value (SOC) at time \(t_0\) is already known, the battery SOC at the specific time \(t\) can be obtained from the result of the following equation [10]:

\[
SOC(t) = SOC(t_0) + \frac{1}{C} \int_{t_0}^{t} (I_+ - I_-) dt
\] (2)

where: \(C\) is the rated capacity of battery, \(I_+\) is the battery current and \(I_-\) is the battery current by the loss reactions.

The state-of-charge SOC of the battery must be determinate accurately. Also the capacity of a battery tends to decrease with age, this being expressed as state-of-health (SOH). It is a metric to evaluate the aging level of batteries, which often includes capacity fade and/or power fade. It gives very useful information for predicting when the battery should be removed.
Battery SOH monitoring methods are reviewed in [11]. In this paper the Coulomb counting method was applied. There is a technique based on Ah counting which is very much used for the estimation of the SOH. Through the charging or discharging methods, the number of Ah which are either charged or discharged are counted, this way the transferred amount of Ah are tracked and consequently the remaining capacity is known [12]. The used equation to estimate the SOH Eq.3 needs as input parameters, the measured capacity $C$ and the nominal capacity $C_n$. 

$$\text{SOH} = \frac{C}{C_n} \cdot 100\%$$  \hspace{1cm} (3)

Based on SOC, SOH, temperature and if needed the short-term previous discharge/recharge history the new parameter the state-of-function SOF can be determined [7].

4. HV battery tests

The HV battery is one of the most important elements of the hybrid powertrain. Despite many years of warranty provided by hybrid car manufacturers, users of these cars are afraid of its consumption, whereby they will have to replace it with another one. Therefore, the attempt to determine the parameters which are also essential for the operation of the hybrid powertrain and prognosis in respect of its further use has been made. However, they are not available in the case of the on-board diagnostics.

The object of the research which aims at determining the efficiency and capacity of the HV battery is of over ten years old hybrid car. Toyota was the first company which launched the cars with hybrid powertrain on the market. The Prius model has already had four generations. The Prius cars of the second generation have been produced since 2004 [13]. Therefore, their batteries are now several years old. The 13-year-old car - Toyota Prius has been tested. It is equipped with the HV battery with the rated voltage of 201.6V and the capacity of 6.5Ah. It is built of 14 supervised blocks. Each block contains 12 nickel-hydride cells (two modules of 6 cells) with the rated voltage of 1.2V each.

The test has been carried out in a chassis dynamometer in the Department of Automotive Mechatronics which is located in the Faculty of Mechanical Engineering of the University of Technology and Humanities in Radom (Figure 2a).

This dynamometer, in addition to the energy reception from the wheels (braking of the car) has the ability to drive the wheels (simulation of downhill driving). It is possible by the usage of the brake in the form of two electrical machines with a power of 50kW each and the controller produced by Apator company. When braking a car, electrical machines operate as generators, but when they drive, they operate as electric motors. Both dynamometer rollers measure the torque and speed of a car. The brake control system enables to brake or drive the wheels of a car in a given torque or speed of a car. The air system visible at the front of a car consists of three blowers with the adjustable air volume. They are responsible for the air flow through the radiator and exhaust system.

The HV battery current has been measured by means of the current sensor, operating in the on-board battery control system (Figure 2c). The sensor is powered with a stabilized 5V voltage and its output signal equals 2.5V for the zero battery current and changes by ± 2V for the current ± 200A. The measuring computer has been connected to the wires which has connected the sensor with the battery controller. The IBM PC computer, produced by the GAGE company, with A/D converter card has been used to record the battery current signal (Figure 2b).

The tests has consisted in recording the battery current during the 1800 seconds of the hybrid powertrain work. The test has assumed discharging the battery to the lowest level allowed by the controller and then charging it to the highest level. Continuous measurement of the current and the level of charge have made the efficiency and capacity assessment of the battery possible.

The level of the battery charge could be read from the on-board battery control system by means of the diagnostic tester which has consisted of the diagnosis interface ADP-186 and the PC with the CARS software produced by Autocom company (Figure 2b).
In the first part of the research, drive in a traffic jam has been simulated. It has aimed at discharging the battery to the lowest level, consuming the lowest possible current from it. The next step has been the acceleration of a car and simulation of the descent from the hill during which the battery has been charged to the highest level predicted by its controller. In the next phase, the drive up the hill has been simulated using a high power drive system. During this time, the battery has been intensely discharged. The next simulation has relied on the several changes in the load which has resembled the driving in a traffic jam. Then the load has been set in such a manner that the battery could be charged with the excess of energy generated in the internal combustion engine. The last stage of the test is another slow discharge of the battery while driving in a traffic jam. At this stage, the level of charge should be similar to the one at the beginning of the test.

5. Test results
The tests have been carried out according to the accepted program. The Figure 3 presents their results. It shows the battery’s current flow within a period of time. The time intervals of the every test phase is marked on the graph.

The current flowing into the battery has positive values on the graph, while the values of the current drawn from the battery are negative. At the time when the test has started, the battery has been charged up to 44%.

The first 417 seconds of the test has been simulated by the drive in a traffic jam. During this time, because of the necessity of acceleration and low battery level, the internal combustion engine has started up three times: from 99 to 113 second, from 226 to 237 second and from 380 to 389 second charging the battery with the excess of energy. The air conditioning has started up from 166 to 178 second. In 417 second the level of charge has reached 41% and it has not been possible to further discharge the battery. From 417 to 444 second, the car has been accelerated and the battery has been charged by means of the excess of energy from the internal combustion engine. The drive from a hill
has been simulated from 444 to 731 second by means of driving the wheels of a car. During this time, the battery has charged from 41% to 75% of its capacity. From 473 to 484 seconds an increased regenerative braking mode has been (gear lever in position „B”). When the battery charged to 75%, the regenerative braking has been transformed into the internal combustion engine braking, as the speed of the second one has significantly increased. The simulation of the drive with the use of high power of engines has started after charging the battery and decreasing the car's speed. In this phase, lasting up to 949 seconds, the electrical machine operating as an engine, has drawn a big current from the battery, quickly reducing its charge level. The dynamic driving in traffic has been simulated from 949 to 1019 second, and then from 1130 second a calm drive. During a calm drive, the battery has been charged by means of the excess of energy from the internal combustion engine. The drive in a traffic jam has been simulated from 1130 second to the end of the test. As at the beginning of the test, the internal combustion engine has started up in the moments of acceleration. The test has not been finished with the same level of charge as in the beginning. The battery has been charged to 50.5% at the end of the test.

Figure 3. The battery’s current flow during a half-hour test with the selection of time intervals for its individual stages

The obtained data have been used to determine the present battery capacity and its current efficiency. In order to make it possible, two curves are presented on the graph mentioned below. The former refers to the $E_+-$ energy which is supplied to the battery in Ah. The latter concerns $E_-$ energy which is connected with the supplied current (Figure 4). The piece of the test in which the battery was intensely charged, i.e. from the starting time ($t_p$) to the final time ($t_k$) has been applied in order to determine the efficiency of the battery. The ratio of total energy supplied to the increase in the level of charge is in line with the capacity of the battery. The total energy supplied to the battery is the differential between the supplied energy ($E_+$) and the absorbed energy ($E_-$). The differential between the energy supplied in Ah within a certain period of time ($t_p$, $t_k$) is deemed as the supplied energy, whereas the differential between the energy absorbed in Ah ($E_-$) within the same period of time is deemed as the absorbed energy. The increase of the battery’s charge level is the differential between
the level of charge, concerning the piece of the SOC (State-of-Charge) test selected from the end \((t_k)\) and the beginning \((t_p)\). Therefore, the current capacity of the battery may be determined by:

\[
C = \frac{E_+ (t_k) - E_- (t_p) - E_- (t_k) + E_+ (t_p)}{SOC (t_k) - SOC (t_p)} \cdot 100\% 
\]  

\((4)\)

\[E_k, [Ah], \quad t \quad [s]\]

\[I_k, [A], \quad SOC \quad [%]\]

Figure 4. The method of determining the capacity and efficiency of the battery

The capacity of the 13-year-old HV battery which designates from the above dependence and measurements was \(C = 5.33\text{Ah}\). In accordance with the equation \((3)\) the state-of-health SOH can be evaluated.

\[
SOH = \frac{5.33\text{Ah}}{6.54\text{Ah}} \cdot 100\% = 82\% 
\]  

\((5)\)

The battery’s SOC at each point has been determined in accordance with the following equation (see equation \(2\)).

\[
SOC(t) = SOC(t_0) + \frac{E_+ (t) - E_- (t)}{C} \cdot 100\% 
\]  

\((6)\)

The SOC value has been read four times during the tests. At the beginning, the SOC(0) has amounted to 44%, \(SOC(t_0) = 41\%\), \(SOC(t_k) = 75\%\) and at the end of the SOC(1800) = 50.5%. The SOC value from the battery’s controller has been read by means of the diagnostic tester with the resolution of 0.5%. The SOC value, determined on the basis of the above dependence, at the end of the test lasting 1800s (0.5h) has reached the value of 50.8%.

6. Summary

The HV battery is a very important element of the drive in cars with the hybrid powertrain. It accumulates the excess of energy generated by the internal combustion engine. This engine operates in the optimal conditions in order to ensure high efficiency as well as recover the kinetic energy during braking of a car. Its high efficiency has a decisive impact on the efficiency of the entire hybrid powertrain.
The price of an HV battery is the significant part of the entire car’s price. Therefore, it is necessary to assess its condition. The information available, by means of the diagnostic tester, does not precisely determine the HV battery condition. The test has been carried out in this research work. Its results have completed this information. Batteries with their age and number of charging and discharging cycles lose their capacity. Determining the capacity and efficiency of the charging and discharging process significantly extends information concerning the condition of the very important element of the hybrid powertrain.

The following conclusions may be drawn from the carried out research:

- it is possible to measure the battery’s current with the use of the sensor existing in the system. What is more, the battery’s condition may be assessed,
- during the research of the 13-year-old battery in the car with a mileage of 100 000 km, its capacity has decreased to 5,33 Ah, i.e. 18%, the SOH parameter dropped to 82%,
- during half-hour exploitation, the battery’s level of charge has varied from 41% to 75%, which is narrower scope than the information announced by the car’s manufacturer,
- the efficiency of the battery’s current has achieved nearly 100%, and the difference has been within the margin of error concerning the reading of the resolution,
- it is to assume that such a high efficiency is connected with the SOC scope of the battery exploitation.

References

[1] Chau KT, Wong YS, Overview of power management in hybrid electric vehicles 2002 Energy Conversion and Management 43 p 1953
[2] Szumanowski A 2000 Fundamentals of Hybrid Vehicle Drives. Monograph book, ITE Warszawa.
[3] Lechowicz A, Augustynowicz 2017 A Simulation studies of hybrid powertrain for urban vehicles, Journal of KONES Powertrain and Transport Vol. 24 No. 4 p 149
[4] Joint publication 2008 Hybrid Drives, Fuel Cells and Alternative Fuels 2008 Technical Instruction Booklet, Robert Bosch GmbH
[5] Lechowicz A, Jantos J 2010 Hybrid powertrain for light vehicle Machine Design p 129
[6] Merkisz J, Pielecha I 2006 Alternative drive vehicles. WNT Warszawa
[7] Meissner E, Richter G 2003 Battery Monitoring and Electrical Energy Management - Precondition for future vehicle electric power systems Journal of Power Sources 116(1) p 79
[8] Piller S, Perrin M, Jossen A 2001 Methods for state-of-charge determination and their applications J Power Sources 96(1) p 113
[9] Puchalski A 2013 On-board diagnostics of vehicle battery Wiadomości Elektrotechniczne 9 p 36
[10] Jeon S, Yun JJ and Bae S 2015 Comparative Study on the Battery State-of-Charge Estimation Method Indian Journal of Science and Technology 8(26), DOI: 10.17485/ijst/2015/v8i26/81677
[11] Berecibar M, et al 2016 Critical review of state-of- health estimation methods of Li-ion batteries for real applications, Renewable and Sustainable Energy Reviews 56 p572
[12] Ng KS, Moo CS, Chen YP, Hsieh YC 2009 Enhanced coulomb counting method for estimating state-of-charge and state-of-health of lithium-ion batteries Applied Energy 86(9) p 1506
[13] Olszewski M 2005 Evaluation of 2004 Toyota Prius Hybrid Electric Drive System, U.S. Department of Energy, Washington DC