

Method for optimizing the service life of a traction battery of a vehicle

Technical field

- 5 The invention relates to a method for optimizing the service life of a traction battery of a vehicle and to an arrangement for operating an electrically operated vehicle.

State of the art

The traction battery is an essential component of electrically driven vehicles. The traction battery is subjected to an aging process which results in the usable capacity (that is to say the storable and retrievable energy) decreasing and the internal resistance of the traction battery increasing. The aging can be divided into an aging on account of the loads during operation and into a calendar aging.

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The aging on account of the vehicle operation depends on various parameters, inter alia on the charging and discharging powers which occur and the cell temperatures. A different operation therefore also results in a different aging. Correspondingly, the service life of identical batteries can be different, the service life generally denoting the number of travel kilometers achieved up to a predefined residual capacity (for example 80% of the initial capacity).

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Methods are known for increasing the service life of traction batteries by influencing the vehicle operation.

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- For example, US 2022/0126723 A1 (GM Cruise) relates to the fleet-based optimization of traction batteries of electric vehicles. For this purpose, the current state of health (SOH) is measured by means of impedance spectroscopy. The measurement results of many vehicles in the fleet are compared with one another in order to determine parameters
- 5 such as the remaining service life or factors for increased battery aging; a machine learning model can also be trained on the basis of the data in order to estimate the battery capacity, the remaining service life or other parameters. Measures for optimizing the SOH include, in particular, restrictions on the use or charging of a specific battery or an adaptation of the route assignments. A restriction on the energy consumption for the
- 10 heating, ventilation and air conditioning system (HVAC) is also possible. The current SOH can be determined from time to time by means of a charge count; on the basis of the corresponding data, it is possible to develop approaches which permit a more rapid determination of the SOH which places less stress on the battery and which can be carried out more frequently.
- 15 An increase in the battery service life is often associated with restrictions on the driving operation and/or with losses in comfort. Excessive battery-saving operation in order to ensure a minimum service life is therefore not desired.

SUMMARY OF THE INVENTION

- The object of the invention is to provide a method for optimizing the service life of a
- 20 traction battery of a vehicle, which method belongs to the technical field mentioned at the outset and ensures that a predefined service life of the traction battery is achieved with minimized disadvantageous effects on the driving operation and/or the user comfort.

The solution to the object is defined by the features of claim 1. According to the invention, a method for optimizing the service life of a traction battery of a vehicle comprises the following steps:

- 5 a) determining an effective state of health of the traction battery with a first periodicity;
- b) determining an estimated state of health of the traction battery with a second periodicity, starting from a last determined effective state of health, taking into account usage data of the vehicle since a last determination of the estimated state of health, by applying an aging model for the traction battery;
- 10 c) operating the vehicle on the basis of the estimated state of health and a current traction energy demand, wherein at least one battery load-relevant control parameter is newly determined with at least a third periodicity.

The aging model for the traction battery is calibrated after determining the effective state of health.

- 15 The state of health of a traction battery is regularly referred to as the state of health (SOH). It is defined as the ratio between a remaining charge capacity $Q_b(t)$ to an original charge capacity $Q_{b,init}$:

$$\Psi(t) = \frac{Q_b(t)}{Q_{b,init}}.$$

- 20 The use data are data relating to the use of the vehicle which are relevant to the aging of the battery. They may have been determined at the level of the vehicle (e.g. speeds, accelerations, traction powers, operating times, etc.) and/or at the level of the traction battery (e.g. retrieved power, charging power, charge level, cell temperatures, etc.).

Various aging models for the traction battery can be used. Such models are available, for example, in the Open Source project OpenSesame (M. Beyeler, S. S. Bhoir, S. Broennimann, Y. Moullet, Open-SESAME-Battery, V1.1, <https://gitlab.ti.bfh.ch/oss/esrec/open-sesame> (2022)).

- 5 According to the invention, the estimated state of health of the traction battery is taken into account during the operation of the vehicle in addition to the current traction energy demand (and possible further input parameters, relating, for example, to the desired operation of a heating, cooling or air conditioning system and further components of the vehicle). In this context, at least one battery load-relevant control parameter is repeatedly
10 newly determined. The battery aging can be influenced by the specification of this control parameter, in particular with regard to ensuring a predetermined battery service life with the least possible restrictions in the driving operation and/or minimum energy consumption.

- The periodicities are selected, in particular, such that the new determination of the
15 battery load-relevant control parameter takes place frequently in order to take account of the changing requirements in the driving operation. The determination of the estimated state of health can take place less frequently, for example in each case after the completion of a driving mission or when the vehicle is parked in a depot or the like. The determination of the effective state of health is effected in particular by explicit
20 determination of the residual capacity of the traction battery using known procedures. These are time-consuming; accordingly, this procedure is carried out significantly less frequently.

- The mentioned steps can take place substantially regularly, according to a predetermined time pattern and/or in the case of predetermined triggering criteria, such as, for example,
25 when the vehicle is parked, in the context of maintenance work or the like.

According to the invention, the aging model is calibrated depending on the behavior of the specific traction battery, i.e. the model is adapted in order to describe the aging of this specific traction battery in the best possible manner. An initial aging model can initially be predefined universally, wherein knowledge from the operation of a vehicle
5 fleet or a partial fleet with identical or analogous traction batteries can be (also) taken into account in the definition of the initial aging model and/or in the calibration.

The method according to the invention therefore makes it possible to ensure that the traction battery neither ages too quickly and correspondingly has to be replaced too early, nor is it treated too gently, which can result in inefficient driving operation,
10 increased energy consumption or losses in comfort. With the aid of the method according to the invention, it can likewise be avoided that batteries with too high a capacity and therefore an unnecessarily high weight are used in order to ensure the service life and/or the requirements in the driving operation. The choice of the vehicle used on a specific line and/or its configuration can likewise be optimized. On account of
15 the regular determinations of the effective state of health and the adaptation thereof by means of intermediate estimations, a realistic SOH value is continuously available as a basis for the operation of the vehicle, at the same time systematic deviations of the SOH value from the actual state of health, which are summed over the service life, are avoided.

The control parameter is advantageously determined on the basis of a deviation of the
20 estimated state of health from a reference curve. The deviation is updated, in particular, according to the second periodicity, that is to say during a new determination of the estimated state of health.

The reference curve represents an expected development of the state of health of the traction battery. If the estimated state of health is better than according to the reference
25 curve, measures for protecting the traction battery, which result, for example, in restrictions in the driving operation or a higher energy consumption, can be reduced. If

the estimated state of health is worse than according to the reference curve, measures for protecting the traction battery can be triggered or intensified. The relatively narrow-meshed determination or estimation of the state of health on the basis of specific use data enables short-term measures in this context and ultimately avoids both excessive degradation of the traction battery and unnecessary restrictions or too high an energy consumption on account of excessive protection of the traction battery.

The reference curve is preferably determined in such a way that the traction battery has a predefined state of health at a predefined mileage. It is thus predefined, for example, that the traction battery still has an SOH or residual capacity of 80% at a mileage of 1.2 million km. The reference curve of the SOH is, in particular, a function of the distance traveled and can have a linear or non-linear dependence. The latter can be expedient in order to take account of age-dependent influences on the battery aging. Depending on the traction battery and vehicle, for example, intensified aging at lower SOH can result.

The predefined service life is therefore targeted in a closed control loop. The aim is operation which is as efficient and comfortable as possible while ensuring the required battery service life.

The reference curve is advantageously newly calculated after determining the effective state of health. Instead of the overall curve between the first use of the new traction battery and the predefined mileage, the newly calculated reference curve therefore also represents the time period between the last determination and the predefined mileage, wherein the SOH value of the last determination forms the starting value of the curve. If this is higher than according to the preceding definition of the reference curve, (somewhat) more rapid aging is accepted, if it is lower, the battery is additionally protected in order to achieve (somewhat) slower aging.

The usage data taken into account for determining the estimated state of health advantageously comprise a curve of a battery charge state since the last determination. It has been shown that, based on the curve of this one value, a reliable estimation can be achieved, wherein both the influences of consumers and also as a result of charging and
5 braking processes are also taken into account indirectly and influences of the respective state of charge can be included in the estimation. The estimation can be carried out based on the curve itself and/or on the first and/or second derivative of the battery charge state. If required, even higher derivatives can also be taken into account.

In a preferred embodiment, the estimated state of health results from the last determined
10 effective state of health minus a sum of degradation estimations which were carried out based on the aging model, starting from the usage data, since the last determination of the effective state of health. Each degradation estimation in this case covers a time period since the preceding estimation.

For calibrating the aging model, the estimated state of health of the traction battery is
15 preferably compared with the determined effective state of health at the time of determining the effective state of health. The difference corresponds to an overestimation or underestimation of the effective aging. By means of an adaptation of the aging model, the degree of overestimation or underestimation can be reduced, which generally results in a better estimation for the subsequent interval. In particular,
20 individual characteristics of the specific traction battery are automatically taken into account by the calibration, i.e. the aging model adapts itself automatically to the specific traction battery.

For determining the control parameter (at least temporarily or in addition to other target variables), an optimization is advantageously carried out with regard to a maximization
25 of a first target variable corresponding to a service life of the traction battery. This optimization therefore makes it possible to increase the service life or to increase the

residual capacity (or the SOH) at the predefined mileage. It is required, in particular, when the state of health of the battery is worse than required at a specific time, for example lower than according to a reference curve. A maximization of the service life results, in particular, by the minimization of damaging operating phases, for example by a
5 restriction of the charging power, in particular during braking processes, or by a restriction of the retrieved power by a reduced acceleration and/or a temporary reduction of the retrieved power of vehicle components (e.g. the HVAC).

With regard to the maximization of the first target variable, an influence of operating parameters on the state of health of the traction battery is advantageously determined
10 on the basis of the usage data of the vehicle and the determined effective state of health. It is therefore possible to determine, in a vehicle-specific and traction-battery-specific manner, which operating configurations, measures and events result in increased (or reduced) battery aging. Influences of the battery aging itself can likewise be taken into account automatically in this way: it is determined automatically, for example, when
15 certain processes at a higher battery age represent an additional load. A self-learning control system therefore results which automatically detects operating points which are damaging for the traction battery (including vehicle-specific and battery-specific dependencies and influences of the battery aging) and triggers measures within the scope of a control loop in order to ensure the required service life of the traction battery
20 with the least possible impairment of the driving operation and of the user comfort.

The relationship between the operating parameters and the influence on the state of health of the traction battery can be determined, for example, with the aid of machine-learning techniques, including regression methods.

For determining the control parameter (at least temporarily or in addition to other target
25 variables), an optimization is advantageously carried out with regard to a minimization of a second target variable corresponding to a (primary) energy consumption of the

vehicle.

The aim of the method according to the invention is, in particular, to ensure a predetermined battery service life without the traction battery having to be protected excessively, which can result in restrictions in the driving operation and, in particular, in increased energy consumption. For example, in order to protect the battery, a maximum power consumption of the traction battery during braking processes can be restricted, which means that a certain part of the braking energy is not recuperated, but rather, for example, is converted into heat in braking resistors. If such a restriction is then not necessary at all or is necessary only to a reduced extent without endangering the attainment of the service life, the optimization is possible with regard to a reduction in the energy consumption.

Particularly preferably, depending on the deviation of the estimated state of health from the reference curve, a weighting of the first and the second target variable is adapted in the optimization. In particular, a stronger weighting of the first target variable takes place if the estimated state of health falls below the reference curve, while a stronger weighting of the second target variable is possible if the estimated state of health is better than according to the reference curve.

The trade-off between the (primary) energy consumption and the battery aging can thus be set automatically and in an optimum manner by varying an individual parameter.

A first period of the first periodicity is advantageously longer than a second period of the second periodicity, and the second period is longer than the third period of the third periodicity. In this case, in particular:

- the first period is 14 days to 400 days,
- the second period is 1 hour to 24 hours, and/or
- the third period is 0.1 to 10 s.

The determination of the effective state of health thus only has to be carried out relatively rarely, for example in the context of periodic maintenance work. The new determination of the estimated state of health, for example after each mission or daily after the end of use, simultaneously enables sufficiently narrow-meshed taking into account of the battery aging in the driving operation. The determination of the control parameter takes place more frequently in order to take account of the changing requirements in the driving operation.

If a plurality of control parameters are newly determined depending on the estimated state of health, the corresponding periodicities can coincide or deviate from one another. Thus, the drive power can be newly determined, for example, more frequently than control parameters for the HVAC.

The method according to the invention can be used in particular in the operation of battery-electric vehicles, particularly preferably in the case of buses for passenger transport, for example in line operation. In the present case, a "battery-electric vehicle" is understood to mean a vehicle whose drive power is generated by means of one or more electric motors which are fed by one or more traction batteries, the electrical energy for the traction battery or batteries being fed from external current sources during charging operations. The charging operations can take place in a stationary manner and/or during travel, for example via overhead lines.

The method according to the invention is particularly advantageous for operating vehicles which comprise a current collector in order to receive electrical energy from an overhead line during a driving operation. In this case, in particular, trolley buses are concerned which are capable of covering partial routes without receiving electrical drive energy from the overhead line, the drive energy being taken from the traction battery on these partial routes. Thus, lines which are not continuously equipped with overhead lines

can also be travelled on. The traction battery is recharged on the partial routes with overhead line.

In the case of trolley buses, excessive battery-saving operation can result in increased overall energy consumption. This can be avoided with the aid of the method according
5 to the invention.

With the aid of the method according to the invention, in particular, the charging power can also be set as a control parameter depending on the estimated state of health of the traction battery. Trolley buses which can be operated according to the invention can also
10 comprise charging connections in order to receive electrical energy, in addition to the current collectors for the overhead line, in order, for example, to precharge the traction battery of the vehicle in a depot before an operating cycle.

In principle, the method can also be used in hybrid vehicles which, in addition to the traction battery and to one or more electric drive motors, comprise an internal combustion engine for generating electrical energy and/or direct mechanical drive
15 power. In the case of power-split hybrid vehicles, the at least one battery load-relevant control parameter also comprises, in particular, the division of the retrieved power between the battery and the internal combustion engine.

The method is suitable for operating a vehicle which is used in a line operation, wherein predicted driving data of a line travelled on or to be travelled on are taken into account
20 in the determination of the control parameter. On the basis of such information, for example, the charge level of the traction battery can be controlled in such a way that, on the one hand, sufficient drive energy is available on the entire line and, on the other hand, as much braking energy as possible can be recuperated in corresponding passages with the least possible loading of the traction battery. Similarly, in the case of trolley buses,

the state of charge of the traction battery can be conditioned with regard to an imminent charging process in a partial section with overhead line.

The method can also be used to assign vehicles of the same type to individual lines in the context of a fleet on the basis of the estimated state of health of their traction battery.

- 5 Thus, for example, vehicles whose traction batteries have a below-average state of health can be assigned lines to which a low loading of the traction battery is assigned, while vehicles whose traction batteries have an above-average state of health are assigned lines with a higher loading. Alternatively, a battery exchange between two or more vehicles is recommended. By means of the periodic new estimation of the state of health,
- 10 overshooting effects of such measures are avoided: on account of the updated estimations for all vehicles of the fleet, a new assignment can take place at any time, so that, as seen over the entire fleet, a compensation of the loadings takes place.

The control parameter preferably comprises one or more of the following parameters:

- a) a state of charge;
- 15 b) a charging power;
- c) a retrieved power from the traction battery;
- d) a maximum acceleration of the vehicle;
- e) a maximum recuperation current of the vehicle;
- f) a consumption power for a braking resistance;
- 20 g) an operating parameter of a heating, ventilation and/or air conditioning system of the vehicle;
- h) an operating parameter of an interior lighting and/or of an interior information system and/or of other ancillary consumers of the vehicle;
- i) an operating parameter of a thermal management system for the drive battery.

The state of charge and the charging power can be a predefined value or a minimum or maximum value. The maximum or optimum depth of discharge (DOD) therefore forms a possible control parameter. The charging power can relate both to the stationary retrieval or to the retrieval from an overhead line. The retrieved power from the traction battery
 5 can then be predefined as a control parameter if there is a direct retrieval possibility of primary energy during the driving operation, in particular from an overhead line, from a fuel cell or—in the case of a hybrid vehicle—from an internal combustion engine, either directly as a drive or indirectly via a generator.

If the predefined maximum recuperation current is reached and additional braking power
 10 is required, a braking resistance for converting excess energy into heat and/or an additional mechanical braking system can be used. The operating parameter of the HVAC can be a predefined temperature of the vehicle interior. However, the HVAC system is preferably operated or switched off briefly, in operating phases of high load, with reduced power. If a heat accumulator or a cold accumulator is present, the latter can be
 15 filled in phases with low loading of the traction battery or with excess recuperation energy and used in phases with high loading for the operation of the HVAC system. Instead of operating parameters of the HVAC system, a maximum power of the entirety of the ancillary consumers can be predefined.

The thermal management system for the traction battery can also be influenced within
 20 certain limits in order to avoid brief load peaks, for example by a corresponding unit being briefly reduced in its power or switched off, it also being possible to accept situationally higher temperature levels.

Influences of a switch-off procedure or a power reduction can be compensated by a corresponding power increase in advance or after such a measure. If an imminent
 25 measure is already known to the vehicle controller, for example during operation on a known line, the compensation can take place wholly or partly anticipatorily.

Further control parameters relate to the triggering of instructions to the vehicle driver, for example in relation to a setpoint speed or the initiation of a braking procedure.

If the method according to the invention is used in conjunction with a trolleybus with integrated traction battery, in particular the power to be received from the overhead line forms one of the control parameters, since in general, by increasing the proportion of the required power which is retrieved from the overhead line, the battery can be relieved and therefore the aging can be delayed, while at the same time the required overall energy increases on account of the higher resistances in the overhead line network. The desired balance of energy efficiency and battery service life can thus be achieved by suitable variation of the proportion of the retrieved power from the overhead line, according to the method according to the invention. Load peaks in the overhead power network can also be advantageously influenced thereby.

An arrangement according to the invention for operating an electrically operated vehicle according to the method according to the invention comprises:

- 15 a) the electrically operated vehicle with a traction battery for driving at least one drive assembly of the vehicle; and
- b) a measuring device for determining an effective state of health of the traction battery of the vehicle;

wherein the vehicle comprises the following:

- 20 c) a processing device for determining an estimated state of health of the traction battery;
- d) a calibration device;
- e) a vehicle controller for operating the vehicle;

wherein

- the processing device is configured to receive the last determined effective state of health from the measuring device, to receive usage data of the vehicle from the vehicle controller and to determine the estimated state of health starting from the effective state of health and taking into account the usage data since a last determination of the estimated state of health, by applying an aging model for the traction battery;
- the calibration device is configured to calibrate the aging model on the basis of the determined effective state of health received by the arrangement; and
- the vehicle controller is configured to determine at least one battery load-relevant control parameter on the basis of the estimated state of health and a current traction energy demand.

The measuring device is, in particular, arranged in a stationary manner, for example in a maintenance center or in a workshop. The last determined effective state of health can be received directly from the measuring device or indirectly, for example from the vehicle controller, to which these data were previously transmitted by the measuring device or by a corresponding server.

Further advantageous embodiments and combinations of features of the invention result from the following detailed description and the entirety of the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings used to explain the exemplary embodiment show:

FIG. 1 a schematic block diagram of an embodiment of an arrangement according to the invention for operating an electrically operated vehicle;

- FIG. 2 a schematic illustration of the method according to the invention for optimizing the service life of a traction battery of a vehicle;
- FIG. 3 a schematic illustration of the power balance of the sources and loads of the electrically operated vehicle;
- 5 FIG. 4A the resulting power distribution in the case of an operating strategy for maximizing the overall energy consumption;
- FIG. 4B the resulting power distribution in the case of an operating strategy for maximizing the battery service life; and
- FIG. 5 results of a lifetime simulation for comparing the results of the method
10 according to the invention with a method without regular recalibration.

In principle, identical parts are provided with identical reference symbols in the figures.

Ways of Carrying Out the Invention

FIG. 1 shows a schematic block diagram of an embodiment of an arrangement according to the invention for operating an electrically operated vehicle. Connections for transmitting electrical power are shown in solid lines, connections for transmitting open-loop and closed-loop control signals are shown in dash-dotted lines, and connections for the (temporary) transmission of measurement signals are shown in dashed lines. The vehicle is a trolley bus 10 which can receive current from an overhead line via a current collector 13 during driving operation, during travel and at a standstill. The trolley bus 10 also has a charging connection 14 which enables a wired power supply, for example in a depot where the trolley bus 10 is parked outside its operating phases.

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The electrical energy is stored in a traction battery 12 of the trolley bus 10. In this case, in a manner known per se, Li-ion batteries with a capacity of, for example, 72 kWh are concerned, which makes it possible to travel on relatively long partial routes without overhead line. In addition to the traction battery 12 and the charging connection 14, the
 5 operating components 10a of the trolley bus 10 comprise the drive assembly 11 which comprises a plurality of electric motors fed by the traction battery 12, auxiliary consumers 15 (for example heating, ventilation and air conditioning, lighting, on-board entertainment etc.), a braking resistor 17 and a current distributor 16 via which the traction battery 12 is connected, on the one hand, to the current collector 13 and to a
 10 downstream unidirectional DC voltage converter 18 and to the charging connection 14 and, on the other hand, to the consumers, that is to say the drive assembly 11, the braking resistor 17 and the auxiliary consumers 15. In this case, it should be noted that the drive assembly 11 acts as a generator in the recuperation mode and can correspondingly feed back electrical energy into the traction battery 12.

15 The trolley bus 10 furthermore comprises a control system 20. This contains a vehicle controller 21 with various control modules which control and monitor, on the one hand, the drive assembly 11 and, on the other hand, the further vehicle components including the auxiliary consumers 15. Furthermore, the control system 20 comprises a processing device 22 for estimating the state of health of the traction battery 12 and a calibration
 20 device 23 for updating the aging model. Both are in turn connected to the vehicle controller 21 for receiving vehicle information and for transmitting control parameters.

The trolley bus 10 can be connected at a standstill to a measuring device 50 for determining the effective state of health of the traction battery 12. This determination supplies, in particular, the current (residual) capacity and takes place by known methods,
 25 for example by a complete charging and discharging cycle with detection of the transferred energy.

FIG. 2 is a schematic illustration of the method according to the invention for optimizing the service life of a traction battery of a vehicle, namely of the trolley bus 10. The method comprises a plurality of feedback loops at different time levels.

In the lowest level 40.1, in a manner known per se, driving signals 45 and further control
 5 signals of the vehicle driver (and, if appropriate, of a control center of the operator) are detected and transmitted to the operating components 10a of the trolley bus 10. At the same time, the driving signals 45 and further control signals or a selection of these signals are transmitted to the vehicle controller 21.

In a next higher level 40.2, starting from signals of the operating components 10a (which
 10 are provided, if appropriate, via the vehicle controller 21), a degradation estimation 61 is carried out on the basis of a model. This represents a measure of the degradation which the traction battery 12 has experienced on account of the driving operation and the operation of the ancillary consumers 15 since a last update. The degradation is then subtracted from a last known value for the state of health (SOH) in order to obtain an
 15 updated SOH estimation 62 of the state of health of the traction battery 12. Based on the updated SOH estimation 62, an SOH comparison 63 with a setpoint value is now carried out. If the updated estimation falls below the setpoint value, measures must be taken in order to reduce the degradation of the traction battery 12. If the updated estimation exceeds the setpoint value, the operation of the trolley bus 10 can be optimized to a
 20 greater extent with regard to other criteria (e.g. overall energy consumption, comfort functions, etc.). Ultimately, the result of the SOH comparison 63 therefore has effects on the driving operation; accordingly, it is therefore transmitted to the vehicle controller 21.

At the highest level 40.3, an effective SOH measurement 71 is carried out, in the case of a stationary trolley bus 10, with the aid of the measuring device 50. The remaining battery
 25 capacity is determined and, from this, the current effective value of the SOH $\tilde{\Psi}_i$ is determined by a comparison with the initial capacity. The result of this SOH measurement

71 serves, on the one hand, for the model calibration 72 of the model used for the degradation estimation 61 and, on the other hand, for the updating 73 of the reference profile which is required in the SOH comparison 63.

The reference profile results from the following variables:

- 5 - a predefined state of health Ψ_{EOL} at a predefined mileage d_{EOL} ;
- the current mileage d ; and
- the last determined effective SOH $\tilde{\Psi}_i$ at a mileage d_i .

In the simplest case, a linear decrease in the SOH is assumed, so that the setpoint value Ψ_d at the mileage d results as follows:

$$10 \quad \Psi_d = \tilde{\Psi}_i - \left(\frac{\tilde{\Psi}_i - \Psi_{EOL}}{d_{EOL} - d_i} \right) (d - d_i).$$

In each new effective SOH measurement 71, the slope of the decrease is thus determined again and the updating 73 mentioned is carried out.

The decrease can in principle also be parameterized by a nonlinear relationship.

The degradation estimation 61 is carried out based on usage data of the vehicle. In the
 15 exemplary embodiment shown, the degradation estimation results from the curve of the state of charge of the traction battery 12 since the last determination. The degradation can then be calculated using an aging model. Suitable for this purpose is, for example, the freely available tool OpenSesame, which makes it possible to simulate Li-ion batteries (M. Beyeler, S. S. Bhoir, S. Broennimann, Y. Moullet, Open-SESAME-Battery, V1.1,
 20 <https://gitlab.ti.bfh.ch/oss/esrec/open-sesame> (2022)). In addition to information on the battery (capacity, cell chemistry) and on the starting state (SoC, SOH), time series with values of the state of charge (SoC), the input or output power (which can in principle be

calculated from the SoC curve with sufficient time resolution) and the cell temperature are included in the simulation. The result contains, inter alia, an estimation of the battery degradation for the given cycle.

The quality of this estimation is iteratively improved due to the calibration 72 of the model: For this purpose, in each SOH measurement 71, the estimated degradation 5 $(\hat{\Psi}[k-1] - \hat{\Psi}[k])$ since the preceding SOH measurement (as the sum of the estimated degradations) is compared with the difference $\tilde{\Psi}[k-1] - \tilde{\Psi}[k]$ between the effectively measured SOH values. For this purpose, a degradation error is first calculated as follows:

$$e_{deg}[k] = \frac{(\tilde{\Psi}[k-1] - \tilde{\Psi}[k]) - (\hat{\Psi}[k-1] - \hat{\Psi}[k])}{(\hat{\Psi}[k-1] - \hat{\Psi}[k])}.$$

10 This error value is then used in a PI controller in order to determine a correction factor γ_k at the time t_k as follows:

$$\gamma_k = 1 + K_{MM}(e_{deg}[k] + \frac{1}{T_{MM}} \sum_{i=1}^k e_{deg}[i] \cdot (\tau_{meas}[i] - \tau_{meas}[i-1])),$$

wherein K_{MM} denotes the amplification as usual and T_{MM} denotes the time constant. In order to correct the result $(\hat{\Psi}[k-1] - \hat{\Psi}[k])$ of the degradation estimation 61, the 15 correction factor is multiplied by this before the summation with the predetermined degradations is carried out in order to obtain the updated SOH estimation 62.

At the same time, in each new SOH measurement 71, the sum of the degradations is set to zero again, i.e. the further degradation estimations 61 are carried out starting from the last determined effective SOH value.

20 In the context of the vehicle controller 21, the results from the SOH comparison 63 are now taken into account. In particular, depending on the requested power (drive power and power for further consumers), it is determined which proportion of the power is

taken from the traction battery 12 and which is taken directly from the overhead line via the current collector. If the overhead line is not available in an operating section, additional operating parameters (e.g. the power of the ancillary consumers 15) can be varied. However, these operating parameters can also be set if a retrieval possibility from the overhead line is present.

For taking into account the results from the SOH comparison 63, the adaptive ECMS approach known per se is used (L. Guzzella, A. Sciarretta, Vehicle Propulsion Systems, Springer-Verlag Berlin Heidelberg, 2013; A. Sciarretta, L. Guzzella, Control of hybrid electric vehicles, IEEE Control Systems Magazine 27 (2) (2007) 60-70; L. Serrao, S. Onori, G. Rizzoni, ECMS as a realization of Pontryagin's minimum principle for HEV control, in: 2009 American Control Conference, 2009, pp. 3964-3969). The approach has been developed for vehicles with hybrid-electric drive, but can—as illustrated below—also be used for vehicles with vehicle-bound traction battery and additional retrieval possibility for electrical energy (e.g. from a fuel cell or overhead line).

In this approach, the Hamilton function $H(\cdot)$ is derived by applying the Pontryagin's minimum principle to the problem of optimum control. This function is dependent on the values of two so-called equivalence factors $s_{\xi}(t)$ and $s_{\psi}(t)$ which represent the value of the two states SOC and SOH relative to the energy consumption. The value of $s_{\psi}(t)$ is determined in the second level 40.2, as described below.

On the basis of the values of the two equivalence factors, the division between battery current and overhead line current is determined, which results in an optimum compensation between the lowest possible overall energy consumption and a maximum battery service life, taking into account the desired battery service life. The division is achieved by a minimization of the local Hamilton function $H(\cdot)$. The specific form of the Hamilton function depends on the respective vehicle and drive. An example of the exemplary embodiment shown is given below.

The operating strategy is now adapted with the aid of a PI controller in that $s_\xi(t)$ is adapted depending on the current value $\xi(t)$ of the SOC: If $\xi(t)$ exceeds a constant reference value ξ_{ref} , the operating strategy favors a discharge of the traction battery 12, while electrical energy is preferably received from the overhead line if the reference value is undershot. For this purpose, the equivalence factor for the SOC is calculated as follows:

$$e_\xi(t) = \xi_{ref} - \xi(t),$$

$$s_\xi(t) = s_{\xi,FF}(s_\Psi(t)) + K_\xi(\xi(t)) \cdot (e_\xi(t) + \frac{1}{T_\xi} \int_{t_0}^t e_\xi(t) dt).$$

In this case, K_ξ and T_ξ denote the amplification or the time constant of the PI controller as usual. The amplification K_ξ can be dependent on the SOC in order to increase the aggressiveness of the controller in the vicinity of the SOC limits, while it is reduced in the SOC ranges in between. The time constant T_ξ should be selected to be slower than a corresponding time constant of the expected disturbances. The feed-forward component $s_{\xi,FF}(s_\Psi(t))$ is added in order to compensate for the influence of the control loop for the battery health (level 40.2) on the control loop for the operating strategy (level 40.1). It has been found on the basis of simulations that the feed-forward component can be defined, for example, as follows:

$$s_{\xi,FF}(s_\Psi) = 1.5 \cdot 10^{-11} \cdot s_\Psi + 800.$$

This definition takes account of the fact that, in the case of a high value for the equivalence factor s_Ψ for the battery health, a higher value for the other equivalence factor s_ξ is also necessary in order to make charge-sustaining operation of the traction battery possible.

At the first level 40.1, the controller must be able to react to changes in the requested power; the update interval can be correspondingly set to 1 s, for example.

The control loop for the battery health in the second level 40.2 serves to keep the SOH trajectory of the traction battery 12 close to the reference profile. In this level, an update is sufficient after each driving phase; an update therefore generally takes place in each case after a few hours. On account of the slow battery aging, deviations from the SOH reference trajectory also result comparatively slowly.

Using the model mentioned for the battery aging, the value $\Delta\hat{\Psi}$ for the degradation estimation 61 results from the trajectory $\vec{\xi}$ of the SOC since the last update. This is multiplied by the correction factor γ_k mentioned. The value $\hat{\Psi}$ for the updated SOH estimation 62 then results from a summation of the degradation estimations 61.

10 The deviation of the current SOH estimation 62 from the corresponding reference value results as

$$e_{\Psi}[j] = \Psi_{ref}[j] - \hat{\Psi}[j],$$

which is incorporated into a PI controller as follows:

$$u_{\Psi}[j] = u_{\Psi,0} + K_{\Psi} \cdot \left(e_{\Psi}[j] + \frac{1}{T_{\Psi}} \sum_{i=1}^j e_{\Psi}[i] \cdot (\tau_{tr}[i] - \tau_{tr}[i-1]) \right).$$

15 In turn, $u_{\Psi,0}$ denotes the starting value of the controller, K_{Ψ} denotes the amplification and T_{Ψ} denotes the time constant.

It has been found that the sensitivity of the operating strategy in relation to a change in the equivalence factor s_{Ψ} is best represented on a logarithmic scale; accordingly, the result of the second level 40.2 at a time $\tau[j]$ is defined as follows:

20
$$s_{\Psi}[j] = 10^{u_{\Psi}[j]}.$$

In the context of a simulation study, the method according to the invention was tested on the basis of a trolley bus which can receive current from a DC overhead line with the aid of its current collector and at the same time can store electrical energy in its traction battery 12. On account of its unidirectional DC voltage converter, it is not possible to feed back energy into the network. Viewed topologically, the drivetrain is therefore very similar to a series hybrid drivetrain where a motor-generator assumes the role of the network for recharging the traction battery. The trolley bus considered has the following characteristic values:

Vehicle length	18.7 m
Driving weight	18.8 t
Maximum number of passengers	163
Cell chemistry Drive battery	LTO
battery cell capacity	23 Ah
Battery configuration	324s 4p

In the context of the simulation study, the operation of the bus on various routes in realistic, everyday driving missions was considered. The underlying model is described in the article F. Widmer, A. Ritter, P. Duhr, C. H. Onder, Battery lifetime extension through optimal design and control of traction and heating systems in hybrid drivetrains, eTransportation 14 (2022) 100196, <https://doi.org/10.1016/j.etrans.2022.100196>, Chapter 2.

The components illustrated schematically in FIG. 3 are taken into account for the power balance:

- a feed point 1 from which the trolley bus 10 is supplied with current via a network 2;
- the DC voltage converter 18;
- the current distributor 16 via which the power flows run between the individual sources and consumers;
- the drive battery 12;
- the drive assembly 11 and the auxiliary consumers 15; and
- the braking resistance 17.

The arrows represent the possible energy flow. The following power balance results:

$$P_{c,out}(t) + P_b(t) = P_{req}(t) + P_{brk}(t), \quad (1)$$

wherein $P_{c,out}(t)$ denotes the power at the output of the DC voltage converter 18, $P_b(t)$ denotes the discharging power of the traction battery 12, $P_{req}(t)$ denotes the required power of the drive assembly 11 and of the auxiliary consumers 15 and $P_{brk}(t)$ denotes the power which is consumed in the braking resistance 17.

If it is assumed that $P_{req}(t)$ results from the driving mission and the other requirements (HVAC, etc.), there are two degrees of freedom, namely the power consumption from the traction battery 12 and the energy to be dissipated in the braking resistance 17. For the application to the trolley bus, the parameters $P_b(t)$ and $P_{brk}(t)$ are therefore considered as input variables. The power of the braking resistance $P_{brk}(t)$ is not negative:

$$P_{brk}(t) \geq 0. \quad (2)$$

The battery can both store and deliver energy.

As indicated above, the lithium titanate oxide battery cells (LTO) of the traction battery 12 of the trolley bus 10 have a capacity of 23 Ah. The traction battery 12 consists of 1296 cells in a 324-series-4-parallel configuration. The battery model used comprises an ideal voltage source $U_{b,oc}(t)$ in series with an internal resistance $R_b(t)$. The value both of the open-circuit voltage of the internal resistance varies with the state of charge (SOC). The corresponding profiles result from the OpenSESAME package mentioned, scaled for the specific battery configuration. The current which is required to deliver a specific discharging power $P_b(t)$ results as follows:

$$I_b(t) = \frac{U_{b,oc}(t) - \sqrt{U_{b,oc}(t)^2 - 4 \cdot P_b(t) \cdot R_b(t)}}{2 \cdot R_b(t)}. \quad (3)$$

The state of charge SOC, denoted by $\xi(t)$, denotes the ratio between the current charge and the maximum charge capacity $Q_b(t)$. It results from the following differential equation:

$$\frac{d}{dt} \xi(t) = -\frac{I_b(t)}{Q_b(t)} = -\frac{I_b(t)}{\Psi(t) \cdot Q_{b,init}},$$

wherein $\Psi(t)$ denotes the SOH as defined above.

In addition to the decreasing capacity, the aging of the traction battery 12 also manifests in an increased internal resistance. In the context of the simulation study, this effect is likewise taken into account. However, instead of calculating the profile of the SOR separately, it is assumed at this point in a simplified manner that the SOR is linearly related to the SOH. This linear relationship was determined on the basis of preceding experiments with the OpenSESAME package mentioned. However, the OpenSESAME

package mentioned also readily makes it possible to calculate the internal resistance, so that this variable can be integrated, if required, into the simulation or into an operating method according to the invention.

5 Ultimately, OpenSESAME makes it possible to determine the degradation of the traction battery over a specific cycle, depending on the profiles of the charging/discharging power, of the SOC and of the cell temperature, wherein the use cycle of a battery is subdivided into an equivalent set of subcycles and the degradation is determined as a superposition of cycle and calendar aging.

10 The simulated trolley bus 10 comprises a powerful system for the temperature control of the battery cells. With systems currently available, the cell temperature can be kept in a relatively narrow band, for example between 10° C. and 25° C., wherein the aging of LTO cells does not react very sensitively to different temperatures in this band. At a specific outside temperature, the resulting cell temperature can additionally be kept in a narrow window of approximately 2-3° C. The changes in the battery temperature as a result of
15 different outside temperatures can therefore be considered as external disturbances and integrated into the driving mission. In order to calculate the calendar aging of the traction battery 12, downtimes of the trolley bus 10 outside the driving missions in which the vehicle is generally located in the depot are modeled with a constantly predefined temperature.

20 In an extension of the method described, however, for example, the temperature management of the battery can be integrated with further control parameters into the operating method.

The network 2 which transmits electrical power from the feed point 1 via the current collector 13 to the DC voltage converter 18 of the trolley bus 10 is modeled as an ideal

voltage source $U_{g,OC}$ in series with a line resistance R_g . Correspondingly, the following results for the power which reaches the DC voltage converter 18:

$$P_{c,in}(t) = P_s(t) - \frac{R_g}{U_{g,OC}^2} \cdot P_s(t)^2, \quad (4)$$

5 wherein $P_s(t)$ represents the power at the feed point 1.

The network current $I_g(t)$ is restricted in order to avoid excessive wear on account of heat development between the current collector 13 and the overhead line. The upper limit $\bar{I}_g$ depends on the vehicle speed $v(t)$ and compliance with the latter is ensured by the vehicle controller 21.

10 The driving route can comprise sections in which no overhead line is available. This is taken into account with a two-valued indicator function $\chi(t)$ which assumes the value 1 if an overhead line is available and the value 0 if this is not the case. The following conditions therefore result:

$$0 \leq P_s(t) \leq \chi(t) \cdot \bar{I}_g(v(t)) \cdot U_{g,OC}. \quad (5)$$

The unidirectional DC voltage converter 18 is represented by an affine efficiency model. The following results for the power which is available at its output:

$$P_{c,out}(t) = \eta_c \cdot P_{c,in}(t) - P_0, \quad (6)$$

20 wherein the constants η_c and P_0 denote the converter efficiency or the no-load losses.

According to the ECMS approach, the optimum power distribution (power split) is calculated by the minimization of the so-called Hamiltonian function which results from the application of the Pontryagin's minimum principle (PMP). For the derivation of the Hamiltonian function, only the state variables SOC and SOH are taken into account in the context of the model as mentioned above, with the result that operating states which are particularly disadvantageous for the internal resistance are not specifically prevented. However, owing to the correlation mentioned with operating states which are harmful for the capacitance-related SOH, this generally does not lead to problems.

For the state update function of the SOH, the time-based instantaneous degradation $\psi(t)$ is introduced as follows:

$$\frac{d}{dt}\Psi(t) = -\psi(t).$$

In the article F. Widmer, A. Ritter, P. Duhr, C. H. Onder, Battery lifetime extension through optimal design and control of traction and heating systems in hybrid drivetrains, eTransportation 14 (2022) 100196, it is described how the cycle-based approach of OpenSESAME can be transformed in order to obtain the following estimation for the degradation:

$$\begin{aligned} \psi(t) \approx & \zeta_{cyc,\xi}(\xi(t)) \cdot \zeta_{cyc,\vartheta_b}(\vartheta_b(t)) \cdot \zeta_{cyc,\delta}(\delta(t)) \cdot \zeta_{cyc,C}(\mathcal{C}(t)) \cdot \frac{|C(t)| \cdot \Delta\Psi_{cyc,0}}{2 \cdot \Psi(t)} \\ & + \zeta_{cal,\xi}(\xi(t)) \cdot \zeta_{cal,\vartheta_b}(\vartheta_b(t)) \cdot \psi_{cal,0}, \end{aligned} \quad (7)$$

wherein the scaling factors $\zeta_{cyc,\xi}$, ζ_{cyc,ϑ_b} , $\zeta_{cyc,\delta}$ and $\zeta_{cyc,C}$ serve to scale the degradation $\Delta\Psi_{cyc,0}$ of a reference cycle depending on the SOC, the cell temperature, the depth of discharge (DOD) $\delta(t)$ and the C-rate $\mathcal{C}(t)$ of the traction battery. Similarly, with the scaling factors $\zeta_{cal,\xi}$ and ζ_{cal,ϑ_b} , the reference value $\psi_{cal,0}$ for the calendar aging is scaled

depending on the SOC and the cell temperature. In this case, the C-rate is defined relative to the nominal battery capacity, i.e.

$$C(t) = \frac{I_b(t)}{Q_{b,init}}.$$

In the determination of the optimum power distribution at the time t , $\xi(t)$, $\vartheta_b(t)$ and $\Psi(t)$ can be considered as given. In addition, as likewise described in the article F. Widmer et al. mentioned, a constant value δ_0 can be selected for the depth of discharge (DOD) as a simplified assumption. The following two new variables can therefore be introduced:

$$a_{deg}(\xi(t), \vartheta_b(t), \Psi(t)) = \zeta_{cyc,\xi}(\cdot) \cdot \zeta_{cyc,\vartheta_b}(\cdot) \cdot \zeta_{cyc,\delta}(\cdot) \cdot \frac{\Delta\Psi_{cyc,0}}{2 \cdot \Psi(t)},$$

$$b_{deg}(\xi(t), \vartheta_b(t)) = \zeta_{cal,\xi}(\cdot) \cdot \zeta_{cal,\vartheta_b}(\cdot) \cdot \psi_{cal,0}.$$

This results directly:

$$\psi(t) \approx a_{deg}(\cdot) \cdot \zeta_{cyc,C}(C(t)) \cdot |C(t)| + b_{deg}(\cdot).$$

(8)

The abovementioned simplifications are carried out for the determination of the optimum power distribution by minimizing the Hamiltonian function. However, the cycle-based OpenSESAME models are used directly for the estimation of the degradation at the second level. (The OpenSESAME models are likewise used in the simulation study presented here in order to calculate the actual aging of the battery.)

The following thus results for the state update function:

$$\frac{d}{dt} \begin{bmatrix} \xi(t) \\ \Psi(t) \end{bmatrix} = \begin{bmatrix} -\frac{I_b(t)}{\Psi(t) \cdot Q_{b,init}} \\ -\psi(t) \end{bmatrix}.$$

With regard to the minimization of the overall energy consumption, the following results from the Pontryagin's minimum principle for the Hamiltonian function:

$$H(\cdot) = P_s(\cdot) + \lambda(\cdot)^T \cdot \begin{bmatrix} -\frac{I_b(\cdot)}{\Psi(\cdot) \cdot Q_{b,init}} \\ -\psi(\cdot) \end{bmatrix},$$

wherein, in favor of simpler legibility, all mathematical dependencies have been omitted.

- 5 The equivalence factors $s_\xi(t)$ and $s_\Psi(t)$ are introduced as negative values of the corresponding co-state variables $\lambda(t)$. The following minimization problem therefore results:

$$\arg \min_{P_b, P_{brk}} \left(P_s(P_{req}, P_b, P_{brk}) + \frac{s_\xi}{\Psi \cdot Q_{b,init}} \cdot I_b(P_b, \xi, \Psi, \Phi) + s_\Psi \cdot \psi(P_b, \xi, \theta_b, \Psi, \Phi) \right),$$

wherein, for reasons of clarity, the time dependency has been omitted for all variables.

- 10 The result corresponds to the optimum power distribution.

The arguments result from the above equations:

- $P_s(P_{req}, P_b, P_{brk})$ from equations (1), (4) and (6);

- $I_b(P_b, \xi, \Psi, \Phi)$ from equation (3);

- $\psi(P_b, \xi, \theta_b, \Psi, \Phi)$ from equation (8).

- 15 In addition, the minimization is subjected to the conditions according to equations (2) and (5), P_{req} , ϑ_b and the upper limit $\bar{P}_s$ for the power draw from the network result from the driving mission and the equivalence factors s_ξ and s_Ψ are set by the corresponding controllers.

The minimization can be solved in approximately 20 ms on a commercial personal computer with an Intel Core i7-8565U processor unit. The method described can therefore be used without further ado for the regular determination of the power split, in the lowest level 40.1 of the method according to the invention (update rate in the
 5 region of 1 s).

As described above, the selected operating strategy depends primarily on the deviation of the estimated state of health of the traction battery from a desired state: if the state of health is better, an operating strategy which favors a minimization of the overall energy is selected; if the state of health is worse, an operating strategy which favors a
 10 maximization of the service life of the traction battery is selected. FIGS. 4A, 4B show the resulting power distribution in the case of an operating strategy with a high weighting of a low overall energy consumption (FIG. 4A, equivalence factor $s_\psi = 3.2 \cdot 10^{10}$) and in the case of an operating strategy with a high weighting of a high battery service life (FIG. 4B, equivalence factor $s_\psi = 3.2 \cdot 10^{13}$). In each case, depending on the required power
 15 P_{req} (horizontal axis, in kW), the power values P_b for the energy draw from the traction battery or the energy storage in the traction battery (medium-gray point cloud 91.1, 91.2), the power values $P_{c,out}$ for the energy draw from the overhead line (dark-gray point cloud 92.1, 92.2) and the power values P_{brk} for the dissipation in the braking resistance (light-gray point cloud 93.1, 93.2), in each case on the vertical axis, in kW, are illustrated.
 20 The finely dashed, horizontal lines represent the maximum power from the primary current source $\bar{P}_s$ at 50 km/h, the coarse dashed lines represent the required power P_{req} .

It can be seen without further ado from the illustrations that the braking resistance is not used in the energy-oriented operating strategy (FIG. 4A), whereas it is used in the battery-health-oriented operating strategy (FIG. 4B) in order to avoid excessively high charging
 25 powers of more than approximately 180 kW.

- In the energy-oriented operating strategy (FIG. 4A), the energy draw from the overhead line takes place in a uniform manner, with maximum powers which are significantly lower than those in the battery-health-oriented operating strategy (FIG. 4B). This avoids energy losses on account of the significantly higher resistance of the overhead line compared with the internal resistance of the traction battery. If the overhead line can deliver sufficient power in the battery-health-oriented operating strategy in order to cover the demand (here up to approximately 130 kW), the energy demand is here primarily covered by the overhead line and the traction battery is primarily used if higher powers are required.
- 10 In the example shown, the battery-health-oriented operating strategy results in a reduction in the battery degradation by 31.4% and in an increased overall energy consumption of 5.1%.

The operating method according to the invention was tested in the context of a plurality of simulations. One of the simulations was based on 16 different driving missions on four different bus routes, the relevant characteristics of which were determined by measurements on a real vehicle. The routes had different availabilities of electrical energy from overhead lines, between approximately 50% and 100% of the distance travelled on. The routes were also distinguished by different altitude differences and maximum speeds which can be driven. The selection of the driving missions additionally covered all seasons and thus various uses of the HVAC system. The missions were defined by data with a time resolution of 1 s.

FIG. 5 shows the results of a lifetime simulation, the results of the method according to the invention being compared with those of a method without regular recalibration. The lifetime simulation was based on the following scenario:

- SOH measurements are carried out in each case after 180 missions, that is to say after approximately 6 months.
 - The SOH measurements are superimposed with Gaussian-distributed noise (mean value 0, standard deviation $\sigma = 0.001$).
- 5 - The target state of health at 1.2 million travel kilometers is 80%.
- In a first operating phase, the simulated trolley bus is used on three routes, with a network coverage of 90-100%. After approximately 0.3 million km, the bus is used for 0.1 million km on a route with a network coverage of only approximately 50%. The previous route selection is then used again.
- 10 The results of a simulation with active recalibration according to the invention and, in comparison therewith, the results of a simulation without regular recalibration are now illustrated in FIG. 5. The three illustrations (a)-(c) show the curve of various parameters as a function of the driving distance d (in million km). The value of the battery health (SOH) Ψ is illustrated in the uppermost illustration (a). The circles correspond to the periodic
- 15 SOH measurements 81. The curve 82 (solid line) shows the effective curve of the battery health with active recalibration. It should be noted that this value is effectively known in the real application of the operating method according to the invention only at the times of the SOH measurements 81. Between these times, the operation is carried out based on an estimation 83 (dashed line). The reference curve 84 (dotted line) is updated with
- 20 each SOH measurement. As can be readily seen from FIG. 5 (a), all these curves are close to one another and, with the desired service life of the traction battery of 1.2 million km, the traction battery has a state of health of 80.3%, very close to the specification of 80%.
- Without recalibration, the battery health is permanently underestimated in the case illustrated, because the degradation is overestimated. This is because the degradation is
- 25 then estimated according to the approximation (7) which does not take into account

effects dependent on the depth of discharge (DOD). In addition, the most influential scaling factor $\zeta_{cyc,C}$ is approximated by a piecewise linear function for positive and negative rates of C. This results in an actual curve 86 (solid line) (unknown in the real case) and the battery health at 1.2 million travel kilometers is over 85%. Analogously thereto, the required overall energy was 8.8% higher than in the context of the operating method according to the invention. The estimation 87 (dashed line) and the reference curve 88 (dotted line) run significantly lower in this case than in the case with recalibration, but are not able to compensate for the estimation errors which continuously add up during the simulation, and the difference from the actual SOH continuously increases.

The curve 101 of the parameter γ with recalibration and the curve 102 of the parameter γ without recalibration are illustrated in the lowermost illustration (c) of FIG. 5. It is shown that it settles at values of 0.6-0.8 and corrects the estimated degradation correspondingly downward. By contrast, the parameter γ (trivially) remains at a value of 1 in a simulation without recalibration.

The curves of the equivalence factor s_ψ for the battery health (in J) with recalibration (curve 111) and without recalibration (curve 112) are illustrated in the middle illustration (b) of FIG. 5. On account of the correction of the overestimated battery degradation, significantly lower values of the equivalence factor for the battery health can be selected in the first case than in the case without correction. In the second case, a large weight is continuously assigned to the protection of the battery, the increased battery aging within the interval cannot be completely compensated for in the stressful operating interval between 0.3 and 0.4 million km, but the compensation takes place reliably in the model with recalibration after the return to the previous route selection. This shows that, when a fleet with a plurality of vehicles operated according to the invention is included, the

different loads associated with the operation on different routes can be compensated for in the long term by a targeted route allocation of the vehicles.

Further simulations have shown that, on account of the regular determinations of the effective state of health of the traction battery, the recalibration of the degradation
5 estimations and the recalculation of the reference curves, the method according to the invention also reliably takes account of further influences, for example incorrect estimations of the calendar degradation or a sudden drop in the state of health, for example on account of relatively long downtimes or improper handling with the battery.

The invention is not restricted to the exemplary embodiment shown. Thus, the method
10 can be extended with further control parameters, for example with regard to charging in the stationary state (for example in the depot between driving missions) and/or the control of the HVAC system or further components. The method is additionally applicable not only to trolley buses, but also, for example, to hybrid vehicles or purely electric vehicles with stationary charging operations.

15 In summary, it can be stated that the invention provides a method for optimizing the service life of a traction battery of a vehicle, which method ensures that a predefined service life of the traction battery is achieved with minimized disadvantageous effects on the overall energy consumption and/or the user comfort.

Claims

1. Method for optimizing the service life of a traction battery of a vehicle, comprising the following steps:
 - 5 a) determining an effective state of health of the traction battery with a first periodicity;
 - b) determining an estimated state of health of the traction battery with a second periodicity, starting from a last determined effective state of health, taking into account usage data of the vehicle since a last determination of the estimated state of health, by applying an aging model for the traction battery;
 - 10 c) operating the vehicle on the basis of the estimated state of health and a current traction energy demand, wherein at least one battery load-relevant control parameter is newly determined with at least a third periodicity;

wherein the aging model for the traction battery is calibrated after determining the effective state of health.
- 15 2. The method according to claim 1, characterized in that the control parameter is determined on the basis of a deviation of the estimated state of health from a reference curve.
3. The method according to claim 2, characterized in that the reference curve is determined in such a way that the traction battery has a predefined state of health at
 - 20 a predefined mileage.
4. The method according to claim 2 or 3, characterized in that the reference curve is newly calculated after determining the effective state of health.

5. The method according to any of claims 1 to 4, characterized in that the usage data taken into account for determining the estimated state of health comprise a curve of a battery charge state since the last determination.
6. The method according to any of claims 1 to 5, characterized in that, for calibrating
5 the aging model, the estimated state of health of the traction battery is compared with the determined effective state of health at the time of determining the effective state of health.
7. The method according to any of claims 1 to 6, characterized in that, for determining the control parameter, an optimization is carried out with regard to a maximization
10 of a first target variable corresponding to a service life of the traction battery.
8. The method according to claim 7, characterized in that, with regard to the maximization of the first target variable, an influence of operating parameters on the state of health of the traction battery is determined on the basis of the usage data of the vehicle and the determined effective state of health.
- 15 9. The method according to any of claims 1 to 8, characterized in that, for determining the control parameter, an optimization is carried out with regard to a minimization of a second target variable corresponding to an energy consumption of the vehicle.
10. The method according to claims 2, 7 or 8, and 9, characterized in that, depending on the deviation of the estimated state of health from the reference curve, a weighting
20 of the first and the second target variable is adapted in the optimization.
11. The method according to any of claims 1 to 10, wherein a first period of the first periodicity is longer than a second period of the second periodicity and wherein the second period is longer than the third period of the third periodicity and wherein in particular

- the first period is 14 days to 400 days,
- the second period is 1 hour to 24 hours, and/or
- the third period is 0.1 to 10 s.

12. The method according to any of claims 1 to 11, characterized in that the vehicle is a
5 battery-electric vehicle.

13. The method according to claim 12, characterized in that the vehicle comprises a
current collector in order to receive electrical energy from an overhead line during a
driving operation.

14. The method according to any of claims 1 to 13, characterized in that the vehicle is
10 used in a line operation and predicted driving data of a line travelled on or to be
travelled on are taken into account in the determination of the control parameter.

15. The method according to any of claims 1 to 14, characterized in that the control
parameter comprises one or more of the following parameters:

- a) a state of charge;
- 15 b) a charging power;
- c) a retrieved power from the traction battery;
- d) a maximum acceleration of the vehicle;
- e) a maximum recuperation current of the vehicle;
- f) a consumption power for a braking resistance;
- 20 g) an operating parameter of a heating, ventilation and/or air conditioning system
of the vehicle;

- h) an operating parameter of an interior lighting and/or of an interior information system and/or of other ancillary consumers of the vehicle;
- i) an operating parameter of a thermal management system for the drive battery.

16. Arrangement for operating an electrically operated vehicle, comprising

- 5 a) the electrically operated vehicle with a drive battery for driving at least one drive assembly of the vehicle; and
- b) a measuring device for determining an effective state of health of the traction battery of the vehicle;

wherein the vehicle comprises the following:

- 10 c) a processing device for determining an estimated state of health of the traction battery;
- d) a calibration device;
- e) a vehicle controller for operating the vehicle;

wherein

- 15 - the processing device is configured to receive the last determined effective state of health from the measuring device, to receive usage data of the vehicle from the vehicle controller and to determine the estimated state of health starting from the effective state of health and taking into account the usage data since a last determination of the estimated state of health, by applying an aging
- 20 model for the traction battery;
- the calibration device is configured to calibrate the aging model on the basis of the determined effective state of health received by the arrangement; and

- the vehicle controller is configured to determine at least one battery load-relevant control parameter on the basis of the estimated state of health and a current traction energy demand.