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(54) TRACTION BATTERY CONTROLLER EMPLOYING REFINED STATE-OF-CHARGE UNCERTAINTY BOUND IN ESTIMATING CAPACITY OF TRACTION BATTERY

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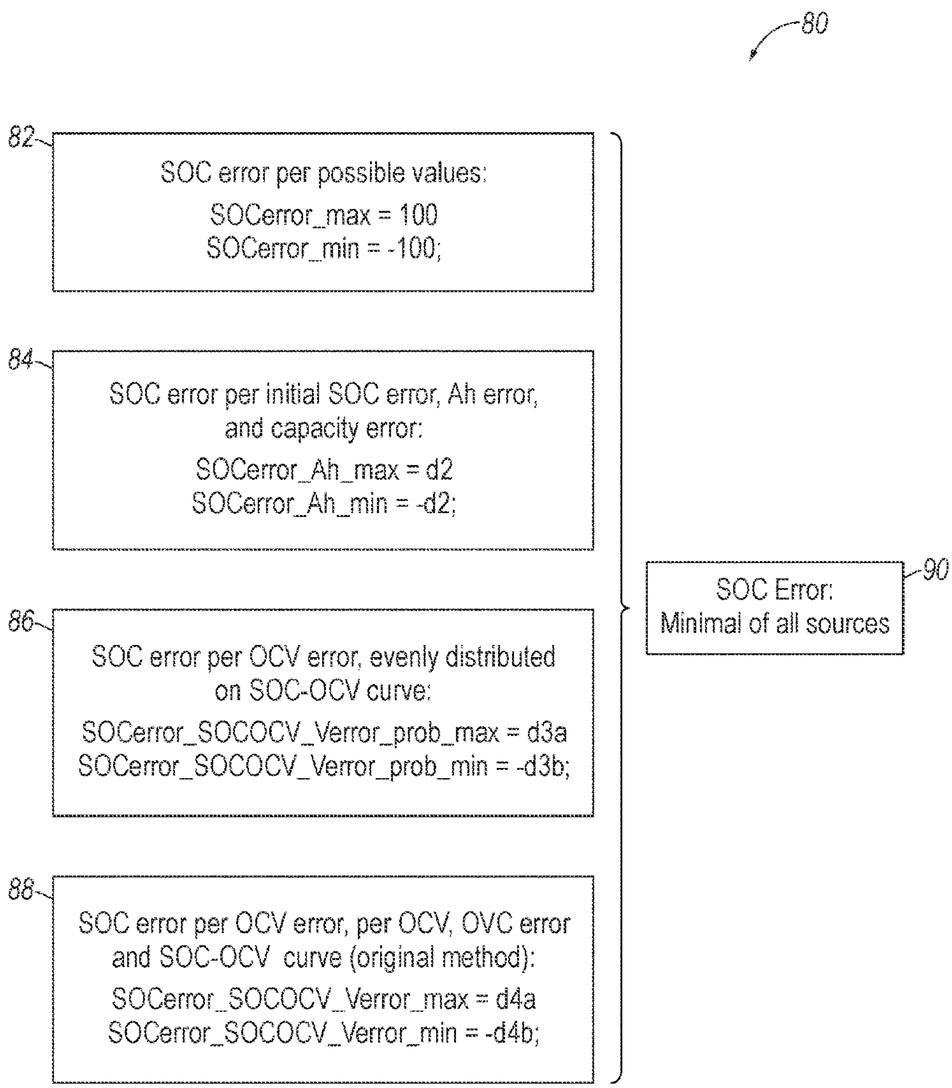
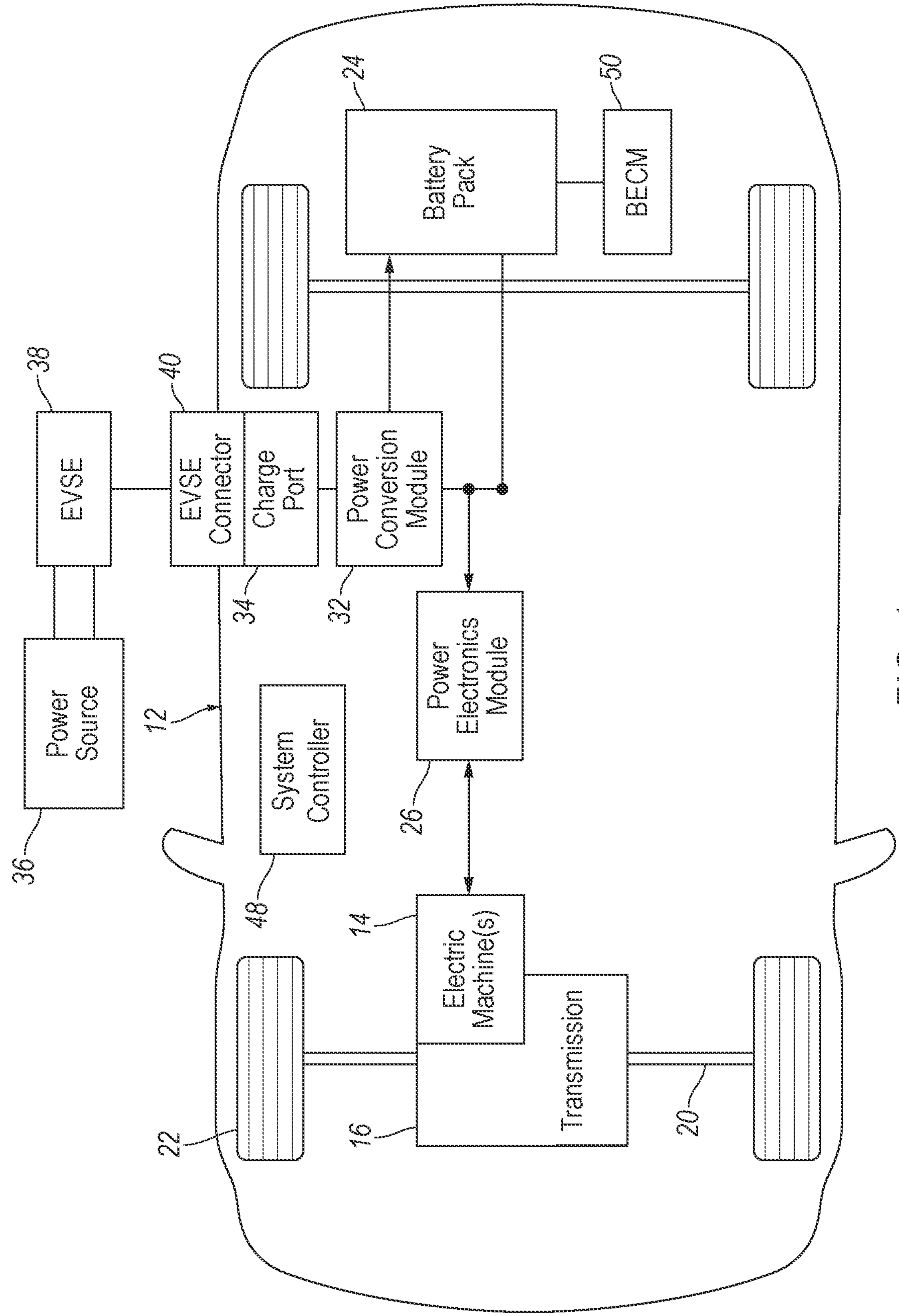
(57) ABSTRACT

A system includes a battery and a controller. The battery has a state-of-charge (SOC) with a SOC uncertainty. The controller is configured to charge and discharge the battery based on a capacity of the battery according to the SOC with a bound of the SOC uncertainty. The bound of the SOC uncertainty is based on consideration of multiple SOC uncertainty factors to thereby be reduced relative to being based on consideration of less than all of the SOC uncertainty factors.





Battery Pack
24
BECM
50
EVSE
38
EVSE Connector
40
Charge Port
34
Power Conversion Module
32
Power Source
36
12
System Controller
48
Power Electronics Module
26
Electric Machine(s)
14
Transmission
16
20
22

FIG. 1

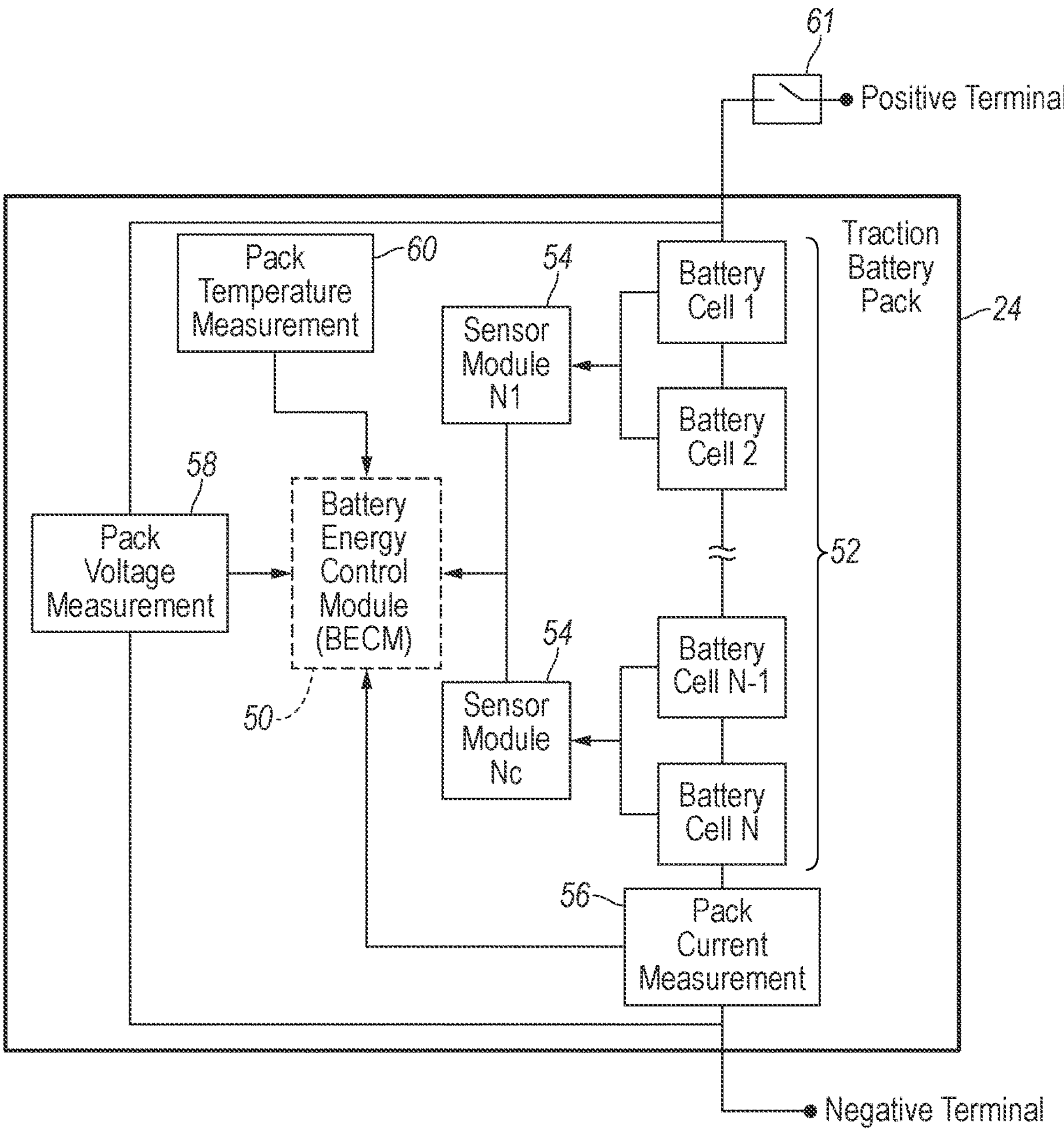

61
Positive Terminal
Traction Battery Pack
24
Pack Temperature Measurement
60
54
Sensor Module N1
Battery Cell 1
Battery Cell 2
58
Pack Voltage Measurement
Battery Energy Control Module (BECM)
52
50
54
Sensor Module Nc
Battery Cell N-1
Battery Cell N
56
Pack Current Measurement
Negative Terminal

FIG. 2

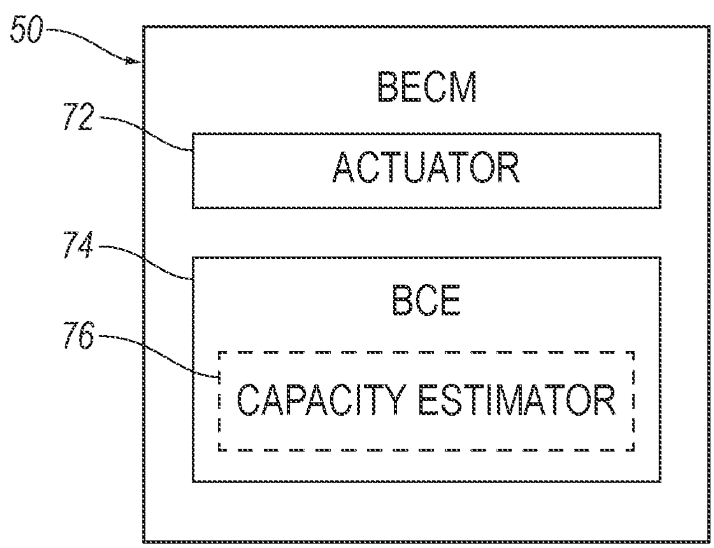


FIG. 3

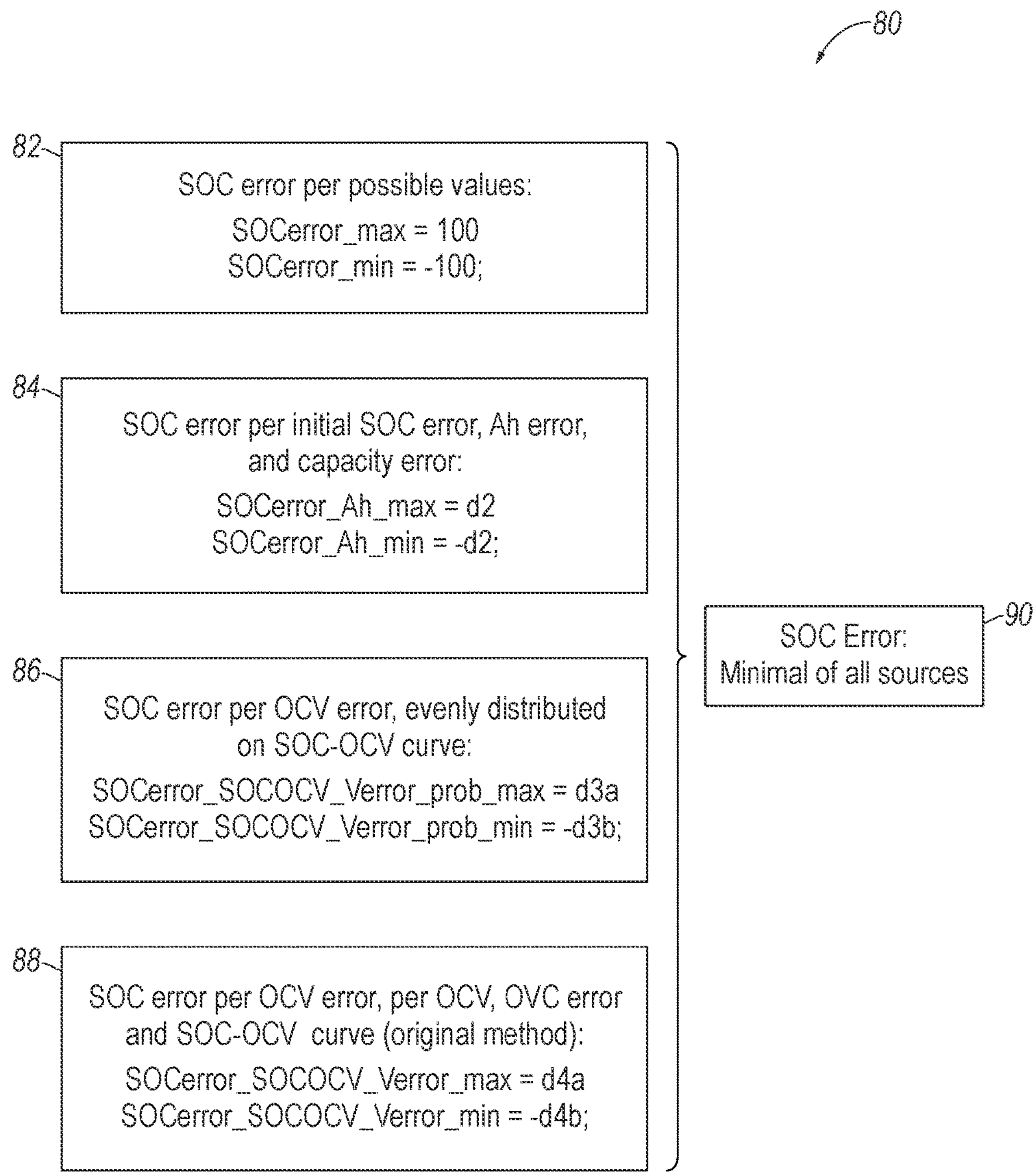

80
82
SOC error per possible values:
SOCerror_max = 100
SOCerror_min = -100;
84
SOC error per initial SOC error, Ah error, and capacity error:
SOCerror_Ah_max = d2
SOCerror_Ah_min = -d2;
86
SOC error per OCV error, evenly distributed on SOC-OCV curve:
SOCerror_SOCOCV_Verror_prob_max = d3a
SOCerror_SOCOCV_Verror_prob_min = -d3b;
88
SOC error per OCV error, per OCV, OVC error and SOC-OCV curve (original method):
SOCerror_SOCOCV_Verror_max = d4a
SOCerror_SOCOCV_Verror_min = -d4b;
90
SOC Error:
Minimal of all sources

FIG. 4

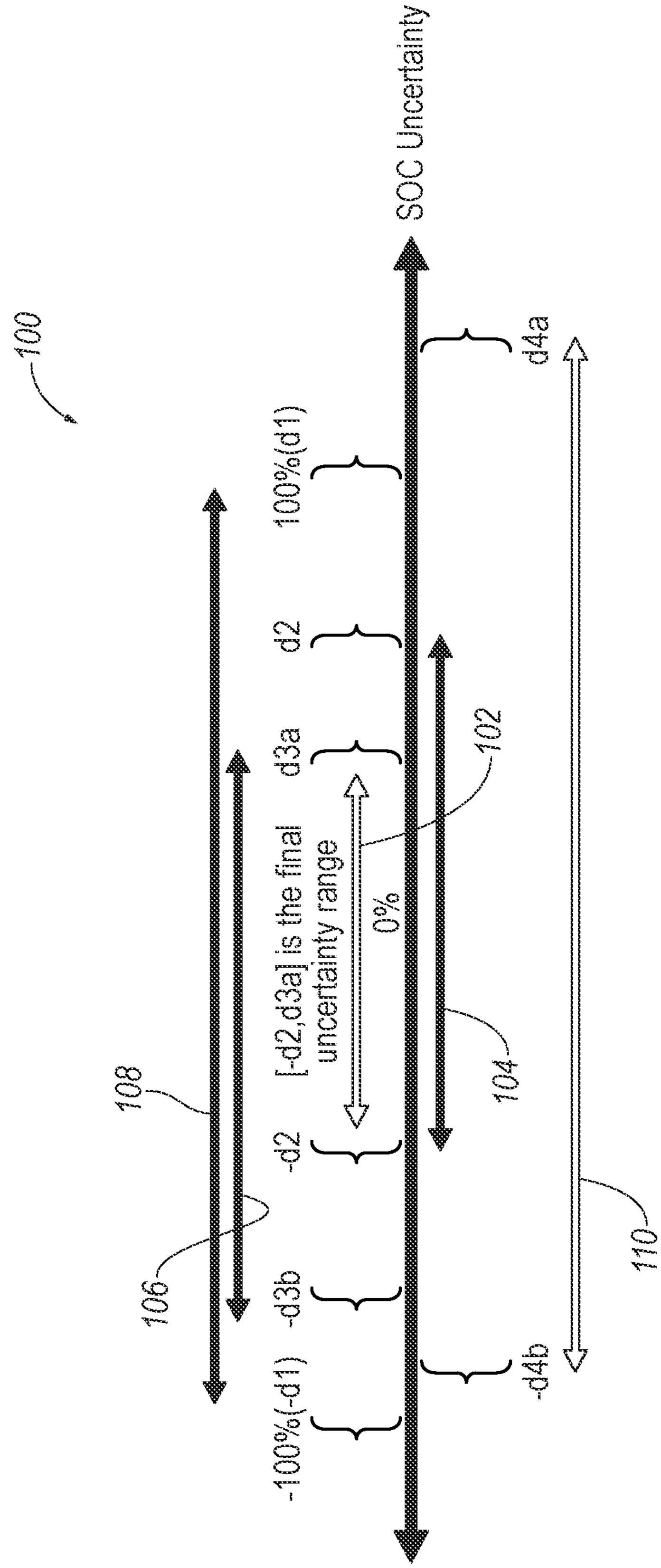

100
SOC Uncertainty
d4a
100%(d1)
d2
d3a
102
[-d2,d3a] is the final
uncertainty range
0%
104
108
-d2
106
-d3b
110
-100%(-d1)
-d4b

FIG. 5

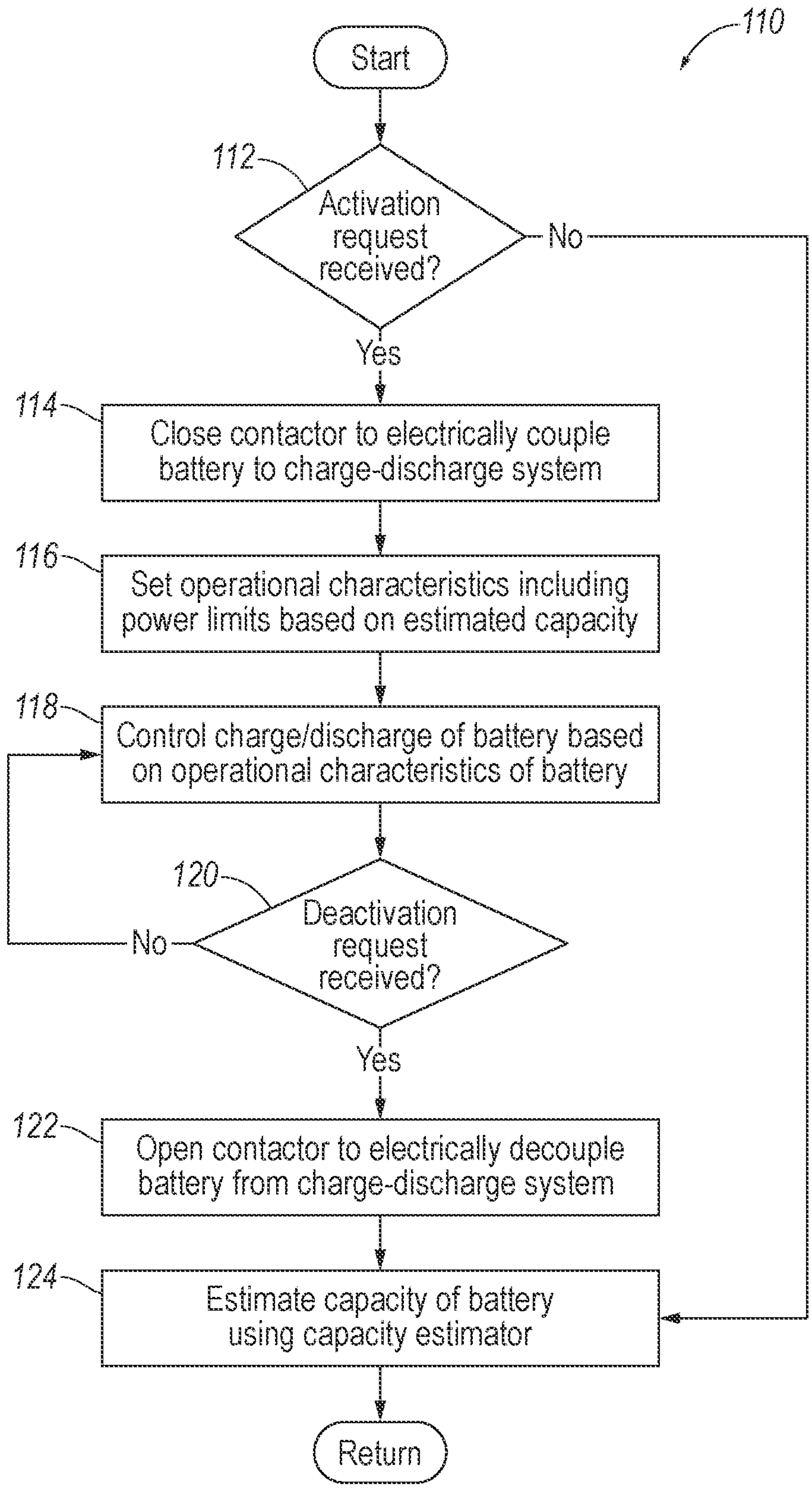

110
Start
112
Activation request received?
No
Yes
114
Close contactor to electrically couple battery to charge-discharge system
116
Set operational characteristics including power limits based on estimated capacity
118
Control charge/discharge of battery based on operational characteristics of battery
120
Deactivation request received?
No
Yes
122
Open contactor to electrically decouple battery from charge-discharge system
124
Estimate capacity of battery using capacity estimator
Return

FIG. 6

TRACTION BATTERY CONTROLLER EMPLOYING REFINED STATE-OF-CHARGE UNCERTAINTY BOUND IN ESTIMATING CAPACITY OF TRACTION BATTERY

TECHNICAL FIELD

[0001] The present disclosure relates to detecting a capacity of a traction battery of an electrified vehicle for use in controlling the operation of the traction battery and/or the vehicle.

BACKGROUND

[0002] An electrified vehicle includes a traction battery for providing power to a motor of the vehicle to propel the vehicle. Operating characteristics of the traction battery, such as its charge capacity, may be monitored for use in controlling the operation of the traction battery and/or the vehicle.

SUMMARY

[0003] A system includes a battery and a controller. The battery has a state-of-charge (SOC) with a SOC uncertainty. The controller is configured to charge and discharge the battery based on a capacity of the battery according to the SOC with a bound of the SOC uncertainty. The bound of the SOC uncertainty (i.e., the SOC uncertainty bound) is based on consideration of multiple SOC uncertainty factors to thereby be reduced relative to being based on consideration of less than all of the SOC uncertainty factors.

[0004] In embodiments, each SOC uncertainty factor is associated with its own bound of the SOC uncertainty. The bound of the SOC uncertainty is the smallest bound of the SOC uncertainty factors.

[0005] In embodiments, each SOC uncertainty factor is associated with its own bound of the SOC uncertainty and the bound of each SOC uncertainty factor is a range between a negative value and a positive value. The bound of the SOC uncertainty is a range between (i) the negative value having a lowest magnitude amongst the negative values and (ii) the positive value having a lowest magnitude amongst the positive values.

[0006] A first one of the SOC uncertainty factors may be indicative of the SOC uncertainty based on an uncertainty of a voltage measurement of the battery and a SOC-OCV (open-circuit voltage) table that are used together in estimating the SOC. The bound of the SOC uncertainty is reduced relative to being based on consideration of just the first one of the SOC uncertainty factors. Another one of the SOC uncertainty factors may be indicative of the SOC uncertainty based on a range of an amount of SOC uncertainty that is physically possible. Another one of the SOC uncertainty factors may be indicative of the SOC uncertainty based on an uncertainty of an ampere-hour integration measurement that is used in estimating the SOC. Another one of the SOC uncertainty factors may be indicative of the SOC uncertainty based on distributed voltage measurements of the battery that are used in estimating the SOC. Another one of the SOC uncertainty factors may be indicative of the SOC uncertainty based on an uncertainty pertaining to differences of a SOC-OCV (open-circuit voltage) table at different voltage measurements in which the SOC-OCV table with the different voltage measurements are used in estimating the SOC.

[0007] A method includes detecting a SOC of a battery, estimating an uncertainty of the SOC based on consideration of multiple SOC uncertainty factors, and detecting a capacity of the battery according to the SOC with the estimated SOC uncertainty. The estimated SOC uncertainty is reduced relative to an uncertainty of the SOC estimated based on consideration of less than all of the SOC uncertainty factors such that the capacity has reduced uncertainty. The method further includes charging and discharging the battery based on the capacity.

[0008] An electrified vehicle includes a traction battery and a controller. The controller is configured to detect a SOC of the traction battery and to estimate an uncertainty of the SOC based on consideration of multiple SOC uncertainty factors. The estimated SOC uncertainty is reduced relative to an uncertainty of the SOC estimated based on consideration of less than all of the SOC uncertainty factors. The controller is configured to charge and discharge the traction battery based on a capacity of the traction battery according to the SOC with the estimated SOC uncertainty.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** illustrates a block diagram of a battery electric vehicle (BEV);

[0010] FIG. **2** illustrates a block diagram of an arrangement for a traction battery controller of the BEV to monitor a traction battery of the BEV;

[0011] FIG. **3** illustrates a block diagram of the traction battery controller, the traction battery controller including a capacity estimator for estimating a capacity of the traction battery according to a state-of-charge (SOC) of the traction battery;

[0012] FIG. **4** illustrates a block diagram depictive of SOC uncertainty factors considered by the traction battery controller in estimating an SOC uncertainty bound for the SOC of the traction battery;

[0013] FIG. **5** illustrates a graph of exemplary values for the SOC uncertainty factors considered by the traction battery controller in estimating the SOC uncertainty bound; and

[0014] FIG. **6** illustrates a flowchart depicting operation of the traction battery controller in controlling the traction battery and/or the vehicle based on the capacity of the traction battery according to the SOC of the traction battery with the estimated SOC uncertainty bound.

DETAILED DESCRIPTION

[0015] Detailed embodiments of the present disclosure are disclosed herein; however, it is to be understood that the disclosed embodiments are merely exemplary of the present disclosure that may be embodied in various and alternative forms. The figures are not necessarily to scale; some features may be exaggerated or minimized to show details of particular components. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the present disclosure.

[0016] Referring now to FIG. **1**, a block diagram of an electrified vehicle (EV) **12** in the form of a battery electric vehicle (BEV) is shown. BEV **12** includes a powertrain having one or more traction motors ("electric machine(s)") **14**, a traction battery ("battery" or "battery pack") **24**, and a power electronics module **26** (e.g., an inverter). In the BEV configuration, traction battery **24** provides all of the propulsion power and the vehicle does not have an engine. In other variations, the EV may be a plug-in or regular hybrid electric vehicle (PHEV, HEV) further having an engine.

[0017] Traction motor **14** is part of the powertrain of BEV **12** for powering movement of the BEV. In this regard, traction motor **14** is mechanically connected to a transmission **16** of BEV **12**. Transmission **16** is mechanically connected to a drive shaft **20** that is mechanically connected to wheels **22** of BEV **12**. Traction motor **14** can provide propulsion capability to BEV **12** and is capable of operating as a generator. Traction motor **14** acting as a generator can recover energy that may normally be lost as heat in a friction braking system of BEV **12**.

[0018] Traction battery **24** stores electrical energy that can be used by traction motor **14** for propelling BEV **12**. Traction battery **24** typically provides a high-voltage (HV) direct current (DC) output. Traction battery **24** is electrically connected to power electronics module **26**. Traction motor **14** is also electrically connected to power electronics module **26**. Power electronics module **26**, such as an inverter, provides the ability to bi-directionally transfer energy between traction battery **24** and traction motor **14**. For example, traction battery **24** may provide a DC voltage while traction motor **14** may require a three-phase alternating current (AC) current to function. Inverter **26** may convert the DC voltage to a three-phase AC current to operate traction motor **14**. In a regenerative mode, inverter **26** may convert three-phase AC current from traction motor **14** acting as a generator to DC voltage compatible with traction battery **24**.

[0019] In addition to providing electrical energy for propulsion of BEV **12**, traction battery **24** may provide electrical energy for use by other electrical systems of the BEV including HV loads such as electric heater and air-conditioner systems, and low-voltage (LV) loads such as an auxiliary battery.

[0020] Traction battery **24** is rechargeable by an external power source **36** (e.g., the grid). External power source **36** may be electrically connected to electric vehicle supply equipment (EVSE) **38**. EVSE **38** provides circuitry and controls to control and manage the transfer of electrical energy between external power source **36** and BEV **12**. External power source **36** may provide DC or AC electric power to EVSE **38**. EVSE **38** may have a charge connector **40** for plugging into a charge port **34** of BEV **12**. A power conversion module **32** of EV **12**, such as an on-board charger having a DC/DC converter, may condition power supplied from EVSE **38** to provide the proper voltage and current levels to traction battery **24**. Power conversion module **32** may interface with EVSE **38** to coordinate the delivery of power to traction battery **24**.

[0021] The various components described above may have one or more associated controllers to control and monitor the operation of the components. The controllers can be microprocessor-based devices. The controllers may communicate via a serial bus (e.g., Controller Area Network (CAN)) or via discrete conductors.

[0022] For example, a system controller **48** ("vehicle controller") is present to coordinate the operation of the various components. Controller **48** includes electronics, software, or both, to perform the necessary control functions for operating BEV **12**. Controller **48** may be a combination vehicle system controller and powertrain control module (VSC/PCM). Although controller **48** is shown as a single device, controller **48** may include multiple controllers in the form of multiple hardware devices, or multiple software controllers with one or more hardware devices. In this regard, a reference to a "controller" herein may refer to one or more controllers.

[0023] Controller **48** implements a battery energy control module (BECM) **50**. BECM **50** is in communication with traction battery **24**. BECM **50** is a traction battery controller operable for managing the charging and discharging of traction battery **24** and for monitoring operating characteristics of the traction battery. BECM **50** is operable to implement algorithms to detect (e.g., estimate) the operating characteristics of traction battery **24**. BECM **50** controls the operation and performance of traction battery **24** based on the operating characteristics of the traction battery. The operation and performance of other systems and components of BEV **12** may be controlled by BECM **50** and/or other controllers of the BEV based on the operating characteristics of traction battery **24**.

[0024] Operating characteristics of traction battery **24** include its charge capacity ("capacity") and its state-of-charge (SOC). The capacity of traction battery **24** is indicative of the maximum amount of electrical energy that the traction battery may store. The SOC of traction battery **24** is indicative of a present amount of electrical charge stored in the traction battery. The SOC of traction battery **24** may be represented as a percentage of the maximum amount of electrical charge that may be stored in the traction battery (i.e., as a percentage of the capacity). BECM **50** may output the SOC of traction battery **24** to inform the driver of BEV **12** how much charge remains in the traction battery, similar to a fuel gauge.

[0025] Another operating characteristic of traction battery **24** is its power capability. The power capability of traction battery **24** is a measure of the maximum amount of power the traction battery can provide (i.e., discharge) or receive (i.e., charge) for a specified time period. As such, the power capability of traction battery **24** corresponds to discharge and charge power limits which define the amount of electrical power that may be supplied from or received by the traction battery at a given time. These limits can be provided to other vehicle controls, for example, through a vehicle system controller (VSC), so that the information can be used by systems that may draw power from or provide power to traction battery **24**. Vehicle controls are to know how much power traction battery **24** can provide (discharge) or take in (charge) in order to meet the driver demand and to optimize the energy usage. As such, knowing the power capability of traction battery **24** allows electrical loads and sources to be managed such that the power requested is within the limits that the traction battery can handle.

[0026] Referring now to FIG. **2**, with continual reference to FIG. **1**, a block diagram of an arrangement for BECM **50** to monitor traction battery **24** is shown. As indicated in FIG. **2**, traction battery **24** is comprised of a plurality of battery cells **52**. Battery cells **52** are physically connected together (e.g., connected in series as shown in FIG. **2**) between a positive terminal (i.e., a positive power bus) and a negative terminal (i.e., a negative power bus). More generally, traction battery **24** comprises one or more battery cell modules that are electrically connected together, and each battery cell module comprises one or more battery cells **52** that are electrically connected together. For simplicity of discussion, it is assumed that the battery cell module(s) are connected in series and that battery cells **52** are connected in series.

[0027] BECM **50** is operable to monitor pack level (i.e., traction battery level) characteristics of traction battery **24** such as battery current **56**, battery voltage **58**, and battery temperature **60**. Battery current **56** is the current outputted (i.e., discharged) from or inputted (i.e., charged) to traction battery **24**. Battery voltage **58** is the terminal voltage of traction battery **24**.

[0028] BECM **50** is also operable to measure and monitor battery cell level characteristics of battery cells **52** of traction battery **24**. For example, terminal voltage, current, and temperature of one or more of battery cells **52** may be measured. BECM **50** may use a battery sensor **54** to measure the battery cell level characteristics. Battery sensor **54** may measure the characteristics of one or multiple battery cells **52**. BECM **50** may utilize Nc battery sensors **54** to measure the characteristics of all battery cells **52**. Each battery sensor **54** may transfer the measurements to BECM **50** for further processing and coordination. Battery sensor **54** functionality may be incorporated internally to BECM **50**.

[0029] Traction battery **24** may have one or more temperature sensors such as thermistors in communication with BECM **50** to provide data indicative of the temperature of battery cells **52** of the traction battery for the BECM to monitor the temperature of the traction battery and/or the battery cells. BEV **12** may further include a temperature sensor to provide data indicative of ambient temperature for BECM **50** to monitor the ambient temperature.

[0030] BECM **50** controls the operation and performance of traction battery **24** based on the monitored traction battery and battery cell level characteristics. For instance, BECM **50** may use the monitored characteristics to detect operating characteristics of traction battery **24** (e.g., the capacity, the SOC, the power capability, etc., of the traction battery) such as for use in controlling the traction battery and/or BEV **12**.

[0031] As shown in FIG. **2**, one or more contactors **61** is provided to inhibit or permit electric current from traveling through the power buses to/from traction battery **24**. Specifically, contactors **61** are operable to electrically decouple traction battery **24** from/to a charge/discharge system of BEV **12**. The charge/discharge system includes components that either charge traction battery **24** or act as a load to draw electric power from the traction battery. Thus, the charge/discharge system may include inverter **26** and power conversion module **32** among other components. Contactors **61** may be placed in various suitable positions in BEV **12**, such as between the positive power bus and inverter **26**.

[0032] BECM **50** is configured to open or close contactors **61** based on a message/request from controller **48**. Controller **48** is configured to detect when BEV **12** is to be turned ON (i.e., key on) or OFF (i.e., key off) based on an activation input (e.g., a user pressing a button associated with activating/deactivating the BEV). When BEV **12** is to be turned ON, controller **48** provides an activation request to BECM **50** to close contactors **61**, thereby coupling traction battery **24** to the charge/discharge system. When BEV **12** is to be turned OFF, controller **48** provides a deactivation request to BECM **50** to open contactors **61**, thereby decoupling traction battery **24** from the charge/discharge system. In addition, controller **48** is configured to have BECM **50** close contactors **61** by sending the activation request when traction battery **24** is to be charged or to be discharged. Likewise, controller **48** is configured to have BECM **50** open contactors **61** by sending the deactivation request when traction battery **24** is not to be charged or discharged.

[0033] Referring now to FIG. **3**, a block diagram of BECM **50** is shown. BECM **50** includes an actuator **72** for operating contactors **61** in the closed/opened positions. BECM **50** further includes a battery characteristics estimator (BCE) **74**. BCE **74** is configured to estimate operational characteristics of traction battery **24** including the capacity, the SOC, and the power capability of the traction battery. BCE **74** includes a capacity estimator **76** to estimate the capacity of traction battery **24**. The operation carried out by BCE **74** (more generally, BECM **50**) in estimating the capacity of traction battery **24** will now be described.

[0034] The capacity Q of traction battery **24** can be estimated as follows:

$$Q = \frac{\sum I\Delta t}{(SOC_i - SOC_f)} \tag{1}$$

[0035] I is the current of traction battery **24**, Δt is is the sampling time, SOC_i is the initial SOC of the traction battery, and SOC_f is the final SOC of the traction battery.

[0036] Per the equation (1), the estimate of the capacity of traction battery **24** depends on the SOC of the traction battery. Accordingly, if the SOC of traction battery **24** is known well enough (particularly, if each of the initial SOC and the final SOC are known well enough), then the estimated capacity will be accurate. Conversely, if the SOC of traction battery **24** is not known well enough, then the estimated capacity will not be as accurate. That is, the accuracy of the estimation of the capacity depends on the accuracy of the SOC.

[0037] The accuracy of the SOC depends on the amount of uncertainty (i.e., error) of the SOC. A SOC having less uncertainty has a higher accuracy than a SOC having a high uncertainty. As such, SOC uncertainty is an important component in estimating battery capacity. The charging and discharging of traction battery **24** is controlled depending on operational characteristics of the traction battery including its capacity and/or other operational characteristics dependent on the capacity. Thus, accurate capacity estimation is highly desired and therefore estimation of the SOC with less uncertainty is highly desired. In general, SOC uncertainty estimation influences the overall capacity estimation to link a tighter bound to better capacity estimation accuracy, faster updating rate, better DTE (distance-to-empty) and power charge/discharge limits calculations, etc.

[0038] An existing method of simply using a SOC-OCV (open-circuit voltage) curve slope and voltage measurement error to estimate the SOC is normally not the best representation of the real SOC uncertainty. Accordingly, in this case, the capacity estimation may not be most accurate. For instance, the capacity estimation, such as using an adaptive filter approach, may not utilize individual capacity estimation efficiently because the filtering weight depends on SOC uncertainty estimation, among other factors.

[0039] The capacity with an overall estimation uncertainty (or error) bound can be expressed as:

$$Q = \frac{\sum I\Delta t}{(SOC_i - SOC_f)} \pm \left(\frac{\sum I\Delta t}{(SOC_i - SOC_f)}\right) \sqrt{\left(\frac{U(\sum I\Delta t)}{\sum I\Delta t}\right)^2 + \left(\frac{\sqrt{U(SOC_i)^2 + U(SOC_f)^2}}{(SOC_i - SOC_f)}\right)^2} \quad (2)$$

[0040] The equation (2) is a summation of the capacity estimation from the equation (1) and an overall capacity uncertainty bound U(Q) that is represented by the following equation:

$$U(Q) = \pm\left(\frac{\sum I\Delta t}{(SOC_i - SOC_f)}\right) \sqrt{\left(\frac{U(\sum I\Delta t)}{\sum I\Delta t}\right)^2 + \left(\frac{\sqrt{U(SOC_i)^2 + U(SOC_f)^2}}{(SOC_i - SOC_f)}\right)^2} \quad (3)$$

[0041] The overall capacity uncertainty bound U(Q) is the amount of uncertainty (e.g., tolerance) of the capacity estimation.

[0042] The equation (2) pertains to a methodology to estimate both the capacity Q and the uncertainty in the capacity estimation U(Q).

[0043] The overall capacity uncertainty bound U(Q) provides an overall estimation error bound for capacity estimation. As set forth in the equation (3), the overall capacity uncertainty bound U(Q) includes the previously introduced factors: ΣIΔt, which is the integration of current (net ampere-hour throughput) of traction battery **24** between contactor close event #1 and contactor close event #2; SOC_i, which is the SOC at the contactor close event #2; and SOC_f, which is SOC at the contactor close event #1. ΣIΔt is measured by sensing the current during the two close events. SOC_i, and SOC_f, which depend on the voltage and temperature of traction battery **24**, are obtained via a SOC-OCV lookup table.

[0044] As further set forth in the equation (3), the overall capacity uncertainty bound U(Q) further includes the following factors: U(ΣIΔt), which is the uncertainty in the net ampere-hour throughput measurement; $U(SOC_i)$, which is the uncertainty in the SOC-OCV lookup at contactor close event #2; and $U(SOC_f)$, which is the uncertainty in the SOC-OCV lookup at contactor close event #1.

[0045] From the above equations, a ratio of the overall capacity uncertainty bound U(Q) to the capacity Q as a percentage is represented by the following equation:

$$\frac{U(Q)}{Q} = 100 * \sqrt{\left(\frac{U(\sum I\Delta t)}{\sum I\Delta t}\right)^2 + \left(\frac{\sqrt{U(SOC_i)^2 + U(SOC_f)^2}}{(SOC_i - SOC_f)}\right)^2} \quad (4)$$

[0046] As set forth, the amount of the overall capacity uncertainty bound U(Q) depends on the amount of uncertainty in the uncertainty components U(ΣIΔt), $U(SOC_i)$, and $U(SOC_f)$.

[0047] In accordance with the present disclosure, BECM **50** is operable to reduce the amount of uncertainty in the uncertainty components $U(SOC_i)$ and $U(SOC_f)$. That is, BECM **50** is operable to estimate a tighter bound for SOC error and thereby reduce the SOC uncertainty. The SOC uncertainty "U(SOC)", or the SOC uncertainty bound, is the amount of uncertainty of $U(SOC_i)$ and $U(SOC_f)$ taken individually and/or in combination. BECM **50** estimates a tighter (i.e., refined) SOC uncertainty bound for more accurate estimation of the capacity of traction battery **24**.

[0048] As indicated above, an existing method for SOC uncertainty estimation involves simply using a SOC-OCV curve slope and voltage measurement error to estimate the SOC. In this regard, the SOC uncertainty U(SOC) is calculated using the slope from the SOC-OCV curve at the given OCV estimation with consideration of the uncertainty in the OCV and the SOC. This is represented by the following equation:

$$\Delta SOC = \frac{\partial SOC}{\partial OCV} * \Delta OCV \quad (5)$$

[0049] ΔSOC is the SOC uncertainty,

$$\frac{\partial SOC}{\partial OCV}$$

is the slope of the SOC-OCV curve, and ΔOCV is the OCV uncertainty.

[0050] The existing method considers that SOC uncertainty is bounded by OCV error and the OCV-SOC curve slope. However, the existing method may produce a larger SOC estimation uncertainty bound compared with the true bound of the SOC uncertainty as the existing method does not further consider the following SOC uncertainty factors.

[0051] One SOC uncertainty factor not considered is that SOC uncertainty is between (−100%, 100%) as the SOC is defined as a percentage falling within a range of 0%-100%. Another SOC uncertainty factor not considered is that SOC uncertainty is bounded by known capacity error (either from BOL (begin-of-life or after certain operations), current integration error, and initial SOC error. Another SOC uncertainty factor not considered is that SOC uncertainty should be taken with voltage measurement error evenly distributed within its own error bound, and correspondingly, SOC uncertainty should come from average SOC error, based on OCV-SOC lookup table, and averaging on the potential OCV value distribution. Another SOC uncertainty factor not considered is that SOC uncertainty should never be higher compared with the cumulative error of the last SOC uncertainty, and the total ampere-hour integration based SOC change uncertainty.

[0052] BECM **50** in accordance with the present disclosure considers at least two or more of such SOC uncertainty factors in estimating the SOC uncertainty. Each SOC uncertainty factor is associated with its own SOC error bound. BECM **50** uses the minimal of all of the SOC error bounds in estimating the SOC uncertainty.

[0053] In one implementation, BECM **50** considers the SOC uncertainty factor considered by the existing method and at least one the above-noted SOC uncertainty factors not considered by the existing method. In another implementation, BECM **50** considers the SOC uncertainty factor considered by the existing method and at least all of the above-noted SOC uncertainty factors not considered by the existing method.

[0054] Referring now to FIG. **4**, a block diagram **80** depictive of SOC uncertainty factors considered by BECM **50** in estimating the SOC uncertainty bound for the SOC of traction battery **24** is shown. As described, in overview, there are different ways of establishing SOC error bound at any given time. A first SOC uncertainty factor is that at any moment SOC error cannot exceed +/−100% due to the definition of SOC, indicated by block **82**. A second SOC uncertainty factor is that SOC error cannot be more than the initial SOC error, capacity error, and ampere-hour integration error combined (in a statistics way), indicated by block **84**. A third SOC uncertainty factor is that SOC error, per the SOC-OCV curve, can be established using an evenly-distributed OCV error at a given OCV value, and averaged out, indicated by block **86**. A fourth SOC uncertainty is that SOC error can be established using the SOC-OCV curve at the given OCV value, OCV error, and SOC-OCV slope value, indicated by block **88**. The overall SOC error cannot exceed any of these SOC error bounds, indicated by block **90**.

[0055] In further detail, the first SOC uncertainty factor (i.e., potential error bound #1) pertains to adding higher and lower physically possible bounds for the SOC uncertainty estimation. This is the easiest SOC uncertainty factor to implement. For the SOC estimation at any time, the SOC uncertainty cannot have an error that is beyond +/−100%. Accordingly, BECM **50** considers this limit for SOC calculations. As indicated in block **82**, the first SOC error bound is denoted as [−d1, d1], where d1=SOCerror_max=100%, and −d1=SOCerror_min=−100%.

[0056] The second SOC uncertainty factor (i.e., potential error bound #2) pertains to the SOC error per the initial SOC error, Ah error, and capacity error. There are use cases where traction battery **24** starts its operation with an accurate initial SOC value. For example, (even for lithium-iron phosphate (LFP) traction batteries), if the discharge is starting from a relatively high SOC or if charging is starting from a relatively low SOC after rest, then the initial SOC error can be within, e.g., 2% of true value, of course depending on voltage measurement accuracy. For such use case, it is possible to find another SOC error bound. Ah error has been established as, e.g., 1%. Capacity error should be well within, e.g., 30% of true value. This can be reduced even more if usage of traction battery **24** is considered. Because traction battery **24** starts with BOL accuracy (of capacity, which is within, e.g., 2%), and with the assumption that the algorithm has established capacity estimation within a desired bound, BECM **50** sets the capacity error at 5%.

[0057] This SOC uncertainty factor percentage "d" can be quantified per the following equation:

$$d=\sqrt{(\mathrm{RUSOC\_init})^2+(RUAh)^2+(RUCap)^2} \tag{6}$$

[0058] "RU" is the relative uncertainty.

[0059] Using the noted values for each RU component, this SOC uncertainty factor percentage "d" is calculated per the following equation:

$$d=\sqrt{(0.02)^2+(0.01)^2+(0.05)^2}=0.0548\text{ (or 5.48\%)} \tag{7}$$

[0060] The value of this percentage factor can then be transformed into "absolute error": d2=f(OCV)*d, for example if SOC as looked up from OCV is 70%. In this case, as indicated in block **84**, the second SOC error bound is denoted as [−d2, d2], where d2=SOCerror_Ah_max=5.48%*0.70=3.84%, and −d2=SOCerror_Ah_min=−3.84%.

[0061] The third SOC uncertainty factor (potential error bound #3) pertains to SOC error based on the assumption of OCV error even distribution and the SOC-OCV curve. It is understood that for the SOC-OCV curve (the one-to-one relationship normally exhibited for certain types of traction batteries at SOC range from 0% to 100%) may have different slopes at different SOC values (or OCV values). BECM **50** uses the SOC-OCV curve slope to find the worst case slope and this value is used as a "divider" to get the evenly distributed OCV values if needed. This represents the worst case scenario. Once an OCV, and an error bound, are established based on the distribution grid size, BECM **50** can calculate all SOC values with respect to the "reference" SOC (that is based on OCV value itself). BECM **50** takes the average of all SOC errors on one side, the positive side SOC error and the negative side SOC error can be calculated as above. As indicated in block **86**, the third SOC error bound is denoted as [−d3b, d3a], where d3a=SOCerror_SOCOCV_Verror_prob_max, and −d3b=SOCerror_SOCOCV_Verror_prob_min (these two percentage values d3a and −d3b may be different in magnitude).

[0062] An example of calculating the third SOC error bound is as follows. This example assumes that using a pertinent SOC-OCV curve the following information is obtained: estimated OCV=3.32 V (60.999% SOC); OCV estimation error=+/−12 mV; range of OCV (with uncertainty)=[3.308, 3.332]; minimal slope=1 mV/1% SOC; and calculated SOC error per OCV distribution: [−7.6667 −5.0000 −3.0000 −2.3333 −1.6667 −1.0000 −0.8571 −0.7143 −0.5714 −0.4286 −0.2857 −0.1429 −0.0000 0.1429 0.2857 0.4286 0.5714 0.7143 0.8571 1.0000 1.1538 1.3077 1.4615 1.6154 1.7692]. In this case, the SOC uncertainty (positive, average)=0.9423%; and the SOC uncertainty (negative, average)=−1.9722%. As such, the SOC uncertainty bound due to SOC-OCV slope changes and OCV measurement uncertainty is [−1.9722%, 0.9423%].

[0063] The fourth SOC uncertainty factor (potential error bound #4) pertains to the existing method involving using a SOC-OCV curve slope and voltage measurement error to estimate the SOC. As such, the SOC error can be established using the SOC-OCV curve at the given OCV value, OCV error, and SOC-OCV slope value per the above equation (5). As indicated in block **88**, the fourth SOC error bound is denoted as [−d4b, d4a], where d4a=SOCerror_SOCOCV_Verror_max, and −d4b=SOCerror_SOCOCV_Verror_min (these two percentage values d4a and −d4b may be different in magnitude).

[0064] In estimating the SOC uncertainty, BECM **50** uses the minimal SOC error bound based on all of the first, second, third, and fourth SOC uncertainty factors, as indicated in block **90**. This minimal SOC error bound is the SOC uncertainty bound. Compared with the existing method, in which the SOC uncertainty bound is the fourth SOC error bound per the fourth SOC uncertainty factor, the SOC uncertainty bound is estimated based on all of the first, second, third, and fourth SOC uncertainty factors. In practice, these four SOC uncertainty factors considered together result in BECM **50** estimating a SOC uncertainty bound that is smaller than the fourth SOC error bound. As such, compared with the existing method, BECM **50** estimates a refined SOC uncertainty bound (i.e., a more limited or tighter SOC uncertainty bound that is smaller than the fourth SOC error bound) for the SOC of traction battery **24**. In turn, BECM **50** estimates the capacity of traction battery **24** according to the SOC of the traction battery with the estimated SOC uncertainty bound and controls the traction battery and/or BEV **12** based on the capacity. Of course, in relatively rare situations, the fourth SOC error bound is the lowest SOC uncertainty bound (i.e., the first, second, third, and fourth SOC uncertainty factors considered together result in BECM **50** estimating a SOC uncertainty bound that is equal to the fourth SOC error bound).

[0065] Referring now to FIG. **5**, with continual reference to FIG. **4**, a graph **100** of exemplary values for the SOC uncertainty factors considered by BECM **50** in estimating the SOC uncertainty bound is shown. Graph **100** is to explain in further detail how BECM **50** uses the minimal SOC error bound based on all of the first, second, third, and fourth SOC uncertainty factors in estimating the SOC uncertainty bound. In operation, once all possible sources of SOC uncertainties are enlisted and calculated (i.e., d1, −d1, d2, −d2, d3a, −d3b, d4a, and −d4b), the least amount of SOC uncertainty (from each positive/negative percentage side) can be used to estimate the SOC uncertainty. On the positive percentage side, the SOC uncertainty: USOC+=min (d1, d2, d3a, d4a). On the negative percentage side, the SOC uncertainty: USOC−=max (−d1, −d2, −d3b, −d4b). The final SOC uncertainty range: final USOC=[USOC−, USOC+]. The absolute SOC uncertainty: absolute USOC=[−max(abs (USOC−), USOC+), max(abs(USOC−), USOC+)]. These values are "absolute error" in the sense that it is true SOC unit percentage and not relative to some reference value.

[0066] As shown in graph **100**, for these exemplary values for the SOC uncertainty factors, the least amount of SOC uncertainty on the positive percentage side is d3a, and the least amount of SOC uncertainty on the negative percentage side is-d2. Hence, the final SOC uncertainty range is [-d2, d3a], indicated by range **102**. Note that the final SOC uncertainty range is lower than each of the SOC uncertainty ranges [d2, −d2], [d3a, −d3b], [d1, −d1], and [d4a, −d4b], respectively indicated by ranges **104**, **106**, **108**, and **110**.

[0067] Referring now to FIG. **6**, with continual reference to FIGS. **3**, **4**, and **5**, a flowchart **110** depicting operation of BECM **50** in controlling traction battery **24** and/or BEV **12** based on the capacity of the traction battery according to the SOC of the traction battery with the estimated SOC uncertainty bound is shown. In operation, BECM **50** determines if an activation request is received, as indicated by decision block **112**. If received, BECM **50** closes contactors **61** to electrically couple traction battery **24** to the charge/discharge system of BEV **12** (i.e., key on event), as indicated by block **114**. BECM **50** then sets operational characteristics including power limits based on the capacity of traction battery **24** estimated after the last deactivation of BEV **12**, as indicated by block **116**. In turn, BECM **50** controls the charge/discharge of traction battery **24** based on the operational characteristics of the traction battery, as indicated by block **118**.

[0068] BECM **50** continues with the controlling of the charge/discharge of traction battery **24** until a deactivation request is received, as indicated by decision block **120**. Once the deactivation request is received, BECM **50** opens contactors **61** to electrically decouple traction battery **24** from the charge/discharge system (i.e., key off event), as indicated by block **122**. BECM **50** then estimates the capacity of traction battery **24** using capacity estimator **76** as described above, as indicated by block **124**. Further, as indicated by flowchart **110**, BECM **50** may estimate the capacity of traction battery **24** when no activation request is received.

[0069] As described, in accordance with the present disclosure, BECM **50** considers various SOC uncertainty factors in estimating the uncertainty of the SOC of traction battery **24** for use in estimating the capacity of the traction battery. By considering various SOC uncertainty factors, the estimate of the SOC uncertainty is typically tighter (i.e., more limited or reduced) than the SOC uncertainty estimated with consideration of just one of the SOC uncertainty factors. Particularly, the estimate of the SOC uncertainty is typically tighter than the SOC uncertainty estimated with consideration of just the SOC uncertainty factor pertaining to an existing method involving the SOC-OCV slope and voltage uncertainty. In addition to the SOC uncertainty factor pertaining to the existing method, other SOC uncertainty factors considered by BECM **50** include factors involving voltage measurement distribution, actual SOC-OCV curve differences at different voltage values, physically possible values of SOC uncertainty, and operational SOC uncertainty.

[0070] In sum, BECM **50** provides the benefit of obtaining tighter SOC uncertainty for capacity estimation. Compared with the existing method, the approach implemented by BECM **50** may drastically reduce SOC estimation uncertainty based on the given battery cell properties, OCV measurement (estimation), and the estimation uncertainty associated with it. In particular, a reduced SOC estimation uncertainty may lead to fewer number of samples used for accurately estimating battery capacity and may lead to a larger weight used in adaptive filter for battery capacity estimation. Separate from capacity estimation, a reduced SOC estimation uncertainty may lead to better use of OCV estimation for SOC initialization purpose. This will in turn support more accurate SOC and DTE estimation for traction battery controls.

[0071] While exemplary embodiments are described above, it is not intended that these embodiments describe all possible forms of the present disclosure. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the present disclosure. Additionally, the features of various implementing embodiments may be combined to form further embodiments of the present disclosure.

What is claimed is:

1. A system comprising:

a battery having a state-of-charge (SOC) with a SOC uncertainty; and

a controller configured to charge and discharge the battery based on a capacity of the battery according to the SOC with a bound of the SOC uncertainty, the bound of the SOC uncertainty being based on consideration of multiple SOC uncertainty factors to thereby be reduced relative to being based on consideration of less than all of the SOC uncertainty factors.

2. The system of claim **1** wherein:

each SOC uncertainty factor is associated with its own bound of the SOC uncertainty; and

the bound of the SOC uncertainty is the smallest bound of the SOC uncertainty factors.

3. The system of claim **1** wherein:

each SOC uncertainty factor is associated with its own bound of the SOC uncertainty and the bound of each SOC uncertainty factor is a range between a negative value and a positive value; and

the bound of the SOC uncertainty is a range between (i) the negative value having a lowest magnitude amongst the negative values and (ii) the positive value having a lowest magnitude amongst the positive values.

4. The system of claim **1** wherein:

a first one of the SOC uncertainty factors is indicative of the SOC uncertainty based on an uncertainty of a voltage measurement of the battery and a SOC-OCV (open-circuit voltage) table that are used together in estimating the SOC; and

the bound of the SOC uncertainty is reduced relative to being based on consideration of just the first one of the SOC uncertainty factors.

5. The system of claim **4** wherein:

another one of the SOC uncertainty factors is indicative of the SOC uncertainty based on a range of an amount of SOC uncertainty that is physically possible.

6. The system of claim **4** wherein:

another one of the SOC uncertainty factors is indicative of the SOC uncertainty based on an uncertainty of an ampere-hour integration measurement that is used in estimating the SOC.

7. The system of claim **4** wherein:

another one of the SOC uncertainty factors is indicative of the SOC uncertainty based on distributed voltage measurements of the battery that are used in estimating the SOC.

8. The system of claim **4** wherein:

another one of the SOC uncertainty factors is indicative of the SOC uncertainty based on an uncertainty pertaining to differences of a SOC-OCV (open-circuit voltage) table at different voltage measurements in which the SOC-OCV table with the different voltage measurements are used in estimating the SOC.

9. The system of claim **1** wherein:

the controller is further configured to detect and update the capacity while the battery is being charged and discharged.

10. The system of claim **1** wherein:

the battery is a traction battery of an electrified vehicle.

11. A method comprising:

detecting a state-of-charge (SOC) of a battery;

estimating an uncertainty of the SOC based on consideration of multiple SOC uncertainty factors;

detecting a capacity of the battery according to the SOC with the estimated SOC uncertainty, the estimated SOC uncertainty being reduced relative to an uncertainty of the SOC estimated based on consideration of less than all of the SOC uncertainty factors such that the capacity has reduced uncertainty; and

charging and discharging the battery based on the capacity.

12. The method of claim **11** wherein:

each SOC uncertainty factor is associated with a bound of the uncertainty of the SOC; and

the estimated SOC uncertainty is the smallest bound of the SOC uncertainty factors.

13. The method of claim **11** wherein:

each SOC uncertainty factor is associated with a bound of the uncertainty of the SOC and the bound of each SOC uncertainty factor is a range between a negative value and a positive value; and

the estimated SOC uncertainty is a range between (i) the negative value having a lowest magnitude amongst the negative values and (ii) the positive value having a lowest magnitude amongst the positive values.

14. The method of claim **11** wherein:

a first one of the SOC uncertainty factors is indicative of the uncertainty of the SOC based on an uncertainty of a voltage measurement of the battery and a SOC-OCV (open-circuit voltage) table that are used together in detecting the SOC; and

the estimated SOC uncertainty is reduced relative to the uncertainty of the SOC estimated based on consideration of just the first one of the SOC uncertainty factors.

15. The method of claim **14** wherein:

another one of the SOC uncertainty factors is indicative of the SOC uncertainty based on one of:

a range of an amount of SOC uncertainty that is physically possible;

an uncertainty of an ampere-hour integration measurement that is used in detecting the SOC;

distributed voltage measurements of the battery that are used in detecting the SOC; or

an uncertainty pertaining to differences of a SOC-OCV (open-circuit voltage) table at different voltage measurements in which the SOC-OCV table with the different voltage measurements are used in detecting the SOC.

16. An electrified vehicle comprising:

a traction battery; and

a controller configured to detect a state-of-charge (SOC) of the traction battery and to estimate an uncertainty of the SOC based on consideration of multiple SOC uncertainty factors, the estimated SOC uncertainty being reduced relative to an uncertainty of the SOC estimated based on consideration of less than all of the SOC uncertainty factors; and

the controller is further configured to charge and discharge the traction battery based on a capacity of the traction battery according to the SOC with the estimated SOC uncertainty.

17. The electrified vehicle of claim **16** wherein:

each SOC uncertainty factor is associated with a bound of the uncertainty of the SOC; and

the estimated SOC uncertainty estimated by the controller is the smallest bound of the SOC uncertainty factors.

18. The electrified vehicle of claim **16** wherein:

each SOC uncertainty factor is associated with a bound of the uncertainty of the SOC and the bound of each SOC uncertainty factor is a range between a negative value and a positive value; and the estimated SOC uncertainty estimated by the controller is a range between (i) the negative value having a lowest magnitude amongst the negative values and (ii) the positive value having a lowest magnitude amongst the positive values.

19. The electrified vehicle of claim **16** wherein:

a first one of the SOC uncertainty factors is indicative of the uncertainty of the SOC based on an uncertainty of a voltage measurement of the battery and a SOC-OCV (open-circuit voltage) table that are used together in detecting the SOC; and

the estimated SOC uncertainty estimated by the controller is reduced relative to the uncertainty of the SOC estimated based on consideration of just the first one of the SOC uncertainty factors.

20. The electrified vehicle of claim **16** wherein:

a first one of the SOC uncertainty factors is indicative of the uncertainty of the SOC based on an uncertainty of a voltage measurement of the battery and a SOC-OCV (open-circuit voltage) table that are used together in detecting the SOC; and

a second one of the SOC uncertainty factors is indicative of the SOC uncertainty based on a range of an amount of SOC uncertainty that is physically possible; and

a third one of the SOC uncertainty factors is indicative of the SOC uncertainty based on an uncertainty of an ampere-hour integration measurement that is used in detecting the SOC.

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