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(54) **TECHNIQUES FOR MEASURING BATTERY SYSTEM STATE OF POWER**

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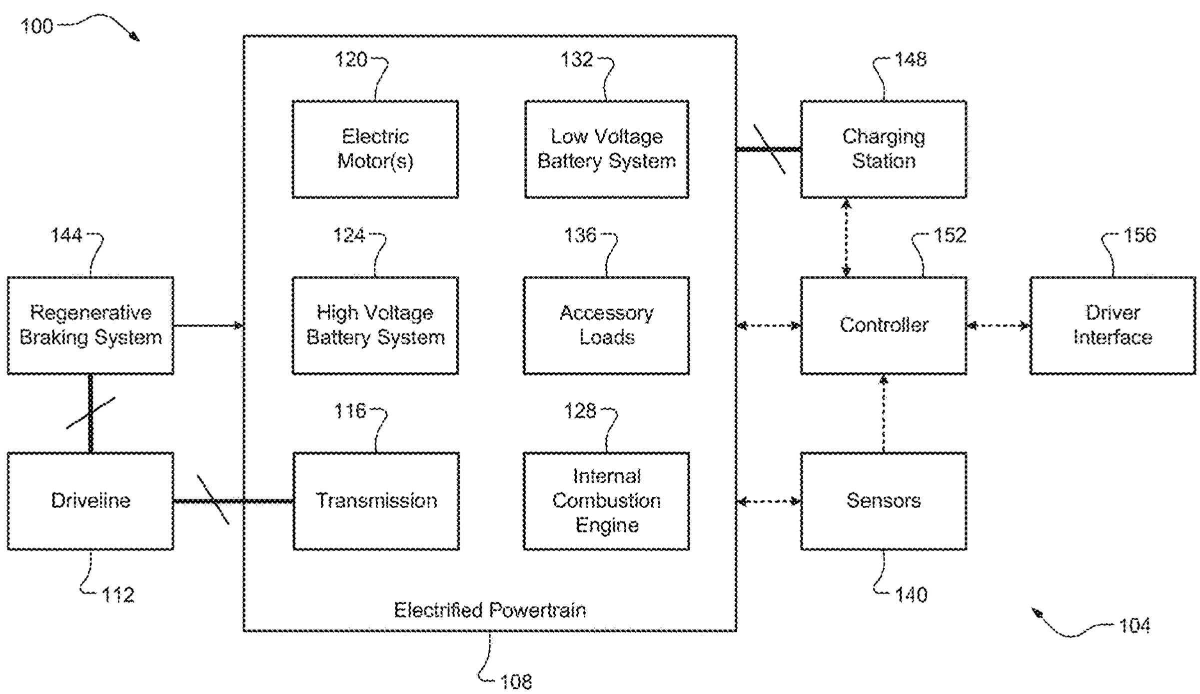
(57) **ABSTRACT**

A state of power (SOP) measurement technique includes determining an initial power command corresponding to a potential SOP of a battery system and performing an iterative power command searching process including charging the battery system to a fully-charged state of charge (SOC), discharging the battery system to a set of SOC breakpoints until the battery system reaches a fully-discharged SOC, after reaching each SOC breakpoint, applying a power command as a constant power pulse to the battery system, the power command being the initial power command or a subsequently updated power command, and based on whether a current or voltage of the battery system exceeds an error tolerance, updating the initial power command and repeating the iterative power command searching process, or outputting the initial power command or the subsequently updated power command as a measured SOP of the battery system.



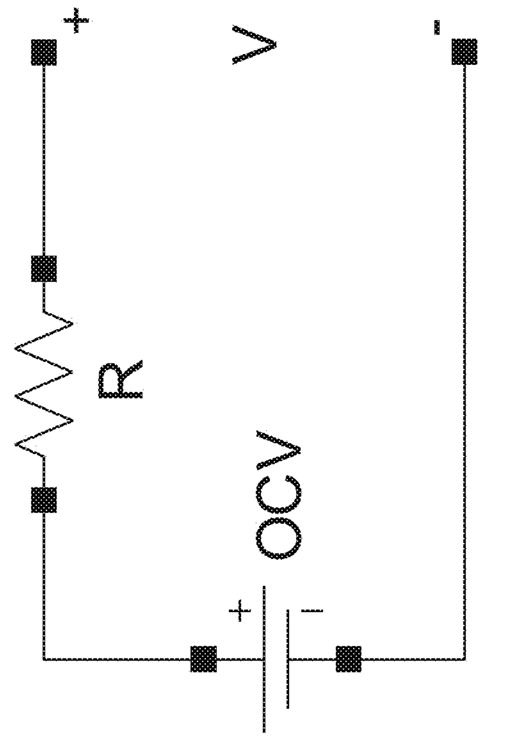

50
+
-
V
R
OCV
+
-

FIG. 1B

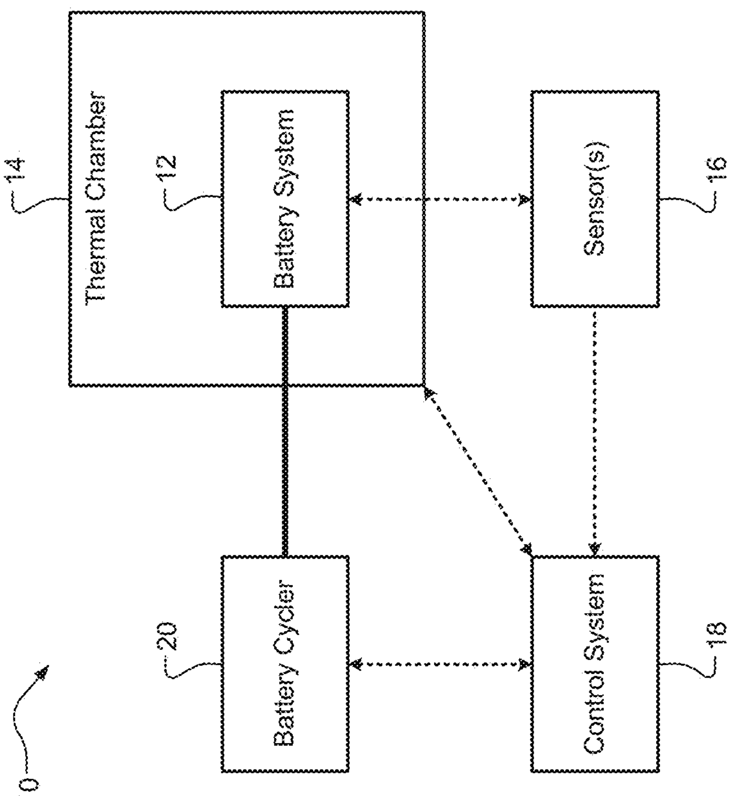

14
Thermal Chamber
12
Battery System
Sensor(s)
16
20
Battery Cycler
Control System
18
10

FIG. 1A

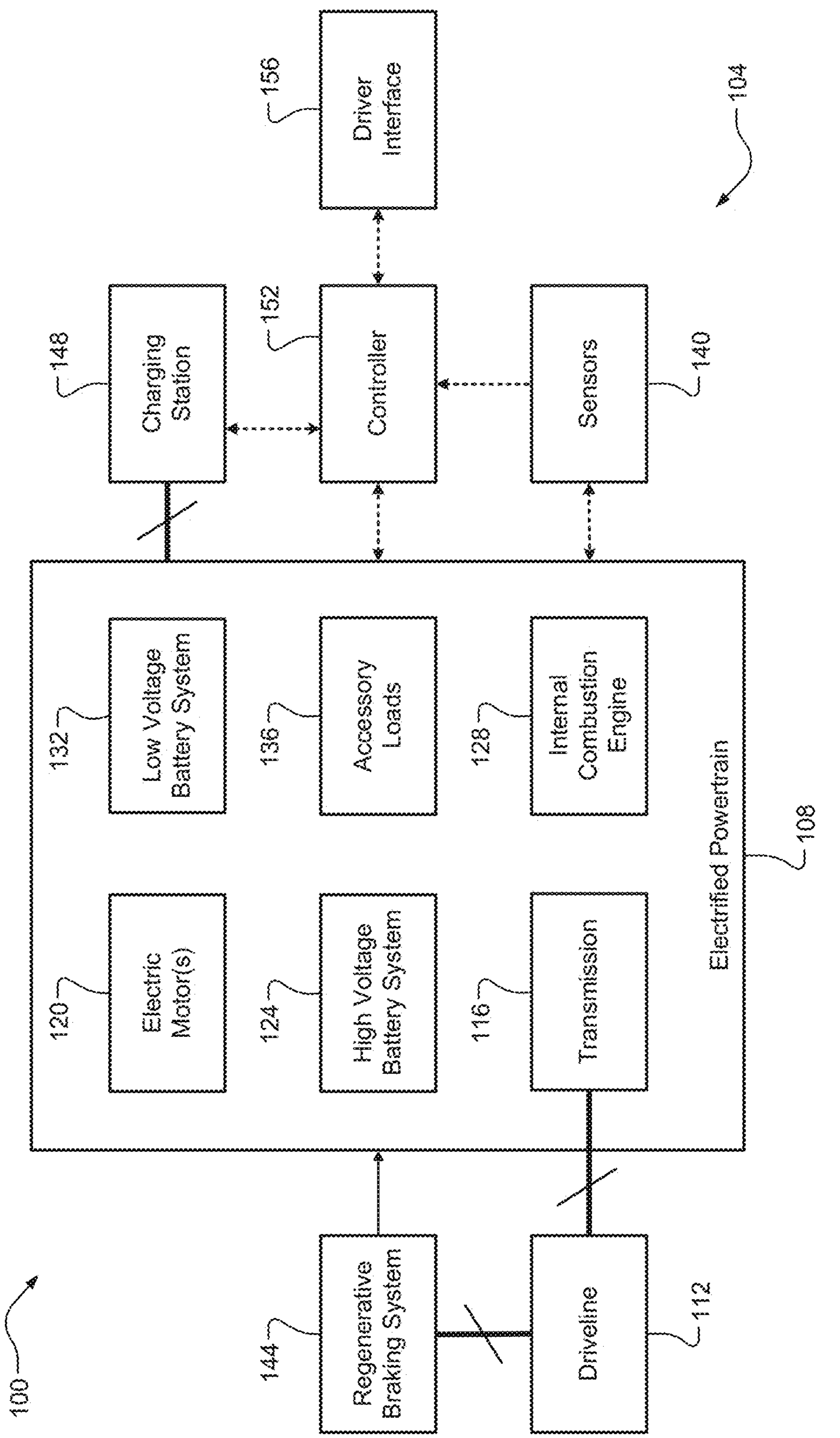

100
104
Driver Interface
156
Charging Station
148
Controller
152
Sensors
140
Low Voltage Battery System
132
Accessory Loads
136
Internal Combustion Engine
128
Electric Motor(s)
120
High Voltage Battery System
124
Transmission
116
Electrified Powertrain
108
Regenerative Braking System
144
Driveline
112

FIG. 1C

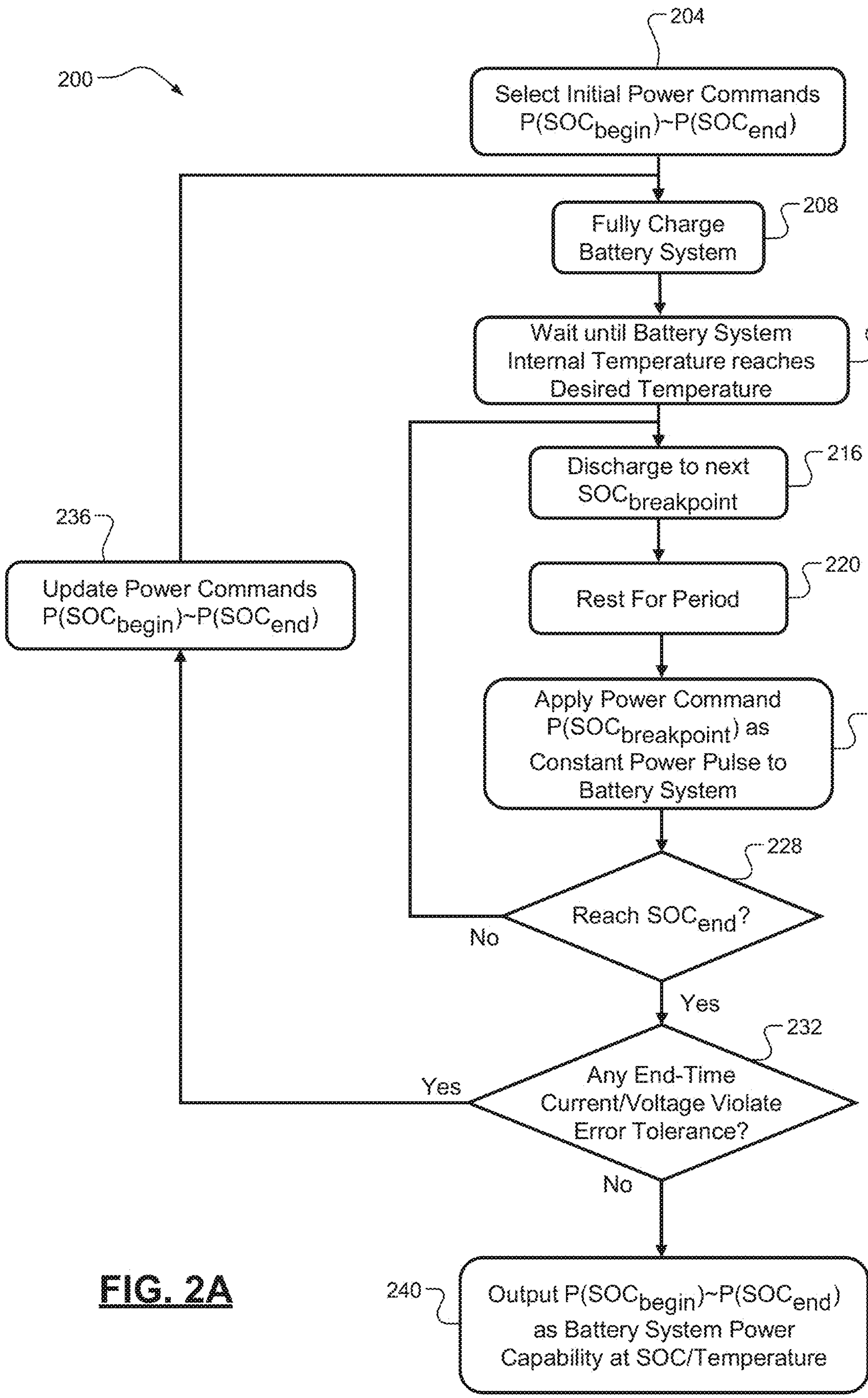

200
204
Select Initial Power Commands P(SOCbegin)~P(SOCend)
208
Fully Charge Battery System
212
Wait until Battery System Internal Temperature reaches Desired Temperature
216
Discharge to next SOCbreakpoint
220
Rest For Period
224
Apply Power Command P(SOCbreakpoint) as Constant Power Pulse to Battery System
228
Reach SOCend?
No
Yes
232
Any End-Time Current/Voltage Violate Error Tolerance?
Yes
No
236
Update Power Commands P(SOCbegin)~P(SOCend)
240
Output P(SOCbegin)~P(SOCend) as Battery System Power Capability at SOC/Temperature

FIG. 2A

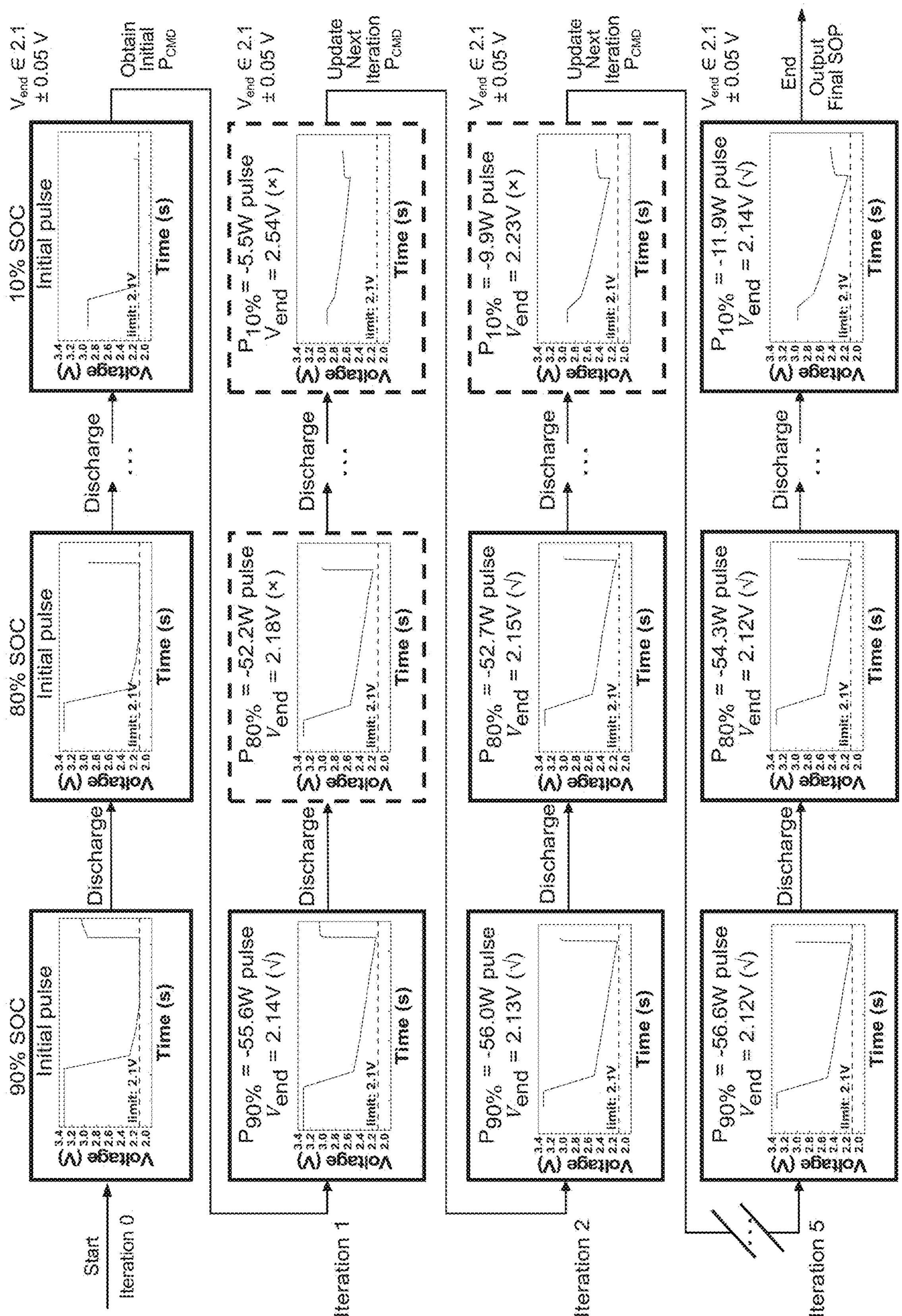

Start
Iteration 0
90% SOC
Initial pulse
80% SOC
Initial pulse
10% SOC
Initial pulse
Discharge
Voltage (V)
Time (s)
limit: 2.1V
V_end ∈ 2.1 ± 0.05 V
Obtain Initial P_CMD
Iteration 1
P90% = -55.6W pulse
Vend = 2.14V (√)
P80% = -52.2W pulse
Vend = 2.18V (×)
P10% = -5.5W pulse
Vend = 2.54V (×)
Update Next Iteration P_CMD
Iteration 2
P90% = -56.0W pulse
Vend = 2.13V (√)
P80% = -52.7W pulse
Vend = 2.15V (√)
P10% = -9.9W pulse
Vend = 2.23V (×)
Iteration 5
P90% = -56.6W pulse
Vend = 2.12V (√)
P80% = -54.3W pulse
Vend = 2.12V (√)
P10% = -11.9W pulse
Vend = 2.14V (√)
End
Output Final SOP

FIG. 2B

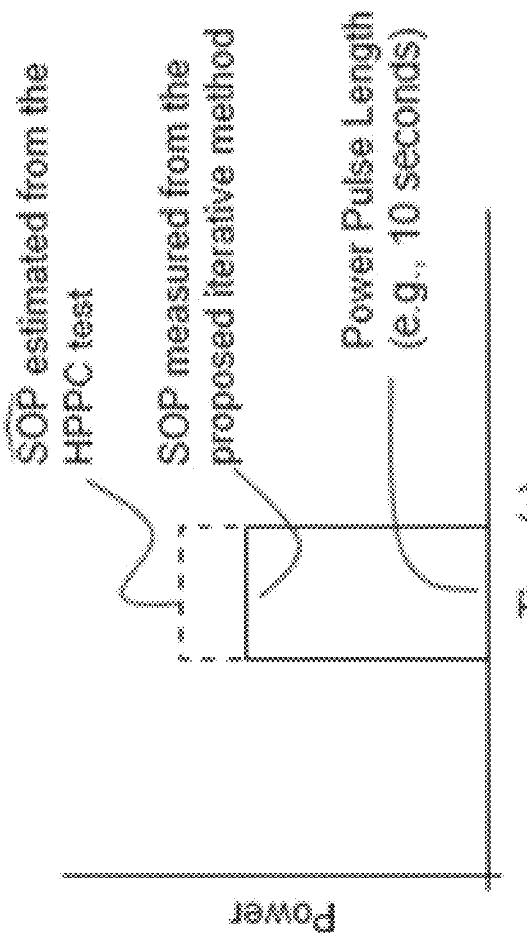

Power
Time (s)
$\widehat{SOP}$ estimated from the HPPC test
SOP measured from the proposed iterative method
Power Pulse Length (e.g., 10 seconds)

FIG. 3A

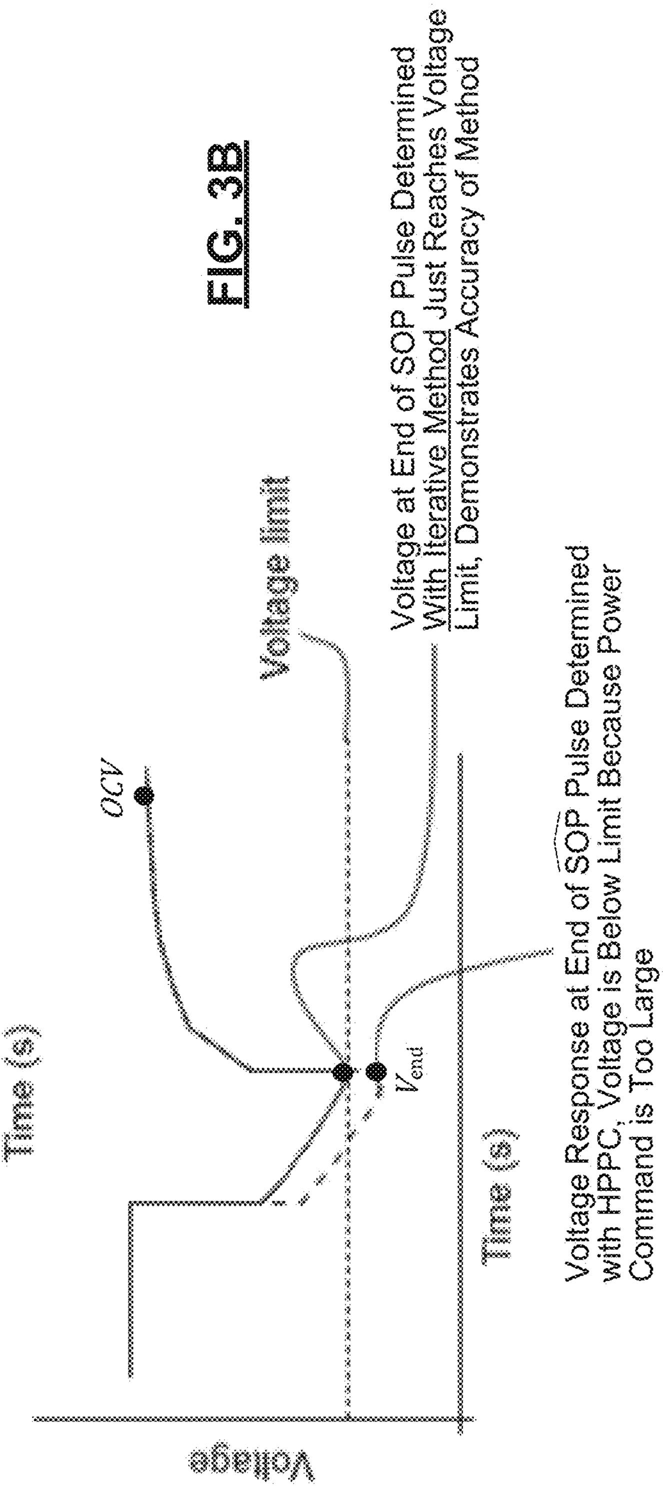

Voltage
Time (s)
OCV
V_{end}
Voltage limit
Voltage at End of SOP Pulse Determined With Iterative Method Just Reaches Voltage Limit, Demonstrates Accuracy of Method
Voltage Response at End of $\widehat{SOP}$ Pulse Determined with HPPC, Voltage is Below Limit Because Power Command is Too Large

FIG. 3B

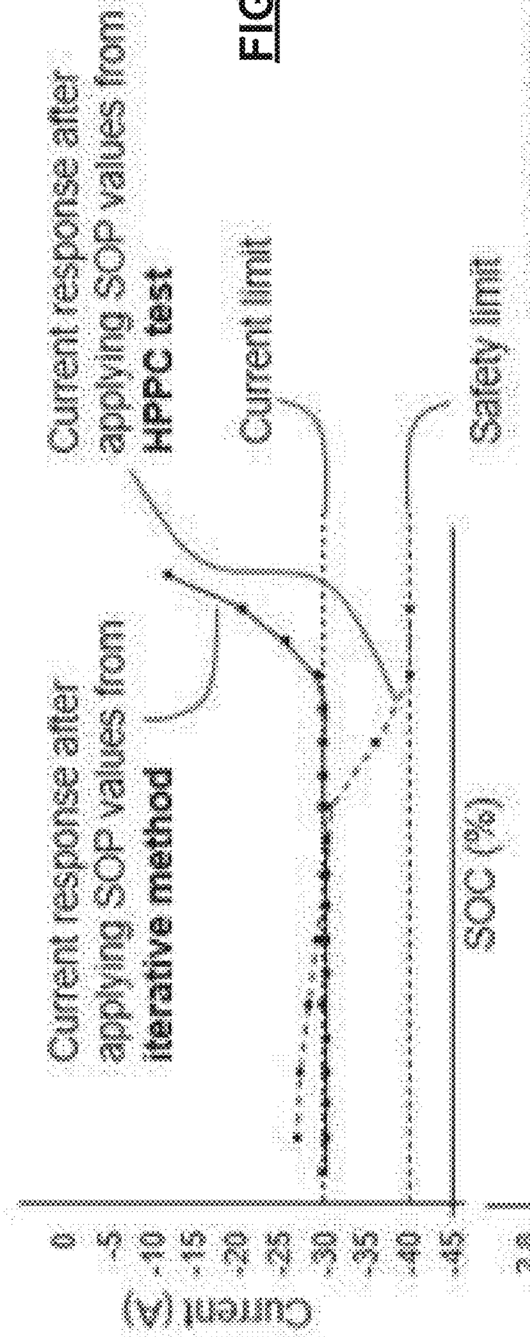

Current response after applying SOP values from **HPPC test**
Current limit
Safety limit
Current response after applying SOP values from **iterative method**
Current (A)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
SOC (%)

FIG. 3C

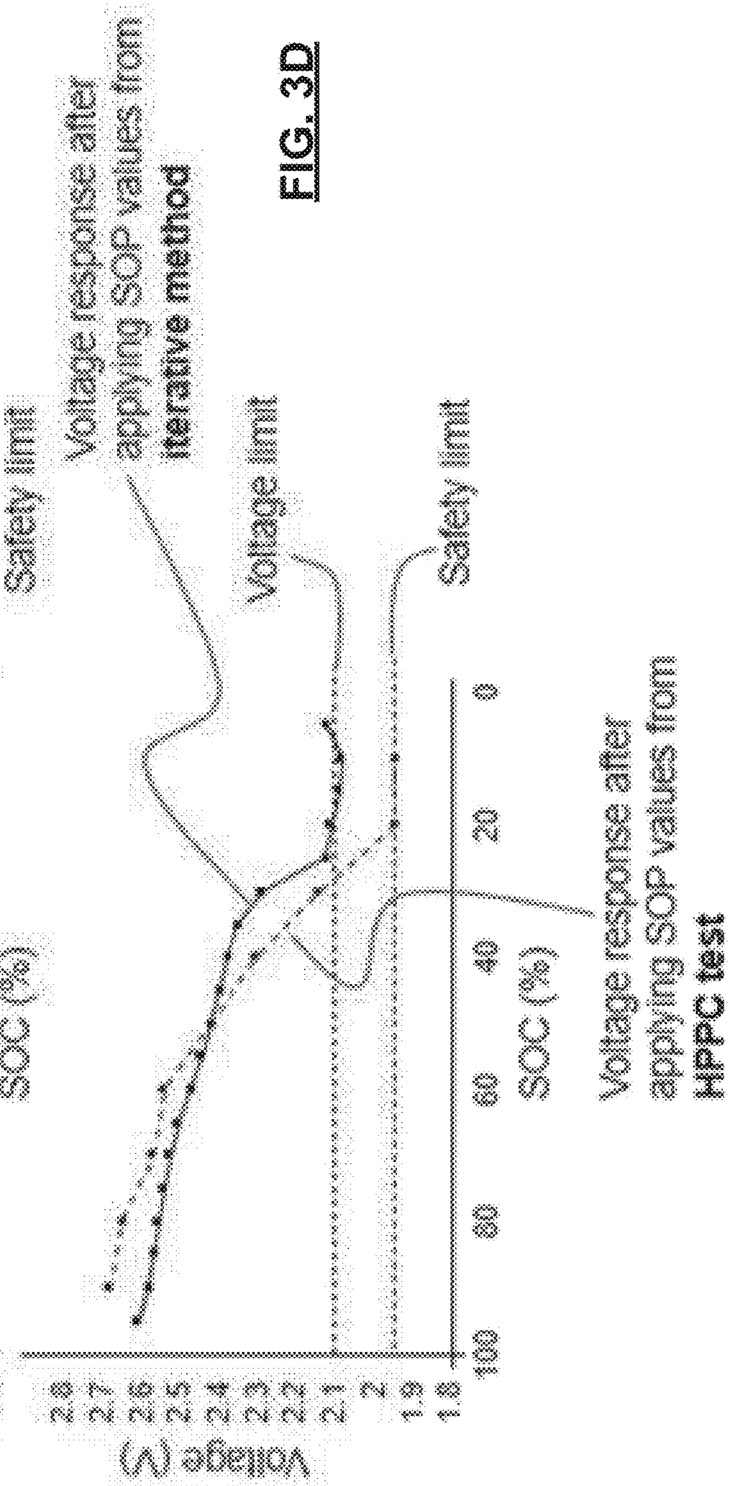
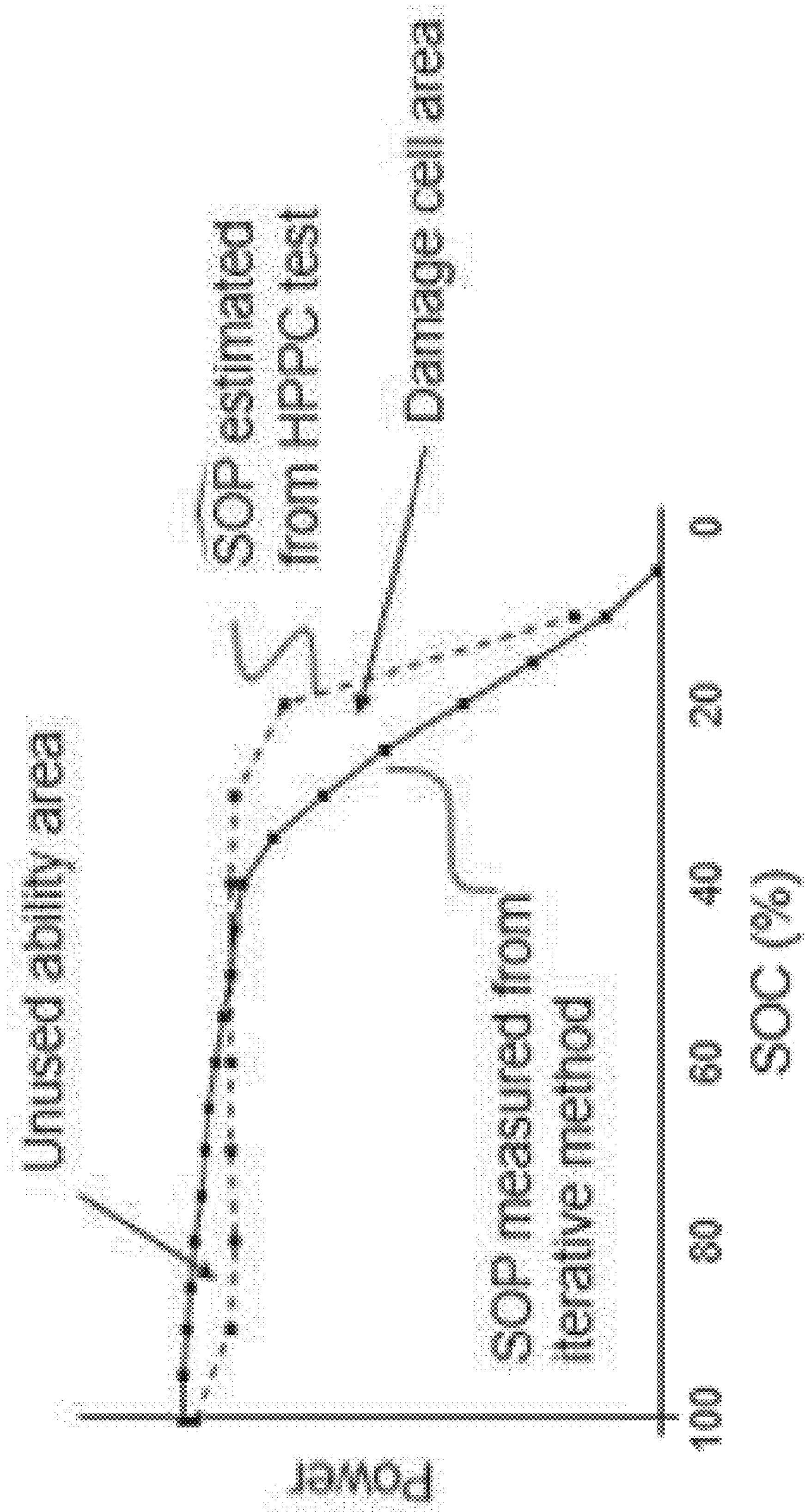

Voltage response after applying SOP values from **iterative method**
Voltage limit
Safety limit
Voltage response after applying SOP values from **HPPC test**
Voltage (V)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
100
80
60
40
20
0
SOC (%)

FIG. 3D



Unused ability area
SOP estimated from HPPC test
Damage cell area
SOP measured from iterative method
Power
SOC (%)
100
80
60
40
20
0

FIG. 3E

TECHNIQUES FOR MEASURING BATTERY SYSTEM STATE OF POWER

FIELD

[0001] The present application generally relates to battery systems and, more particularly, to techniques for measuring battery system state of power.

BACKGROUND

[0002] An electrified vehicle has an electrified powertrain including one or more battery systems that provide electrical energy (i.e., current) to power one or more electric motors and receive electrical energy from various possible sources for recharging. The power that a battery system can provide/receive is a finite value limited by the battery cell structure and its chemical reactions therein. To ensure the battery system remains within a safe operating region, the maximum power that the battery system can supply to loads (e.g., an electric motor) or receive (e.g., via an external charging station or a regenerative braking system) before reaching a respective voltage, current, state of charge (SOC), and/or temperature limit must be accurately determined to avoid malfunctions or faults. These power limits are also known as the battery system's power capability or state of power (SOP). Battery system SOP cannot be directly measured with a sensor and instead requires a unique measurement or estimation procedure based on other parameters.

[0003] Battery system SOP can be measured or estimated via offline techniques in which tests are performed on the battery system in a laboratory environment, or through online estimation techniques in which an algorithm estimates SOP during regular operation (i.e., driving for an electrified vehicle). While there are a number of common offline and online SOP estimation techniques, in which SOP is calculated from measured values or a model, the accuracy of estimation techniques can only be verified with a true measurement of SOP. An SOP measurement technique, by contrast, measures SOP through an iterative method, and in the final iteration applies the actual measured SOP pulse to the battery, thereby demonstrating that at the final timestep of the pulse the voltage, current, SOC, and/or temperature limit is reached. While such SOP measurement techniques are necessary to validate both online and offline SOP estimation methods, there are currently no widely accepted methods to measure SOP accurately (in contrast to other battery parameters, such as SOC and state of health, or SOH). Accordingly, there exists an opportunity for improvement in the relevant art.

SUMMARY

[0004] According to one example aspect of the invention, a state of power (SOP) measurement system for a battery system is presented. In one exemplary implementation, the SOP measurement system comprises a set of sensors configured to measure a set of parameters of the battery system, the set of parameters including at least a state of charge (SOC) and a current or voltage of the battery system and a control system configured to determine an initial power command corresponding to a potential SOP of the battery system and perform an iterative power command searching process including preparing the battery system by charging the battery system to a fully-charged SOC, discharging the battery system to a set of SOC breakpoints until the battery system reaches a fully-discharged SOC, after reaching each SOC breakpoint, applying a power command as a constant power pulse to the battery system, the power command being the initial power command or a subsequently updated power command, when a current or voltage of the battery system exceeds an error tolerance, updating the initial power command and repeating the iterative power command searching process, and when the current or voltage of the battery system does not exceed the error tolerance, outputting the initial power command or the subsequently updated power command as a measured SOP of the battery system.

[0005] In some implementations, the initial power command is a power based on an SOP estimation algorithm to be validated, and wherein the SOP estimation algorithm to be validated is one of a battery model-based SOP estimation algorithm and a machine learning-based SOP estimation algorithm. In some implementations, the initial power command is a power determined using a pulse-based battery test. In some implementations, the pulse-based battery test is one of a hybrid power pulse characterization (HPPC) test, a constant voltage (CV) test, a constant current (CC) test, and a constant current, constant voltage (CCCV) or constant power (CP) test. In some implementations, the fully-charged SOC is approximately 100% and the fully-discharged SOC is approximately 0%.

[0006] In some implementations, the set of parameters of the battery system further includes an internal temperature of the battery system, the battery system is placed in a thermal chamber that is temperature-controlled by the control system, and the preparing of the battery system further includes the internal temperature of the battery system achieving a desired temperature. In some implementations, the iterative power capability searching technique further comprises determining an open circuit voltage (OCV) of the battery system after the discharging and a rest period. In some implementations, the discharging of the battery system is a constant discharge rate. In some implementations, the discharging of the battery system is a vehicle drive cycle discharge or a load profile for an application of interest. In some implementations, the battery system is a high voltage battery system of an electrified powertrain of an electrified vehicle, and wherein the control system is configured to output the measured SOP of the high voltage battery system into a controller of the electrified vehicle that utilizes the measured SOP of the high voltage battery system for control of the electrified powertrain.

[0007] According to another example aspect of the invention, an SOP measurement method for a battery system is presented. In one exemplary implementation, the SOP measurement method comprises providing a set of sensors configured to measure a set of parameters of the battery system, the set of parameters including at least a state of charge (SOC) and a current or voltage of the battery system and providing a control system configured to determine an initial power command corresponding to a potential SOP of the battery system and perform an iterative power command searching process including preparing the battery system by charging the battery system to a fully-charged SOC, discharging the battery system to a set of SOC breakpoints until the battery system reaches a fully-discharged SOC, after reaching each SOC breakpoint, applying a power command as a constant power pulse to the battery system, the power command being the initial power command or a subsequently updated power command, when a current or voltage of the battery system exceeds an error tolerance, updating the initial power command and repeating the iterative power command searching process, and when the current or voltage of the battery system does not exceed the error tolerance, outputting the initial power command or the subsequently updated power command as a measured SOP of the battery system.

[0008] In some implementations, the initial power command is a power based on an SOP estimation algorithm to be validated, and wherein the SOP estimation algorithm to be validated is one of a battery model-based SOP estimation algorithm and a machine learning-based SOP estimation algorithm. In some implementations, the initial power command is a power using a pulse-based battery test. In some implementations, the pulse-based battery test is one of an HPPC test, a CV test, a CC test, and a CCCV or constant power CP test. In some implementations, the fully-charged SOC is approximately 100% and the fully-discharged SOC is approximately 0%.

[0009] In some implementations, the set of parameters of the battery system further includes an internal temperature of the battery system, the battery system is placed in a thermal chamber that is temperature-controlled by the control system, and the preparing of the battery system further includes the internal temperature of the battery system achieving a desired temperature. In some implementations, the iterative power capability searching technique further comprises determining an OCV of the battery system after the discharging and a rest period. In some implementations, the discharging of the battery system is a constant discharge rate. In some implementations, the discharging of the battery system is a vehicle drive cycle discharge or a load profile for an application of interest. In some implementations, the battery system is a high voltage battery system of an electrified powertrain of an electrified vehicle, and wherein the control system is configured to output the measured SOP of the high voltage battery system into a controller of the electrified vehicle that utilizes the measured SOP of the high voltage battery system for control of the electrified powertrain.

[0010] Further areas of applicability of the teachings of the present application will become apparent from the detailed description, claims and the drawings provided hereinafter, wherein like reference numerals refer to like features throughout the several views of the drawings. It should be understood that the detailed description, including disclosed embodiments and drawings referenced therein, are merely exemplary in nature intended for purposes of illustration only and are not intended to limit the scope of the present disclosure, its application or uses. Thus, variations that do not depart from the gist of the present application are intended to be within the scope of the present application.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIGS. **1**A and **1**B are a functional block diagram of an example state of power (SOP) measurement system for a battery system and an example open circuit voltage-resistance (OCV-R) equivalent circuit model according to the principles of the present application;

[0012] FIG. **1**C is a functional block diagram of an electrified vehicle having an example battery management system according to the principles of the present application;

[0013] FIG. **2**A is a flow diagram of an example SOP measurement method for a battery system according to the principles of the present application;

[0014] FIG. **2**B is a diagram illustrating an iterative power command searching process to measure the SOP of a battery system according to the principles of the present application; and

[0015] FIGS. **3**A-**3**E are example plots illustrating comparative performance of a conventional SOP estimation technique and the SOP measurement technique according to the principles of the present application.

DESCRIPTION

[0016] As previously discussed, conventional state of power (SOP) estimation algorithms are lacking and there are no widely accepted methods to measure/estimate SOP accurately, in contrast to other battery system parameters such as state of charge (SOC) and state of health (SOH). The most common conventional offline SOP estimation technique is a hybrid pulse power characterization (HPPC) test method, which determines battery discharging and charging internal resistance from the application of current pulses at different SOCs and then uses an open circuit voltage-resistance (OCV-R) battery equivalent circuit model (ECM) to calculate SOP. The battery's internal resistance varies when applied with different magnitudes of current pulses, especially at low temperatures. Moreover, during the HPPC test method, the current magnitude of the battery is usually different from when the battery reaches the current or voltage limit. Therefore, the battery's internal resistance calculated from it is not accurate, especially at low temperatures. Thus, the HPPC test method is not guaranteed to provide accurate battery power capability values. Other conventional offline estimation techniques include constant voltage (CV), constant current (CC), and constant current, constant voltage (CCCV) test methods.

[0017] In the CV and CC offline SOP estimation methods, the battery voltage or current is set for a given pulse time to the lowermost threshold for discharging or uppermost threshold for charging and the battery current or voltage is recorded against time. The pulse will terminate early if the current limit is reached during a CV pulse or if the voltage limit is reached during a CC pulse. The SOP based on the voltage limitation or current limitation is then obtained by multiplying the recorded battery current and voltage at the last time step of the pulse. The CCCV test method is similar except that the pulses do not terminate early if the voltage or current limits are reached, they instead continue while operating at the current or voltage limit thresholds. For example, for a CCCV discharge pulse, constant current will be applied and if the lower voltage limit is reached, current will be reduced to regulate the voltage at that value. In this way, the commanded pulse length (e.g., 10 seconds) will always be achieved during a CCCV test, but the pulse may be constant current for part of the pulse time and constant voltage for part of the pulse time. Similar to the CV or CC test methods, the SOP is then calculated by multiplying the voltage and current at the end of the pulse. These test methods achieve a more accurate offline estimation of SOP compared to the HPPC test because the battery continuously operates at maximum current or maximum voltage during the tests, ensuring the test conditions are more similar to an actual constant power pulse at the maximum power capability. However, the power value applied to the cell varies when operating at CC, CV, or CCCV mode. According to the definition of SOP, the accuracy of SOP can only be genuinely verified by an actual constant power pulse test. Therefore, these tests also cannot guarantee the accuracy of their measured power capability values.

[0018] One offline SOP measurement technique is a constant power test method. In the constant power test method, a CCCV test method is first performed to get a first iteration SOP estimate that is then applied as a constant power pulse to the battery. Based on the voltage error, this method then modifies the next iteration SOP with a specific power increment (e.g., 2 Watts, or W) and then applies it to the battery iteratively. This iterative process will be terminated when the voltage error is within the tolerance. Since this method applies a constant power pulse to the battery, its accuracy can be intuitively evaluated by the gap between the pulse end-time voltage and the voltage limit. Because power is varied at a set increment each iteration, it will need a considerable number of iterations if higher SOP precision, for example, 0.1 W, is required, possible prematurely aging the battery and impacting the SOP result. Each iteration also takes considerable time since the battery needs to be charged/discharged back to the pre-pulse SOC level and needs time to cool between pulses. In addition, this test method only considers voltage-limited SOP and ignores the current-limited, temperature, and SOC-limited cases. Finally, batteries have long electrochemical dynamics, which will be impacted by the application of consecutive power pulses, resulting in the power measured by this technique being inaccurate, especially for certain battery chemistries (e.g., lithium iron phosphate, or $LiFePO_4$) and low temperatures.

[0019] Accordingly, the present application is directed to improved offline SOP measurement systems and methods for a battery system, such as battery systems for electrified vehicles. While electrified vehicles are specifically discussed herein, it will be appreciated that the battery system SOP measurement systems/methods of the present application are applicable to any suitable battery systems, including non-vehicle applications (e.g., consumer electronics, electrified aircraft, and electrified marine vessels). These battery systems and methods utilize a new, unique test method for accurately measuring the SOP of an electrified vehicle's battery system or validating the accuracy of offline or online SOP estimation algorithms or measurement methods. This test method can also be described as an iterative power capability searching method. In the beginning, an initial power command is selected and applied at different SOC breakpoints. This initial power command could be any suitable value, as the iterative searching process will eventually narrow in on the actual, measured SOP of the battery system. Two specific examples of the initial power command are (i) a power determined using a conventional pulse-based offline SOP estimation (HPPC, CV, CC, CCCV, etc.) and (ii) a power based on another offline or online SOP estimation algorithm.

[0020] After fully charging (e.g., and achieving a desired temperature, such as in a temperature-controlled chamber environment), the battery system is discharged (e.g., constant current discharge, or vehicle drive cycle discharge, such as for the UDDS or USO6 drive cycle, etc.) to specific SOC breakpoints, and corresponding power commands ($P_{SOC\_BREAKPOINT}$) will be applied as constant power pulses of time length T to the battery system, with the discharge and power pulse steps being repeated until the battery system reaches the final SOC breakpoint SOC_{END} and is therefore fully depleted. When any one of the voltage or current values at the end of the constant power pulses are not within an error tolerance, the power command values for the corresponding SOC breakpoints will be updated. The battery system will be fully charged and the process will be repeated until a power command iteration results in no error tolerance being exceeded. Fully recharging the battery and repeating the discharge and power pulse process ensures that each power pulse has the same history, i.e., the same discharge profile in the recent past, which is a critical feature of the present application because it ensures that the method works for batteries with strong history-dependent properties like $LiFePO_4$ chemistries. The primary benefit is a highly accurate battery system SOP measurement, which potentially results in extended battery system usage (and increased vehicle/fuel efficiency), increased battery system life, and thermal runaway and/or other damage (e.g., overloading) prevention (which could reduce replacement/warranty costs).

[0021] Referring now to FIGS. **1**A and **1**B, a functional block diagram of an example SOP measurement system **10** for a battery system **12** and an example open-circuit voltage-resistance (OCV-R) equivalent circuit model **50** for the battery system **12** according to the principles of the present application is illustrated. The SOP measurement system **10** could be utilized in an offline (e.g., a lab) testing environment (i.e., not online by a vehicle controller). The battery system **12** is placed in a temperature-controlled or regulated thermal chamber **14** such that the temperature of the battery system **12** can be controlled so its internal temperature reaches a desired temperature for SOP measurement. A set of one or more sensors **16** are configured to measure electrical and thermal parameters of the battery system **12**, such as voltage, current, and temperature. A control system or controller **18** (e.g., a computer system) is configured to execute software to perform the SOP measurement process according to the present application. This includes, for example, controlling the thermal chamber **14** to a desired temperature and controlling charging/discharging of the battery system **12** via a battery cycler **20**, while also measuring parameters of the battery system **12** using the sensor (s) **16**. This process will be described in greater detail below.

[0022] Referring now to FIG. **1**C, a functional block diagram of an electrified vehicle **100** having an example battery management system (also referred to as "BMS") **104** according to the principles of the present application is illustrated. The electrified vehicle **100** is propulsively powered by an electrified powertrain **108** that generates and transfers drive torque to a driveline **112** via a transmission **116** (e.g., a single-speed or multi-speed automatic transmission). The electrified powertrain **108** includes one or more electric motors **120** powered by a high voltage battery system **124** and an optional internal combustion engine **128** configured to combust a mixture of air and fuel (diesel, gasoline, etc.). In other words, as the one or more electric motors **120** are operated to generate drive torque (torque consumer mode), the SOC of the high voltage battery system **124** is depleted. The high voltage battery system **124** could be, for example, a lithium-ion based battery pack. The electrified powertrain **108** also includes a low voltage battery system **132** (e.g., a 12 volt lead-acid or lithium-ion battery system) configured to power low voltage loads of accessory loads **136** of the electrified vehicle **100** (lights, gauges, displays, etc.). Some of the accessory loads **136** may be high voltage accessory loads powered by the high voltage battery system **124**, such as pumps, fans, compressors, heaters, and the like.

[0023] A direct current (DC) to DC converter (not shown) or other suitable system could be implemented between the high and low voltage battery systems **124**, **132** for stepping up/down respective DC voltages (e.g., for recharging therebetween). The electrified powertrain **108** also includes a regenerative braking system **140** is configured to brake (decelerate) the driveline **116** and convert the kinetic energy to electrical energy, such as for recharging the high voltage battery system **124**. In certain configurations (e.g., plug-in hybrid electric vehicle, or PHEV, configurations), the high voltage battery system **124** could also be recharged using an external charging station **144** (e.g., a roadside or residential charging station) and electrified vehicle supply equipment (EVSE). A set of sensors **148** measure operational parameters of the electrified powertrain **108**, such as speeds, altitude, current/voltage/temperature, SOC, and the like. A controller **152** controls operation of the electrified vehicle **100**, including controlling the electrified powertrain **108** to satisfy a torque request (e.g., via a driver interface **156**, such as an accelerator pedal). It will be appreciated that the torque request may not come directly from the driver, but instead could be a torque request generated by an advanced driver assistance (ADAS) or autonomous driving system. The controller **152** is also configured to perform at least a portion of battery management techniques of the present application, which will now be described in greater detail with reference to a method flowchart.

[0024] Referring now to FIG. **2**A and with continued reference to FIGS. **1**A-**1**C, a flow diagram of an example SOP measurement method **200** for the battery system **12** according to the principles of the present application is illustrated. This method **200** is applicable to any battery system **12**, including offline SOP measurement of the high voltage battery system **124** of the electrified vehicle **100**, which could be determined by the control system **16** and then loaded into the controller **152** of the electrified vehicle **100** for various uses. At **204**, the control system **16** begins the iterative power capability searching technique to estimate the SOP of the battery system **12**. First, the control system **12** selects initial power commands. This could be, for example, any suitable power command, such as (i) a power (based on current/voltage) determined using a conventional pulse-based test (HPPC, CV, CC, CCCV, etc.) and (ii) a power based on another offline or online SOP estimation algorithm. At **208**, the control system **16** fully charges the battery system **12** to a first SOC (e.g., at a one-hour charge rate, or C rate) corresponding to a fully-charged battery system. This first SOC could be, for example, 100%, but it will be appreciated that it could also be slightly less than 100%, such as 98%. At **212**, the control system **16** waits until an internal temperature of the battery system **12** achieves a desired temperature. This could include thermal conditioning (heating/cooling the thermal chamber **14**) and then monitoring the battery system internal temperature. The desired temperature could be, for example any of a number of temperatures (−20° C., −10° C., 0° C., 10° C., 20° C., 25° C., 40° C., etc.).

[0025] Next, at **216**, the control system **16** discharges the battery system **12** to a first SOC breakpoint ($SOC_{breakpoint}$) at a first discharge rate. This first SOC breakpoint $SOC_{breakpoint}$ could be, for example, approximately 5% less than the first SOC, or ~95%. The term "SOC breakpoint" as used herein refers to each SOC level that is desired to be tested. SOC breakpoints may be selected based on where the behavior of the battery cells of the battery system **124** begins to change (e.g., its charging/discharging characteristics), such as due to its chemistry. To discharge to the next SOC breakpoint, any type of discharge profile may be used, for example, a constant current discharge rate or a drive cycle profile discharging (UDDS, USO6, etc.). Powe capability is dependent on how the battery system **12** is discharged, so the discharge profile should be chosen accordingly. Once the first SOC breakpoint $SOC_{breakpoint}$ is reached, the method **200** continues to **220** where the control system **16** waits for a rest period (e.g., ~5 seconds) such that the battery system **12** has a chance to stabilize and have its OCV, or pseudo/approximate OCV, determined. At **224**, the control system **16** applies an initial power command $P(SOC_{breakpoint})$ as a constant power pulse to the battery system **12**. At **228**, the control system **16** determines whether the SOC of the battery system **12** has reached its end value SOC_{end}. When false, the method **200** continues and returns to **216**. When true, the method **200** proceeds to **232**. At **232**, the control system **16** determines whether any end-time currents/voltages violated an error tolerance (e.g., +/−0.05 volts). When false, the method **200** proceeds to **240** where the current iteration's power command is output as the final SOC measurement for the battery system **12** and the method **200** ends. When false, however, the method **200** continues to **236** where the control system **16** updates the power command for a next iteration and the method **200** returns to **208** and the iterative process repeats.

[0026] As part of the above, the OCV-R battery model **50** (FIG. **1**B) can be used to update the battery power command for each iteration. As discussed above, the OCV is determined after the rest periods during the method **200**. The measured current and voltage at the end of the power pulse (I_{end} and V_{end}) are used to calculate the battery internal resistance as:

$$R = \left|\frac{V_{end} - OCV}{I_{end}}\right|.$$

The voltage at the end of the power pulse V_{end} and the OCV are also illustrated in the voltage versus time plot of FIG. **3**B. After calculating R using the OCV-R battery model, the next-iteration power capability P_{k+1} can be calculated as follows:

Current−limited discharging power

$$\text{capability:}\begin{cases} V_{est} = OCV - I_{dis-max} \times R \\ P_{I-dis} = I_{dis-max} \times V_{est},\ V_{est} > V_{min} \end{cases}$$

Voltage−limited discharging power

$$\text{capability:}\begin{cases} I_{est} = (OCV - V_{min})/R \\ P_{V-dis} = V_{min} \times I_{est},\ I_{est} < I_{max} \end{cases}$$

-continued

Current−limited discharging power

$$\text{capability:}\begin{cases} V_{est} = OCV + I_{char-max} \times R \\ P_{I-char} = I_{char-max} \times V_{est},\ V_{est} < V_{max} \end{cases}$$

Voltage−limited charging power

$$\text{capability:}\begin{cases} I_{est} = (V_{max} - OCV)/R \\ P_{V-char} = V_{max} \times I_{est},\ I_{est} < I_{max} \end{cases}$$

$$\text{Discharging power capability:} P_{dis} = \text{MIN}(|P_{I-dis}|, |P_{V-dis}|)$$

$$\text{Charging power capability:} P_{char} = \text{MIN}(|P_{I-char}|, |P_{V-char}|)$$

In the above, OCV is the open circuit voltage, I_{end} and V_{end} are the measured current and voltage at the end of the power pulse, R is the battery internal resistance, and $I_{char-max}$, $I_{dis-max}$, V_{min}, and V_{max} are preset or predetermined current and voltage limits.

[0027] The above equations calculate the next power command by assuming the battery resistance calculated from power pulse P_k is the same as for the next calculated power command value P_{k+1}. It is important to note that battery resistance may vary non-linearly with different magnitudes of power, especially at low temperatures, where battery resistance may vary by one-third or more between small and large power values. Nevertheless, this iterative updating strategy eventually approaches the actual voltage or current limited power capability value. This is because as the power is updated, the commanded power will become progressively closer to the SOP, and as the power approaches the SOP, the resistance calculated from the power pulse will be closer to the correct value. It may take more than 10 iterations to find the accurate power capability at extreme situations. To accelerate the SOP searching process, the present application proposes a novel way to estimate the resistance from previous power pulses. Instead of assuming the battery resistance is constant between two different power pulses, it is assumed to change linearly according to the voltage or current magnitude. First, the corresponding resistances from the last two power pulses for a given SOC breakpoint are calculated as R_{k-1} and R_k. Then, the resistance's rate of change will be linearly estimated by the differential of resistance and voltage or current. Finally, the estimated resistance for the next-iteration power pulse $\hat{R}_{k+1}$ can be estimated by:

$$\text{Current−limited case:}\begin{cases} \dfrac{dR}{dI} = \dfrac{R_k - R_{k-1}}{I_k - I_{k-1}} \\ \hat{R_{k-1}} = \dfrac{dR}{dI} \times (I_{limit} - I_k) + R_k \end{cases}, \text{ and}$$

$$\text{Voltage−limited case:}\begin{cases} \dfrac{dR}{dV} = \dfrac{R_k - R_{k-1}}{V_k - V_{k-1}} \\ \hat{R_{k-1}} = \dfrac{dR}{dV} \times (V_{limit} - V_k) + R_k \end{cases}.$$

[0028] The above-described iterative power command searching process to measure the SOP of the battery system **12** is graphically illustrated in the diagram of FIG. **2**B. In a top row of plots (iteration 0), a CCCV test is applied as iteration 0 to obtain an initial power commands P_{CMD} as the battery system **12** is discharge, (e.g., in intervals of 10%). In a second row of plots (iteration 1), at least two of the stages (80% SOC and 10% SOC) have end voltage values that exceed the error tolerance (2.1V+/−0.05V) after applying the initial power commands as constant power pulses to the battery system. Thus, the power command P_{CMD} is updated and the process repeats. This continues until a fifth iteration (iteration 5, in the bottom row of plots), where the end voltage V_{end} is within the error tolerance at each SOC discharge stage. Thus, the iterative search process is complete and the final power command values are output as the SOP (the measured SOP of the battery system **12**).

[0029] Referring now to FIGS. **3**A-**3**E, example plots illustrating comparative performance of a conventional SOP estimation technique and the SOP measurement technique according to the principles of the present application are illustrated. In FIG. **3**A, a comparison of the estimated SOP from an HPPC test and measured SOP from the SOP measurement technique of the present application are shown, with the measured SOP being less than the estimated SOP. In FIG. **3**B, the voltage response after applying the measured SOP in comparison to using the estimated SOP is shown, and it can be seen that the more accurate measured SOP results in the voltage response just reaching (but not exceeding) the voltage limit whereas the estimate SOP (which is too large) exceeds the voltage limit. FIGS. **3**C-**3**D similarly illustrate current and voltage responses after applying the estimated SOP from the HPPC test to the measured SOP using the iterative SOP measurement technique of the present application. Again, the current and voltage responses for the measured SOP just reaches voltage or current limits in all SOC breakpoint cases, whereas the current and voltage responses for the estimated SOP from the HPPC test deviate from the current/voltage limits and even reach more drastic critical safety limits. Finally, in FIG. **3**E, the more accurate measured SOP provides for extended battery system usability (e.g., greater power available for application) at higher SOC levels compared to the estimated SOP from the HPPC test as well as avoidance of potential damage at lower SOC levels (too large of power casing voltage to fall below minimum).

[0030] It will be appreciated that the term "controller" as used herein refers to any suitable control device or set of multiple control devices that is/are configured to perform at least a portion of the techniques of the present application. Non-limiting examples include an application-specific integrated circuit (ASIC), one or more processors and a non-transitory memory having instructions stored thereon that, when executed by the one or more processors, cause the controller to perform a set of operations corresponding to at least a portion of the techniques of the present application. The one or more processors could be either a single processor or two or more processors operating in a parallel or distributed architecture.

[0031] It should also be understood that the mixing and matching of features, elements, methodologies and/or functions between various examples may be expressly contemplated herein so that one skilled in the art would appreciate from the present teachings that features, elements and/or functions of one example may be incorporated into another example as appropriate, unless described otherwise above.

What is claimed is:

1. A state of power (SOP) measurement system for a battery system, the SOP measurement system comprising:

a set of sensors configured to measure a set of parameters of the battery system, the set of parameters including at least a state of charge (SOC) and a current or voltage of the battery system; and

a control system configured to determine an initial power command corresponding to a potential SOP of the battery system and perform an iterative power command searching process including:

preparing the battery system by charging the battery system to a fully-charged SOC;

discharging the battery system to a set of SOC breakpoints until the battery system reaches a fully-discharged SOC;

after reaching each SOC breakpoint, applying a power command as a constant power pulse to the battery system, the power command being the initial power command or a subsequently updated power command;

when a current or voltage of the battery system exceeds an error tolerance, updating the initial power command and repeating the iterative power command searching process; and

when the current or voltage of the battery system does not exceed the error tolerance, outputting the initial power command or the subsequently updated power command as a measured SOP of the battery system.

2. The SOP measurement system of claim **1**, wherein the initial power command is a power based on an SOP estimation algorithm to be validated, and wherein the SOP estimation algorithm to be validated is one of a battery model-based SOP estimation algorithm and a machine learning-based SOP estimation algorithm.

3. The SOP measurement system of claim **1**, wherein the initial power command is a power determined using a pulse-based battery test.

4. The SOP measurement system of claim **3**, wherein the pulse-based battery test is one of a hybrid power pulse characterization (HPPC) test, a constant voltage (CV) test, a constant current (CC) test, and a constant current, constant voltage (CCCV) or constant power (CP) test.

5. The SOP measurement system of claim **1**, wherein the fully-charged SOC is approximately 100% and the fully-discharged SOC is approximately 0%.

6. The SOP measurement system of claim **1**, wherein:

the set of parameters of the battery system further includes an internal temperature of the battery system;

the battery system is placed in a thermal chamber that is temperature-controlled by the control system; and

the preparing of the battery system further includes the internal temperature of the battery system achieving a desired temperature.

7. The SOP measurement system of claim **1**, wherein the iterative power capability searching technique further comprises determining an open circuit voltage (OCV) of the battery system after the discharging and a rest period.

8. The SOP measurement system of claim **1**, wherein the discharging of the battery system is a constant discharge rate.

9. The SOP measurement system of claim **1**, wherein the discharging of the battery system is a vehicle drive cycle discharge or a load profile for an application of interest.

10. The SOP measurement system of claim **9**, wherein the battery system is a high voltage battery system of an electrified powertrain of an electrified vehicle, and wherein the control system is configured to output the measured SOP of the high voltage battery system into a controller of the electrified vehicle that utilizes the measured SOP of the high voltage battery system for control of the electrified powertrain.

11. A state of power (SOP) measurement method for a battery system, the SOP measurement method comprising:

providing a set of sensors configured to measure a set of parameters of the battery system, the set of parameters including at least a state of charge (SOC) and a current or voltage of the battery system; and

providing a control system configured to determine an initial power command corresponding to a potential SOP of the battery system and perform an iterative power command searching process including:

preparing the battery system by charging the battery system to a fully-charged SOC;

discharging the battery system to a set of SOC breakpoints until the battery system reaches a fully-discharged SOC;

after reaching each SOC breakpoint, applying a power command as a constant power pulse to the battery system, the power command being the initial power command or a subsequently updated power command;

when a current or voltage of the battery system exceeds an error tolerance, updating the initial power command and repeating the iterative power command searching process; and

when the current or voltage of the battery system does not exceed the error tolerance, outputting the initial power command or the subsequently updated power command as a measured SOP of the battery system.

12. The SOP measurement method of claim **11**, wherein the initial power command is a power based on an SOP estimation algorithm to be validated, and wherein the SOP estimation algorithm to be validated is one of a battery model-based SOP estimation algorithm and a machine learning-based SOP estimation algorithm.

13. The SOP measurement method of claim **11**, wherein the initial power command is a power using a pulse-based battery test.

14. The SOP measurement method of claim **13**, wherein the pulse-based battery test is one of a hybrid power pulse characterization (HPPC) test, a constant voltage (CV) test, a constant current (CC) test, and a constant current, constant voltage (CCCV) or constant power (CP) test.

15. The SOP measurement method of claim **11**, wherein the fully-charged SOC is approximately 100% and the fully-discharged SOC is approximately 0%.

16. The SOP measurement method of claim **11**, wherein:

the set of parameters of the battery system further includes an internal temperature of the battery system;

the battery system is placed in a thermal chamber that is temperature-controlled by the control system; and

the preparing of the battery system further includes the internal temperature of the battery system achieving a desired temperature.

17. The SOP measurement method of claim **11**, wherein the iterative power capability searching technique further comprises determining an open circuit voltage (OCV) of the battery system after the discharging and a rest period.

18. The SOP measurement method of claim **11**, wherein the discharging of the battery system is a constant discharge rate.

19. The SOP measurement method of claim **11**, wherein the discharging of the battery system is a vehicle drive cycle discharge or a load profile for an application of interest.

20. The SOP measurement method of claim **19**, wherein the battery system is a high voltage battery system of an electrified powertrain of an electrified vehicle, and wherein the control system is configured to output the measured SOP of the high voltage battery system into a controller of the electrified vehicle that utilizes the measured SOP of the high voltage battery system for control of the electrified powertrain.

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