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Plett

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(45) **Date of Patent: Nov. 4, 2008**

(54) **SYSTEM, METHOD, AND ARTICLE OF MANUFACTURE FOR DETERMINING AN ESTIMATED BATTERY STATE VECTOR**

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(73) Assignee: **LG Chem, Ltd.** (KR)

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(22) Filed: **Nov. 10, 2005**

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(51) **Int. Cl.**
H02J 7/00 (2006.01)

(52) **U.S. Cl.** **320/132**; 324/432

(58) **Field of Classification Search** 324/427, 324/430, 433, 434, 432; 320/127, 128, 149, 320/DIG. 21, 132; 702/63, 64, 65, 83, 111, 702/146, 147, 181, 182, 190, 191, 192, 193, 702/194, 195, 199

See application file for complete search history.

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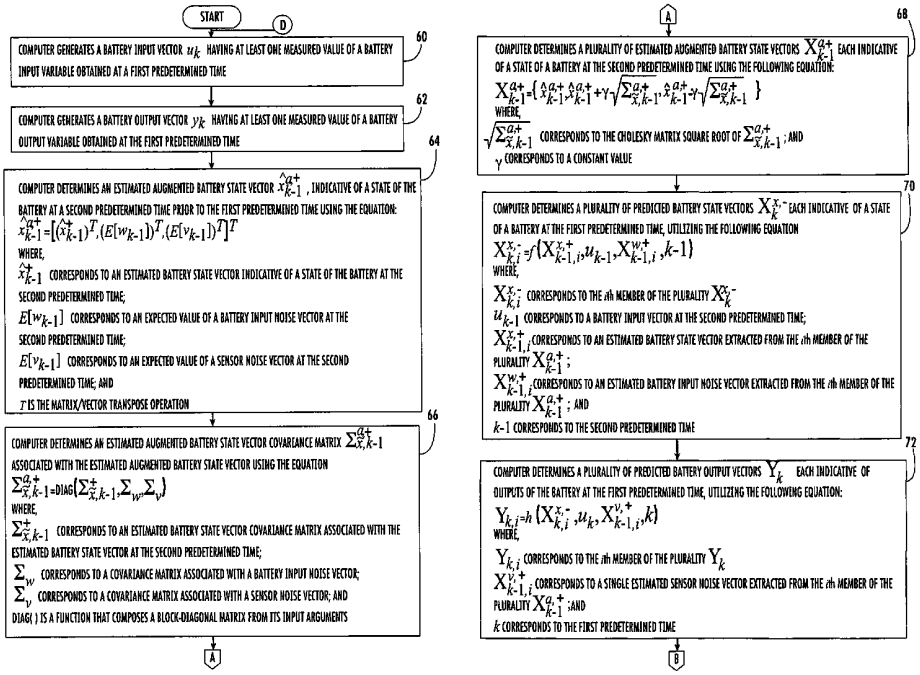
(57) **ABSTRACT**

A system, a method, and an article of manufacture for determining an estimated battery state vector indicative of a state of a battery are provided. The method determines a first estimated battery state vector indicative of the state of the battery at a first predetermined time based on a plurality of predicted battery state vectors, a plurality of predicted battery output vectors, and a first battery output vector.

15 Claims, 9 Drawing Sheets



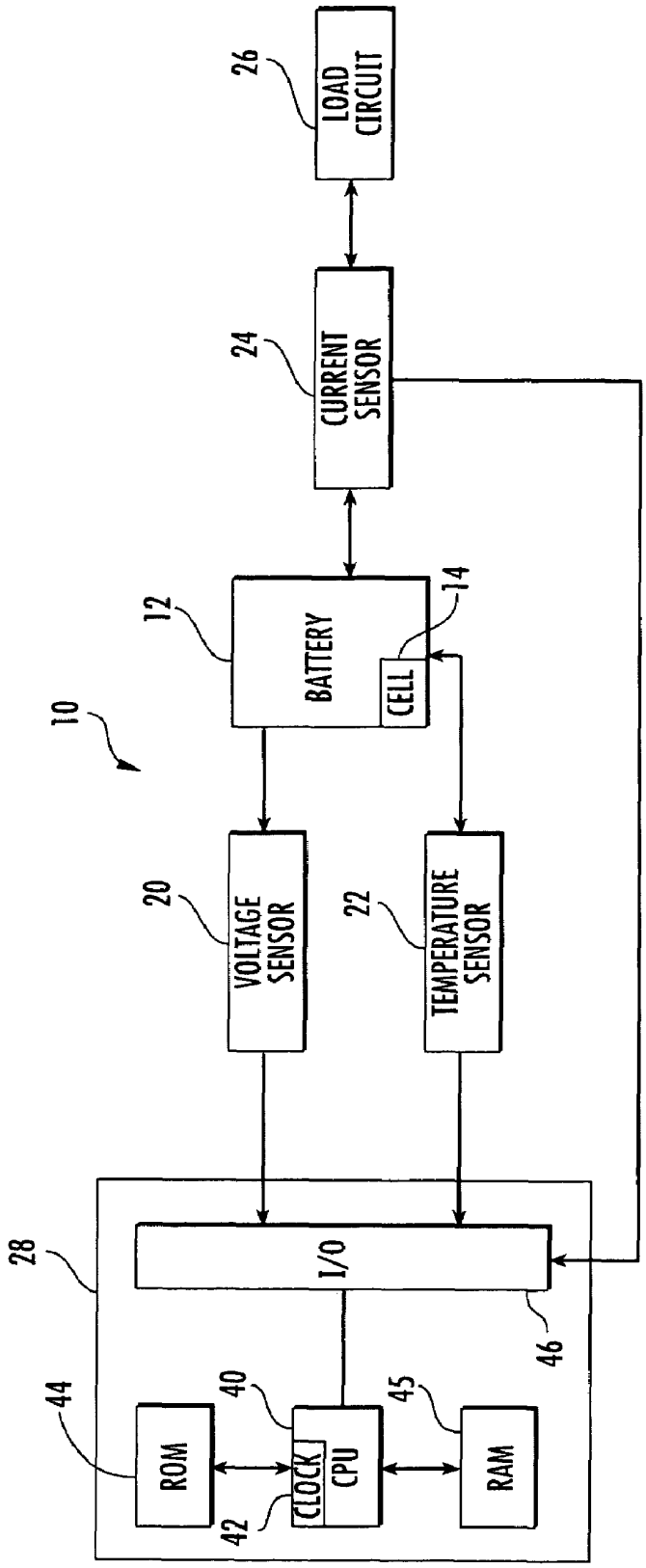

26
LOAD CIRCUIT
24
CURRENT SENSOR
12
BATTERY
14
CELL
10
20
VOLTAGE SENSOR
22
TEMPERATURE SENSOR
28
I/O
46
44
ROM
40
CLOCK
CPU
42
45
RAM

FIG. 1

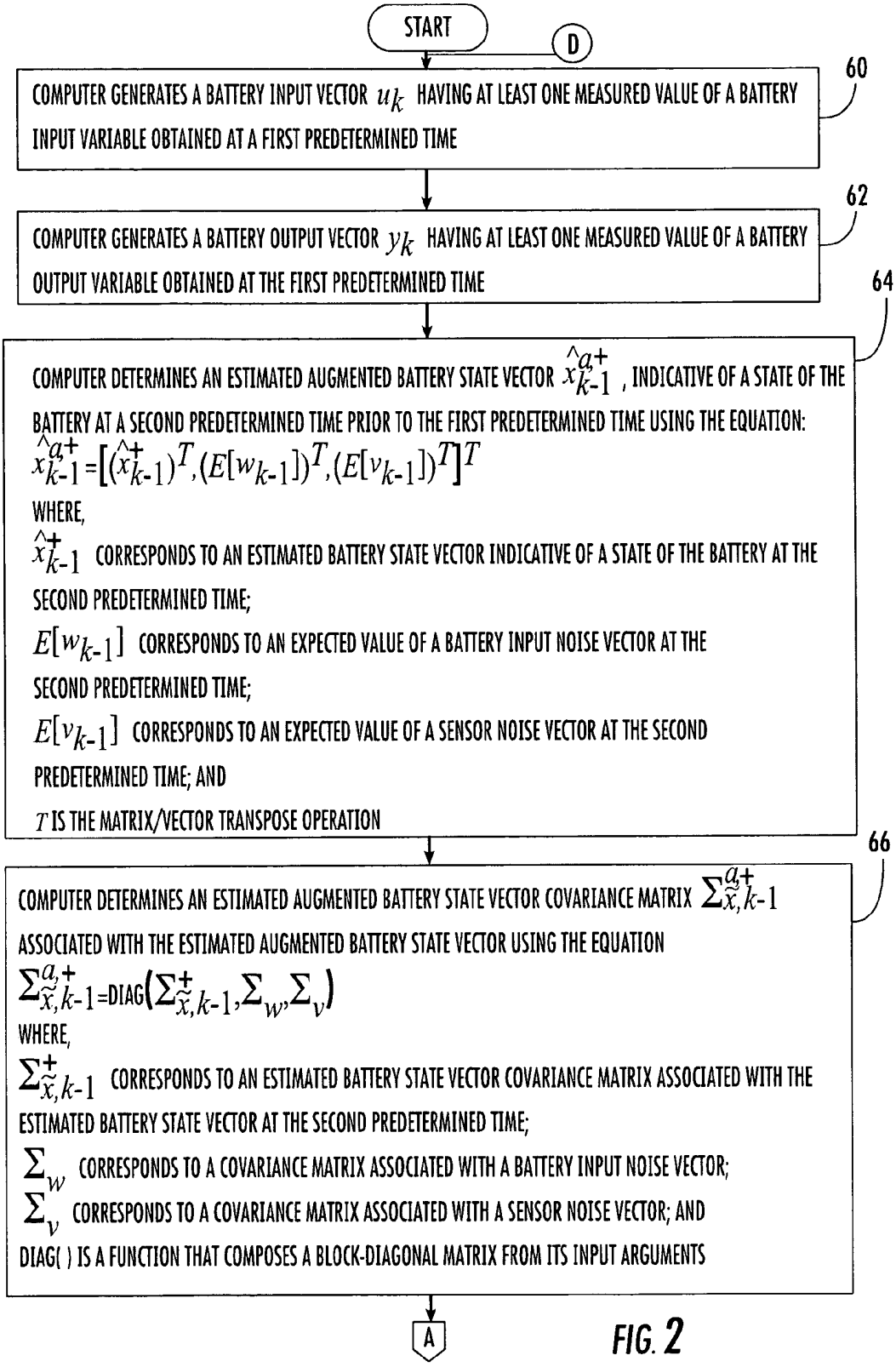

START
D
COMPUTER GENERATES A BATTERY INPUT VECTOR u_k HAVING AT LEAST ONE MEASURED VALUE OF A BATTERY INPUT VARIABLE OBTAINED AT A FIRST PREDETERMINED TIME
60
COMPUTER GENERATES A BATTERY OUTPUT VECTOR y_k HAVING AT LEAST ONE MEASURED VALUE OF A BATTERY OUTPUT VARIABLE OBTAINED AT THE FIRST PREDETERMINED TIME
62
64
COMPUTER DETERMINES AN ESTIMATED AUGMENTED BATTERY STATE VECTOR $\hat{x}^{a,+}_{k-1}$, INDICATIVE OF A STATE OF THE BATTERY AT A SECOND PREDETERMINED TIME PRIOR TO THE FIRST PREDETERMINED TIME USING THE EQUATION:
$\hat{x}^{a,+}_{k-1}=[(\hat{x}^{+}_{k-1})^T,(E[w_{k-1}])^T,(E[v_{k-1}])^T]^T$
WHERE,
$\hat{x}^{+}_{k-1}$ CORRESPONDS TO AN ESTIMATED BATTERY STATE VECTOR INDICATIVE OF A STATE OF THE BATTERY AT THE SECOND PREDETERMINED TIME;
$E[w_{k-1}]$ CORRESPONDS TO AN EXPECTED VALUE OF A BATTERY INPUT NOISE VECTOR AT THE SECOND PREDETERMINED TIME;
$E[v_{k-1}]$ CORRESPONDS TO AN EXPECTED VALUE OF A SENSOR NOISE VECTOR AT THE SECOND PREDETERMINED TIME; AND
T IS THE MATRIX/VECTOR TRANSPOSE OPERATION
66
COMPUTER DETERMINES AN ESTIMATED AUGMENTED BATTERY STATE VECTOR COVARIANCE MATRIX $\Sigma^{a,+}_{\tilde{x},k-1}$ ASSOCIATED WITH THE ESTIMATED AUGMENTED BATTERY STATE VECTOR USING THE EQUATION
$\Sigma^{a,+}_{\tilde{x},k-1}=\mathrm{DIAG}(\Sigma^{+}_{\tilde{x},k-1},\Sigma_w,\Sigma_v)$
WHERE,
$\Sigma^{+}_{\tilde{x},k-1}$ CORRESPONDS TO AN ESTIMATED BATTERY STATE VECTOR COVARIANCE MATRIX ASSOCIATED WITH THE ESTIMATED BATTERY STATE VECTOR AT THE SECOND PREDETERMINED TIME;
Σ_w CORRESPONDS TO A COVARIANCE MATRIX ASSOCIATED WITH A BATTERY INPUT NOISE VECTOR;
Σ_v CORRESPONDS TO A COVARIANCE MATRIX ASSOCIATED WITH A SENSOR NOISE VECTOR; AND
DIAG( ) IS A FUNCTION THAT COMPOSES A BLOCK-DIAGONAL MATRIX FROM ITS INPUT ARGUMENTS
A

FIG. 2

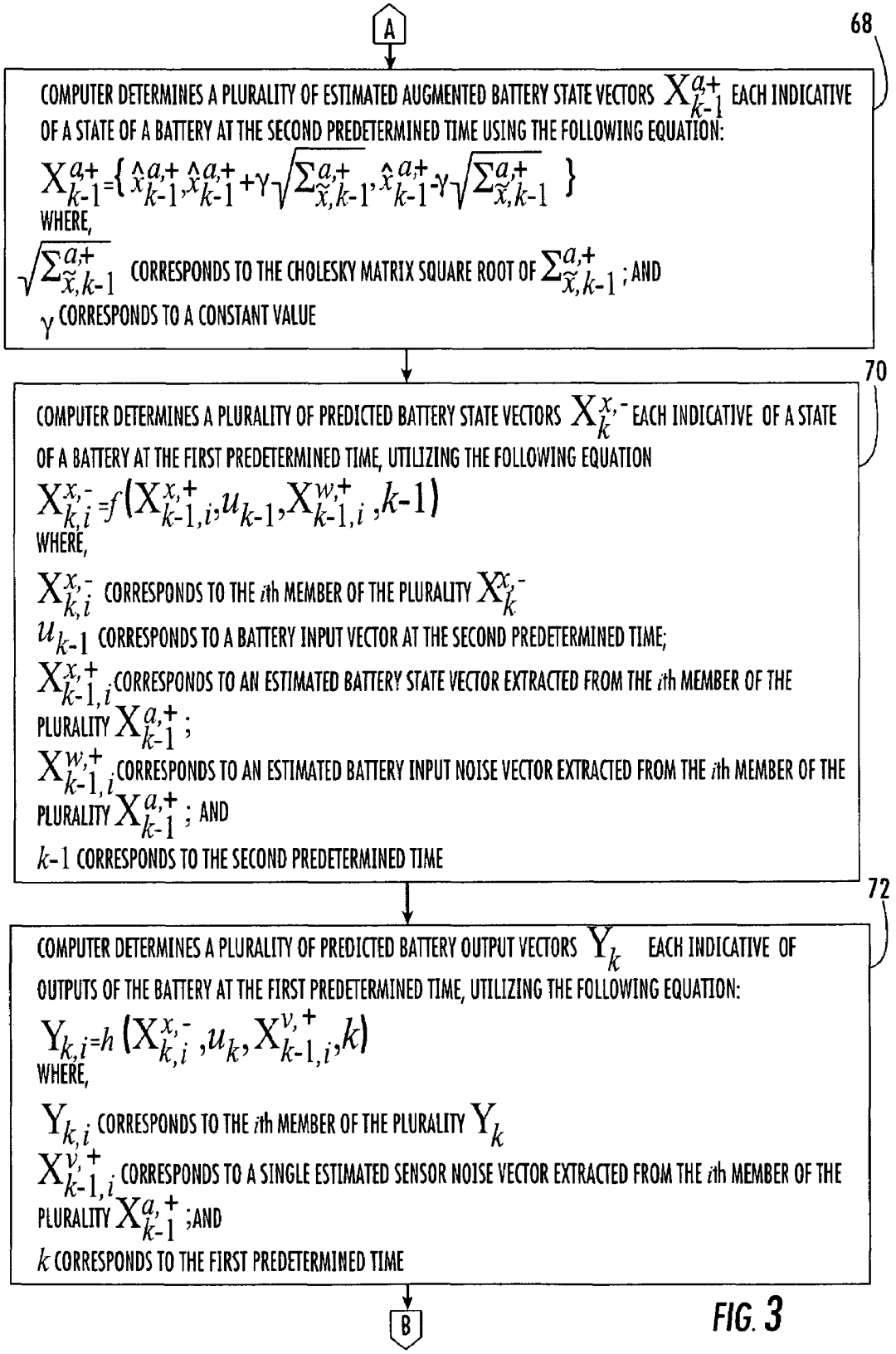

A
68
COMPUTER DETERMINES A PLURALITY OF ESTIMATED AUGMENTED BATTERY STATE VECTORS $X_{k-1}^{a,+}$ EACH INDICATIVE OF A STATE OF A BATTERY AT THE SECOND PREDETERMINED TIME USING THE FOLLOWING EQUATION:
$X_{k-1}^{a,+}=\{\hat{x}_{k-1}^{a,+}, \hat{x}_{k-1}^{a,+}+\gamma\sqrt{\Sigma_{\tilde{x},k-1}^{a,+}}, \hat{x}_{k-1}^{a,+}-\gamma\sqrt{\Sigma_{\tilde{x},k-1}^{a,+}}\}$
WHERE,
$\sqrt{\Sigma_{\tilde{x},k-1}^{a,+}}$ CORRESPONDS TO THE CHOLESKY MATRIX SQUARE ROOT OF $\Sigma_{\tilde{x},k-1}^{a,+}$; AND
γ CORRESPONDS TO A CONSTANT VALUE
70
COMPUTER DETERMINES A PLURALITY OF PREDICTED BATTERY STATE VECTORS $X_k^{x,-}$ EACH INDICATIVE OF A STATE OF A BATTERY AT THE FIRST PREDETERMINED TIME, UTILIZING THE FOLLOWING EQUATION
$X_{k,i}^{x,-}=f(X_{k-1,i}^{x,+}, u_{k-1}, X_{k-1,i}^{w,+}, k-1)$
WHERE,
$X_{k,i}^{x,-}$ CORRESPONDS TO THE ith MEMBER OF THE PLURALITY $X_k^{x,-}$
u_{k-1} CORRESPONDS TO A BATTERY INPUT VECTOR AT THE SECOND PREDETERMINED TIME;
$X_{k-1,i}^{x,+}$ CORRESPONDS TO AN ESTIMATED BATTERY STATE VECTOR EXTRACTED FROM THE ith MEMBER OF THE PLURALITY $X_{k-1}^{a,+}$;
$X_{k-1,i}^{w,+}$ CORRESPONDS TO AN ESTIMATED BATTERY INPUT NOISE VECTOR EXTRACTED FROM THE ith MEMBER OF THE PLURALITY $X_{k-1}^{a,+}$; AND
$k-1$ CORRESPONDS TO THE SECOND PREDETERMINED TIME
72
COMPUTER DETERMINES A PLURALITY OF PREDICTED BATTERY OUTPUT VECTORS Y_k EACH INDICATIVE OF OUTPUTS OF THE BATTERY AT THE FIRST PREDETERMINED TIME, UTILIZING THE FOLLOWING EQUATION:
$Y_{k,i}=h(X_{k,i}^{x,-}, u_k, X_{k-1,i}^{v,+}, k)$
WHERE,
$Y_{k,i}$ CORRESPONDS TO THE ith MEMBER OF THE PLURALITY Y_k
$X_{k-1,i}^{v,+}$ CORRESPONDS TO A SINGLE ESTIMATED SENSOR NOISE VECTOR EXTRACTED FROM THE ith MEMBER OF THE PLURALITY $X_{k-1}^{a,+}$; AND
k CORRESPONDS TO THE FIRST PREDETERMINED TIME
B

FIG. 3

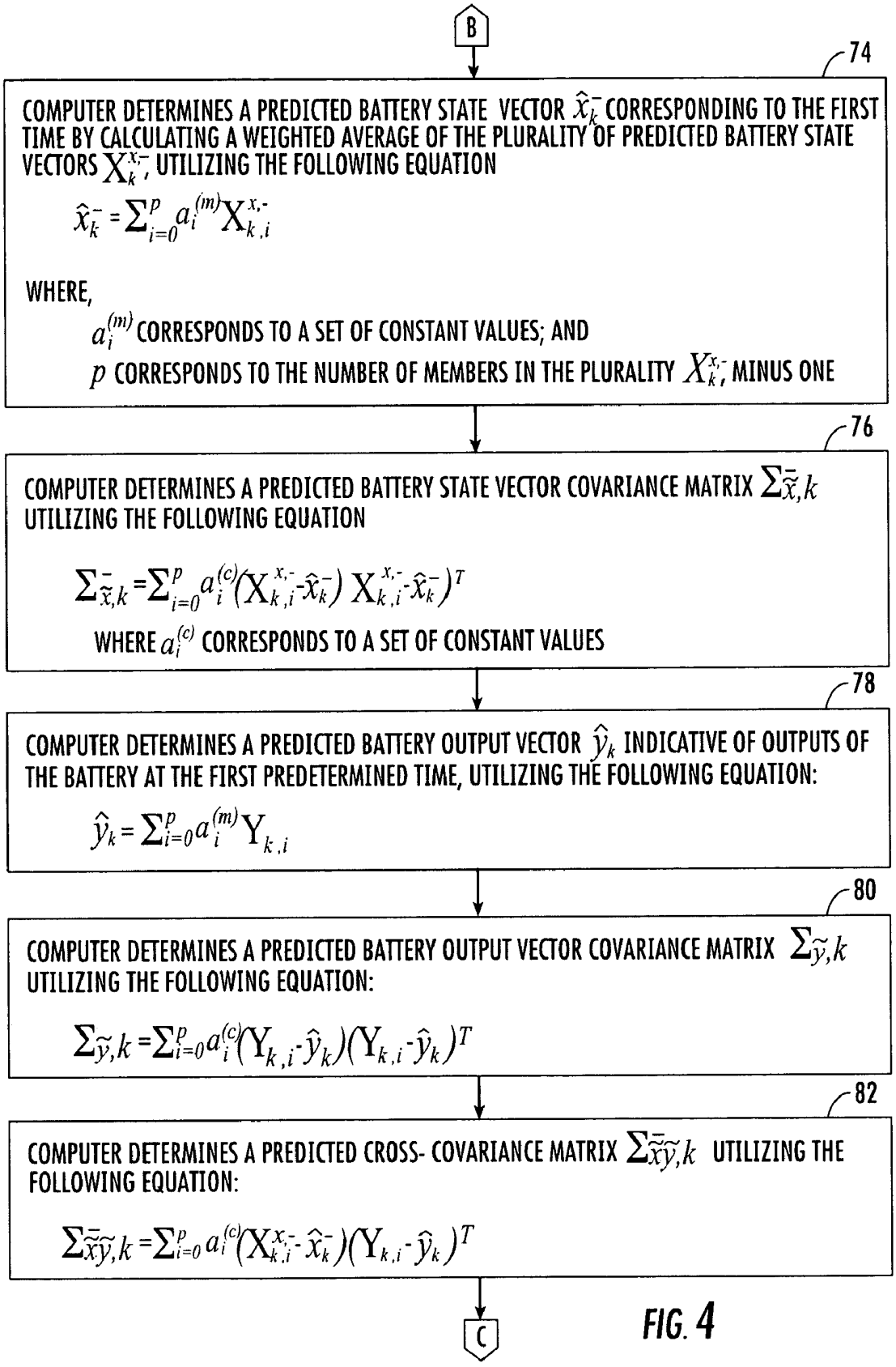
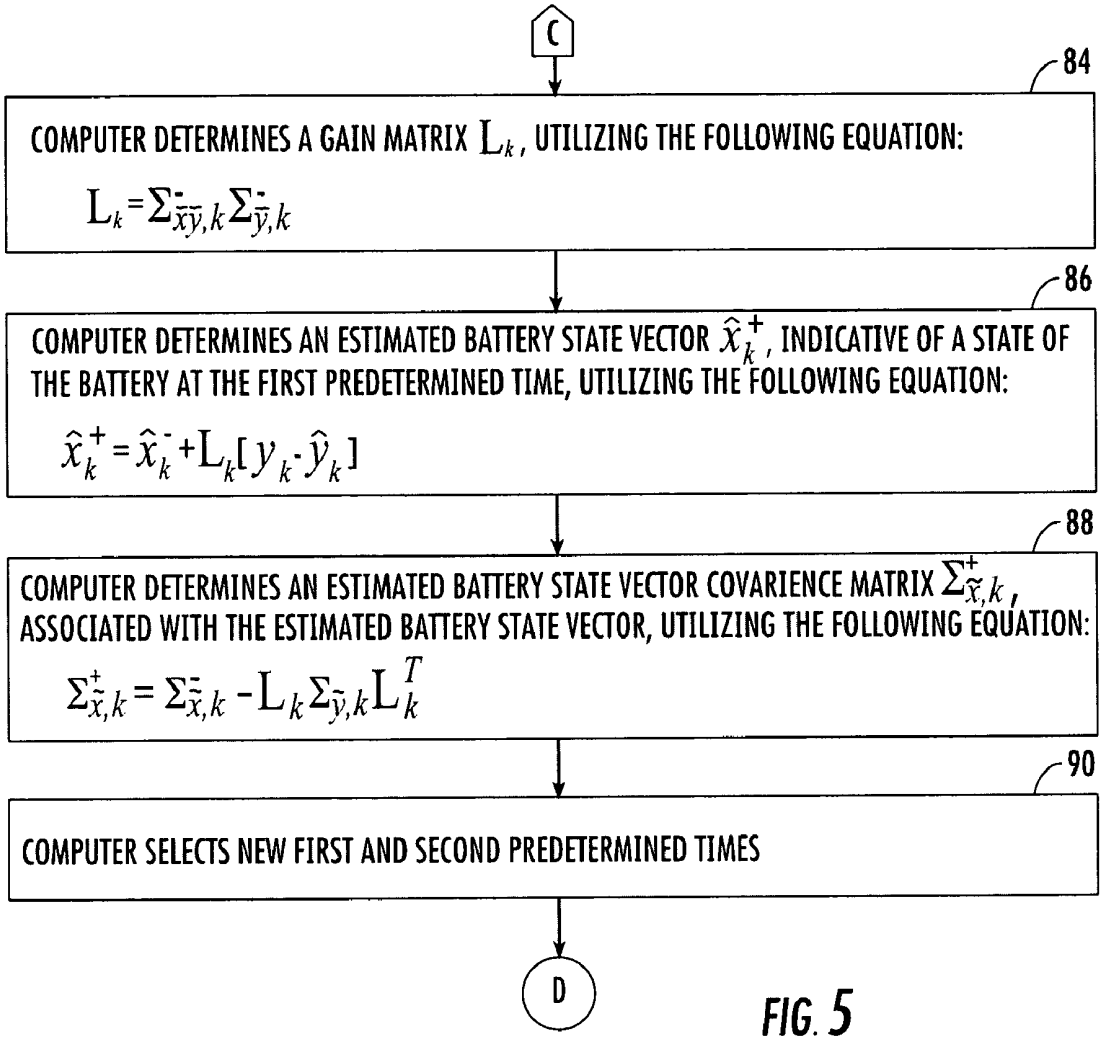

B
74
COMPUTER DETERMINES A PREDICTED BATTERY STATE VECTOR $\hat{x}_k^-$ CORRESPONDING TO THE FIRST TIME BY CALCULATING A WEIGHTED AVERAGE OF THE PLURALITY OF PREDICTED BATTERY STATE VECTORS $X_k^{x,-}$, UTILIZING THE FOLLOWING EQUATION
$\hat{x}_k^- = \sum_{i=0}^{p} a_i^{(m)} X_{k,i}^{x,-}$
WHERE,
$a_i^{(m)}$ CORRESPONDS TO A SET OF CONSTANT VALUES; AND
p CORRESPONDS TO THE NUMBER OF MEMBERS IN THE PLURALITY $X_k^{x,-}$ MINUS ONE
76
COMPUTER DETERMINES A PREDICTED BATTERY STATE VECTOR COVARIANCE MATRIX $\Sigma_{\tilde{x},k}^-$ UTILIZING THE FOLLOWING EQUATION
$\Sigma_{\tilde{x},k}^- = \sum_{i=0}^{p} a_i^{(c)} (X_{k,i}^{x,-} - \hat{x}_k^-)(X_{k,i}^{x,-} - \hat{x}_k^-)^T$
WHERE $a_i^{(c)}$ CORRESPONDS TO A SET OF CONSTANT VALUES
78
COMPUTER DETERMINES A PREDICTED BATTERY OUTPUT VECTOR $\hat{y}_k$ INDICATIVE OF OUTPUTS OF THE BATTERY AT THE FIRST PREDETERMINED TIME, UTILIZING THE FOLLOWING EQUATION:
$\hat{y}_k = \sum_{i=0}^{p} a_i^{(m)} Y_{k,i}$
80
COMPUTER DETERMINES A PREDICTED BATTERY OUTPUT VECTOR COVARIANCE MATRIX $\Sigma_{\tilde{y},k}$ UTILIZING THE FOLLOWING EQUATION:
$\Sigma_{\tilde{y},k} = \sum_{i=0}^{p} a_i^{(c)} (Y_{k,i} - \hat{y}_k)(Y_{k,i} - \hat{y}_k)^T$
82
COMPUTER DETERMINES A PREDICTED CROSS- COVARIANCE MATRIX $\Sigma_{\tilde{x}\tilde{y},k}^-$ UTILIZING THE FOLLOWING EQUATION:
$\Sigma_{\tilde{x}\tilde{y},k}^- = \sum_{i=0}^{p} a_i^{(c)} (X_{k,i}^{x,-} - \hat{x}_k^-)(Y_{k,i} - \hat{y}_k)^T$
C

FIG. 4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COMPUTER DETERMINES A GAIN MATRIX L_k, UTILIZING THE FOLLOWING EQUATION:
$L_k = \Sigma^{-}_{\tilde{x}\tilde{y},k} \Sigma^{-}_{\tilde{y},k}$
86
COMPUTER DETERMINES AN ESTIMATED BATTERY STATE VECTOR $\hat{x}_k^+$, INDICATIVE OF A STATE OF THE BATTERY AT THE FIRST PREDETERMINED TIME, UTILIZING THE FOLLOWING EQUATION:
$\hat{x}_k^+ = \hat{x}_k^- + L_k[y_k - \hat{y}_k]$
88
COMPUTER DETERMINES AN ESTIMATED BATTERY STATE VECTOR COVARIENCE MATRIX $\Sigma^{+}_{\tilde{x},k}$, ASSOCIATED WITH THE ESTIMATED BATTERY STATE VECTOR, UTILIZING THE FOLLOWING EQUATION:
$\Sigma^{+}_{\tilde{x},k} = \Sigma^{-}_{\tilde{x},k} - L_k \Sigma_{\tilde{y},k} L_k^T$
90
COMPUTER SELECTS NEW FIRST AND SECOND PREDETERMINED TIMES
D

FIG. 5

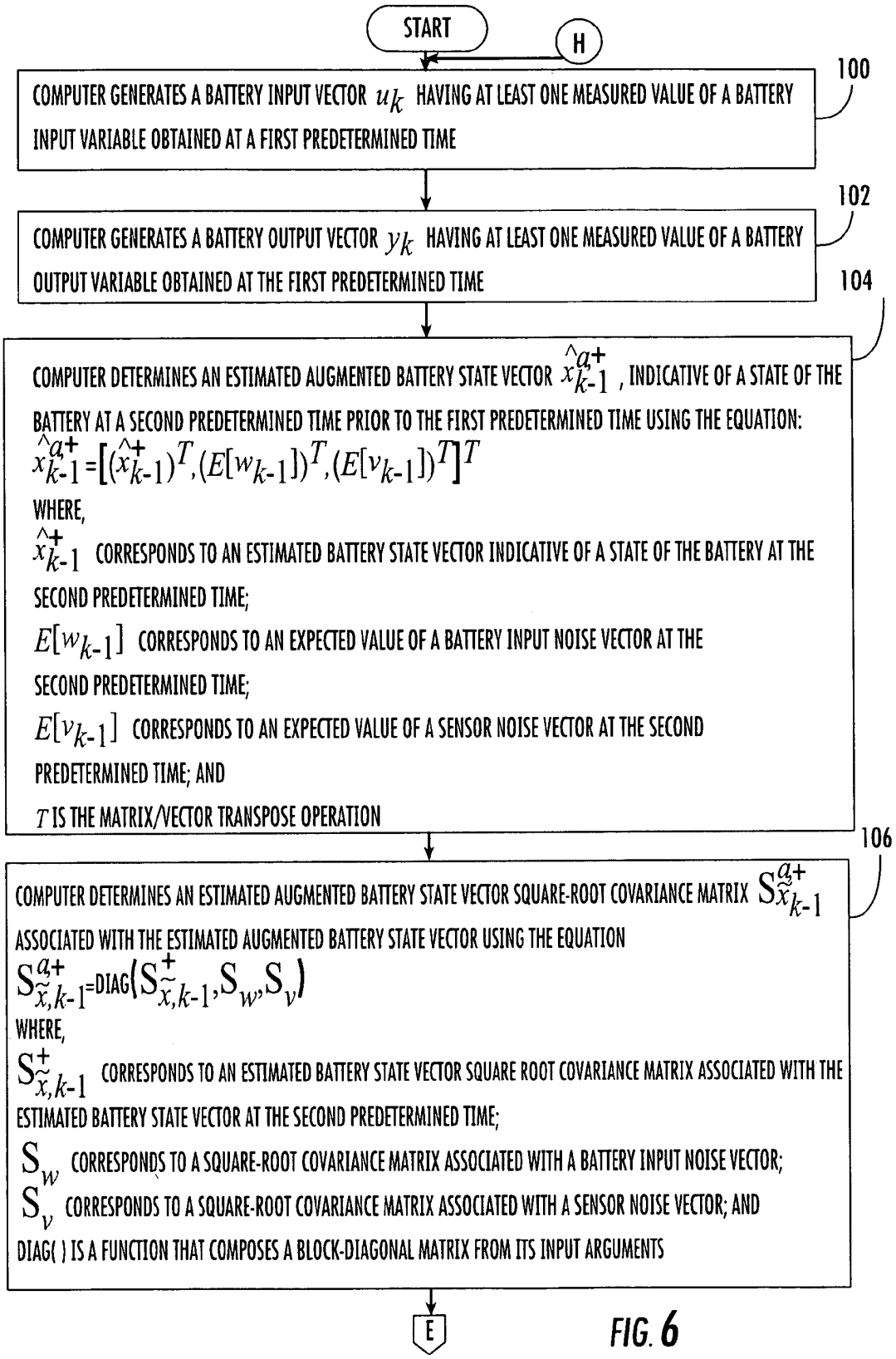
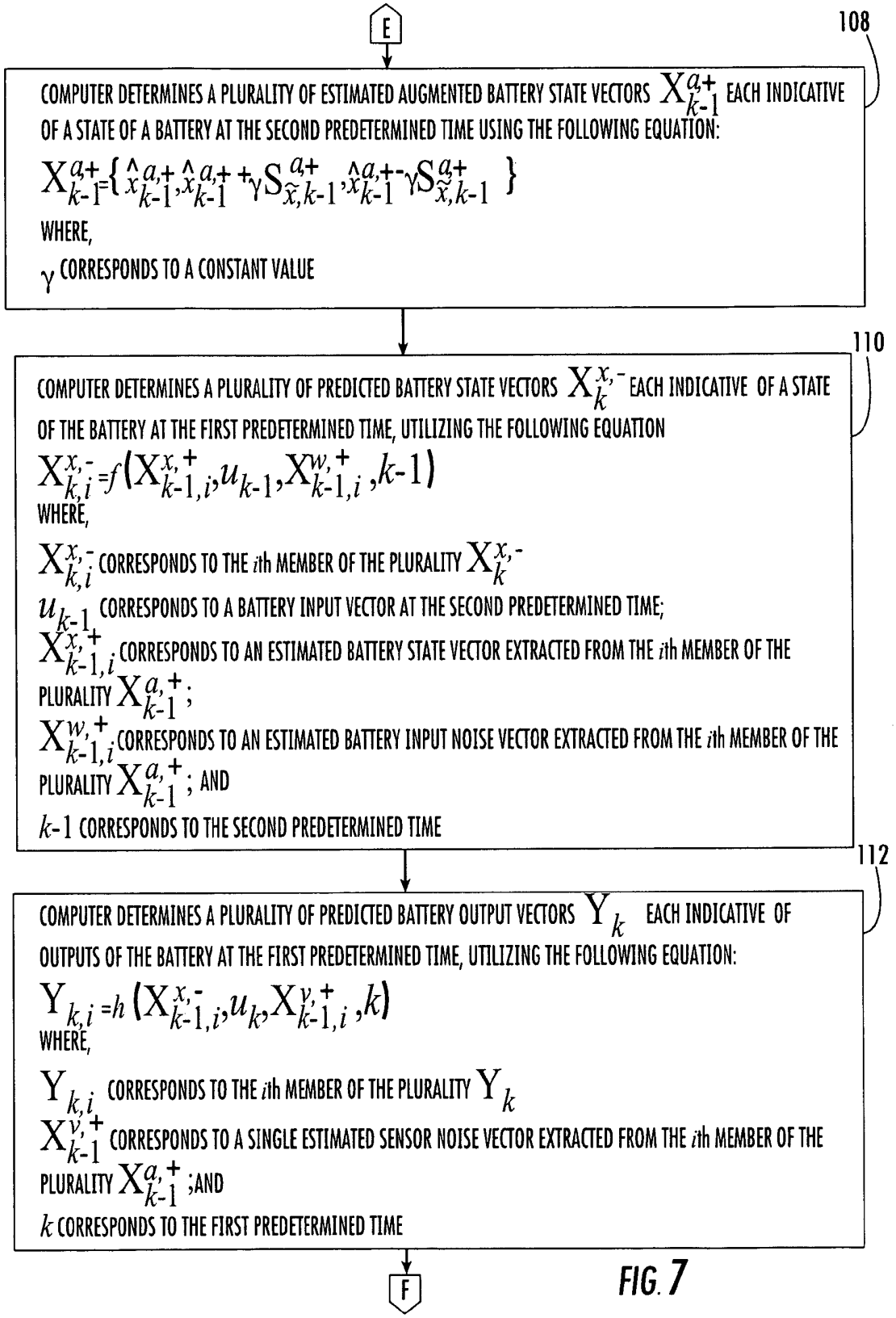

START
H
COMPUTER GENERATES A BATTERY INPUT VECTOR u_k HAVING AT LEAST ONE MEASURED VALUE OF A BATTERY INPUT VARIABLE OBTAINED AT A FIRST PREDETERMINED TIME
100
COMPUTER GENERATES A BATTERY OUTPUT VECTOR y_k HAVING AT LEAST ONE MEASURED VALUE OF A BATTERY OUTPUT VARIABLE OBTAINED AT THE FIRST PREDETERMINED TIME
102
COMPUTER DETERMINES AN ESTIMATED AUGMENTED BATTERY STATE VECTOR $\hat{x}^{a+}_{k-1}$, INDICATIVE OF A STATE OF THE BATTERY AT A SECOND PREDETERMINED TIME PRIOR TO THE FIRST PREDETERMINED TIME USING THE EQUATION:
$\hat{x}^{a+}_{k-1}=[(\hat{x}^{+}_{k-1})^T,(E[w_{k-1}])^T,(E[v_{k-1}])^T]^T$
WHERE,
$\hat{x}^{+}_{k-1}$ CORRESPONDS TO AN ESTIMATED BATTERY STATE VECTOR INDICATIVE OF A STATE OF THE BATTERY AT THE SECOND PREDETERMINED TIME;
$E[w_{k-1}]$ CORRESPONDS TO AN EXPECTED VALUE OF A BATTERY INPUT NOISE VECTOR AT THE SECOND PREDETERMINED TIME;
$E[v_{k-1}]$ CORRESPONDS TO AN EXPECTED VALUE OF A SENSOR NOISE VECTOR AT THE SECOND PREDETERMINED TIME; AND
T IS THE MATRIX/VECTOR TRANSPOSE OPERATION
104
COMPUTER DETERMINES AN ESTIMATED AUGMENTED BATTERY STATE VECTOR SQUARE-ROOT COVARIANCE MATRIX $S^{a,+}_{\tilde{x}_{k-1}}$ ASSOCIATED WITH THE ESTIMATED AUGMENTED BATTERY STATE VECTOR USING THE EQUATION
$S^{a,+}_{\tilde{x},k-1}=\mathrm{DIAG}(S^{+}_{\tilde{x},k-1},S_w,S_v)$
WHERE,
$S^{+}_{\tilde{x},k-1}$ CORRESPONDS TO AN ESTIMATED BATTERY STATE VECTOR SQUARE ROOT COVARIANCE MATRIX ASSOCIATED WITH THE ESTIMATED BATTERY STATE VECTOR AT THE SECOND PREDETERMINED TIME;
S_w CORRESPONDS TO A SQUARE-ROOT COVARIANCE MATRIX ASSOCIATED WITH A BATTERY INPUT NOISE VECTOR;
S_v CORRESPONDS TO A SQUARE-ROOT COVARIANCE MATRIX ASSOCIATED WITH A SENSOR NOISE VECTOR; AND
DIAG( ) IS A FUNCTION THAT COMPOSES A BLOCK-DIAGONAL MATRIX FROM ITS INPUT ARGUMENTS
106
E

FIG. 6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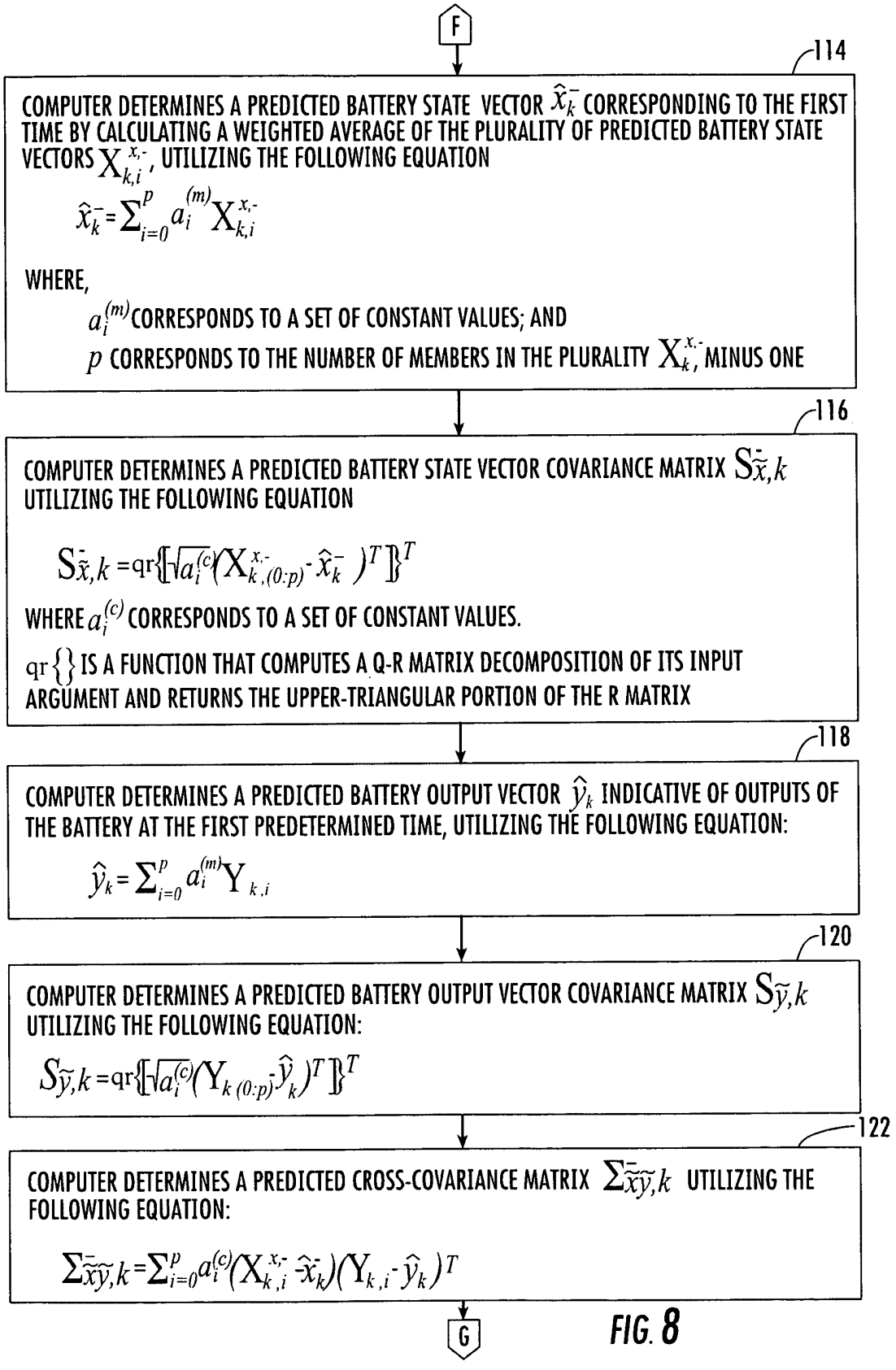
108
COMPUTER DETERMINES A PLURALITY OF ESTIMATED AUGMENTED BATTERY STATE VECTORS $X_{k-1}^{a,+}$ EACH INDICATIVE OF A STATE OF A BATTERY AT THE SECOND PREDETERMINED TIME USING THE FOLLOWING EQUATION:
$X_{k-1}^{a,+}=\{\hat{x}_{k-1}^{a,+},\hat{x}_{k-1}^{a,+}+\gamma S_{\tilde{x},k-1}^{a,+},\hat{x}_{k-1}^{a,+}-\gamma S_{\tilde{x},k-1}^{a,+}\}$
WHERE,
γ CORRESPONDS TO A CONSTANT VALUE
110
COMPUTER DETERMINES A PLURALITY OF PREDICTED BATTERY STATE VECTORS $X_k^{x,-}$ EACH INDICATIVE OF A STATE OF THE BATTERY AT THE FIRST PREDETERMINED TIME, UTILIZING THE FOLLOWING EQUATION
$X_{k,i}^{x,-}=f(X_{k-1,i}^{x,+},u_{k-1},X_{k-1,i}^{w,+},k-1)$
WHERE,
$X_{k,i}^{x,-}$ CORRESPONDS TO THE ith MEMBER OF THE PLURALITY $X_k^{x,-}$
u_{k-1} CORRESPONDS TO A BATTERY INPUT VECTOR AT THE SECOND PREDETERMINED TIME;
$X_{k-1,i}^{x,+}$ CORRESPONDS TO AN ESTIMATED BATTERY STATE VECTOR EXTRACTED FROM THE ith MEMBER OF THE PLURALITY $X_{k-1}^{a,+}$;
$X_{k-1,i}^{w,+}$ CORRESPONDS TO AN ESTIMATED BATTERY INPUT NOISE VECTOR EXTRACTED FROM THE ith MEMBER OF THE PLURALITY $X_{k-1}^{a,+}$; AND
k-1 CORRESPONDS TO THE SECOND PREDETERMINED TIME
112
COMPUTER DETERMINES A PLURALITY OF PREDICTED BATTERY OUTPUT VECTORS Y_k EACH INDICATIVE OF OUTPUTS OF THE BATTERY AT THE FIRST PREDETERMINED TIME, UTILIZING THE FOLLOWING EQUATION:
$Y_{k,i}=h(X_{k-1,i}^{x,-},u_k,X_{k-1,i}^{v,+},k)$
WHERE,
$Y_{k,i}$ CORRESPONDS TO THE ith MEMBER OF THE PLURALITY Y_k
$X_{k-1}^{v,+}$ CORRESPONDS TO A SINGLE ESTIMATED SENSOR NOISE VECTOR EXTRACTED FROM THE ith MEMBER OF THE PLURALITY $X_{k-1}^{a,+}$; AND
k CORRESPONDS TO THE FIRST PREDETERMINED TIME
F

FIG. 7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114
COMPUTER DETERMINES A PREDICTED BATTERY STATE VECTOR $\hat{x}_k^-$ CORRESPONDING TO THE FIRST TIME BY CALCULATING A WEIGHTED AVERAGE OF THE PLURALITY OF PREDICTED BATTERY STATE VECTORS $X_{k,i}^{x,-}$, UTILIZING THE FOLLOWING EQUATION
$\hat{x}_k^- = \sum_{i=0}^{p} a_i^{(m)} X_{k,i}^{x,-}$
WHERE,
$a_i^{(m)}$ CORRESPONDS TO A SET OF CONSTANT VALUES; AND
p CORRESPONDS TO THE NUMBER OF MEMBERS IN THE PLURALITY $X_k^{x,-}$, MINUS ONE
116
COMPUTER DETERMINES A PREDICTED BATTERY STATE VECTOR COVARIANCE MATRIX $S_{\tilde{x},k}^-$ UTILIZING THE FOLLOWING EQUATION
$S_{\tilde{x},k}^- = \mathrm{qr}\{[\sqrt{a_i^{(c)}}(X_{k,(0:p)}^{x,-} - \hat{x}_k^-)^T]\}^T$
WHERE $a_i^{(c)}$ CORRESPONDS TO A SET OF CONSTANT VALUES.
$\mathrm{qr}\{\}$ IS A FUNCTION THAT COMPUTES A Q-R MATRIX DECOMPOSITION OF ITS INPUT ARGUMENT AND RETURNS THE UPPER-TRIANGULAR PORTION OF THE R MATRIX
118
COMPUTER DETERMINES A PREDICTED BATTERY OUTPUT VECTOR $\hat{y}_k$ INDICATIVE OF OUTPUTS OF THE BATTERY AT THE FIRST PREDETERMINED TIME, UTILIZING THE FOLLOWING EQUATION:
$\hat{y}_k = \sum_{i=0}^{p} a_i^{(m)} Y_{k,i}$
120
COMPUTER DETERMINES A PREDICTED BATTERY OUTPUT VECTOR COVARIANCE MATRIX $S_{\tilde{y},k}$ UTILIZING THE FOLLOWING EQUATION:
$S_{\tilde{y},k} = \mathrm{qr}\{[\sqrt{a_i^{(c)}}(Y_{k(0:p)} - \hat{y}_k)^T]\}^T$
122
COMPUTER DETERMINES A PREDICTED CROSS-COVARIANCE MATRIX $\Sigma_{\tilde{x}\tilde{y},k}^-$ UTILIZING THE FOLLOWING EQUATION:
$\Sigma_{\tilde{x}\tilde{y},k}^- = \sum_{i=0}^{p} a_i^{(c)}(X_{k,i}^{x,-} - \hat{x}_k^-)(Y_{k,i} - \hat{y}_k)^T$
G

FIG. 8

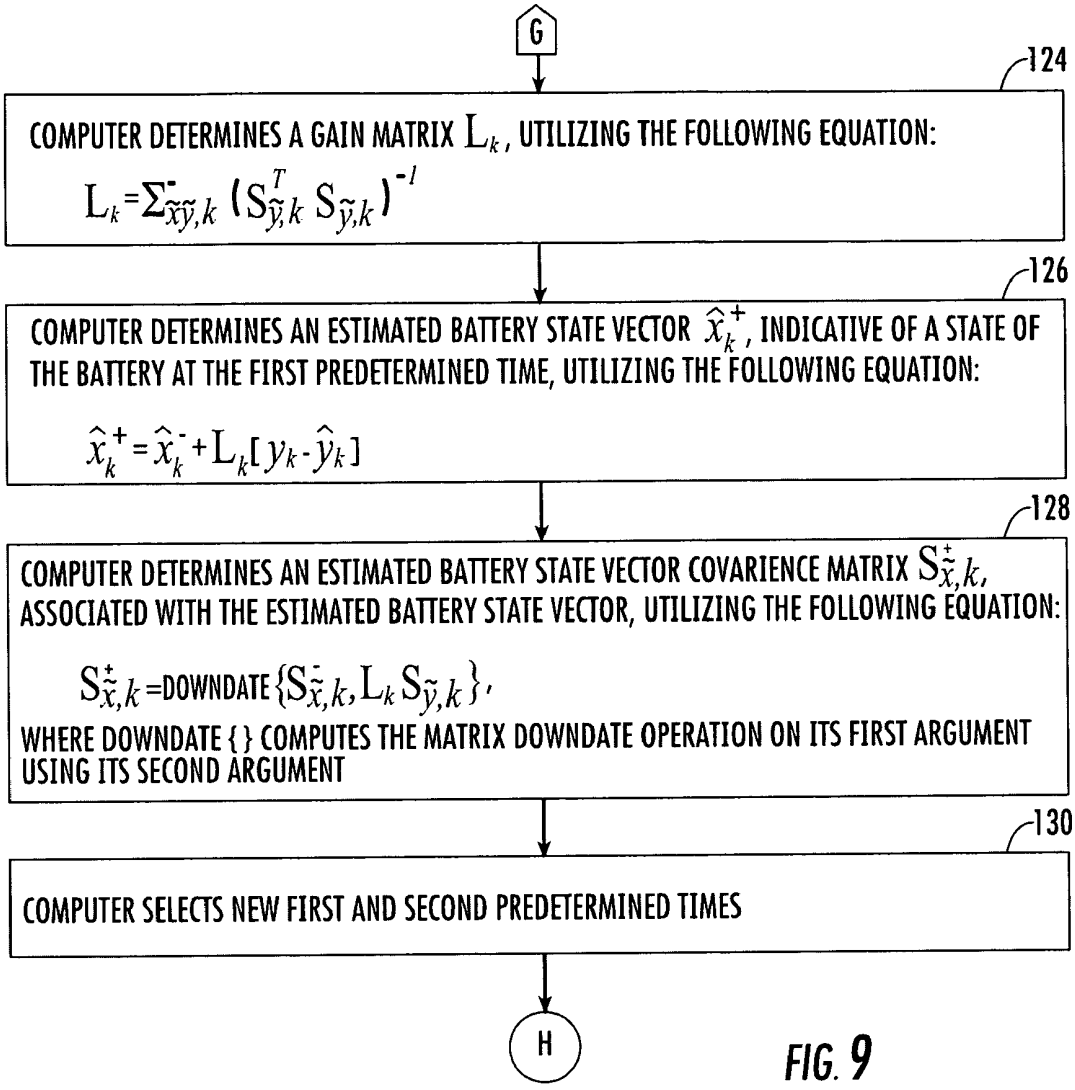
G
124
COMPUTER DETERMINES A GAIN MATRIX L_k, UTILIZING THE FOLLOWING EQUATION:
$L_k = \Sigma^{-}_{\tilde{x}\tilde{y},k} (S^{T}_{\tilde{y},k} S_{\tilde{y},k})^{-1}$
126
COMPUTER DETERMINES AN ESTIMATED BATTERY STATE VECTOR $\hat{x}_k^{+}$, INDICATIVE OF A STATE OF THE BATTERY AT THE FIRST PREDETERMINED TIME, UTILIZING THE FOLLOWING EQUATION:
$\hat{x}_k^{+} = \hat{x}_k^{-} + L_k[y_k - \hat{y}_k]$
128
COMPUTER DETERMINES AN ESTIMATED BATTERY STATE VECTOR COVARIENCE MATRIX $S^{+}_{\tilde{x},k}$, ASSOCIATED WITH THE ESTIMATED BATTERY STATE VECTOR, UTILIZING THE FOLLOWING EQUATION:
$S^{+}_{\tilde{x},k} = \text{DOWNDATE}\{S^{-}_{\tilde{x},k}, L_k S_{\tilde{y},k}\}$,
WHERE DOWNDATE { } COMPUTES THE MATRIX DOWNDATE OPERATION ON ITS FIRST ARGUMENT USING ITS SECOND ARGUMENT
130
COMPUTER SELECTS NEW FIRST AND SECOND PREDETERMINED TIMES
H

FIG. 9

SYSTEM, METHOD, AND ARTICLE OF MANUFACTURE FOR DETERMINING AN ESTIMATED BATTERY STATE VECTOR

BACKGROUND OF THE INVENTION

Batteries are used in a wide variety of electronic and electrical devices. It is desirable to be able to estimate the internal state of a battery, including a state-of-charge (SOC). The SOC is a value that indicates the present available capacity of the battery that may be used to do work.

Mathematical algorithms have been utilized to determine a state of a battery. The inventor herein, however, has recognized that the mathematical algorithms have been unable to provide a highly accurate estimate of an internal state of a battery because they are not sufficiently optimized for batteries having non-linear operational characteristics. Since batteries generally have non-linear operational characteristics, a more accurate method is needed.

Accordingly, the inventor herein has recognized a need for a system and a method for more accurately determining an estimated battery state.

BRIEF DESCRIPTION OF THE INVENTION

A method for determining an estimated battery state vector indicative of a state of a battery at a first predetermined time in accordance with an exemplary embodiment is provided. The method includes determining a first plurality of estimated augmented battery state vectors that are indicative of a state of the battery, a battery input noise, a sensor noise, an uncertainty of the state of the battery, an uncertainty of the battery input noise, and an uncertainty of the sensor noise at a second predetermined time prior to the first predetermined time. The method further includes determining a second plurality of predicted battery state vectors that are indicative of the state of the battery and an uncertainty of the state of the battery at the first predetermined time based on the first plurality of estimated augmented battery state vectors. The method further includes determining a third plurality of predicted battery output vectors that are indicative of at least one output variable of the battery and an uncertainty of the output variable at the first predetermined time based on the first plurality of estimated augmented battery state vectors and the second plurality of predicted battery state vectors. The method further includes determining a first battery output vector having at least one measured value of a battery output variable. The method further includes determining a first estimated battery state vector indicative of the state of the battery at the first predetermined time based on the second plurality of predicted battery state vectors, the third plurality of predicted battery output vectors, and the first battery output vector.

A system for determining an estimated battery state vector indicative of a state of a battery at a first predetermined time in accordance with another exemplary embodiment is provided. The system includes a sensor configured to generate a first signal indicative of an output variable of the battery. The system further includes a computer operably coupled to the sensor. The computer is configured to determine a first plurality of estimated augmented battery state vectors that are indicative of a state of the battery, a battery input noise, a sensor noise, an uncertainty of the state of the battery, an uncertainty of the battery input noise, and an uncertainty of the sensor noise at a second predetermined time prior to the first predetermined time. The computer is further configured to determine a second plurality of predicted battery state vectors that are indicative of the state of the battery and an uncertainty of the state of the battery at the first predetermined time based on the first plurality of estimated augmented battery state vectors. The computer is further configured to determine a third plurality of predicted battery output vectors that are indicative of an at least one output variable of the battery and an uncertainty of the output variable at the first predetermined time based on the first plurality of estimated augmented battery state vectors and the second plurality of predicted battery state vectors. The computer is further configured to determine a first battery output vector based on the first signal. The computer is further configured to determine a first estimated battery state vector indicative of the state of the battery at the first predetermined time based on the second plurality of predicted battery state vectors, the third plurality of predicted battery output vectors, and the first battery output vector.

An article of manufacture in accordance with another exemplary embodiment is provided. The article of manufacture includes a computer storage medium having a computer program encoded therein for determining an estimated battery state vector indicative of a state of a battery at a first predetermined time. The computer storage medium includes code for determining a first plurality of estimated augmented battery state vectors that are indicative of a state of the battery, a battery input noise, a sensor noise, an uncertainty of the state of the battery, an uncertainty of the battery input noise, and an uncertainty of the sensor noise at a second predetermined time prior to the first predetermined time. The computer storage medium further includes code for determining a second plurality of predicted battery state vectors that are indicative of the state of the battery and an uncertainty of the state of the battery at the first predetermined time based on the first plurality of estimated augmented battery state vectors. The computer storage medium further includes code for determining a third plurality of predicted battery output vectors that are indicative of at least one output variable of the battery and of an uncertainty of the output variable at the first predetermined time based on the first plurality of estimated augmented battery state vectors and the second plurality of predicted battery state vectors. The computer storage medium further includes code for determining a first battery output vector having at least one measured value of a battery output variable. The computer storage medium further includes code for determining a first estimated battery state vector indicative of the state of the battery at the first predetermined time based on the second plurality of predicted battery state vectors, the third plurality of predicted battery output vectors, and the first battery output vector.

Other systems and/or methods according to the embodiments will become or are apparent to one with skill in the art upon review of the following drawings and detailed description. It is intended that all such additional systems and methods be within the scope of the present invention, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic of a system for determining an estimated battery state vector in accordance with an exemplary embodiment;

FIGS. **2-5** are flowcharts of a method for determining an estimated battery state vector in accordance with another exemplary embodiment; and

FIGS. **6-9** are flowcharts of a method for determining an estimated battery state vector in accordance with another exemplary embodiment.

DETAILED DESCRIPTION OF THE INVENTION

Referring to FIG. **1**, a system **10** for estimating a state vector associated with a battery **12** is illustrated. The battery **12** includes at least a battery cell **14**. Of course, the battery **12** can include a plurality of additional battery cells. Each battery cell can be either a rechargeable battery cell or a non-rechargeable battery cell. Further, each battery cell can be constructed using an anode and a cathode having electro-chemical configurations known to those skilled in the art. An input variable is defined as a value of a battery input signal at a specific time. For example, an input variable can comprise one of a current entering the battery and a temperature of the battery. An output variable is defined as a value of a battery output signal at a specific time. For example, an output variable can comprise one of a battery output voltage and a battery pressure.

The system **10** includes one or more voltage sensors **20**, a load circuit **26**, and a computational unit such as a computer **28**, and may also include one or more of a temperature sensor **22**, and a current sensor **24**.

The voltage sensor **20** is provided to generate a first output signal indicative of the voltage produced by one or more of the battery cells of the battery **12**. The voltage sensor **20** is electrically coupled between the I/O interface **46** of the computer **28** and the battery **12**. The voltage sensor **20** transfers the first output signal to the computer **28**. For clarity of presentation, a single voltage sensor will be described herein. However, it should be noted that in an alternate embodiment of system **10** a plurality of voltage sensors (e.g., one voltage sensor per battery cell) are utilized in system **10**.

The temperature sensor **22** is provided to generate a second output signal indicative of one or more temperatures of the battery **12**. The temperature sensor **22** is disposed proximate the battery **12** and is electrically coupled to the I/O interface **46** of the computer **28**. The temperature sensor **22** transfers the second output signal to the computer **28**. For clarity of presentation, a single temperature sensor will be described herein. However, it should be noted that in an alternate embodiment of system **10** a plurality of temperature sensors (e.g., one temperature sensor per battery cell) are utilized in system **10**.

The current sensor **24** is provided to generate a third output signal indicative of a current sourced or sunk by the battery cells of the battery **12**. The current sensor **24** is electrically coupled between the battery **12** and the load circuit **26**. The current sensor **24** is further electrically coupled to the I/O interface **46** of the computer **28**. The current sensor **24** transfers the third output signal to the computer **28**.

The load circuit **26** is electrically coupled to the current sensor **24** and sinks or sources a current from the battery **12**. The load circuit **26** comprises any electrical device that can be electrically coupled to the battery **12**.

The computer **28** is provided for determining an estimated battery state vector associated with the battery **12**, as will be explained in greater detail below. The computer **28** includes a central processing unit (CPU) **40**, a read-only memory (ROM) **44**, a volatile memory such as a random access memory (RAM) **45** and an input/output (I/O) interface **46**. The CPU **40** operably communicates with the ROM **44**, the RAM **45**, and the I/O interface **46**. The CPU **40** includes a clock **42**. The computer readable media including ROM **44** and RAM **46** may be implemented using any of a number of known memory devices such as PROMs, EPROMs, EEPROMS, flash memory or any other electric, magnetic, optical or combination memory device capable of storing data, some of which represent executable instructions used by the CPU **40**.

For purposes of understanding, the notation utilized in the equations of the following methods will be described. The circumflex symbol indicates an estimated or predicted quantity (e.g., $\hat{x}$ indicates an estimate of the true quantity x). The superscript symbol "−" indicates an a priori estimate (i.e., a prediction of a quantity's present value based on past data). The superscript symbol "+" indicates an a posteriori estimate (e.g., $\hat{x}_k^+$ is the estimate of true quantity x at time index k based on all measurements taken up to and including time k). The tilde symbol indicates the error of an estimated quantity (e.g., $\tilde{x}_k^- = x_k - \hat{x}_k^-$ and $\tilde{x}_k^+ = x_k - \hat{x}_k^+$). The symbol $\Sigma_{xy} = E[xy^T]$ indicates the correlation or cross correlation of the variables in its subscript (the quantities described herein are zero-mean, so the correlations are identical to covariances). The symbol Σ_x indicates the same quantity as Σ_{xx}. The superscript "T" is a matrix/vector transpose operator.

Before providing a detailed discussion of the methodologies for determining a state associated with the battery **12**, a general overview will be provided. The state vector may include, for example, a state of charge (SOC) value associated with the battery **12**, a hysteresis voltage, or a polarization voltage. The SOC value is a value from 0-100 percent, that indicates a present available capacity of the battery **12** that may be used to do work.

A mathematical model of battery cell behavior is used in the method to compute an estimate of the state vector of the battery **12**. It is assumed that a mathematical model of the battery cell dynamics is known, and may be expressed using a discrete-time state-space model comprising a state equation and an output equation, as will be described below.

The state equation utilized to determine the state vector associated with the battery **12** is as follows:

$$x_k = f(x_{k-1}, u_{k-1}, w_{k-1}, k-1)$$

wherein,

x_k is the state vector associated with the battery **12** at time index k;

u_k is a variable representing a known/deterministic input to the battery **12**;

w_k is a battery input noise vector that models some unmeasured input which affects the state of the system; and

$f(x_{k-1}, u_{k-1}, w_{k-1}, k-1)$ is a state transition function.

An output vector associated with the battery **12** is determined utilizing the following equation:

$$y_k = h(x_k, u_k, v_k, k)$$

wherein,

$h(x_k, u_k, v_k, k)$ is a measurement function; and

v_k is sensor noise that affects the measurement of the output of battery **12** in a memory-less mode, but does not affect the state vector of battery **12**.

Referring to FIGS. **2-5**, a method for determining an estimated battery state vector indicative of a state of the battery **12** in accordance with an exemplary embodiment will now be explained. The method can be implemented utilizing software algorithms executed by the controller **28**. The software algorithms are stored in either the ROM **44** or the RAM **45**.

At step **60**, the computer **28** generates a battery input vector u_k having at least one measured value of a battery input variable obtained at a first predetermined time.

Next at step **62**, the computer **28** generates a battery output vector y_k having at least one measured value of a battery output variable obtained at the first predetermined time.

Next at step **64**, the computer **28** determines an estimated augmented battery state vector $\hat{x}_{k-1}^{a,+}$, indicative of a state of the battery at a second predetermined time prior to the first predetermined time using the equation:

$$\hat{x}_{k-1}^{a,+}=[(\hat{x}_{k-1}^{+})^T,(E[w_{k-1}])^T,(E[v_{k-1}])^T]^T$$

where,

$\hat{x}_{k-1}^{+}$ corresponds to an estimated battery state vector indicative of a state of the battery at the second predetermined time;

$E[w_{k-1}]$ corresponds to an expected value of a battery input noise vector at the second predetermined time;

$E[v_{k-1}]$ corresponds to an expected value of a sensor noise vector at the second predetermined time; and

T is the matrix/vector transpose operation.

Next at step **66**, the computer **28** determines an estimated augmented battery state vector covariance matrix $\Sigma_{\hat{x},k-1}^{a,+}$ associated with the estimated augmented battery state vector using the equation:

$$\Sigma_{\hat{x},k-1}^{a,+}=\text{diag}(\Sigma_{\hat{x},k-1}^{+},\Sigma_w,\Sigma_v)$$

where,

$\Sigma_{\hat{x},k-1}^{+}$ corresponds to an estimated battery state vector covariance matrix associated with the estimated battery state vector at the second predetermined time;

Σ_w corresponds to a covariance matrix associated with a battery input noise vector;

Σ_v corresponds to a covariance matrix associated with a sensor noise vector; and

diag( ) is a function that composes a block-diagonal matrix from its input arguments.

Next at step **68**, the computer **28** determines a plurality of estimated augmented battery state vectors $X_{k-1}^{a,+}$ each indicative of a state of a battery at the second predetermined time using the following equation:

$$X_{k-1}^{a,+}=\{\hat{x}_{k-1}^{a,+},\hat{x}_{k-1}^{a,+}+\gamma\sqrt{\Sigma_{\tilde{x},k-1}^{a,+}},\hat{x}_{k-1}^{a,+}-\gamma\sqrt{\Sigma_{\tilde{x},k-1}^{a,+}}\}$$

where,

$\sqrt{\Sigma_{\tilde{x},k-1}^{a,+}}$ corresponds to the Cholesky matrix square root of $\Sigma_{\tilde{x},k-1}^{a,+}$; and

γ corresponds to a constant value.

Next at step **70**, the computer **28** determines a plurality of predicted battery state vectors $X_k^{x,-}$ each indicative of a state of the battery at the first predetermined time, utilizing the following equation:

$$X_{k\,i}^{x,-}=f(X_{k-1\,i}^{x,+},u_{k-1},X_{k-1\,i}^{w,+},k-1)$$

where

$X_{k,i}^{x,-}$ corresponds to the ith member of the plurality $X_k^{x,-}$

u_{k-1} corresponds to a battery input vector at the second predetermined time;

$X_{k-1,i}^{x,+}$ corresponds to an estimated battery state vector extracted from the ith member of the plurality $X_{k-1}^{a,+}$;

$X_{k-1,i}^{w,+}$ corresponds to an estimated battery input noise vector, extracted from the ith member of the plurality $X_{k-1}^{a,+}$; and

k−1 corresponds to the second predetermined time.

Next at step **72**, a computer **28** determines a plurality of predicted battery output vectors Y_k each indicative of outputs of the battery at the first predetermined time, utilizing the following equation:

$$Y_{k,i}=h(X_{k,i}^{x,-},u_k,X_{k-1,i}^{v,+},k)$$

where,

$Y_{k,i}$ corresponds to the ith member of the plurality Y_k;

$X_{k-1,i}^{v,+}$ corresponds to a single estimated sensor noise vector extracted from the ith member of the plurality $X_{k-1}^{a,+}$; and

k corresponds to the first predetermined time.

Next at step **74**, the computer **28** determines a predicted battery state vector $\hat{x}_k^{-}$ corresponding to the first time by calculating a weighted average of the plurality of predicted battery state vectors $X_k^{x,-}$, utilizing the following equation:

$$\hat{x}_k^{-}=\Sigma_{i=0}^{p}\alpha_i^{(m)}X_{k,i}^{x,-}$$

where,

$\alpha_i^{(m)}$ corresponds to a set of constant values; and

p corresponds to the number of members in the plurality $X_k^{x,-}$, minus one.

Next at step **76**, the computer **28** determines a predicted battery state vector covariance matrix $\Sigma_{\hat{x},k}^{-}$, utilizing the following equation:

$$\Sigma_{\hat{x},k}^{-}=\Sigma_{i=0}^{p}\alpha_i^{(c)}(X_{k,i}^{x,-}-\hat{x}_k^{-})(X_{k,i}^{x,-}-\hat{x}_k^{-})^T$$

where, $\alpha_i^{(c)}$ corresponds to a set of constant values.

Next at step **78**, the computer **28** determines a predicted battery output vector $\hat{y}_k$ indicative of outputs of the battery at the first predetermined time, utilizing the following equation:

$$\hat{y}_k=\Sigma_{i=0}^{p}\alpha_i^{(m)}Y_{k,i}.$$

Next at step **80**, the computer **28** determines a predicted battery output vector covariance matrix $\Sigma_{\hat{y},k}$, utilizing the following equation:

$$\Sigma_{\hat{y},k}=\Sigma_{i=0}^{p}\alpha_i^{(c)}(Y_{k,i}-\hat{y}_k)(Y_{k,i}-\hat{y}_k)^T.$$

Next at step **82**, the computer **28** determines a predicted cross-covariance matrix $\Sigma_{\hat{x}\hat{y},k}^{-}$, utilizing the following equation:

$$\Sigma_{\hat{x}\hat{y},k}^{-}=\Sigma_{i=0}^{p}\alpha_i^{(c)}(X_{k,i}^{x,-}-\hat{x}_k^{-})(Y_{k,i}-\hat{y}_k)^T.$$

Next at step **84**, the computer **28** determines a gain matrix L_k, utilizing the following equation:

$$L_k=\Sigma_{\hat{x}\hat{y},k}^{-}\Sigma_{\hat{y},k}^{-1}.$$

Next at step **86**, the computer **28** determines an estimated battery state vector $\hat{x}_k^{+}$, indicative of a state of the battery at the first predetermined time, utilizing the following equation:

$$\hat{x}_k^{+}=\hat{x}_k^{-}+L_k[y_k-\hat{y}_k].$$

Next at step **88**, the computer **28** determines an estimated battery state vector covariance matrix $\Sigma_{\hat{x},k}^{+}$, associated with the estimated battery state vector, utilizing the following equation:

$$\Sigma_{\hat{x},k}^{+}=\Sigma_{\hat{x},k}^{-}-L_k\Sigma_{\hat{y},k}L_k^T.$$

Next at step **90**, the computer **28** selects new first and second predetermined times. After step **90**, the method returns to step **60**.

Referring to FIGS. **6-9**, a method for determining an estimated battery state vector indicative of a state of the battery **12** in accordance with another exemplary embodiment will now be explained. The method can be implemented utilizing software algorithms executed by the controller **28**. The software algorithms are stored in either the ROM **44** or the RAM **45**.

At step **100**, the computer **28** generates a battery input vector u_k having at least one measured value of a battery input variable obtained at a first predetermined time.

Next at step **102**, the computer **28** generates a battery output vector y_k having at least one measured value of a battery output variable obtained at the first predetermined time.

Next at step **104**, computer **28** determines an estimated augmented battery state vector $\hat{x}_{k-1}^{a,+}$, indicative of a state of the battery **12** at a second predetermined time prior to the first predetermined time using the equation:

$$\hat{x}_{k-1}^{a,+}=[(\hat{x}_{k-1}^{+})^T,(E[w_{k-1}])^T,(E[v_{k-1}])^T]^T$$

where,

$\hat{x}_{k-1}^{+}$ corresponds to an estimated battery state vector indicative of a state of the battery at the second predetermined time;

$E[w_{k-1}]$ corresponds to an expected value of a battery input noise vector at the second predetermined time;

$E[v_{k-1}]$ corresponds to an expected value of a sensor noise vector at the second predetermined time; and

T is the matrix/vector transpose operation.

Next at step **106**, the computer **28** determines an estimated augmented battery state vector square-root covariance matrix $S_{\tilde{x},k-1}^{a,+}$ associated with the estimated augmented battery state vector using the equation:

$$S_{\tilde{x},k-1}^{a,+}=\mathrm{diag}(S_{\tilde{x},k-1}^{+},S_w,S_v)$$

where,

$S_{\tilde{x},k-1}^{+}$ corresponds to an estimated battery state vector square-root covariance matrix associated with the estimated battery state vector at the second predetermined time;

S_w corresponds to a square-root covariance matrix associated with a battery input noise vector;

S_v corresponds to a square-root covariance matrix associated with a sensor noise vector; and

diag( ) is a function that composes a block-diagonal matrix from its input arguments.

Next at step **108**, the computer **28** determines a plurality of estimated augmented battery state vectors $X_{k-1}^{a,+}$ each indicative of a state of a battery at the second predetermined time using the following equation:

$$X_{k-1}^{a,+}=\{\hat{x}_{k-1}^{a,+},\hat{x}_{k-1}^{a,+}+\gamma S_{\tilde{x},k-1}^{a,+},\hat{x}_{k-1}^{a,+}-\gamma S_{\tilde{x},k-1}^{a,+}\}$$

where, γ corresponds to a constant value.

Next at step **110**, the computer **28** determines a plurality of predicted battery state vectors $X_k^{x,-}$ each indicative of a state of the battery at the first predetermined time, utilizing the following equation:

$$X_{k,i}^{x,-}=f(X_{k-1,i}^{x,+},u_{k-1},X_{k-1,i}^{w,+},k-1)$$

where

$X_{k,i}^{x,-}$ corresponds to the ith member of the plurality $X_k^{x,-}$

u_{k-1} corresponds to a battery input vector at the second predetermined time;

$X_{k-1,i}^{x,+}$ corresponds to an estimated battery state vector extracted from the ith member of the plurality $X_{k-1}^{a,+}$;

$X_{k-1,i}^{w,+}$ corresponds to an estimated battery input noise vector, extracted from the ith member of the plurality $X_{k-1}^{a,+}$; and

k−1 corresponds to the second time.

Next at step **112**, the computer **28** determines a plurality of predicted battery output vectors Y_k each indicative of outputs of the battery **12** at the first predetermined time, utilizing the following equation:

$$Y_{k,i}=h(X_{k,i}^{x,-},u_k,X_{k-1,i}^{v,+},k)$$

where,

$Y_{k,i}$ corresponds to the ith member of the plurality Y_k;

$X_{k-1,i}^{v,+}$ corresponds to a single estimated sensor noise vector extracted from the ith member of the plurality $X_{k-1}^{a,+}$; and

k corresponds to the first predetermined time.

Next at step **114**, the computer **28** determines a predicted battery state vector $\hat{x}_k^{-}$ corresponding to the first time by calculating a weighted average of the plurality of predicted battery state vectors $X_k^{x,-}$, utilizing the following equation:

$$\hat{x}_k^{-}=\Sigma_{i=0}^{p}\alpha_i^{(m)}X_{k,i}^{x,-}$$

where,

$\alpha_i^{(m)}$ corresponds to a set of constant values; and

p corresponds to the number of members in the plurality $X_k^{x,-}$, minus one.

Next at step **116**, the computer **28** determines a predicted battery state vector square-root covariance matrix $S_{\tilde{x},k}^{-}$, utilizing the following equation:

$$S_{\tilde{x},k}^{-}=qr\{[\sqrt{\alpha_i^{(c)}}(X_{k,(0:p)}^{x,-}-\hat{x}_k^{-})^T]\}^T.$$

where,

$\alpha_i^{(c)}$ corresponds to a set of constant values.

qr{ } is a function that computes a Q-R matrix decomposition of its input argument and returns the upper-triangular portion of the R matrix.

Next at step **118**, computer **28** determines a predicted battery output vector $\hat{y}_k$ indicative of outputs of the battery at the first predetermined time, utilizing the following equation:

$$\hat{y}_k=\Sigma_{i=0}^{p}\alpha_i^{(m)}Y_{k,i}.$$

Next at step **120**, the computer **28** determines a predicted battery output vector square-root covariance matrix $S_{\tilde{y},k}$, utilizing the following equation:

$$S_{\tilde{y},k}=qr\{[\sqrt{\alpha_i^{(c)}}(Y_{k,(0:p)}-\hat{y}_k)^T]\}^T.$$

Next at step **122**, the computer **28** determines a predicted cross-covariance matrix $\Sigma_{\tilde{x}\tilde{y},k}^{-}$, utilizing the following equation:

$$\Sigma_{\tilde{x}\tilde{y},k}^{-}=\Sigma_{i=0}^{p}\alpha_i^{(c)}(X_{k,i}^{x,-}-\hat{x}_k^{-})(Y_{k,i}-\hat{y}_k)^T.$$

Next at step **124**, the computer **28** determines a gain matrix L_k, utilizing the following equation:

$$L_k=\Sigma_{\tilde{x}\tilde{y},k}^{-}(S_{\tilde{y},k}^{T}S_{\tilde{y},k})^{-1}.$$

Next at step **126**, the computer **28** determines an estimated battery state vector $\hat{x}_k^{+}$, indicative of a state of the battery at the first predetermined time, utilizing the following equation:

$$\hat{x}_k^{+}=\hat{x}_k^{-}+L_k[y_k-\hat{y}_k].$$

Next at step **128**, the computer **28** determines an estimated battery state vector square-root covariance matrix $S_{\tilde{x},k}^{+}$, associated with the estimated battery state vector, utilizing the following equation:

$$S_{\tilde{x},k}^{+}=\mathrm{downdate}\{S_{\tilde{x},k}^{-},L_k\tilde{Sy},k\},$$

where downdate{ } computes the matrix downdate operation on its first argument using its second argument.

Next at step **130**, the computer **28** selects new first and second predetermined times. After step **130**, the method advances to step **100**.

The system, method, and article of manufacture for determining an estimated battery state vector indicative of the state of a battery provide a substantial advantage over other systems and methods. In particular, the system, method, and article of manufacture provide a technical effect of more accurately determining the estimated battery state vector for a battery having non-linear operational characteristics.

The above-described methods can be embodied in the form of computer program code containing instructions embodied in tangible media, such as floppy diskettes, CD ROMs, hard drives, or any other computer-readable storage medium, wherein, when the computer program code is loaded into and executed by a computer, the computer becomes an apparatus for practicing the invention. The above-described methods can also be embodied in the form of computer program code, for example, whether stored in a storage medium, loaded into and/or executed by a computer, or transmitted over some transmission medium, loaded into and/or executed by a computer, or transmitted over some transmission medium, such as over electrical wiring or cabling, through fiber optics, or via electromagnetic radiation, wherein, when the computer program code is loaded into an executed by a computer, the computer becomes an apparatus for practicing the methods. When implemented on a general-purpose microprocessor, the computer program code segments configure the microprocessor to create specific logic circuits.

While the invention is described with reference to the exemplary embodiments, it will be understood by those skilled in the art that various changes may be made and equivalent elements e may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to the teachings of the invention to adapt to a particular situation without departing from the scope thereof. Therefore, is intended that the invention not be limited the embodiment disclosed for carrying out this invention, but that the invention includes all embodiments falling with the scope of the intended claims. Moreover, the use of the term's first, second, etc. does not denote any order of importance, but rather the term's first, second, etc. are used to distinguish one element from another.

What is claimed is:

1. A method for determining an estimated battery state vector indicative of a state of a battery at a first predetermined time, the method comprising:

determining a first plurality of estimated augmented battery state vectors that are indicative of a state of the battery, a battery input noise, a sensor noise, an uncertainty of the state of the battery, an uncertainty of the battery input noise, and an uncertainty of the sensor noise at a second predetermined time prior to the first predetermined time;

determining a second plurality of predicted battery state vectors that are indicative of the state of the battery and an uncertainty of the state of the battery at the first predetermined time based on the first plurality of estimated augmented battery state vectors;

determining a third plurality of predicted battery output vectors that are indicative of at least one output variable of the battery and an uncertainty of the output variable at the first predetermined time based on the first plurality of estimated augmented battery state vectors and the second plurality of predicted battery state vectors;

determining a first battery output vector having at least one measured value of a battery output variable; and

determining a first estimated battery state vector indicative of the state of the battery at the first predetermined time based on the second plurality of predicted battery state vectors, the third plurality of predicted battery output vectors, and the first battery output vector.

2. The method of claim **1**, wherein determining the first plurality of estimated augmented battery state vectors comprises:

retrieving an estimated battery state vector indicative of the state of the battery at the second predetermined time from a memory;

determining a first estimated augmented battery state vector indicative of the state of the battery, the battery input noise, and the sensor noise at the second predetermined time, based on the estimated battery state vector, an expected battery input noise vector, and an expected sensor noise vector;

retrieving an estimated battery state vector covariance matrix indicative of an uncertainty of the state of the battery at the second predetermined time from the memory;

determining a first estimated augmented battery state vector covariance matrix indicative based on the estimated battery state vector covariance matrix, a covariance matrix indicative of an uncertainty of the battery input noise and a covariance matrix indicative of an uncertainty of the sensor noise; and

determining the first plurality of estimated augmented battery state vectors based on the first estimated augmented battery state vector and the first estimated augmented battery state vector covariance matrix.

3. The method of claim **2**, wherein determining the first plurality of estimated augmented battery state vectors comprises:

setting one member of the first plurality of estimated augmented battery state vectors equal to the first estimated augmented battery state vector;

setting a first additional set of L members of the first plurality of estimated augmented battery state vectors equal to the first estimated augmented battery state vector added to a constant value multiplied by respective columns extracted from a matrix square-root of the first estimated augmented battery state vector covariance matrix, where L is the length of the first estimated augmented battery state vector; and

setting a second additional set of L members of the first plurality of estimated augmented battery state vectors equal to the constant value multiplied by respective columns extracted from the matrix square-root of the first estimated augmented battery state vector covariance matrix subtracted from the first estimated augmented battery state vector.

4. The method of claim **1**, wherein determining the first plurality of estimated augmented battery state vectors comprises:

retrieving an estimated battery state vector indicative of the state of the battery at the second predetermined time from a memory;

determining a first estimated augmented battery state vector indicative of the state of the battery, the battery input noise, and the sensor noise at the second predetermined time based on the estimated battery state vector, an expected battery input noise vector, and an expected sensor noise vector;

retrieving an estimated battery state vector square-root covariance matrix indicative of an uncertainty of the state of the battery at the second predetermined time from the memory;

determining a first estimated augmented battery state vector square-root covariance matrix indicative of an uncertainty of the state of the battery, the battery input noise, and the sensor noise, based on the estimated battery state vector square-root covariance matrix, a covariance matrix indicative of an uncertainty of the battery input noise and a covariance matrix indicative of an uncertainty of the sensor noise; and

determining the first plurality of estimated augmented battery state vectors based on the first estimated augmented

battery state vector and the first estimated augmented battery state vector square-root covariance matrix.

5. The method of claim **4**, wherein determining the first plurality of estimated augmented battery state vectors comprises:

setting one member of the first plurality of estimated augmented battery state vectors equal to the first estimated augmented battery state vector;

setting a first additional set of L members of the first plurality of estimated augmented battery state vectors equal to the first estimated augmented battery state vector added to a constant value multiplied by respective columns extracted from the estimated augmented battery state vector square-root covariance matrix, where L is the length of the estimated augmented battery state vector; and

setting a second additional set of L members of the first plurality of estimated augmented battery state vectors equal to the constant value multiplied by respective columns extracted from the first estimated augmented battery state vector square-root covariance matrix subtracted from the first estimated augmented battery state vector.

6. The method of claim **1**, wherein determining the second plurality of predicted battery state vectors comprises:

extracting values indicative of the state of the battery and of an uncertainty of the state of the battery at the second predetermined time from the first plurality of estimated augmented battery state vectors, to obtain a fourth plurality of estimated battery state vectors;

extracting values indicative of the battery input noise and an uncertainty of the battery input noise at the second predetermined time from the first plurality of estimated augmented battery state vectors, to obtain a fifth plurality of estimated battery input noise vectors;

generating the first battery input vector having at least one measured value of a battery input variable at the second predetermined time; and

determining the second plurality of predicted battery state vectors based on the fourth plurality of predicted battery state vectors, the fifth plurality of predicted battery input noise vectors, and the first battery input vector.

7. The method of claim **1**, wherein determining the third plurality of predicted battery output vectors comprises:

extracting values indicative of the sensor noise and of an uncertainty of the sensor noise at the second predetermined time from the first plurality of estimated augmented battery state vectors, to obtain a fourth plurality of estimated sensor noise vectors;

generating the first battery input vector having at least one measured value of a battery input variable at the first predetermined time; and

determining the third plurality of predicted battery output vectors based on the second plurality of predicted battery state vectors, the first battery input vector, the fourth plurality of estimated sensor noise vectors.

8. The method of claim **1**, wherein determining the first estimated battery state vector comprises:

determining a first predicted battery state vector indicative of the state of the battery at the first predetermined time based on the second plurality of predicted battery state vectors;

determining a first predicted battery output vector indicative of at least one output variable of the battery at the first predetermined time based on the third plurality of predicted output vectors;

determining a gain matrix based on the first predicted battery state vector, the first predicted battery output vector, the second plurality of predicted battery state vectors, and the third plurality of predicted battery output vectors; and

calculating the first estimated battery state vector based on the first predicted battery state vector, the first predicted battery output vector, the gain matrix, and the first battery output vector.

9. The method of claim **8**, wherein determining the first predicted battery state vector comprises calculating a weighted average of the second plurality of predicted battery state vectors.

10. The method of claim **8**, wherein determining the first predicted battery output vector comprises calculating a weighted average of the third plurality of predicted battery output vectors.

11. The method of claim **8**, wherein determining the gain matrix comprises:

determining a first predicted battery output vector covariance matrix based on the first predicted battery output vector and the third plurality of predicted battery output vectors;

determining a first predicted cross-covariance matrix between a battery output vector and a battery state vector based on the first predicted battery output vector, the third plurality of predicted battery output vectors, the first predicted battery state vector, and the second plurality of predicted battery state vectors; and

calculating the gain matrix based on the first predicted cross-covariance matrix and the first predicted battery output vector covariance matrix.

12. The method of claim **11**, wherein determining the first predicted battery output vector covariance matrix comprises:

determining a first predicted battery output vector square-root covariance matrix based on the first predicted battery output vector and the third plurality of predicted battery output vectors; and

calculating the first predicted battery output vector covariance matrix based on the first predicted battery output vector square-root covanance matrix and the first predicted battery output vector square-root covariance matrix.

13. The method of claim **8**, wherein calculating the first estimated battery state vector comprises:

determining an innovation vector based on the first battery output vector and the first predicted battery output vector;

determining an update vector based on the gain matrix and the innovation vector; and

calculating the first estimated battery state vector based on the predicted battery state vector and the update vector.

14. The method of claim **8**, further comprising determining an estimated battery state vector covariance matrix at the first predetermined time based on the first predicted battery state vector, the second plurality of predicted battery state vectors, the gain matrix, and the first predicted battery output vector covariance matrix.

15. The method of claim **8**, further comprising determining an estimated battery state vector square-root covariance matrix at the first predetermined time based on the first predicted battery state vector, the second plurality of predicted battery state vectors, the gain matrix, and a predicted battery output vector square-root covariance matrix.

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