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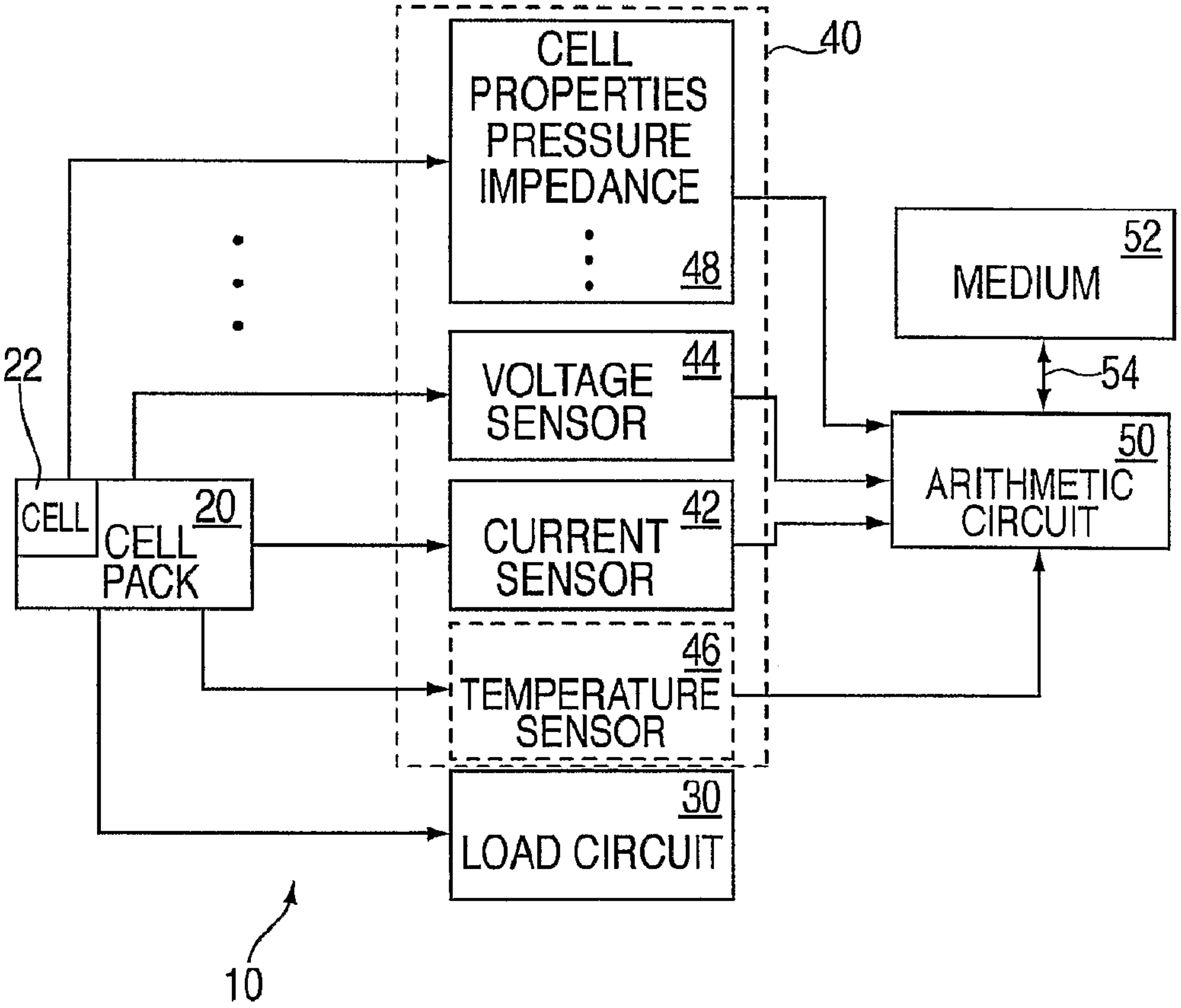

(57) **Abrégé/Abstract:**

Methods and apparatus for estimating the state and parameters of an electrochemical cell. More particularly, for example, a method for estimating present states and present parameters of an electrochemical cell system comprising: estimating a state value

(57) **Abrégé(suite)/Abstract(continued)**:

of the electrochemical cell with a cell state filter to estimate the state value; estimating a parameter value of the electrochemical cell with a cell parameter filter to estimate the parameter value, and exchanging information between the cell state filter and the cell parameter filter. Also an apparatus configured to estimate present states and present parameters of an electrochemical cell comprising: a first component configured to estimate a cell state value; and a second component configured to estimate a cell parameter value. The first component and second component are in operable communication to exchange information there between.

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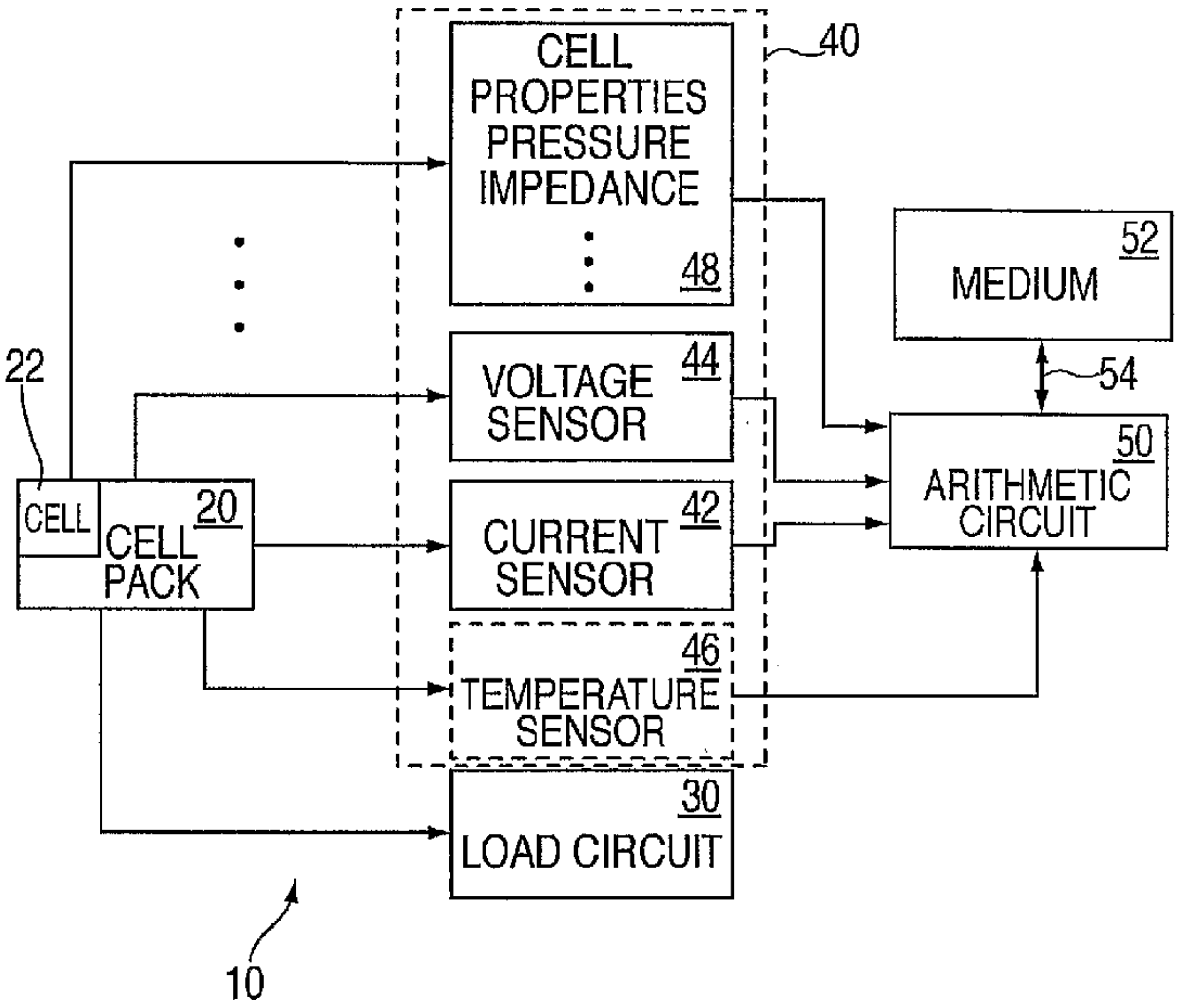
(54) **Title:** STATE AND PARAMETER ESTIMATION FOR AN ELECTROCHEMICAL CELL



(57) **Abstract:** Methods and apparatus for estimating the state and parameters of an electrochemical cell. More particularly, for example, a method for estimating present states and present parameters of an electrochemical cell system comprising: estimating a state value of the electrochemical cell with a cell state filter to estimate the state value; estimating a parameter value of the electrochemical cell with a cell parameter filter to estimate the parameter value, and exchanging information between the cell state filter and the cell parameter filter. Also an apparatus configured to estimate present states and present parameters of an electrochemical cell comprising: a first component configured to estimate a cell state value; and a second component configured to estimate a cell parameter value. The first component and second component are in operable communication to exchange information there between.

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STATE AND PARAMETER ESTIMATION FOR AN ELECTROCHEMICAL CELL

Technical Field

The present invention relates to methods and apparatus for estimation of battery pack system state and model parameters using digital filtering techniques. In particular, dual Kalman filtering and dual extended Kalman filtering.

Background Art

In the context of rechargeable battery pack technologies, it is desired in some applications to be able to estimate quantities that are descriptive of the present battery pack condition, but that may not be directly measured. Some of these quantities may change rapidly, such as the pack state-of-charge (SOC), which can traverse its entire range within minutes. Others may change very slowly, such as cell capacity, which might change as little as 20% in a decade or more of regular use. The quantities that tend to change quickly comprise the "state" of the system, and the quantities that tend to change slowly comprise the time varying "parameters" of the system.

In the context of the battery systems, particularly those that need to operate for long periods of time, as aggressively as possible without harming the battery life, for example, in Hybrid Electric Vehicles (HEVs), Battery Electric Vehicles (BEVs), laptop computer batteries, portable tool battery packs, and the like, it is desired that information regarding quickly varying parameters (*e.g.*, SOC) be used to estimate how much battery energy is presently available to do work, and so forth. Further, it may be desirable to ascertain information regarding slowly varying parameters (*e.g.*, total capacity) in order to keep the prior calculations precise over the lifetime of the pack, extending its useful service time, and help in determining the state-of-health (SOH) of the pack.

There are a number of existing methods for estimating the state of a cell, which are generally concerned with estimating three quantities: SOC (a quickly varying quantity), power-fade, and capacity-fade (both slowly time varying). Power fade may be calculated if the present and initial pack electrical resistances are known, and capacity fade may be calculated if present and initial pack total capacities are known, for example, although other methods may also be used. Power- and capacity-fade are often lumped under the description "state-of-health" (SOH). Some other information may be derived using the values of these variables, such as the maximum power available from the pack at any given time. Additional state members or parameters may also be needed for specific applications, and individual algorithms would typically be required to find each one.

SOC is a value, typically reported in percent, that indicates the fraction of the cell capacity presently available to do work. A number of different approaches to estimating SOC have been employed: a discharge test, ampere-hour counting (Coulomb counting), measuring the electrolyte, open-circuit voltage measurement, linear and nonlinear circuit modeling, impedance spectroscopy, measurement of internal resistance, coup de fouet, and some forms of Kalman filtering. The discharge test must completely discharge the cell in order to determine SOC. This test interrupts system function while the test is being performed and can be overly time consuming rendering it not useful for many applications. Ampere-hour counting (Coulomb counting) is an "open loop" methodology whose accuracy degrades over time by accumulated measurement error. Measuring the electrolyte is only feasible for vented lead-acid batteries, and therefore has limited applicability. Open-circuit voltage measurement may be performed only after extended periods of cell inactivity, and for cells with negligible hysteresis effect and does not work in a dynamic setting. Linear and nonlinear circuit modeling methods do not yield SOC directly; SOC must be inferred from the calculated values. Impedance spectroscopy requires making measurements not always available in a general application. Measurement of internal resistance is very sensitive to measurement error, and requires measurements not available in general applications. Coup de fouet works for lead-acid batteries only. Forms of Kalman filtering that do not use SOC as a filter state do not directly yield error bounds on the estimate. In another method, described in U.S. Patent No. 6,534,954, a filter, preferably a Kalman filter is used to estimate SOC by employing a known mathematical model of cell dynamics and measurements of cell voltage, current, and temperature. This method directly estimates state values. However, it does not address parameter values.

Not only is knowledge of SOC desired, but also knowledge of SOH. In this context, power fade refers to the phenomenon of increasing cell electrical resistance as the cell ages. This increasing resistance causes the power that can be sourced/sunk by the cell to drop. Capacity fade refers to the phenomenon of decreasing cell total capacity as the cell ages. Both the cell's resistance and capacity are time-varying parameters. The prior art uses the following different approaches to estimate SOH: the discharge test, chemistry-dependent methods, Ohmic tests, and partial discharge. The discharge test completely discharges a fully charged cell in order to determine its total capacity. This test interrupts system function and wastes cell energy. Chemistry-dependent methods include measuring the level of plate corrosion, electrolyte density, and "coup de fouet" for lead-acid batteries. Ohmic tests include resistance, conductance and impedance tests, perhaps combined with fuzzy-logic algorithms and/or neural networks. These methods require invasive measurements. Partial discharge and other methods compare cell-under-test to a good cell or model of a good cell.

There is a need for a method to concurrently estimate the state and parameters of a cell. Furthermore, there is a need for tests that do not interrupt system function and do not waste energy, methods that are generally applicable (*i.e.*, to different types of cell electrochemistries and to different applications), methods that do not require invasive measurements, and more rigorous approaches. There is a need for methods and apparatus for automatically estimating time-varying parameters, such as the cell's resistance and capacity. There is a need for a method that will work with different configurations of parallel and/or series cells in a battery pack.

Disclosure of the Invention

Disclosed herein in one or more exemplary embodiments are methods and apparatus for estimating the state and parameters of an electrochemical cell. More particularly, for example, estimating state and parameter values of a cell.

A first aspect of the invention is a method for estimating present states and present parameters of an electrochemical cell system comprising: estimating a state value of the electrochemical cell with a cell state filter to estimate said state value; and estimating a parameter value of the electrochemical cell with a cell parameter filter to estimate said parameter value, wherein said estimating a state value comprises: making an internal state prediction of said cell; making an uncertainty prediction of said internal state prediction; correcting said internal state prediction and said uncertainty prediction; and applying an algorithm that iterates said making an internal state prediction, said making an uncertainty prediction and said correcting to yield an ongoing estimation to said state and an ongoing uncertainty to said state estimating, and wherein said estimating a parameter value comprises: making an internal parameter prediction of said cell; making an uncertainty prediction of said internal parameter prediction; correcting said internal parameter prediction and said uncertainty prediction; and applying an algorithm that iterates said making an internal parameter prediction, said making an uncertainty prediction and said correcting to yield an ongoing estimation to said parameter and an ongoing uncertainty to said parameter estimation.

Another aspect is an apparatus configured to estimate present states and present parameters of an electrochemical cell comprising: a first component configured to estimate a cell state value; and a second component configured to estimate a cell parameter value, wherein said first component is configured to estimate a state value comprises: a component configured to make an internal state prediction of said cell; a component configured to make an uncertainty prediction of said internal state prediction; a component configured to correct said internal state prediction and said uncertainty prediction; and a component configured to apply an algorithm that iterates steps taken by said component configured to make an internal state prediction, said component configured to make an uncertainty prediction and said component configured to correct to yield an ongoing estimation to said state and an ongoing uncertainty to said state estimating, and wherein said second component is configured to estimate a parameter value comprises: a component configured to make an internal parameter prediction of said cell; a component configured to make an uncertainty prediction of said internal parameter prediction; a component configured to correct said internal parameter prediction and said uncertainty prediction; and a component configured to apply an algorithm that iterates steps taken by said component configured to make an internal parameter prediction, said component configured to make an uncertainty prediction and said component configured to correct to yield an ongoing estimation to said parameter and an ongoing uncertainty to said parameter estimating.

Further, disclosed herein in another exemplary embodiment is a storage medium encoded with a machine-readable computer program code, wherein said storage medium includes instructions for causing a computer to implement a method for estimating present states and present parameters of an electrochemical cell comprising: estimating a state value of the electrochemical cell with a cell state filter to estimate said state value; and estimating a parameter value of the electrochemical cell with a cell parameter filter to estimate said parameter value, wherein said estimating a state value comprises: making an internal state prediction of said cell; making an uncertainty prediction of said internal state prediction; correcting said internal state prediction and said uncertainty prediction; and applying an algorithm that iterates said making an internal state prediction, said making an uncertainty prediction and said correcting to yield an ongoing estimation to said state and an ongoing uncertainty to said state estimating, and wherein said estimating a parameter value comprises: making an internal parameter prediction of said cell; making an uncertainty prediction of said internal parameter prediction; correcting said internal parameter prediction and said uncertainty prediction; and applying an algorithm that iterates said making an internal parameter prediction, said making an uncertainty prediction and said correcting to yield an ongoing estimation to said parameter and an ongoing uncertainty to said parameter estimation.

Brief Description of the Drawings

These and other features, aspects and advantages of the present invention will become better understood with regard to the following description, appended claims and accompanying drawings wherein like elements are numbered alike in the several Figures:

FIGURE 1 is a block diagram illustrating an exemplary system for state and parameter estimation in accordance with an exemplary embodiment of the invention; and

FIGURE 2 is a block diagram depicting a method of dual filtering, in accordance with an exemplary embodiment of the invention.

Best Mode For Carrying Out The Invention

Disclosed herein are various embodiments and methods, systems and apparatus for the estimation of states and parameters of an electrochemical cell using dual filtering. Referring now to Figures 1 and 2, in the following description, numerous specific details are set forth in order to provide a more complete understanding of the present invention. It will be appreciated that while the exemplary embodiments are described with reference to a battery cell, numerous electrochemical cells hereinafter referred to as a cell, may be employed, including, but not limited to, batteries, battery packs, ultracapacitors, capacitor banks, fuel cells, electrolysis cells, and the like, as well as combinations including at least one of the foregoing. Furthermore, it will be appreciated that a battery or battery pack may include a plurality of cells, where the exemplary embodiments disclosed herein are applied to one or more cells of the plurality.

One or more exemplary embodiments of the present invention estimate cell state and parameter values using dual filtering. One or more exemplary embodiments of the present invention estimate cell state and parameter values using dual Kalman filtering. Some embodiments of the present invention estimate cell state and parameter values using dual extended Kalman filtering. Some embodiments simultaneously estimate SOC, power- and/or capacity-fade, while others estimate additional cell state values and/or additional time-varying parameter values. It will further be appreciated that while the term filtering is employed for description and illustration of the exemplary embodiments, the terminology is intended to include methodologies of recursive prediction and correction commonly denoted as filtering, including but not limited to Kalman filtering and/or extended Kalman filtering.

FIG. 1 shows the components of the state and parameter estimator system 10 according an embodiment of the present invention. Electrochemical cell pack 20 comprising a plurality of cells 22, e.g., battery is connected to a load circuit 30. For example, load circuit 30 could be a motor in an Electric Vehicle (EV) or a Hybrid Electric Vehicle (HEV). An apparatus for measuring various cell characteristics and properties is provided as 40. The measurement apparatus 40 may include but not be limited to a device for measurement of cell terminal voltage such as a voltage sensor 42, e.g. a voltmeter and the like, while measurements of cell current are made with a current sensing device 44, e.g., an ammeter and the like. Optionally, measurements of cell temperature are made with a temperature sensor 46, e.g., a thermometer and the like. Pressure sensors and/or impedance sensors 48 are also possible and may be employed for selected types of cells. Various sensors may be employed as needed to evaluate the characteristics and properties of the cell(s). Voltage, current, and optionally temperature measurements are processed with an arithmetic circuit 50, e.g., processor or computer, which estimates the states and parameters of the cell(s). The system may also include a storage medium 52 comprising any computer usable storage medium known to one of ordinary skill in the art. The storage medium is in operable communication with arithmetic circuit 50 employing various means, including, but not limited to a propagated signal 54. It should be appreciated that no instrument is required to take measurements from the internal chemical components of the cell 12 although such instrumentation may be used with this invention. Also note that all measurements may be non-invasive; that is, no signal must be injected into the system that might interfere with the proper operation of load circuit 30.

In order to perform the prescribed functions and desired processing, as well as the computations therefore (e.g., the modeling, estimation of states and parameters prescribed herein, and the like), arithmetic circuit 50 may include, but not be limited to, a processor(s), gate array(s), custom logic, computer(s), memory, storage, register(s), timing, interrupt(s), communication interfaces, and input/output signal interfaces, as well as combinations comprising at least one of the foregoing. Arithmetic circuit 50 may also include inputs and input signal filtering and the like, to enable accurate sampling and conversion or acquisitions of signals from communications interfaces and inputs. Additional features of arithmetic circuit 50 and certain processes therein are thoroughly discussed at a later point herein.

One or more embodiments of the invention may be implemented as new or updated firmware and software executed in arithmetic circuit 50 and/or other processing controllers. Software functions include, but are not limited to firmware and may be implemented in hardware, software, or a combination thereof. Thus a distinct advantage of the present invention is that it may be implemented for use with existing and/or new processing systems for electrochemical cell charging and control.

In an exemplary embodiment, Arithmetic circuit 50 uses a mathematical model of the cell 12 that includes indicia of a dynamic system state, including, but not limited to, the SOC as a model state. In one embodiment of the present invention, a discrete-time model is used. An exemplary model in a (possibly nonlinear) discrete-time state-space form has the form:

$$\begin{aligned} x_{k+1} &= f(x_k,u_k,\theta_k)+w_k \\ y_k &= g(x_k,u_k,\theta_k)+v_k, \end{aligned} \qquad (1)$$

where x_k is the system state, θ_k is the set of time varying model parameters, u_k is the exogenous input, y_k is the system output, and w_k and v_k are "noise" inputs—all quantities may be scalars or vectors. $f(\cdot,\cdot,\cdot)$ and $g(\cdot,\cdot,\cdot)$ are functions defined by the cell model being used. Non-time-varying numeric values required by the model may be embedded within $f(\cdot,\cdot,\cdot)$ and $g(\cdot,\cdot,\cdot)$, and are not included in θ_k.

The system state includes, at least, a minimum amount of information, together with the present input and a mathematical model of the cell, needed to predict the present output. For a cell 12, the state might include: SOC, polarization voltage levels with respect to different time constants, and hysteresis levels, for example. The system exogenous input u_k includes at minimum the present cell current i_k , and may, optionally, include cell temperature (unless temperature change is itself modeled in the state). The system parameters θ_k are the values that change only slowly with time, in such a way that they may not be directly determined with knowledge of the system measured input and output. These might include: cell capacity, resistance, polarization voltage time constant(s), polarization voltage blending factor(s), hysteresis blending factor(s), hysteresis rate constant(s), efficiency factor(s), and so forth. The model output y_k corresponds to physically measurable cell quantities or those directly computable from measured quantities at minimum for example, the cell voltage under load.

A mathematical model of parameter dynamics is also utilized. An exemplary model has the form:

$$\begin{aligned} \theta_{k+1} &= \theta_k + r_k \\ d_k &= g(x_k, u_k, \theta_k) + e_k. \end{aligned} \qquad (2)$$

The first equation states that the parameters are essentially constant, but that they may change slowly over time, in this instance, modeled by a fictitious "noise" process denoted, r_k. The "output" of the optimum parameter dynamics is the cell output estimate plus some estimation error e_k.

With models of the system state dynamics and parameter dynamics defined, in an exemplary embodiment, a procedure of dual filtering is applied. Once again, alternatively, dual Kalman filters may be employed, or dual extended Kalman filters. Furthermore, combinations of the abovementioned may also be employed. Table 1 is an exemplary implementation of the methodology and system utilizing dual extended Kalman filtering. The procedure is initialized by setting the parameter estimate $\hat{\theta}$ to the best guess of the true parameters, e.g., $\hat{\theta} = E[\theta_0]$, and by setting the state estimate $\hat{x}$ to the best estimate of the cell state, e.g., $\hat{x} = E[x_0]$. The estimation-error covariance matrices $\Sigma_{\tilde{x}}^{+}$ and $\Sigma_{\tilde{\theta}}^{+}$ are also initialized. For example, an initialization of SOC might be estimated/based on a cell voltage in a look-up table, or information that was previously stored when a battery pack/cell was last powered down. Other examples might incorporate the length of time that the battery system had rested since powerdown and the like.

Table 1: Dual extended Kalman filter for state and weight update.

State-space models:

$$x_{k+1} = f(x_k, u_k, \theta_k) + w_k \quad \text{and} \quad \theta_{k+1} = \theta_k + r_k$$

$$y_k = g(x_k, u_k, \theta_k) + v_k \qquad d_k = g(x_k, u_k, \theta_k) + e_k,$$

where w_k, v_k, r_k and e_k are independent, zero-mean, Gaussian noise processes of covariance matrices Σ_w, Σ_v, Σ_r and Σ_e, respectively.

Definitions:

$$A_{k-1} = \left.\frac{\partial f(x_{k-1}, u_{k-1}, \hat{\theta}_k^-)}{\partial x_{k-1}}\right|_{x_{k-1}=\hat{x}_{k-1}^+} \qquad C_k^x = \left.\frac{\partial g(x_k, u_k, \hat{\theta}_k^-)}{\partial x_k}\right|_{x_k=\hat{x}_k^-} \qquad C_k^\theta = \left.\frac{d\, g(\hat{x}_k^-, u_k, \theta)}{d\theta}\right|_{\theta=\hat{\theta}_k^-}$$

Initialization: For $k=0$, set

$$\hat{\theta}_0^+ = E[\theta_0], \quad \Sigma_{\tilde{\theta},0}^+ = E[(\theta_0 - \hat{\theta}_0^+)(\theta_0 - \hat{\theta}_0^+)^T]$$

$$\hat{x}_0^+ = E[x_0], \quad \Sigma_{\tilde{x},0}^+ = E[(x_0 - \hat{x}_0^+)(x_0 - \hat{x}_0^+)^T].$$

Computation: For $k = 1, 2, \ldots,$ compute:

Time update for the weight filter [I corrected the following equation]

$$\hat{\theta}_k^- = \hat{\theta}_{k-1}^+$$

$$\Sigma_{\tilde{\theta},k}^- = \Sigma_{\tilde{\theta},k-1}^+ + \Sigma_r.$$

Time update for the state filter

$$\hat{x}_k^- = f(\hat{x}_{k-1}^+, u_{k-1}, \hat{\theta}_k^-)$$

$$\Sigma_{\tilde{x},k}^- = A_{k-1}\Sigma_{\tilde{x},k-1}^+ A_{k-1}^T + \Sigma_w.$$

Measurement update for the state filter

$$L_k^x = \Sigma_{\tilde{x},k}^-(C_k^x)^T[C_k^x\Sigma_{\tilde{x},k}^-(C_k^x)^T + \Sigma_v]^{-1}$$

$$\hat{x}_k^+ = \hat{x}_k^- + L_k^x[y_k - g(\hat{x}_k^-, u_k, \hat{\theta}_k^-)]$$

$$\Sigma_{\tilde{x},k}^+ = (I - L_k^x C_k^x)\Sigma_{\tilde{x},k}^-.$$

Measurement update for the weight filter

$$L_k^\theta = \Sigma_{\tilde{\theta},k}^-(C_k^\theta)^T[C_k^\theta\Sigma_{\tilde{\theta},k}^-(C_k^\theta)^T + \Sigma_e]^{-1}$$

$$\hat{\theta}_k^+ = \hat{\theta}_k^- + L_k^\theta[y_k - g(\hat{x}_k^-, u_k, \hat{\theta}_k^-)]$$

$$\Sigma_{\tilde{\theta},k}^+ = (I - L_k^\theta C_k^\theta)\Sigma_{\tilde{\theta},k}^-.$$

In this example, several steps are performed in each measurement interval. First, the previous parameter estimate is propagated forward in time. The new parameter estimate is equal to the old parameter estimate, and the parameter error uncertainty is larger due to the passage of time (accommodated for in the model by the fictitious driving noise r_k). Various possibilities exist for updating the parameter uncertainty estimate—the table gives only one example. The state estimate and its uncertainty are propagated forward one step in time. A measurement of the cell output is made, and compared to the predicted output based on the state estimate, $\hat{x}$ and parameter estimate, $\hat{\theta}$; the difference is used to update the values of $\hat{x}$ and $\hat{\theta}$. It may readily be appreciated that the steps outlined in the table may be performed in a variety of orders. While the table lists an exemplary ordering for the purposes of illustration, those skilled in the art will be able to identify many equivalent ordered sets of equations.

Turning now to FIG. 2 as well, an exemplary implementation of an exemplary embodiment of the invention is depicted. Two filters run in parallel are depicted. One filter 101/102 adapting the state estimate, $\hat{x}$ and one filter 103/104 adapting the parameter estimate, $\hat{\theta}$. Additionally, information exchange between the filters permits updates from the parameter estimation filter 103/104 to the state estimation filter 101/102. Both filters 101/102, 103/104 have a time update or prediction aspect and a measurement update or correction aspect. State time update/prediction block 101 receives as input the previous exogenous input u_{k-1} (which might include cell current and/or temperature, for example) along with the previously estimated system state value $\hat{x}_{k-1}^{+}$ and state uncertainty estimate $\Sigma_{\tilde{x},k-1}^{+}$, and present predicted parameters $\hat{\theta}_k^-$. The state time update/prediction block 101 provides predicted state $\hat{x}_k^-$ and predicted state uncertainty $\Sigma_{\tilde{x},k}^-$ output to state measurement update/correction block 102, and to parameter measurement update/correction block 104. State measurement update/correction block 102 provides current system state estimate $\hat{x}_k^+$ and state uncertainty estimate $\Sigma_{\tilde{x},k}^+$. Parameter time update/prediction block 103 receives as input the previous time varying parameters estimate $\hat{\theta}_{k-1}^+$ and parameter uncertainty estimate $\Sigma_{\tilde{\theta},k-1}^+$. Parameter time update/prediction block 103 outputs predicted parameters $\hat{\theta}_k^-$ and predicted parameter uncertainty $\Sigma_{\tilde{\theta},k}^-$ to the parameter measurement update/correction block 104 and state time update block 101. Parameter measurement update block 104, which provides current parameter estimate $\hat{\theta}_k^+$ and parameter uncertainty estimate $\Sigma_{\tilde{\theta},k}^+$. It will also be appreciated that a minus notation denotes that the vector is the result of the prediction components 101, 103 of the filters, while the plus notation denotes that the vector is the result of the correction component 102/104 of the filters.

Embodiments of this invention require a mathematical model of cell state and output dynamics for the particular application. In the examples above, this is accomplished by defining specific functions for $f(\cdot,\cdot,\cdot)$ and $g(\cdot,\cdot,\cdot)$. An exemplary embodiment uses a cell model that includes effects due to one or more of the open-circuit-voltage (OCV) for the cell, internal resistance, voltage polarization time constants, and a hysteresis level. For the purpose of example, parameter values are fitted to this model structure to model the dynamics of high-power Lithium-Ion Polymer Battery (LiPB) cells, although the structure and methods presented here are general and apply to other electrochemistries.

In this example, SOC is captured by one state of the model. This equation is

$$z_k[m+1] = z_k[m] - (\eta_i \Delta t / C_k) i_k[m] \qquad (3)$$

where Δt represents the inter-sample period (in seconds), C_k represents the capacity of cell number k in the pack (in ampere-seconds), $z_k[m]$ is the SOC of cell k at time index m, i_k, is the current out of cell k, and η_i is the Coulombic efficiency of a cell at current level i_k.

In this example, the polarization voltage levels are captured by several filter states. If we let there be n_f polarization voltage time constants, then

$$f_k[m+1] = A_f f_k[m] + B_f i_k[m]. \qquad (4)$$

The matrix $A_f \in \Re^{n_f \times n_f}$ may be a diagonal matrix with real-valued polarization voltage time constants $a_1 \cdots a_{n_f}$. If so, the system is stable if all entries have magnitude less than one. The vector $B_f \in \Re^{n_f \times 1}$ may simply be set to n_f "1"s. The entries of B_f are not critical as long as they are non-zero. The value of n_f entries in the A_f matrix are chosen as part of the system identification procedure to best fit the model parameters to measured cell data. The A_f and B_f matrices may vary with time and other factors pertinent to the present battery pack operating condition.

In this example, the hysteresis level is captured by a single state

$$h_k[m+1]=\exp\left(-\left|\frac{\eta_i i_k[m]\gamma\Delta t}{C}\right|\right)h_k[m]+\left(1-\exp\left(-\left|\frac{\eta_i i_k[m]\gamma\Delta t}{C}\right|\right)\right)\mathrm{sgn}(i_k[m]), \qquad (5)$$

where γ is the hysteresis rate constant, again found by system identification.

In this example, the overall model state is $x_k[m]=\left[f_k[m]^T \quad h_k[m] \quad z_k[m]\right]^T$, where other orderings of states are possible. The state equation for the model is formed by combining all of the individual equations identified above.

In this example, the output equation that combines the state values to predict cell voltage is

$$v_k[m]=\mathrm{OCV}(z_k[m])+Gf_k[m]-Ri_k[m]+Mh_k[m], \qquad (6)$$

where $G\in\Re^{1\times n_f}$ is a vector of polarization voltage blending factors $g_1\cdots g_{n_f}$ that blend the polarization voltage states together in the output, R is the cell resistance (different values may be used for discharge/charge), and M is the hysteresis blending factor. Note, G may be constrained such that the dc-gain from i_k to Gf_k is zero.

In this example, the parameters are

$$\theta=\left[\eta,\ C,\ a_1\cdots a_{n_f},\ g_1\cdots g_{n_f-1},\ \gamma,\ R,\ M\right]^T. \qquad (7)$$

In any embodiment, the dual filters will adapt a state estimate and a parameter estimate so that a model input-output relationship matches the measured input-output data as closely as possible. This does not guarantee that the model state converges to physical state values. An exemplary embodiment takes extra steps to ensure that one model state converges to SOC. In yet another embodiment, the cell model used for dual filtering may be augmented with a secondary cell model that includes as outputs those states that must converge to their correct values. A specific example of such an augmented cell model (with output augmented with SOC) is

$$g(x_k,u_k,\theta)=\begin{bmatrix}\mathrm{OCV}(z_k)-Ri_k+h_k+Gf_k\\ z_k\end{bmatrix}. \quad (8)$$

The augmented model output is compared to a measured output in the dual filter. In an exemplary embodiment, a measured value for SOC may be approximated using $\hat{z}_k$ derived as

$$\begin{aligned} y_k &\approx \mathrm{OCV}(z_k)-Ri_k\\ \mathrm{OCV}(z_k) &\approx y_k+Ri_k\\ \hat{z}_k &= \mathrm{OCV}^{-1}(v_k+Ri_k). \end{aligned} \quad (9)$$

By measuring the voltage of a cell under load, the cell current, and having knowledge of R, (perhaps through $\hat{\theta}$ from a dual filter), and knowing the inverse OCV function for the cell chemistry, this example computes a noisy estimate of SOC, $\hat{z}_k$.

In this example, a dual filter is run on this modified model, with the "measured" information in the measurement update being

$$\begin{bmatrix}v_k\\ \hat{z}_k\end{bmatrix}.$$

Experimentation has shown that while the "noise" of $\hat{z}_k$ (short-term bias due to hysteresis effects and polarization voltages being ignored) prohibits it from being used as the primary estimator of SOC, its expected long-term behavior in a dynamic environment is accurate, and maintains the accuracy of the SOC state in the dual filter.

Another exemplary embodiment includes methods for estimating important aspects of SOH without employing a full dual filter. The full dual filter method may be computationally intensive. If precise values for the full set of cell model parameters are not necessary, then other methods potentially less complex or computationally intensive might be used. The exemplary methodologies determine cell capacity and resistance using filtering methods. The change in capacity and resistance from the nominal "new-cell" values give capacity fade and power fade, which are the most commonly employed indicators of cell SOH.

In this example, to estimate cell resistance using a filtering mechanism, we formulate a model:

$$\begin{aligned} R_k[m+1] &= R_k[m] + r_k[m] \\ y_k[m] &= \mathrm{OCV}(z_k[m]) - i_k[m]R_k[m] + e_k[m] \end{aligned} \qquad (10)$$

where $R_k[m]$ is the cell resistance and is modeled as a constant value with a fictitious noise process r_k allowing adaptation. $y_k[m]$ is a crude estimate of the cell's voltage, i_k is the cell current, and e_k models estimation error. If we use an estimate of z_k from the state filter in a dual estimator, or from some other source, then we simply apply a filter to this model to estimate cell resistance. In the standard filter, we compare the model's prediction of y_k with the true measured cell voltage, and use the difference to adapt R_k.

Note that the above model may be extended to handle different values of resistance for a variety of conditions of the cell. For example, differences based on charge and discharge, different SOCs, and different temperatures. The scalar R_k would be changed into a vector comprising all of the resistance values being modified, and the appropriate element from the vector would be used each time step of the filter during the calculations.

In this example, to estimate cell capacity using a filter, we again formulate a cell model:

$$\begin{aligned} &C_k[m+1] = C_k[m] + r_k[m] \\ &\qquad 0 = z_k[m] - z_k[m-1] + \eta_i i_k[m-1]\Delta t / C_k[m-1] + e_k[m]. \end{aligned} \tag{11}$$

Again, a filter is formulated using this model to produce a capacity estimate. As the filter runs, the computation in the second equation (right-hand-side) is compared to zero, and the difference is used to update the capacity estimate. Note that good estimates of the present and previous states-of-charge are desired, possibly from a filter estimating SOC. Estimated capacity may again be a function of temperature (and so forth), if desired, by employing a capacity vector, from which the appropriate element is used in each time step during calculations.

Industrial Applicability

Thus, a method for simultaneous estimation of cell state and parameters has been described in conjunction with a number of specific embodiments. One or more embodiments use one or more Kalman filters. Some embodiments use one or more extended Kalman filters. Further, some embodiments include a mechanism to force convergence of state-of-charge. One or more embodiments include a simplified parameter filter to estimate resistance, while some embodiments include a simplified parameter filter to estimate total capacity. The present invention is applicable to a broad range of applications, and cell electrochemistries.

The disclosed method may be embodied in the form of computer-implemented processes and apparatuses for practicing those processes. The method can also be embodied in the form of computer program code containing instructions embodied in tangible media 52, 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 capable of executing the method. The present method 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 as data signal 54 transmitted whether a modulated carrier wave or not, 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 and executed by a computer, the computer becomes an apparatus capable of executing the method. When implemented on a general-purpose microprocessor, the computer program code segments configure the microprocessor to create specific logic circuits.

It will be appreciated that the use of first and second or other similar nomenclature for denoting similar items is not intended to specify or imply any particular order unless otherwise stated. Furthermore, the use of the terminology "a" and "at least one of" shall each be associated with the meaning "one or more" unless specifically stated otherwise.

While the invention has been described with reference to an exemplary embodiment, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A method for estimating present states and present parameters of an electrochemical cell system comprising:

estimating a state value of the electrochemical cell with a cell state filter to estimate said state value, said estimating the state value comprising:

making an internal state prediction of said cell comprising:

determining a parameter estimate;

determining a current measurement;

determining a voltage measurement;

using said parameter estimate, said current measurement and said voltage measurement in a parameter mathematical model to make said internal parameter prediction;

making a state uncertainty prediction of said internal state prediction comprising:

using said parameter estimate and said current measurement, said voltage measurement, and said temperature measurement in a state mathematical model to make said uncertainty prediction;

correcting said internal state prediction and said state uncertainty prediction; and

applying a state algorithm that iterates said making an internal state prediction, said making a state uncertainty prediction and said correcting to yield an ongoing estimation to said internal state prediction and an ongoing uncertainty to said internal state prediction; and estimating a parameter value of the electrochemical cell with a cell parameter filter to estimate said parameter value, said estimating the parameter value comprising:

making an internal state prediction of said cell;

making a parameter uncertainty prediction of said internal state prediction;

correcting said internal parameter prediction and said parameter uncertainty prediction; and

applying a parameter algorithm that iterates said making an internal parameter prediction, said making a parameter uncertainty prediction and said correcting to yield an ongoing estimation to said internal parameter prediction and an ongoing uncertainty to said internal parameter prediction,

wherein said internal parameter includes one or more of:

a polarization voltage time constant,

a polarization voltage blending factor,

a hysteresis blending factor, and

a hysteresis rate constant.

2. The method of claim 1, wherein said correcting said internal state prediction comprises:

computing a gain factor;

computing a corrected internal state prediction using said gain factor, said voltage measurement and said internal state prediction; and

computing a corrected state uncertainty prediction using said gain factor and said state uncertainty prediction.

3. The method of claim 2, wherein said applying a state algorithm comprises using said corrected internal state prediction and said corrected state uncertainty prediction to obtain predictions for a next time step where said state algorithm repeats.

4. The method of claim 3, wherein said state algorithm is at least one of a Kalman Filter and an extended Kalman Filter.

5. The method of claim 4, wherein said internal state includes at least one of state-of-charge, voltage polarization levels, and hysteresis levels.

6. An apparatus configured to estimate present states and present parameters of an electrochemical cell comprising:

a first component configured to estimate a cell state value, said first component comprising:

a component configured to make an internal state prediction of said cell, said component comprising:

a component configured to determine a parameter estimate;

a component configured to determine a current measurement;

a component configured to determine a voltage measurement;

a component configured to use said parameter estimate and said current measurement and said voltage measurement in a mathematical model to make said internal state prediction;

a component configured to make a state uncertainty prediction of said internal state prediction;

a component configured to correct said internal state prediction and said state uncertainty prediction;

a component configured to apply a state algorithm that iterates steps taken by said component configured to make an internal state prediction, said component configured to make a state uncertainty prediction and said component configured to correct to yield an ongoing estimation to said internal state prediction and an ongoing uncertainty to said internal state prediction; and

a second component configured to estimate a cell parameter value, said second component comprising:

a component configured to make an internal parameter prediction of said cell;

a component configured to make a parameter uncertainty prediction of said internal parameter prediction;

a component configured to correct said internal parameter prediction and said parameter uncertainty prediction; and

a component configured to apply a parameter algorithm that iterates steps taken by said component configured to make an internal parameter prediction, said component configured to make a parameter uncertainty prediction and said component configured to correct to yield an ongoing estimation to said internal parameter prediction and an ongoing uncertainty to said internal parameter prediction, wherein said internal parameter includes one or more of:

a polarization voltage time constant,
a polarization voltage blending factor,
a hysteresis blending factor, and
a hysteresis rate constant.

7. The apparatus of claim 6, wherein said component configured to make a state uncertainty prediction comprises a component configured to use said parameter estimate, a current measurement and a voltage measurement in a mathematical model to make said state uncertainty prediction.

8. The apparatus of claim 7, wherein said component configured to correct said internal state prediction comprises:

a component configured to compute a gain factor;

a component configured to compute a corrected internal state prediction using said gain factor, said voltage measurement and said internal state prediction; and

a component configured to compute a corrected state uncertainty prediction using said gain factor and said state uncertainty prediction.

9. The apparatus of claim 8, wherein said component configured to apply a state algorithm comprises a component configured to use said corrected internal state prediction and said corrected state uncertainty prediction to obtain predictions for a next time step where said state algorithm repeats.

FIG. 1

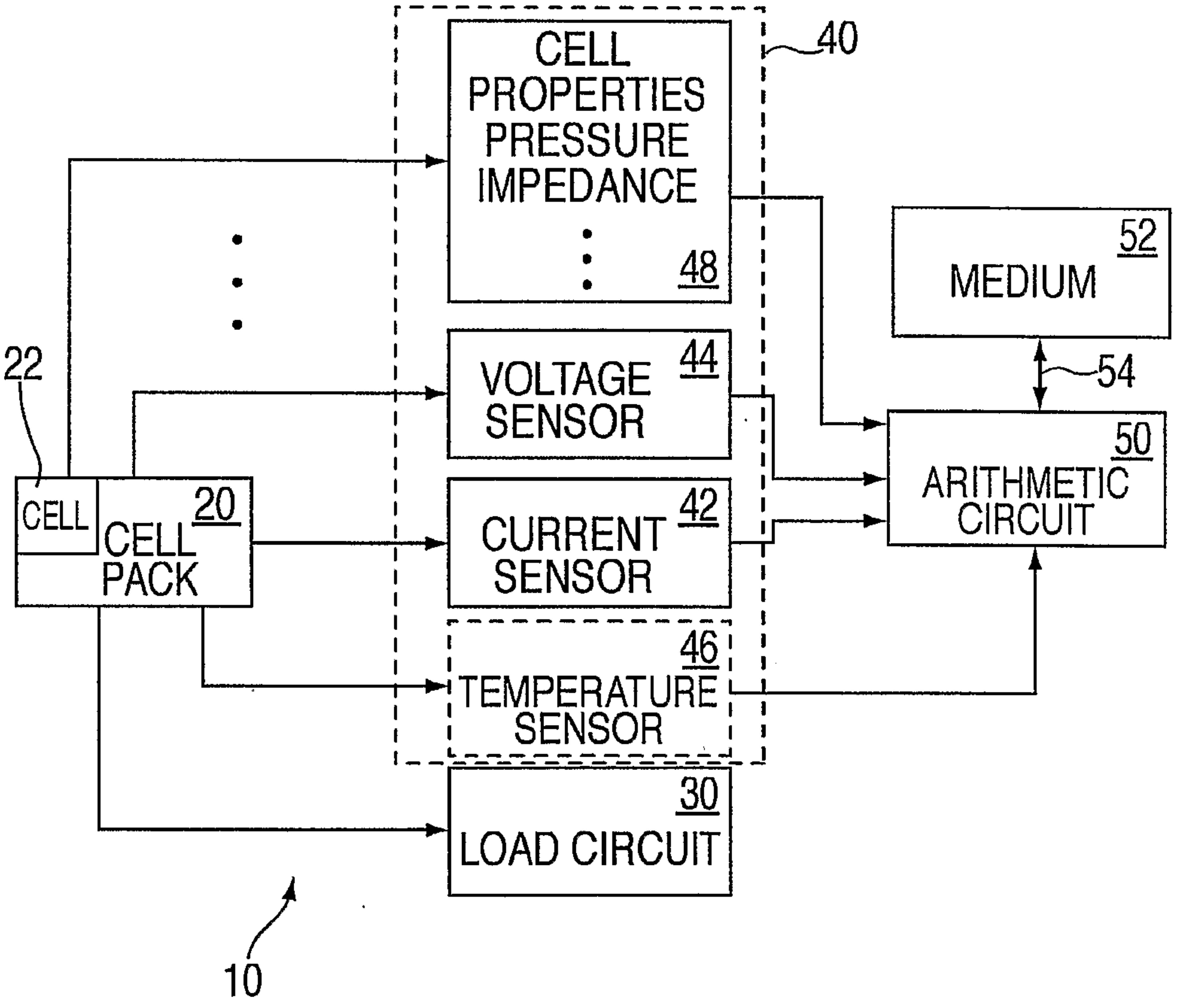
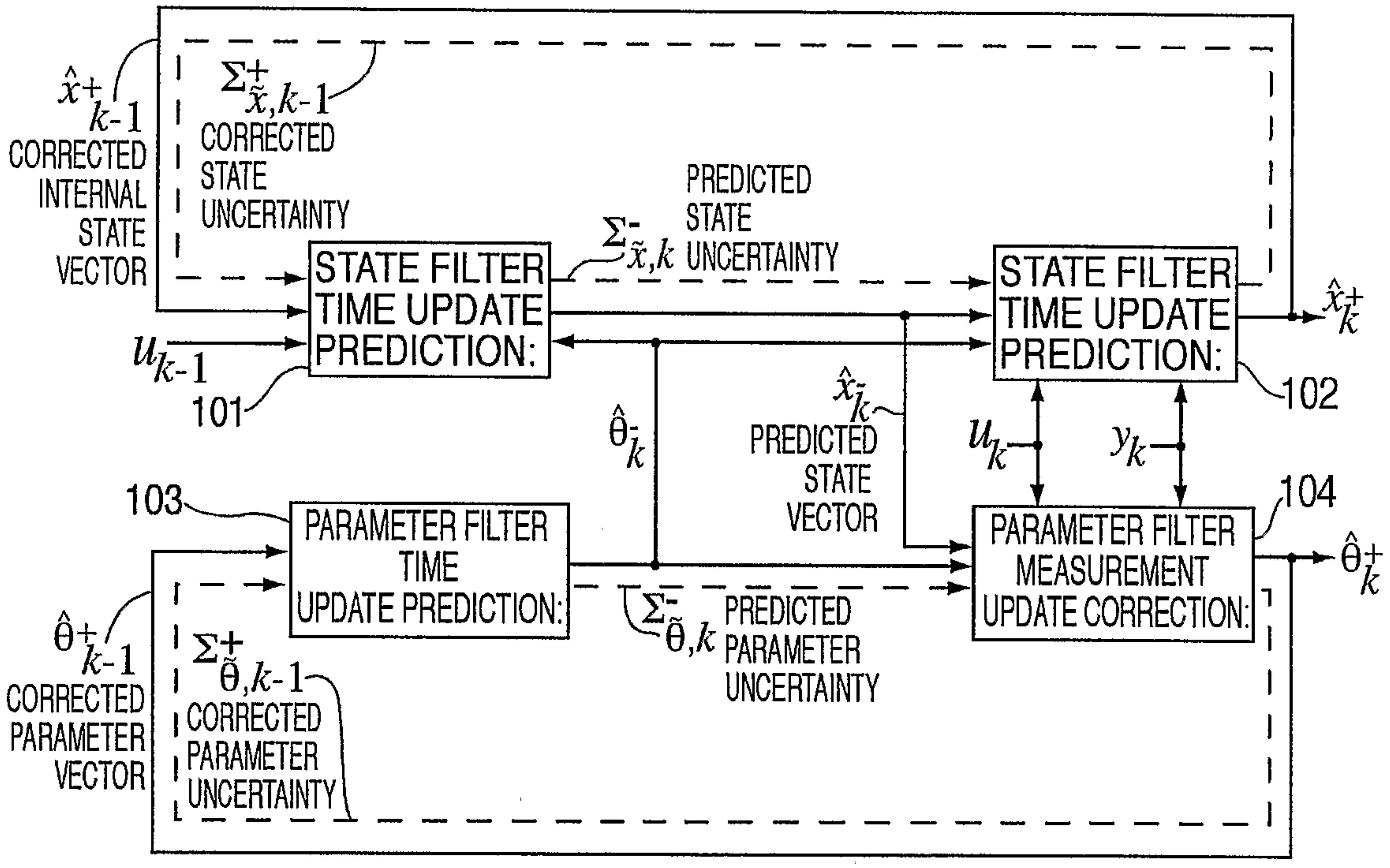

CELL PROPERTIES PRESSURE IMPEDANCE
48
40
52
MEDIUM
54
22
VOLTAGE SENSOR
44
50
ARITHMETIC CIRCUIT
CELL
20
CELL PACK
CURRENT SENSOR
42
46
TEMPERATURE SENSOR
30
LOAD CIRCUIT
10

FIG. 2


$\hat{x}^+_{k-1}$
CORRECTED INTERNAL STATE VECTOR
$\Sigma^+_{\tilde{x},k-1}$
CORRECTED STATE UNCERTAINTY
$\Sigma^-_{\tilde{x},k}$
PREDICTED STATE UNCERTAINTY
STATE FILTER TIME UPDATE PREDICTION:
STATE FILTER TIME UPDATE PREDICTION:
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u_{k-1}
101
102
$\hat{\theta}^-_k$
$\hat{x}^-_k$
PREDICTED STATE VECTOR
u_k
y_k
103
104
PARAMETER FILTER TIME UPDATE PREDICTION:
PARAMETER FILTER MEASUREMENT UPDATE CORRECTION:
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$\hat{\theta}^+_{k-1}$
CORRECTED PARAMETER VECTOR
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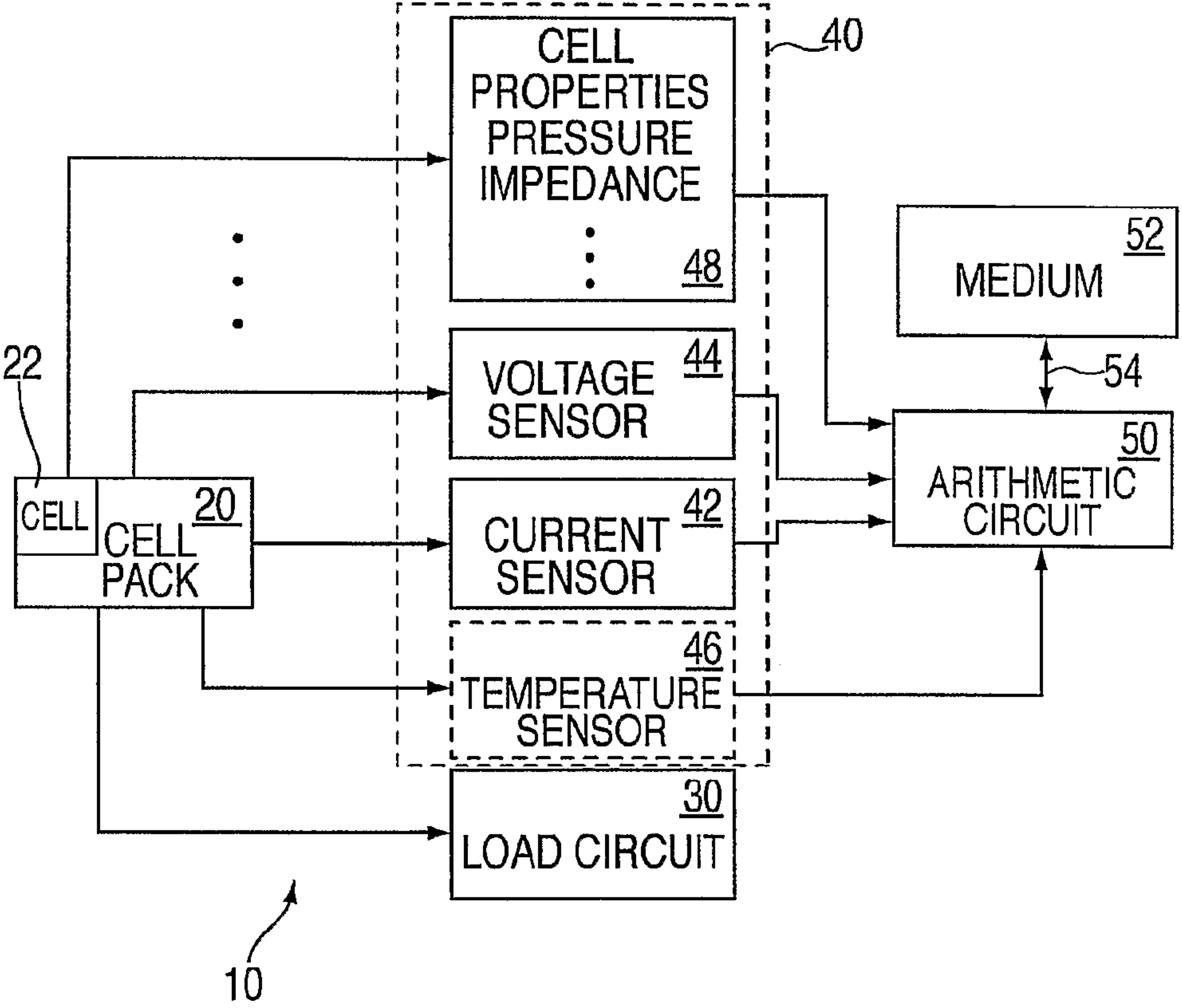
CORRECTED PARAMETER UNCERTAINTY
$\Sigma^-_{\tilde{\theta},k}$
PREDICTED PARAMETER UNCERTAINTY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TEMPERATURE SENSOR
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LOAD CIRCUIT
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