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Hanking

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(54) BATTERY STRING MONITORING SYSTEM

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H01M 10/48	(2006.01)
H01M 10/42	(2006.01)

(52) **U.S. Cl.**

CPC ***G01R 31/3658*** (2013.01); ***G01R 31/3679*** (2013.01); ***H01M 10/4207*** (2013.01); ***H01M 10/482*** (2013.01)

(58) **Field of Classification Search**

CPC G01R 31/3658; G01R 31/3679; H01M 10/4207; H01M 10/482
USPC 324/434, 426, 425
See application file for complete search history.

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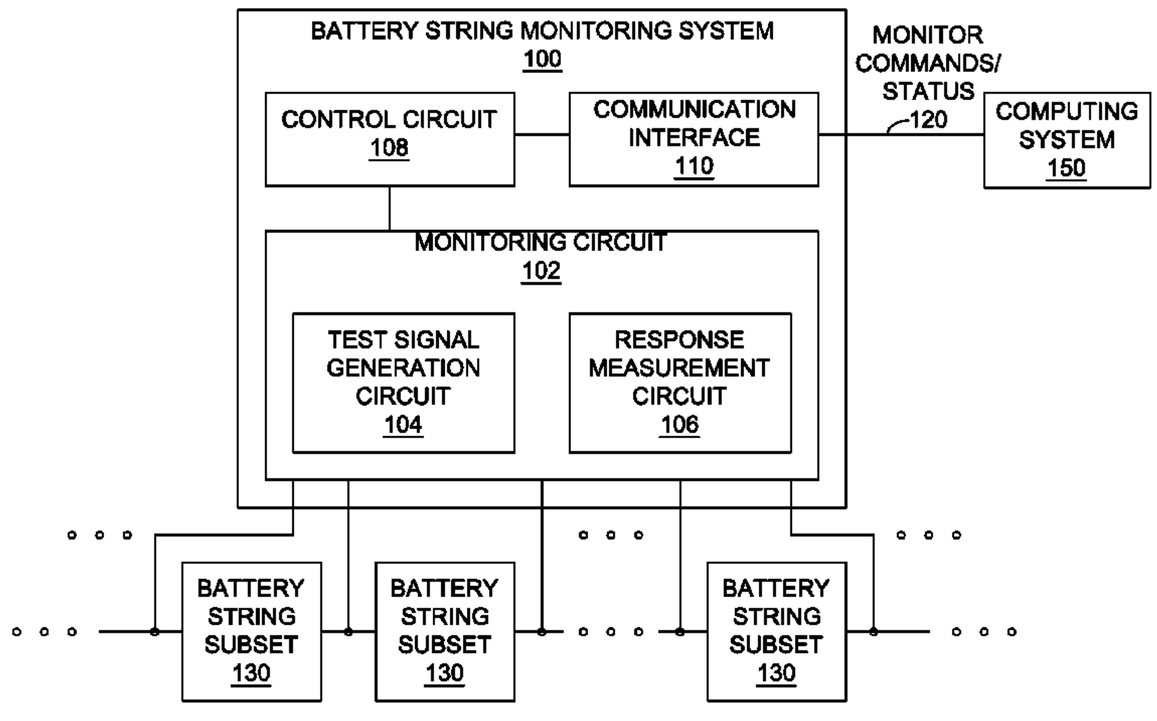
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(74) *Attorney, Agent, or Firm* — Polsinelli PC

(57) **ABSTRACT**

Aspects of the present disclosure involve a monitoring system for a plurality of batteries connected in series. In one example, the monitoring system includes a monitoring circuit to be coupled across each of a plurality of distinct contiguous subsets of the batteries as a unit. The monitoring circuit includes at least one test signal generation circuit to generate a test signal and apply the test signal to each subset of the batteries, and at least one response measurement circuit to measure a response of each subset of the batteries to the test signal. The monitoring system also includes a control circuit to identify at least one of the subsets of the batteries as including a failing battery based on the measured response of each subset of the batteries.

13 Claims, 10 Drawing Sheets



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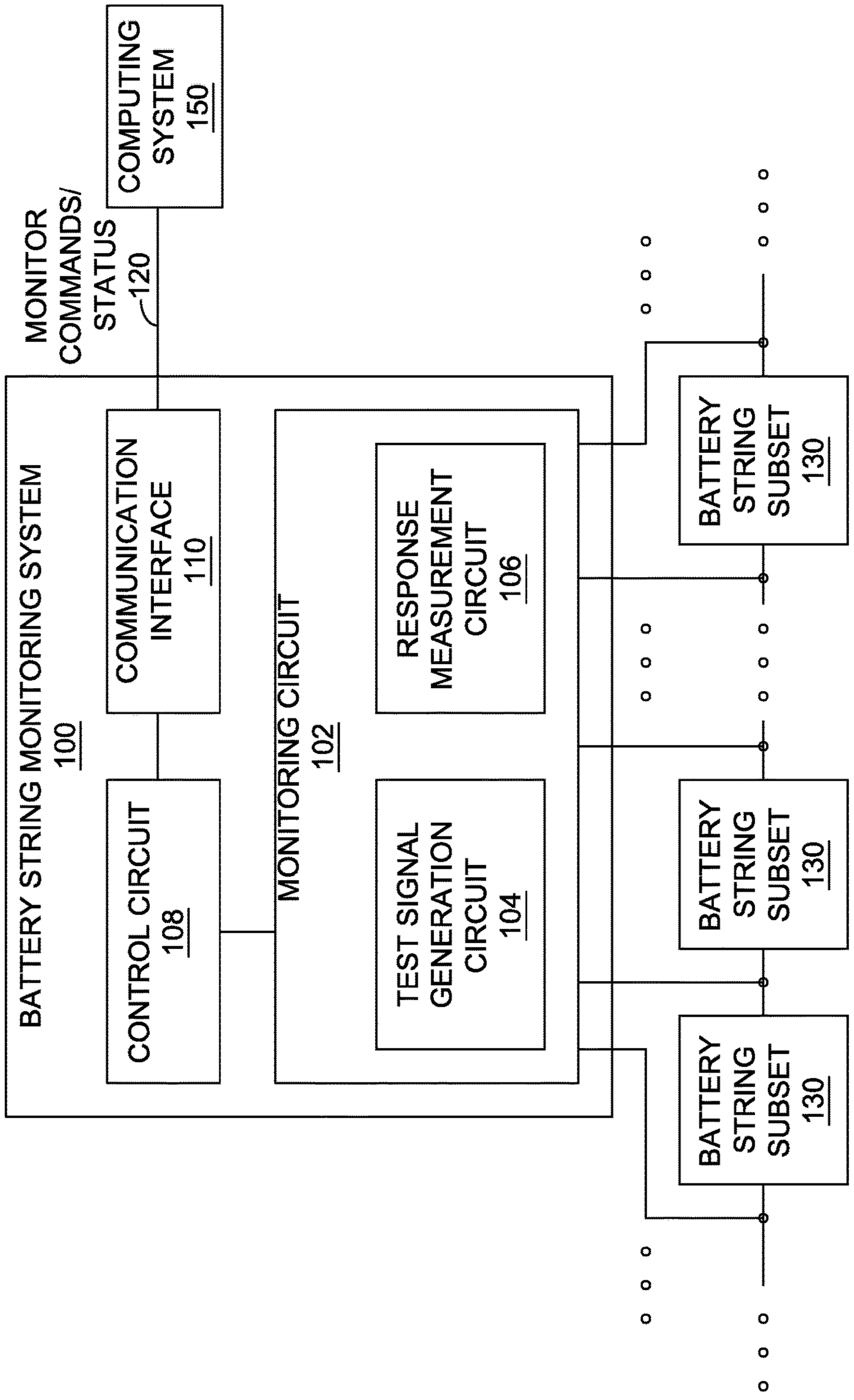

COMPUTING SYSTEM 150
MONITOR COMMANDS/ STATUS 120
BATTERY STRING MONITORING SYSTEM 100
COMMUNICATION INTERFACE 110
CONTROL CIRCUIT 108
MONITORING CIRCUIT 102
RESPONSE MEASUREMENT CIRCUIT 106
TEST SIGNAL GENERATION CIRCUIT 104
BATTERY STRING SUBSET 130
BATTERY STRING SUBSET 130
BATTERY STRING SUBSET 130
BATTERY STRING SUBSET 130

FIG. 1

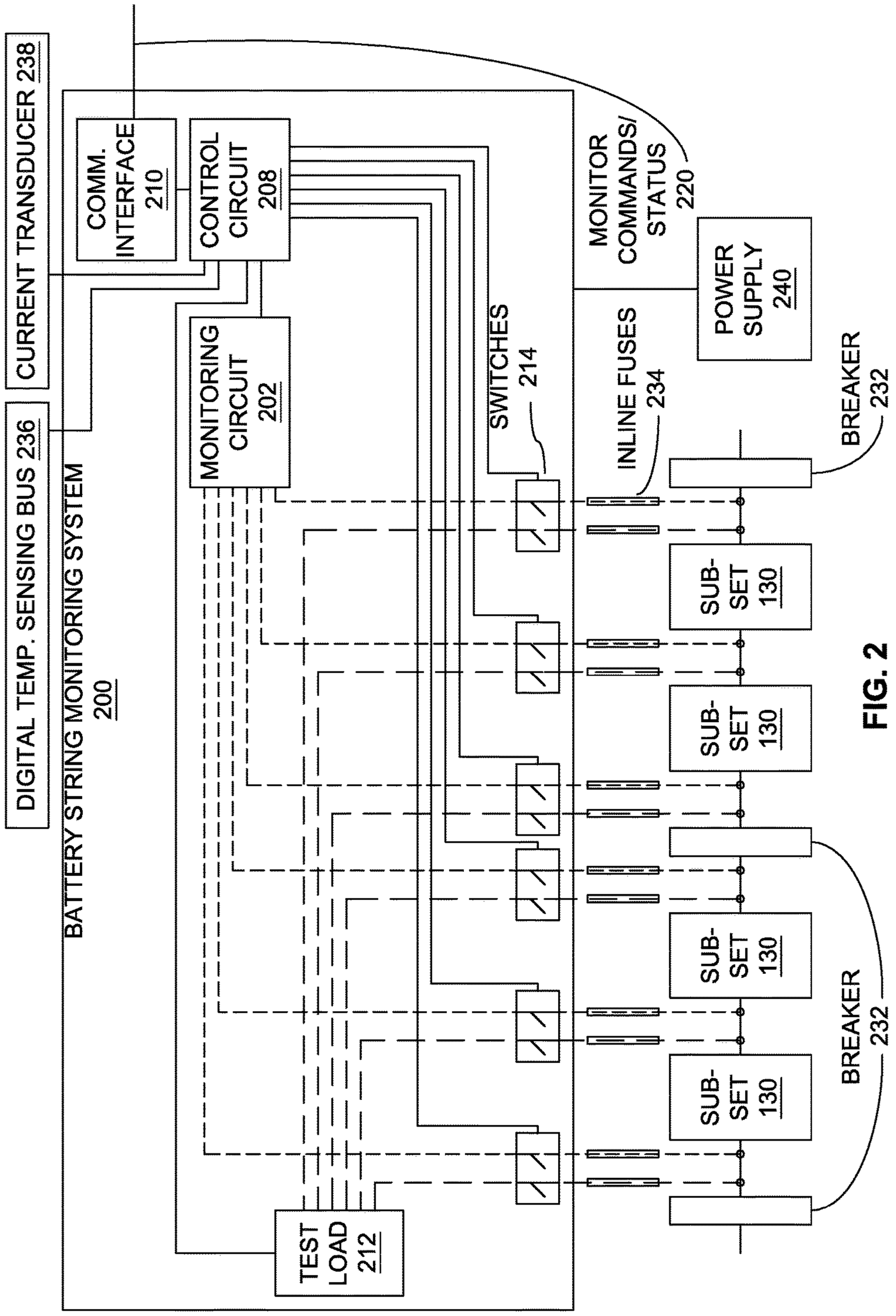

BATTERY STRING MONITORING SYSTEM
200
DIGITAL TEMP. SENSING BUS 236
CURRENT TRANSDUCER 238
COMM. INTERFACE 210
CONTROL CIRCUIT 208
MONITORING CIRCUIT 202
MONITOR COMMANDS/ STATUS 220
SWITCHES 214
INLINE FUSES 234
POWER SUPPLY 240
BREAKER 232
SUB-SET 130
SUB-SET 130
SUB-SET 130
SUB-SET 130
BREAKER 232
TEST LOAD 212

FIG. 2

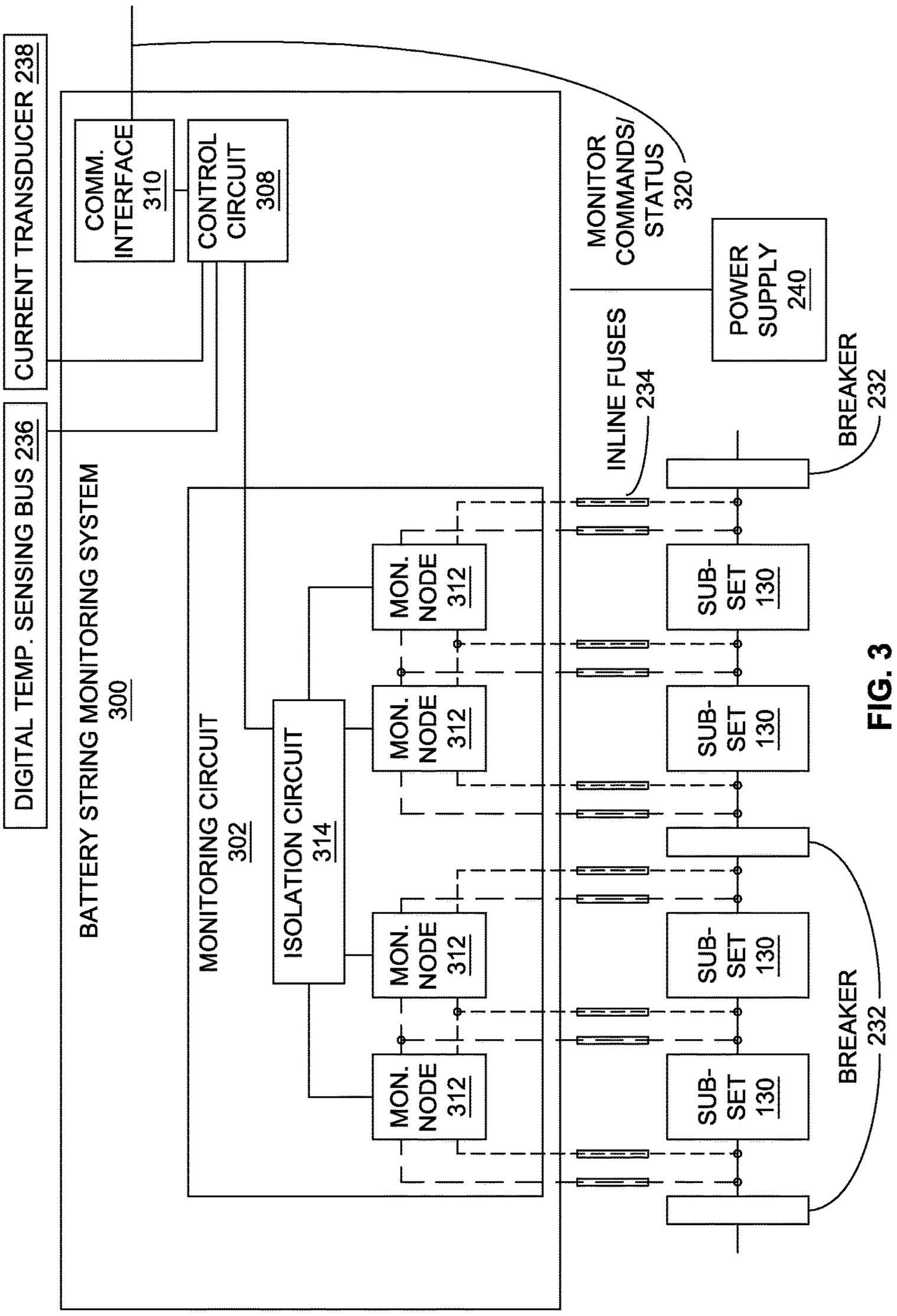

BATTERY STRING MONITORING SYSTEM 300
CURRENT TRANSDUCER 238
DIGITAL TEMP. SENSING BUS 236
COMM. INTERFACE 310
CONTROL CIRCUIT 308
MONITOR COMMANDS/ STATUS 320
POWER SUPPLY 240
MONITORING CIRCUIT 302
ISOLATION CIRCUIT 314
MON. NODE 312
MON. NODE 312
MON. NODE 312
MON. NODE 312
INLINE FUSES 234
BREAKER 232
SUB-SET 130
SUB-SET 130
SUB-SET 130
SUB-SET 130
BREAKER 232

FIG. 3

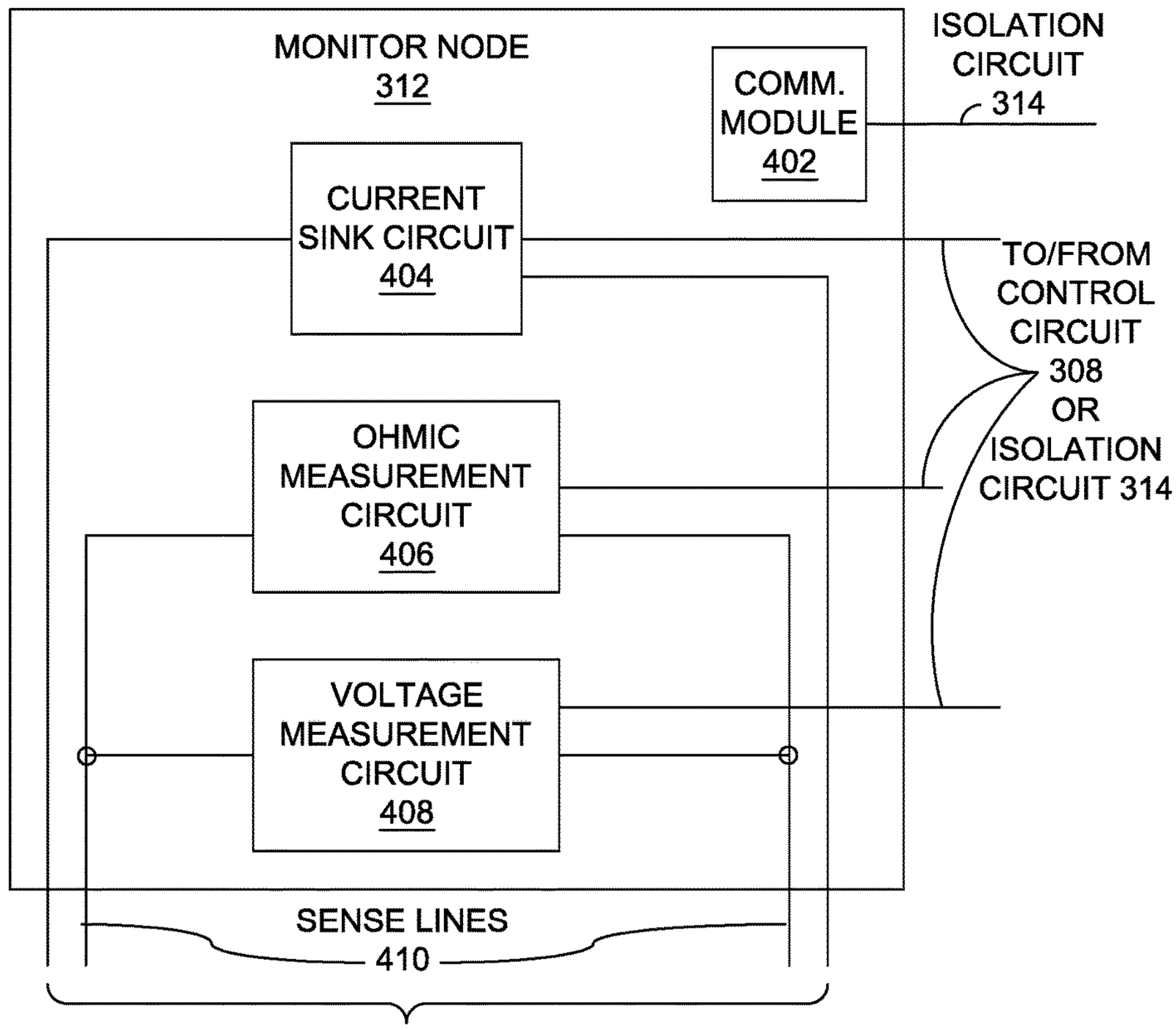

MONITOR NODE
312
COMM. MODULE
402
FROM ISOLATION CIRCUIT
314
CURRENT SINK CIRCUIT
404
TO/FROM CONTROL CIRCUIT
308
OR
ISOLATION CIRCUIT 314
OHMIC MEASUREMENT CIRCUIT
406
VOLTAGE MEASUREMENT CIRCUIT
408
SENSE LINES
410
ACROSS SUBSET
130

FIG. 4

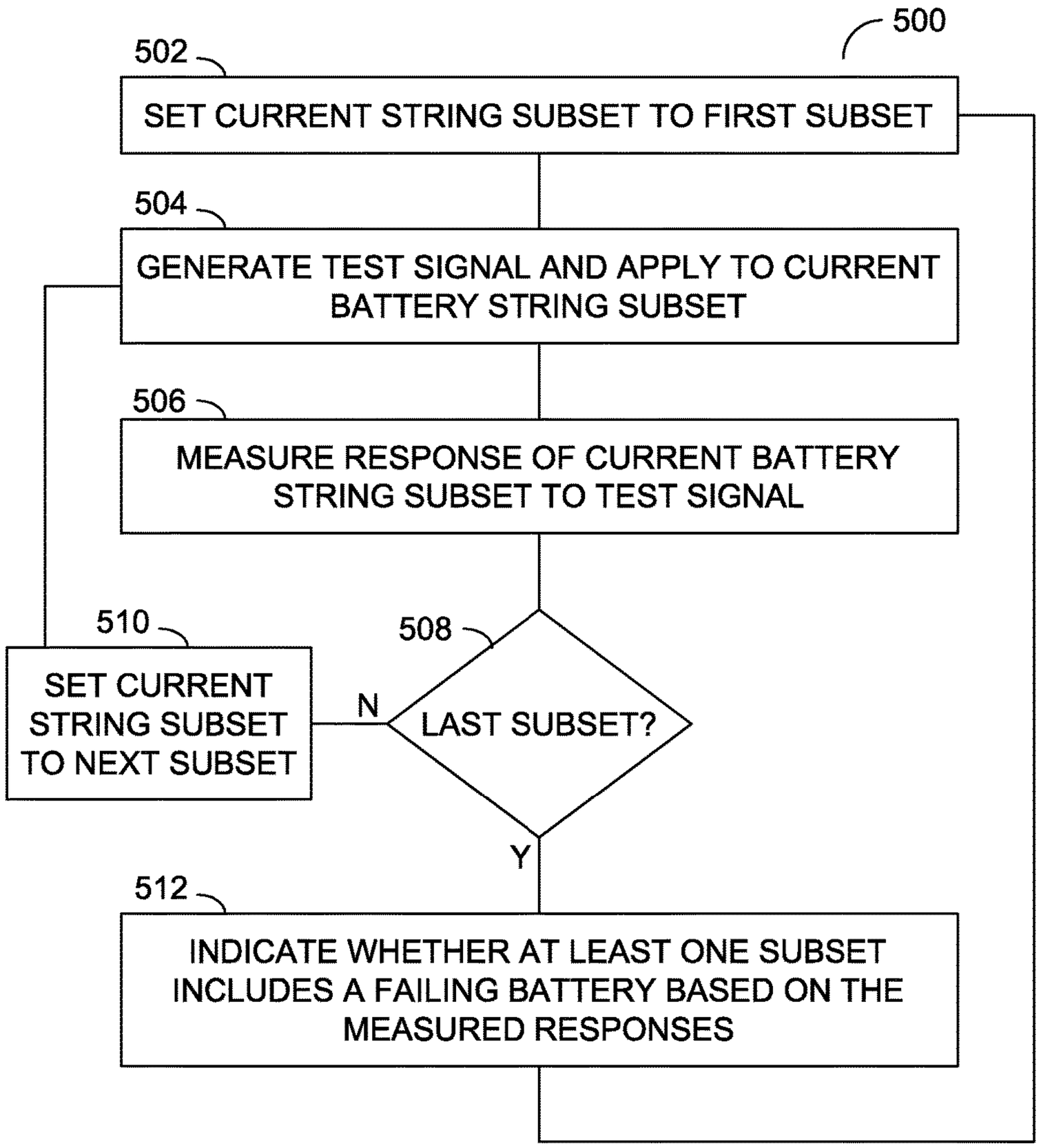

500
502
SET CURRENT STRING SUBSET TO FIRST SUBSET
504
GENERATE TEST SIGNAL AND APPLY TO CURRENT BATTERY STRING SUBSET
506
MEASURE RESPONSE OF CURRENT BATTERY STRING SUBSET TO TEST SIGNAL
508
LAST SUBSET?
N
Y
510
SET CURRENT STRING SUBSET TO NEXT SUBSET
512
INDICATE WHETHER AT LEAST ONE SUBSET INCLUDES A FAILING BATTERY BASED ON THE MEASURED RESPONSES

FIG. 5

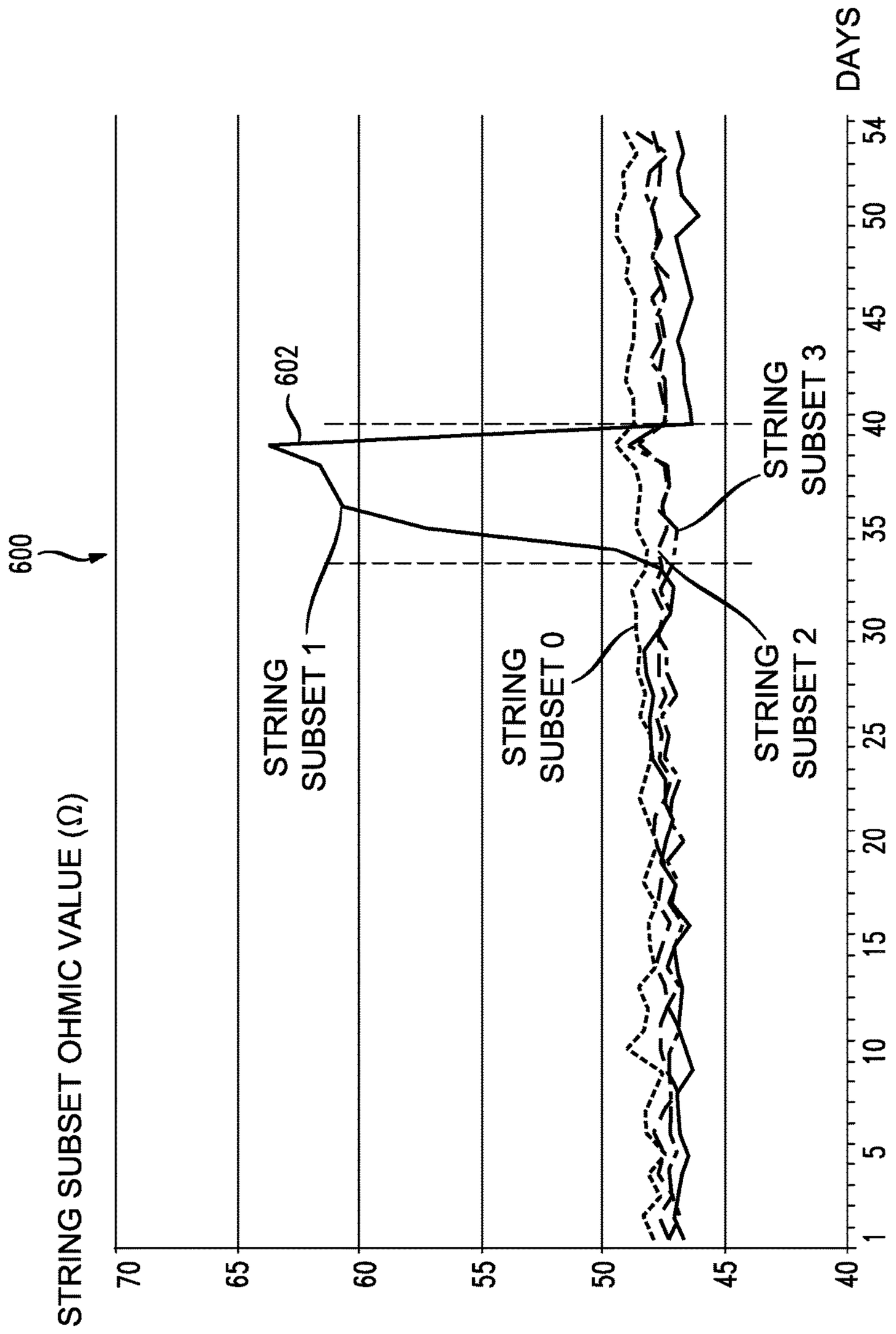

600
STRING SUBSET OHMIC VALUE (Ω)
70
65
60
55
50
45
40
DAYS
1
5
10
15
20
25
30
35
40
45
50
54
602
STRING SUBSET 1
STRING SUBSET 0
STRING SUBSET 2
STRING SUBSET 3

FIG. 6

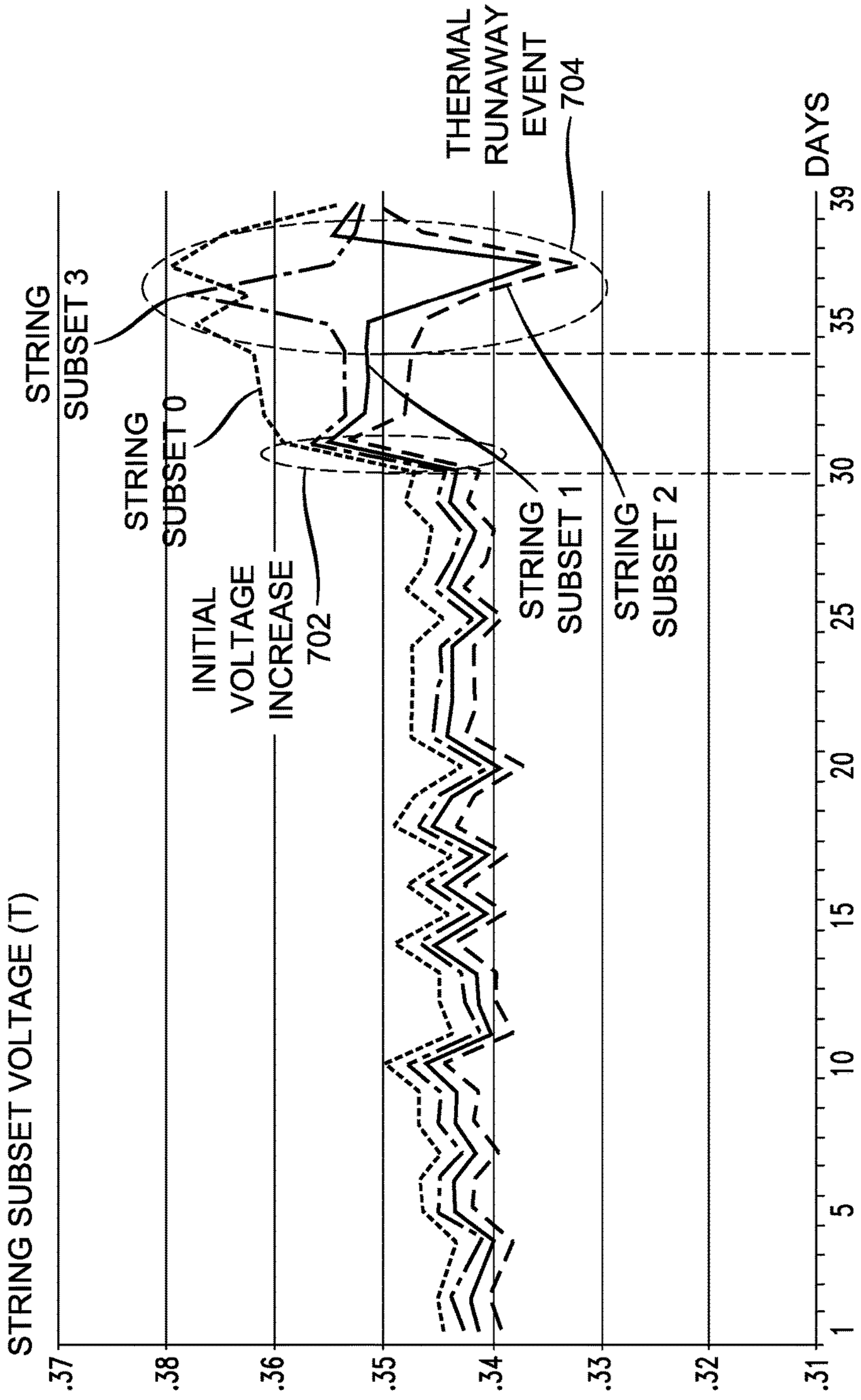

THERMAL RUNAWAY EVENT 704
DAYS
39
35
30
25
20
15
10
5
1
STRING SUBSET 3
STRING SUBSET 0
INITIAL VOLTAGE INCREASE 702
STRING SUBSET 1
STRING SUBSET 2
STRING SUBSET VOLTAGE (T)
.37
.38
.36
.35
.34
.33
.32
.31

FIG. 7

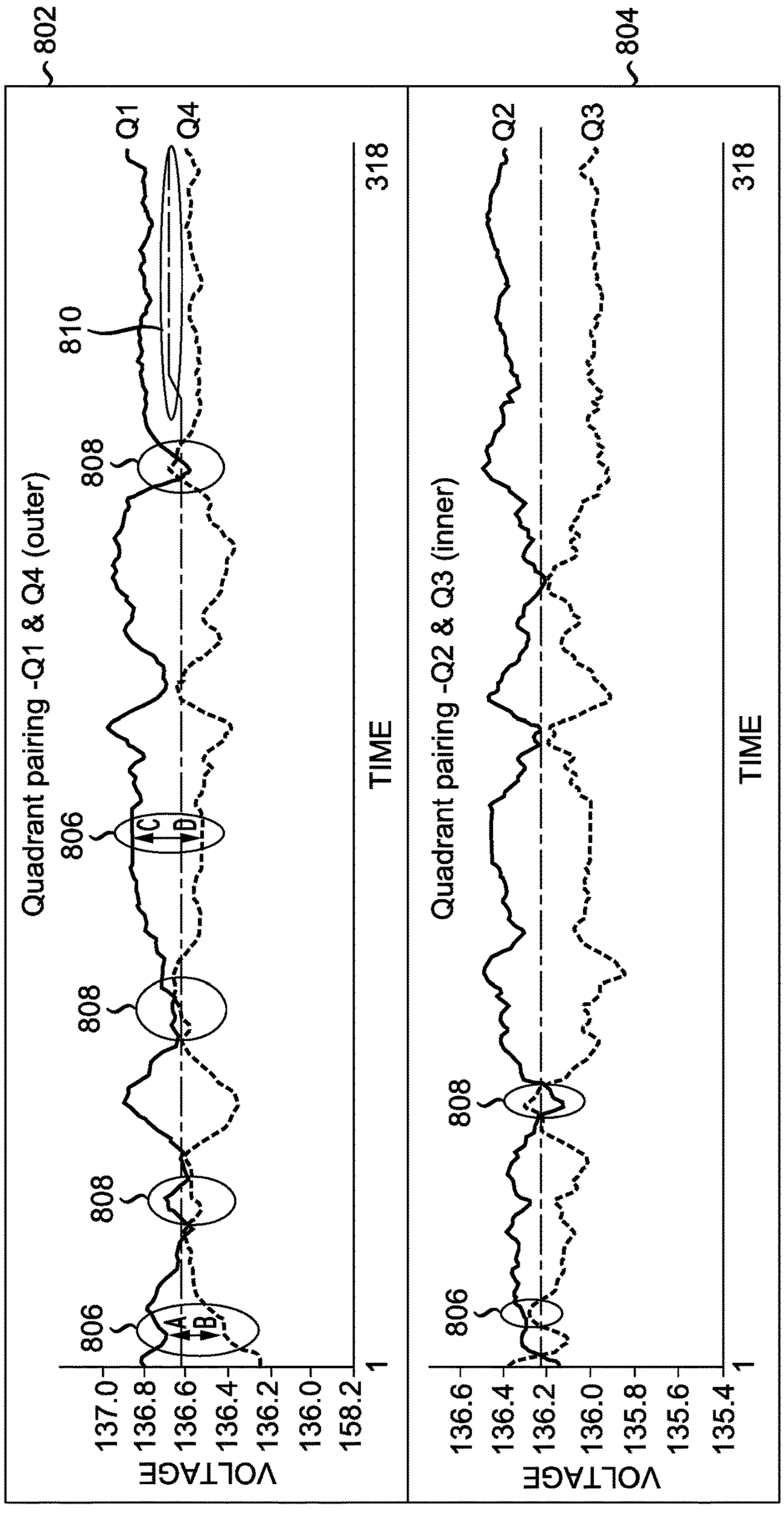

802
804
Q1
Q4
Q2
Q3
318
318
810
808
808
806
806
808
808
806
A
B
C
D
Quadrant pairing -Q1 & Q4 (outer)
Quadrant pairing -Q2 & Q3 (inner)
TIME
TIME
VOLTAGE
VOLTAGE
137.0
136.8
136.6
136.4
136.2
136.0
158.2
1
136.6
136.4
136.2
136.0
135.8
135.6
135.4
1

FIG. 8

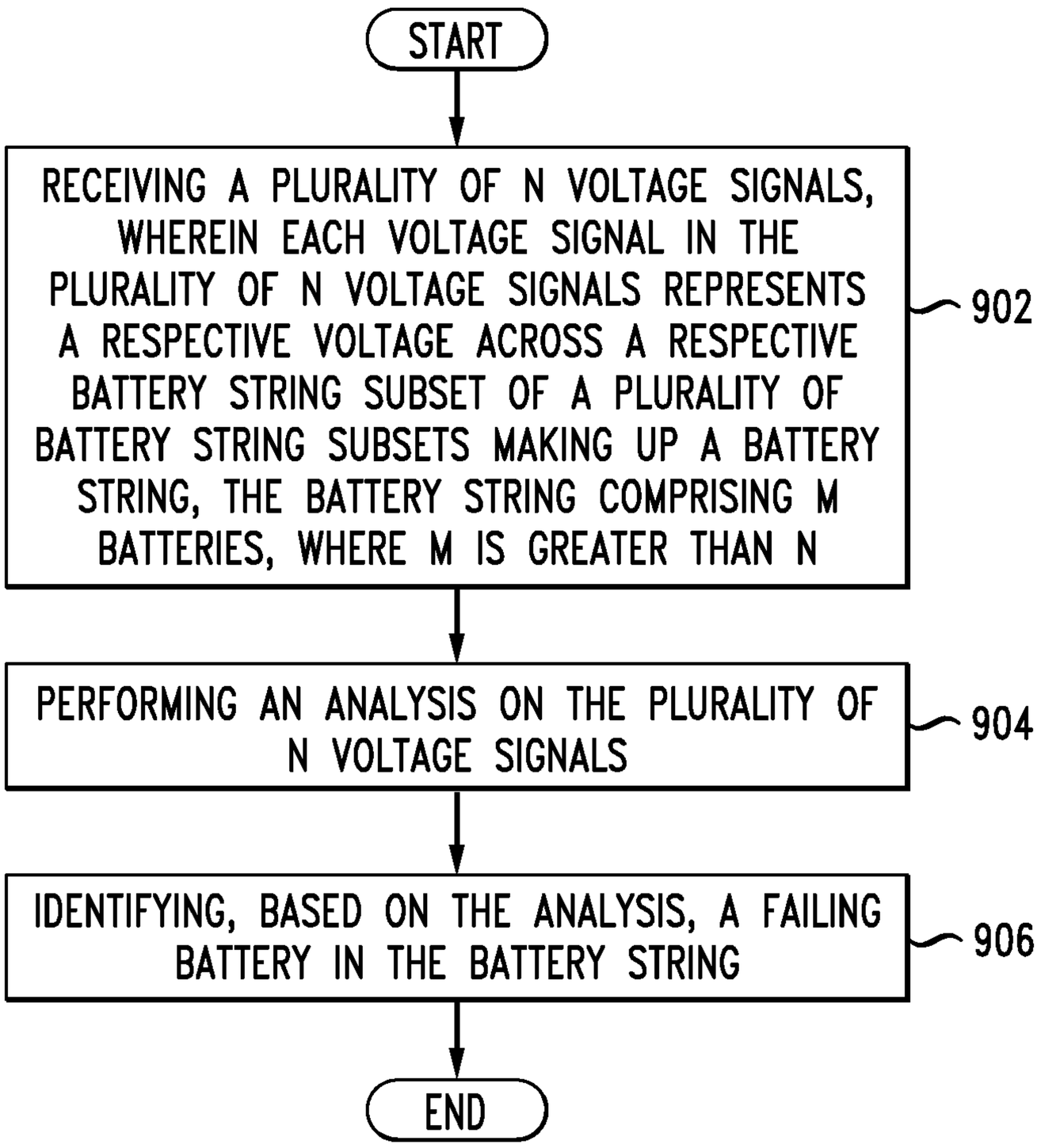

START
RECEIVING A PLURALITY OF N VOLTAGE SIGNALS, WHEREIN EACH VOLTAGE SIGNAL IN THE PLURALITY OF N VOLTAGE SIGNALS REPRESENTS A RESPECTIVE VOLTAGE ACROSS A RESPECTIVE BATTERY STRING SUBSET OF A PLURALITY OF BATTERY STRING SUBSETS MAKING UP A BATTERY STRING, THE BATTERY STRING COMPRISING M BATTERIES, WHERE M IS GREATER THAN N
902
PERFORMING AN ANALYSIS ON THE PLURALITY OF N VOLTAGE SIGNALS
904
IDENTIFYING, BASED ON THE ANALYSIS, A FAILING BATTERY IN THE BATTERY STRING
906
END

FIG. 9

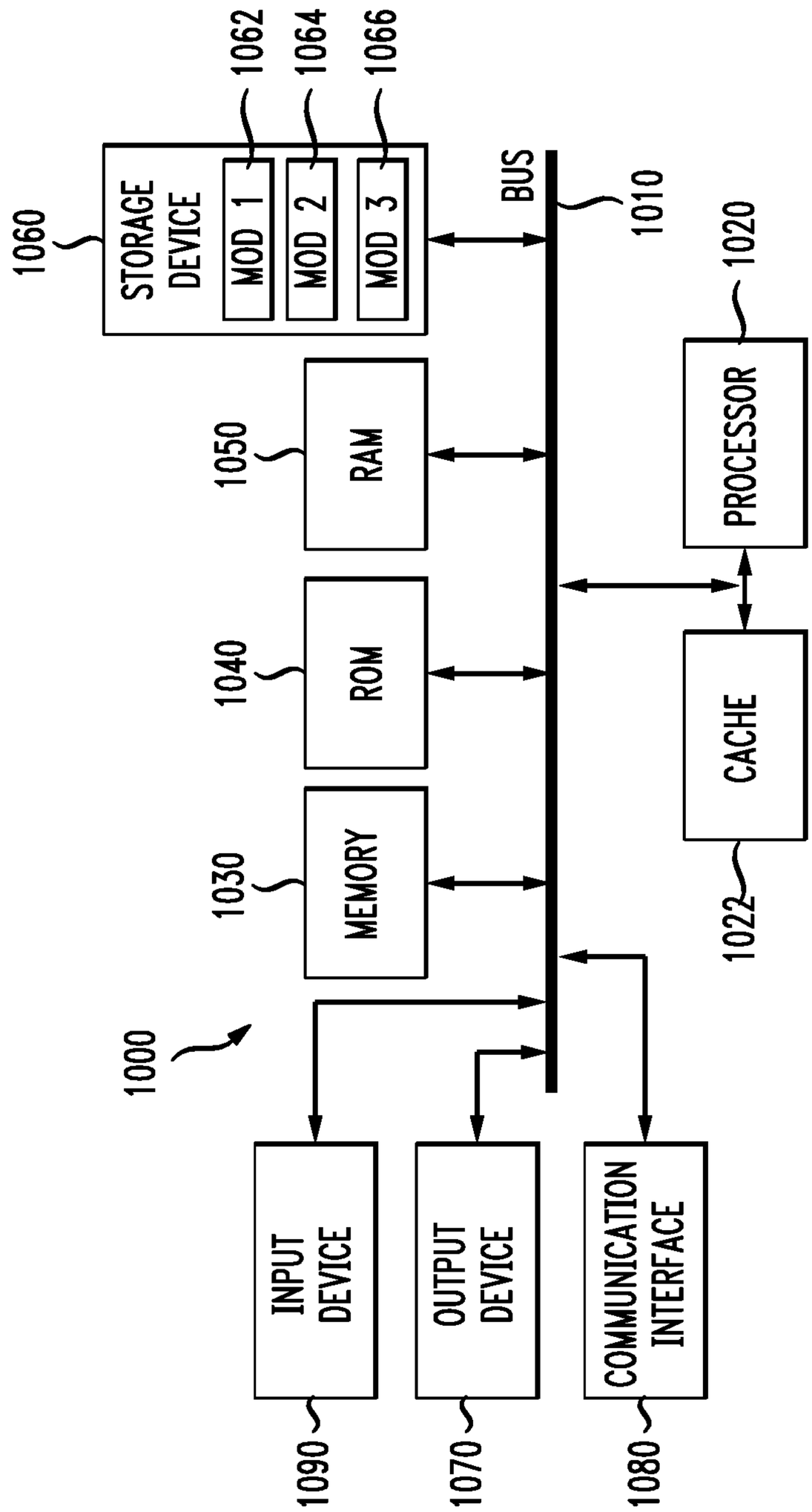

1000
1010
BUS
1020
PROCESSOR
1022
CACHE
1030
MEMORY
1040
ROM
1050
RAM
1060
STORAGE DEVICE
MOD 1
MOD 2
MOD 3
1062
1064
1066
1070
OUTPUT DEVICE
1080
COMMUNICATION INTERFACE
1090
INPUT DEVICE

FIG. 10

BATTERY STRING MONITORING SYSTEM

RELATED APPLICATIONS

This application is related to and claims priority under 35 U.S.C. § 119(e) from U.S. Patent Application No. 62/238,223,filed Oct. 7, 2015entitled "BATTERY STRING MONITORING SYSTEM," the entire contents of which is incorporated herein by reference for all purposes.

TECHNICAL FIELD

Aspects of the present disclosure relate generally to electrical batteries and, more specifically, to a monitoring system for a battery string.

BACKGROUND

Electrical batteries play an indispensable role in commercial and industrial systems, such as, for example, as an alternate source of power in an uninterruptible power supply (UPS) system. In such systems, each individual battery, or "jar," may supply a relatively small voltage, with several such batteries arranged or connected in series as a battery "string" to supply an overall voltage approximately equal to the sum of the battery voltages that is useful for the electronic system being supported.

To ensure the batteries in such a system are functioning properly and perform as expected when the need arises, such a system oftentimes includes a separate monitoring circuit for each battery. Typically, each monitor periodically tests its corresponding battery in an attempt to identify any battery that may be failing so that such a battery may be replaced before overall system performance is adversely affected. While such per-battery testing can be effective in identifying poorly performing batteries, such individual monitoring circuits may be considered expensive in some industrial or commercial applications. As a result, many types of battery systems, such as those employed in various facets of the telecommunications, utilities, cable television, railroad, and oil and gas industries, remain unmonitored.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments are illustrated in referenced figures of the drawings. It is intended that the embodiments and figures disclosed herein are to be considered illustrative rather than limiting. The use of the same reference numerals in different drawings indicates similar or identical items.

FIG. **1** is a block diagram of an example battery string monitoring system;

FIG. **2** is a block diagram of an example battery string monitoring system in which a single test load is applied across each of a plurality of subsets of the battery string in succession;

FIG. **3** is a block diagram of an example battery string monitoring system in which a separate monitor node is provided for each subset of the battery string to be monitored;

FIG. **4** is a block diagram of an example monitor node employable in the example battery string monitoring system of FIG. **3**;

FIG. **5** is a flow diagram of an example method of monitoring a battery string by monitoring subsets of the battery string;

FIG. **6** is a graph of example battery string subset ohmic value measurements over time that may be employed to identify a subset that includes a failing battery;

FIG. **7** is a graph of example battery string subset voltage measurements over time that may be employed to identify a subset that includes a battery exhibiting a thermal runaway event.

FIG. **8** illustrates two exemplary quadrant pairings of voltage measurements over time that may be employed to identify a subset that includes a failing battery;

FIG. **9** illustrates an example method embodiment; and

FIG. **10** illustrates an exemplary computer system which can be used to practice the methods and concepts disclosed herein.

DETAILED DESCRIPTION

The disclosed battery monitoring system uses readings of voltages at multiple points on a battery string to determine the integrity of the battery string. Using these voltage readings, the system can determine if individual batteries are failing within the battery string. However, unlike individual battery monitors for each battery in the string, the disclosed system uses fewer voltage points than the number of batteries in the string. For example, if there are forty batteries on a battery string, battery monitoring using the disclosed system may only have four voltage monitoring points—each respective voltage value corresponding to voltage across a respective substring of ten batteries in the overall battery string. In another example, if a battery string contained five batteries, battery monitoring using the disclosed system may only use two voltage monitoring points—one corresponding to voltage across two of the batteries in the battery string, and another corresponding to voltage across the remaining three batteries in the battery string.

In other words, the battery monitoring system disclosed herein receives at least one voltage value which covers at least two batteries in series. As a minimum, the battery string should contain at least three batteries, with a first voltage reading covering a single battery and a second voltage reading covering the remaining two batteries. Preferably, the voltage readings cover symmetric substrings of batteries. For example, a battery string of forty batteries could record four measurements (one for every ten batteries), thereby dividing the string into quadrants. Dividing the battery string into quadrants reveals changes in the voltage measurements which are mirrored in the corresponding quadrants. By comparing the quadrant voltages, failing battery strings and/or individual failing batteries can be identified.

In a quadrant analysis, where the battery substring has been divided into four equal quadrants and voltages for each respective quadrant are analyzed by the monitoring system. For example, consider a battery string having a series of battery string subsets labeled A-B-C-D, which are located in that order. The voltage for quadrant A will mirror that of quadrant D (the "outer" voltages), and the voltage for quadrant B will mirror that of quadrant C (the "inner" voltages). By analyzing the voltages, their relative symmetry (or lack thereof), and overall behavior over time, determinations regarding the health and integrity of the batteries can be made.

In non-quadrant analyses with more or less voltage measurements, the mirroring principles of a quadrant analysis are likewise applicable inasmuch as symmetry exists between the respective substrings corresponding to the voltage measurements. When symmetry does not exist in the substrings, the system can compensate accordingly. In one

example of compensating for a non-symmetric circumstance, a first voltage reading of a single battery can be provided to the monitoring system with a second voltage reading of a pair of batteries. The system, in analyzing the two voltages, can compensate for the difference in the respective substrings by (for example) doubling the voltage of the first voltage within the analysis, halving the voltage of the second voltage within the analysis, or otherwise adjusting the values being processed. In another example where compensation might be required for the analysis, the number of batteries between two substrings may be equal, but the types or qualities of the batteries may differ based on age, type, size, capability, etc.

In another non-quadrant analysis example, consider the circumstance where the number of voltage measurements is an odd number. The system can, inasmuch as is possible, seek to find at least one point of symmetry in the voltage measurements. Thus in an exemplary configuration where there are five voltage measurements, A-B-C-D-E, the C measurement can be a center measurement, with B & D forming an "inner" measurement having some degree of mirroring between the respective voltage readings, and A & E forming an "outer" measurement having some degree of mirroring between the respective voltage readings. The system, in analyzing the five measurements, can use the mirroring aspects of B & D and A & E, in conjunction with the voltage values of C, to make determinations regarding the health of the respective battery strings.

Having provided an overview of the general concepts disclosed herein, the disclosure now turns to the figures for additional details. FIG. **1** is a block diagram of an example battery string monitoring system **100**. The battery string monitoring system **100** is capable of testing or measuring groups or subsets **130** of batteries, in addition to individual batteries, of a battery string. The battery string includes multiple batteries that are connected in series to generate a voltage for an electrical or electronic system. As illustrated in FIG. **1**, the battery string monitoring system **100** is coupled across each subset **130**. Each subset **130** in this example includes two or more series-connected batteries. According to at least some embodiments, the number of batteries, as well as the nominal voltage of each battery, in each subset **130** of the battery string being monitored by the battery string monitoring system **100** is the same. However, other embodiments of the battery string monitoring system **100** may be applied to battery strings in which the nominal battery voltages, as well as the number of batteries in each subset **130**, may vary from subset **130** to subset **130**.

The battery string monitoring system **100** of FIG. **1** may include a monitoring circuit **102**, a control circuit **108**, and a communication interface **110**. Additionally, the monitoring circuit **102** may include at least one test signal generation circuit **104** and at least one response measurement circuit **106**. Further, the battery string monitoring system **100** may include additional active and/or passive components, such as one or more resistors, capacitors, inductors, transistors, signal receivers, signal transmitters, output components (e.g., one or more light-emitting diodes (LEDs), sound generation devices, and/or the like), microcontrollers, digital signal processors (DSPs) or other algorithmic processors, but such components are not explicitly depicted in FIG. **1** to simplify the following discussion.

The test signal generation circuit **104** may be configured to generate at least one test signal and apply that test signal to a battery string subset **130**. The test signal may be, for example, a direct current (DC) or alternating current (AC) voltage or current impressed upon the battery string subset **130** for some period of time, such as, for example, some number of milliseconds. The response measurement circuit **106** may be configured to measure a response of the battery string subset **130**, such as a voltage or a current, to the test signal and/or to normal operation conditions of the battery. Depending on the particular embodiment, the application of the test signal and/or the measurement of the response may occur, for example, while the battery string subset **130** is delivering power, while the battery string subset **130** is being charged, and/or while the battery string subset **130** is at least temporarily disconnected from a power source and/or a load.

The control circuit **108** may be configured to generate and provide control and/or timing signals to the monitoring circuit **102**, such as signals to initiate the generation and application of test signals in the test signal generation circuit **104**, and signals to retrieve the responses measured in the response measurement circuit **106**. In some examples, one or more of the signals between the control circuit **108** and the monitoring circuit **102** may be carried by way of a particular communication connection, such as, for example, an RS-232 serial communication connection. Further, in some embodiments, the measured responses may be in the form of analog and/or digital signals provided by the monitoring circuit **102** to the control circuit **108**. In some examples, the control circuit **108** may provide such signals according to some schedule maintained at the control circuit **108**, while in other embodiments, the control circuit **108** may receive monitor commands **120** from a local and/or remote computing system **150** via the communication interface **110** to initiate the test signal generation and response measurement functions. In addition, the control circuit **108** may provide monitor status **120**, such as the measured responses and/or other information based on the measured responses, such as an indication of a particular battery string subset **130** that includes a battery that may be failing, to the computing system **150**. In some embodiments, the local and/or remote computing system **150** may be configured to determine whether a particular battery string subset **130** includes a failing battery based on the status information **120** being received from the control circuit **108** via the communication interface **110**. In some examples, a local computing system **150** may be a computing system located at the same site at which the battery string and the battery string monitoring system **100** are located, while a remote computing system **150** may be a computing system located external to such a site.

The control circuit **108** may include analog and/or digital circuitry configured to perform the various operations above, and may also include a microcontroller, DSP, and/or other algorithmic processor that may execute instructions stored in a memory accessible via the control circuit **108** to perform the various operations of the control circuit **108** described herein.

The communication interface **110** may be configured to receive monitor commands **120** from, and/or transmit monitor status **120** to, the computing system **150** via a wired or wireless communication connection or network. Examples of such a communication network may include one or more of an Ethernet network, a Universal Serial Bus (USB) connection, a cable communication network, a Digital Subscriber Line (DSL) network, a cellular network, and the like.

In some examples, the battery string monitoring system **100** and/or the computing system **150** may include a measurement database in which measurements obtained by the response measurement circuit **106** may be stored over time. In an embodiment, the stored measurements may be analyzed at the computing system **150** and/or the monitoring

system **100** to discover patterns over time that may indicate the presence or future appearance of a battery failure or problem.

FIG. **2** is a block diagram of an example battery string monitoring system **200** in which a single test load **212** (or set of test loads) is applied across each of a plurality of subsets **130** of a battery string in succession to test the batteries of each subset **130**. In one particular example, each subset **130** may include ten batteries of twelve volts (V) output voltage each, resulting in a voltage of 120 V for each subset **130**. Also in this example, the battery string includes four total subsets **130**, or quadrants, resulting in an overall string voltage of 480 V. However, in other examples, any number of subsets **130**, any number of batteries per subset **130** (including a varying number of batteries from one subset **130** to another), and any level of output voltage per battery, may be employed in conjunction with the battery string monitoring system **200**.

Also incorporated in the battery string may be one or more circuit breakers **232** placed at various locations between subsets **130** of the battery string, which may be configured to create an open circuit between subsets **130** upon detection of an overcurrent condition. While the breakers **232** of FIG. **2** are shown as being positioned at every two subsets **130** in the battery string, other locations for the breakers **232** are also possible.

As illustrated in FIG. **2**, the battery string monitoring system **200** includes a monitoring circuit **202** that may serve as the monitoring circuit **102** of FIG. **1**, a control circuit **208** that may serve as the control circuit **108** of FIG. **1**, and a communication interface **210** that may serve as the communication interface **110** of FIG. **1**. The battery string monitoring system **200** may also include a plurality of switches **214** in addition to the test load **212** noted above. The battery string monitoring system **200** may be powered by way of a power supply **240** separate from the battery string in at least some examples.

The monitoring circuit **202** may be configured to apply a generated test signal to a particular subset **130** of the battery string, and to measure the associated response of the subset **130**, by way of a pair of connections associated with each subset **130** (depicted as shorter-dashed lines in FIG. **2**).

The test load **212** may be any combination of electrical components (e.g., resistors, capacitors, inductors, transistors, and so on) to be applied across each of the subsets **130** according to a current configuration of the switches **214**. In some embodiments, the test load **212** may provide a separate load designated for each subset **130** to be monitored, with each load being applied across a pair of connections (indicated by longer-dashed lines in FIG. **2**). In other examples, the test load **212** may include more than one load circuit for each subset **130**, each of which may be selectable by the control circuit **208** in turn.

Each of the switches **214** are depicted in FIG. **2** as a dual-pole, single-throw (DPST) switch that is electronically controlled by the control circuit **208**. In one embodiment, one half of the switch **214** couples a connection of the test load **212** to an end of a subset **130** of the string, while the other half of the switch **214** couples a connection of the monitoring circuit **202** to that same end of the subset **130**. Consequently, the control circuit **208**, in one example, may be configured to close two adjacent switches **214** (as the switches **214** are depicted in FIG. **2**) for some period of time so that the monitoring circuit **202** and the test load **212** are both coupled across one of the subsets **130** of the battery string. Once coupled in such a manner, the monitoring circuit **202** may apply a test signal to the coupled subset **130** (such as by way of a test signal generation circuit similar to the test signal generation circuit **104** of FIG. **1**) and measure a response of the subset **130** to the test signal (such as by way of a response measurement circuit similar to the response measurement circuit **106** of FIG. **1**) in conjunction with the test load **212**.

The control circuit **208** may employ the monitoring circuit **202** and the test load **212** as described above to test or monitor each of the subsets **130**, one at a time. Further, the control circuit **208** may initiate such monitoring in response to one or more commands **220** received via the communication interface **210** from a local or remote computing system, and provide measurements and related information as status **220** via the communication interface **210** in return.

The control circuit **208** may also be coupled with other sensors or transducers not directly connected with the subsets **130**. For example, the control circuit **208** may communicate with a digital temperature sensing bus **236**, in which multiple temperature sensors are coupled to a single communication bus to provide digital temperature information, such as ambient temperatures measured at multiple locations in the proximity of the battery string. The control circuit **208** may relay the received temperature information via the communication interface **210**, and/or may employ the temperature information to interpret or process the measured responses from each of the battery subsets **130**. The control circuit **208** may also communicate with a current transducer **238**, such as a current transducer that, for example, senses an electrical current through the battery string and converts that current to a voltage, digital value, or some other indication to be forwarded to the control circuit **208**. As with the temperature information, the control circuit **208** may forward that information via the communication interface **210** to a remote and/or local computing system.

Also depicted in FIG. **2**, connecting each switch **214** to the subsets **130** of the battery string may be a pair of inline fuses **234**. Each of the inline fuses **234** may be configured to create an open circuit between its corresponding subsets **130** and switch **214** in response to a higher-than-desired current, which may be caused, for example, by a short circuit in the battery string monitoring system **200**, an overvoltage condition in a subset **130** of the battery string, or another fault, thus protecting the battery string and/or the battery string monitoring system **200** from current-related damage. Other examples of the battery string monitoring system **200** may not include the inline fuses **234**.

FIG. **3** is a block diagram of an example battery string monitoring system **300** in which a separate monitor node **312** is provided for each subset **130** of the battery string to be monitored. Components of the battery string monitoring system **300** and surrounding environment that are similar to those of the battery string monitoring system **200** of FIG. **2**, such as the subsets **130** of the battery string, the circuit breakers **232**, the inline fuses **234**, the communication interface **310** and associated monitor commands and status **320**, the digital temperature sensing bus **236**, the current transducer **238**, and the power supply **240**, may perform the same or similar functions as those described above.

The monitoring circuit **302**, which may serve as the monitoring circuit **102** of FIG. **1**, may include a number of monitor nodes **312** equal to or greater than the number of subsets **130** of the battery string to be monitored. Each monitor node **312** may include a first pair of connections (depicted as the longer-dashed lines of FIG. **3**) to a test load located internal to the monitor node **312**, as well as a second pair of connections (illustrated by the shorter-dashed lines of FIG. **3**) to a test signal generation circuit and/or a response

measurement circuit (similar to the test signal generation circuit **104** and/or the response measurement circuit **106** of FIG. **1**) located within the monitor node **312**. An example of the monitor node **312** is discussed in greater detail below in conjunction with FIG. **4**.

The control circuit **308** may control the operation of each monitor node **312**, such as the initiation of the test signal generation and response measurement operations, through an isolation circuit **314**. In some embodiments, the isolation circuit **314** may include one or more components that electrically isolate the control circuit **308** from each of the monitor nodes **312**. In one particular example, the isolation circuit **314** may include one or more opto-isolators that couple the control circuit **308** with each of the monitor nodes **312** by way of an optical transmission path to provide the desired electrical isolation. In other examples, the control circuit **308** and the monitor nodes **312** may be electrically isolated from each other by way of transformers (to provide magnetic flux coupling) or capacitive couplers (to facilitate electric field coupling) without the use of a direct electrically conductive connection. Such isolation may be employed to allow the battery string monitoring system **300** to conform to one or more consumer safety standards, such as those provided by Underwriters Laboratories, the Canadian Standards Association, and the like. In other implementations, the isolation circuit **314** may include one or more digital and/or analog isolator circuits, DC-to-DC converters, and/or other components for coupling data, power, and/or other electrical signals or lines between a selected monitor node **312** and the control circuit **308**.

FIG. **4** is a block diagram of an example monitor node **312** employable in the example battery string monitoring system **300** of FIG. **3**. In one example, the monitor node **312** may include a communication module **402**, a current sink circuit **404**, an ohmic measurement circuit **406**, and a voltage measurement circuit **408**. Other components or modules not explicitly illustrated in the monitor node **312** may be included in other embodiments. In some implementations, the monitor node **312** may be powered by way of a DC-to-DC converter within the isolation circuit **314** that provides isolation for the monitoring system **300** against large voltages (e.g., 1 kilovolt (kV) DC at the monitor node **312**.

The communication module **402** may be a communication connection, such as, for example, an RS-232 serial communication connection to facilitate the receipt of commands from the control circuit **308** and/or the transmission of responses or status to the control circuit **308** via one or more digital isolators within the isolation circuit **314**.

The current sink circuit **404** may be configured to sink a known amount of current from the battery string subset **130** to which the monitor node **312** is coupled, thus operating as a test load applied to the subset **130**, and possibly as a test signal generation circuit (such as the test signal generation circuit **104** of FIG. **1**) for measurement purposes. In one example, the current sink circuit **404** may include a metal-oxide-semiconductor field-effect transistor (MOSFET) controlled by a driving circuit to sink current from the subset **130** based on a voltage value from a digital-to-analog converter (DAC). The digital value provided to the DAC from which the voltage value is generated may be set by way of the control circuit **308** via the communication module **402**. The current sink circuit **404** may further include an operational amplifier configured to measure the sink current across a sense resistor and to apply an appropriate voltage to the MOSFET via the driving circuit to yield a desired sink current. In one embodiment, the operational amplifier may be configured with a voltage gain (e.g., a gain of ten) so that the voltage across the sense resistor, and hence the resistance value of the resistor and the power dissipated by that resistor, may be reduced by that same gain factor. In some examples, the current sink circuit **404** may return an indication of the measured sink current as an analog or digital value to the control circuit **308**.

In one embodiment, the current sink circuit **404** may sink current temporarily according to a sine wave with a DC offset, resulting in a current sink signal that varies from zero volts to a maximum peak-to-peak voltage, as determined via the DAC. In one example, the frequency of the current sink signal may be 1 kilohertz (kHz), although other frequencies may be utilized in other embodiments. The length of time that the current sink signal is active may be controlled via the control circuit **308**.

In some examples, the current sink circuit **404** may include a second MOSFET connected in series with the first MOSFET to protect the system against a possible failure of the current sink circuit **404** due to overheating. More specifically, the second MOSFET may be large, and thus may be able to handle more current than the first MOSFET and thus dissipate heat generated by a large voltage and an associated large amount of power created when the current sink signal is active. To effect this safety feature, a temperature sensor may be mounted to the second MOSFET and configured to deactivate the driving circuit in response to the temperature sensed exceeding some predetermined threshold.

The ohmic measurement circuit **406** may be configured to measure an internal resistance of the battery string subset **130** to which the monitor node **312** is coupled when the current sink circuit **404** is actively sinking current from the subset **130**. In one example, the ohmic measurement circuit **406** may measure a voltage drop across the subset **130** while the current sink circuit **404** is operating, the voltage drop representing the sink current multiplied by the internal resistance of the subset **130**. In one embodiment, the ohmic measurement circuit **406** may include an AC-coupled differential amplifier connected across the subset **130**. In this scenario, the differential amplifier may output a DC-offset sine wave corresponding to the sinusoidal current sinking signal produced by the current sink circuit **404**, with the amplitude of that sine wave corresponding to the internal resistance of the subset **130** multiplied by the sink current. In some examples, the output of the differential amplifier may be filtered using a two-pole analog filter configured to pass a 3.2 kHz sine wave. The resulting filtered sine wave may then be provided to the control circuit **308** along with the current measurement from the current sink circuit **404** to determine the resulting subset **130** internal resistance (e.g., by dividing the measured voltage of the filtered sine wave by the current measurement provided by the current sink circuit **404**). In some embodiments, the control circuit **308** may include one or more analog-to-digital converters (ADCs) (e.g., a 12-bit ADC rated for a maximum input voltage of 2.5 V) to convert the received analog signals for the voltage and current from the ohmic measurement circuit **406** and the current sink circuit **404**, respectively.

In one embodiment, the ohmic measurement circuit **406** may also include an operational amplifier having a gain that may be programmed via the control circuit **308**. In one example, the control circuit **308** may set the gain of the operational amplifier so that the amplitude of the filtered sine wave does not exceed the maximum input voltage of the ADC of the control circuit **308**.

The voltage measurement circuit **408** may be configured to measure the voltage of the battery string subset **130** to

which the monitor node **312** is coupled, such as during times when the current sink circuit **404** is not actively sinking current from the subset **130**. In one example, the voltage measurement circuit **408** may include a resistor divider circuit configured to measure a known fraction of the voltage of the subset **130**. Further, the voltage measurement circuit **408** may include an operational amplifier, such as a unity gain amplifier, serving as a buffer that receives the output of the resistor divider and provides an analog value indicating the voltage of the subset **130** to the control circuit **308**. As indicated above, the control circuit **308** may include an ADC that converts the analog value into a digital value representing the subset **130** voltage. In some examples, the control circuit **308** may include a DSP that internally incorporates the one or more ADCs.

As shown in FIG. **4**, the ohmic measurement circuit **406** and the voltage measurement circuit **408** may be connected across the subset **130** using sense lines **410** that are separate from the connection of the current sink circuit **404** to the subset **130**, thus separating the connections for the test load and measurement functions of the monitor node **312** to the subset **130**. In other examples, the current sink circuit **404**, the ohmic measurement circuit **406**, and the voltage measurement circuit **408** may be connected via a single pair or multiple pairs of connections across the subset **130**.

FIG. **5** is a flow diagram of an example method **500** of monitoring a battery string by monitoring subsets of the battery string. While the method **500** is described below as being performed by one of more of the various embodiments described herein (e.g., the battery string monitoring systems **100**, **200**, and **300** of FIGS. **1**, **2**, and **3**, respectively), other systems not specifically described herein may perform the various operations of the method **500** in other embodiments.

In the method **500**, a control circuit (e.g., the control circuit **108** of FIG. **1**) may set an indication of a current battery string subset **130** to a first subset **130** of the subsets **130** (operation **502**). A test signal generation circuit (e.g., the test signal generation circuit **104** of FIG. **1**) may generate a test signal (e.g., a current sinking signal operating as a test load, as discussed above) and apply that signal to the current battery string subset **130** (operation **504**). A response measurement circuit (e.g., the response measurement circuit **106** of FIG. **1**) may measure the response of the current battery string subset to the test signal (operation **506**). If the last subset **130** has not been processed (operation **508**), the current string subset indication may be set to a next subset **130** (operation **510**), and the test signal generation operation (operation **504**) and the response measurement operation (operation **506**) may be performed on the new current subset **130**. If, instead, the last subset **130** has been monitored (operation **508**), the control circuit or another portion of the battery string monitoring system may determine and/or indicate whether at least one subset **130** includes a failing battery based at least in part on the measured responses (operation **512**). After the determination as to whether a subset **130** includes a failing battery, the control circuit may at some point thereafter begin monitoring each of the subsets **130** of the battery string once more (operation **502**). In some examples, the control circuit may be responsible for initiating the test signal generation and response measurement operations in response to a command received from a local or remote computing system, as described above. Similarly, the control system may forward the measured responses to the local or remote computing system for processing to determine whether one or more subsets **130** may include a failing battery.

While the operations **502-512** are depicted as operations performed in a particular sequence, at least some of the operations **502-512** of FIG. **5** may be performed in other orders of execution, including in a parallel, overlapping, or concurrent manner. For example, the test signal generation operation (operation **504**) and the response measurement operation (operation **506**) may be performed on each of the subset **130** concurrently or simultaneously, if allowed by the architecture of the particular battery string monitoring system employed.

FIG. **6** is a graph of example battery string subset ohmic (e.g., resistance) value measurements obtained over time that may be employed to identify a subset **130** that includes a failing battery. In this specific example, ohmic measurements taken over a number of days for each of four subsets **130** of a battery string, such as the subsets **130** of FIGS. **1**, **2**, and **3**, are displayed according to their measured ohmic value in ohms (Ω). The subsets **130** are labeled in FIG. **6** as String Subset 0, 1, 2, and 3. In some examples, a monitoring circuit (e.g., the monitoring circuit **102** of FIG. **1**) may assert a test signal, such as current sink signal to the battery subset **130** and measure a response voltage across the subset **130**, possibly by way of an active test load. Dividing the measured voltage across the subset **130** by the sink current may yield a measured ohmic value for the subset **130**, as discussed earlier.

As shown in FIG. **6**, while the ohmic value for each of the subsets **130** is measured to be between 45Ω and 50Ω from Day 1 through approximately Day 33, the ohmic value of String Subset 1 increases significantly beginning at approximately at Day 34 until Day 39, at which point the ohmic value of String Subset 1 is measured to be about 64Ω, possibly indicating that at least one of the batteries of String Subset 1 is failing. The particular failing battery within String Subset 1 may be specifically identified thereafter, such as by a technician that personally tests or otherwise inspects the batteries of String Subset 1 based on the information of FIG. **6**, and replaced, as shown at Day 40, thus returning String Subset 1 to a desired operational state. Alternatively, the particular failing battery within String Subset 1 may be specifically identified based on measurements initiated by the test signal generation circuit **104**, where the measurements and subsequent analysis are specifically identified to determine which battery in the subset is failing.

FIG. **7** is a graph of example battery string subset voltage measurements obtained over time that may be employed to identify a subset **130** that includes a battery exhibiting a thermal runaway event. A thermal runaway event, in at least some examples, may be characterized as a positive feedback condition in which changes in the operation of the battery, such as an internal short circuit that develops within the battery, excessive ambient temperatures applied to the battery, or some physical damage inflicted on the battery, causes an increase in temperature in the battery, causing a worsening of the condition, resulting in greater heat being generated, and so forth until the battery is rendered inoperative.

As illustrated in FIG. **7**, the monitoring circuit may measure the string subset voltage (displayed in volts (V)) over a number of days. In some embodiments, this measurement may not involve a particular test signal to be asserted across the string **130**, or involve connecting a particular test load across the subset **130**. In other examples, the monitoring circuit may apply a particular test load of a known resistance while the voltage measurement across the subset **130** is taken. In this example, the string subset voltage for each of the subsets **130** measures as 34 to 35 V up

through Day 30, at which point an initial voltage increase **702** may be seen based on the measured voltage across each of the subsets **130** increasing approximately 1 to 1.5 V over the course of a day or two. In at least some examples, the initial voltage increase **702** across all (or at least a plurality) of the string subsets **130** (e.g., String Subset 0, 1, 2, and 3) may be indicative of an impending thermal runaway event in a battery of at least one of the subsets **130**.

After the initial voltage increase **702** a few days thereafter at about Day 35, the measured voltage across two of the subsets (e.g., Sting Subset 0 and String Subset 3) increase approximately 1 V or more while the voltage across the two remaining subsets **130** (e.g., String Subset 1 and String Subset 2) falls approximately 1.5 V. The falling voltages of String Subset 1 and String Subset 2 may be indicative of a thermal runaway event **704** in progress, while the rising voltages of String Subset 0 and String Subset 3 may be a response by those subsets **130** to compensate for the falling voltages of String Subset 1 and String Subset 2. Under this scenario, a technician may then replace one or more batteries within String Subset 1 and/or String Subset 2 based on a personal inspection of the batteries, which may include further testing or monitoring of the individual batteries in response to the measured voltages shown. In the particular example of FIG. **7**, the battery replacements may occur at about Day 38, resulting in a relative normalization of the voltages for each of the subsets **130**.

As shown in FIG. **7**, the initial voltage increase **702** of the subsets **130** may provide an early indication to a technician or other personnel of the subsequent thermal runaway event **704**. While in the case of FIG. **7**, the initial voltage increase **702** precedes the thermal runaway event by approximately one week, other advanced warnings of two weeks or more may be possible. In addition, use of the battery string monitoring systems **100**, **200**, and **200** of FIGS. **1**, **2**, and **3**, respectively, as described above, facilitate early warning and subsequent detection of a thermal runaway event by measuring voltages of the subsets **130**, as opposed to employing direct temperature measurements of the batteries.

FIG. **8** illustrates two exemplary quadrant pairings of voltage measurements over time that may be employed to identify a subset that includes a failing battery. The top pairing **802** shows voltage readings for Quadrant 1 (Q1) and Quadrant 4 (Q4) in a string of batteries, Q1 corresponding to a first substring and Q4 corresponding to a final substring where there are, in total, four substrings in the battery substring. Similarly, the bottom pairing **804** shows voltage readings for Quadrant 2 (Q2) and Quadrant 3 (Q3) in a string of batteries, Q2 corresponding to a second substring and Q3 corresponding to a third substring of the four substrings in the battery substring.

In this example, the voltage for each respective quadrant shifts over time, with the shifts being mirrored (for the most part) by the voltage reading for the paired quadrant. Thus as the voltage for Q1 goes up, the voltage for Q4 goes down, and vice versa. The mirroring takes place around a central voltage. In the case of Q2 & Q3, this central voltage remains constant throughout the entire time period being monitored. However, for Q1 & Q4, the central voltage moves **810** at over time. Movement in the central voltage between paired quadrants, such as the increase **810** in Q1 & Q4, and discrepancies in the mirroring between the respectively paired quadrants, can indicate errors in battery substrings and/or individual batteries.

For example, a processor receiving the voltage data for the respective quadrants may determine the points where voltages for the respective quadrants are not evenly distributed around the central voltage **86** indicate a failing substring and/or battery (see, for example, the difference "A" of Q1 from the central voltage compared to the difference "B" of Q4, or the later discrepancy between the differences "C" and "D"). Similarly, when the respective voltages for the quadrants "cross" one another or the central voltage **808** (such as when the quadrant which normally has a higher voltage has a lower voltage than its paired quadrant), or otherwise express statistically uncommon behavior, the processor can identify that an error is occurring. Identifying statistically uncommon behavior can occur through use of historical behavior to determine if an activity or voltage of one or more of the quadrants is outside of normal statistical thresholds defined by the historical data and/or a user. As the various voltages are received, the system can ensure that the voltages and behaviors of the various quadrants conform to the historical and/or defined behavior. When the battery strings are outside conformance, the system can automatically generate a ticket such that a technician can inspect (and possibly replace) one or more batteries within the string.

FIG. **9** illustrates an example method embodiment which can be performed by the computing system **150** illustrated in FIG. **1**. The computing system **150** receives a plurality of N voltage signals, receiving, via a processor, a plurality of N voltage signals, wherein each voltage signal in the plurality of N voltage signals represents a respective voltage across a respective battery string subset of a plurality of battery string subsets making up a battery string, the battery string comprising M batteries, where M is greater than N (**902**). The computing system **150** then performs performing an analysis on the plurality of N voltage signals (**904**) and identifies, based on the analysis, a failing battery in the battery string (**904**).

The voltages received each correspond to distinct points in the battery string from the remaining voltage signals. In one configuration, the number of voltage signals received is four, with the overall battery string being divided into quadrants. During the analysis, each quadrant can be compared to the others, with the analysis identifying batteries and/or strings in need of additional testing based voltages, history, and/or on a mirroring effect between the quadrants. More specifically, the analysis can pair first and fourth quadrants on the string together, can pair the second and third quadrants together, and identify errors based on where a quadrant displays behavior not mirrored in its respective pair. The computing system **150** can also store the voltages received for the respective quadrants and develop determinations based on the historical data. Once the computing system **150** has identifying a failing battery (or a failing battery string), the system **150** can generate a notification for a user to inspect the battery. This notification can be emailed, displayed via a GUI, or otherwise communicated to the user.

FIG. **10** illustrates an exemplary computer system **150** which can be used to practice the methods and concepts disclosed herein. The exemplary system **1000** includes a processing unit (CPU or processor) **1010** and a system bus **1005** that couples various system components including the system memory **1015** such as read only memory (ROM) **1020** and random access memory (RAM) **1025** to the processor **1010**. The system **1000** can include a cache **1012** of high speed memory connected directly with, in close proximity to, or integrated as part of the processor **1010**. The system **1000** copies data from the memory **1015** and/or the storage device **1030** to the cache **1012** for quick access by the processor **1010**. In this way, the cache **1012** provides a performance boost that avoids processor **1010** delays while waiting for data. These and other modules can control or be

configured to control the processor **1010** to perform various actions. Other system memory **1015** may be available for use as well. The memory **1015** can include multiple different types of memory with different performance characteristics. It can be appreciated that the disclosure may operate on a computing device **1000** with more than one processor **1010** or on a group or cluster of computing devices networked together to provide greater processing capability. The processor **1010** can include any general purpose processor and a hardware module or software module, such as module 1 **1032**, module 2 **1034**, and module 3 **1036** stored in storage device **1030**, configured to control the processor **1010** as well as a special-purpose processor where software instructions are incorporated into the actual processor design. The processor **1010** may essentially be a completely self-contained computing system, containing multiple cores or processors, a bus, memory controller, cache, etc. A multi-core processor may be symmetric or asymmetric.

The system bus **1005** may be any of several types of bus structures including a memory bus or memory controller, a peripheral bus, and a local bus using any of a variety of bus architectures. A basic input/output (BIOS) stored in ROM **1020** or the like, may provide the basic routine that helps to transfer information between elements within the computing device **1000**, such as during start-up. The computing device **1000** further includes storage devices **1030** such as a hard disk drive, a magnetic disk drive, an optical disk drive, tape drive or the like. The storage device **1030** can include software modules **1032**, **1034**, **1036** for controlling the processor **1010**. Other hardware or software modules are contemplated. The storage device **1030** is connected to the system bus **1005** by a drive interface. The drives and the associated computer-readable storage media provide non-volatile storage of computer-readable instructions, data structures, program modules and other data for the computing device **1000**. In one aspect, a hardware module that performs a particular function includes the software component stored in a tangible computer-readable storage medium in connection with the necessary hardware components, such as the processor **1010**, bus **1005**, display **1035**, and so forth, to carry out the function. In another aspect, the system can use a processor and computer-readable storage medium to store instructions which, when executed by the processor, cause the processor to perform a method or other specific actions. The basic components and appropriate variations are contemplated depending on the type of device, such as whether the device **1000** is a small, handheld computing device, a desktop computer, or a computer server.

Although the exemplary embodiment described herein employs the hard disk **1030**, other types of computer-readable media which can store data that are accessible by a computer, such as magnetic cassettes, flash memory cards, digital versatile disks, cartridges, random access memories (RAMs) **1025**, and read only memory (ROM) **1020**, may also be used in the exemplary operating environment. Tangible computer-readable storage media, computer-readable storage devices, or computer-readable memory devices, expressly exclude media such as transitory waves, energy, carrier signals, electromagnetic waves, and signals per se.

To enable user interaction with the computing device **1000**, an input device **1045** represents any number of input mechanisms, such as a microphone for speech, a touch-sensitive screen for gesture or graphical input, keyboard, mouse, motion input, speech and so forth. An output device **1035** can also be one or more of a number of output mechanisms known to those of skill in the art. In some instances, multimodal systems enable a user to provide multiple types of input to communicate with the computing device **1000**. The communications interface **1040** generally governs and manages the user input and system output. There is no restriction on operating on any particular hardware arrangement and therefore the basic features here may easily be substituted for improved hardware or firmware arrangements as they are developed.

For clarity of explanation, the illustrative system embodiment is presented as including individual functional blocks including functional blocks labeled as a "processor" or processor **1010**. The functions these blocks represent may be provided through the use of either shared or dedicated hardware, including, but not limited to, hardware capable of executing software and hardware, such as a processor **1010**, that is purpose-built to operate as an equivalent to software executing on a general purpose processor. For example the functions of one or more processors presented in FIG. **10** may be provided by a single shared processor or multiple processors. (Use of the term "processor" should not be construed to refer exclusively to hardware capable of executing software.) Illustrative embodiments may include microprocessor and/or digital signal processor (DSP) hardware, read-only memory (ROM) **1020** for storing software performing the operations described below, and random access memory (RAM) **1025** for storing results. Very large scale integration (VLSI) hardware embodiments, as well as custom VLSI circuitry in combination with a general purpose DSP circuit, may also be provided.

The logical operations of the various embodiments are implemented as: (1) a sequence of computer implemented steps, operations, or procedures running on a programmable circuit within a general use computer, (2) a sequence of computer implemented steps, operations, or procedures running on a specific-use programmable circuit; and/or (3) interconnected machine modules or program engines within the programmable circuits. The system **1000** shown in FIG. **10** can practice all or part of the recited methods, can be a part of the recited systems, and/or can operate according to instructions in the recited tangible computer-readable storage media. Such logical operations can be implemented as modules configured to control the processor **1010** to perform particular functions according to the programming of the module. For example, FIG. **10** illustrates three modules Mod1 **1032**, Mod2 **1034** and Mod3 **1036** which are modules configured to control the processor **1010**. These modules may be stored on the storage device **1030** and loaded into RAM **1025** or memory **1015** at runtime or may be stored in other computer-readable memory locations.

Embodiments within the scope of the present disclosure may also include tangible and/or non-transitory computer-readable storage media for carrying or having computer-executable instructions or data structures stored thereon. Such tangible computer-readable storage media can be any available media that can be accessed by a general purpose or special purpose computer, including the functional design of any special purpose processor as described above. By way of example, and not limitation, such tangible computer-readable media can include RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to carry or store desired program code means in the form of computer-executable instructions, data structures, or processor chip design. When information is transferred or provided over a network or another communications connection (either hardwired, wireless, or combination thereof) to a computer, the computer properly views the connection as a computer-readable medium. Thus, any such

connection is properly termed a computer-readable medium. Combinations of the above should also be included within the scope of the computer-readable media.

Computer-executable instructions include, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing device to perform a certain function or group of functions. Computer-executable instructions also include program modules that are executed by computers in stand-alone or network environments. Generally, program modules include routines, programs, components, data structures, objects, and the functions inherent in the design of special-purpose processors, etc. that perform particular tasks or implement particular abstract data types. Computer-executable instructions, associated data structures, and program modules represent examples of the program code means for executing steps of the methods disclosed herein. The particular sequence of such executable instructions or associated data structures represents examples of corresponding acts for implementing the functions described in such steps.

Other embodiments of the disclosure may be practiced in network computing environments with many types of computer system configurations, including personal computers, hand-held devices, multi-processor systems, microprocessor-based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, and the like. Embodiments may also be practiced in distributed computing environments where tasks are performed by local and remote processing devices that are linked (either by hard-wired links, wireless links, or by a combination thereof) through a communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

In view of at least some of the embodiments described herein, effective and efficient monitoring of various characteristics of a battery string may be performed on multiple-battery subsets of the string, as opposed to individual batteries, thus reducing the overall hardware costs of monitoring, thereby rendering such embodiments applicable to many types of battery systems not currently being monitored due to cost considerations.

As used herein, the term "or" may be construed in either an inclusive or exclusive sense. Moreover, plural instances may be provided for resources, operations, or structures described herein as a single instance. Additionally, boundaries between various resources and operations may be arbitrary, and particular operations are illustrated in a context of specific illustrative configurations. In general, structures and functionality presented as separate resources in the example configurations may be implemented as a combined structure or resource. Similarly, structures and functionality presented as a single resource may be implemented as separate resources.

While the present disclosure has been described with reference to various embodiments, these embodiments are illustrative, and the scope of the disclosure is not limited to such embodiments. Various modifications and additions can be made to the exemplary embodiments discussed herein without departing from the scope of the disclosure. For example, while the embodiments described above refer to particular features, the scope of this disclosure also includes embodiments having different combinations of features, as well as embodiments that do not include all of the described features. Accordingly, the scope of the disclosure is intended to embrace all such alternatives, modifications, and variations, together with all equivalents thereof.

The invention claimed is:

1. A monitoring system, comprising:

a monitoring circuit electrically connected to each of a plurality of distinct contiguous subsets of a plurality of batteries connected in series, the monitoring circuit comprising:

at least one test signal generation circuit which generates a test signal and applies the test signal to each subset of the plurality of batteries; and

at least one response measurement circuit which measures a response of each subset of the plurality of batteries to the test signal; and

a control circuit identifying at least one of the subsets of the plurality of batteries as including a failing battery based on the response of each subset of the plurality of batteries.

2. The monitoring system of claim **1**, the monitoring circuit further comprising:

a plurality of monitor nodes, each of the plurality of monitor nodes coupled across a separate one of the subsets of the plurality of batteries, each of the monitor nodes comprising:

one of the at least one test signal generation circuit to generate the test signal and apply the test signal to the subset of the plurality of batteries; and

one of the at least one response measurement circuit to measure the response of the subset of the plurality of batteries to the test signal.

3. The monitoring system of claim **1**, further comprising:

a measurement database storing the response of each subset of the plurality of batteries over time, wherein the control circuit identifies at least one failing battery based on the responses stored in the measurement database.

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

the response comprises a voltage of the subset of the plurality of batteries; and

the control circuit identifies an impending thermal runaway condition in at least one of the plurality of batteries in response to the voltage of the subset increasing over a first period of time.

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

the response comprises a first measured voltage of a first subset of the plurality of batteries; and

the control circuit identifies the impending thermal runaway condition based on the measured voltage decreasing over a second period of time following the first period of time while a second measured voltage of a second subset of the plurality of batteries increases over the second period of time.

6. The monitoring system of claim **1**, wherein:

the response comprises a measured voltage and a measured current for the subset of the plurality of batteries; and

the control circuit determines an ohmic value for each subset of the plurality of batteries based on the measured voltage and the measured current for each subset of the plurality of batteries, and identifies each subset of the plurality of batteries having a rising ohmic value as having the failing battery.

7. A method comprising:

receiving, via a processor, a plurality of N voltage signals, wherein each voltage signal in the plurality of N voltage signals represents a respective voltage across a respective battery string subset of a plurality of battery

string subsets making up a battery string, the battery string comprising M batteries, where M is greater than N;

performing, via the processor, an analysis on the plurality of N voltage signals:

identifying, based on the analysis, one of a failing battery in the battery string and a failing battery string subset; and

generating a notification for a user to inspect the one of a failing battery in the battery string and a failing battery string subset.

8. A battery monitoring system, comprising:

a processor;

a test signal generator;

a signal response receiver; and

a plurality of battery connections, wherein:

each battery connection in the plurality of battery connections is connected to a respective subset in a battery string;

the test signal generator generates a test signal and applies the test signal to each of the respective subsets via the plurality of battery connections;

the signal response receiver receives a response from each of the respective subsets in response to the test signal, to yield a plurality of responses; and

the processor identifies an error in the battery string based on the plurality of responses.

9. The battery monitoring system of claim **8**, wherein the plurality of battery connections comprises at least four.

10. The battery monitoring system of claim **8**, wherein at least one subset in the battery string having a battery connection has at least two batteries connected in series.

11. The battery monitoring system of claim **8**, wherein the processor identifies the error based on mirroring in the plurality of responses.

12. The battery monitoring system of claim **8**, wherein the plurality of responses comprise voltage responses and current responses.

13. The battery monitoring system of claim **8**, wherein the processor generates an error report for a user describing the error.

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