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(54) **Title:** FINE-CONTROLLED BATTERY-CHARGING SYSTEM

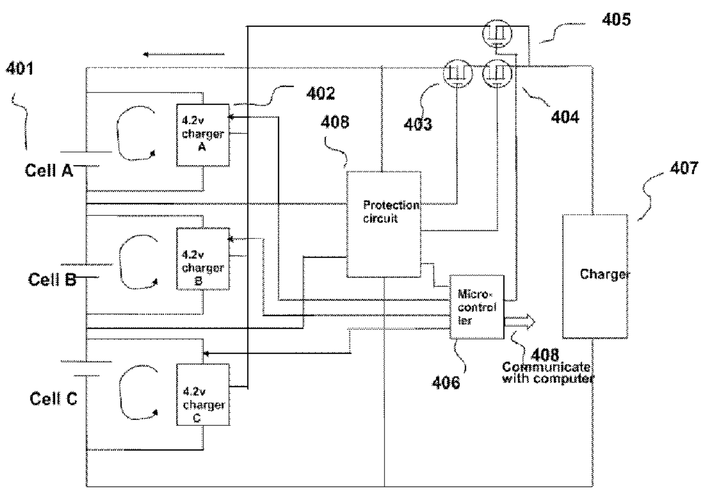

FIG 4

(57) **Abstract:** One or more small chargers with microcontroller circuitry, located inside the battery pack, are used to finely control individual cell charging and overall battery-pack charging in order to identify a more-efficient battery-charge termination point and avoid battery-cell degradation from over-charging. Battery cells are connected in series with a series of small chargers connected across each individual cell. A microcontroller and associated switches turn off the main charge when any of the cells reaches full charge voltage, then activate a series of small chargers, powered by the external charger, which then provide charge only to the cells that still need to be charged. The microcontroller acts as a current detector and voltage detector for all of the cells, stores information such as the amount of time it takes to charge the battery pack, the remaining charge in the battery pack, etc., and communicates this information to the host computing system.

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Fine-Controlled Battery-Charging System

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority from U.S. application number 60/915,708, filed May 3, 2007, which application is incorporated herein by reference for all purposes.

BACKGROUND OF THE INVENTION

A lithium-ion battery pack is typically composed of multiple cells. These cells are combined in series and in parallel in order to compose a pack with the desired voltage and capacity characteristics. When such a battery pack is charged with a typical charging system, each of the series-connected cells receives the same amount of current for the same time period independently of its actual charging needs.

This method of charging presents a problem because the voltage of individual cells may vary significantly due to manufacturing-lot differences, internal cell-impedance variations, usage conditions, etc. Because of such voltage differences among cells, it is possible that some cells may get overcharged, resulting in reduced cell life.

In addition, such overcharging may cause:

- Deterioration of the metallic lithium plating, resulting in loss of effective electrode area;
- Deterioration of the resolution of the ion electro-conductive electrolyte, and leakage of electrolytes;
- Decrease in ion intercalation gross weight because of the destruction of the crystal structure of the anode material; and
- Overheating of lithium-ion battery packs, causing flames, smoke, and even explosions.

To avoid such dangerous situations, chargers are designed conservatively so that they will stop the charging process as soon as they detect the first cell belonging to a series connection reach its full charging capacity. This detection is typically accomplished by monitoring the voltage of each individual cell and comparing it with a value set by the manufacturer. When, during the charging cycle, the voltage of any single cell reaches the maximum value, charging is terminated for the whole pack, even if the majority of the cells have not reached their maximum capacity.

The constant-current/constant-voltage charger commonly used today is insufficient for both safety and pack efficiency reasons. Some battery-pack manufacturers attempt to improve safety by attaching a current detector in series with cells in the battery pack, which forces the charger to stop after the charging current drops below a certain value, corresponding approximately 95% of an average cell's capacity. This method affects negatively both cell/pack performance and cell/pack life. In addition, battery-pack manufacturers typically utilize a protection circuit. However, the accuracy of these protection circuits is not sufficient and they offer minimal safety as they can only detect a problem when it is almost too late, rather like having a fire alarm sound off after half of the house has burned down.

The reason battery manufacturers elect to terminate charging, for safety reasons, at a point corresponding to 95% of capacity and not at another point, has to do with the way lithium-ion batteries receive their charge. Charge is received at different levels of efficiency during the charging process. These levels can be visualized in Figure 6, where 95% represents a point on the curve that, using present technology, can be easily identified.

Several balancing methods have been proposed in the past. None of those balancing methods is widely used today, as their effectiveness is questionable. One such method, for example, proposes using a bypass circuit for each cell. When one cell within a battery pack reaches its maximum charge voltage, the charging current is branched to the bypass circuit shown in Figure 1. The cell charging current decreases and the voltage of the battery pack decreases.

For example and referring to Figure 1, when the voltage of cell A is fully charged, the voltage detector (103) turns on the bypass circuit (102). The voltage of the cell terminal is:

$$V_e = V_{oc} + I_{chg} \times R \qquad \text{(Equation 1)}$$

where: V_c is the cell terminal voltage;
V_{oc} is the cell open-circuit voltage;
I_{chg} is the charge current and;
R is the cell internal resistance.

Charging current I_{chg} (105) is divided by the bypass circuit and decreases. Battery terminal voltage decreases according to Equation 1. However, the total current (106) can actually increase when the battery terminal voltage decreases under a constant-voltage charge. That is, the total current (106) from the charger (104) increases *even if* the charging current I_{chg} (105) decreases due to the current-dividing circuit (102). Therefore, a cell can be overcharged — exceed the rated full-charge voltage — possibly resulting in fire.

Another proposed method of correcting the cell-charge balance uses switching capacitors to transfer energy from a higher voltage cell to a lower voltage cell, and is depicted in Figure 2. Capacitor (203) is charged by the voltage of cell A (201) when switch A (202) is

ON. The energy stored by the capacitor (203) is transferred to cell B (201') when switch B (202') is ON. Cell B (201') is charged by the capacitor (203) if the voltage of cell B (201') is lower than that of the voltage of cell A (201).

However, because the energy, which can be stored in any commercially available capacitor, is extremely small, and because the resultant amount of energy available for transfer is also small, it is necessary to constantly switch between the two cells. Such quick switching is difficult, expensive to achieve, and requires power, thereby draining the battery. This defeats one of the purposes of cell-charge balancing — improving battery performance. It does, however, offer a good level of safety.

Shortened battery-pack life is an ongoing issue as a result of improper charging. Figure 5 shows a graph detailing the difference in battery-pack life cycle when a pack is charged to 4.2V and at 4.25V. If the charge is completed accurately at 4.2V, the manufacturer can guarantee a life of roughly 1000 cycles. However, at just 4.25V, this life cycle decreases dramatically to around 400 cycles.

The problems associated with building a battery pack, which include performance differences of each manufacturing lot, environmental conditions, etc., are not easy to overcome. To minimize these problems, some manufacturers try to build packs from the same lot. Unfortunately, any small difference between cells grows greater and greater over time as improper charging causes cells to deteriorate at different rates. As shown in Figure 3, when charge/discharge is repeated, cells A, B, and C of a lithium-ion battery pack can be charged at 4.3V, 4.2V, and 4.1V, respectively. This happens because charging by an external charger relies on the total battery pack voltage, and not on the voltage of the individual cells. This results in a battery pack with a shorter life and greater risk of fire.

BRIEF SUMMARY OF THE INVENTION

The invention greatly enhances battery life and performance by using a new method for cell-charge balancing, while also achieving an enhanced level of safety. The invention uses one or more small chargers with microcontroller circuitry located inside the battery pack and poses no safety risk.

Battery-pack cells are connected in series with a series of small chargers connected across each individual cell. A microcontroller and associated switches turn off the main external charge when any of the cells reaches full charge voltage, then activate a series of small chargers, which are powered by the external charger, which then provide charge only to the cells that still need to be charged. A fail-safe protection circuit and associated switches protect the battery from over-current conditions.

The microcontroller acts as a current detector and voltage detector for all of the cells. The microcontroller also stores information such as the amount of time it takes to charge the battery pack, the remaining charge in the battery pack, etc., and communicates this information to the host system, following either the protocol of the industry-standard Smart Battery System or any other custom protocol. Alternatively, for cost savings at the expense of some functionality, the microcontroller may be replaced by a series of current detectors and voltage detectors, one set for each cell.

A microcontroller offers greater simplicity as well as slightly higher accuracy. For example, anytime there is a certain voltage difference among cells, the charger for the cell with the lowest voltage may be enabled by the microcontroller. Using a microcontroller allows for even minute corrections in cell-voltage balancing for the battery pack.

Because the invention facilitates fine control over individual cell charging, this invention enables the identification of another more efficient battery-charge termination point to be used.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 depicts an existing art solution that uses charging bypass circuitry.

Figure 2 depicts an existing art method of correcting the cell-charge balance using switching capacitors to transfer energy from a higher voltage cell to a lower voltage cell.

Figure 3 depicts an existing art method that uses a constant-voltage-charging strategy that relies on the measurement of the total battery-pack terminal voltage.

Figure 4 depicts one embodiment's circuit schematic detailing how the charge system invention can be achieved using a microcontroller and a series of smaller chargers.

Figure 5 shows a graph detailing the difference in battery-pack life cycle when a pack is charged to 4.2V and at 4.25V.

Figure 6 shows the battery charging current under constant voltage.

Figure 7 depicts the ability to make minute corrections in cell-voltage balancing for the battery pack.

DETAILED DESCRIPTION

<u>First Embodiment</u>

The invention greatly enhances battery life and performance by using a new method for cell-charge balancing, while also achieving an enhanced level of safety. The invention uses a small charger located inside the battery pack and poses no safety risk. Refer to Figure 4 (for 400-series references), Figure 6 (for 600-series references), and Figure 7 (for 700-series references). It should be noted that while this description is applied to lithium-ion battery packs as an example, the invention can easily be applied to charging systems for other types of batteries.

Figure 4 provides a circuit schematic detailing how the charge system invention can be achieved. In one embodiment, a microcontroller (406) is used. Alternative embodiments may use a series of current detectors instead of or in conjunction with a microcontroller (406). In the current example depicted in Figure 4, a three-cell battery pack is used, though the invention can be applied to any size of battery packs.

Cells A, B, and C (401) are connected in series. A series of small chargers A, B, and C (402) are connected across each individual cell. Charge switch (404) is switched OFF, turning OFF the external charge (407), when any of the cells reaches full charge voltage, as detected by the microcontroller (406). At this point, switch (405) is turned ON, using the power of the external charger (407) to provide energy to the individual small chargers A, B, and C (402). These small chargers then provide charge only to the cells that still need to be charged.

Figure 6 shows the charging current under constant voltage. The horizontal axis represents charging time (606), while the vertical axis shows charging current (607). Point A (601) is the point that any of the cells A, B, or C (401) has reached 4.2V.

An external charger (407) supplies the total charging current (602) until it reaches Point A (601). The chargers A, B, and C in the battery pack (402) supply the charging current for the three cells (603, 604, and 605) corresponding to the voltage of the associated cell since Point A (601).

Switch (403) is designed to prevent over-discharging of the battery pack by terminating discharge when any individual cell reaches a minimum voltage value (over-discharging). Switch (403) is controlled by the protection circuit (408). The protection circuit (408) is a fail-safe circuit that protects the battery from over-current conditions.

Microcontroller (406) acts as a current detector and voltage detector for all of the cells. The microcontroller (406) also stores information such as the amount of time it takes to charge the battery pack, the remaining charge in the battery pack, etc., and communicates this information to the host system, following either the protocol of the industry-standard Smart Battery System or any other custom protocol. As mentioned before, for cost savings at the expense of some functionality, the microcontroller (406) may be replaced by a series of current detectors and voltage detectors, one set for each cell.

It should be noted that using a microcontroller (406) offers greater simplicity as well as slightly higher accuracy. For example, anytime there is a certain voltage difference among cells, the charger for the cell with the lowest voltage may be enabled by the microcontroller (406).

Using a microcontroller (703) allows for even minute corrections in cell-voltage balancing for the battery pack. Refer to Figures 6 and 7 for the discussion of the following example. A charger (705), corresponding to the lowest voltage cell, is turned ON by the microcontroller (703) if the difference between the maximum voltage and the minimum voltage of the cells in series exceeds 0.1V at Point A (601): $V_{max} - V_{min} > 0.1V$.

In summary, because the invention facilitates fine control over individual cell charging, this invention enables the identification of another more efficient battery-charge termination point to be used.

Second Embodiment

This embodiment encompasses a method for charging a battery, with the battery comprising a plurality cells in series, and each of the plurality of cells defining a respective condition of charge. The method comprises the steps of:

- Applying a first charging current to the battery, thereby charging each of the plurality of cells, until a predetermined charging threshold has been reached, and thereafter ceasing the first charging current; and
- Applying to each of the cells a respective second charging current, each respective second charging current controlled responsive to the condition of charge of the respective cell, the charging current for each of the respective cells ceased only after the condition of charge has exceeded the predetermined charging threshold.

The method described above can be further extended wherein each of the respective second charging currents is no greater than one-half the first charging current.

The method described above can be further extended wherein the cells are lithium-ion cells. However, the invention is not limited to lithium-ion battery applications.

Third Embodiment

This embodiment encompasses a battery pack system that comprises first and second charging terminals that are accessible external to the battery pack, with the battery pack containing a plurality of cells in series. The battery pack further comprises:

- A respective charger connected with each of the plurality of cells;

- A first switch disposed to connect and disconnect the first and second charging terminals with the series-connected cells; and
- A second switch disposed to connect the first and second charging terminals to the respective chargers.

The system described above can be further extended by incorporating a means for disconnecting the first switch when a first predetermined charging threshold has been reached. Typically, this is accomplished using a microcontroller and a control-switch system, but can also employ a set of current detectors instead of or in conjunction with a microcontroller.

The system described above can be further extended by incorporating a means for connecting the second switch after the first switch has been disconnected. Typically, this is accomplished using a microcontroller and a control-switch system, but can also employ a set of current detectors instead of or in conjunction with a microcontroller.

The system described above can be further extended wherein each charger charges its respective cell only until a respective second predetermined threshold has been reached.

The system described above can be further extended wherein the cells are lithium-ion cells. However, the invention is not limited to lithium-ion battery applications.

<u>Potential for Obvious Variations and Improvements</u>

Those skilled in the art will have no difficultly devising myriad obvious variations and improvements to the invention, all of which are intended to be encompassed within the scope of the claims which follow.

CLAIMS

What is claimed is:

1. A method for charging a battery, the battery comprising a plurality cells in series, each of the plurality of cells defining a respective condition of charge, the method comprising the steps of:

   applying a first charging current to the battery, thereby charging each of the plurality of cells, until a predetermined charging threshold has been reached, and thereafter ceasing the first charging current; and

   applying to each of the cells a respective second charging current, each respective second charging current controlled responsive to the condition of charge of the respective cell, the charging current for each of the respective cells ceased only after the condition of charge has exceeded the predetermined charging threshold.

2. The method of claim 1, wherein each of the respective second charging currents is no greater than one-half the first charging current.

3. The method of claim 1, wherein the cells are lithium-ion cells.

4. A battery pack comprising first and second charging terminals accessible external to the battery pack, the battery pack containing a plurality of cells in series, the battery pack further comprising:

   a respective charger connected with each of the plurality of cells;

   a first switch disposed to connect and disconnect the first and second charging terminals with the series-connected cells; and

   a second switch disposed to connect the first and second charging terminals to the respective chargers.

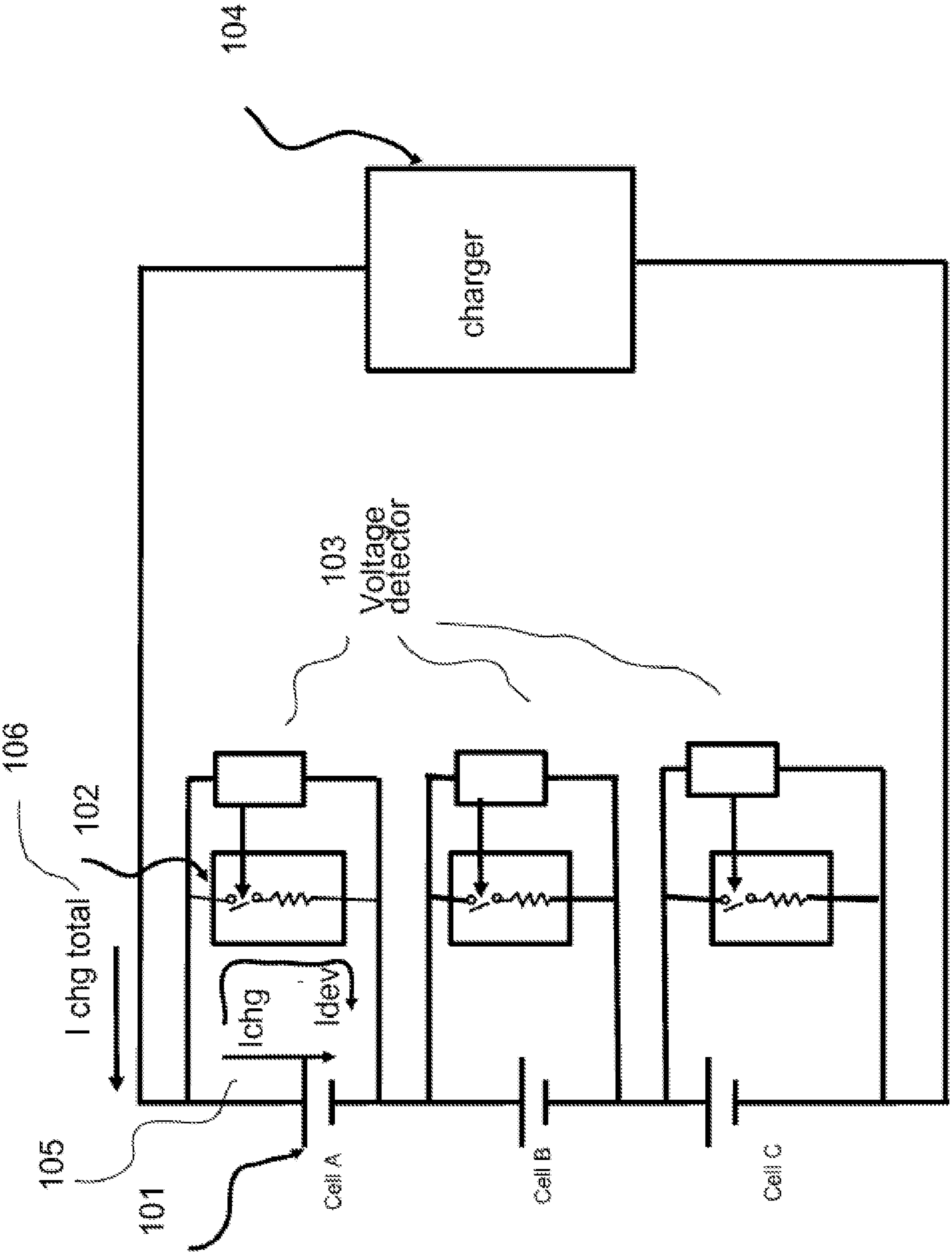
5. The battery pack of claim 4, further comprising means disconnecting the first switch when a first predetermined charging threshold has been reached.

6. The battery pack of claim 5, further comprising means connecting the second switch after

the first switch has been disconnected.

7. The battery pack of claim 4, wherein each charger charges its respective cell only until a respective second predetermined threshold has been reached.

8. The battery pack of claim 4, wherein the cells are lithium-ion cells.



-- Prior Art --

Fig 1

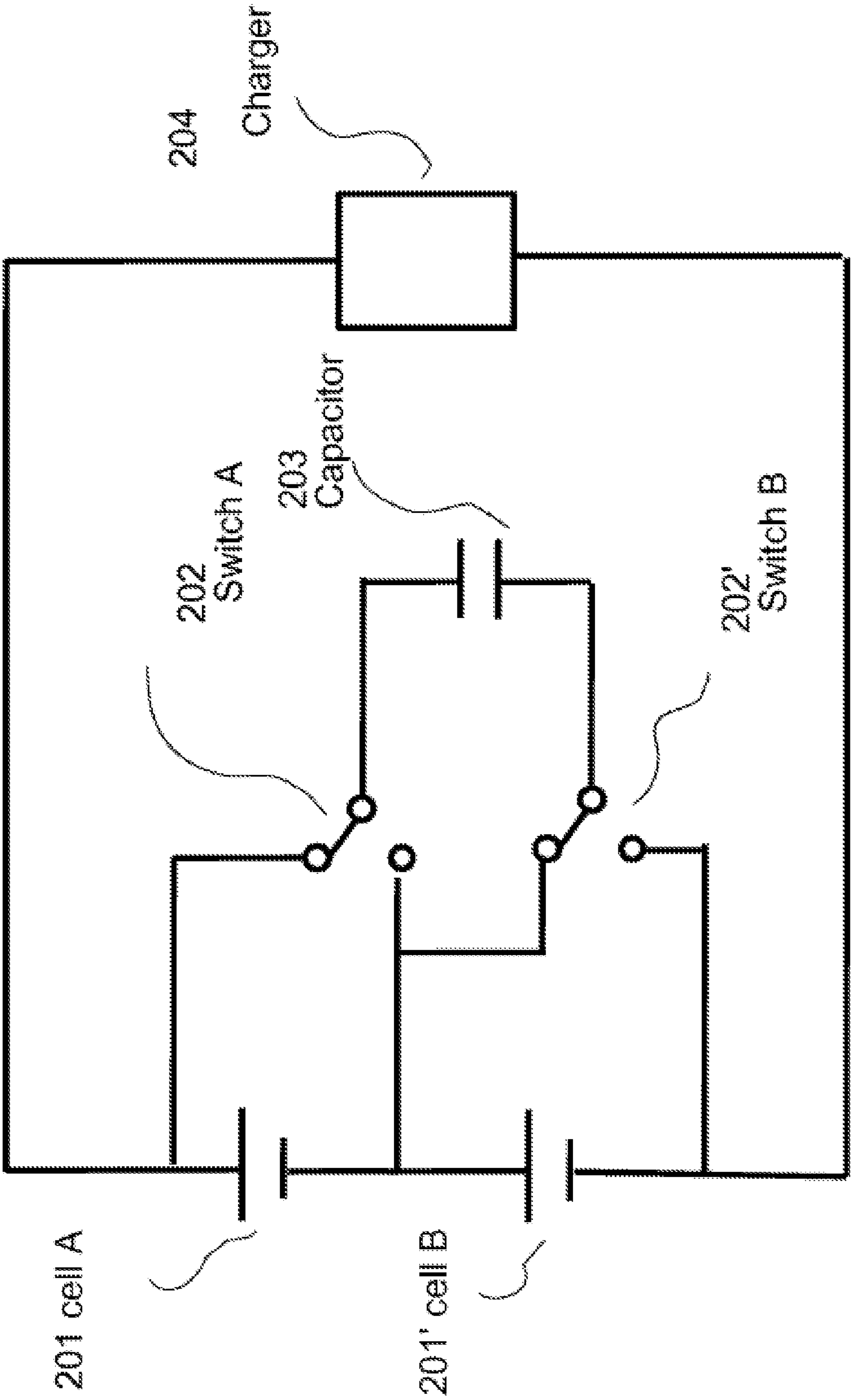


Fig 2

-- Prior Art --

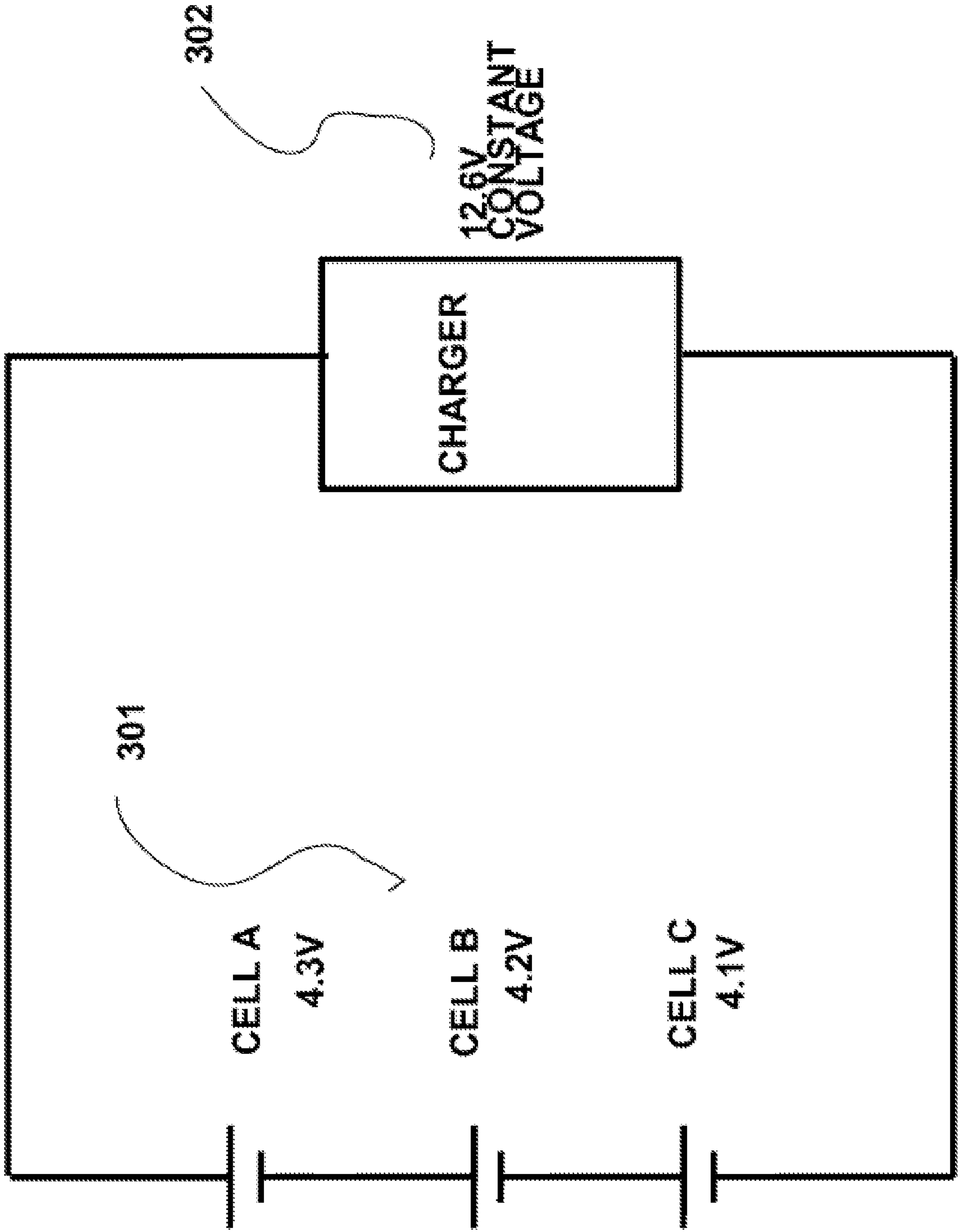


Fig 3

-- Prior Art --

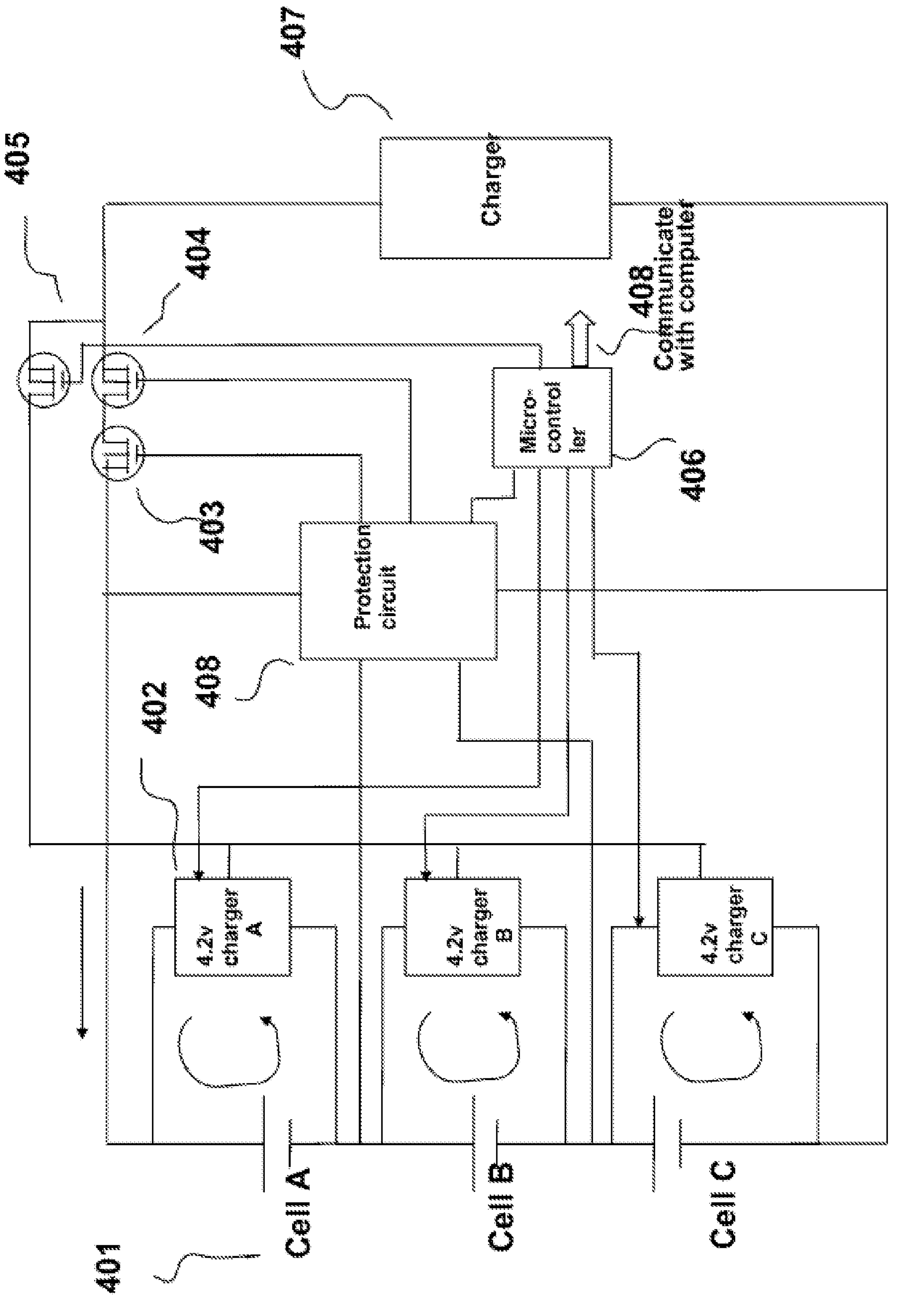

407
405
Charger
404
408
Communicate with computer
Micro-controller
406
403
Protection circuit
408
402
4.2v charger A
4.2v charger B
4.2v charger C
Cell A
Cell B
Cell C
401

FIG 4

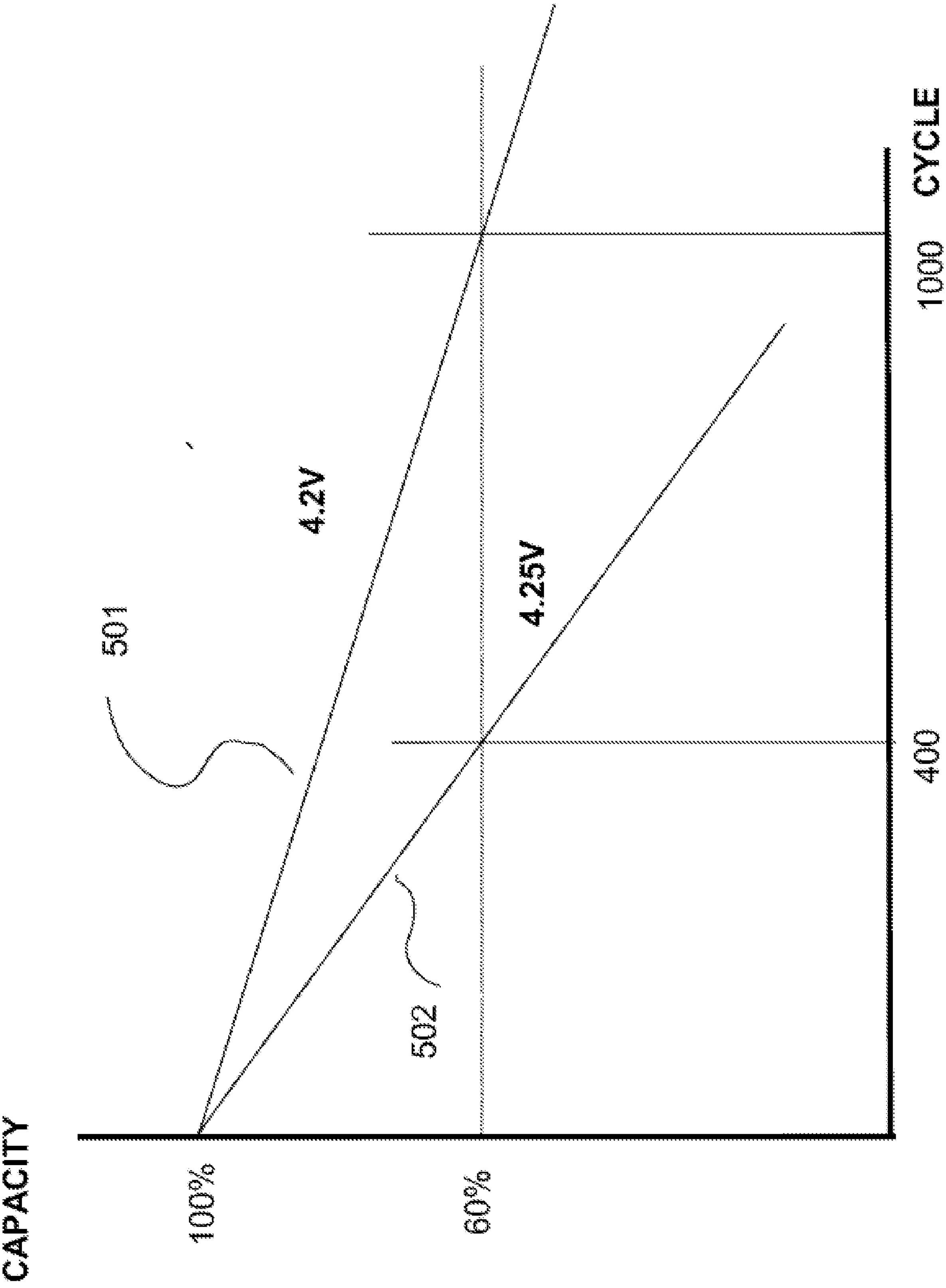


Fig5

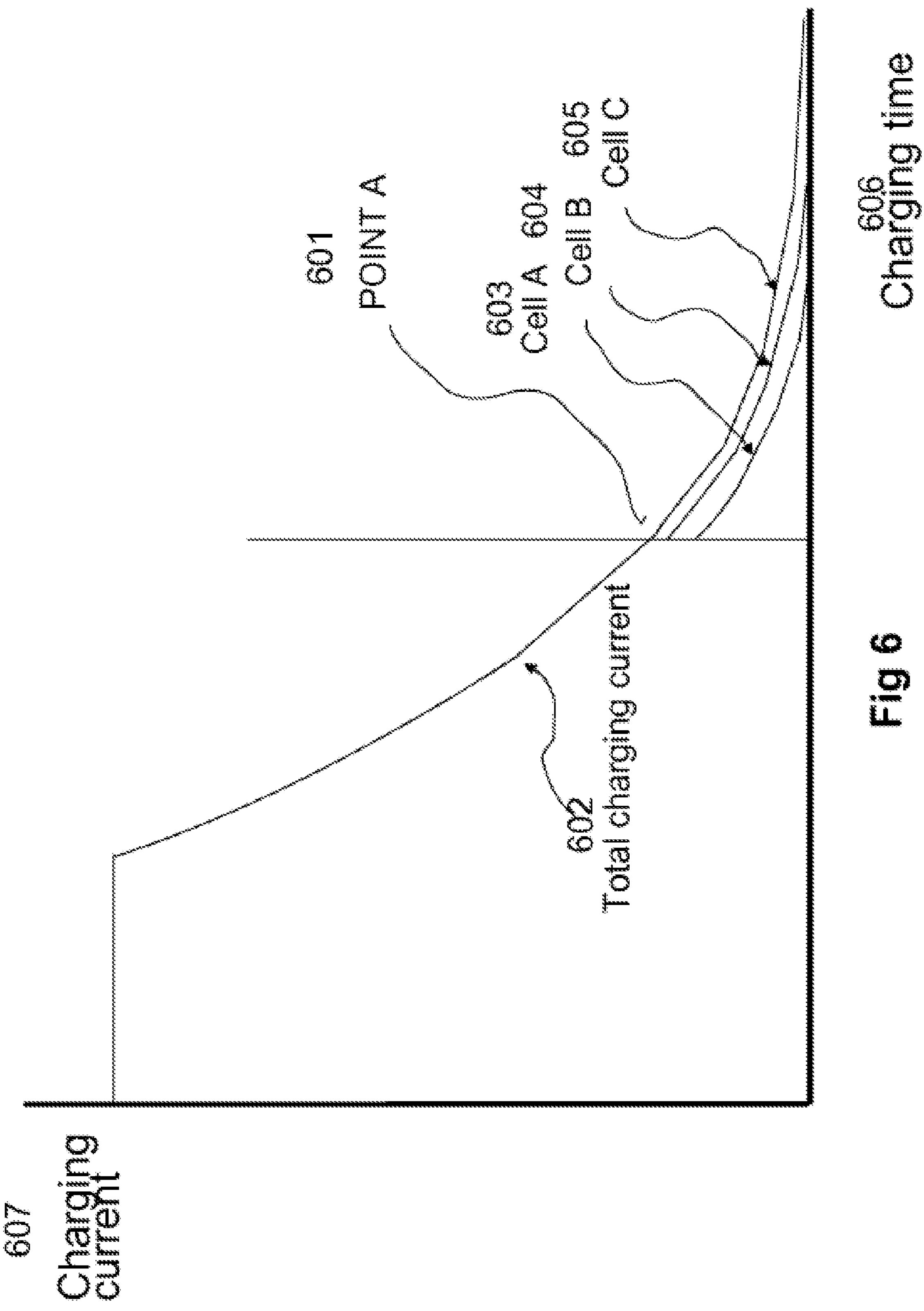

601
POINT A
603
Cell A
604
Cell B
605
Cell C
602
Total charging current
606
Charging time
607
Charging
current

Fig 6

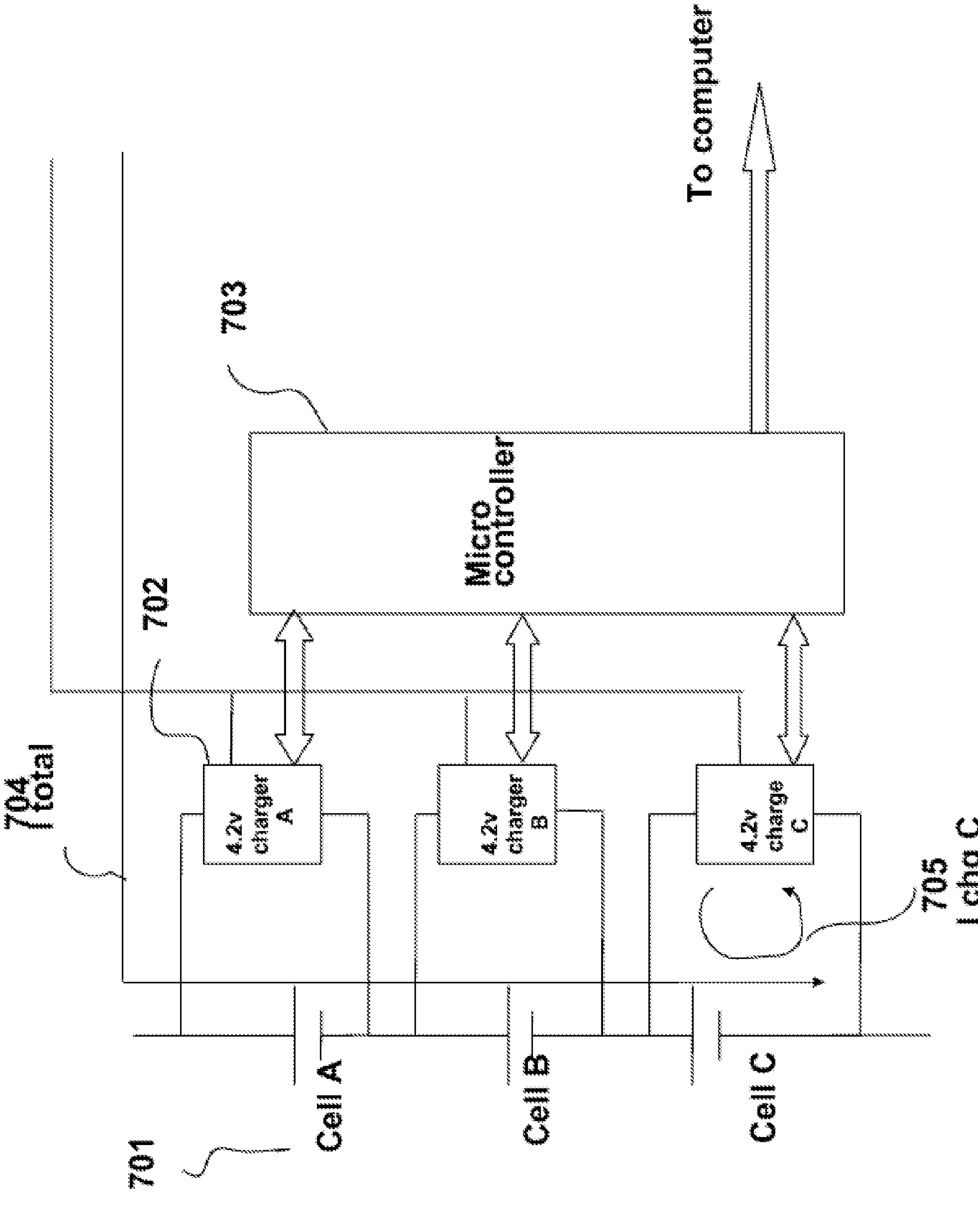

To computer
703
Micro controller
702
704
I total
4.2v charger A
4.2v charger B
4.2v charge C
705
I chg C
Cell A
Cell B
Cell C
701

Fig 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2008/062535

A. CLASSIFICATION OF SUBJECT MATTER

H01M 10/44(2006.01)i, H02J 7/04(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 8 : H01M 10/44

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKIPASS (KIPO internal) "charging", "current", "terminal", "switch"

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 09084275A (NISSAN MOTOR CO., LTD.) 28 March 1997 Y See abstract, paragraphs [0001]-[0032], claims 1-6, figures 1-2.	1-8
Y	US 5780991A (CLIFFORD BRAKE, et al.) 14 July 1998 Y See abstract, columns 1-10, claims 1-19, figures 6-8.	1-8
A	US 5869949A (TSUTOMU NISHIKAWA, et al.) 09 February 1999 A See abstract, columns 1-15, claims 1-26, figures 1, 5-21.	1-8
A	KR 1020000073379 A (WESTECH KOREA CO., LTD) 05 December 2000 A See abstract, pages 1-5, claims 1-11, figures 1-5.	1-8
A	JP 13095170A (MATSUSHITA ELECTRIC IND CO., LTD) 06 April 2001 A See abstract, paragraphs [0001]-[0038], claims 1-6, figure 1.	1-8

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search

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Date of mailing of the international search report

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Name and mailing address of the ISA/KR

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Facsimile No. 82-42-472-7140

Authorized officer

CHOI Byung Chul

Telephone No. 82-42-481-8402

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2008/062535

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 09084275A	28.03.1997	None	
US 5780991A	14.07.1998	None	
US 5869949A	09.02.1999	JP 10-229650 A2	25.08.1998
KR 1020000073379A	05.12.2000	None	
JP 13095170A	06.04.2001	None	