



## (51) International Patent Classification:

*H02J* 1/00 (2006.01)      *H02J* 7/14 (2006.01)  
*H02J* 3/32 (2006.01)      *H02J* 7/34 (2006.01)

## (21) International Application Number:

PCT/US2017/019306

## (22) International Filing Date:

24 February 2017 (24.02.2017)

## (25) Filing Language:

English

## (26) Publication Language:

English

## (30) Priority Data:

62/299,212      24 February 2016 (24.02.2016)      US

(71) Applicants: **THE REGENTS OF THE UNIVERSITY OF COLORADO, A BODY CORPORATE** [US/US]; 1800 Grant Street, 8th Floor, Denver, Colorado 80203 (US). **UTAH STATE UNIVERSITY** [US/US]; 1780 North Research Park Way, Suite 108, North Logan, Utah 84341 (US).

(72) Inventors: **MAKSIMOVIC, Dragan**; c/o The Regents of the University of Colorado, 4845 Pearl East Circle, Suite 200, Boulder, Colorado 80309 (US). **AFRIDI, Khurram K.**; c/o The Regents of the University of Colorado, 4845 Pearl East Circle, Suite 200, Boulder, Colorado 80309 (US). **ZANE, Regan A.**; c/o Utah State University, 1780 N. Research Park Way, Suite 108, North Logan, Utah 84341 (US). **PLETT, Gregory L.**; c/o The Regents of the University of Colorado, 4845 Pearl East Circle, Suite 200, Boulder, Colorado 80309 (US). **TRIMBOLI, Michael Scott**; c/o The Regents of the University of Colorado, 4845

Pearl East Circle, Suite 200, Boulder, Colorado 80309 (US).

(74) Agent: **OSBORNE, Thomas J.**; Dinsmore & Shohl LLP, 1775 Sherman Street, Suite 2500, Denver, Colorado 80203 (US).

(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

## Published:

— with international search report (Art. 21(3))

(54) Title: HETEROGENEOUS ENERGY STORAGE SYSTEM AND METHOD OF CONTROLLING A HETEROGENEOUS ENERGY STORAGE SYSTEM

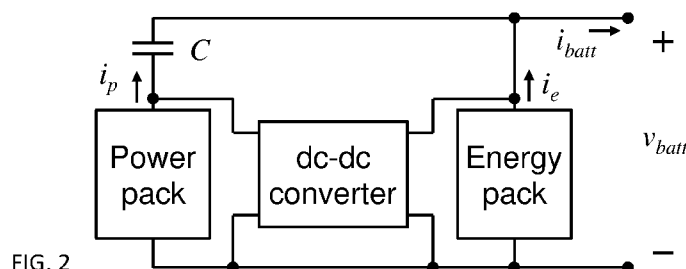


FIG. 2

(57) Abstract: A heterogeneous energy storage device and a method for controlling a heterogeneous energy storage device are provided. In one implementation, a heterogeneous energy storage device is provided. The heterogeneous energy storage device includes a first energy storage device, a second energy storage device and a capacitive device. The first energy storage device has a first energy capacity and a first power to energy ratio (P/E). The second energy storage device has a second total energy capacity and a second P/E ratio different from the first P/E ratio. The capacitive device is coupled in series with the first energy storage device, wherein the second energy storage device is coupled in parallel with the series combination of the capacitive device and the first energy storage device. In another implementation, a method of controlling a heterogeneous energy storage device including a first energy storage device and a second energy storage device is provided.

# HETEROGENEOUS ENERGY STORAGE SYSTEM AND METHOD OF CONTROLLING A HETEROGENEOUS ENERGY STORAGE SYSTEM

## CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application claims the benefit of United States provisional application no. 62/299,212, filed February 24, 2016, which is hereby incorporated by reference as though fully set forth herein.

## BACKGROUND

### Field

**[0002]** The instant invention relates to heterogeneous energy storage systems.

### Background

**[0003]** Battery systems for electric vehicles (EV) and other applications can be improved in theory by combining power optimized cells and energy optimized cells rather than compromising with a single chemistry that must meet both the power and energy demands of the application. A conventional energy storage system (ESS) is optimized by selecting single-chemistry cells with specific power to energy ratio  $P^*/E^*$  equal to the application required power to energy ( $P/E$ ) ratio, as shown in Fig. 1 for an example Li-ion NMC chemistry. Fig. 1 also shows a Ragone chart for the Li-ion LTO chemistry. An optimized heterogeneous combination of NMC and LTO cells with specific energy  $E_{max}$  and specific power  $P_{max}$ , respectively, can meet the same power and energy requirements with the total system weight reduced by  $1 - E^*/E_{max} - (P/E) \times (E^*/P_{max}) = 48\%$  for the example considered in Fig. 1.

**[0004]** Even though heterogeneous energy storage systems offer considerable reduction in weight, in most cases, single chemistry solutions are used in industry due to multiple factors: (1) cells of different types operate with different voltages and current limits and are difficult to combine in series or parallel, (2) solutions presented in the literature to date either combine modules directly in parallel, requiring cell characteristics to match, utilize only one module type at a time, resulting in an underutilized system, or require power converters to operate as series buffers between heterogeneous modules, resulting in high cost, low efficiency, and increased size and weight, and (3) the control systems considered apply brute-force extensions of standard passive battery

management systems (BMS) to all modules, resulting in increased cost. Hence, there is a need for an energy storage system architecture that achieves the benefits of combining different battery chemistries, without the additional cost and complexity of previously proposed methods.

#### BRIEF SUMMARY

**[0005]** To overcome these shortcomings, an energy storage system architecture is provided in some implementations that may realize the capabilities of heterogeneous energy and power optimized cells without the loss, complexity and cost associated with power conversion or power management functions.

**[0006]** In one implementation, for example, a heterogeneous energy storage device is provided. In this particular implementation, the heterogeneous energy storage device includes a first energy storage device, a second energy storage device and a capacitive device. The first energy storage device has a first energy capacity and a first power to energy ratio (P/E). The second energy storage device has a second total energy capacity and a second P/E ratio different from the first P/E ratio. The capacitive device is coupled in series with the first energy storage device, wherein the second energy storage device is coupled in parallel with the series combination of the capacitive device and the first energy storage device.

**[0007]** In another implementation, a method of controlling a heterogeneous energy storage device including a first energy storage device and a second energy storage device is provided. In this implementation, the method includes: providing a capacitive device in series with the first energy storage; coupling the second energy storage device in parallel with the series combination of capacitive device and the first energy storage device, wherein the capacitive device provides DC decoupling between the first energy storage device and the second energy storage device.

**[0008]** The foregoing and other aspects, features, details, utilities, and advantages of the present invention will be apparent from reading the following description and claims, and from reviewing the accompanying drawings.

### BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Fig. 1 shows optimization of a conventional energy storage system by selecting single-chemistry cells with a specific power-to-energy ratio equal to an application required power-to-energy ratio.

[0010] Fig. 2 shows an example architecture implementation of a Composite Heterogeneous Energy Storage System (CHESS).

[0011] Figs. 3A and 3B show simulation results for an example 16 kWh energy-optimized NMC pack and 0.9 kWh power-optimized LTO pack.

[0012] Fig. 4 shows another example implementation of a Composite Heterogeneous Energy Storage System (CHESS) architecture with multiple power battery packs.

[0013] Fig. 5 shows yet another example implementation of a Composite Heterogeneous Energy Storage System (CHESS) architecture that includes switches connected in series with the power pack and the energy pack.

[0014] Fig. 6 shows another example implementation of a Composite Heterogeneous Energy Storage System (CHESS) architecture that includes a switched capacitor network connected in series with the power pack

[0015] Fig. 7 shows an example implementation of a switched capacitor network connected in series with a power pack in a Composite Heterogeneous Energy Storage System (CHESS) architecture.

### DETAILED DESCRIPTION

[0016] In various implementations, an energy storage system architecture and method of controlling such a system is provided. For example, systems and methods that realize full capabilities of heterogeneous energy and power optimized cells without the loss, complexity and cost associated with power conversion or power management functions may be provided. In one implementation, for example, an architecture named *Composite Heterogeneous Energy Storage System (CHESS)* uses capacitors in addition to different types of battery cells (see Fig. 2 as an example implementation) and may be used to achieve breakthrough performance. For example, the CHESS system of Fig. 2 offers more than 50% longer EV range for equal weight, volume, life and cost compared to commercial state-of-the-art EV battery systems.

**[0017]** In one particular implementation, for example, a power pack (comprising power optimized cells) is ac coupled to an energy pack (comprising energy optimized cells) using a capacitive device (e.g., a small capacitor module  $C$ ). The capacitive device may include any type of capacitor(s), such as but not limited to an ultra-capacitor or some other type of capacitor (e.g., electrolytic, film, ceramic, mica, etc.) depending on the application. The capacitive device provides DC decoupling between cells of different types; hence, eliminating (or at least significantly reducing) circulating currents, while allowing power sharing between the power optimized and energy optimized cells. Although various implementations may refer to blocking or otherwise decoupling DC currents, minor leakage currents such as associated with various types of capacitors may be present as one of ordinary skill in the art would appreciate.

**[0018]** In various implementations, a total battery current  $i_{batt}$  is divided between the two packs naturally, requiring no additional series power converters or contactors. Energy balancing and battery management functions are achieved using a small, low-power, parallel-connected DC-DC converter, e.g., a modular battery management system (BMS) converter. In this approach, which is cost-neutral to existing BMS solutions, heterogeneous modules may be continuously balanced using enhanced electrochemical control for optimal utilization

**[0019]** FIG. 2 shows an example architecture implementation of a Composite Heterogeneous Energy Storage System (CHESS) that combines an ac-coupled power pack and an energy pack in parallel, with a low-power dc-dc converter performing energy balancing and battery management functions. In this example implementation, Fig. 2 shows an approach that overcomes the three mentioned limitations of typical approaches to combine power optimized and energy optimized cells. In the CHESS approach implementation, for example, a power pack (comprising power optimized cells) is ac coupled to an energy pack (comprising energy optimized cells) using a capacitor module  $C$  (e.g., a small capacitor module). The capacitor may be an ultra-capacitor or some other type of capacitor (e.g., electrolytic, film, ceramic, mica, etc.) depending on the application. The capacitor  $C$  provides dc decoupling between cells of different types; hence, eliminating (or at least significantly reducing) circulating currents, while allowing power sharing between the power optimized and energy optimized cells. The total battery current  $i_{batt}$  is divided between the two packs naturally, requiring no additional series power converters or contactors.

Energy balancing and battery management functions are achieved using a small, low-power, parallel-connected dc-dc converter, e.g., a modular battery management system (BMS) converter. In this approach, which is cost-neutral to existing BMS solutions, heterogeneous modules are continuously balanced using enhanced electrochemical control for optimal utilization.

**[0020]** Operation of an example CHESS implementation using a 16 kWh energy-optimized NMC pack and 0.9 kWh power-optimized LTO pack is illustrated in Fig. 3 by simulations on a US06 cycle for a Chevy Volt sized vehicle. In this example, compared to the conventional 16 kWh system, weight is reduced by 40%. Equivalently, for the same weight, the EV range can be extended by more than 60%. Hence, a full scale plug-in hybrid-electric vehicle (PHEV) battery pack using the proposed approach and present-day cell technologies would have more than 50% longer EV range on the US06 cycle compared to a 7.6 kWh commercial PHEV pack of equal weight, volume, life and cost. Given the roadmap for energy and power optimized cells, even higher benefits can be expected in the future, with breakthrough impact on the EV Everywhere Grand Challenge targets.

#### System Design and Control

**[0021]** Compared to conventional single-chemistry systems, a heterogeneous energy storage system, such as a CHESS implementation, involves complex interactions among system modules, both in the design optimization phase, and during real-time operation. This may require application of electrochemical modeling expertise in the design phase, to come up with designs leading to optimum composition of energy, power, and capacitor modules, together with required voltage, current and power ratings of the dc-dc converter, as well as practical system cost/performance models. This may be done using electrochemical model-based controls to compute physics-based power limits on both packs; eking out maximum performance and life from each during dynamic operation under various temperatures and cycling conditions.

#### DC-DC Converter and BMS Realization

**[0022]** Various implementations of a CHESS concept system provide cost-effective realization of dc-dc converter and BMS functions. A modular BMS technology, which has been developed and

demonstrated for single-chemistry systems, is also appropriate with suitable extensions to a more complex CHESS architecture.

#### Other Design Considerations

**[0023]** Note that the open circuit voltage of the power pack and the energy pack can be different in the CHESS architecture. This is made possible by the inclusion of a capacitor module in the CHESS architecture and is an advantage of various implementations. In these implementations, this allows the use of cells types with different nominal voltages in the power pack than those used in the energy pack. This also enables the number of series cells in the power pack and the energy pack to be different.

#### Description of Example Variants

##### a. CHESS with Multiple Power Packs

**[0024]** In one implementation a composite heterogeneous energy storage system is provided with multiple power packs, connected to each other and the energy pack through ac coupling capacitor modules, as shown in Fig. 4. The power packs can be of the same or different cell chemistries, and have the same or different number of series and parallel connected cells.

##### b. CHESS with Series Switches

**[0025]** In another implementation, switches are included in series with the power pack and the energy pack, as illustrated in Fig. 5. In this implementation, an additional degree of control over the current flowing through each of the two packs is provided.

**[0026]** An extension of this variant is an architecture with multiple power and energy packs (potentially of same or different cell chemistries and same or different number of series and parallel connected cells) each separated from one another by a series switch. The power packs in this architecture could share an ac coupling capacitor module, or there could be a separate capacitor(s) for each of the power packs.

##### c. CHESS with Multiple Switched Capacitors

**[0027]** In another implementation, a switched capacitor network (with a plurality of capacitors and switches) in series with the power pack is provided, as illustrated in Fig. 6. An example

implementation of this switched capacitor network connected as described above is shown in Fig. 7. Other combinations of switches and capacitors are also possible.

**[0028]** Although embodiments of this invention have been described above with a certain degree of particularity, those skilled in the art could make numerous alterations to the disclosed embodiments without departing from the spirit or scope of this invention. All directional references (e.g., upper, lower, upward, downward, left, right, leftward, rightward, top, bottom, above, below, vertical, horizontal, clockwise, and counterclockwise) are only used for identification purposes to aid the reader's understanding of the present invention, and do not create limitations, particularly as to the position, orientation, or use of the invention. Joinder references (e.g., attached, coupled, connected, and the like) are to be construed broadly and may include intermediate members between a connection of elements and relative movement between elements. As such, joinder references do not necessarily infer that two elements are directly connected and in fixed relation to each other. It is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative only and not limiting. Changes in detail or structure may be made without departing from the spirit of the invention as defined in the appended claims.

## CLAIMS

What is claimed is:

1. A heterogeneous energy storage device comprising:
  - a first energy storage device having a first energy capacity and a first power to energy ratio (P/E);
  - a second energy storage device having a second total energy capacity and a second P/E ratio different from the first P/E ratio;
  - a capacitive device coupled in series with the first energy storage device, wherein the second energy storage device is coupled in parallel with the series combination of the capacitive device and the first energy storage device.
2. The heterogeneous energy storage device of claim 1 wherein the capacitive device is configured to block DC current from flowing through the series combination of the capacitive device and the first energy storage device.
3. The heterogeneous energy storage device of claims 1 or 2 wherein the capacitive device does not include a power converter circuit.
4. The heterogeneous energy storage device of any of the preceding claims wherein the heterogeneous energy storage device requires no additional series connected power converters or contactors.
5. The heterogeneous energy storage of any of the preceding claims wherein the capacitive device comprises at least one capacitor coupled in series with the first energy storage device.
6. The heterogeneous energy storage device of any of the preceding claims wherein the capacitive device comprises a combination of at least one capacitor and at least one switch coupled with the at least one capacitor.
7. The heterogeneous energy storage device of any of the preceding claims further comprising a parallel connected DC-DC converter coupled in parallel between the first energy storage device and the second energy storage device.

8. The heterogeneous energy storage device of claim 7 wherein the DC-DC converter is adapted to provide energy balancing between the first energy storage device and the second energy storage device.
9. The heterogeneous energy storage device of claims 7 or 8 wherein the DC-DC converter is adapted to provide at least one battery management function for at least one of the first energy storage device and the second energy storage device.
10. The heterogeneous energy storage device of any of the preceding claims wherein the first energy storage device comprises at least one power optimized cell.
11. The heterogeneous energy storage device of any of the preceding claims wherein the second energy storage device comprises at least one energy optimized cell.
12. The heterogeneous energy storage device of any of the preceding claims wherein the capacitive device provides DC decoupling between the first energy storage device and the second energy storage device.
13. The heterogeneous energy storage device of any of the preceding claims wherein the capacitive device comprises at least one capacitor selected from the group comprising: an ultra-capacitor, a super-capacitor, an electrolytic capacitor, a film capacitor, and a mica capacitor.
14. The heterogeneous energy storage device of any of the preceding claims wherein a third energy storage device having a third total energy capacity and a third P/E ratio is coupled in series with a second capacitive device and the series combination of the second capacitive device and the third energy storage device is coupled in parallel with (i) the series combination of the capacitive device and the first energy storage device and (ii) the second energy storage device.
15. The heterogeneous energy storage device of any of the preceding claims wherein the third energy storage device comprises at least one energy storage cell that is a same type of energy storage cell as at least one energy storage cell of the first energy storage device.
16. The heterogeneous energy storage device of any of the preceding claims wherein the third energy storage device comprises at least one energy storage cell that is a different type of energy storage cell as at least one energy storage cell of the first energy storage device.
17. The heterogeneous energy storage device of any of the preceding claims wherein a first switch is coupled in series between the first energy storage device and the capacitive device.

18. The heterogeneous energy storage device of any of the preceding claims wherein a second switch is coupled in series with the second energy storage device.
19. The heterogeneous energy storage device any of the preceding claims wherein the capacitive device comprises a switched capacitor network.
20. The heterogeneous energy storage device of claim 18 wherein the switched capacitor network comprises a plurality of capacitors and switches in series with the first energy storage device.
21. The heterogeneous energy storage device of any of the preceding claims wherein the heterogeneous energy storage device is coupled to an electric or hybrid electric vehicle.
22. A method of controlling a heterogeneous energy storage device comprising a first energy storage device and a second energy storage device, the method comprising:
  - providing a capacitive device in series with the first energy storage;
  - coupling the second energy storage device in parallel with the series combination of capacitive device and the first energy storage device, wherein the capacitive device provides DC decoupling between the first energy storage device and the second energy storage device.
23. The method of claim 22 wherein the capacitive device is configured to block DC current from flowing through the series combination of the capacitive device and the first energy storage device.
24. The method of claims 22 or 23 wherein the capacitive device does not include a power converter circuit.
25. The method of any of the claims 22 through 24 wherein the heterogeneous energy storage device the capacitive requires no additional series connected power converters or contactors.
26. The method of any of claims 22 through 25 wherein the capacitive device comprises at least one capacitor coupled in series with the first energy storage device.
27. The method of any of claims 22 through 26 wherein the capacitive device comprises a combination of at least one capacitor and at least one switch coupled with the at least one capacitor.

28. The method of any of claims 22 through 27 further comprising a parallel connected DC-DC converter coupled in parallel between the first energy storage device and the second energy storage device.

29. The method of claim 28 wherein the DC-DC converter is adapted to provide energy balancing between the first energy storage device and the second energy storage device.

30. The method of claims 28 or 29 wherein the DC-DC converter is adapted to provide at least one battery management function for at least one of the first energy storage device and the second energy storage device.

31. The method of any of claims 22 through 30 wherein the first energy storage device comprises at least one power optimized cell.

32. The method of any of claims 22 through 31 wherein the second energy storage device comprises at least one energy optimized cell.

33. The method of any of claims 22 through 32 wherein the capacitive device provides DC decoupling between the first energy storage device and the second energy storage device.

34. The method of any of claims 22 through 33 wherein the capacitive device comprises at least one capacitor selected from the group comprising: an ultra-capacitor, a super-capacitor, an electrolytic capacitor, a film capacitor, and a mica capacitor.

35. The method of any of claims 22 through 34 wherein a third energy storage device having a third total energy capacity and a third P/E ratio is coupled in series with a second capacitive device and the series combination of the second capacitive device and the third energy storage device is coupled in parallel with (i) the series combination of the capacitive device and the first energy storage device and (ii) the second energy storage device.

36. The method of any of claims 22 through 35 wherein the third energy storage device comprises at least one energy storage cell that is a same type of energy storage cell as at least one energy storage cell of the first energy storage device.

37. The method of any of claims 22 through 36 wherein the third energy storage device comprises at least one energy storage cell that is a different type of energy storage cell as at least one energy storage cell of the first energy storage device.

38. The method of any of claims 22 through 37 wherein a first switch is coupled in series between the first energy storage device and the capacitive device.
39. The method of any of claims 22 through 38 wherein a second switch is coupled in series with the second energy storage device.
40. The method any of claims 22 through 39 wherein the capacitive device comprises a switched capacitor network.
41. The method of claim 40 wherein the switched capacitor network comprises a plurality of capacitors and switches in series with the first energy storage device.
42. The method of any of claims 22 through 41 wherein the heterogeneous energy storage device is coupled to an electric or hybrid electric vehicle.

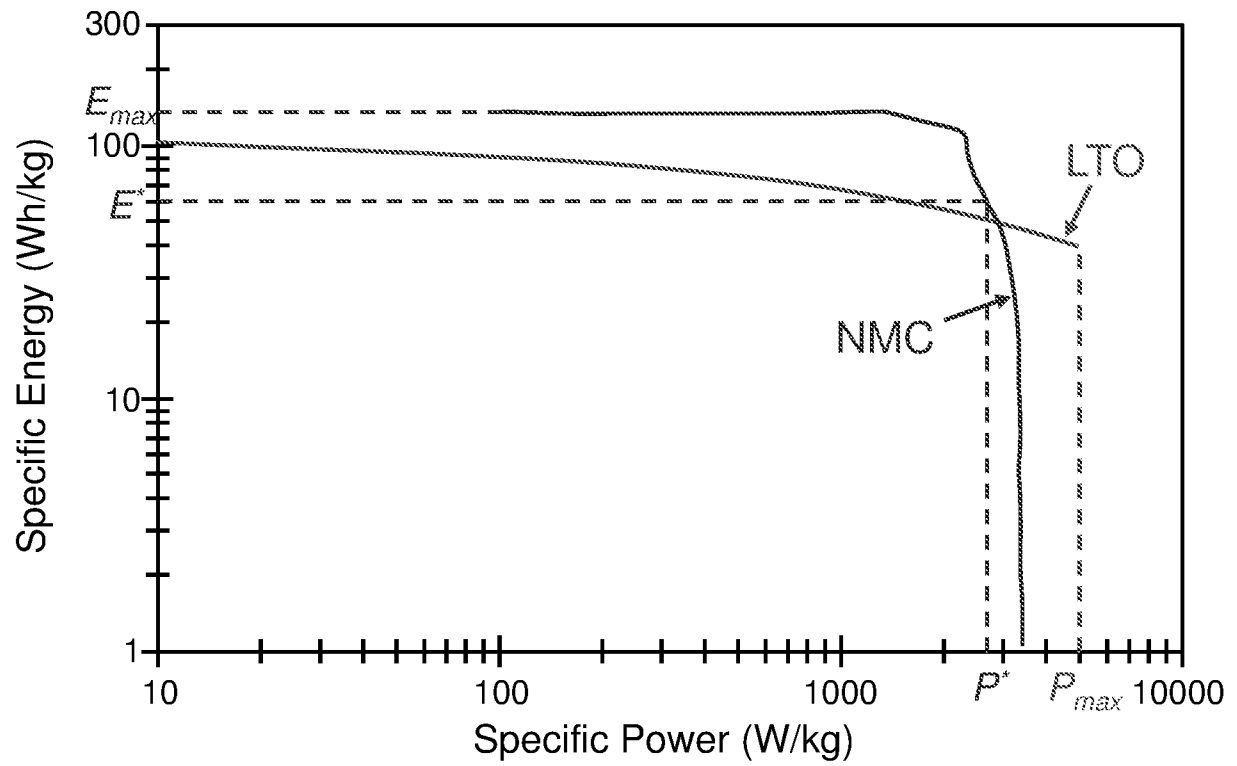


FIG. 1

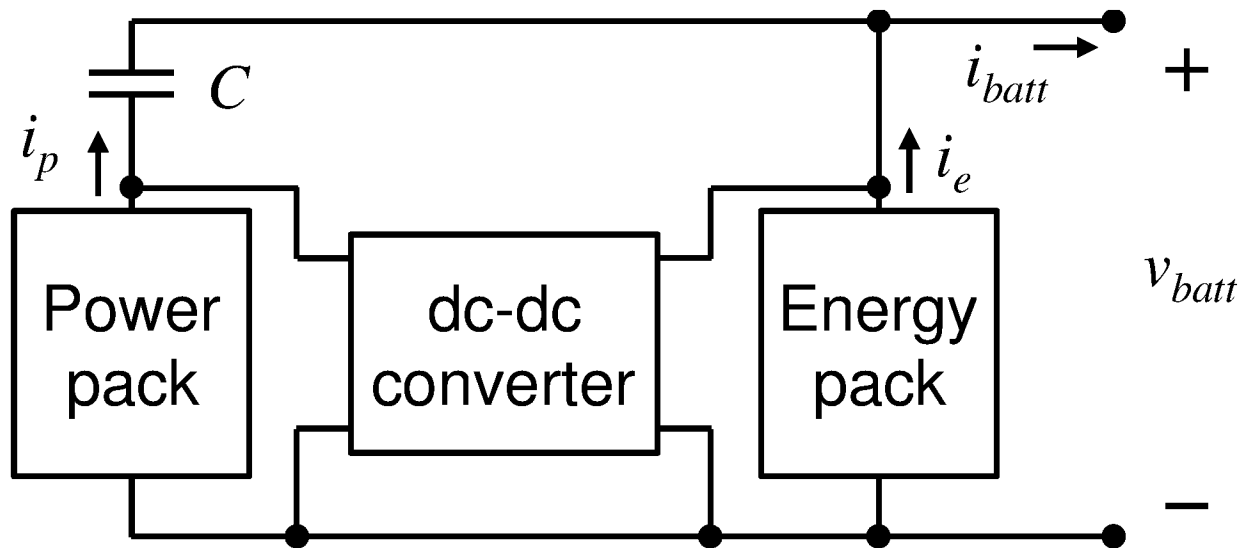


FIG. 2

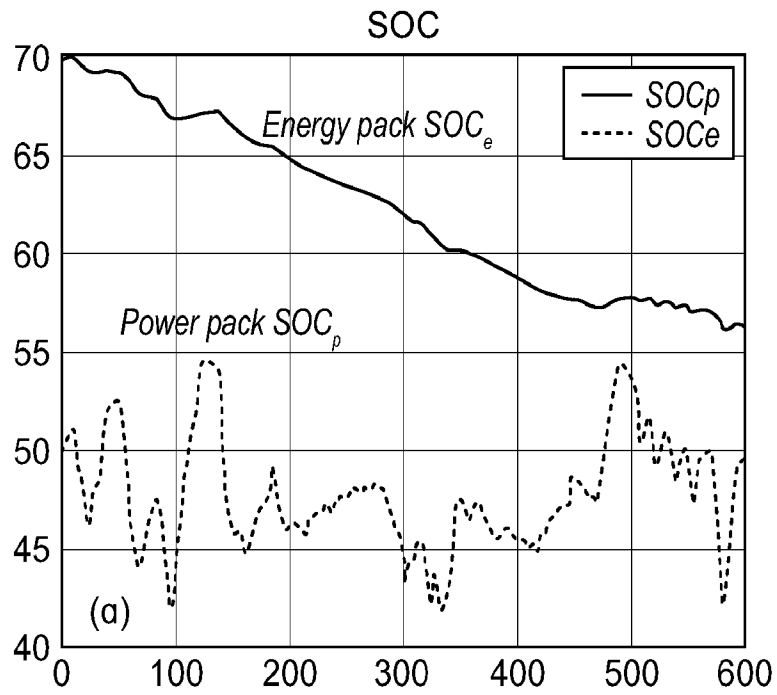


FIG. 3A

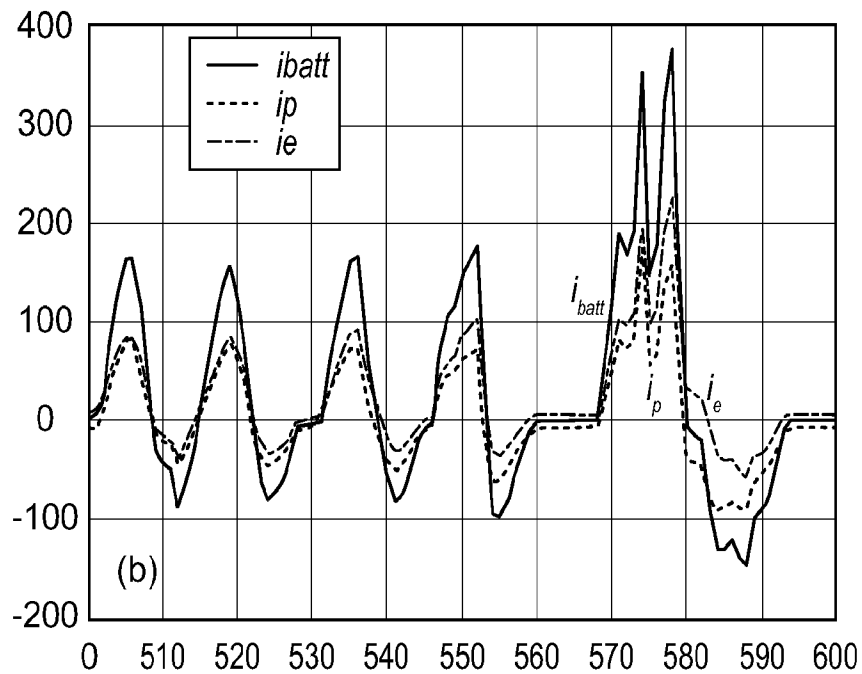


FIG. 3B

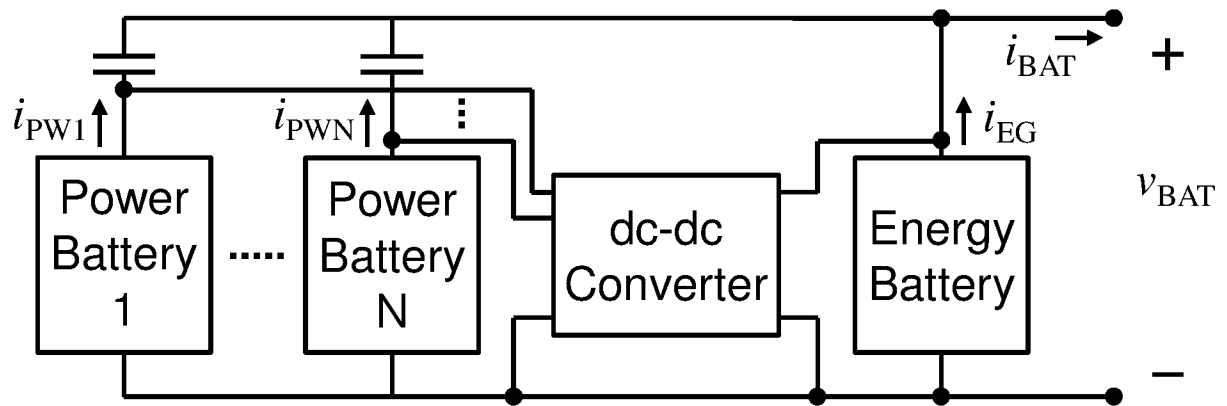


FIG. 4

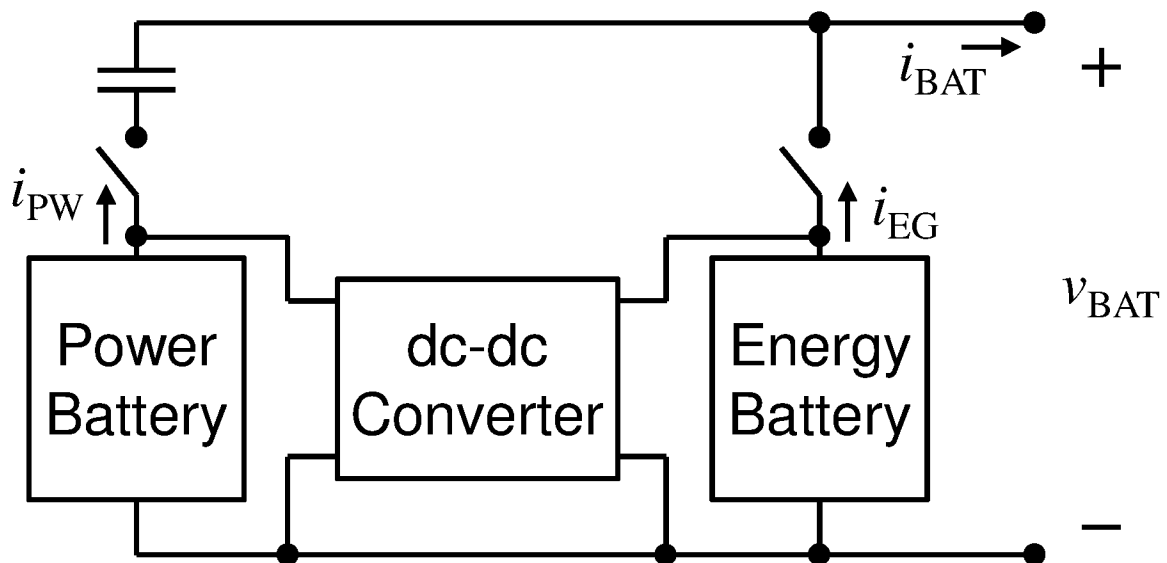


FIG. 5

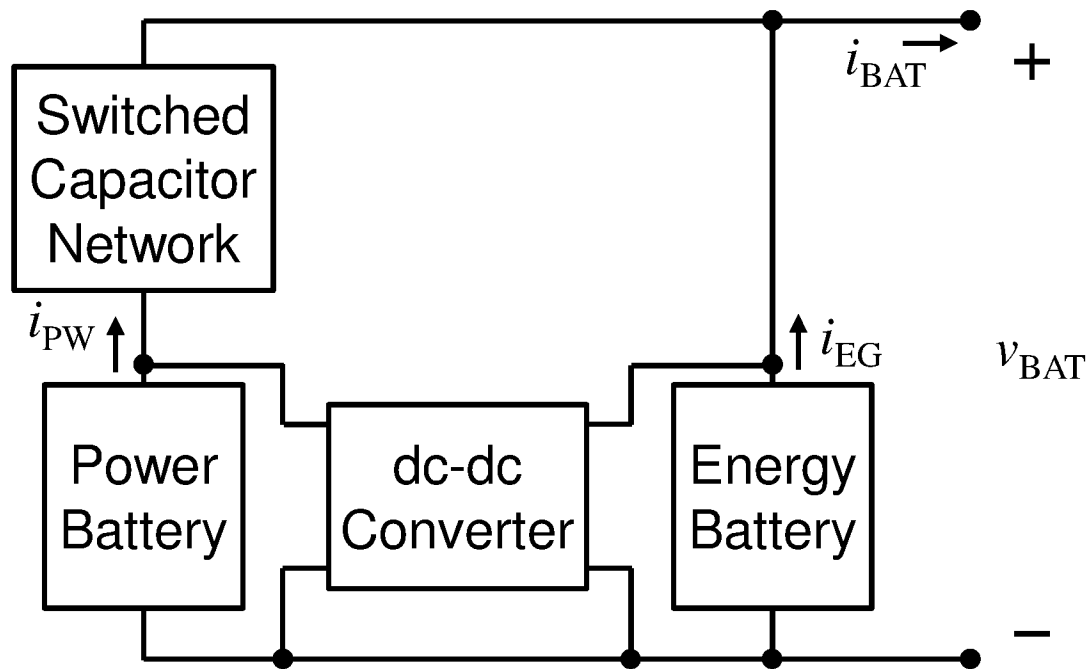


FIG. 6

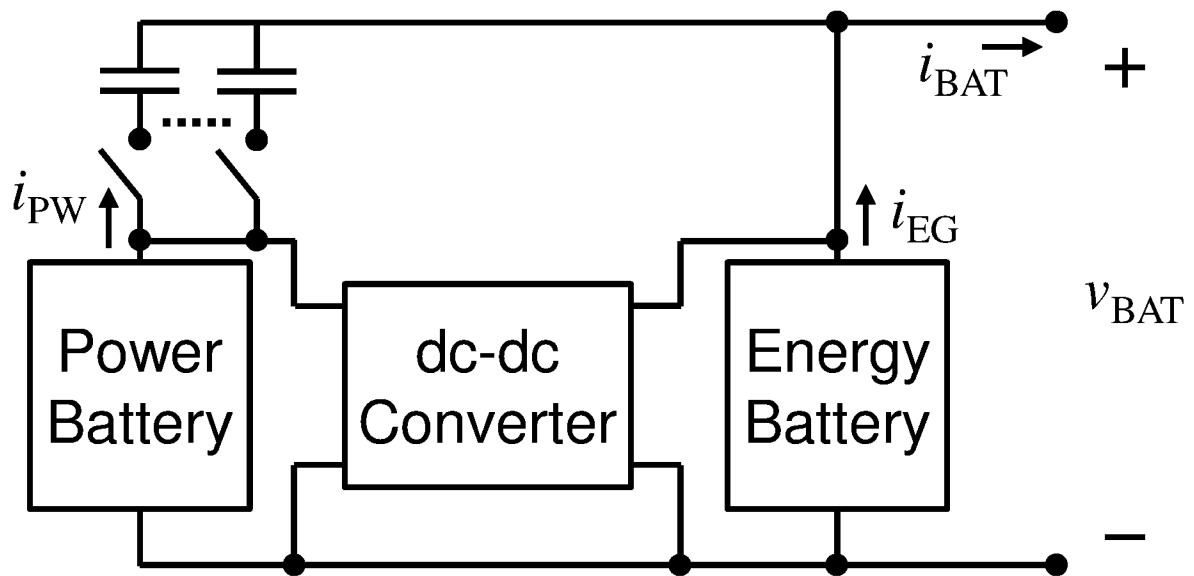


FIG. 7

# INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US2017/019306

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H02J 1/00; H02J 3/32; H02J 7/14; H02J 7/34 (2017.01)

CPC - H02J 3/32; H02J 3/36; H02J 7/1423; H02J 7/345 (2017.02)

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)

See Search History document

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

USPC - 123/596; 315/206; 315/224 (keyword delimited)

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

See Search History document

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|-----------|------------------------------------------------------------------------------------|-----------------------|
| Y         | US 2014/0327298 A1 (WINKLER et al) 06 November 2014 (06.11.2014) entire document   | 1-3, 22-24            |
| Y         | US 2010/0090525 A1 (KING et al) 15 April 2010 (15.04.2010) entire document         | 1-3                   |
| Y         | US 8,339,056 B1 (XIONG et al) 25 December 2012 (25.12.2012) entire document        | 2, 22-24              |
| A         | US 2012/0156528 A1 (COOLEY) 21 June 2012 (21.06.2012) entire document              | 1-3, 22-24            |
| A         | US 5,559,402 A (CORRIGAN, III) 24 September 1996 (24.09.1996) entire document      | 1-3, 22-24            |
| A         | US 8,912,911 B2 (KRUG et al) 16 December 2014 (16.12.2014) entire document         | 1-3, 22-24            |
| A         | US 5,849,426 A (THOMAS et al) 15 December 1998 (15.12.1998) entire document        | 1-3, 22-24            |
| A         | US 2003/0169022 A1 (TURNER et al) 11 September 2003 (11.09.2003) entire document   | 1-3, 22-24            |

☐ 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 another 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

18 April 2017

Date of mailing of the international search report

05 MAY 2017

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents

P.O. Box 1450, Alexandria, VA 22313-1450

Facsimile No. 571-273-8300

Authorized officer

Blaine R. Copenheaver

PCT Helpdesk: 571-272-4300

PCT OSP: 571-272-7774

# INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2017/019306

## Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:
  
2. ☐ Claims Nos.:  
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
  
3. ☒ Claims Nos.: 4-21, 25-42  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

## Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
  
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

### Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.