



(51) International Patent Classification:

B60L 11/12 (2006.01) **H02J 7/34** (2006.01)
B60L 11/18 (2006.01)

(21) International Application Number:

PCT/US2015/052232

(22) International Filing Date:

25 September 2015 (25.09.2015)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/058,353 1 October 2014 (01.10.2014) US

(71) Applicant: **BALLARD POWER SYSTEMS INC.**
[CA/CA]; 9000 Glenlyon Parkway, Burnaby, British
Columbia V5J 5J8 (CA).(71) Applicant (for VC only): **BALLARD MATERIAL
PRODUCTS INC.** [US/US]; Two Industrial Avenue,
Lowell, Massachusetts 01851-5199 (US).(72) Inventor: **PATERSON, Paul, L.**; 1583 Elinor Crescent,
Port Coquitlam, British Columbia V3C 2Y3 (CA).(74) Agents: **SOLTANI, Bobby, B.** et al.; Seed Intellectual
Property Law Group PLLC, Suite 5400, 701 Fifth Avenue,
Seattle, Washington 98104-7064 (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, 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, KN, KP, KR, 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).

Declarations under Rule 4.17:

- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))
- as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))
- of inventorship (Rule 4.17(iv))

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(54) Title: MULTI-MODE HYBRID CONTROL FOR RANGE-EXTENDED PLUG-IN VEHICLES

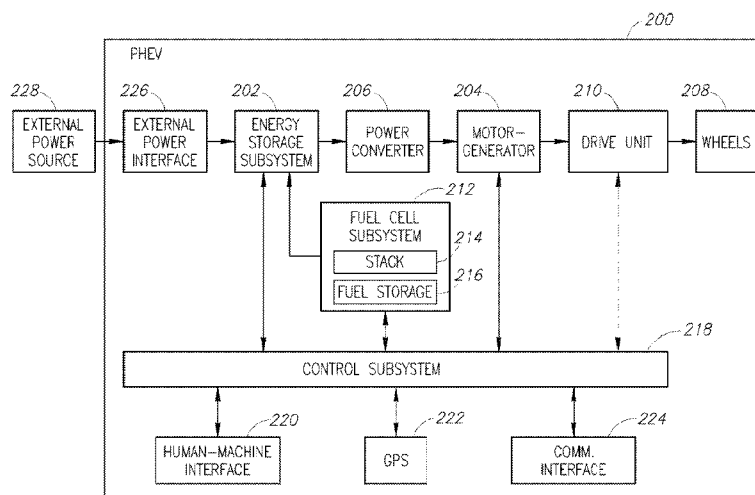


FIG. 2

(57) Abstract: Multi-mode control systems and methods for range-extended plug-in electric vehicles. The plug-in electric vehicle principally utilizes a battery as an energy source and employs a secondary power source, such as a fuel cell subsystem, as a battery charger to extend the range of the vehicle. A control subsystem operates the secondary power source to minimize fuel consumption near an end of a trip. In some operating modes, the secondary power source operates at full rated power to reduce the required run time of the secondary power source, thereby increasing its lifetime. The secondary power source may also operate more efficiently at full rated power as compared to operating in a part power or load-following mode.



Published:

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

MULTI-MODE HYBRID CONTROL FOR RANGE-EXTENDED PLUG-IN VEHICLES

BACKGROUND

Technical Field

5 The present disclosure relates to power management for range-extended plug-in electric vehicles.

Description of the Related Art

10 Plug-in hybrid electric vehicles (PHEV) are an extension of existing hybrid electric vehicle (HEV) technology, in which a primary battery pack is supplemented with a secondary power source (e.g., an internal combustion engine, a fuel cell system) to gain increased mileage and reduced vehicle emissions. A PHEV adds the capability of recharging the battery pack from a standard electrical outlet or other external power source. Because the battery pack has a large capacity, the PHEV can be operated primarily by
15 electric propulsion for a substantial distance, for example, a battery operation range of 10-40 miles, after a full battery recharge. The secondary power source is only started to assist vehicle propulsion in limited circumstances such as high speed and/or high power demand operations due to system constraints. After the usable battery electricity is depleted, the secondary power source
20 takes over the primary role in vehicle propulsion by consuming fuel energy (e.g., gasoline, diesel, hydrogen). By relying on electrical energy from the grid to charge the battery and then using that energy for a significant fraction of vehicle travel, the amount of fuel consumed by the PHEV is greatly reduced, especially when the traveling distance is close to the battery operation range.

25 While conventional HEVs are operated to maintain the battery state of charge (SOC) at a nearly constant level, a PHEV generally uses as much pre-saved battery electric ("grid") energy as possible before the next battery charge event due to the relatively lower cost of grid-supplied electric

energy. After the battery's SOC decreases to a desired charge-sustaining level or a lowest conservative level, the PHEV resumes operation as a conventional HEV. In order to ensure that the grid-supplied electric energy is expended, the base PHEV control mode largely uses up the electric energy first and the
5 secondary power source takes over the leading role in vehicle propulsion only when the battery is substantially discharged.

Figure 1 shows a plot 10 of a state of charge 12 for a battery of a PHEV in the aforementioned two operation modes, namely a discharging mode (DM) and a charge-sustaining mode (CSM). In the example shown, a mostly
10 charged PHEV is driven in the discharging mode for the first part of the trip, where the battery's SOC exhibits a net decrease between points 14 and 16. Due to the lower cost of electricity compared to fuel, the available battery electric energy is used for vehicle usage function before the next PHEV plug-in recharge event to largely displace fuel consumption. Since knowledge of the
15 occurrence of the next battery recharge event is usually unknown, by default, the PHEV operation starts in the discharging mode to maximize the likelihood of battery depletion before the end of the trip.

During the discharging mode, the battery's electric energy is used primarily to propel the vehicle, thereby maximally or near maximally depleting
20 the electric energy stored in the battery. In the discharging mode, the secondary power source is kept in an off state or at a very low power level. By primarily utilizing the battery energy to propel the vehicle early in the trip, the PHEV fuel consumption is minimized when the trip distance is close to the battery operation range. Once the battery's SOC decreases to a predetermined
25 sustaining level (e.g., 20% SOC), the vehicle switches to the charge-sustaining mode at point 16, where the battery's SOC is kept within a certain range close to the desired sustaining SOC level. In the charge-sustaining mode, the vehicle is mainly powered by the secondary power source (i.e., fuel energy). At point 18, the trip has ended and the vehicle is proximate an external power
30 source, such as an electrical outlet. The battery may then be recharged to the fully charged condition via the external power source.

BRIEF SUMMARY

A hybrid vehicle may be summarized as including: an electric machine coupled to provide propulsion power for the hybrid vehicle; an energy storage subsystem electrically coupled to the electric machine to provide at least one of: a source of electrical energy to the electrical machine, and a sink of electrical energy from the electrical machine; a fuel cell subsystem electrically coupled to the energy storage subsystem to charge the energy storage subsystem; and a control subsystem electrically coupled to the electric machine, the energy storage subsystem, and the fuel cell subsystem, the control subsystem receives next charging opportunity information, the next charging opportunity information at least partially indicative of an anticipated next opportunity to charge the energy storage subsystem via a power source other than the fuel cell subsystem, the control system monitors a state of charge of the energy storage subsystem and causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem according to a normal control mode or an approaching next charging opportunity control mode based at least in part on the received next charging opportunity information, wherein in the normal control mode the control subsystem repeatedly: permits depletion of the energy storage subsystem to a first state of charge; and causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge; and in the approaching next charging opportunity control mode the control subsystem: permits depletion of the energy storage subsystem to a third state of charge, the third state of charge lower than the second state of charge; and causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem proximate the third state of charge.

The next charging opportunity information may include at least one of: an anticipated distance until a next opportunity to charge the energy storage subsystem via a power source other than the fuel cell subsystem; an

anticipated time of operation until a next opportunity to charge the energy storage subsystem via a power source other than the fuel cell subsystem; and an anticipated energy output requirement for the energy storage subsystem until a next opportunity to charge the energy storage subsystem via a power

5 source other than the fuel cell subsystem. The anticipated energy output requirement may be based at least in part on at least one of route information, terrain information, speed limit information, traffic information, temperature information, and vehicle load information. The next charging opportunity information may be based at least in part on an input to the control subsystem

10 via a human-machine interface. The next charging opportunity information may be based at least in part on data collected by the control subsystem concerning a driving pattern of the hybrid vehicle or a driving pattern of a driver of the hybrid vehicle. The hybrid vehicle may further include: a global positioning system (GPS) navigation system coupled to the control subsystem, wherein the

15 next charging opportunity information is based at least in part on signals from the GPS navigation subsystem. The energy storage subsystem may include at least one of an electrochemical battery cell and an ultra-capacitor cell, the hybrid vehicle further comprising: a charger interface coupled to the hybrid vehicle and to an external power source to charge the energy storage

20 subsystem. The first state of charge may be less than 25% of full charge for the energy storage subsystem and the second state of charge may be greater than 70% of full charge for the energy storage subsystem. The first state of charge and the third state of charge may be approximately equal to each other. The fuel cell subsystem may include a plurality of fuel cells electrically coupled

25 in series to form a fuel cell stack.

A system to control the operation of a hybrid machine may be summarized as including an electric machine, an energy storage subsystem electrically coupled to the electric machine, and a fuel cell subsystem electrically coupled to the energy storage subsystem to charge the energy

30 storage subsystem, the system comprising: a processor operatively coupled to the electric machine, the energy storage subsystem, and the fuel cell

subsystem, the processor: receives next charging opportunity information, the next charging opportunity information at least partially indicative of an anticipated next opportunity to charge the energy storage subsystem via a power source other than the fuel cell subsystem; monitors a state of charge of the energy storage subsystem; and causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem according to a normal control mode or an approaching next charging opportunity control mode based at least on part on the received next charging opportunity information, wherein: in the normal control mode the processor permits depletion of the energy storage subsystem to a first state of charge, and causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge; and in the approaching next charging opportunity control mode the processor permits depletion of the energy storage subsystem to a third state of charge, the third state of charge lower than the second state of charge, and causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem proximate the third state of charge.

The next charging opportunity information may be based at least in part on an input via a human-machine interface. The hybrid machine may include a hybrid vehicle, and the next charging opportunity information may be based at least in part on data collected concerning a driving pattern of the hybrid vehicle or a driving pattern of a driver of the hybrid vehicle. The processor may receive the next charging opportunity information from a global positioning system (GPS) navigation subsystem. The energy storage subsystem may include at least one of an electrochemical battery cell and an ultra-capacitor cell. The first state of charge may be less than 25% of the fully charged state of charge for the energy storage subsystem and the second state of charge may be greater than 70% of the fully charged state of charge for the energy storage subsystem. The first state of charge and the third state of charge may be approximately equal to each other. The fuel cell subsystem

may include a plurality of fuel cells electrically coupled in series to form a fuel cell stack.

A method to control a hybrid machine having an electric machine, an energy storage subsystem electrically coupled to the electric machine, and a secondary electrical power delivery subsystem electrically coupled to the energy storage subsystem to charge the energy storage subsystem, may be summarized as including: receiving charging opportunity information in a processor-readable medium, the next charging opportunity information at least partially indicative of an anticipated next opportunity to charge the energy storage subsystem via a power source other than the secondary electrical power delivery subsystem; monitoring a state of charge for the energy storage subsystem; autonomously causing the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem according to a normal control mode or an approaching next charging opportunity control mode based at least on part on the received next charging opportunity information, wherein the normal control mode comprises: permitting depletion of the energy storage subsystem to a first state of charge; and causing the secondary electrical power delivery subsystem to operate at full rated power to provide electrical energy to the energy storage subsystem to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge; and the approaching next charging opportunity control mode comprises: causing the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at or below a third state of charge.

Causing the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at or below a third state of charge may include repeatedly: permitting depletion of the energy storage subsystem to fourth state of charge, the fourth state of charge lower than the third state of charge; and causing the secondary electrical power delivery subsystem to provide electrical

energy to the energy storage subsystem to charge the energy storage subsystem from the fourth state of charge to the third state of charge. Causing the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at
5 or below a third state of charge may include causing the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at a charge-sustaining state of charge, the charge-sustaining charge at or below the third state of charge. Receiving next charging opportunity information may include receiving
10 an input via a human-machine interface. The hybrid machine may include a hybrid vehicle, and receiving next charging opportunity information may include receiving data concerning a driving pattern of the hybrid vehicle or a driving pattern of a driver of the hybrid vehicle. Receiving next charging opportunity information may include receiving signals from a global positioning system
15 (GPS) navigation system. Causing the secondary electrical power delivery subsystem to operate at full rated power to provide electrical energy to the energy storage subsystem to charge the energy storage subsystem from the first state of charge to the second state of charge higher than the first state of charge may include causing the secondary electrical power delivery subsystem
20 to charge the energy storage subsystem from a state of charge less than 25% of the fully charged state of charge for the energy storage subsystem to a state of charge greater than 70% of the fully charged state of charge for the energy storage subsystem. Permitting depletion of the energy storage subsystem to a first state of charge may include permitting depletion of the energy storage
25 subsystem to the charge-sustaining state of charge.

A method to control a hybrid vehicle during a trip, the hybrid vehicle having an electric machine, an energy storage subsystem electrically coupled to the electric machine, and a secondary electrical power delivery subsystem electrically coupled to the energy storage subsystem to charge the
30 energy storage subsystem, may be summarized as including: detecting a state of charge for the energy storage subsystem; operating the secondary electrical

power delivery subsystem at full rated power to charge the energy storage subsystem from a first state of charge to a second state of charge higher than the first state of charge when the state of charge for the energy storage subsystem is detected to be at or below the first state of charge; receiving an
5 indication at least partially indicative of an anticipated upcoming end of the trip; permitting depletion of the energy storage subsystem to the first state of charge; and operating the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at a charge-sustaining state of charge.

10 Operating the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at a charge-sustaining state of charge may include operating the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy
15 storage subsystem at a state of charge that is less than 50% of the state of charge of the energy storage subsystem when fully charged.

A method to control a hybrid machine, the hybrid machine having an electric machine, an energy storage subsystem electrically coupled to the electric machine, and a secondary electrical power delivery subsystem
20 electrically coupled to the energy storage subsystem to charge the energy storage subsystem, may be summarized as including: for a duration time when the hybrid machine is electrically decoupled from an external power source: detecting a state of charge for the energy storage subsystem; repetitively permitting depletion of the energy storage subsystem to a first state of charge;
25 and repetitively causing the secondary electrical power delivery subsystem to operate at full rated power to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge when the state of charge for the energy storage subsystem is detected to be at or below the first state of charge, the second state of charge less than
30 50% of the state of charge of the energy storage subsystem when fully charged.

Repetitively causing the secondary electrical power delivery subsystem to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge may include causing the secondary electrical power delivery subsystem to charge

5 the energy storage subsystem from a state of charge less than 25% of the state of charge of the energy storage subsystem when fully charged to a state of charge less than 30% of the state of charge of the energy storage subsystem when fully charged.

A system to control the operation of a hybrid machine, the hybrid

10 machine comprising an electric machine, an energy storage subsystem electrically coupled to the electric machine, and a secondary electrical power delivery subsystem electrically coupled to the energy storage subsystem to charge the energy storage subsystem, may be summarized as including: a processor operatively coupled to the electric machine, the energy storage

15 subsystem, and the fuel cell subsystem, wherein for a duration time when the hybrid machine is electrically decoupled from an external power source, the processor: detects a state of charge for the energy storage subsystem; repetitively permits depletion of the energy storage subsystem to a first state of charge; and repetitively causes the secondary electrical power delivery

20 subsystem to operate at full rated power to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge when the state of charge for the energy storage subsystem is detected to be at or below the first state of charge, the second state of charge less than 50% of the state of charge of the energy storage

25 subsystem when fully charged.

The first state of charge may be less than 25% of the state of charge of the energy storage subsystem when fully charged, and the second state of charge may be less than 30% of the state of charge of the energy storage subsystem when fully charged.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

In the drawings, identical reference numbers identify similar elements or acts. The sizes and relative positions of elements in the drawings are not necessarily drawn to scale. For example, the shapes of various
5 elements and angles are not drawn to scale, and some of these elements are arbitrarily enlarged and positioned to improve drawing legibility. Further, the particular shapes of the elements as drawn are not intended to convey any information regarding the actual shape of the particular elements, and have been solely selected for ease of recognition in the drawings.

10 Figure 1 is an example plot of a battery state of charge (SOC) versus trip distance for a conventional control strategy for a plug-in hybrid electric vehicle to complete a trip that is longer than the operation range for a battery of the vehicle.

Figure 2 is a schematic diagram illustrating a hybrid plug-in
15 electric vehicle, according to at least one illustrated embodiment.

Figure 3 is a flow diagram depicting a power management process for a range-extended plug-in electric vehicle, according to at least one illustrated embodiment.

Figure 4 is a plot of a battery SOC versus trip distance for a
20 control strategy for a plug-in hybrid electric vehicle to complete a trip that is longer than the operation range for a battery of the vehicle, according to at least one illustrated embodiment.

Figure 5 is a plot of a power level for a secondary power source versus trip distance for the control strategy of Figure 4, according to at least
25 one illustrated embodiment.

Figure 6 is a plot of a battery SOC versus trip distance for a control strategy for a plug-in hybrid electric vehicle to complete a trip that is longer than the operation range for a battery of the vehicle, according to at least one illustrated embodiment.

Figure 7 is a plot of a power level for a secondary power source versus trip distance for the control strategy of Figure 6, according to at least one illustrated embodiment.

5 Figure 8 is a plot of a battery SOC versus trip distance for a control strategy for a plug-in hybrid electric vehicle to complete a trip that is longer than the operation range for a battery of the vehicle, according to at least one illustrated embodiment.

Figure 9 is a plot of a power level for a secondary power source versus trip distance for the control strategy of Figure 8, according to at least
10 one illustrated embodiment.

DETAILED DESCRIPTION

In the following description, certain specific details are set forth in order to provide a thorough understanding of various disclosed embodiments. However, one skilled in the relevant art will recognize that embodiments may be
15 practiced without one or more of these specific details, or with other methods, components, materials, etc. In other instances, well-known structures associated with power or control systems for electric vehicles have not been shown or described in detail to avoid unnecessarily obscuring descriptions of the embodiments.

20 Unless the context requires otherwise, throughout the specification and claims that follow, the word "comprise" and variations thereof, such as, "comprises" and "comprising" are to be construed in an open, inclusive sense, that is as "including, but not limited to."

Reference throughout this specification to "one embodiment" or
25 "an embodiment" means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular

features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

As used in this specification and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the content
5 clearly dictates otherwise. It should also be noted that the term "or" is generally employed in its broadest sense, that is, as meaning "and/or" unless the content clearly dictates otherwise.

The headings and Abstract of the Disclosure provided herein are for convenience only and do not interpret the scope or meaning of the
10 embodiments.

Embodiments of the present disclosure are directed to multi-mode control or power management systems and methods for range-extended plug-in electric vehicles and other electrical machines. The plug-in electric vehicles principally utilize a primary energy storage subsystem (e.g., one or more
15 electrochemical battery cells and/or super- or ultra-capacitor cells) as a rechargeable energy source and employ a secondary power source, such as a fuel cell subsystem or an internal combustion engine, as a source of energy to charge the primary energy storage subsystem to extend the range of the vehicle. In some operating modes, the secondary power source operates at full
20 rated power to reduce the required run-time of the secondary power source, thereby increasing the lifetime of the secondary power source. The secondary power source may also operate more efficiently at full rated power as compared to operating in a part power or load-following mode.

Figure 2 shows a range extended plug-in hybrid electrical
25 machine or vehicle 200, according to one or more embodiments. The vehicle 200 may include a ground-based vehicle (e.g., car, bus), an aircraft, an aquatic vehicle, or can even take non-vehicle forms. For example, the vehicle or machine 200 may be implemented as a backup power system for various power applications, such as cell phone base stations power applications,
30 building power applications, etc. In the discussion below, examples may be provided in the context of ground-based vehicles for the purpose of explanation.

The vehicle 200 includes an energy storage subsystem 202 and at least one electrical machine such as a motor-generator 204 that converts the stored energy into motion, such as rotary motion. The energy storage subsystem 202 may comprise one or more electrochemical battery cells (*i.e.*,
5 batteries). For example, the energy storage subsystem 202 may include one or more lithium ion cells coupled in parallel and/or coupled in series. In some embodiments, the energy storage subsystem 202 is capable of delivering a peak power of approximately 150-250 kW, delivering an operational power of approximately 130-180 kW, and providing a DC bus output voltage of 500 –
10 750. The energy storage subsystem 202 may be capable of delivering more or less power and may be capable of operating at higher or lower output voltages as suits the particular application. In some embodiments, the energy storage subsystem 202 may utilize one or more lithium ion nano-iron-phosphate cells, for example.

15 The vehicle 200 may also include an electrical power converter 206 to convert energy from the energy storage subsystem 202 into energy usable by the motor-generator 204. In some embodiments, the motor-generator 204 may generate energy that is transmitted to the power converter 206, which converts the energy into a form that may be stored by the energy
20 storage subsystem 202. Thus, in addition to converting energy into motion, the motor-generator 204 can also capture energy from regenerative processes, such as braking.

The power converter 206 may include one or more transistors, such as metal-oxide semiconductor field effect transistors (MOSFETs),
25 insulated gate bipolar transistors (IGBTs), etc. In some embodiments, the power converter 206 may include a switch bank or bridge that receives direct current (DC) from the energy storage subsystem 202 and outputs alternating current (AC) to the motor-generator 204 (*e.g.*, alternator). For example, the alternating current may be three-phase alternating current. In some
30 embodiments, such as during a regenerative braking process, the power converter 206 converts (*e.g.*, rectifies) an alternating current signal into direct

current power to be stored in the energy storage subsystem 202. The power converter 206 may also convert energy from the energy storage subsystem 202 into energy usable by electrical loads other than the motor-generator 204, such as lights, power windows, power seats, windshield wipers, etc. For example, 5 the power converter 206 may step a voltage up or down (e.g., a switch-mode DC-DC converter). The motor-generator 204 may, for example, be a three-phase alternating current motor-generator. The motor-generator 204 may include a plurality of electrical motors.

The motor-generator 204 may be coupled to wheels 208 of the 10 vehicle 200 via an optional drive unit 210 (e.g., transmission, gearset, transaxle, etc.). In some implementations, rotary motion may be transferred from the drive unit 210 to the wheels 208 via one or more axles (not shown).

The vehicle 200 also includes a secondary power source, which is illustrated as a fuel cell subsystem 212, electrically coupled to the energy 15 storage subsystem 202 to provide energy thereto to charge the energy storage subsystem 202. The fuel cell subsystem 212 may be a polymer electrolyte membrane (PEM) fuel cell system, a solid oxide fuel cell system, a molten carbonate fuel cell system, or any other type of fuel cell system. The fuel cell subsystem 212 can include a plurality of individual fuel cells arranged in any 20 configuration known to those of skill in the art. For example, the fuel cell subsystem 212 may include one or more fuel cell stacks 214, one or more fuel cell columns, etc. The fuel cell subsystem 212 may include a fuel storage 216 that stores a consumable and replenishable fuel, such as liquid or gaseous hydrogen. The fuel cell subsystem 212 may also include one or more power 25 converters (not shown). A non-limiting example of a suitable fuel cell subsystem 212 is the FCvelocity-HD6 fuel cell module offered by Ballard Power Systems, Inc. of Burnaby, British Columbia, Canada.

The secondary power source may be a power source other than a fuel cell subsystem 212. Generally, the secondary power source may also be 30 any fuel-burning engine that consumes or burns any of a variety of fuels, such as fossil fuels, synthetic fuels, and bio fuels. In some implementations, a power

converter (e.g., a DC/DC converter, an AC/DC converter, etc.) may be coupled between the secondary power source and the energy storage subsystem 202 so that energy from the secondary power source may be provided to the energy storage subsystem in a form suitable for storage by the energy storage

5 subsystem.

The vehicle 200 also includes a control subsystem 218 operatively coupled to the energy storage subsystem 202, the fuel cell subsystem 212, the motor-generator 204, and the transmission 210. As discussed in further detail below, the control subsystem 218 may also be
10 coupled to a human-machine interface 220, a global positioning system (GPS) navigation system 222, and a wired and/or wireless communications interface 224.

The control subsystem 218 may include one or more computing devices, such as one or more processors, microcontrollers, microprocessors,
15 digital signal processors (DSPs), graphical processing units (GPUs), or application specific integrated circuits (ASICs), and associated software or hardware constructs, and/or one or more processor-readable media to carry out certain functions and methods. The computing devices may be embodied in a single central processing unit, or may be distributed such that a subsystem or
20 function has its own dedicated processor. Moreover, some embodiments of subsystems may be provided as a computer program product including nontransitory processor-readable medium having stored thereon instructions that may be used to program a computer (or other electronic device) to perform processes or methods described herein. The nontransitory processor-readable
25 medium may include, but is not limited to, hard drives, floppy diskettes, optical disks, CD-ROMs, DVDs, read-only memories (ROMs), random access memories (RAMs), EPROMs, EEPROMs, flash memory, magnetic or optical cards, solid-state memory devices, or other types of machine-readable media suitable for storing electronic instructions.

30 The control subsystem 218 is operative to control the operation of the fuel cell subsystem 212 which in turn controls the amount of energy

provided to charge the energy storage subsystem 202. For example, the control subsystem 218 may command or cause the fuel cell subsystem 212 to be in an OFF mode wherein substantially no power is delivered to the energy storage subsystem 202, in a fully ON mode wherein full or near full rated power (e.g., 75 kW, 150 kW, etc.) is delivered to the energy storage subsystem, or a "part power" or "load following" mode wherein a power level less than full rated power is delivered to the energy storage subsystem. Specific examples of control methods are discussed below with reference to Figures 4-9.

The control subsystem 218 is also operative to detect or monitor the state of charge (SOC) of the energy storage subsystem 202. The control subsystem 218 may detect coulombs, watt-hours, or other measure indicative of how much energy is in the energy storage subsystem 202. In some embodiments, the energy storage subsystem 202 includes components or circuitry that provides the SOC information to the control subsystem 218.

The vehicle 200 also includes an external power interface 226 that facilitates selective coupling with an external power source 228. For example, the external power source 228 may be a charging station coupled to a municipal or other power grid. The external power source 228 may be positioned in any location, such as near a highway, in a parking lot, in a garage, at a fueling station, etc. In some embodiments, the external power source 228 may convert alternating current power into power storable by the energy storage subsystem 202. In some embodiments, the external power interface 226 may provide suitable energy conversion circuitry to convert power from the external power source 228 into a form storable by the energy storage subsystem 202. Such energy conversion circuitry may be integrated within the vehicle 200, or may be separate therefrom.

As noted above, the vehicle 200 may include a human-machine interface (HMI) 220 coupled to the control subsystem 218. The HMI 220 may receive input regarding operational preferences or trip information (e.g., distance or time until the end of a trip or until the vehicle 200 reaches a charging station), as well as other types of input. The HMI 220 may include one

or more buttons, keys, touch screens, voice capturing devices, image-capturing devices, or any other type of device capable of capturing input from a user, directly or indirectly. The HMI 220 may also include one or more output devices such as displays, illumination sources, speakers, etc.

5 The vehicle 200 may also include the GPS navigation system 222 coupled to the control subsystem 218. The GPS navigation system 222 receives GPS signals to determine the location of the vehicle 200, and provides positioning data to the control subsystem 218. The positioning data may indicate the location of the vehicle 200, the location of a trip destination (e.g.,
10 home, work, etc.), the location of an external power source 228, or other positioning information.

 The vehicle 200 may also include the wired and/or wireless communications interface 224 coupled to the control subsystem 218. The communications interface 224 may allow the control subsystem 218 to
15 communicate with one or more external devices. For example, the communications interface 224 may facilitate communication between the control subsystem 218 and a computing device of a user, such as a smart phone. As another example, the communications interface 224 may facilitate communication between the control subsystem 218 and a remote server over a
20 network (e.g., the Internet).

 Utilizing the HMI 220, the GPS system 222, the communications interface 224, an electronic odometer, and/or wireless information from fleet operations, the control subsystem 218 may be able identify or predict when the vehicle 200 will arrive at an external power source 228. Such information may
25 be provided directly by the user or may be derived from various data, such as previous driving patterns, user inputs, user profiles, GPS data, map data, odometer data, fleet operations data, third-party data, etc. As discussed below, the control subsystem 218 utilizes the identified distance or time to the next charging station information to control the operation of the fuel cell subsystem
30 212 to charge the energy storage subsystem 202. Generally, the control subsystem 218 may command or cause the fuel cell subsystem 212 to

selectively operate at full rated power to reduce the required run-time of the fuel cell subsystem, thereby allowing the fuel cell subsystem to operate more efficiently while simultaneously increasing its lifetime. Moreover, utilizing the determined or identified distance or time until the next charging station, the control subsystem 218 controls the fuel cell subsystem 212 to allow the vehicle 200 to use as much energy from the energy storage subsystem 202 as possible before the next charging event so that use of the fuel cell subsystem is minimized. This is advantageous because of the relatively lower cost of grid-supplied electric energy compared to fuel costs. Thus, since the occurrence of the next recharge event is known in the embodiments disclosed herein, the control subsystem 218 is able to maximize the likelihood of depletion of the energy storage subsystem 202 before the end of the trip, thereby achieving significant fuel savings.

Figure 3 is a flow diagram of a method 300 of operation for controlling the power delivered by the fuel cell subsystem 212 to the energy storage subsystem 202 of the vehicle 200. The method 300 starts at 302 when a user starts the vehicle 200 and begins a trip, for example, after the energy storage subsystem 202 has been fully charged at the external power source 228.

At 304, the control subsystem 218 detects or monitors the state of charge for the energy storage subsystem 202. The hardware utilized to implement detection and monitoring of the state of charge may be associated with the control subsystem 218, with the energy storage subsystem 202, or with an independent state of charge monitoring subsystem.

At 306, the control subsystem 218 commands or causes the fuel cell subsystem 212 to charge the energy storage subsystem 202 according to a normal trip operational mode control strategy. Examples of control strategies for the normal trip operational mode are discussed below with reference to Figures 4-9.

At 308, the control subsystem 218 receives distance to next charge information or other anticipated next charging opportunity information

(e.g., anticipated time until the next charging opportunity, anticipated energy output requirements until the next charging opportunity). The control subsystem 218 may receive the anticipated next charging opportunity information at any time. For example, in some implementations, the anticipated
5 next charging opportunity information may be received prior to the beginning of operation, or the information may be received while the energy storage subsystem 202 is operated according to a normal trip operational mode control strategy. In implementations where the next charging opportunity information includes anticipated energy requirements until the next charging opportunity,
10 the control subsystem 218 may utilize any suitable data that may impact anticipated energy requirements, such as route information, terrain, speed limits, traffic, temperature, vehicle load, etc. The control subsystem 218 may utilize a combination of information, such as the energy requirement for the energy storage subsystem 202 until the next charging opportunity and the time
15 until the next charging opportunity. The control subsystem 218 may store the received distance to next charge information in a processor-readable medium. The distance to next charge information provides an indication of the distance until the vehicle 200 next reaches a charging station.

For example, a user may input a destination address into the GPS
20 navigation system 222 of the vehicle 200. The destination address and location information from the GPS navigation system 222 may be used by the control subsystem 218 to identify the distance to next charge information. As another example, the user may input into the HMI 220 that he or she plans to stop at a charging station that is 20 miles away. As another example, the control
25 subsystem 218 may predict the route of the vehicle 200 based at least in part on previous driving patterns for the vehicle or the driver of the vehicle. For instance, the control subsystem 218 may recognize that the vehicle 200 is traveling to the user's place of work by recognizing a particular route, day, and time normally traveled by the user.

30 At 310, the control subsystem 218 determines that the distance to the next charging event is near (e.g., the vehicle 200 is approaching a charging

station, a battery swapping station, etc.). For example, utilizing the distance to next charge information and optionally other data (e.g., GPS data, odometer data, velocity data, elapsed time data), the control subsystem 218 determines that the vehicle 200 will arrive at a charging station within a certain distance
5 (e.g., 10-20 miles, etc.). This determination may be made at any time, including before a trip has begun or while the trip is in progress. For example, prior to the beginning of a trip, the control subsystem 218 may detect that the vehicle will follow a predicable route (e.g., a daily commute) during the trip, and the control subsystem may use this information prior to the beginning of the trip to
10 determine when the next charging opportunity is expected.

In response to determining the end of a trip is near, the control subsystem 218 commands or causes the fuel cell subsystem 212 to charge the energy storage subsystem 202 according to an end-of-trip operational mode or approaching next charging opportunity operational mode at 312. Generally, the
15 control subsystem 218 may control the fuel cell subsystem 212 in a way that the energy storage subsystem 202 is substantially depleted when the vehicle 200 arrives at the charging station to minimize fuel expended by the fuel cell subsystem. More specifically, the control subsystem 218 may minimize or terminate operation of the fuel cell subsystem 212 to utilize the energy that
20 remains in the energy storage subsystem 202 to propel the electric vehicle 200 to the charging destination. Examples of control strategies for the end-of-trip operational mode are discussed below with reference to Figures 4-9.

The method 300 ends at 314. For example, the method may end when the vehicle 200 arrives at a charging station and the energy storage
25 subsystem 202 is charged via the external power source 228. The method 300 may begin again once the vehicle 200 begins a new trip (e.g., departs from a charging station).

Figures 4 and 5 illustrate two control modes for the control subsystem 218, according to one embodiment. Specifically, Figure 4 shows a
30 state of charge (SOC) 400 for the energy storage subsystem 202 of Figure 2 during a trip that spans between a beginning point 402 and an end point 404.

Figure 5 shows an output power level 500 of a secondary power source, such as the fuel cell subsystem 212, during the trip. Figures 4 and 5 show the SOC 400 and the output power level 500, respectively, during a normal operational mode (NM) and an end-of-trip operational mode (EOTM).

5 In the normal operational mode, the control subsystem 218 permits the SOC 400 of the energy storage subsystem 202 to be depleted to a specified first state of charge at point 406. The control subsystem 218 then commands or causes the fuel cell subsystem 212 to operate at full rated power or substantially full rated power to charge the energy storage subsystem 202 to
10 a higher second state of charge, achieved at point 408. As an example, the first state of charge may be approximately 20% of the state of charge of the energy control subsystem 218 when fully charged (*i.e.*, 100% SOC, or "full charge"), and the second SOC may be approximately 80% SOC. These percentages are provided as examples, although other percentages or ranges
15 of percentages are contemplated. In some embodiments, the second state of charge is less than 100% SOC to allow for charging the energy storage subsystem 202 through regenerative processes, as discussed above.

 Once the fuel cell subsystem 212 has charged the energy storage subsystem 202 to the second state of charge at point 408, the control
20 subsystem 218 may shut off or disengage the fuel cell subsystem 212 to permit the SOC 400 of the energy storage subsystem 202 to again be depleted to the first state of charge at point 410. This cycle may continue while the control subsystem 218 operates in the normal operational mode during the trip.

 As discussed above, the control subsystem 218 receives next
25 charging opportunity information, which is at least partially indicative of an anticipated (*e.g.*, predicted, estimated, expected, identified) next opportunity to charge the vehicle 200. When the control subsystem 218 determines the vehicle 200 has reached a specified distance D_1 to the next charging station, the control subsystem 218 transitions into the end-of-trip operational mode at
30 point 412. In the end-of-trip operational mode, the control subsystem 218 permits the SOC 400 of the energy storage subsystem 202 to be depleted to a

third state of charge at point 414. In some embodiments, the third state of charge may be the same as the first state of charge (e.g., 20% SOC). Once the energy storage subsystem 202 has reached the third state of charge, the control subsystem 218 engages the fuel cell subsystem 212 at part power or in a load-following mode to maintain a relatively constant state of charge of the energy storage subsystem. This mode may be referred to as a charge-neutral or a charge-sustaining mode.

The control subsystem 218 continues to operate in the end-of-trip operational mode until the vehicle 200 reaches the charging station at the end point 404. Note that since the energy storage subsystem 202 is maintained at a relatively low SOC during the end portion of the trip, use of the fuel cell subsystem 212 is minimized so that the external power source 228, rather than the fuel cell subsystem, can be used to charge the energy storage subsystem from the low third state of charge once the vehicle 200 has reached the charging station. A benefit of the end-of-trip operational mode is illustrated by a dashed line 416, which shows the additional fuel that would be required if the control subsystem 218 continued to operate in the normal operational mode without switching into the end-of-trip operational mode.

It is noted that although the illustrated embodiment shows the control subsystem 218 activating the end-of-trip operational mode at point 412 after receiving the next charging opportunity information, it should be appreciated that the control subsystem may activate the end-of-trip operational mode at any time. For example, the control subsystem 218 may activate the end-of-trip operational mode at any time before the end of a discharge cycle and after the end of a preceding charging cycle. Thus, the determination of the next charging opportunity information need not be precise to obtain the advantages disclosed herein (e.g., maximizing fuel economy while minimizing run time of the fuel cell subsystem).

Figures 6 and 7 illustrate another implementation of a normal operational mode (NM) and an end-of-trip operational mode (EOTM) for the control subsystem 218. Figure 6 shows a state of charge 600 for the energy

storage subsystem 202 of Figure 2 during a trip that spans between a beginning point 602 and an end point 604, and Figure 7 shows an output power level 700 of a secondary power source, such as the fuel cell subsystem 212, during the trip.

5 In the implementation shown in Figures 6 and 7, the normal operational mode is substantially the same as the normal operational mode illustrated in Figures 4 and 5. As with the previous example, when the control subsystem 218 determines the vehicle 200 has reached a specified distance D_2 to the next charging station at point 606, the control subsystem 218 transitions
10 into an end-of-trip operational mode. In this implementation, rather than engaging the fuel cell subsystem 212 in a part power mode or load-following mode to maintain a relatively constant state of charge at the energy storage subsystem 202, the control subsystem 218 first permits the SOC 600 of the energy storage subsystem to be depleted to the relatively low third state of
15 charge (e.g., 20% SOC) at point 608, then cycles the fuel cell subsystem 212 between the full rated power mode and the OFF mode to maintain the SOC within a relatively low range. For example, the control subsystem 218 may command or cause the fuel cell subsystem 212 to deliver full rated power to charge the energy storage subsystem 202 from the lower third state of charge
20 (e.g., 15% SOC, 20% SOC) to a slightly higher fourth state of charge (e.g., 25% SOC, 30% SOC), then disengage the fuel cell subsystem to permit the SOC to be depleted back to the third state of charge. This cycle may be repeated until the vehicle 200 reaches a charging station at the end point 604.

 In the implementation of Figures 6 and 7, the fuel cell subsystem
25 212 is operated at full rated power rather than part power, which minimizes its time of operation and improves its efficiency. Further, since in the end-of-trip operational mode the energy storage subsystem 202 is maintained at a relatively low SOC 600, the vehicle 200 arrives at the external power source 228 with the energy storage subsystem having a low SOC so that the relatively
30 low cost external power source may be used to charge the energy storage subsystem.

In addition to monitoring the SOC 600 of the energy storage subsystem 202, the control subsystem 218 may also utilize other variables to control the operation of the fuel cell subsystem 212 in the end-of-trip operational mode. For example, the control subsystem 218 may set a time
5 duration to alternatively operate the fuel cell subsystem 212 in the full rated power mode and the OFF mode (e.g., a 50% duty cycle with a period of 10 minutes, a 70% duty cycle with a period of five minutes, etc.).

The range of SOC levels may be chosen to provide a suitable ON/OFF switching rate for the fuel cell subsystem 212 during the end-of-trip operational mode. As can be appreciated, if the range is small (e.g., 20-22%
10 SOC), the fuel cell subsystem 212 will be cycle much more rapidly that if the range is larger (e.g., 15-30% SOC). The SOC range and/or switching rate may be selected to provide a desired balance between fuel savings and the wear imposed on one or more components of the vehicle 200 due to repeatedly
15 switching the fuel cell subsystem 212 between the ON state and the OFF state.

Figures 8 and 9 illustrate another example of a control strategy for the vehicle 200. Figure 8 shows a state of charge 800 for the energy storage subsystem 202 of Figure 2 during a trip that spans between a beginning point 802 and an end point 804, and Figure 9 shows an output power level 900 of a
20 secondary power source, such as the fuel cell subsystem 212, during the trip.

In this implementation, the control subsystem 218 operates in a charge depletion operational mode (CDM) and an end-of-trip operational mode (EOTM). In the charge depletion mode, the control subsystem 218 permits the SOC 800 of the energy storage subsystem 202 to be depleted to a specified
25 first state of charge (e.g., 15% SOC, 25% SOC, etc.) at point 806. The control subsystem 218 then switches into the end-of-trip operational mode, in which the control subsystem cycles the fuel cell subsystem 212 between a full rated power state and an OFF state to maintain the SOC of the energy storage subsystem 202 at a relatively low range of SOC. For example, the control
30 subsystem 218 may maintain the SOC of the energy storage subsystem 202 between 20-25% SOC, between 15-30% SOC, and the like.

In the implementation of Figures 8 and 9, since the distance and/or time until the next charging station may not be known, the control subsystem 218 starts in the charge depletion operational mode to maximize the likelihood of depletion of the energy storage subsystem 202 before the end of the trip. During the charge depletion operational mode, the fuel cell subsystem 212 may be kept in the OFF state or at a very low power level. By primarily utilizing the energy of the energy storage subsystem 202 to propel the vehicle 200 early in the trip, the fuel consumption of the fuel cell subsystem 212 is minimized when the trip distance is close to the operating range of the energy storage subsystem. Once the SOC 800 of the energy storage subsystem 202 decreases to a relatively low state (shown as point 806), the vehicle 200 switches to the end-of-trip operational mode, where the SOC of the energy storage subsystem is kept within a certain relatively low range (e.g., close to a desired charge-sustaining SOC level). In the end-of-trip operational mode, the fuel cell subsystem 212 is cycled between the full rated power mode and the OFF mode, which minimizes the run time for the fuel cell subsystem and improves its efficiency. At the end point 804, the trip has ended and the vehicle 200 is proximate the external power source 228, such as an electrical outlet. The energy storage subsystem 202 may then be recharged to the fully charged condition via the external power source 228.

The foregoing detailed description has set forth various embodiments of the devices and/or processes via the use of block diagrams, schematics, and examples. Insofar as such block diagrams, schematics, and examples contain one or more functions and/or operations, it will be understood by those skilled in the art that each function and/or operation within such block diagrams, flowcharts, or examples can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or virtually any combination thereof. In one embodiment, the present subject matter may be implemented via Application Specific Integrated Circuits (ASICs). However, those skilled in the art will recognize that the embodiments disclosed herein, in whole or in part, can be equivalently implemented in standard integrated

circuits, as one or more computer programs running on one or more computers (e.g., as one or more programs running on one or more computer systems), as one or more programs running on one or more controllers (e.g., microcontrollers) as one or more programs running on one or more processors
5 (e.g., microprocessors), as firmware, or as virtually any combination thereof, and that designing the circuitry and/or writing the code for the software and or firmware would be well within the skill of one of ordinary skill in the art in light of this disclosure.

Those of skill in the art will recognize that many of the methods or
10 algorithms set out herein may employ additional acts, may omit some acts, and/or may execute acts in a different order than specified.

In addition, those skilled in the art will appreciate that the mechanisms taught herein are capable of being distributed as a program product in a variety of forms, and that an illustrative embodiment applies equally
15 regardless of the particular type of nontransitory signal bearing media used to actually carry out the distribution. Examples of nontransitory signal bearing media include, but are not limited to, the following: recordable type media such as floppy disks, hard disk drives, CD ROMs, digital tape, and computer memory.

20 The various embodiments described above can be combined to provide further embodiments. Aspects of the embodiments can be modified, if necessary, to employ systems, circuits and concepts of the various patents, applications and publications to provide yet further embodiments.

These and other changes can be made to the embodiments in
25 light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the claims to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the claims are not
30 limited by the disclosure.

This application also claims the benefit of U.S. Provisional Patent Application No. 62/058,353, filed October 1, 2014, and is incorporated herein by reference in its entirety.

CLAIMS

1. A hybrid vehicle, comprising:
 - an electric machine coupled to provide propulsion power for the hybrid vehicle;
 - an energy storage subsystem electrically coupled to the electric machine to provide at least one of: a source of electrical energy to the electrical machine, and a sink of electrical energy from the electrical machine;
 - a fuel cell subsystem electrically coupled to the energy storage subsystem to charge the energy storage subsystem; and
 - a control subsystem electrically coupled to the electric machine, the energy storage subsystem, and the fuel cell subsystem, the control subsystem receives next charging opportunity information, the next charging opportunity information at least partially indicative of an anticipated next opportunity to charge the energy storage subsystem via a power source other than the fuel cell subsystem, the control system monitors a state of charge of the energy storage subsystem and causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem according to a normal control mode or an approaching next charging opportunity control mode based at least on part on the received next charging opportunity information, wherein in the normal control mode the control subsystem repeatedly:
 - permits depletion of the energy storage subsystem to a first state of charge; and
 - causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge;
 - and in the approaching next charging opportunity control mode the control subsystem:

permits depletion of the energy storage subsystem to a third state of charge, the third state of charge lower than the second state of charge; and

causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem proximate the third state of charge.

2. The hybrid vehicle of claim 1 wherein the next charging opportunity information comprises at least one of:

an anticipated distance until a next opportunity to charge the energy storage subsystem via a power source other than the fuel cell subsystem;

an anticipated time of operation until a next opportunity to charge the energy storage subsystem via a power source other than the fuel cell subsystem; and

an anticipated energy output requirement for the energy storage subsystem until a next opportunity to charge the energy storage subsystem via a power source other than the fuel cell subsystem.

3. The hybrid vehicle of claim 2 wherein the anticipated energy output requirement is based at least in part on at least one of route information, terrain information, speed limit information, traffic information, temperature information, and vehicle load information.

4. The hybrid vehicle of claim 1 wherein the next charging opportunity information is based at least in part on an input to the control subsystem via a human-machine interface.

5. The hybrid vehicle of claim 1 wherein the next charging opportunity information is based at least in part on data collected by the control

subsystem concerning a driving pattern of the hybrid vehicle or a driving pattern of a driver of the hybrid vehicle.

6. The hybrid vehicle of claim 1, further comprising:
a global positioning system (GPS) navigation system coupled to the control subsystem, wherein the next charging opportunity information is based at least in part on signals from the GPS navigation subsystem.

7. The hybrid vehicle of claim 1 wherein the energy storage subsystem comprises at least one of an electrochemical battery cell and an ultra-capacitor cell, the hybrid vehicle further comprising:
a charger interface coupled to the hybrid vehicle and to an external power source to charge the energy storage subsystem.

8. The hybrid vehicle of claim 1 wherein the first state of charge is less than 25% of full charge for the energy storage subsystem and the second state of charge is greater than 70% of full charge for the energy storage subsystem.

9. The hybrid vehicle of claim 1 wherein the first state of charge and the third state of charge are approximately equal to each other.

10. The hybrid vehicle of claim 1 wherein the fuel cell subsystem comprises a plurality of fuel cells electrically coupled in series to form a fuel cell stack.

11. A system to control the operation of a hybrid machine, the hybrid machine comprising an electric machine, an energy storage subsystem electrically coupled to the electric machine, and a fuel cell subsystem electrically coupled to the energy storage subsystem to charge the energy storage subsystem, the system comprising:

a processor operatively coupled to the electric machine, the energy storage subsystem, and the fuel cell subsystem, the processor:

receives next charging opportunity information, the next charging opportunity information at least partially indicative of an anticipated next opportunity to charge the energy storage subsystem via a power source other than the fuel cell subsystem;

monitors a state of charge of the energy storage subsystem; and

causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem according to a normal control mode or an approaching next charging opportunity control mode based at least in part on the received next charging opportunity information, wherein:

in the normal control mode the processor permits depletion of the energy storage subsystem to a first state of charge, and causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge; and

in the approaching next charging opportunity control mode the processor permits depletion of the energy storage subsystem to a third state of charge, the third state of charge lower than the second state of charge, and causes the fuel cell subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem proximate the third state of charge.

12. The system of claim 11 wherein the next charging opportunity information is based at least in part on an input via a human-machine interface.
13. The system of claim 11 wherein the hybrid machine comprises a hybrid vehicle, and the next charging opportunity information is based at least in part on data collected concerning a driving pattern of the hybrid vehicle or a driving pattern of a driver of the hybrid vehicle.
14. The system of claim 11 wherein the processor receives the next charging opportunity information from a global positioning system (GPS) navigation subsystem.
15. The system of claim 11 wherein the energy storage subsystem comprises at least one of an electrochemical battery cell and an ultra-capacitor cell.
16. The system of claim 11 wherein the first state of charge is less than 25% of the fully charged state of charge for the energy storage subsystem and the second state of charge is greater than 70% of the fully charged state of charge for the energy storage subsystem.
17. The system of claim 11 wherein the first state of charge and the third state of charge are approximately equal to each other.
18. The system of claim 11 wherein the fuel cell subsystem comprises a plurality of fuel cells electrically coupled in series to form a fuel cell stack.
19. A method to control a hybrid machine having an electric machine, an energy storage subsystem electrically coupled to the electric

machine, and a secondary electrical power delivery subsystem electrically coupled to the energy storage subsystem to charge the energy storage subsystem, the method comprising:

- receiving charging opportunity information in a processor-readable medium, the next charging opportunity information at least partially indicative of an anticipated next opportunity to charge the energy storage subsystem via a power source other than the secondary electrical power delivery subsystem;

- monitoring a state of charge for the energy storage subsystem;
- autonomously causing the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem according to a normal control mode or an approaching next charging opportunity control mode based at least in part on the received next charging opportunity information,

- wherein the normal control mode comprises:

- permitting depletion of the energy storage subsystem to a first state of charge; and

- causing the secondary electrical power delivery subsystem to operate at full rated power to provide electrical energy to the energy storage subsystem to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge;

- and the approaching next charging opportunity control mode comprises:

- causing the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at or below a third state of charge.

20. The method of claim 19 wherein causing the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at or below a third state of charge comprises repeatedly:

 permitting depletion of the energy storage subsystem to fourth state of charge, the fourth state of charge lower than the third state of charge; and

 causing the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to charge the energy storage subsystem from the fourth state of charge to the third state of charge.

21. The method of claim 19 wherein causing the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at or below a third state of charge comprises causing the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at a charge-sustaining state of charge, the charge-sustaining charge at or below the third state of charge.

22. The method of claim 19 wherein receiving next charging opportunity information comprises receiving an input via a human-machine interface.

23. The method of claim 19 wherein the hybrid machine comprises a hybrid vehicle, and receiving next charging opportunity information comprises receiving data concerning a driving pattern of the hybrid vehicle or a driving pattern of a driver of the hybrid vehicle.

24. The method of claim 19 wherein receiving next charging opportunity information comprises receiving signals from a global positioning system (GPS) navigation system.

25. The method of claim 19 wherein causing the secondary electrical power delivery subsystem to operate at full rated power to provide electrical energy to the energy storage subsystem to charge the energy storage subsystem from the first state of charge to the second state of charge higher than the first state of charge comprises causing the secondary electrical power delivery subsystem to charge the energy storage subsystem from a state of charge less than 25% of the fully charged state of charge for the energy storage subsystem to a state of charge greater than 70% of the fully charged state of charge for the energy storage subsystem.

26. The method of claim 19 wherein permitting depletion of the energy storage subsystem to a first state of charge comprises permitting depletion of the energy storage subsystem to the charge-sustaining state of charge.

27. A method to control a hybrid vehicle during a trip, the hybrid vehicle having an electric machine, an energy storage subsystem electrically coupled to the electric machine, and a secondary electrical power delivery subsystem electrically coupled to the energy storage subsystem to charge the energy storage subsystem, the method comprising:

detecting a state of charge for the energy storage subsystem;

operating the secondary electrical power delivery subsystem at full rated power to charge the energy storage subsystem from a first state of charge to a second state of charge higher than the first state of charge when the state of charge for the energy storage subsystem is detected to be at or below the first state of charge;

receiving an indication at least partially indicative of an anticipated upcoming end of the trip;

permitting depletion of the energy storage subsystem to the first state of charge; and

operating the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at a charge-sustaining state of charge.

28. The method of claim 27 wherein operating the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at a charge-sustaining state of charge comprises operating the secondary electrical power delivery subsystem to provide electrical energy to the energy storage subsystem to maintain the energy storage subsystem at a state of charge that is less than 50% of the state of charge of the energy storage subsystem when fully charged.

29. A method to control a hybrid machine, the hybrid machine having an electric machine, an energy storage subsystem electrically coupled to the electric machine, and a secondary electrical power delivery subsystem electrically coupled to the energy storage subsystem to charge the energy storage subsystem, the method comprising:

for a duration time when the hybrid machine is electrically decoupled from an external power source:

detecting a state of charge for the energy storage subsystem;

repetitively permitting depletion of the energy storage subsystem to a first state of charge; and

repetitively causing the secondary electrical power delivery subsystem to operate at full rated power to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge when the state of charge for the energy storage subsystem is detected to be at or below the first state of charge, the second state of charge less than 50% of the state of charge of the energy storage subsystem when fully charged.

30. The method of claim 29 wherein repetitively causing the secondary electrical power delivery subsystem to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge comprises causing the secondary electrical power delivery subsystem to charge the energy storage subsystem from a state of charge less than 25% of the state of charge of the energy storage subsystem when fully charged to a state of charge less than 30% of the state of charge of the energy storage subsystem when fully charged.

31. A system to control the operation of a hybrid machine, the hybrid machine comprising an electric machine, an energy storage subsystem electrically coupled to the electric machine, and a secondary electrical power delivery subsystem electrically coupled to the energy storage subsystem to charge the energy storage subsystem, the system comprising:

a processor operatively coupled to the electric machine, the energy storage subsystem, and the fuel cell subsystem, wherein for a duration time when the hybrid machine is electrically decoupled from an external power source, the processor:

detects a state of charge for the energy storage subsystem;

repetitively permits depletion of the energy storage subsystem to a first state of charge; and

repetitively causes the secondary electrical power delivery subsystem to operate at full rated power to charge the energy storage subsystem from the first state of charge to a second state of charge higher than the first state of charge when the state of charge for the energy storage subsystem is detected to be at or below the first state of charge, the second state of charge less than 50% of the state of charge of the energy storage subsystem when fully charged.

32. The system of claim 31 wherein the first state of charge is less than 25% of the state of charge of the energy storage subsystem when fully charged, and the second state of charge is less than 30% of the state of charge of the energy storage subsystem when fully charged.

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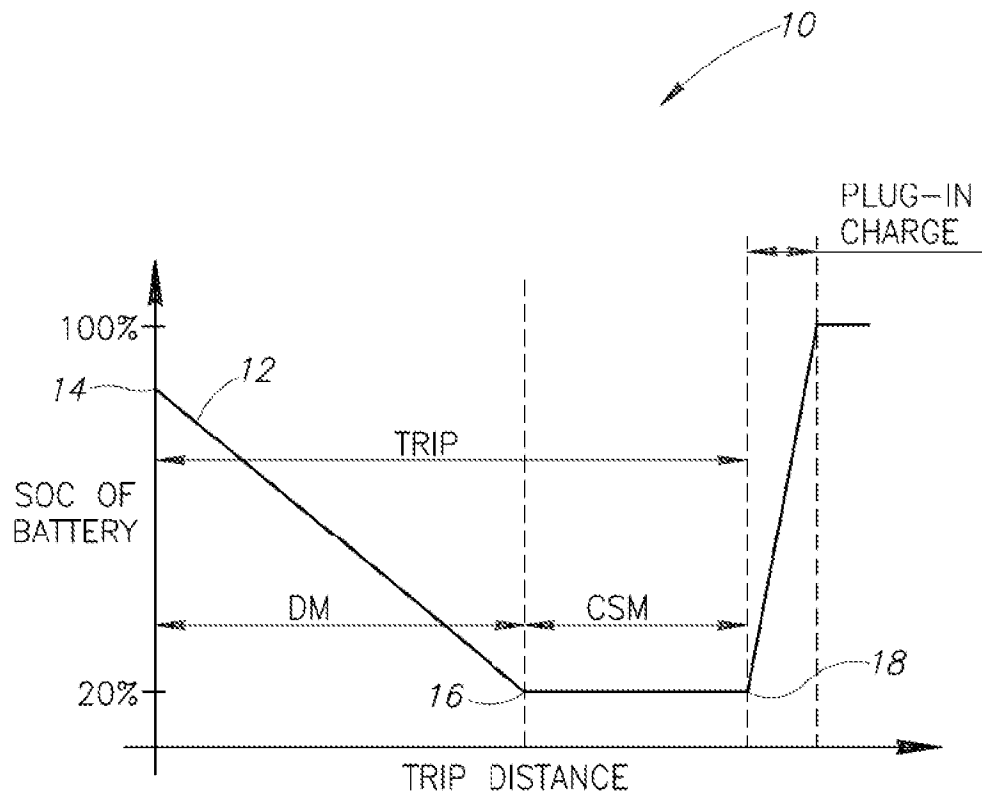


FIG.1
(PRIOR ART)

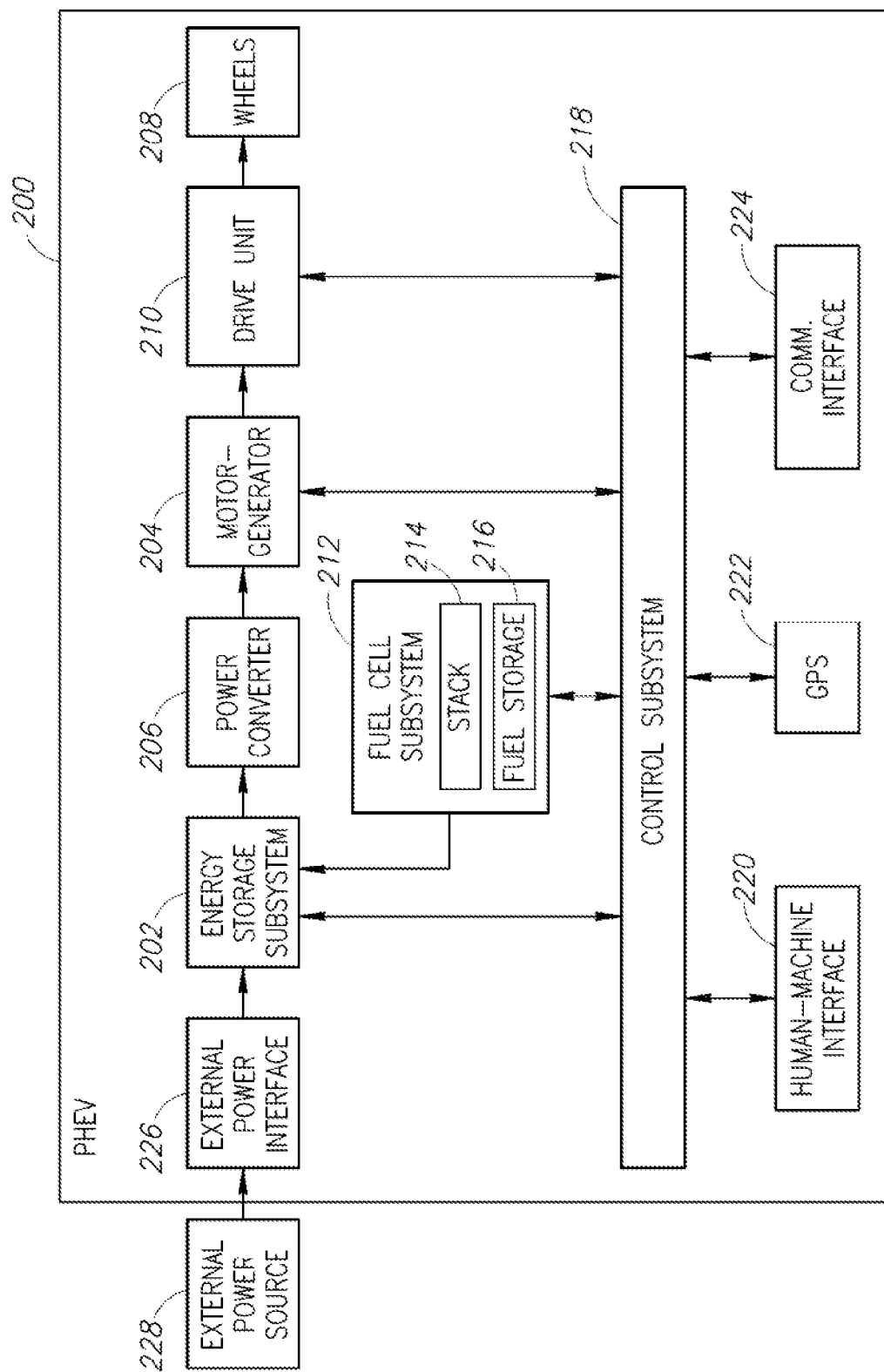


FIG.2

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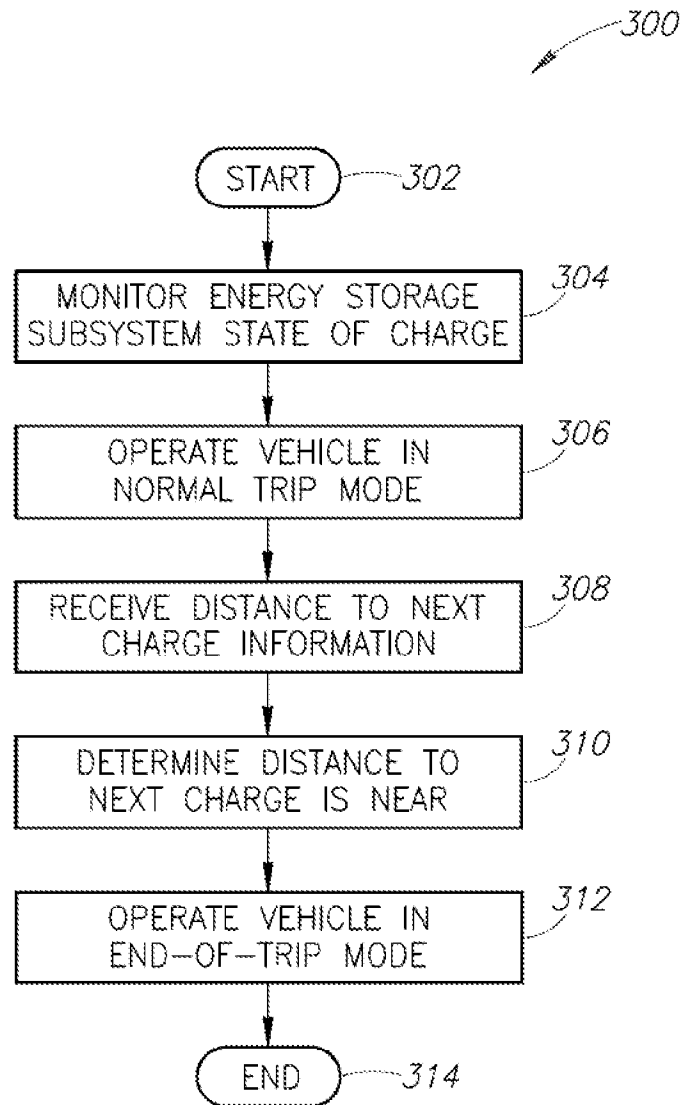


FIG.3

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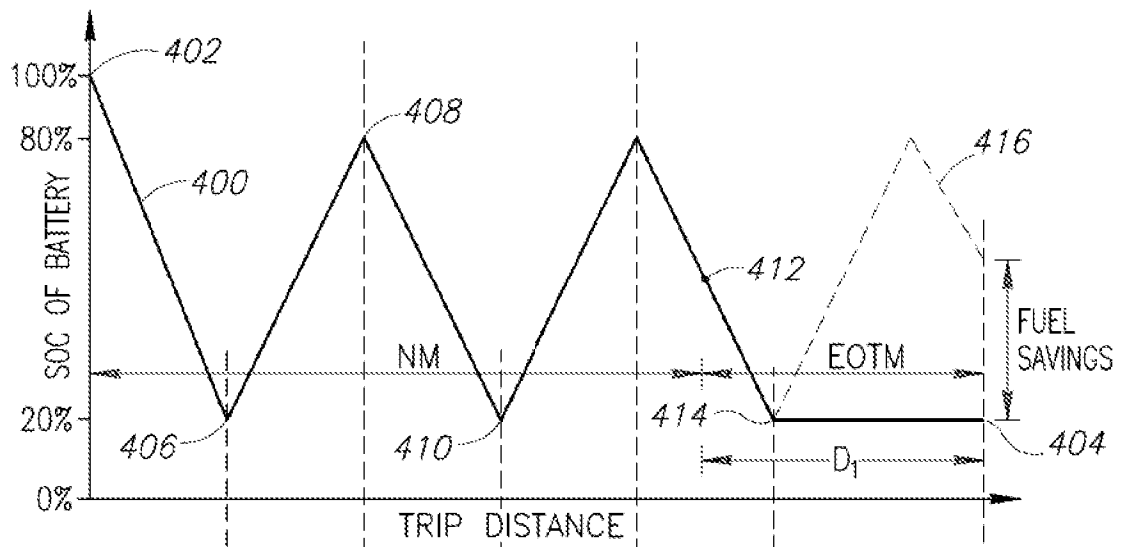


FIG. 4

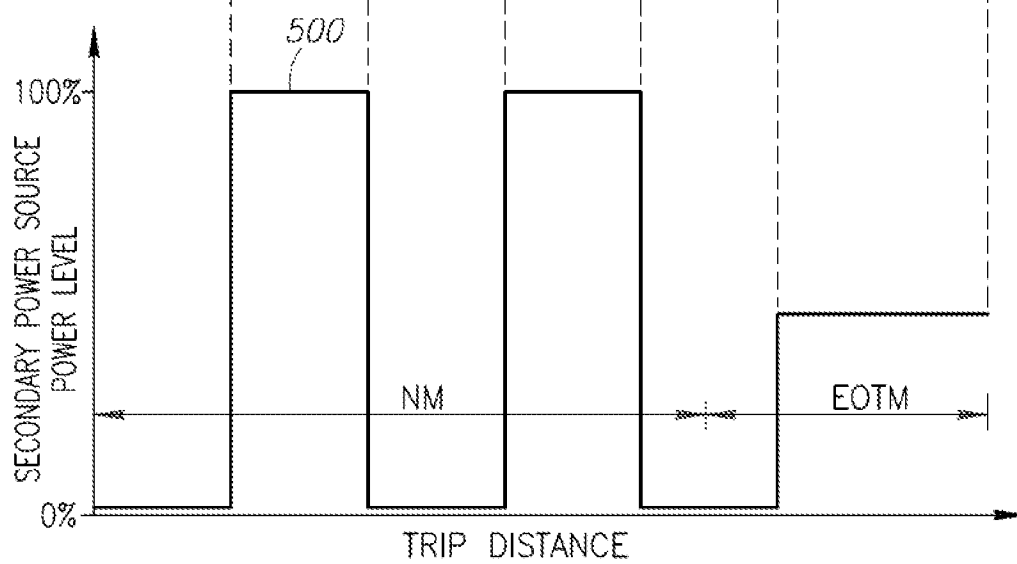


FIG. 5

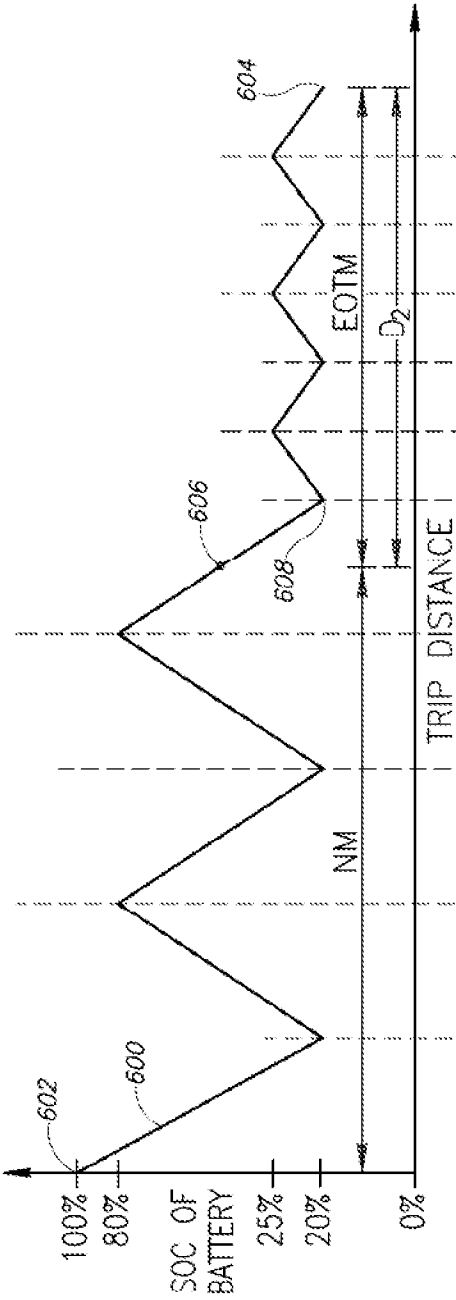


FIG. 6

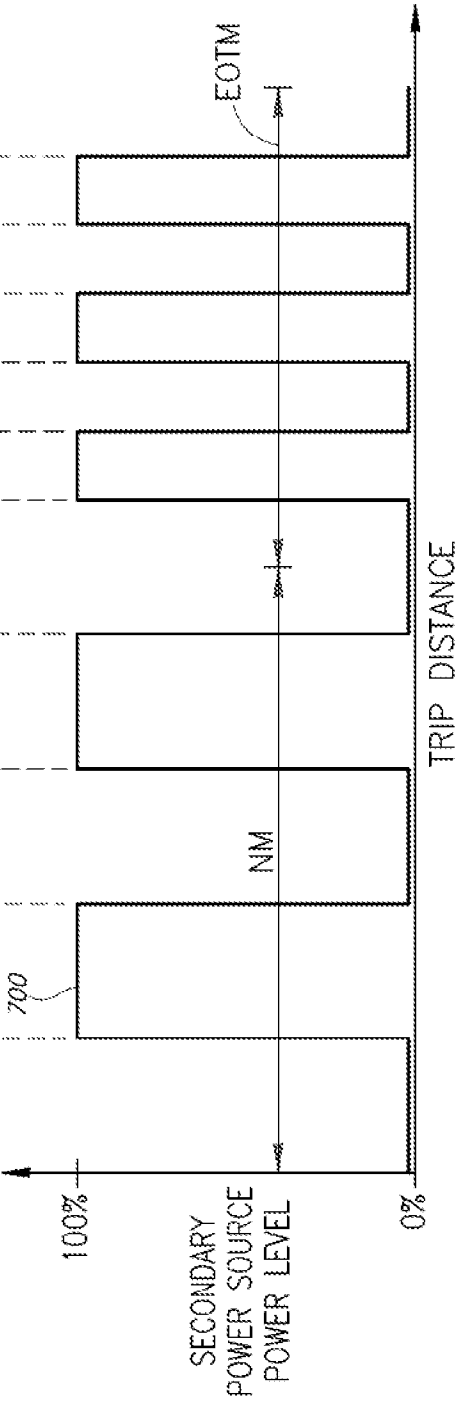


FIG. 7

FIG. 8

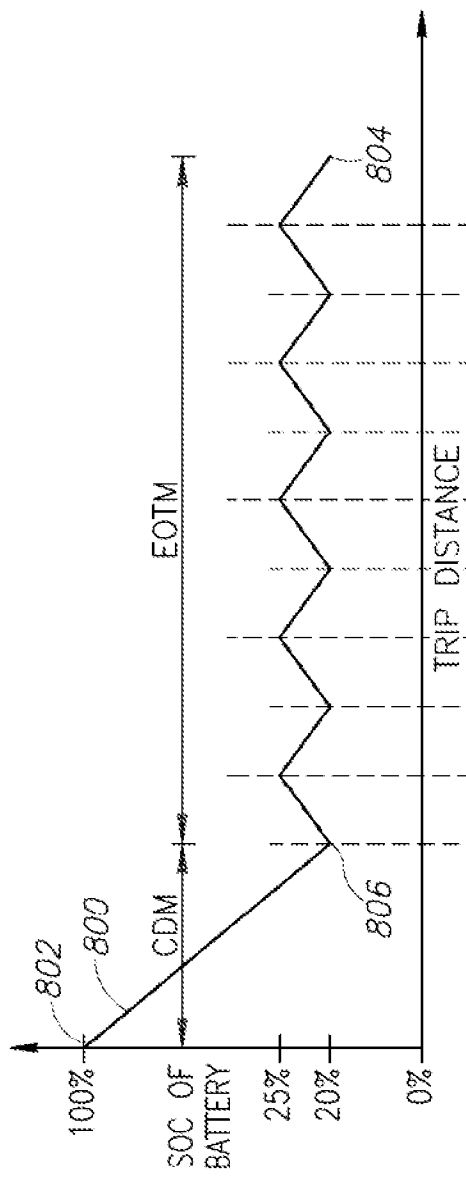
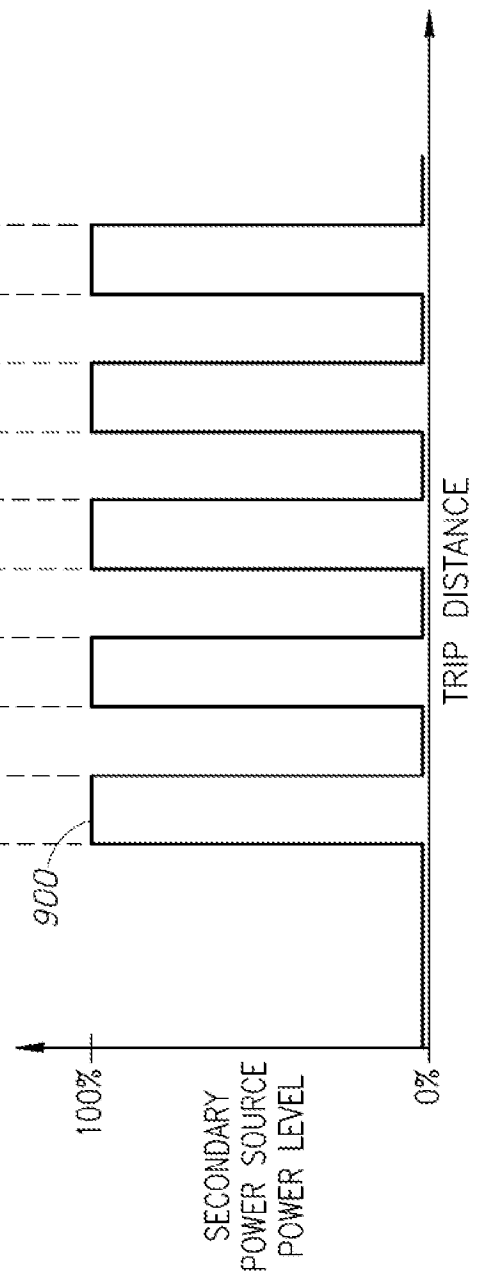


FIG. 9



INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/052232

A. CLASSIFICATION OF SUBJECT MATTER
INV. B60L11/12 B60L11/18 H02J7/34
ADD.

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)
B60L H02J

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)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2013/044357 A1 (MAGNA E CAR SYSTEMS OF AMERICA INC [US]; PARROTT JIM [CA]; STORC ROBER) 4 April 2013 (2013-04-04) the whole document -----	1,11,19, 27,29,31
X	US 2013/066505 A1 (KELTY KURT RUSSELL [US] ET AL) 14 March 2013 (2013-03-14) the whole document -----	1-32
X	US 2010/280687 A1 (TATE JR EDWARD D [US] ET AL) 4 November 2010 (2010-11-04) the whole document -----	1-32
X	US 2012/035795 A1 (YU HAI [US] ET AL) 9 February 2012 (2012-02-09) the whole document -----	1-32



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

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"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

11 December 2015

Date of mailing of the international search report

21/12/2015

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Davis, Alan

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2015/052232

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2013044357	A1	04-04-2013	NONE

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			US 2013066504 A1 14-03-2013
			US 2013066505 A1 14-03-2013
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			WO 2009042857 A2 02-04-2009

US 2010280687	A1	04-11-2010	CN 101920702 A 22-12-2010
			DE 102010018447 A1 18-11-2010
			US 2010280687 A1 04-11-2010

US 2012035795	A1	09-02-2012	NONE
