



(43) International Publication Date  
22 September 2016 (22.09.2016)

WIPO | PCT

(10) International Publication Number  
**WO 2016/146971 A1**

(51) International Patent Classification:  
*H01M 8/04537* (2016.01) *H01M 10/48* (2006.01)  
*H01M 8/04664* (2016.01)

(21) International Application Number:  
PCT/GB2016/050652

(22) International Filing Date:  
10 March 2016 (10.03.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
1504415.9 16 March 2015 (16.03.2015) GB

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(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).

Published:

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

(54) Title: CONDITION MONITORING OF A FUEL CELL STACK

(57) Abstract: The disclosure provides a method of monitoring the condition of at least one cell of a fuel cell stack and/or at least one cell of an electrical energy storage device. The fuel cell stack is connected to the input terminals of a power converter and the output terminals of the power converter are connected to the storage device to charge the storage device. The storage device and the fuel cell stack are arranged to supply electrical power to an electrical load. The method comprises operating the power converter to generate an oscillating output from the fuel cell stack, and connecting this oscillating output to the storage device; sensing the voltage across the at least one cell of the fuel cell stack and the current therein, and/or sensing the voltage across the at least one cell of the storage device and the current therein; for the at least one cell of the fuel cell stack and/or the at least one cell of the storage device, calculating from the sensed voltage and current the complex impedance of the cell; and comparing the calculated complex impedance with information indicative of a relationship between (i) the complex impedance and (ii) information indicative of the condition of the at least one cell, to give an indication of the condition of the at least one cell.



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## CONDITION MONITORING OF A FUEL CELL STACK

### FIELD

- 5 This disclosure relates to a method of monitoring the condition of at least one cell of a fuel cell stack and/or at least one cell of a battery. In one embodiment, such a method is used in a fuel cell hybrid electric vehicle.

### BACKGROUND

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- In order to address concern over climate change, governments have set ambitious targets for reducing the emission of gasses referred to as “greenhouse gasses”. For example, the UK Government has set a target of an 80% reduction of all greenhouse emissions in the UK by 2050. The automotive sector is a major contributor to current greenhouse gas
- 15 emissions, with current fleet average emissions standing at approximately 120 gCO<sub>2</sub>/km. In order to meet the total UK emissions targets, fleet averages would need to decrease to approximately 20 gCO<sub>2</sub>/km by 2050. With lightweight and turbocharging technology, this can theoretically be pushed to approximately 80 gCO<sub>2</sub>/km. This is still some way from the 2050 targets. It will be understood that similar initiatives are being pursued by
- 20 governments in other countries and so this is not a problem that arises only in the UK.

- Electric vehicles present an attractive solution to this problem for the reason that battery electric vehicles and hydrogen fuel cell vehicles (FCV) offer zero local emissions during operation. However, current battery electric vehicles – that is electric vehicles in which all
- 25 electrical power is provided by an on-board battery – suffer from limited range due to the limited energy densities (100 km ranges are often quoted) and long charging times of currently available batteries. While research is on-going to address these drawbacks, step changes are not expected in the near future.

- 30 FCVs, using hydrogen, currently offer the other main alternative to battery electric vehicles. In a FCV, fuel cells are used to generate electricity from an on-board store of hydrogen. FCVs have significantly higher energy density and faster refuelling times than battery electric vehicles. Current limitations to the adoption of FCVs include durability and cost due to the catalysts and membranes needed for construction of the fuel cells. The
- 35 operating efficiency of fuel cells is also highly sensitive to factors such as temperature, reactant flows and membrane hydration, with fuel cells operating best under moist, warm conditions with sufficient reactant flows. In large automotive systems, such as passenger

cars, however, in which several individual fuel cells in the form of a fuel cell stack would be used, operating conditions for individual cells of the stack can vary significantly from each other. If the condition of individual cells is not monitored and controlled, inefficiencies and even catastrophic failure of the whole system may result.

5

The need for condition monitoring of individual fuel cells is therefore of critical importance. Existing diagnostic methods are usually limited to simple cell voltage and current monitoring and offer limited information regarding the true state of individual cells. More advanced methods based on electrochemical impedance measurements (EIS) provide  
10 comprehensive information, but these are impractical to implement on a vehicle due to the excessive cost and bulkiness of the measuring equipment needed for EIS measurement.

Accordingly, there is a need for an improved solution to the condition monitoring of fuel cells.

15

## SUMMARY

According to a first aspect of this invention, there is provided a method of monitoring the condition of at least one cell of a fuel cell stack and/or at least one cell of an electrical  
20 energy storage device, the fuel cell stack connected to the input terminals of a power converter and the output terminals of the power converter connected to the storage device to charge the storage device; the storage device and the fuel cell stack arranged to supply electrical power to an electrical load; the method comprising the steps of:

- operating the power converter to generate an oscillating output from the fuel cell  
25 stack, and connecting this oscillating output to the storage device;
- sensing the voltage across the at least one cell of the fuel cell stack and the current therein, and/or sensing the voltage across the at least one cell of the storage device and the current therein;
- for the at least one cell of the fuel cell stack and/or the at least one cell of the  
30 storage device, calculating from the sensed voltage and current the complex impedance of the cell; and
- comparing the calculated complex impedance with information indicative of a relationship between (i) the complex impedance and (ii) information indicative of the condition of the at least one cell, to give an indication of the condition of the at  
35 least one cell.

The calculating step may comprise calculating from the sensed voltage and current the complex impedance of the at least one cell at each of a plurality of different frequencies of the oscillating output. The step of operating the power converter may comprise operating the power converter to generate an oscillating output at each of the plurality of different  
5 frequencies.

The electrical energy storage device may be in the form of a battery. The electrical energy storage device may comprise a Faradaic, pseudo-Faradaic and/or non-Faradaic electrochemical storage device. For example the electrical energy storage device may be  
10 or comprise one more or all of a battery or batteries, capacitors, supercapacitors and other similar devices.

In other aspects, and in general terms, there is provided a method of causing a ripple current in one of an energy source and storage device, which causes the opposite effect  
15 in the other of the energy source and storage device. The two devices are connected together in one of the ways stated herein, with the ripple current being caused accordingly.

[Technical Effects:]

20 Thus, in more everyday terms, there is provided a method of using electrochemical impedance spectroscopy (EIS) to monitor the condition of a cell of a fuel cell stack and/or a battery in situ – for example, when connected to the power electronics and a useful load of the application which it is to power – by making use of the existing power electronics. This avoids the need for dedicated equipment to carry out the EIS and have avoids the  
25 added cost, size, weight and complexity of such dedicated equipment. Reducing cost, size, weight and complexity are important factors in the design and commercial success of both vehicles and smaller electrical devices.

EIS is a procedure sometimes used in a laboratory to obtain measurements of an  
30 individual cell in a way that enables the decoupling of different resistances in an electrochemical device. It relies on using a large and expensive digital signal generator to draw or supply a small sinusoidal AC current from the cell or draw/ apply small AC voltage across the cell terminals at different frequencies. By ascertaining the frequency response of the complex impedance of the cell using a frequency response analyser, vital  
35 information relating to the state of health and state of charge of the cell can be ascertained. In EIS, knowledge of the history of the cell is not always required (in contrast

with Coulomb counting) and so errors do not accumulate over time to reduce the accuracy of deductions as to the condition of the cell.

- In embodiments of the invention, EIS is taken out of the laboratory and made to work in situ – that is, in applications in which cells are used to provide useful power to supply a load and absorb power from a source. Examples of this might be cells used in an electric or hybrid electric vehicle, or even cells used in a smaller device such as a hand-held mobile telephone or a portable computer. By unconventionally controlling the power converter such that its input impedance is varied, a varying current can be drawn from the cell and then sensed together with the voltage across the cell to allow the complex impedance of the cell to be calculated. The complex impedance at a known or sensed frequency or frequencies can then be used to ascertain the individual state of health and state of charge of the cell.
- WO2012/025706 discloses using a similar approach to monitor the condition of a battery. However, the method of the first aspect disclosed herein differs from that disclosed in WO2012/025706 in that, in this method, a fuel cell stack is included in the arrangement (this was absent from WO2012/025706) and a motor controller is not used to perturb the battery as was the case in WO2012/025706. Instead, the present approach uses the power converter used to control the fuel cell stack output to perturb the fuel cell stack, and it uses the subsequent charging of the battery to perturb the battery.

[Other Features:]

- The method may include disconnecting the fuel cell stack and/or the electrical energy storage device from the electrical load or an electrical supply (in the event of either or both being connected to an electrical load or supply). The method may include connecting the fuel cell stack and the electrical energy storage device to the electrical load or supply. The electrical load may comprise one or more traction motors. The or each traction motor may also function as an electrical supply during, for example, regenerative braking.

- According to a second aspect of this invention, there is provided a method of monitoring the condition of at least one cell of a fuel cell stack and/or at least one cell of an electrical energy storage device, the fuel cell stack connected to input terminals of a first power converter; the electrical energy storage device connected to a second power converter,

and the two power converters connected to supply electrical power to an electrical load;  
the method comprising the steps of:

- operating the first power converter to generate an oscillating output from the fuel cell stack;
- 5     • operating the second power converter to supply an oscillating output from the electrical energy storage device, the oscillating output from the electrical energy storage device combining with the oscillating output from the fuel cell stack to provide a substantially steady electrical supply to the electrical load;
- 10    • sensing the voltage across the at least one cell of the fuel cell stack and the current therein, and/or sensing the voltage across the at least one cell of the electrical energy storage device and the current therein;
- for the at least one cell of the fuel cell stack and/or the at least one cell of the electrical energy storage device, calculating from the sensed voltage and current the complex impedance of the cell; and
- 15    • comparing the calculated complex impedance with information indicative of a correlation between (i) the complex impedance and (ii) information indicative of the condition of the at least one cell, to give an indication of the condition of the at least one cell.

20    As om the first aspect, the electrical energy storage device may be in the form of a battery. The electrical energy storage device may comprise a Faradaic, pseudo-Faradaic and/or non-Faradaic electrochemical storage device. For example the electrical energy storage device may be or comprise one more or all of a battery or batteries, capacitors, supercapacitors and other similar devices.

25

The calculating step may comprise calculating from the sensed voltage and current the complex impedance of the at least one cell at each of a plurality of different frequencies of the oscillating output. The step of operating the power converter may comprise operating the power converter to generate an oscillating output at each of the plurality of different

30    frequencies.

The method may comprise the fuel cell stack and the electrical energy storage device connected to supply electrical power to the electrical load, and optionally a second power converter connected to the electrical energy storage device.

35

The battery may be substituted by any other electrochemical energy storage device, such as, for example, non-faradaic electrochemical capacitors and pseudo and faradaic electrochemical capacitors.

- 5 The power converter and/or the second power converter may be a DC to DC converter. The electrical load may comprise the motor and the motor controller of a vehicle, for example a fuel cell hybrid electric vehicle.

- The or each oscillating output may comprise a periodically varying current (or voltage) and/or a ripple current (or voltage) and/or a sinusoidal oscillating current (or voltage). The  
10 or each varying current (or voltage) may comprise a current with any waveform whatsoever, periodic or not.

- The method may comprise the or each oscillating output comprising a varying current that  
15 takes the form of a pseudo-random binary sequence, such as a maximal length sequence.

The voltage and current sensed and used to calculate the complex impedance may be noise and/or other spectral content present as a result of normal operation.

- 20 [Fitting to a Model]

- In the comparing step, the information indicative of the correlation may be stored information. The method may comprise comparing the calculated complex impedance and the frequency of the oscillating supply against information indicative of a correlation  
25 between (i) those quantities and (ii) the information indicative of the condition of the at least one cell.

- For a battery cell (and optionally for cells of other electrochemical storage devices), the information indicative of the condition of the at least one cell may comprise information  
30 indicative of, for example, the state of life of the cell (overall complex impedance being indicative of state of life) , the state of charge of the cell and/or degradation rate of the cell. The information indicative of the state of charge of the cell may be information indicative of the charge transfer processes occurring at electrode-electrolyte interfaces. The information indicative of the degradation rate may be information indicative of the  
35 resistance of the solid electrolyte interface (SEI) of the cell. The information indicative of degradation may comprise information indicative of the high frequency intercept on the

complex impedance spectrum (Nyquist plot). This is especially useful with li-polymer cells – their “bulk” resistance (indicated by HF intercept) can change drastically over cycles.

- The information indicative of a correlation between the complex impedance and the
- 5 condition of the at least one cell may be information indicative of a correlation between a component of an equivalent circuit, the equivalent circuit being obtained by the application of a mathematical algorithm to empirical data relating to the cell. The empirical data may comprise EIS data at different states of charge.
- 10 For fuel cells, the EIS is indicative of slightly different things. There is no concept of state of charge in fuel cells but it can tell you about the state of health. The high frequency intercept is related to the membrane hydration. The wetter the fuel cell the better its performance and thus lower the high frequency intercept. Normally there are two charge transfer curves (one for hydrogen and one for oxygen). A change in one of these in the
- 15 EIS will suggest a problem with the anode or cathode respectively. The low frequency component will give information about mass transport. If one of the channels is blocked with water this would affect. Thus FC EIS can give information about membrane hydration which has very slow time constants such that hydration levels can be controlled by external balance of plant components. The information indicative of the condition of the at
- 20 least one cell may be formulated accordingly.

- As temperature can affect impedance response, it is also envisaged that temperature of the at least one cell may be sensed and used to correct for the effect of temperature. Accordingly, the information which may be stored information may also take account of
- 25 cell temperature. For example, that information may be at least partly a function of temperature, or there may be separate sets of information, each for a respective temperature.

[Other Aspects]

- 30 According to a third aspect of this invention, there is provided processing and control means for a power converter, the processing and control means programmed and operable to control the power converter in accordance with the method defined above.
- 35 The processing and control means may be further arranged to receive information from sensing means indicative of the quantities sensed in the sensing steps defined hereinabove.

The processing and control means may be further arranged to carry out the comparing step.

- 5 According to a fourth aspect of this invention, there is provided a control system comprising the processing and control means and further comprising the sensing means.

According to a fifth aspect of this invention, there is provided a computer program having code portions executable by the processing and control means to cause the processing  
10 and control means to operate as define hereinabove.

According to a sixth aspect of this invention, there is provided a record carrier comprising thereon or therein a record of the code portions. The record carrier may comprise an optical storage medium, such as, for example, a computer-readable disk such as, for  
15 example, a CD-ROM or DVD-ROM. The record carrier may comprise a solid-state storage medium such as, for example, volatile memory and/or non-volatile memory; it may comprise, for example, an EPROM, and EEPROM and/or flash memory. The record carrier may be a signal; it may be a wireless signal.

- 20 According to a seventh aspect of this invention, there is provided a vehicle comprising a control system as defined hereinabove.

Features of other embodiments are defined in the appended claims.

- 25 [Application to segmented passive hybrid arrangement]

According to a further aspect of this invention, methods disclosed herein may be used to monitor the condition of a system comprising apparatus for supplying electrical energy to a varying load, the apparatus comprising fuel cells and energy storage devices, wherein a fuel  
30 cell subset comprising one or a plurality of series-connected ones of the fuel cells, having a first no-load open-circuit potential thereacross, is connected in parallel with an energy storage device subset comprising one or a plurality of series-connected ones of the energy storage devices, having a second no-load open-circuit potential thereacross, to form a unit cell and the unit cell is connected in series or parallel with at least one other unit cell, and the fuel cells in  
35 the unit cell and the at least one other unit cell are fuel cells of the same fuel cell stack, wherein the first no-load open-circuit potential and the second no-load open circuit potential are substantially balanced. A switching device is provided to control current flow between the

subset of fuel cells and the energy storage device subset in the or each unit cell. The switching frequency of the or each switching devices may be controlled in accordance with any method disclosed herein to give an excitation signal suitable for EIS analysis.

## 5 BRIEF DESCRIPTION OF THE DRAWINGS

Specific embodiments of the invention are described below by way of example only and with reference to the drawings, in which:

10 Figure 1 is a schematic diagram of the power train of a fuel cell hybrid electric vehicle;

Figure 2 is a flow chart of a method of operating the power train;

Figure 3 is a schematic diagram of an alternative power train of a fuel cell hybrid electric  
15 vehicle;

Figure 4 is a schematic diagram of a further alternative power train of a fuel cell hybrid electric vehicle;

20 Figure 5 shows in schematic form detail of a segmented fuel cell and battery arrangement of a passive hybrid system; and

Figure 6 shows switches used to control the Figure 5 arrangement.

## 25 DETAILED DESCRIPTION

Figure 1 shows in schematic form a first embodiment in which components of the power train 10 of a fuel cell hybrid electric vehicle (not shown). With continued reference to Figure 1, the drive train 10 has a fuel cell stack 20 made up of several fuel cells (not  
30 shown) connected together in series. In this embodiment, the fuel cell is hydrogen fuel cell. Other fuel cells may be used in other embodiments. The power train 10 also has a battery 30 made up of several battery cells (not shown) connected together in series. In this embodiment, the battery is a lithium-ion battery pack. Other battery packs, or indeed other forms of storing electrical energy, for example electrical energy storage devices  
35 comprising a plurality of electrical energy storage cells connected together to make up the device, may be used in other embodiments. The terminals of the fuel cell stack 20 are connected to to the input of a first DC to DC converter 25, and the battery pack is

connected to a second DC to DC converter 35. The two DC converters 25, 35 are connected to each other, such that the fuel cell stack 20 and the battery pack 30 are also connected in parallel. The terminals of the parallel-connected DC to DC converters 25, 35 are connected to a motor controller 40. The motor controller 40 is connected to supply  
5 electrical power to an electric motor 50 that is mechanically coupled to drive wheels of the vehicle. (It will be understood that in other embodiments in which the motor is an AC motor, an additional DC to AC converter is provided.)

As will become clear from the following description, the power train 10 is arranged and  
10 operable to provide an improved arrangement for monitoring the condition of the fuel cell stack 20 and the battery pack 30.

Although not shown, the first and second DC to DC converters 25, 35 and the motor controller are connected and arranged to be controlled by control signals from an  
15 electronic control unit (ECU) of the vehicle. The ECU is also considered to form part of the drive train 10 in this embodiment.

Although not shown, it is envisaged that the power train 10 further includes sensing means in the form of a digital signal processor, that includes a respective analogue-to-  
20 digital converter for each input channel, connected via differential instrumentation amplifiers to sense the voltage across and current through each cell of the fuel cell stack 20 and each cell of the battery pack 30. The skilled addressee will understand how such an arrangement would be implemented in practice in order to sense the voltage across and current through each cell of the fuel cell stack 20 and the battery pack 30.

25

At least certain of the components described above are to be found in the power trains of existing fuel cell hybrid electric vehicles. At least the fuel cell stack 20, the battery pack 30, the two DC to DC converters 25, 35, the motor controller 40 and the motor 50 are  
30 conventional.

The operation of these components, and in particular the instructions stored in the ECU that determine the operation of these components are, however, not conventional. This operation will now be described.

35

[Operation: MC connected]

Operation of the power train 10 is generally the same as that for existing fuel cell hybrid electric vehicles except in relation to the way in which the power train 10 monitors the condition of the fuel cell stack 20 and the battery pack 30. The ECU includes a record of instructions stored in memory of the ECU and executable by the ECU to carry out a  
5 monitoring routine 100. This routine amounts to an example of a method that embodies the invention. The monitoring routine 100 will now be described with reference to Figure 2.

The monitoring routine 100 starts at step 110 and then proceeds to step 120 in which the  
10 ECU controls the first DC to DC converter 25 to provide from the fuel cell stack 20 a variable output. The variable output, in this example, is in the form of a substantially constant baseline DC current with an AC current superimposed on it, to give a sinusoidal variation in current about the positive baseline value.

15 In step 120, the ECU also simultaneously controls the second DC to DC converter 35 to provide from the battery pack 35 a variable output. This variable output is also, in this example, in the form of a substantially constant baseline DC current with an AC current superimposed on it to give a sinusoidal variation in current about the positive baseline value.

20

The variable output from the first DC to DC converter 25 and the variable output from the second DC to DC converter are chosen so that, when summed, they provide a substantially constant DC supply to the motor controller 40. In other words the AC component of the output from the first DC to DC converter and the AC component from the second DC to  
25 DC converter cancel each other out. The supply to the motor controller 40 is therefore the sum of the two baseline DC currents. The ECU therefore operates to control the two DC to DC converters 25, 35 such that the DC components of the two variable supplies combine in this way to produce the desired supply to the motor controller 40 for operation of the vehicle. It will be appreciated that this desired supply will vary during operation, as  
30 will the proportion of the supply represented by each of the two DC components. The ECU operates to control the two DC to DC converters 25, 35 such that the AC components are selected such that they perturb the fuel cell stack 20 and the battery pack 30 in order that EIS can be carried out in the manner described below.

35 It will be understood that the AC components used in this example could be any varying component that allows EIS to be carried out and that results, once summed, in substantially no undesirable input to the motor controller 40, for example, the two

components may substantially cancel out as in the example above or their variations may substantially cancel out to give a DC current.

While the two DC to DC converters 25, 35 are being controlled in the way described in  
5 step 120, the routine also carries out step 130 in which the voltage across and current through each cell of the fuel cell stack 20 and each cell of the battery pack 30 is sensed. This sensing is done using the digital signal processor. Information indicative of the voltage across and current through each cell is then communicated to the ECU.

10 The routine then progresses to step 140 in which ECU calculates the complex impedance of each cell from the sensed voltage across and sensed current through each cell.

The routine then proceeds to step 150 in which the routine returns and repeats steps 120 to 140, but with the two DC to DC converters 25, 35 being controlled to provide AC  
15 components at a frequency different from that which at they were previously provided, but again such that when summed the variations cancel. This loop is repeated, each time with a different frequency, between a predetermined range of frequencies and at a predetermined number of different frequencies within that range. In the present embodiment it is envisaged that this range should be between approximately 10mHz and  
20 100kHz and it is envisaged that the number of different frequencies would be approximately 20. In other embodiments, these steps may be repeated for more or fewer different frequencies. Once steps 120 to 140 have been repeated for each of the predetermined frequencies, the routine proceeds to step 160. In other embodiments, plural frequencies may be combined into one or more multi-sequences. For example, if a  
25 sine wave is used as an excitation signal, multiple sine waves may be combined into a multi-sine signal.

At step 160, the ECU compares the calculated complex impedance of each cell, together with the frequency of the used to generate that calculation, with a record accessible by the  
30 ECU of a predetermined correlation between those two quantities and, for the battery pack 30, the state of charge and battery degradation rate, and, for the fuel cell stack 20, the level of hydration. For fuel cells, the complex impedance can be used to ascertain whether some of the flow channels are flooded or becoming flooded with water. Should this be ascertained, a control signal can be sent to avoid the fuel cell from becoming  
35 excessively flooded. Fuel cell electrode degradation can also be detected by EIS.

For example, it has been found that the frequency response of the complex impedance of a commercial lithium-ion battery, such as A123 ANR26650, between 100Hz and 1000Hz corresponds to the impedance of the solid electrolyte interface (SEI) of the battery pack and so provides information about the rate of degradation of the battery pack 30. It has  
5 also been found that the frequency response between 1Hz and 100Hz corresponds to the charge transfer processes occurring at the electrode-electrolyte interfaces and so provides an indication as to the state of charge of the battery. Accordingly, comparing the measured frequency response with stored frequency responses allows deductions to be made as to the state of charge of each cell and the rate of degradation of each cell of  
10 the battery pack 30. It is envisaged that the stored frequency responses be in the form of several look-up tables that also take account of other factors, such as by having look-up tables for each of various different operating temperatures and/or stages in the life cycle of the fuel cell stack 20 and the battery pack 30 and/or different discharge current rates. Alternatively, the measured frequency response may be compared with a calculated  
15 frequency response, calculated using an algorithm that takes accounts of these various factors.

The routine then proceeds to step 170 in which these deductions are made available by the ECU to other routines being executed thereby, and also to other components for use  
20 in managing the fuel cell stack 20 and the battery pack 30 effectively.

The monitoring routine 100 then ends at step 180.

In this embodiment, it is envisaged that the monitoring routine 100 be performed  
25 periodically during normal operation of the vehicle 10 in order to provide information as to the condition of the fuel cell stack 20 and the battery pack 30 during operation of the vehicle 10 and so allow for effective management of each. This is made possible by the mutual-cancellation of the variances in the output from each DC to DC converter 25, 35. Without this, there would be undesirable variation in the supply to the motor controller 40  
30 which would affect the performance of the vehicle in an undesirable manner. For example, it is conceivable that applying a ripple current to the motor controller 40 may result in torque ripple at the motor 50 and resulting vibration and acoustic noise in the passenger cabin of the vehicle. The present arrangement, however, can be used during normal operation of the vehicle without giving rise to this disadvantage.

35

[Operation: MC disconnected]

Alternatively or in addition to the routine 100 described above, the two DC to DC converters may be disconnected from the motor controller 40, for example when the vehicle is at rest, and substantially the same approach may be followed. The two variable outputs may be selected such that there is no baseline DC component and such that the AC components cancel out. Alternatively, the two variable outputs may be selected such that there is a positive baseline component to the variable output from the DC to DC converter 25 connected to the fuel cell stack 25 and this is used to charge the battery pack 30, and with the two AC components cancelling out. Other approaches are also envisaged.

10

[Multiple frequencies at once]

In the routine 100 described above the variable output from each DC to DC converter 25, 35 contains only one frequency at a time, but that frequency is subsequently and repeatedly varied across a spectrum to give the frequency response. This approach may therefore be termed a “frequency sweep” approach. An alternative approach that may be used along with the frequency sweep (although not at the same time) or instead of it is to provide a variable output from each DC to DC converter that contains several frequencies. As in the routine 100 described above, the variable components of each variable output would substantially cancel each other out, leaving the sum of the substantially constant components as the supply to the motor controller.

One approach to providing a variable output from each DC to DC converter 25, 35 that contains several frequencies is to superimpose a square pulse current onto each baseline component. The ECU then, as before, calculates the step-response complex impedance of each cell. Again, this can be compared with values stored in the memory to make deductions about the condition of the fuel cell 20 and the battery 30 pack. These deductions can then be made available as before. As this approach relies on a non-sinusoidal pulse, this can be termed a “pulse method”. This pulse method is based on the premise that a narrow pulse contains, in principle, infinite different frequencies and so it is theoretically possible to obtain all the information needed from one pulse response, if an assumption that the system responds linearly is justified. In practice, however, it may not be possible to obtain all the information that is needed in this way and so, in at least some embodiments both the frequency sweep method and the pulse method may be used.

35

A square pulse is used in the arrangement described above. In other embodiments, however, the pulse need not be square. Instead, the pulse could, conceivably, be any

non-periodic waveform. It may, for example, be a step, impulse, ramp and so on. A square pulse may, however, be preferred as it contains the “most” frequencies. The amount of frequency information that can be extracted from other forms of pulse will vary with the particular form of the pulse.

5

Figure 3 shows another embodiment that is generally the same as the Figure 1 embodiment, but with the omission of the DC to DC converter that was connected to the battery pack 30. For simplicity, the same reference numbers are used to refer to  
10 components common to the two embodiments. With the omission of the second DC to DC converter from this Figure 3 embodiment, it will be appreciated that the battery pack 30 must be sized to fit the motor controller 40. The operation of this embodiment is as previously described, but without any operation of the now-omitted DC to DC converter. Specifically, this embodiment can be operated accordingly to routine 100, in the manner  
15 previously described in which the motor controller 40 is disconnected and also according to the “pulse method”.

The principle of motor excitation disclosed above can also be applied to a passive hybrid system such as that shown in Figure 4 and Figure 5. An example of such a system is that  
20 described in WO 2014/195736. The drawback here would be that the load instabilities are reintroduced.

The application of this approach to the system of Figure 4 and Figure 5 builds upon the segmented fuel cell battery passive hybrid system disclosed in WO 2014/195736. The  
25 contents of that application, in so far as they relate to the system shown in Figures 4 and 5, and to the application of the approach disclosed in the present disclosure to that system, are hereby incorporated into the present disclosure. From consulting the earlier publication, in particular the description of the arrangement shown in and described with reference to Figure 11 of that earlier publication, the skilled person will understand that, in  
30 the Figure 4 and Figure 5 system of the present disclosure, a battery (or any secondary energy storage device) is connected across a certain number of individual FCs that match the Open Circuit Potential (OCP) of the battery (or other device) with a switching device between the two. This arrangement was originally developed with the aim of passively balancing batteries in large packs without the need for a Battery Management System  
35 (BMS). However if the switching frequency of the switching devices is controlled in accordance with the present approach, an excitation signal suitable for EIS analysis is also possible.

Effects of the arrangements disclosed herein include the following. In the active hybrid configuration, there is provided the ability of gaining detailed diagnostics information on FCs and batteries in a hybrid vehicle at a low-cost with power electronics which already  
5 exist in a vehicle. Use of the energy storage device, to buffer the excitation signal from the motor controller, results in a higher quality power output for the end-user.

The advantage of the segmented FC passive hybrid system excitation through control of the switching frequencies is that the load oscillation magnitude can be minimised through isolated switching in a small part of the stack. This reduces the overall load oscillations  
10 experienced by the load.

Additional features and further effects of embodiments include:

- The application of on-board vehicle impedance measurements to fuel cell hybrid  
15 systems incorporating a fuel cell and electrochemical energy storage (EES) device (i.e. batteries, non-faradaic electrochemical capacitors & pseudo and faradaic electrochemical capacitors).
- That such hybrid systems could be active hybrids, i.e. with one or more electrical control and voltage regulation systems between the fuel cell, EES and loads,  
20 typically a DC/DC converter.
- That such hybrid systems could be passive hybrids, i.e. with no electrical control and voltage regulation systems between the fuel cell and EES, i.e. they are in parallel with each other and power flow is regulated by their impedances
- That the excitation for the impedance measurements is generated by either, a  
25 dedicated circuit designed for such a purpose, the drivetrain (i.e. by controlling the motor controller and motor), or the hotel loads (i.e. all other loads such as heaters, air conditioning, windscreen wipers, etc), or a combination thereof.
- In the active hybrid configuration, to maintain a minimal external load oscillation/noise, i.e. when the fuel cell is being excited negatively, the battery is  
30 being excited positively and vice versa.
- Multiplexing, to use a method of providing the excitation across a whole stack and/or pack or hybrid stack/pack, but to have a smaller number of measurement circuits than unit cells, in some manifestations just 1 measurement circuit will be  
35 required, and to switch them in to monitor 1 cell at a time. This could significantly reduce the cost of such a system if it is not required to measure the impedance of all unit cells simultaneously.

- For the passive hybrid, the internal switching between the single EES and fuel cells in a single unit cell of the hybrid stack could be used to generate the excitation for the impedance measurement of one or a group of cells at a time, again with no or minimal external load oscillation/noise.
- 5     • For the passive hybrid, the internal switching could be used to isolate the fuel cell stack or EES pack so that each fuel cell or EES cell can be monitored individually. This is explained below:
  - As shown in Figure 6 (a), switches (such as 2 MOSFETS opposing each other) may be used to isolate the system during operation, and these
  - 10       switches can be used to excite each unit cell at a time.
  - In Figure 6 (b) the current is flowing through the fuel cell stack, and then the switches either side of battery unit cell 2 is used to shunt some current through the battery at different frequencies, providing the excitation for that battery cell and/or fuel cell unit cell (this is likely to be preferred to (c) as the
  - 15       fuel cell should normally be under load to minimise degradation).
  - In Figure 6 (c) the same occurs, but now the current is flowing through the battery pack and the switches are used to switch in/out a region of the fuel cell stack.

20   This disclosure also provides:

Clause 1. A method of monitoring the condition of at least one cell of a fuel cell stack and/or at least one cell of an electrical energy storage device, the fuel cell stack connected to the input terminals of a power converter and the output terminals of the

25   power converter connected to the storage device to charge the storage device; the storage device and the fuel cell stack arranged to supply electrical power to an electrical load; the method comprising the steps of:

- operating the power converter to generate an oscillating output from the fuel cell stack, and connecting this oscillating output to the storage device;
- 30   • sensing the voltage across the at least one cell of the fuel cell stack and the current therein, and/or sensing the voltage across the at least one cell of the storage device and the current therein;
- for the at least one cell of the fuel cell stack and/or the at least one cell of the storage device, calculating from the sensed voltage and current the complex
- 35   impedance of the cell; and
- comparing the calculated complex impedance with information indicative of a relationship between (i) the complex impedance and (ii) information indicative of

the condition of the at least one cell, to give an indication of the condition of the at least one cell.

Clause 2. A method according to clause 1 in which the fuel cell stack and/or the battery  
5 are not connected to the electrical load during at least the operating and sensing steps.

Clause 3. A method according to clause 2 comprising the step of disconnecting the fuel cell stack and/or the battery pack from the electrical load for the duration of at least the operating and sensing steps.

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Clause 4. A method according to clause 2 or clause 3, wherein the battery is at least partly discharged such that the oscillating output of the fuel cell stack is supplied to the battery.

15 Clause 5. A method according to clause 1 in which the fuel cell stack and/or the battery are connected to the electrical load during at least the operating and sensing steps.

Clause 6. A method according to clause 5 comprising the step of connecting the fuel cell stack and/or the battery to the electrical load for the duration of at least the operating and  
20 sensing steps.

Clause 7. A method according to clause 1, clause 5 or clause 6, wherein a second power converter is connected to the battery; the first power converter and the second power converter connected to supply the electrical load; wherein the operating step comprises  
25 operating the second power converter to supply an oscillating output from the battery, the oscillating output from the battery combining with the oscillating output from the fuel cell stack to provide a substantially steady electrical supply to the electrical load.

Clause 8. A method of monitoring the condition of at least one cell of a fuel cell stack and/or at least one cell of a battery, the fuel cell stack connected to input terminals of a  
30 first power converter; the battery connected to a second power converter, and the two power converters connected to supply electrical power to an electrical load; the method comprising the steps of:

- operating the first power converter to generate an oscillating output from the fuel  
35 cell stack;
- operating the second power converter to supply an oscillating output from the battery, the oscillating output from the battery combining with the oscillating output

from the fuel cell stack to provide a substantially steady electrical supply to the electrical load;

- sensing the voltage across the at least one cell of the fuel cell stack and the current therein, and/or sensing the voltage across the at least one cell of the battery and the current therein;
- for the at least one cell of the fuel cell stack and/or the at least one cell of the battery, calculating from the sensed voltage and current the complex impedance of the cell; and
- comparing the calculated complex impedance with information indicative of a correlation between (i) the complex impedance and (ii) information indicative of the condition of the at least one cell, to give an indication of the condition of the at least one cell.

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Clause 10. A method according to any preceding clause, wherein the step of operating the or each power converter comprises operating the or each power converter to generate an oscillating output at each of a plurality of different frequencies.

20

Clause 11. A method according to any clause 10, wherein the step of sensing comprises the voltage across the at least one cell of the fuel cell stack and the current therein, and/or sensing the voltage across the at least one cell of the battery and the current therein at each of the plurality of different frequencies.

25

Clause 12. A method according to clause 10 or clause 11, wherein the calculating step comprises calculating from the sensed voltage and current the complex impedance of the at least one cell of the fuel cell stack and/or the at least one cell of the battery at each of the plurality of different frequencies of the oscillating output.

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Clause 13. Processing and control means for a power converter, the processing and control means programmed and operable to control the power converter in accordance with any of clause 1 to clause 12.

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Clause 14. Processing and control means according to clause 13 and further arranged to receive information from sensing means indicative of the quantities sensed in the sensing steps defined hereinabove.

Clause 15. Processing and control means according to clause 14 and further arranged to carry out the comparing step.

- 5 Clause 16. A control system according to clause 14 or clause 15 and comprising the processing and control means and further comprising the sensing means.

- Clause 17. A computer program product comprising code portions executable by processing and control means to cause the processing and control means to carry out a  
10 method according to any of clause 1 to clause 12.

- Clause 18. A record carrier comprising thereon or therein a record of code portions executable by processing and control means to cause the processing and control means to carry out a method according to any of clause 1 to clause 12.  
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Clause 19. A vehicle comprising a control system according to clause 16.

## Claims

1. A method of monitoring the condition of at least one cell of a fuel cell stack and/or at  
5 least one cell of an electrical energy storage device, the fuel cell stack connected to the input terminals of a power converter and the output terminals of the power converter connected to the storage device to charge the storage device; the storage device and the fuel cell stack arranged to supply electrical power to an electrical load; the method comprising the steps of:
- 10     • operating the power converter to generate an oscillating output from the fuel cell stack, and connecting this oscillating output to the storage device;
- sensing the voltage across the at least one cell of the fuel cell stack and the current therein, and/or sensing the voltage across the at least one cell of the storage device and the current therein;
- 15     • for the at least one cell of the fuel cell stack and/or the at least one cell of the storage device, calculating from the sensed voltage and current the complex impedance of the cell; and
- comparing the calculated complex impedance with information indicative of a relationship between (i) the complex impedance and (ii) information indicative of  
20 the condition of the at least one cell, to give an indication of the condition of the at least one cell.
2. A method according to claim 1 in which the fuel cell stack and/or the electrical energy storage device are not connected to the electrical load during at least the operating and  
25 sensing steps.
3. A method according to claim 2 comprising the step of disconnecting the fuel cell stack and/or the electrical energy storage device from the electrical load for the duration of at least the operating and sensing steps.
- 30
4. A method according to claim 2 or claim 3, wherein the electrical energy storage device is at least partly discharged such that the oscillating output of the fuel cell stack is supplied to the electrical energy storage device.
- 35
5. A method according to claim 1 in which the fuel cell stack and/or the electrical energy storage device are connected to the electrical load during at least the operating and sensing steps.

6. A method according to claim 5 comprising the step of connecting the fuel cell stack and/or the electrical energy storage device to the electrical load for the duration of at least the operating and sensing steps.

5

7. A method according to claim 1, claim 5 or claim 6, wherein a second power converter is connected to the electrical energy storage device; the first power converter and the second power converter connected to supply the electrical load; wherein the operating step comprises operating the second power converter to supply an oscillating output from the electrical energy storage device, the oscillating output from the electrical energy storage device combining with the oscillating output from the fuel cell stack to provide a substantially steady electrical supply to the electrical load.

10

8. A method of monitoring the condition of at least one cell of a fuel cell stack and/or at least one cell of an electrical energy storage device, the fuel cell stack connected to input terminals of a first power converter; the electrical energy storage device connected to a second power converter, and the two power converters connected to supply electrical power to an electrical load; the method comprising the steps of:

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- operating the first power converter to generate an oscillating output from the fuel cell stack;
- operating the second power converter to supply an oscillating output from the electrical energy storage device, the oscillating output from the electrical energy storage device combining with the oscillating output from the fuel cell stack to provide a substantially steady electrical supply to the electrical load;
- sensing the voltage across the at least one cell of the fuel cell stack and the current therein, and/or sensing the voltage across the at least one cell of the electrical energy storage device and the current therein;
- for the at least one cell of the fuel cell stack and/or the at least one cell of the electrical energy storage device, calculating from the sensed voltage and current the complex impedance of the cell; and
- comparing the calculated complex impedance with information indicative of a correlation between (i) the complex impedance and (ii) information indicative of the condition of the at least one cell, to give an indication of the condition of the at least one cell.

9. A method according to any preceding claim, wherein the step of operating the or each power converter comprises operating the or each power converter to generate an oscillating output at each of a plurality of different frequencies.

5

10. A method according to any claim 9, wherein the step of sensing comprises sensing the voltage across the at least one cell of the fuel cell stack and the current therein, and/or sensing the voltage across the at least one cell of the electrical energy storage device and the current therein at each of the plurality of different frequencies.

10

11. A method according to claim 9 or claim 10, wherein the calculating step comprises calculating from the sensed voltage and current the complex impedance of the at least one cell of the fuel cell stack and/or the at least one cell of the electrical energy storage device at each of the plurality of different frequencies of the oscillating output.

15

12. Processing and control means for a power converter, the processing and control means programmed and operable to control the power converter in accordance with any of claim 1 to claim 11.

20 13. Processing and control means according to claim 12 and further arranged to receive information from sensing means indicative of the quantities sensed in the sensing steps defined hereinabove.

25 14. Processing and control means according to claim 13 and further arranged to carry out the comparing step.

15. A control system according to claim 13 or claim 14 and comprising the processing and control means and further comprising the sensing means.

30 16. A computer program product comprising code portions executable by processing and control means to cause the processing and control means to carry out a method according to any of claim 1 to claim 11.

35 17. A record carrier comprising thereon or therein a record of code portions executable by processing and control means to cause the processing and control means to carry out a method according to any of claim 1 to claim 11.

18. A vehicle comprising a control system according to claim 15.

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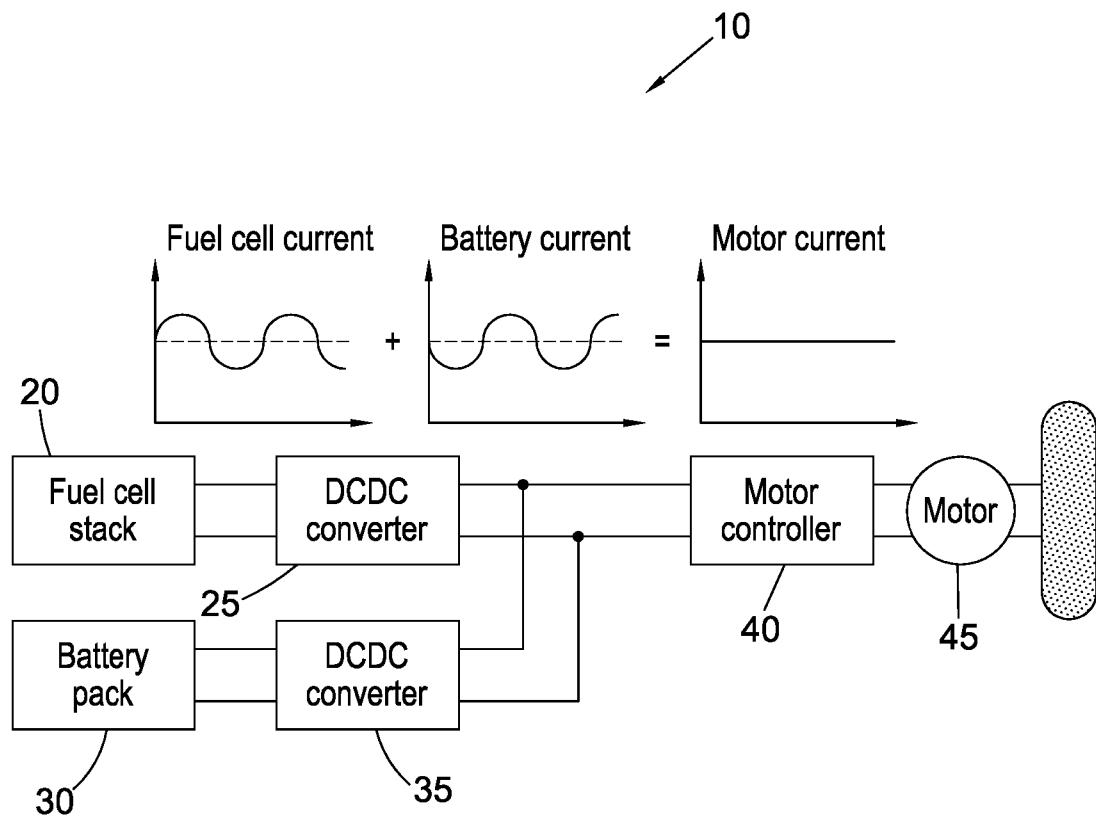


Fig. 1

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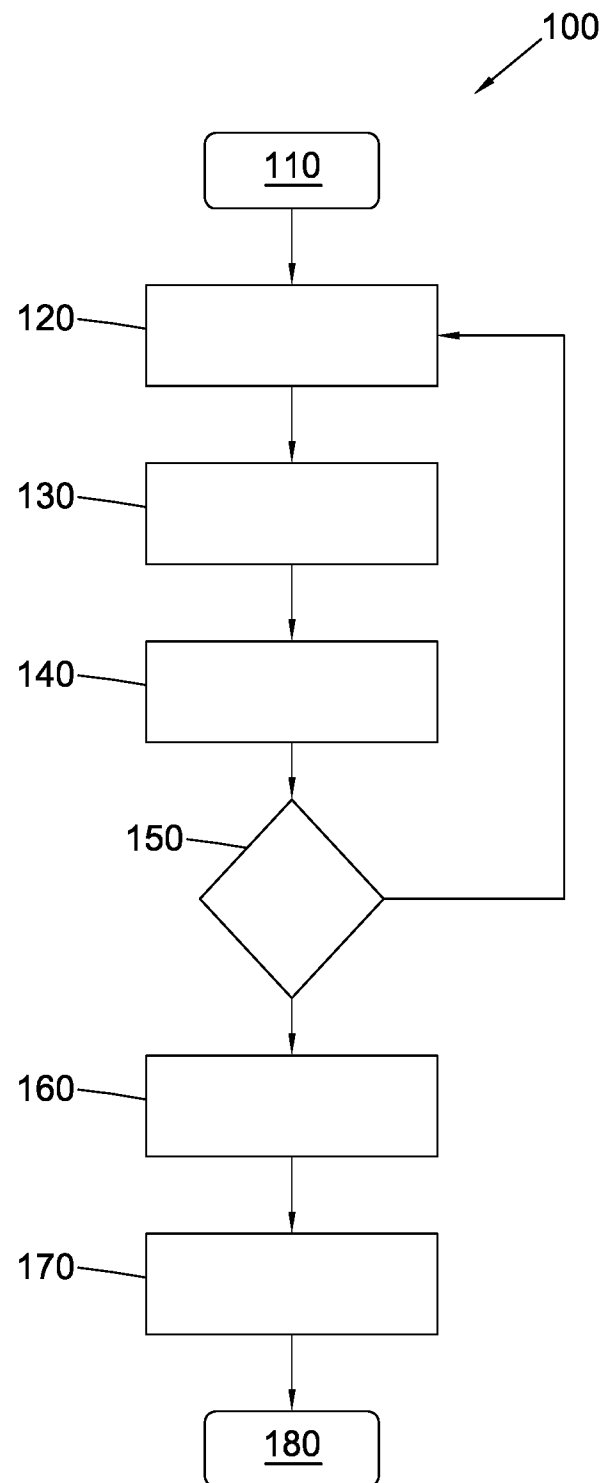


Fig. 2

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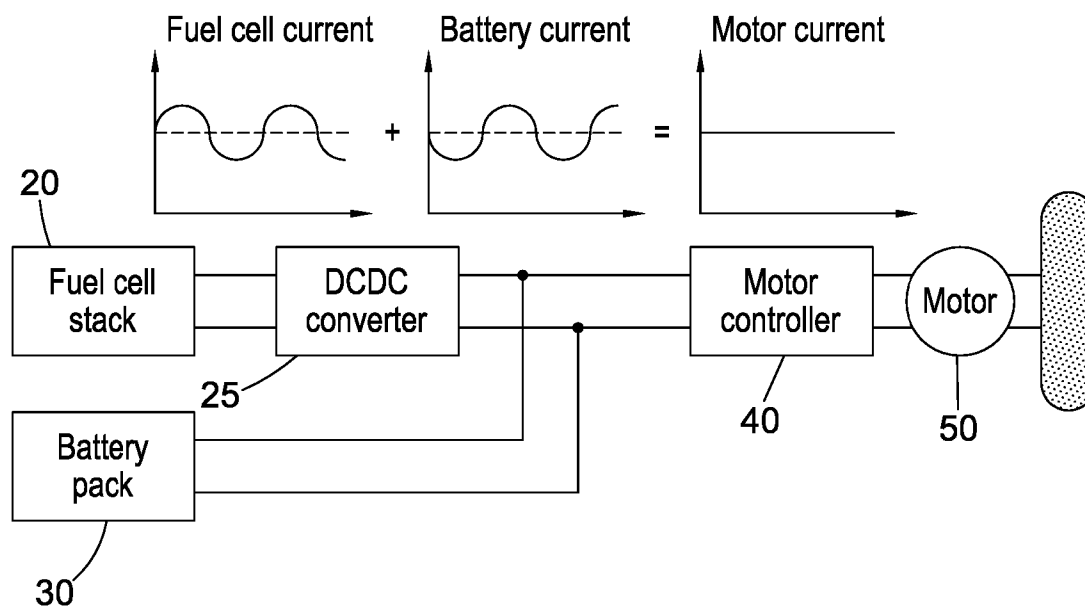


Fig. 3

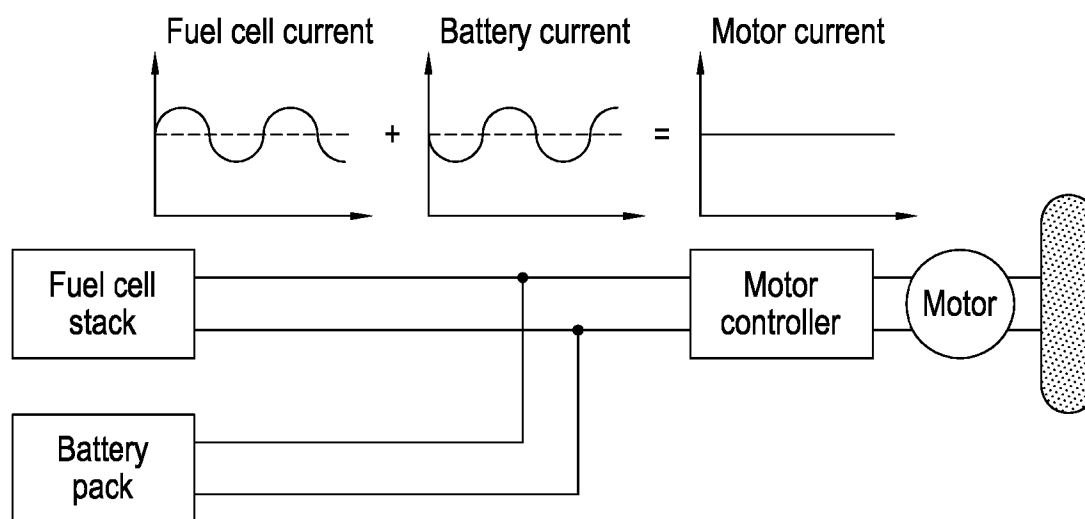


Fig. 4

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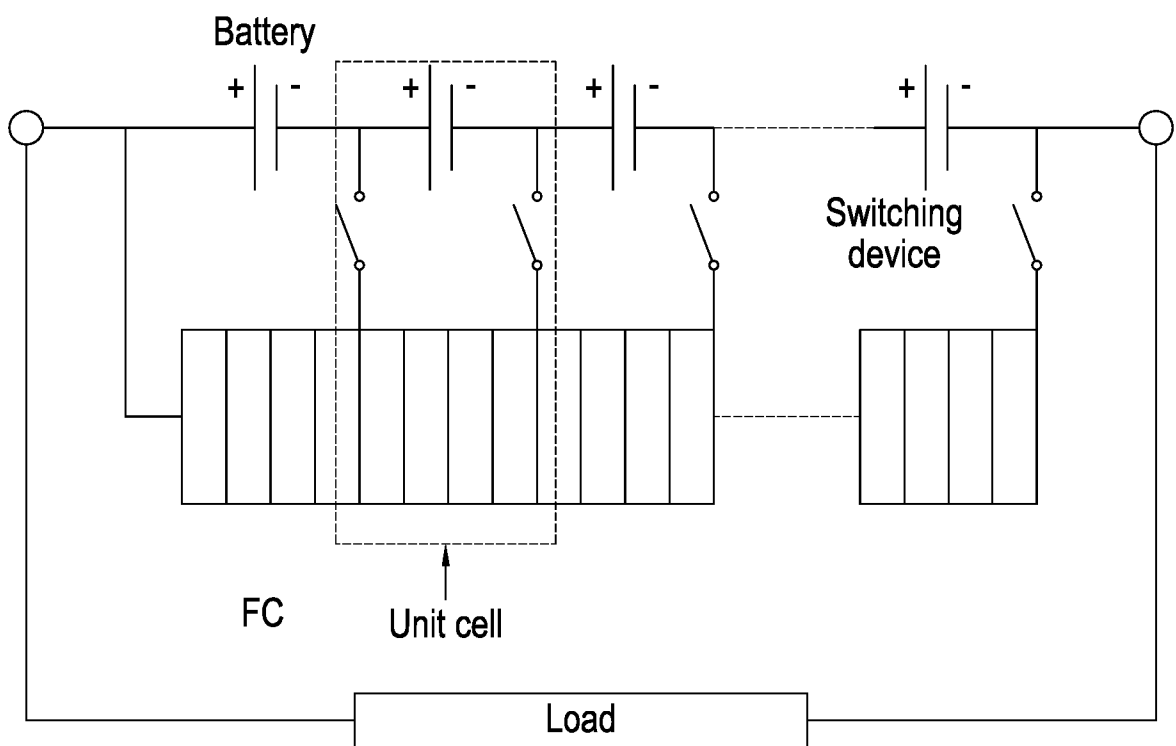


Fig. 5

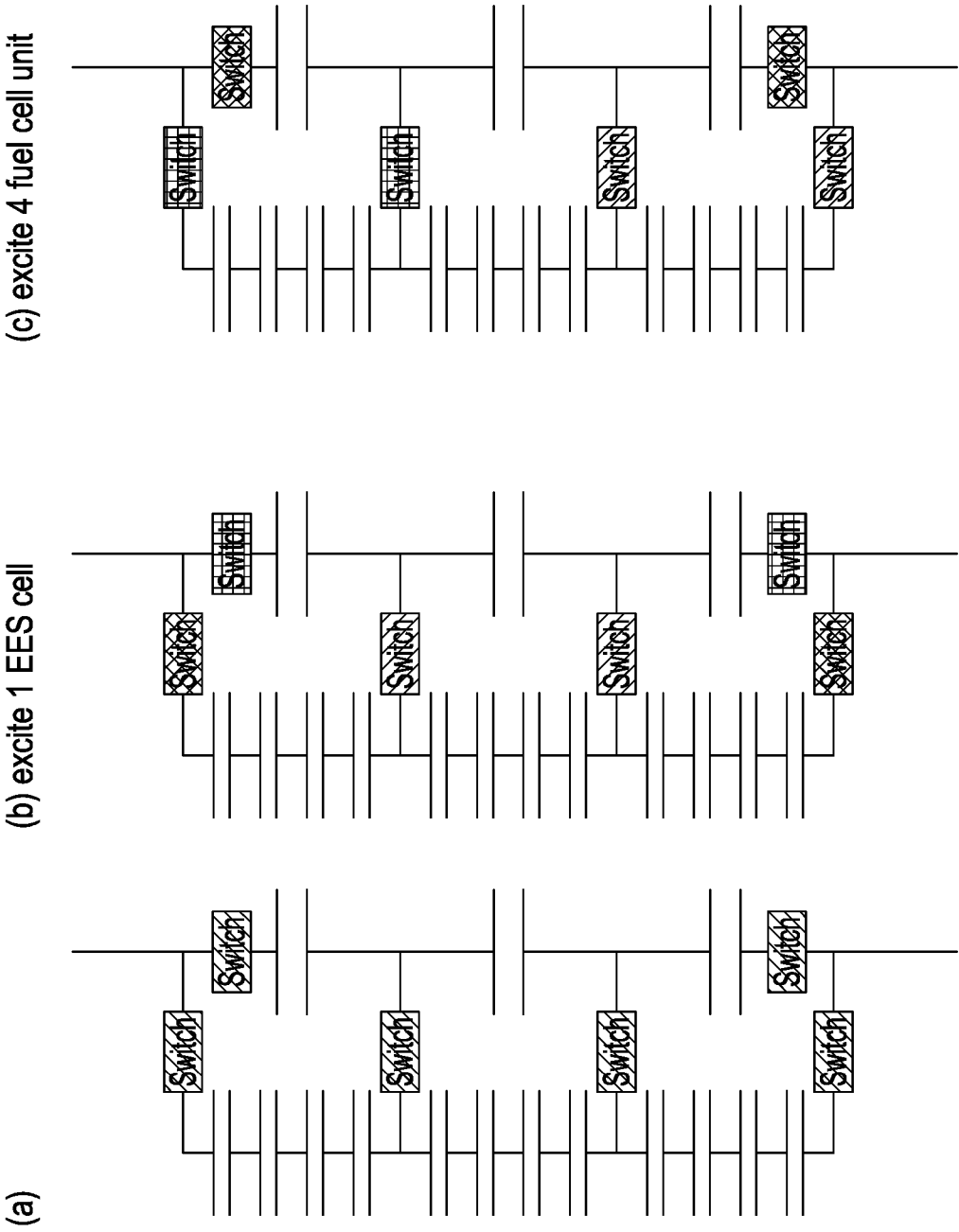


Fig. 6

# INTERNATIONAL SEARCH REPORT

International application No  
PCT/GB2016/050652

## A. CLASSIFICATION OF SUBJECT MATTER

INV. H01M8/04537 H01M8/04664  
ADD. H01M10/48

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)

H01M

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. |
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| Y         | WO 2012/025706 A1 (IMP INNOVATIONS LTD<br>[GB]; BRANDON NIGEL [GB]; MITCHESON PAUL<br>[GB]; YUF) 1 March 2012 (2012-03-01)<br>cited in the application<br>abstract<br>page 11, line 13 - page 20, line 9<br>claims 1-22<br>figures 2, 3 | 1-18                  |



Further documents are listed in the continuation of Box C.



See patent family annex.

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"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

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"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

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Date of the actual completion of the international search

19 April 2016

Date of mailing of the international search report

26/04/2016

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# INTERNATIONAL SEARCH REPORT

International application No  
PCT/GB2016/050652

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                           | Relevant to claim No. |
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Information on patent family members

International application No

PCT/GB2016/050652

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| -----                                     | -----               | -----                                                                                                            | -----                                                                            |