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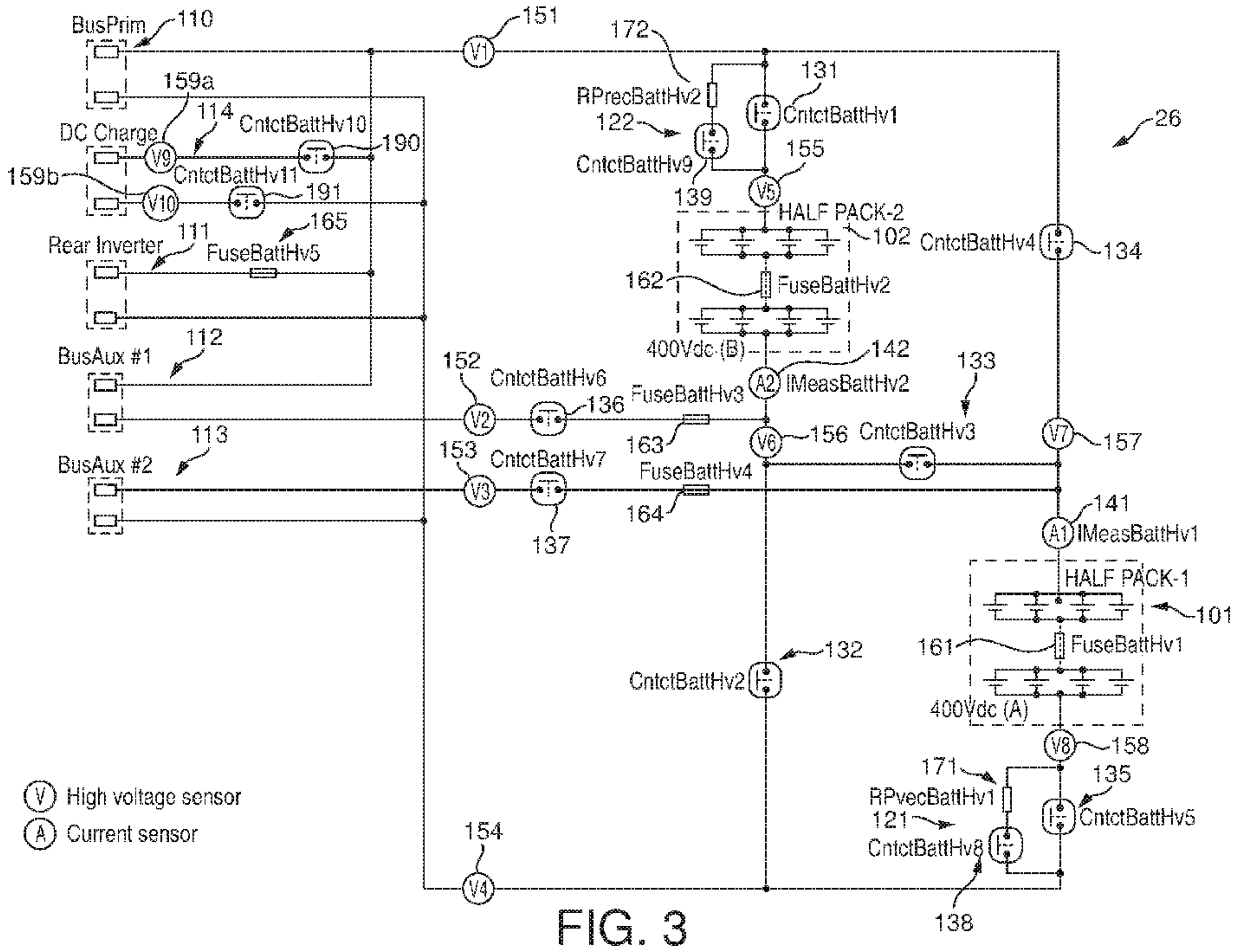

FIG. 3

(57) **Abstract:** A battery pack comprises a plurality of sub-packs (101,102), a primary bus (110), a plurality of switches (131-139) and a diagnostic circuit for diagnosing a failure state of one or more of the switches. The plurality of switches connects the sub-packs (101,102) to the primary bus (110). Each of the switches has an open state, a closed state, and a failure state in which the switch is immovable from the open state or the closed state. Some of the switches are arranged as one or more switch groups, the switches within each switch group being arranged in parallel. The diagnostic circuit comprises voltage sensors (151-158) for measuring a voltage across each switch group and across each switch not arranged within a switch group, and current sensors (141,142) for measuring a current drawn from each sub-pack (101,102). The diagnostic circuit uses the measured voltages and measured currents to determine if any one of the switches is in a failure state.

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BATTERY PACK WITH FAILURE DETECTION SYSTEM

Field of Invention

This invention relates to a battery pack with a failure detection system for use in an electric vehicle. In particular, this invention relates to a method and apparatus for battery pack management using a diagnostic circuit to assist in determination of whether the battery pack is in a fully operational state.

Background of Invention

Electric vehicles, considered here to comprise both vehicles in which motive force is provided solely by a battery pack, but also vehicles in which a battery pack is one of a plurality of alternative sources of power (for example hybrid vehicles), contain battery packs that need to provide sufficient motive power to drive a vehicle. In the case of a fully electric vehicle, electrical current from the battery is passed through an inverter to drive an electric motor. The battery of an electric vehicle will typically also power a number of subsystems within a vehicle.

The battery pack typically contains a large number of cells, each with a positive and a negative terminal. These cells are typically configured as a string of cell groups, with each group comprising a plurality of cells in parallel (to provide sufficient current) and with the string comprising the groups of cells in series (to provide sufficient voltage).

Determination of whether a battery pack such as that described above is functioning properly can also be complex and can require a measurement strategy that is intrusive (in that it affects the operation of the system) and which needs multiple or complex sensors, which can increase the cost and reduce the efficiency of the battery pack. It would be desirable to be able to determine whether failures are present and whether the vehicle can be operated with a simple array of sensors and a straightforward measurement strategy.

Summary of Invention

Accordingly, in a first aspect the invention provides a battery pack comprising: a plurality of sub-packs; a primary bus; a plurality of switches for connecting the sub-packs to the primary bus, each of the switches having an open state, a closed state, and a failure state in which the switch is immovable from the open state or the closed state; and a diagnostic circuit for diagnosing a failure state of one or more of the switches,

wherein: some of the switches are arranged as one or more switch groups, the switches within each switch group being arranged in parallel; the diagnostic circuit comprises voltage sensors for measuring a voltage across each switch group and across each switch not arranged within a switch group, and current sensors for measuring a current drawn from each sub-pack; and the diagnostic circuit uses the measured voltages and measured currents to determine if any one of the switches is in a failure state.

Using this approach, a limited number of sensors may be used to monitor the circuit and to determine when a switch failure has occurred. The disposition of voltage and current measurement points in the battery pack allows for effective determination of switch failure states with limited expense and complexity.

In embodiments, the battery pack further comprises a configuration circuit for configuring the states of the switches, wherein the battery pack has a plurality of operational modes, each operational mode having a different configuration of switch states, and the diagnostic circuit determines if any one of the switches is in a failure state prior to a change in the operational mode of the battery pack. This may be beneficial as it may enable the battery pack to operate in different modes where witch failure is detected.

Such a battery pack may comprise a first sub-pack and a second sub-pack, such that the first sub-pack and the second sub-pack are connected across the primary bus when the switches are in a first configuration, and such that one only of the first sub-pack and the second sub-pack is connected across the primary bus when the switches are in a second configuration. This may be beneficial as it may enable, for example, both first and second sub-packs to be utilised during normal operation, and may enable only one of the first and second sub-packs to be used where a failure is detected with the other of the sub-packs.

In this arrangement, the battery pack may comprise a first path across the primary bus comprising the first sub-pack and a second path across the primary bus comprising the second sub-pack, wherein the battery pack further may comprise a central path connecting the first path to the second path with a central switch disposed on the central path for switching the battery pack between the first configuration and the second configuration. Each of the first path and the second path may comprise a high voltage side and a low voltage side to either side of its connection to the central path, wherein the first sub-pack is disposed on the high voltage side of the first path and the second sub-pack is disposed on the low voltage side of the second path, wherein a first limb switch is disposed on the low voltage side of the first path and a second limb switch is disposed on the high voltage side of the second path. There may also be a switch group for disabling or enabling current flow for a sub-pack in series with each of the first sub-pack and the second sub-pack and on the same voltage side as that sub-pack. Each such switch group may comprise a main switch in parallel with a series combination of a pre-charge resistor and a pre-charge switch.

Such battery packs may comprise at least one auxiliary bus disposed across at least one, but not all, of the sub-packs. The connection to each auxiliary bus may comprise a respective auxiliary bus switch. This may be beneficial as the auxiliary bus may remain functional in the event of a failure of the sub-pack which the auxiliary bus is not disposed across.

In a second aspect, the invention provides an electric vehicle comprising one or more motor units and the battery pack as described above in cases where there is a configuration circuit establishing a plurality of operational modes, wherein the motor units provide motive drive to the vehicle, and wherein the motor units are coupled to the primary bus and operate at an electrical power determined by a current operational mode of the battery pack.

In a third aspect, the invention provides a method of diagnosing a contactor failure within a battery pack, the battery pack comprising a plurality of sub-packs, a primary bus, and a plurality of switches for connecting the sub-packs to the primary bus, each of the switches having an open state, a closed state, and a failure state in which the switch is immovable from the open state or the closed state, wherein some of the switches are arranged as one or more switch groups, the switches within each switch group being arranged in parallel, and wherein the method comprises:

measuring a voltage across each switch group and across each switch not arranged within a switch group; measuring a current drawn from each sub-pack; and using the measured voltages and measured currents to determine if any one of the switches is in a failure state.

This battery pack may be a battery pack of an electric vehicle.

Brief Description of Drawings

Specific embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, of which:

Figure 1 is a first schematic view illustrating the disposition of a battery pack suitable for employing embodiments of the invention in a vehicle;

Figure 2 is schematic view illustrating the internal structure of the battery pack shown in Figure 1;

Figure 3 shows an exemplary configuration circuit for a battery pack in accordance with an embodiment of the invention;

Figure 4 shows a state machine for an embodiment of a high voltage system of an electric vehicle with a battery reconfigurable between 400V and 800V operation;

Figure 5 shows further detail of the diagnostic state of Figure 4;

Figure 6 shows control channel states for use with the configuration circuit of Figure 4 and associated contactor configurations;

Figure 7 describes a transition from a fully disconnected state to an 800V ready state for the state machine of Figure 4;

Figure 8 describes a transition from an 800V ready state to a motoring state for the state machine of Figure 4;

Figures 9 and 10 describe transitions from a motoring state to an 800V ready state and an 800V ready state to a fully disconnected state for the state machine of Figure 4;

Figure 11 describes a transition to a sub-pack limp home state for the state machine of Figure 4;

Figure 12 describes disconnection from a sub-pack limp home state to a fully disconnected state for the state machine of Figure 4;

Figures 13 and 14 describe, respectively, transitions from a fully disconnected state to an 800V charging state and back again;

Figure 15 describes a transition from a fully disconnected state to a 400V ready state for the state machine of Figure 4;

Figure 16 describes a transition from a 400V ready state to a 400V charging state for the state machine of Figure 4;

Figures 17 and 18 describe transitions from a fully disconnected state to a sub-pack 400V ready state and back again for the state machine of Figure 4;

Figure 19 describes a transition from a 400V ready state to a fully disconnected state for the state machine of Figure 4; and

Figure 20 describes a transition from a sub-pack 400V ready state to a fully disconnected state for the state machine of Figure 4.

Description of Specific Embodiments

Figure 1 shows the disposition of a battery pack 1 for which embodiments of the invention could be employed within an electric vehicle 10. It will be recognised by a person skilled in the art that although depicted here as a single unit, such a battery pack 1 may comprise components in separate housings and/or at separate locations within the vehicle, and hence the battery pack may also be viewed as a battery system.

The battery pack 1 is connected to a front motor unit 2 and a rear motor unit 3. These motor units comprise an inverter and an electric motor, and provide motive drive for the vehicle. The battery pack 1 also provides power for a high voltage bus (or multiple such buses) for the vehicle. The high voltage bus powers high power systems within the vehicle (such as air conditioning systems). The high voltage bus is connected to a DC-DC converter which provides a low power bus typically operating at 12V (again, there may be multiple lower power buses).

The embodiments shown here relate to an electric vehicle 10 in which a rechargeable cellular battery operates as the sole power source for providing motive power to the vehicle, but embodiments of the invention can be employed in other vehicle types where battery power is used some or all of the time to provide motive power to the vehicle. For example, embodiments may apply to hybrid vehicles in which a motor may be driven by another power source (such as an internal combustion engine) as well as from a battery, or to other forms of electric vehicle in which energy is provided by another power source (such as a fuel cell) but a battery is an intermediary between this power source and an electric motor.

The battery pack 1 in this case is configurable to provide either 800V or 400V – this allows in particular charging at either 800V or 400V, but also allows for 800V and 400V outputs (and in cases where there is an 800V output, a 400V output may be provided by tapping the output at an intermediate voltage). The high voltage bus may then provide 800V or 400V outputs, with the lower power bus typically providing 12V outputs for driving electronics and other lower powered vehicle systems. As will be described in more detail below, in embodiments of the invention the bus system may be more complex in structure than a monolithic high voltage bus providing a single supply voltage – for example, the high voltage bus may be associated with a lower (but still high) voltage auxiliary bus, which may for example be used to drive systems, such as an air conditioning compressor, which require a significant drive voltage but less than that optimal for driving electric motors of a vehicle. While reference to reconfiguration between 800V and 400V states is used generally below, different specific voltage values may be used in other embodiments – for example, the higher voltage may be 1000V and the lower voltage 500V.

To provide the configurable nature of the battery pack 1, the battery pack 1 comprises first 101 and second 102 sub-packs (which may also be referred to as half-packs for the present embodiment). Each sub-pack 102,102 may comprise one or more battery modules. The connection of these sub-packs 101,102 can be altered according to various requirements using a configuration circuit 26, as depicted in Figure 3. The configuration circuit 26 is controlled by a battery management system (not shown), which may be located within the battery pack 1, or at a location remote from the battery pack 1.

The configuration circuit 26 comprises two battery sub-packs 101 and 102. The configuration circuit 26 allows these to be connected in series (to deliver 800V) or in parallel (to deliver 400V) or with only one sub-pack connected (again, to deliver 400V). The outputs include a primary bus 110 which will normally receive 800V, the rear inverter 111 which will also normally receive 800V to drive the vehicle, and first and second auxiliary buses 113 and 112 which will generally receive 400V, either singly (when the two sub-packs are in series) or in parallel (when the two sub-packs are in parallel). When the sub-packs are in series, the first auxiliary bus is connected across a first sub-pack and the second auxiliary bus is connected across a second sub-pack. Also shown here is a DC charging circuit 114.

In series with each sub-pack there is a contactor group 121, 122 which comprises a contactor in one parallel branch and a contactor and a resistor in the other parallel branch. Whilst described herein as contactors, it will be appreciated that relays may be used, if appropriate, and hence the contactor groups may be thought of more generally as switch groups. The same applies for all mentions of contactors herein. The branch with the contactor alone is the main circuit arrangement for normal operation, whereas the other branch is a pre-charge circuit so that the voltage levels in the circuit are correct before full operation. For the first sub-pack 101 a first main contactor 135 is in parallel with a series combination of a first pre-charge contactor 138 and a first pre-charge resistor 171. For the second sub-pack 102, a second main contactor 131 is in parallel with a series combination of a second pre-charge resistor 172 and a second pre-charge contactor 139.

A group of three contactors – bridging contactor 133 and limb contactors 132 and 134 – control the basic configuration circuit 26. The circuit as a whole forms an H structure, with the sub-packs 101 and 102 each located on a diagonally opposed limb of the H structure. The other two limbs each have a limb contactor thereon. To provide a series connection, the bridging contactor 133 is closed and the limb contactors 132, 134 are driven open circuit. In this arrangement, 800V is seen across the battery pack. Alternatively, to provide a parallel connection the bridging contactor is driven open circuit and the limb contactors are held closed. As will be discussed below, different contactor arrangements may be provided if a contactor failure is identified.

There are two more pairs of contactors associated with the configuration circuit 26, first auxiliary bus contactor 137 and second auxiliary bus contactor 136 forming one pair, and DC charging circuit contactors 190, 191 forming another pair. These contactors can be used to isolate the relevant circuits if required.

The configuration circuit 26 includes sensors to measure voltage and current to determine whether the circuit is operating correctly, and if remedial measures need to be taken to isolate a fault or to allow operation in a limited functionality mode. It is desirable for efficiency and cost to use a limited number of sensors designed to disrupt normal operation of the configuration 26 circuit as little as possible. High voltage sensors are deployed at several points within the circuit. With regard to the buses, a first voltage sensor 151 is disposed at the positive rail of the primary bus and a fourth voltage sensor 154 is disposed at the negative rail of the primary bus. A second voltage sensor 152 is disposed at the negative rail of the second auxiliary bus (the positive rail of this bus is the positive rail of the primary bus), and a third voltage sensor 153 is disposed at the positive rail of the first auxiliary bus (the negative rail of this bus is the negative rail of the primary bus). A sixth and seventh voltage sensor 156, 157 are disposed to either side of the bridging contactor 133. Within the first sub-pack circuit, an eighth voltage sensor 158 is disposed between the first sub-pack 101 itself and the first contactor group 121, and a fifth voltage sensor 155 is similarly disposed within the second sub-pack circuit. A ninth voltage sensor 159a and a tenth voltage sensor 159b are disposed within the DC charging circuit.

For the measurement strategy described below, current is sensed at certain points in the circuit to supplement the voltage measurements described above. Current sensors 141, 142 are thus provided in each sub-pack 101,102, but these themselves comprise two components.

Fuses are disposed in the system at relevant points. Each sub-pack contains a sub-pack fuse 161, 162, and fuses 163, 164 are also provided to isolate the auxiliary loads from each sub-pack. A rear inverter fuse 165 isolates the rear inverter from the positive rail.

As will be described in greater detail below, the auxiliary buses 112, 113 and associated contactors 136, 137 are disposed to allow operation of at least one auxiliary bus if there is an operational sub-pack even if the other sub-pack is not operational.

A state machine for the configuration circuit 26 will now be described with reference to Figure 5. The state machine reverts to an “off” state in which all high voltage contactors are disconnected 600. As can be seen, this is the resting state for the system – normally specific steps are involved in transition to full operational states 640, but in an emergency (a major crash, or when a safety compromising event has been identified) any state may revert directly back to the HV disconnected state 600, with all contactors turned off.

The normal transition in and out of the HV disconnected state 600 is with a diagnostic state 610 in which the operation of the HV system is checked. This diagnostic process is discussed in more detail below. An output of the diagnostic process is to determine whether both sub-packs are available for use, or if only one (or neither) is available. If the HV system is not usable, the system will revert back to the HV disconnected state 600 – otherwise, it will transition 620 to an available system state. If, as will be the normal case, both sub-packs are available, the HV system will transition to the full system available state 621 – however, if only the first sub-pack is available, then the first sub-pack only state 622 is entered, with the second sub-pack state 623 being entered if only the second sub-pack is available – as shown in Figure 5, this may be after a transition through the HV disconnected state 600.

The system then needs to transition to a pre-charge state 630 appropriate for its relevant bus configuration. For the normally operating system, there are two possibilities at this stage – the sub-packs may be connected in series for 800V operation (either motoring or 800V charging) in which case it will use the 800V pre-charge state 631, or connected in parallel for 400V charging in which case it will use the 400V pre-charge state 632. There is only one option for the sub-pack states, as only 400V operation (for 400V charging or limp-home driving) is available, so only a 400V sub-pack pre-charge state 633, 634 can be entered.

When the relevant bus configuration has been entered and pre-charged, an operational mode 640 can be entered. This may be a charging mode, with lower voltage (400V) charging being available both in normal operation (lower voltage charging mode 641) and in sub-pack operation (sub-pack charging mode 642), and higher voltage (800V) charging also being available in normal operation (higher voltage charging mode 643). The normal mode to enter when the HV system is functioning normally is the motoring mode 644 in which the high voltage bus and the rear inverter bus provide a full 800V to the inverters of the motor system. Alternatively, if only one sub-pack is working, the system may enter a sub-pack limp home mode 645 in which case 400V is provided to the inverters and non-essential systems are managed so that power is used safely and effectively.

The implementation of these states using the configuration circuit of Figure 3 will now be described in more detail, with particular reference to control of contactors, and to measurement, diagnostics and management of failure states.

Symmetry of design enables a limited number of control channels (not shown in Figure 3) to be used to control the contactors – seven channels can be used to control the different contactor states required. Channels 1 and 2 can be used to enable the first and second sub-pack respectively, with Channel 3 (providing a common drive signal to first and second main contactors 135, 131) being used to control use of sub-pack mode. Channel 4 controls 400V mode (with a common drive signal to the limb contactors 132, 134) and Channel 5 controls 800V mode, driving the bridging contactor 133. Auxiliary bus control is achieved with Channel 6, providing a common drive signal to first and second auxiliary bus contactors 137, 136. Pre-charge contactors 138 and 139 are controlled with Channel 7. The contactor configurations associated with these control channel states are shown in Figure 6.

Before discussion of other state transitions, failure detection and use of the diagnostic state will be discussed with reference to Figure 4 and Table 1 below. Figure 4 indicates the disposition of contactors in the system, whereas Table 1 indicates safe detection of each single contactor failure state and the available system response when that single contactor failure state is detected. For the purposes of this discussion, a single contactor failure state is where the battery system is suffering from a persistent failure in a single contactor. There are two possible single contactor failure states for each contactor – that the contactor is open circuit and will not close, and that the contactor is closed circuit and will not open.

Contactor Reference	**Short Circuit Impact**	**Short Circuit Detection**	**Open Circuit Impact**	**Open Circuit Detection**
ContactBattHv1 131	No pre-charge capability, can run in 400V s Sub-Pack mode using Sub-Pack1	Monitor voltage across pre-charge circuit and Sub-Pack – non-zero voltage prior to contactor closure indicates short circuit in CntctBattHv1 or 9)	Cannot exit pre-charge	Voltage monitored across series connection of Sub-Pack and pre-charge circuit incorporating CntctBattHv1
ContactBattHv2 132	Loss of BusAux2 Can run in 400V single Sub-Pack mode (using Sub-Pack1)	Detection of pre-charge current when only CntctBattHv8 is closed (pre-charge resistor across Sub-Pack1)	Sub-Pack 2 cannot be connected in parallel mode a) Sub-Pack 1 provides 400V b) Sub-Pack 2 out of circuit c) HV+ (400V) is now referenced to electrical chassis	a) Monitor the voltage across CntctBattHv2 detect missing hard pull down b) No balancing current between the Sub-Packs when CntctBattHv2 & 4 are closed c)Pre-charge failure to ramp voltage correctly when CntctBattHv9 closed (possible O/C pre-charge resistor) d) Have earth leakage failure when CntctBattHv9 is closed
ContactBattHv3 133	Operation at 800V is no longer possible a) 400V operation is possible using either (but only one) of the Sub-Packs b) Switch on load seen by pre-charge contactor (normal operation has this contactor switched off load)	Unexpected pre-charge current when sequencing for 800V operation (CntctBattHv3 is last contactor to close in pre-charge sequence) Will have pre-charge resistor limited short circuit current when pre-charging before 400V mode operation	Sub-Packs cannot be connected in series a)Failure to start pre-charging at 800V	Failure to start pre-charging BUT have correct voltage across both Sub-Pack & pre-charge circuits

ContactBattHv4 134	Loss of BusAux1 Can run in 400V single Sub-Pack mode (using Sub-Pack2)	Will have measured pre-charge current when only CntctBattHv9 is closed (pre-charge resistor across Sub-Pack 2)	Sub-Pack 1 cannot be connected in parallel mode a) Sub-Pack 2 provides 400V b) Sub-Pack 1 out of circuit c) HV- (0V) is now referenced to electrical chassis	a) Monitor the voltage across CntctBattHv4 detect missing hard pull down b) Fail to have any balancing current between the Sub-Packs when CntctBattHv2 & 4 are closed c)Pre-charge failure to ramp voltage correctly when CntctBattHv8 closed (possible O/C pre-charge resistor) d) Have earth leakage failure when CntctBattHv8 is closed
ContactBattHv5 135	No pre-charge capability, can run in 400V Sub-Pack mode using Sub-Pack2	Monitor voltage across pre-charge circuit and Sub-Pack – non-zero voltage prior to contactor closure indicates short circuit in CntctBattHv1 or 9)	Cannot exit pre-charge	Voltage monitored across series connection of Sub-Pack and precharge circuit incorporating CntCctBattHv5
ContactBattHv6 136	Cannot isolate BusAux1 a) Pre-charge turn on load will be seen by CntctBattHv9 b) Can run in 400V single Sub-Pack mode (using Sub-Pack1)	Pre-charge of BusAux1 begins in error when CntctBattHv9 is closed	Pre-charge of BusAux1 does not occur	Detected by monitoring BusAux1 voltage
ContactBattHv7 137	Cannot isolate BusAux2 a) Pre-charge turn on load will be seen by CntctBattHv8 b) Can run in 400V single Sub-Pack mode (using Sub-Pack2)	Pre-charge of BusAux2 begins in error when CntctBattHv8 is closed	Pre-charge of BusAux2 does not occur	Detected by monitoring BusAux2 voltage
ContactBattHv8 138	Can run in 400V single Sub-Pack mode (using Sub-Pack 2)	Voltage monitored across series connection of Sub-Pack and pre-charge circuit incorporating CntctBattHv8 prior to the closure of any contactors	Could run at 400V using Sub-Pack 2	Detected by monitoring Sub-Pack 1 current
ContactBattHv9 139	Can run in 400V single Sub-Pack mode (using Sub-Pack 1)	Voltage monitored across series connection of Sub-Pack and pre-charge circuit incorporating CntctBattHv9 prior to the closure of any contactors	Could run at 400V using Sub-Pack 1	Detected by monitoring Sub-Pack 2 current

Table 1 – Single Contactor Failure States – Measurement and Consequences

As can be seen from Table 1 above, circuit symmetry means that both detection and consequences of failure are essentially similar for particular contactor pairs (though with consequences relating to one sub-pack for one and to the other sub-pack for the other) – these pairs are as follows: first and second main contactors 135, 131; limb contactors 132, 134; first and second auxiliary bus contactors 137, 136; and pre-charge contactors 138 and 139. The only unpaired contactor is bridging contactor 133. Failure states are summarised in Table 1, though some failure states have more complex consequences, as discussed in the following paragraphs.

If a main contactor is short circuited, this will also instantly charge the relevant 400V DC bus capacitor once the relevant auxiliary bus contactor is closed and halve the pre-charge resistance for charging the 800V DC bus capacitance once the pre-charge contactors are closed. If a main contactor is open circuit, then there will be a significant voltage drop across the relevant pre-charge resistor under load.

If a limb contactor is short circuited, then there is a risk of short circuiting the associated sub-pack – the relevant pre-charge resistor limits current during the pre-charge phase, but a short circuit would follow when the relevant main contactor closed to put the battery pack into running mode. If a limb contactor is open circuit, as described above, the sub-pack affected is taken out of circuit.

If the bridging contactor 133 is short circuited, there is a risk of short circuit if either of the limb contactors are closed – this means that not only is 800V operation not possible, but it is necessary to make a decision as to which of the two sub-packs is used, and program the states accordingly.

If a pre-charge contactor is short circuited, there is a risk of pre-charge resistor overload during shut down – however this can be addressed by managing the timing of the relevant main contactor and auxiliary bus contactor transitions. If a pre-charge contactor is open circuit, then it cannot pre-charge the relevant buses – however, running from the other sub-pack is still possible, and in embodiments sequencing could be managed to allow pre-charge to be achieved using the other pre-charge resistor.

As can be seen from the above, this circuit arrangement allows some form of operation using at least one sub-pack for the majority of the single contactor failure states. Every single contactor short circuit can be addressed in such a way to allow use of one of the 400V sub-packs, allowing the vehicle to operate in a “limp home” mode – while this is not the normal operational mode of the vehicle, it is still a viable operational mode in which the vehicle can be used (as opposed to the HV disconnect state 600, which is not considered here to be an operational mode as the vehicle is not functioning as a vehicle in this mode). In such a limp home mode, the power source is still able to drive the motor – often at a reduced capacity – but vehicle functionality may be limited. The circuit arrangement shown therefore allows a limp home mode to be available for any short circuit single contactor failure in the reconfiguration circuit. As can also be seen from Table 1, a number of open circuit single contactor failures also allow a limp home mode to be carried out.

The disposition of voltage and current measurement points in the reconfiguration circuit allows for effective determination of every single contactor failure state with limited expense and complexity. The disposition of voltage measurement points allows for voltage to be measured across each contactor, or contactor group, in the measurement circuit. The term “contactor group” is used here to refer to a parallel circuit in which a contactor is disposed in each parallel path, with the measurement taken between the two branching points. This applies to the main contactor and pre-charge contactor for each sub-pack – these are disposed in a parallel circuit which has the main contactor on one branch and the pre-charge contactor and pre-charge resistor on the other branch. This voltage measurement is supplemented by limited current measurement, requiring only current measurement for each battery pack by first sub-pack current sensor 141 and second sub-pack current sensor 142.

The embodiment shown in Figure 4 provides for two auxiliary buses, each providing a 400V output. These are disposed such that the first auxiliary bus output 113 is connected to the configuration 26 circuit between the first sub-pack 101 and the central contactor 133, and the second auxiliary bus output 112 is connected to the configuration circuit 26 between the second sub-pack 102 and the central contactor 103. This approach allows at least one auxiliary bus to be connected in most failure states – such as for all the single contactor failure short circuit states discussed above – and thus ensures vital systems can continue to operate in the event of failure if they are either provided on both auxiliary buses or can be switched between the two. This may also be used to enable a limp home mode by ensuring that necessary systems driven from a 400V bus will also be available.

A suitable diagnostic state will now be described with reference to Figure 5, involving a number of sub-states. This involves a standby state 6101 (which may be equivalent to HV disconnect 600, but here shown as a separate sub-state) in which the diagnostic process starts and to which the diagnostic state reverts after any detected failure. In the diagnostic process, the central (bridging) contactor 133 is first tested 6102, with reversion to the standby state 6101 in the event of failure. Limb contactors 132, 134 are then tested in turn 6103, 6104 with any failure resulting in reversion to the standby state 6101. If the tested contactors have not failed the system can advance to the both sub-packs available state 621. If there has been a failure, there will be reversion to HV disconnect state 600 but knowledge of the specific failure will, in the case of a single failure, allow progression to one of the sub-pack available states 622, 623.

It should be noted that the diagnostic state 610 is not the only time when fault diagnosis occurs. The measurement system is adapted to determine when other contactors fail by specific responses in the event of failure (see Table 1) which are detectable during the normal start-up sequence. The purpose of the diagnostic state 610 is to ensure that contactor failures that are not otherwise directly detectable as a part of the normal start-up process are nonetheless detected.

This diagnostic state 610 may be entered on start-up, but an alternative possibility is that it could be carried out on shutdown (when speed of response is typically less critical). If no contactor failures are detected on shutdown, it may be reasonably assumed that they will be operational on start-up. However, any appropriate choice may be taken as to when to enter the diagnostic state 610 – it may for example be used on both start-up and shutdown, and would typically be used in the case of shutdown as a result of any system fault.

Transitions between individual states will now be described in more detail below.

The transitions between the HV disconnected state 600 and the normal “ready” state 631 before 800V operation for motoring will now be discussed with reference to Figure 7.

In the HV disconnected state 600, all the contactors described above should be in an open circuit state. If any of the contactors has failed into a short circuit state, this is immediately detectable as there will be a voltage detected between a pair of voltage sensors that have been placed in circuit with each other as a result of the contactor failure; for a main contactor or pre-charge contactor that has short circuited, the relevant sub-pack voltage will be seen across the voltage sensors connected to either end of that sub-pack; for a limb contactor the relevant sub-pack voltage will be seen between the voltage sensor located between the sub-pack battery cells and the pre-charge contactor group and the opposite power rail (i.e. not the one adjacent to the other side of the pre-charge contactor group); for the central contactor 133 the first sub-pack voltage will be seen between the sixth voltage sensor 156 to the second sub-pack side of the central contactor and the eighth voltage sensor to the other side of the first sub-pack battery cells; and for the auxiliary bus contactors the relevant sub-pack voltage will be seen between the voltage sensor to the demand side of the relevant auxiliary bus and the voltage sensor between the contactor group and the sub-pack cells of the associated sub-pack. As indicated above, certain single contactor failures will allow for transition to a 400V state, but these will generally not allow progression to the normal 800V motoring state, so detection of any of these failures in the HV disconnected state will determine possible transitions from the diagnostic state 610 and the path indicated in Figure 7 will not be followed as will lead to unacceptable states (such as a direct short circuit of a sub-pack).

In preparing for the 800V mode, the central contactor 133 is switched to closed circuit. At this point an open circuit failure in central contactor 133 can be detected, as at this point the first sub-pack voltage should be seen between the sixth voltage sensor 156 to the second sub-pack side of the central contactor and the eighth voltage sensor to the other side of the first sub-pack battery cells, so there is an open circuit failure state if it is not.

After this, the auxiliary bus contactors are also closed – similarly, this means that the relevant sub-pack voltage should be seen between the voltage sensor to the demand side of the relevant auxiliary bus and the voltage sensor between the contactor group and the sub-pack cells of the associated sub-pack, and that there is an open circuit failure state if it is not.

The battery pack is not under load at this point, but it is in the both sub-packs available state 621, ready to be primed. To achieve this, the pre-charge process is used to prime the buses. Closing of the pre-charge contactors will indicate other open circuit failure states. If the central contactor 133 is open circuit, neither pre-charge circuit is complete and there will be no pre-charge current detected in either current sensor – there will also be no pre-charge current detected if either pre-charge contactor is open circuit.

When the bus has been primed, the pre-charge circuits are bypassed by closing the respective main contactors for each sub-pack. If either main contactor has an open circuit failure, this will be detectable at this point because the pre-charge resistor will still be taking significant load, so the high voltage drop under load can readily be detected for that sub-pack (for example by the associated current sensor). The pre-charge contactors are then made open circuit to bring the battery pack into the ready state.

The transition from the 800V primed and ready state 631 to the normal motoring state 644 is shown in Figure 8. There is no change in battery pack configuration between these two states, but the inverters can now be driven – typically using a pulse width modulated (PWM) control signal – to provide motive force to the vehicle.

The transition from the normal motoring state 644 back to the HV disconnected state 600 is shown in Figures 9 and 10. Transition to the 800V primed and ready state 631 does not change contactor states, as is shown in Figure 9 – the two states are differentiated only in that no drive signal can be given in the primed and ready state. Transition from the primed and ready state 631 back to the HV disconnected state 600 is slightly simpler than for the opposition transition, as there is no need for any pre-charge steps, only for discharge. Each sub-pack is disconnected by opening its main contactor, and then the auxiliary bus contactors are also disconnected and a discharge path is opened. The central contactor 133 is then opened, leaving the sub-packs fully disconnected – the discharge path remains in circuit to ensure that this is a fully safe disconnected state.

If only one sub-pack is available for use, as will be the case for most single contactor failure states as described above, then the system transitions instead to a limp home state 645. The transitions to this state are shown in Figure 11. In this case, it has been determined in the diagnostic state 610 or otherwise during the start-up sequence that only the first sub-pack 101 can be used, so the second sub-pack 102 is disabled by commanding second main contactor 131, second pre-charge contactor 139, limb contactor 132 and second auxiliary bus contactor 136 to be open circuit. As the battery pack operates in a 400V configuration, central contactor 133 is also open circuit throughout. The system enters the sub-pack primed and ready state by closing the other limb contactor, and then the other auxiliary bus contactor, and entering pre-charge by closing the first sub-pack pre-charge contactor 138. On completion of pre-charge, the first sub-pack main contactor 135 is closed, and the pre-charge circuit disconnected by taking the first sub-pack pre-charge circuit contactor open circuit, thus putting the system into the 400V first sub-pack only primed state 633. This can now transition into the limp home state 645 without change in contactor disposition and drive signal can be provided to power at least one inverter.

In cases where only one sub-pack is in use, there will typically only be one auxiliary bus available for use. There may be some vehicle systems that are most effectively powered off the auxiliary busses and it may be desirable to ensure that this functionality is available even in a limp-home operational state of the vehicle. This could be done by ensuring that such functionality could be obtained from either auxiliary bus. This may involve duplication of certain systems between the first and second auxiliary busses to ensure that this vehicle functionality will be available if either auxiliary bus is available. One such load that will be typically run from an auxiliary bus is the air conditioning (HVAC) compressor. Systems that may be operated from an auxiliary bus in different vehicle types include an electrical generator, water pump, cooling fan, air compressor, oil pump and power steering pump – in some prior art vehicles such systems may be run from a primary bus to ensure that they will be operating if the vehicle is operating, whereas in arrangements as described here they may be run from auxiliary busses with continuity of function still guaranteed. This approach also allows a failure in the relevant system to be managed by simply using the other auxiliary bus – this way failures either in the battery system preventing the use of an auxiliary bus, or of any system on an auxiliary bus, may be managed by switching to the other auxiliary bus.

Disconnection from limp home mode is shown in Figure 12. Again, this shows an arrangement in which the second sub-pack is not enabled, so the same collection of second sub-pack related contactors, and central contactor 133, are open circuit throughout. The return process is again similar as no pre-charge is needed, so as before the relevant sub-pack is disconnected by taking the relevant main contactor open circuit, the relevant auxiliary bus is disconnected by taking the relevant auxiliary bus contactor open circuit and discharge is started, with the system ending in the HV disconnected state 600 with a discharge path still connected.

Transitions in and out of the 800V charging state are shown with reference to Figures 13 and 14. As is shown in Figure 13, the main battery pack contactors are in the same configuration for the 800V primed and ready state 631 and the 800V charging state 643. Where these differ is that junction box contactors that are otherwise open circuit are made closed circuit in the state transition, with the result that the charging voltage is seen across the whole battery pack. Before this is done, the inverters will be disabled using a suitable command (LV ENABLE) from the vehicle control unit (VCU). Transition from the 800V charging state to normal motoring state 644 can be straightforward, as the battery pack contactor configuration is the same. DC charging will be disabled (this is typically controlled together with the AC charging circuit) and when DC charging voltage removal has been confirmed inverters are enabled by a suitable command (such as LV ENABLE). To shut down from 800V charging, the 800V primed and ready state 631 is entered by making the junction box contactors open circuit, with the system reverting back to the HV disconnected state in exactly the same as was described previously from this state in respect of transitioning from the 800V motoring state 644 to the HV disconnected state 600.

400V charging states and associated transitions will now be described with reference to Figures 15 to 20.

Figure 15 shows the transition from the HV disconnected state 600 to the full battery 400V primed and ready state 632 in which both sub-packs are used – in this case, there is little imbalance between the two sub-packs, so charging both sub-packs together is straightforward. As the battery pack is in a 400V mode, the first step is to close the limb contactors 132, 134, with the central contactor 133 left open circuit throughout – this establishes the two sub-packs as operating in parallel. The same sequence is followed as for previous transitions to a ready state – the auxiliary contactors are closed, the pre-charge contactors are closed, with the battery pack seeing load at this point, the main contactors are closed, bypassing the pre-charge contactors, and the pre-charge contactors are opened. In each case, the contactors for each sub-pack transition together with their equivalent contactor from the other sub-pack. The transition to the charging state is achieved by closing the relevant junction box contactors as before (see Figure 16).

Figure 17 shows how the approach of Figure 15 can be modified if there is a significant imbalance between the two sub-packs – in this case, the first sub-pack is significantly under voltage. The decision is taken only to charge the first sub-pack, and the second sub-park is disabled by forcing the relevant contactors (main, pre-charge, limb and auxiliary bus) open circuit. The contactors associated with the first sub-pack transition in the way shown in Figure 15, and the first sub-pack 400V primed state 633 is reached. This transitions to the first sub- pack 400V charging state 642 by disabling the inverter and closing the junction box contactor as before (as shown in Figure 18). This transition can be made smoother by using the pre-charge circuit of the isolated sub-pack when the under voltage sub-pack (here the first sub-pack) approaches the voltage of the isolated sub-pack.

The shut-down process from the full battery 400V primed and ready state 632 is shown in Figure 19 and from the first sub-pack primed and ready state 633 in Figure 20. These differ only in that the contactors associated with the second sub-pack are open circuit throughout in the transition from the first sub-pack primed and ready state, as the second sub-pack is disabled. The same process of disconnecting the operative sub-packs by opening the associated main contactors, disconnecting the auxiliary buses by opening the associated auxiliary bus contactors and starting discharge, and finally reaching the HV disconnected state 600 with discharge in place is performed in each case.

Additional transitions may be required. For example, the battery pack may be configured for 800V charging, but it is determined that 400V charging is preferred (for example, if there is a fast charger output available but at a lower voltage than 800V). In this case, the system should transition back to the HV disconnected state 600, then forwards again to the full battery HV primed and ready state 632 and so to the full battery 400V charging state 643.

Transition from 400V charging to 800V charging may also be required – this may take place if the sub-packs are out of balance, in which case it may be desirable to charge at 400V to bring the two sub-packs into balance, then switch to 800V charging to charge the battery most effectively. Again, this is achieved by transitioning back from the 400V charging state to the HV disconnected state, then forward to the 800V charging state.

Inverter fault determination is out of the scope of this discussion, but it should be noted that inverter faults may be minor, in which case the inverter is not compromising other system elements and may be recovered, or major, in which case it cannot be used. For a major fault, the inverter is taken entirely out of circuit – the line fuse opens. If the fault is minor, the battery pack contactor configuration is unaffected and the inverter is kept connected to the battery pack – however the PWM control signal to the inverter is switched off, so it cannot be driven to provide motive power. If the fault is resolved, the PWM signals can simply be turned on by the VCU.

Embodiments of the invention are described above, by way of example. The skilled person will appreciate that the invention is not limited to these embodiments and that other embodiments falling within the scope of the claims may be developed lacking, or with alternatives to, features of the embodiments described above. As indicated above, embodiments of the invention are in particular not limited to electric vehicles for which all motive force is provided by a rechargeable cellular battery with no other source of motive force provided in the vehicle.

CLAIMS

1. A battery pack comprising:

a plurality of sub-packs;

a primary bus;

a plurality of switches for connecting the sub-packs to the primary bus, each of the switches having an open state, a closed state, and a failure state in which the switch is immovable from the open state or the closed state; and

a diagnostic circuit for diagnosing a failure state of one or more of the switches, wherein:

some of the switches are arranged as one or more switch groups, the switches within each switch group being arranged in parallel;

the diagnostic circuit comprises voltage sensors for measuring a voltage across each switch group and across each switch not arranged within a switch group, and current sensors for measuring a current drawn from each sub-pack; and

the diagnostic circuit uses the measured voltages and measured currents to determine if any one of the switches is in a failure state.

2. The battery pack of claim 1, further comprising a configuration circuit for configuring the states of the switches, wherein the battery pack has a plurality of operational modes, each operational modes having a different configuration of switch states, and the diagnostic circuit determines if any one of the switches is in a failure state prior to a change in the operational mode of the battery pack.

3. The battery pack of claim 1 or claim 2, wherein the battery pack comprises a first sub-pack and a second sub-pack, the first sub-pack and the second sub-pack are connected across the primary bus when the switches are in a first configuration, and one only of the first sub-pack and the second sub-pack is connected across the primary bus when the switches are in a second configuration.

4. The battery pack of claim 3, wherein the battery pack comprises a first path across the primary bus comprising the first sub-pack and a second path across the primary bus comprising the second sub-pack, wherein the battery pack further comprises a central path connecting the first path to the second path with a central switch disposed on the central path for switching the battery pack between the first configuration and the second configuration.

5. The battery pack of claim 4, wherein each of the first path and the second path comprises a high voltage side and a low voltage side to either side of its connection to the central path, wherein the first sub-pack is disposed on the high voltage side of the first path and the second sub-pack is disposed on the low voltage side of the second path, wherein a first limb switch is disposed on the low voltage side of the first path and a second limb switch is disposed on the high voltage side of the second path.

6. The battery pack of claim 5, wherein the first sub-pack is connected in series with and on the same voltage side as a first switch group for disabling or enabling current flow for the first sub-pack, and the second sub-pack is connected in series with and on the same voltage side as a second switch group for disabling or enabling current flow for the second sub-pack.

7. The battery pack of claim 6, wherein each said switch group comprises a main switch in parallel with a series combination of a pre-charge resistor and a pre-charge switch.

8. The battery pack of any preceding claim, wherein the battery pack comprises at least one auxiliary bus disposed across at least one, but not all, of the sub-packs.

9. The battery pack of claim 8, wherein the connection to each auxiliary bus comprises a respective auxiliary bus switch.

10. An electric vehicle comprising one or more motor units and the battery pack of any one of the preceding claims, wherein the motor units provide motive drive to the vehicle, and wherein the motor units are coupled to the primary bus and operate at an electrical power determined by a current operational mode of the vehicle.

11. A method of diagnosing a contactor failure within a battery pack, the battery pack comprising a plurality of sub-packs, a primary bus, and a plurality of switches for connecting the sub-packs to the primary bus, each of the switches having an open state, a closed state, and a failure state in which the switch is immovable from the open state or the closed state, wherein some of the switches are arranged as one or more switch groups, the switches within each switch group being arranged in parallel, and wherein the method comprises:

measuring a voltage across each switch group and across each switch not arranged within a switch group;

measuring a current drawn from each sub-pack; and using the measured voltages and measured currents to determine if any one of the switches is in a failure state.

12. The method of claim 11, wherein the battery pack is a battery pack of an electric vehicle.

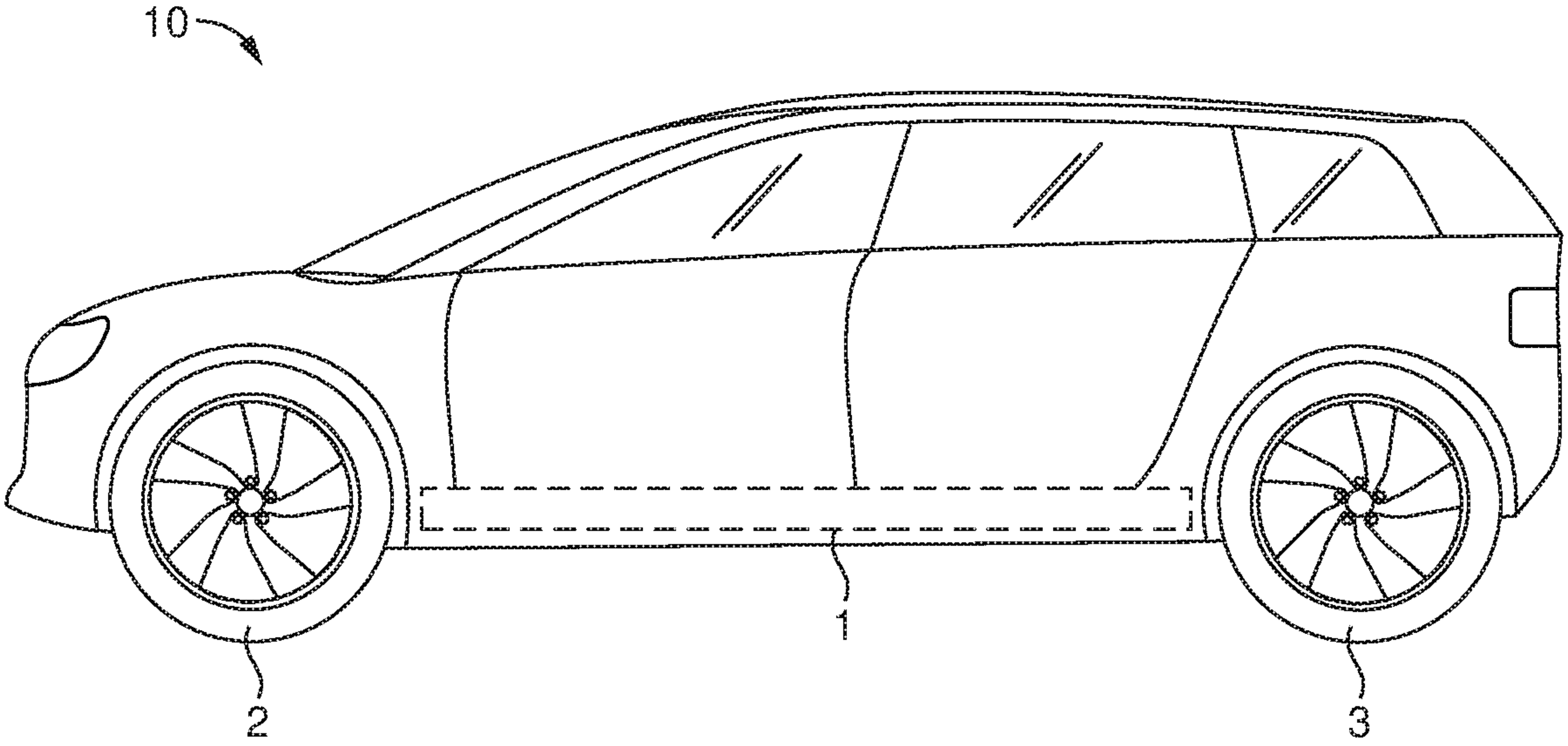


FIG. 1

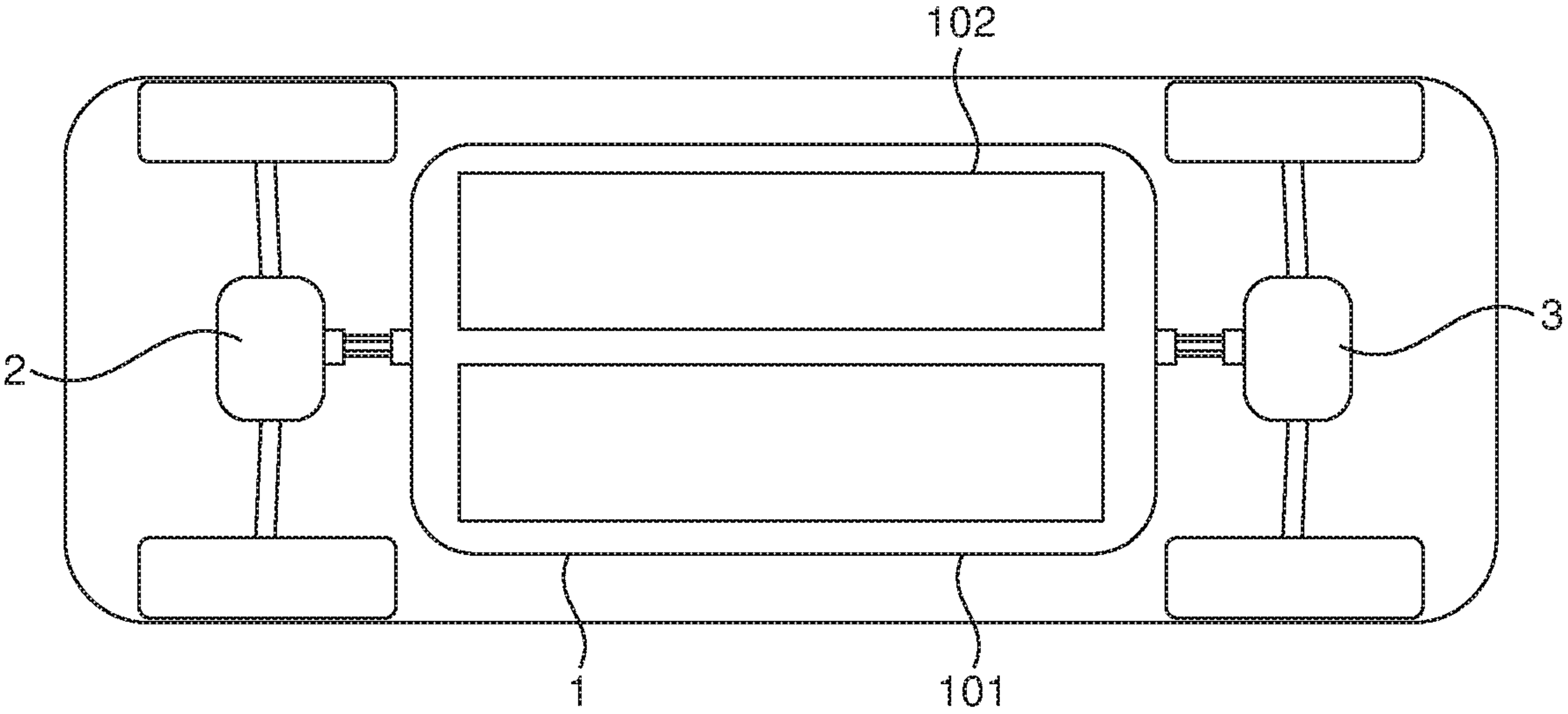


FIG. 2

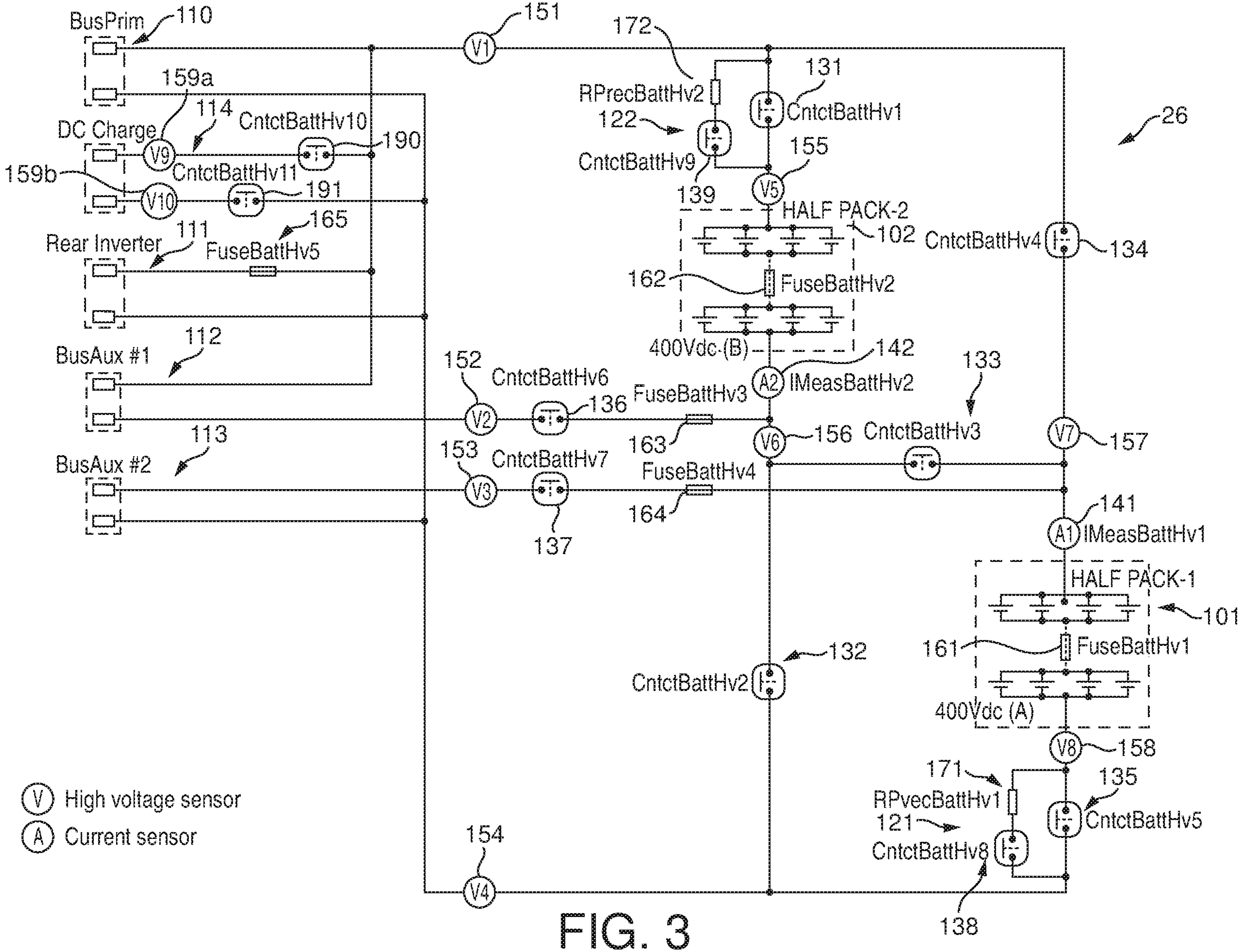
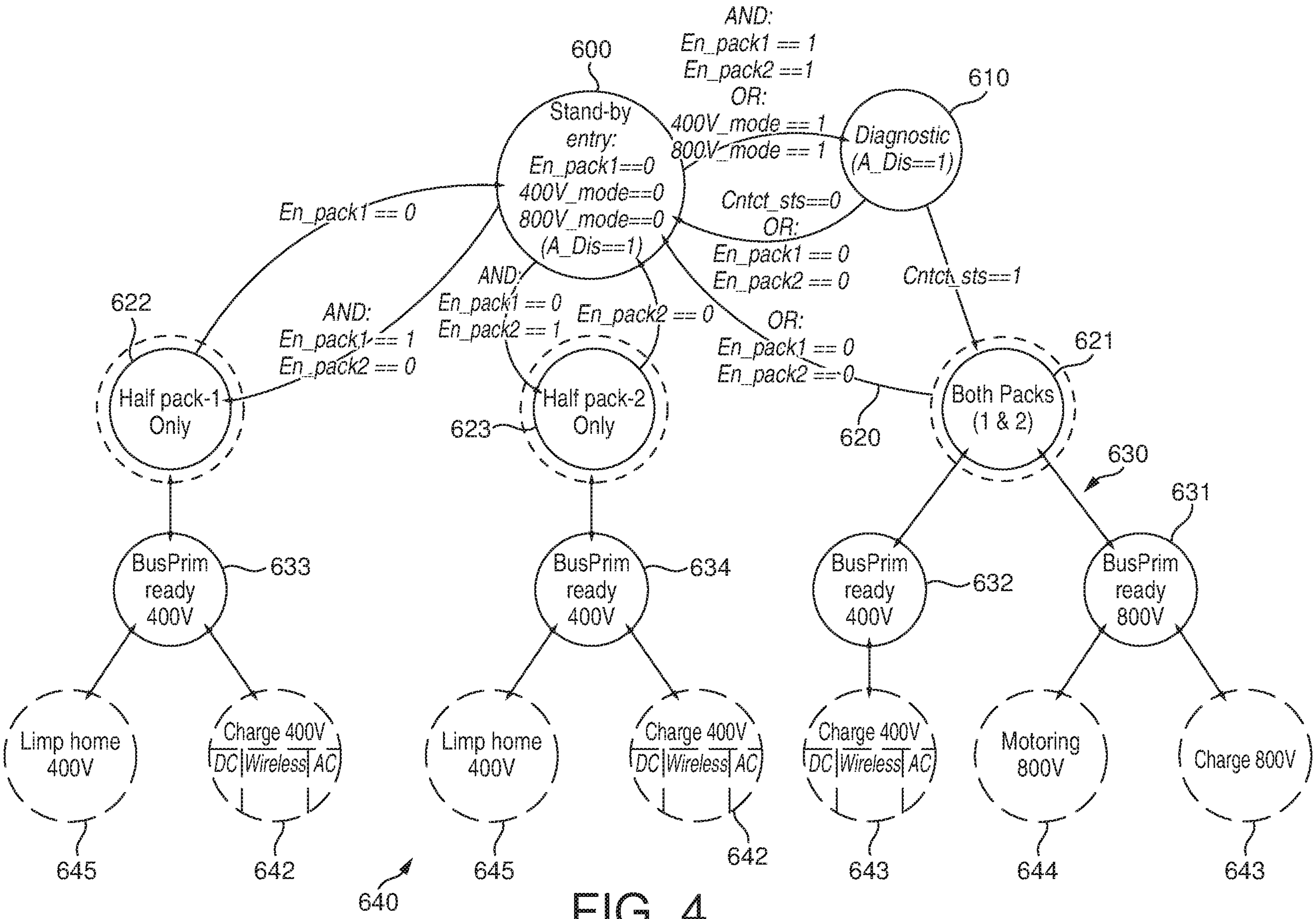

26
BusPrim
110
159a
DC Charge
V9
114
CntctBattHv10
190
159b
V10
CntctBattHv11
191
165
Rear Inverter
111
FuseBattHv5
BusAux #1
112
BusAux #2
113
V1
151
172
RPrecBattHv2
122
CntctBattHv9
139
131
CntctBattHv1
155
V5
HALF PACK-2
102
162
FuseBattHv2
400Vdc-(B)
142
A2
IMeasBattHv2
152
V2
CntctBattHv6
136
FuseBattHv3
163
V6
156
153
V3
CntctBattHv7
137
FuseBattHv4
164
133
CntctBattHv3
CntctBattHv4
134
V7
157
141
A1
IMeasBattHv1
HALF PACK-1
101
161
FuseBattHv1
400Vdc (A)
V8
158
132
CntctBattHv2
171
RPvecBattHv1
121
CntctBattHv8
138
135
CntctBattHv5
154
V4
V High voltage sensor
A Current sensor

FIG. 3


600
Stand-by
entry:
En_pack1==0
400V_mode==0
800V_mode==0
(A_Dis==1)
AND:
En_pack1 == 1
En_pack2 ==1
OR:
400V_mode == 1
800V_mode == 1
610
Diagnostic
(A_Dis==1)
Cntct_sts==0
OR:
En_pack1 == 0
En_pack2 == 0
Cntct_sts==1
En_pack1 == 0
AND:
En_pack1 == 1
En_pack2 == 0
AND:
En_pack1 == 0
En_pack2 == 1
En_pack2 == 0
OR:
En_pack1 == 0
En_pack2 == 0
622
Half pack-1
Only
623
Half pack-2
Only
620
621
Both Packs
(1 & 2)
630
631
BusPrim
ready
400V
633
BusPrim
ready
400V
634
BusPrim
ready
400V
632
BusPrim
ready
800V
Limp home
400V
Charge 400V
DC Wireless AC
Limp home
400V
Charge 400V
DC Wireless AC
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DC Wireless AC
Motoring
800V
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645
642
640
645
642
643
644
643

FIG. 4

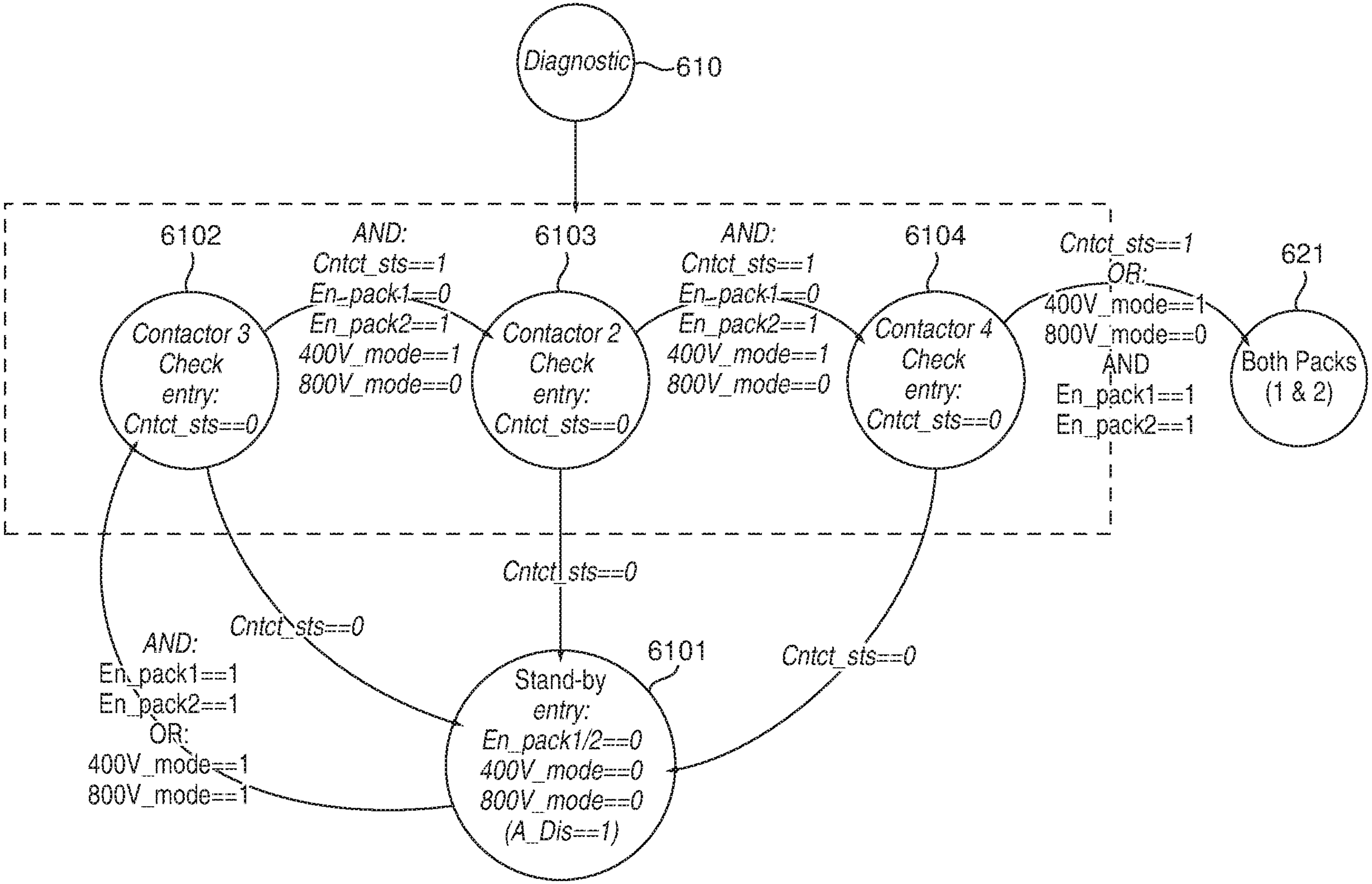
Diagnostic
610
6102
Contactor 3
Check
entry:
Cntct_sts==0
AND:
Cntct_sts==1
En_pack1==0
En_pack2==1
400V_mode==1
800V_mode==0
6103
Contactor 2
Check
entry:
Cntct_sts==0
AND:
Cntct_sts==1
En_pack1==0
En_pack2==1
400V_mode==1
800V_mode==0
6104
Contactor 4
Check
entry:
Cntct_sts==0
Cntct_sts==1
OR:
400V_mode==1
800V_mode==0
AND
En_pack1==1
En_pack2==1
621
Both Packs
(1 & 2)
Cntct_sts==0
Cntct_sts==0
Cntct_sts==0
AND:
En_pack1==1
En_pack2==1
OR:
400V_mode==1
800V_mode==1
6101
Stand-by
entry:
En_pack1/2==0
400V_mode==0
800V_mode==0
(A_Dis==1)

FIG. 5

		[CH1] Half Pack 1 Enable				[CH2] Half Pack 2 Enable						[CH1] Half Pack 1 Enable				[CH2] Half Pack 2 Enable						[CH1] Half Pack 1 Enable				[CH2] Half Pack 2 Enable						[CH1] Half Pack 1 Enable				[CH2] Half Pack 2 Enable					
		0				0						0				1						1				0						1				1					
		[CH3] Half Pack		[CH4] 400V Mode		[CH5] Precharge		[CH6] Auxiliaries		[CH7] 800V Mode		[CH3] Half Pack		[CH4] 400V Mode		[CH5] Precharge		[CH6] Auxiliaries		[CH7] 800V Mode		[CH3] Half Pack		[CH4] 400V Mode		[CH5] Precharge		[CH6] Auxiliaries		[CH7] 800V Mode		[CH3] Half Pack		[CH4] 400V Mode		[CH5] Precharge		[CH6] Auxiliaries		[CH7] 800V Mode	
		0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
Contactor State	CntctBattHv1	0	0	0	0	x	x	x	x	x	x	0	1	0	1	x	x	x	x	x	x	0	0	0	0	x	x	x	x	x	x	0	1	0	1	x	x	x	x	x	x
	CntctBattHv2	x	x	0	0	x	x	x	x	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	1	x	x	x	x	x	x	x	x	0	1	x	x	x	x	x	x
	CntctBattHv3	x	x	x	x	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	1
	CntctBattHv4	x	x	0	0	x	x	x	x	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	1	x	x	x	x	x	x	x	x	0	1	x	x	x	x	x	x
	CntctBattHv5	0	0	0	0	x	x	x	x	x	x	0	0	0	1	x	x	x	x	x	x	0	0	0	0	x	x	x	x	x	x	0	1	0	1	x	x	x	x	x	x
	CntctBattHv6	x	x	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	1	x	x	x	x	x	x	x	x	0	1	x	x	x	x	x	x	x	x	0	1	x	x
	CntctBattHv7	x	x	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	1	x	x
	CntctBattHv8	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	1	x	x	x	x
	CntctBattHv9	x	x	x	x	0	0	x	x	x	x	x	x	x	x	0	1	x	x	x	x	x	x	x	x	0	1	x	x	x	x	x	x	x	x	0	1	x	x	x	x

FIG. 6

State	Reconfig Contactor Reference (CntctBattHv***xx***)															Comment
	Half Pack	1	5	400V Mode	2	4	800V Mode	3	Auxiliaries	6	7	Pre-charge	8	9		
A	**0**	0	0	**0**	0	0	0	0	**0**	0	0	**0**	0	0		HV Disconnected, discharge contactors closed
B	**0**	0	0	**0**	0	0	**1**	1	**0**	0	0	**0**	0	0		Prepare for 800V precharge (no load)
C	**0**	0	0	**0**	0	0	**1**	1	**1**	1	1	**0**	0	0		Auxiliary contactor closed (no load)
D	**0**	0	0	**0**	0	0	**1**	1	**1**	1	1	**1**	1	1		Close pre-charge contactors **(under load)**
E	**1**	1	1	**0**	0	0	**1**	1	**1**	1	1	**1**	1	1		Bypass pre-charge circuits
F	**1**	1	1	**0**	0	0	**1**	1	**1**	1	1	**0**	0	0		Disconnect pre-charge circuits

FIG. 7

State	Reconfig Contactor Reference (CntctBattHv***xx***)													
	Half Pack	1	5	400V Mode	2	4	800V Mode	3	Auxiliaries	6	7	Pre-charge	8	9
F	**1**	1	1	**0**	0	0	**1**	1	**1**	1	1	**0**	0	0
F	**1**	1	1	**0**	0	0	**1**	1	**1**	1	1	**0**	0	0

FIG. 8

State	Reconfig Contactor Reference (CntctBattHv***xx***)													
	Half Pack	1	5	400V Mode	2	4	800V Mode	3	Auxiliaries	6	7	Pre-charge	8	9
F	1	1	1	**0**	0	0	1	1	1	1	1	**0**	0	0
F	1	1	1	**0**	0	0	1	1	1	1	1	**0**	0	0

FIG. 9

State	Reconfig Contactor Reference (CntctBattHv***xx***)															Comment
	Half Pack	1	5	400V Mode	2	4	800V Mode	3	Auxiliaries	6	7	Pre-charge	8	9		
F	**1**	1	1	**0**	0	0	**1**	1	**1**	1	1	**0**	0	0		BusPrim ready at 800V
C	**0**	0	0	**0**	0	0	**1**	1	**1**	1	1	**0**	0	0		Disconnect half packs
B	**0**	0	0	**0**	0	0	**1**	1	**0**	0	0	**0**	0	0		Disconnect auxiliaries and start discharge
A	**0**	0	0	**0**	0	0	**0**	0	**0**	0	0	**0**	0	0		HV disconnected discharge remains engaged

FIG. 10

One Half Pack Available								HPEn1		1	HPEn2		0			
State	Reconfig Contactor Reference (CntctBattHv***xx***)															Comment
	Half Pack	**1**	**5**	400V Mode	**2**	**4**	800V Mode	**3**	Auxiliaries	**6**	**7**	Pre-charge	**8**	**9**		
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0		HV Disconnected, discharge contactors closed
G	0	0	0	1	0	1	0	0	0	0	0	0	0	0		Prepare for 400V precharge (no load)
H	0	0	0	1	0	1	0	0	1	0	1	0	0	0		Auxiliary contactor closed (no load)
I	0	0	0	1	0	1	0	0	1	0	1	1	1	0		Close pre-charge contactors **(under load)**
J	1	0	1	1	0	1	0	0	1	0	1	1	1	0		Bypass pre-charge circuits
K	1	0	1	1	0	1	0	0	1	0	1	0	0	0		Disconnect pre-charge circuits

FIG. 11

One Half Pack Available								HPEn1		1	HPEn2		0			
State	Reconfig Contactor Reference (CntctBattHv***xx***)															Comment
	Half Pack	**1**	**5**	400V Mode	**2**	**4**	800V Mode	**3**	Auxiliaries	**6**	**7**	Pre-charge	**8**	**9**		
K	1	0	1	1	0	1	0	0	1	0	1	0	0	0		BusPrim ready at 400V
H	0	0	0	1	0	1	0	0	1	0	1	0	0	0		Disconnect half packs
G	0	0	0	1	0	0	0	0	0	0	0	0	0	0		Disconnect auxiliaries and start discharge
A	0	0	0	0	0	0	0	0	0	0	0	0	1	0		HV disconnected discharge remains engaged

FIG. 12

State	Reconfig Contactor Reference (CntctBattHv**xx**)															Comment	CntctJbxHv**xx**
	Half Pack			400V Mode			800V Mode		Auxiliaries			Pre-charge					DC Charge
		1	5		2	4		3		6	7		8	9			1&2
F	1	1	1	0	0	0	1	1	1	1	1	0	0	0		BusPrim ready at 800V	0
F	1	1	1	0	0	0	1	1	1	1	1	0	0	0		CntctJbxHv1 & 2 Controlled by AC Charger#1	1

FIG. 13

State																Comment	CntctJbxHv**xx**
	Half Pack			400V Mode			800V Mode		Auxiliaries			Pre-charge					DC Charge
		1	5		2	4		3		6	7		8	9			1&2
F	1	1	1	0	0	0	1	1	1	1	1	0	0	0		BusPrim ready at 800V	1
F	1	1	1	0	0	0	1	1	1	1	1	0	0	0		CntctJbxHv1 & 2 Controlled by AC Charger#1	0

FIG. 14

HV Disconnected → BusPrim ready at 400 V MINIMAL IMBALANCE BETWEEN HALF PACKS (both half packs to be charged together)															
Both Half Packs Available							HPEn1	1	HPEn2	1					
State	Reconfig Contactor Reference (CntctBattHv***xx***)														Comment
	Half Pack	**1**	**5**	400V Mode	**2**	**4**	800V Mode	**3**	Auxiliaries	**6**	**7**	Pre-charge	**8**	**9**	
A	**0**	0	0	**0**	0	0	**0**	0	**0**	0	0	**0**	0	0	HV Disconnected, discharge contactors closed
G	**0**	0	0	**1**	1	1	**0**	0	**0**	0	0	**0**	0	0	Prepare for 400V precharge (no load)
H	**0**	0	0	**1**	1	1	**0**	0	**1**	1	1	**0**	0	0	Auxiliary contactor closed (no load)
I	**0**	0	0	**1**	1	1	**0**	0	**1**	1	1	**1**	1	1	Close pre-charge contactors **(under load)**
J	**1**	1	1	**1**	1	1	**0**	0	**1**	1	1	**1**	1	1	Bypass pre-charge circuits
K	**1**	1	1	**1**	1	1	**0**	0	**1**	1	1	**0**	0	0	Disconnect pre-charge circuits

FIG. 15

BusPrim ready 400V → Charge 400V DC (both half packs)																
Both Half Packs Available					HPEn1	1		HPEn2	1							
State	Reconfig Contactor Reference (CntctBattHv***xx***)														Comment	CntctJbxHv**xx**
	Half Pack	**1**	**5**	400V Mode	**2**	**4**	800V Mode	**3**	Auxiliaries	**6**	**7**	Pre-charge	**8**	**9**		DC Charge **1&2**
K	**1**	1	1	**1**	1	1	**0**	0	**1**	1	1	**0**	0	0	BusPrim ready at 400V	**0**
K	**1**	1	1	**1**	1	1	**0**	0	**1**	1	1	**0**	0	0	CntctJbxHv1 & 2 Controlled by AC Charger#1	1

FIG. 16

HV Disconnected → BusPrim ready at 400V(Charging) Half Pack 1 significantly undervoltage (brought into balance by charging alone)																
Half Pack 1 Available To Charge							HPEn1		1		HPEn2		0			
State	Reconfig Contactor Reference (CntctBattHv***xx***)															Comment
	Half Pack	**1**	**5**	400V Mode	**2**	**4**	800V Mode	**3**	Auxiliaries	**6**	**7**	Pre-charge	**8**	**9**		
A	**0**	0	0	**0**	0	0	0	0	**0**	0	0	**0**	0	0		HV Disconnected, discharge contactors closed
G	**0**	0	0	**1**	0	1	**0**	0	**0**	0	0	**0**	0	0		Prepare for 400V precharge (no load)
H	**0**	0	0	1	0	1	**0**	0	**1**	0	1	**0**	0	0		Auxiliary contactor closed (no load)
I	**0**	0	0	1	0	1	**0**	0	1	0	1	**1**	1	0		Close pre-charge contactors **(under load)**
J	**1**	0	1	1	0	1	**0**	0	1	0	1	**1**	1	0		Bypass pre-charge circuits
K	1	0	1	1	0	1	**0**	0	1	0	1	**0**	0	0		Disconnect pre-charge circuits

FIG. 17

BusPrim ready 400V → Charge 400V DC (one half pack)																	
Both Half Packs Available						HPEn1		1		HPEn2		0					
State	Reconfig Contactor Reference (CntctBattHv**xx**)															Comment	CntctJbxHv**xx**
	Half Pack	**1**	**5**	400V Mode	**2**	**4**	800V Mode	**3**	Auxiliaries	**6**	**7**	Pre-charge	**8**	**9**			DC Charge **1&2**
K	1	0	1	1	0	1	**0**	0	1	0	1	**0**	0	0		BusPrim ready at 400V	**0**
K	1	0	1	1	0	1	**0**	0	1	0	1	**0**	0	0		CntctJbxHv1 & 2 Controlled by AC Charger#1	1

FIG. 18

Both Half Packs Available		HPEn1	1		HPEn2	1	

State	Reconfig Contactor Reference (CntctBattHv***xx***)															Comment
	Half Pack	1	5	400V Mode	2	4	800V Mode	3	Auxiliaries	6	7	Pre-charge	8	9		
K	1	1	1	1	1	1	0	0	1	1	1	0	0	0		BusPrim ready at 400V
H	0	0	0	1	1	1	0	0	1	1	1	0	0	0		Disconnect half packs
G	0	0	0	1	0	0	0	0	0	0	0	0	0	0		Disconnect auxiliaries and start discharge
A	0	0	0	0	0	0	0	0	0	0	0	0	1	0		HV disconnected discharge remains engaged

FIG. 19

One Half Pack Available		HPEn1	1		HPEn2	0	

State	Reconfig Contactor Reference (CntctBattHv***xx***)															Comment
	Half Pack	1	5	400V Mode	2	4	800V Mode	3	Auxiliaries	6	7	Pre-charge	8	9		
K	1	0	1	1	0	1	0	0	1	0	1	0	0	0		BusPrim ready at 400V
H	0	0	0	1	0	1	0	0	1	0	1	0	0	0		Disconnect half packs
G	0	0	0	1	0	0	0	0	0	0	0	0	0	0		Disconnect auxiliaries and start discharge
A	0	0	0	0	0	0	0	0	0	0	0	0	1	0		HV disconnected discharge remains engaged

FIG. 20

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2020/052916

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01R31/00 G01R31/327 H01M10/48

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)

G01R 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

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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
29 January 2021	08/02/2021

Name and mailing address of the ISA/	Authorized officer
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INTERNATIONAL SEARCH REPORT

International application No

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