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(54) **ADAPTIVE PRE-CHARGE CONTROL FOR ELECTRIC VEHICLE DC LINK CAPACITOR**

(57) An adaptive pre-charge control circuit includes include a high-voltage switch and a control circuit. The high-voltage switch controls the flow of current between an electric battery and a DC link capacitor, the electric battery to supply power to an electric vehicle. The DC link capacitor is made up of a sum of individual input capacitors of multiple subunits within an electric vehicle. The control circuit sends a PWM signal to the high-voltage switch based on a difference between an electric battery voltage and a DC link capacitor voltage.

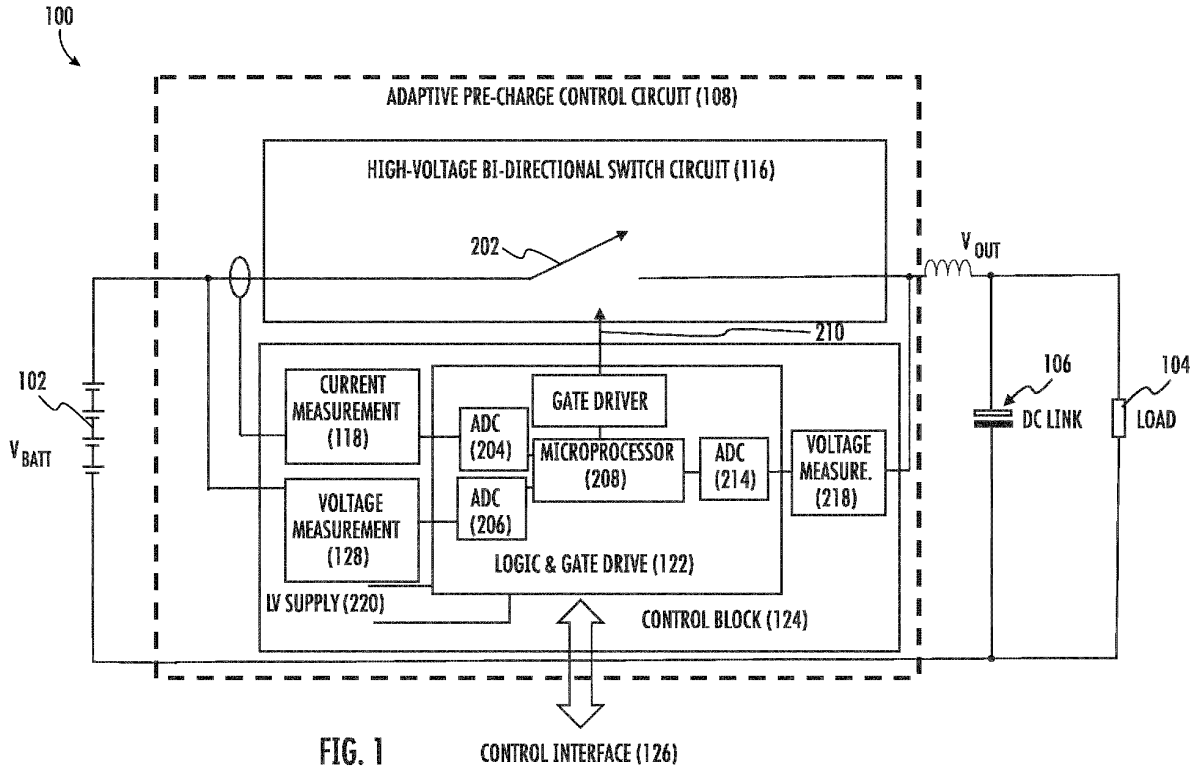

FIG. 1

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Description

Field of the Disclosure

[0001] Embodiments of the present disclosure relate to solid state battery disconnect and protection circuits, including the pre-charge control function.

Background

[0002] Pre-charge circuits are used in high voltage DC applications with capacitive loads that can result in high inrush currents during power up. Pre-charge of the powerline voltages is a preliminary mode which limits the inrush current. The pre-charge circuits thus prevent damage to system components by blocking high amperage current spikes.

[0003] A high voltage system with a large capacitive load can be exposed to high electric current during initial turn-on. If not limited, the current can cause considerable stress or damage to the system components, including, but not limited to, causing contactors to weld closed.

[0004] In electric vehicle applications, battery disconnects are implemented using contactors, overcurrent protection is implemented with a combination of the same contactors controlled by specific circuitry and additional protection elements such as fuses or pyrofuses, and pre-charge control is implemented with additional dedicated circuitry.

[0005] In electric vehicle applications, the large capacitive load is the DC link in the electric motor. The "DC link capacitor" is actually the sum of several parallel capacitors in the subunits within the electric vehicle, one for the electric motor, another for the air conditioning compressor, another for the window enabling, and so on.

[0006] Pre-charging of the DC link capacitor will occur with each vehicle start. The battery voltage may be different in each vehicle start, depending on the battery charge state. Thus, the battery voltage may be any value within the operating range of the battery, for example, 550V-800V in an 800V battery system. The pre-charging circuit limits the inrush current to slowly charge the downstream DC link capacitor. Once the voltage of the DC link capacitor is close to that of the battery, the main switches are permitted to close. Pre-charge circuits thus allow the current to flow in a controlled manner during vehicle startup.

[0007] Pre-charge circuits in electric vehicles, built by an auxiliary switch in series with a large value resistance and placed in parallel with the main switch, control the inrush current going into the vehicle during startup. The main switch is open and the auxiliary switch closed, so that the DC link capacitor is slowly charged, as determined by the resistance. Once the DC link capacitor is sufficiently charged (so that its voltage is close to that of the battery), the main switch is closed all the way and the battery is able to safely supply power to the vehicle.

[0008] The bulky resistors used to implement legacy pre-charge circuits are expensive and occupy a lot of space within the electric vehicle. Additionally, pre-charge contactors are electromechanical components subject to wear and provide a slow response.

[0009] It is with respect to these and other considerations that the present improvements may be useful.

Summary

[0010] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended as an aid in determining the scope of the claimed subject matter.

[0011] An exemplary embodiment of a solid state battery disconnect and protection circuit with an adaptive pre-charge control circuit in accordance with the present disclosure may include a high-voltage switch and a control circuit. The high-voltage switch is connected between an electric battery and a DC link capacitor of an electric vehicle, and the electric vehicle is powered by the electric battery. The control circuit measures a voltage of the electric battery and measures a voltage of the DC link capacitor. The control circuit also sends a pulse width modulated (PWM) signal to the high-voltage switch based on a difference between the electric battery voltage and the DC link capacitor voltage.

[0012] Another exemplary embodiment of an adaptive pre-charge control circuit in accordance with the present disclosure may include a high-voltage switch and a control circuit. The high-voltage switch controls the flow of current between an electric battery and a DC link capacitor. The DC link capacitor is made up of a sum of individual input capacitors of multiple subunits within an electric vehicle. The electric battery supplies power to the electric vehicle. The control circuit sends a pulse width modulated signal to the high-voltage switch based on a difference between an electric battery voltage and a DC link capacitor voltage.

Brief Description of the Drawings

[0013]

FIG. 1 is a diagram illustrating an adaptive pre-charge control circuit for use in an electric vehicle system, in accordance with exemplary embodiments;

FIG. 2 is a diagram illustrating the operating principle of pulse width modulation used by the adaptive pre-charge control circuit of **FIG. 1,** according to exemplary embodiments;

FIGs. 3A-3B are timing diagrams of the adaptive pre-charge control circuit of **FIG. 1,** in accordance with exemplary embodiments; and

FIGs. 4A-4B are timing diagrams of the adaptive pre-charge control circuit of **FIG. 1,** in accordance with exemplary embodiments.

Detailed Description

[0014] An adaptive pre-charge control circuit is disclosed for providing pre-charge capability in an electric vehicle. The adaptive pre-charge control circuit is disposed between an electric battery that supplies power to an electric vehicle and the load of the electric vehicle. By issuing a pulse-width modulated signal to a high-voltage switch, the voltage of a DC link capacitor representing the capacitors of the vehicle load can be slowly changed. Once the voltage of the DC link capacitor is close to that of the electric battery, the high-voltage switch is turned on, enabling current to safely be delivered to the load. The adaptive pre-charge control circuit includes overvoltage protection and current limiting features.

[0015] **FIG. 1** is a representative drawing of an adaptive pre-charge control circuit 108 for providing pre-charge capability in a solid state battery disconnect and protection system 100, according to exemplary embodiments. The solid state battery disconnect and protection system 100 consists of an electric vehicle (EV) battery 102, a load 104, and a DC link capacitor 106, with the adaptive pre-charge control circuit 108 disposed between the EV battery 102 and the load 104. Principally, the load 104 is an EV motor of an electric vehicle, but the load also includes other powered components within the electric vehicle, such as air conditioning compressors, window enabling motors, and so on. Each subunit in the vehicle has an input capacity, with the individual capacitors and number of subunits being unknown. The sum of individual capacitors is the DC link capacity (C_{DC}), symbolized by the DC link capacitor 106.

[0016] The adaptive pre-charge control circuit 108 is a solid state battery disconnect and protection circuit featuring a high-voltage bi-directional switch circuit 116, or high-voltage switch 116 for short, and a control block 124. Solid state battery disconnect and protection circuits use a microprocessor or microcontroller coupled with a current sensor to sample a waveform and detect any overcurrent scenarios. Solid state battery disconnect and protection circuits have very fast response time relative to traditional circuit breakers. The high-voltage switch 116 of the adaptive pre-charge control circuit 108 turns on (closes) or off (opens) to control (enable or prevent) current flow between the EV battery 102 and the load 104. In exemplary embodiments, the control block 124 issues a pulse width modulated (PWM) signal 210 to the high-voltage switch 116, causing a switch 202 therein to turn on and off at a ratio based on the duty cycle of the PWM signal. The on/off rate or number of switching events per time is defined by the PWM switching frequency. The duty cycle defines the ratio between on-time and the switching period.

[0017] A voltage, V_{batt}, of the EV battery 102 and a voltage, V_{out}, of the DC link capacitor 106 are shown. In exemplary embodiments, the adaptive pre-charge control circuit 108 is designed to enable slow charging of the DC link capacitor 106 until its voltage is close to the voltage of the EV battery 102. Once a predefined difference, V_{diff}, between V_{out} and V_{batt} is reached, the high-voltage switch 116 will turn on (close), allowing current to flow freely between the EV battery 102 and the load 104. In this way, the EV battery 102 is able to safely power the load. Stated mathematically, once $V_{batt} - V_{out} \leq V_{diff}$, then the switch will remain closed until the electric vehicle is turned off.

[0018] The control block 124 features a microprocessor 208 and three analog-to-digital converters (ADCs) 204, 206, and 214. The ADC 204 measures the battery voltage, V_{batt}, while the ADC 206 measures the output voltage, V_{out}. Before a computation can be made, the microprocessor 208 is presented with a measurement or a digital representation of the battery voltage, V_{batt}, and the output voltage, V_{out}. The ADCs 204 and 206 measure and convert the voltages to digital values. The microprocessor 208 can then read these results and compute the voltage difference, V_{diff}. Further, the microprocessor 208 generates the PWM pattern to turn the switch 202 on and off. The control block 124 also features current measurement 118 and voltage measurement 128 at the input, V_{batt}, as well as voltage measurement 218 at the output, V_{out}. In exemplary embodiments, the logic and gate drive 122 of the adaptive pre-charge control circuit 108 cause issuance of the PWM signal 210 to the high-voltage switch 116. The PWM signal 210 will enable the high-voltage switch 202 to be turned on or off, thus enabling or preventing current flow between the EV battery 102 and the DC link capacitor 106. By slowly charging the DC link capacitor 106, the current protection block of the adaptive pre-charge control circuit 108 causes the voltage across the DC link capacitor 106 to increase until V_{out} reaches a voltage near that of the EV battery 102, V_{batt}, where the "near voltage" is given by V_{diff}. The adaptive pre-charge control circuit 108 thus implements pre-charge control with a PWM control signal, controlling the pulse width profile to keep the maximum current during the pre-charge within a safe limit. In exemplary embodiments, the value of V_{diff} may be set by the logic and may depend on manufacturer preference, battery voltage, and other factors. In exemplary embodiments, V_{diff} is programmable. Essentially, the minimum V_{diff} is determined to operate such that the adaptive pre-charge control circuit 108 remains in a Safe Operating Area (SOA). If the V_{diff} threshold is set too low below the final battery voltage, it may exceed the SOA in terms of current surge. A dependent factor is the capacitance of the DC link capacitor 106. In exemplary embodiments, a determination is made of an ideal safe limit of the threshold. The logic and gate drive 122 of the control block 124 is connected to a control interface 126, which may be a wired or a wireless connection.

[0019] In exemplary embodiments, the PWM signal

210 of the adaptive pre-charge control circuit 108 supports faster pre-charge using an adaptive measurement method over prior art models which use standard fixed RC time constants. In some embodiments, the current rate of change is measured to help determine an optimum PWM profile.

[0020] In exemplary embodiments, the adaptive pre-charge control circuit 108 is part of the solid state battery disconnect and protection system 100. Regardless of whether in pre-charge mode or regular mode, an overcurrent event will quickly open the high-voltage switch 116. In exemplary embodiments, the sensor used by the current measurement 118 is a Hall-effect sensor that has a pre-defined threshold such that, when the current reaches the threshold, a logic signal will be issued to the logic and gate drive 122. As an alternative to using Hall sensors, the current measurement 118 may use shunt resistances to sense an overcurrent, in some embodiments. In exemplary embodiments, the adaptive pre-charge control circuit 108 also includes a current limiting function. The current sensor in **FIG. 1** consists of the current measurement 118, with the circle denoting the wire being measured. The magnetic flux generated by the flowing current is converted to a voltage via the Hall effect. The voltage is compared to a reference in the sensor that represents the threshold voltage indicating an overcurrent. When an overcurrent occurs, a single logic signal is generated and sent to the logic and gate drive 122. In exemplary embodiments, this happens within millisecond timeframe.

[0021] If the current exceeds a certain limit, the current limiting function is triggered and the adaptive pre-charge control circuit 108 disconnects the battery and load (and stops charging). Without the current limiting function, the current would rise unbounded, stressing or damaging components and interconnects.

[0022] In exemplary embodiments, the switch 202 of the high-voltage switch 116 is a solid state switching device, such as an insulated gate bipolar junction transistor (IGBT), a semiconductor such as a power metal-oxide semiconductor field-effect transistor (MOSFET), a thyristor, a silicon-controlled rectifier (SCR), a triode for alternating current (TRIAC), or any other suitable high-power controlled solid state device. The switch 202 connects or disconnects the EV battery 102 to the vehicle's high-voltage on-board systems. In exemplary embodiments, the switch 202 is bi-directional to allow the EV battery 102 to supply the vehicle (load 104) and to allow a charger to supply the battery. In exemplary embodiments, the switch 202 is controlled by a PWM signal 210 coming from the control block 124.

[0023] Pre-charge circuits are commonly part of high-voltage systems, such as electronic vehicle systems, in which downstream capacitance can be exposed to inrush current when the vehicle is turned on. These pre-charge circuits typically have a large value resistor that is switched in before the vehicle is started and the DC link capacitor is slowly charged. Once the capacitor is sufficiently charged, the switch is closed entirely. Having a set pre-charge threshold does not account for battery discharge after vehicle use. Further, the prior art pre-charge circuits do not utilize pulse-width modulation to control the charging, as is done with the adaptive pre-charge control circuit 108. The adaptive pre-charge control circuit 108 thus provides a novel method to detect battery discharge and set a pre-charge threshold based on initial and final values of battery charge.

[0024] **FIG. 2** is a representative schematic drawing of the operating principle of pulse width modulation used by the adaptive pre-charge control circuit 108, according to exemplary embodiments. In exemplary embodiments, the pulse width of the PWM signal 210 of the adaptive pre-charge control circuit 108 is adapted based on the voltage of V_{batt}. In exemplary embodiments, the adaptive pre-charge control circuit 108 measures the initial battery voltage, V_{batt}, and the DC link capacitor 106 voltage, V_{out}, compares it to the pre-programmed threshold, V_{diff}, and decides accordingly whether to stay in the PWM condition, in which short pulses are issued, or to move to the fully ON condition, in which the switch is closed.

[0025] If the decision is made comparing V_{out} (V_{DC}) to a fixed threshold, different effects may appear depending on how the fixed threshold is set. This is done for two reasons: 1) if the threshold is set too low to consider minimum possible battery voltage, when the battery is fully charged, the inrush current may be too high and 2) if the threshold is set too high to minimize inrush current if the battery is discharged, it may never reach the pre-charge end threshold. The adaptive pre-charge control circuit 108 thus adapts to the health of the battery to solve both conditions.

[0026] For the adaptive pre-charge control circuit 108, after turning on the bi-directional switch 202, the charging current, I_{charge}, builds up. In **FIG. 2,** pulse intervals 302 are shown, with small amounts of current 304, I_{charge}, being issued at each pulse. As the DC link capacitor 106 is initially at zero volts, the charging current without control would be similar to a short circuit current and potentially lead to destruction. By issuing a short pulse, the current remains in safe limits and the DC link capacitor 106 is charged a little. As the current is driven by the voltage difference, V_{diff}, between the battery voltage, V_{batt}, and the DC link voltage, V_{DC}, a growing DC link voltage 306 leads to a lower current for the next pulse. With each pulse, the DC link voltage 306 is increased. From a certain difference, known as the "threshold", the PWM signal 210 can be changed to "turned on". The pulse interval 308 is quite large compared to the earlier pulse intervals 302. The DC link voltage, V_{DC}, quickly reaches the battery voltage, V_{batt}, and the difference between the two becomes zero, thus completing the pre-charging operation. The adaptive pre-charge control circuit 108 thus eliminates the need for bulky pre-charging resistors used in legacy electric vehicles, as well as the correlated losses.

[0027] **FIGs. 3A-3B** are representative timing dia-

grams of empirical tests performed in an EV system, according to exemplary embodiments, which features PWM controlled pre-charge operation but lacks adaptive pre-charge control. The battery voltage of the EV system, V_{batt}, can vary from 120V to 170V at the moment of starting the vehicle, depending on the battery charge. The fixed end-of-pre-charge threshold voltage, $V_{threshold}$, is set to 120V.

[0028] **FIGs. 3A-3B** illustrate a case in which the battery is half charged, and V_{batt} is 150V. At about -0.70ms, vertical lines indicate the PWM controlled pre-charge operation. A steady increasing output voltage, V_{out}, is shown. At point 404, the output voltage, V_{out}, reaches the threshold voltage of 120V. The PWM pulse is released, and V_{out} reaches V_{in} (V_{batt}) with a current peak, which in this case is well within the limits for safe operation.

[0029] **FIGs. 4A-4B** illustrate a case in which the battery is almost fully charged, and V_{batt} is 170V. At ~0.75ms, vertical lines indicate the PWM controlled pre-charge operation. A steadily increasing output voltage, V_{out}, is shown. At point 504, the output voltage, V_{out}, reaches the threshold voltage of 120V. The PWM pulse is released and the current peak exceeds the threshold for safe operation, which may lead to overcurrent damages in the system.

[0030] In addition, if the output voltage, V_{out}, does not reach the fixed end-of-pre-charge threshold voltage, the device will never leave the PWM controlled pre-charge operation. The latest two cases (**FIGs**. **3A-3B** and **FIGs. 4A-4B**) thus illustrate the need for adaptive control. Thus, using the adaptive pre-charge control circuit 108, when the electric vehicle is started, the PWM pre-charge pulse width is adaptive, depending on the voltage of the battery, V_{batt}. For example, if the battery is 800V initially and discharges to 750V, the pre-charge on a subsequent vehicle restart will adjust the pulse width appropriately to charge the DC link capacitor 106 safely, additionally setting an end-of-pre-charge threshold based on the "new" battery voltage. The pre-charge cycle will stop when V_{in} (V_{batt}) = V_{out} (V_{DC}). At that point, DC link capacitor 106 is charged sufficiently, and the high-voltage switch 116 is turned fully ON by the microprocessor 208. Thus, in exemplary embodiments, the adaptive pre-charge control circuit 108 avoids a very large charging current and manages the PWM duty cycle depending on how much the battery has discharged from the initial state.

[0031] The adaptive pre-charge control circuit 108 thus offers several advantages over legacy pre-charge control circuits. The adaptive pre-charge control circuit 108 can monitor battery voltage dynamically to determine an optimum pre-charge threshold. The adaptive pre-charge control circuit 108 PWM can support faster pre-charging using an adaptive measurement method over legacy systems that use fixed RC time constants. And the adaptive pre-charge control circuit 108 can measure the current rate of change to determine an optimum PWM profile.

[0032] As used herein, an element or step recited in the singular and proceeded with the word "a" or "an" should be understood as not excluding plural elements or steps, unless such exclusion is explicitly recited. Furthermore, references to "one embodiment" of the present disclosure are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features.

[0033] While the present disclosure refers to certain embodiments, numerous modifications, alterations, and changes to the described embodiments are possible without departing from the sphere and scope of the present disclosure, as defined in the appended claim(s). Accordingly, it is intended that the present disclosure is not limited to the described embodiments, but that it has the full scope defined by the language of the following claims, and equivalents thereof.

Claims

1. An adaptive pre-charge control circuit, for use in a solid state battery disconnect and protection system, the adaptive pre-charge control circuit comprising:

    a high-voltage switch coupled between an electric battery and a DC link capacitor of an electric vehicle, wherein the electric vehicle is powered by the electric battery; and
    a control circuit to:

        measure a voltage, V_{batt}, of the electric battery;
        measure an output voltage, V_{out}, connected to the DC link capacitor; and
        issue a pulse width modulated (PWM) signal to the high-voltage switch based on a difference, V_{diff}, between V_{batt} and V_{out}.

2. The adaptive pre-charge control circuit of claim 1, the control circuit further comprising:

    a first analog-to-digital converter (ADC) to measure V_{batt}; and
    a second ADC to measure V_{out}.

3. The adaptive pre-charge control circuit of claim 1 or 2, the control circuit further comprising:
    a microprocessor to:

        compute V_{diff}; and
        generate the PWM signal based on V_{diff},

    preferably wherein a width of the PWM signal is based on V_{diff}.

4. The adaptive pre-charge control circuit of any of the preceding claims, further comprising an overvoltage protection circuit to protect the high-voltage switch

from back-EMF.

5. The adaptive pre-charge control circuit of any of the preceding claims, wherein the high-voltage switch comprises one or more semiconductors.

6. The adaptive pre-charge control circuit of any of the preceding claims, the high-voltage switch further comprising an insulated gate bipolar transistor (IGBT).

7. The adaptive pre-charge control circuit of any of the preceding claims, the high-voltage switch further comprising a power metal-oxide semiconductor field-effect transistor, and/or wherein the high-voltage switch is closed once V_{diff} is reached.

8. The adaptive pre-charge control circuit of any of the preceding claims, wherein the high-voltage switch is closed once $V_{batt} = V_{out}$.

9. The adaptive pre-charge control circuit of any of the preceding claims, wherein the DC link capacitor comprises a capacitance of an electric motor of the electric vehicle, and/or
wherein the DC link capacitor comprises a sum of capacitances of subunits of the electric vehicle.

10. An adaptive pre-charge control circuit comprising:

a high-voltage switch to control flow of current between an electric battery and a DC link capacitor, the DC link capacitor comprising a sum of individual input capacitors of a plurality of subunits within an electric vehicle, wherein the electric battery supplies power to the electric vehicle; and
a control circuit to issue a pulse width modulated (PWM) signal to the high-voltage switch based on a difference between an electric battery voltage and a DC link capacitor voltage.

11. The adaptive pre-charge control circuit of claim 10, the control circuit further comprising a microprocessor to:

compute a difference between the electric battery voltage and the DC link capacitor voltage; and
generate the PWM signal based on the computation.

12. The adaptive pre-charge control circuit of claim 10 or 11, the control circuit further comprising: a first analog-to-digital converter (ADC) to measure the electric battery voltage; and
a second ADC to measure the DC link capacitor voltage.

13. The adaptive pre-charge control circuit of any of the claims 10-12 with one of more of the following:

wherein the high-voltage switch comprises a silicon-controlled rectifier;
wherein the high-voltage switch comprises a triode for alternating current.

14. The adaptive pre-charge control circuit of any of the claims 10-13, wherein a width of the PWM signal is computed by the microprocessor, preferably
wherein the width of the PWM signal is increased as the difference between the electric battery voltage and the DC link capacitor voltage decreases.

15. The adaptive pre-charge control circuit of any of the claims 10-14, wherein the high-voltage switch is closed in response to the electric battery voltage being approximately equal to the DC link capacitor voltage.

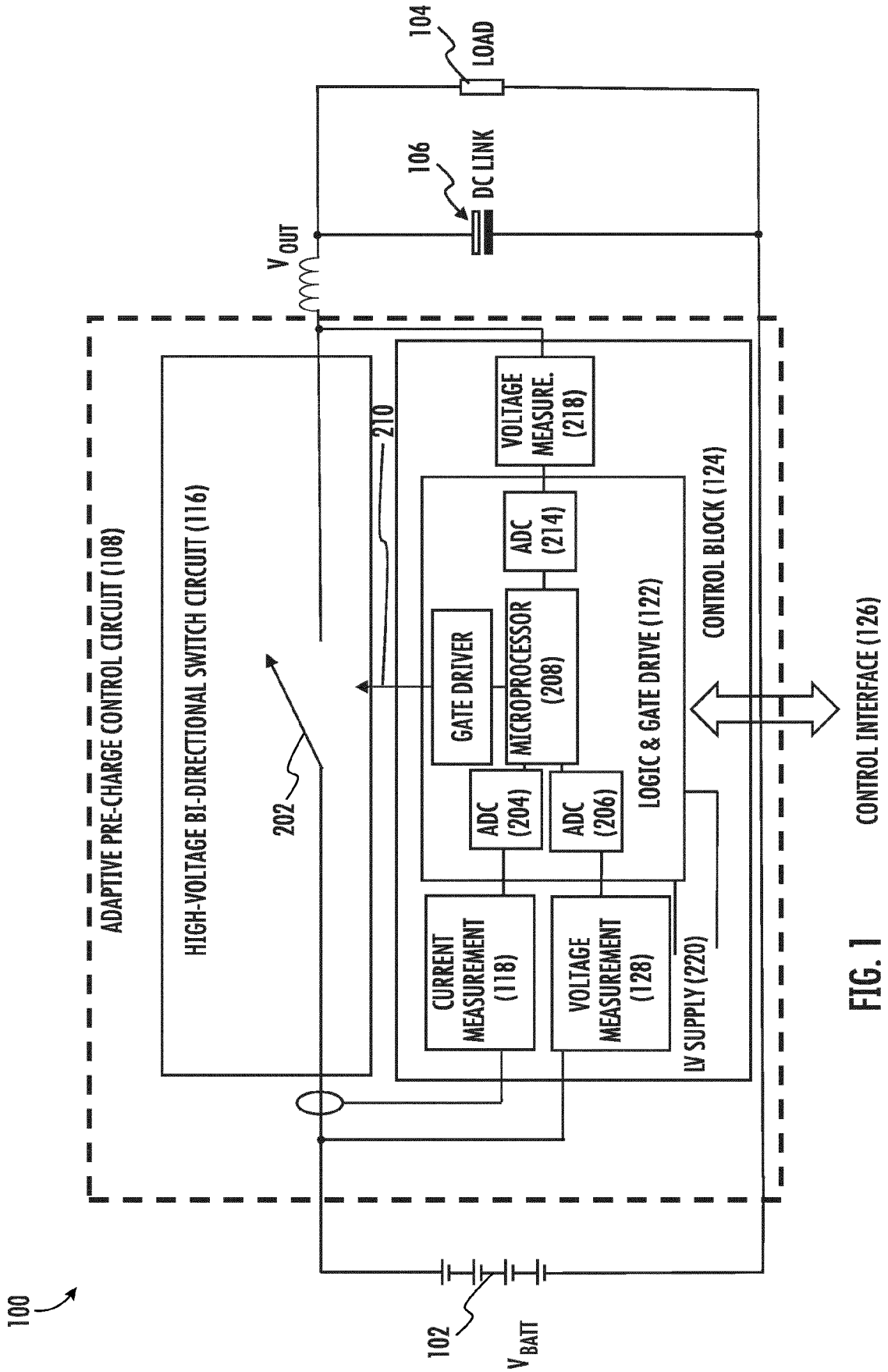

100
102
V_{BATT}
104
LOAD
106
DC LINK
V_{OUT}
ADAPTIVE PRE-CHARGE CONTROL CIRCUIT (108)
HIGH-VOLTAGE BI-DIRECTIONAL SWITCH CIRCUIT (116)
202
210
CONTROL BLOCK (124)
LOGIC & GATE DRIVE (122)
GATE DRIVER
MICROPROCESSOR (208)
ADC (214)
VOLTAGE MEASURE. (218)
ADC (204)
ADC (206)
CURRENT MEASUREMENT (118)
VOLTAGE MEASUREMENT (128)
LV SUPPLY (220)
CONTROL INTERFACE (126)

FIG. 1

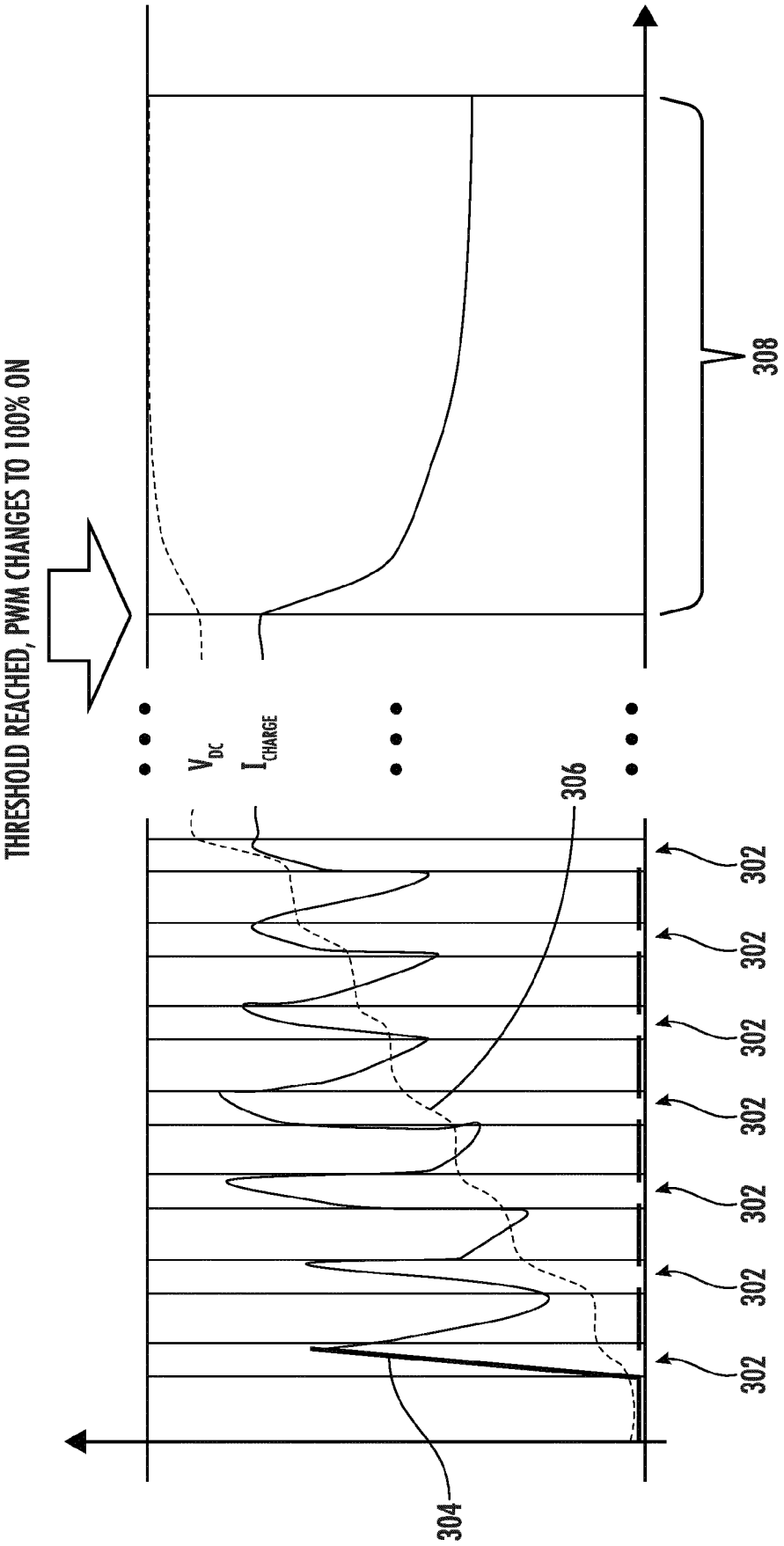
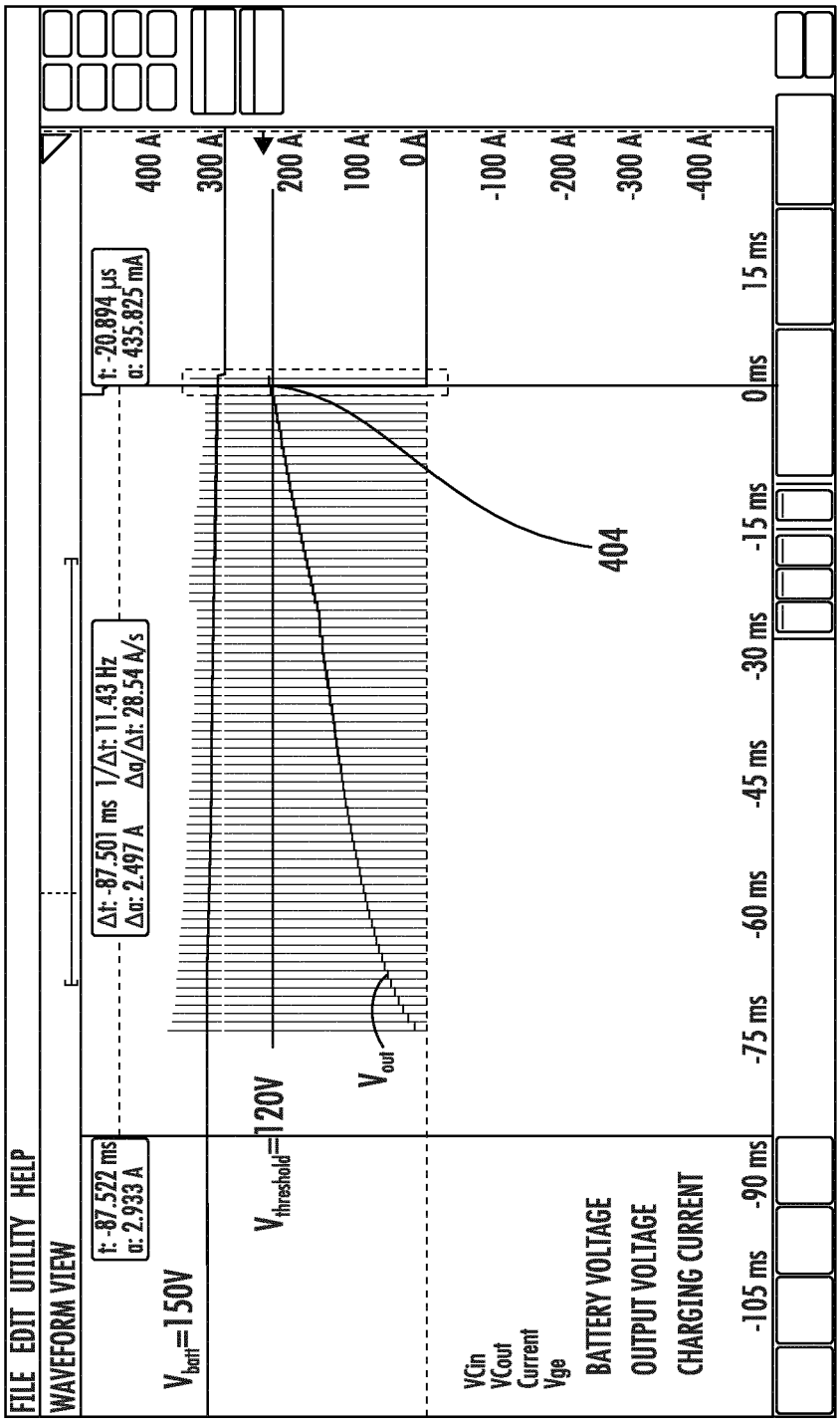

THRESHOLD REACHED, PWM CHANGES TO 100% ON
V_{DC}
I_{CHARGE}
306
308
302
302
302
302
302
302
302
304

FIG. 2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200 A
100 A
0 A
-100 A
-200 A
-300 A
-400 A
-105 ms
-90 ms
-75 ms
-60 ms
-45 ms
-30 ms
-15 ms
0 ms
15 ms
V_{batt}=150V
$V_{threshold}$=120V
V_{out}
404
VCin
VCout
Current
Vge
BATTERY VOLTAGE
OUTPUT VOLTAGE
CHARGING CURRENT

FIG. 3A

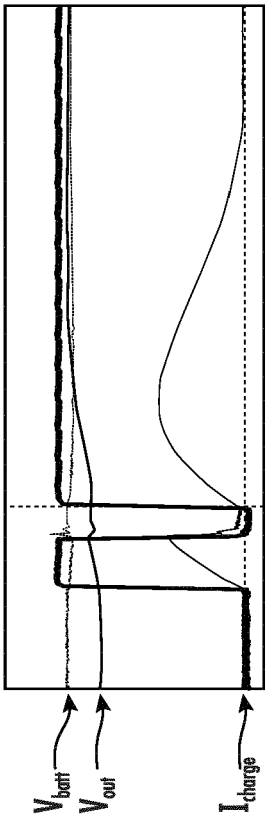
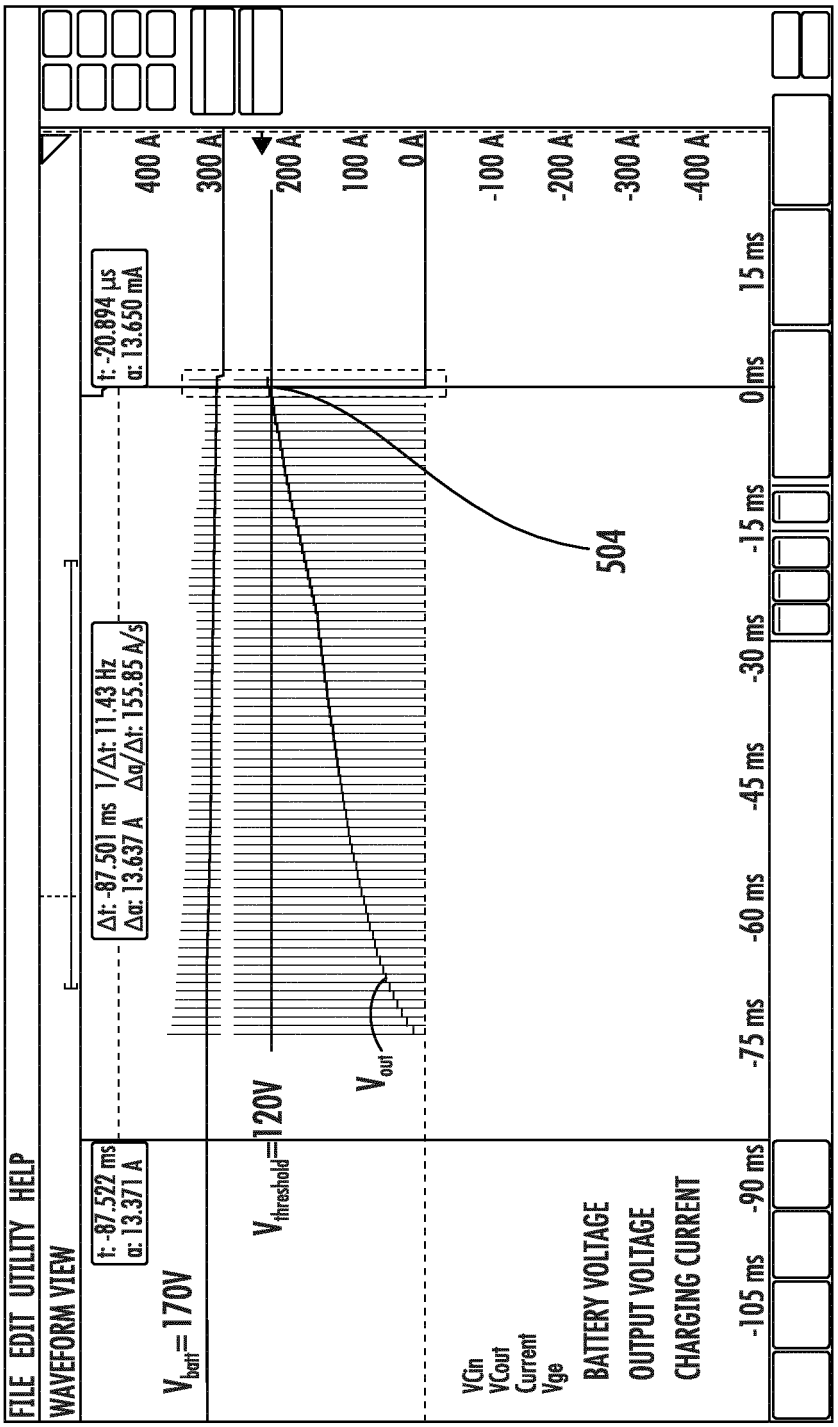

V_{batt}
V_{out}
I_{charge}

FIG. 3B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200 A
100 A
0 A
-100 A
-200 A
-300 A
-400 A
-105 ms
-90 ms
-75 ms
-60 ms
-45 ms
-30 ms
-15 ms
0 ms
15 ms
V_{batt}=170V
$V_{threshold}$=120V
V_{out}
504
VCin
VCout
Current
Vge
BATTERY VOLTAGE
OUTPUT VOLTAGE
CHARGING CURRENT

FIG. 4A

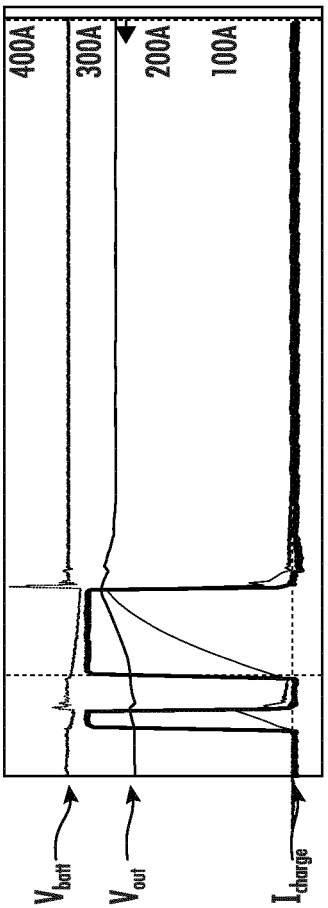
400A
300A
200A
100A
V_{batt}
V_{out}
I_{charge}

FIG. 4B

Europäisches Patentamt
European Patent Office
Office européen des brevets

EUROPEAN SEARCH REPORT

Application Number
EP 23 20 4611

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	WO 2020/194341 A1 (TVS MOTOR CO LTD [IN]) 1 October 2020 (2020-10-01) * paragraphs [0002], [0008], [0012], [0014], [0033] * * figures 1-3 *	1-15	INV. B60L3/04 H02H9/00
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Place of search	Date of completion of the search	Examiner
The Hague	28 February 2024	Herrera Caballero, A

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