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### Battery heating system

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#### Abstract

AC current heating of a battery is performed using a half-bridge based quasi-resonant circuit.

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## Background/Summary

### INTRODUCTION

(1) The subject disclosure relates to heating of high voltage batteries such as Lithium chemistry propulsion batteries found in electric vehicles.

(2) Lithium batteries may be preferred in many applications, including propulsion systems, due to their high energy density. Lithium battery discharge performance at cold temperatures is generally much better than lead-acid or Nickel metal hydride batteries, but discharge performance at cold temperatures is still significantly below battery performance capability at higher temperatures. Low temperature charging is limited by anode plating which may cause performance degradation, capacity loss, internal shorts and irreversible damage. Thus, until a Lithium battery reaches a certain temperature, charging a Lithium battery remains extremely limited and discharge performance is reduced. This is especially true at sub-zero temperatures. Various methods of pre-heating a Lithium battery have been proposed including discharge current self-heating using internal resistance, heating/cooling plates, and PTC devices among others incorporated into the battery structure.

### SUMMARY

(3) In one exemplary embodiment, a heating apparatus for a battery may include a first solid state switch having respective first and second terminals, and a second solid state switch having respective first and second terminals, with the second terminal of the first solid state switch may be coupled to the first terminal of the second solid state switch at a first node. The apparatus may further include a coupling between a positive terminal of the battery and the first node with an inductance between the first node and the battery, a negative terminal of the battery coupled to the second terminal of the second solid state switch at a second node, a capacitance between the second node and the first terminal of the first solid state switch at a third node, and a controller repeatedly

closing the second switch and opening the first switch for a first duration followed by opening the second switch and closing the first switch for a second duration.

(4) In addition to one or more of the features described herein, the inductance may include an intrinsic inductance of the battery.

(5) In addition to one or more of the features described herein, the first solid state switch and the second solid state switch may make one leg of an inverter coupled between a positive DC rail and a negative DC rail.

(6) In addition to one or more of the features described herein, the capacitance may include a capacitor coupled between the positive DC rail and the negative DC rail.

(7) In addition to one or more of the features described herein, the inverter may be a half-bridge inverter.

(8) In addition to one or more of the features described herein, the inverter may be an H-bridge inverter.

(9) In addition to one or more of the features described herein, the inverter may be a polyphase inverter.

(10) In addition to one or more of the features described herein, the controller may be an inverter controller.

(11) In addition to one or more of the features described herein, the closing the switches occurs at zero-voltage conditions.

(12) In another exemplary embodiment, a heating apparatus for a battery may include a battery having a positive terminal and a negative terminal, an electric propulsion system having a polyphase electric machine and a polyphase power inverter, the inverter including a plurality of phase legs coupled between a positive DC rail and a negative DC rail, each phase leg having respective upper and lower switches and a respective phase pole therebetween. Each phase pole may be coupled to a respective phase winding of the polyphase electric machine. The heating apparatus further includes a capacitor coupled between the positive DC rail and the negative DC rail, and a coupling between the positive terminal of the battery and a corresponding phase pole of one of the phase legs with an inductance between the corresponding phase pole and the battery. The negative terminal of the battery may be coupled to the negative DC rail and the positive terminal of the battery may be decoupled from the positive DC rail. The apparatus further includes a controller operating the lower switch of the one of the phase legs complementary to the upper switch of the one of the phase legs, wherein the lower switch is in a closed state while the upper switch is in an open state for a first duration and the lower switch is in an open state while the upper switch is in a closed state for a second duration.

(13) In addition to one or more of the features described herein, the inductance may include an intrinsic inductance of the battery.

(14) In addition to one or more of the features described herein, the heating apparatus may further include a plurality of couplings between the positive terminal of the battery and respective phase poles of a corresponding plurality of phase legs with a respective inductance between the respective phase pole and the battery, and the controller operating the lower switches of the plurality of phase legs complementary to the upper switches of the plurality of phase legs, wherein the lower switches are in a closed state while the upper switches are in an open state for the first duration and the lower switches are in an open state while the upper switches are in a closed state for the second duration.

(15) In addition to one or more of the features described herein, closing the upper switch and the lower switch may occur at zero-voltage conditions.

(16) In addition to one or more of the features described herein, closing the upper switches and the lower switches occurs at zero-voltage conditions.

(17) In addition to one or more of the features described herein, the heating apparatus may include a current sensor for sensing current through the battery, and the controller may be responsive to the

current through the battery and a current setpoint to control the first duration.

(18) In addition to one or more of the features described herein, the current sensor may be a phase winding current sensor corresponding to the one of the phase legs.

(19) In addition to one or more of the features described herein, the controller may be an inverter controller.

(20) In yet another exemplary embodiment, a heating apparatus for a battery may include a quasi-resonant circuit having an inductance, a capacitance, and a solid state half-bridge, and a controller alternating the circuit between a first configuration wherein the inductance is coupled directly across the battery and a second configuration wherein the inductance and the capacitance are in series coupled across the battery.

(21) In addition to one or more of the features described herein, the solid state half-bridge may be one leg of an inverter.

(22) In addition to one or more of the features described herein, the inductance may include an intrinsic inductance of the battery.

(23) The above features and advantages, and other features and advantages of the disclosure are readily apparent from the following detailed description when taken in connection with the accompanying drawings.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

(1) Other features, advantages and details appear, by way of example only, in the following detailed description, the detailed description referring to the drawings in which:

(2) FIG. 1 illustrates a quasi-resonant circuit effecting AC current through a battery, in accordance with one or more embodiments;

(3) FIG. 2 graphically illustrates the operation of a quasi-resonant circuit in accordance with one or more embodiments;

(4) FIG. 3 illustrates an automotive propulsion system including a poly-phase inverter, in accordance with one or more embodiments;

(5) FIG. 4 illustrates an automotive propulsion system including a poly-phase inverter, in accordance with one or more embodiments; and

(6) FIG. 5 illustrates a quasi-resonant circuit effecting AC current through a battery, in accordance with one or more embodiments.

### DETAILED DESCRIPTION

(7) The following description is merely exemplary in nature and is not intended to limit the present disclosure, its application or uses. Throughout the drawings, corresponding reference numerals indicate like or corresponding parts and features. As used herein, control module, module, control, controller, control unit, electronic control unit, processor and similar terms mean any one or various combinations of one or more of Application Specific Integrated Circuit(s) (ASIC), electronic circuit(s), central processing unit(s) (preferably microprocessor(s)) and associated memory and storage (read only memory (ROM), random access memory (RAM), electrically programmable read only memory (EPROM), hard drive, etc.) or microcontrollers executing one or more software or firmware programs or routines, combinational logic circuit(s), input/output circuitry and devices (I/O) and appropriate signal conditioning and buffer circuitry, high speed clock, analog to digital (A/D) and digital to analog (D/A) circuitry and other components to provide the described functionality. A control module may include a variety of communication interfaces including point-to-point or discrete lines and wired or wireless interfaces to networks including wide and local area networks, on vehicle controller area networks and in-plant and service-related networks. Functions of the control module as set forth in this disclosure may be performed in a distributed control

architecture among several networked control modules. Software, firmware, programs, instructions, routines, code, algorithms and similar terms mean any controller executable instruction sets including calibrations, data structures, and look-up tables. A control module has a set of control routines executed to provide described functions. Routines are executed, such as by a central processing unit, and are operable to monitor inputs from sensing devices and other networked control modules and execute control and diagnostic routines to control operation of actuators. Routines may be executed at regular intervals during ongoing engine and vehicle operation. Alternatively, routines may be executed in response to occurrence of an event, software calls, or on demand via user interface inputs or requests.

(8) FIG. 1 illustrates one embodiment of a quasi-resonant circuit **101** effecting AC current through a battery **103** resulting in uniform heating of the battery **103**. Battery may refer to a single battery, multiple batteries, a battery module or a battery pack made up of multiple batteries or battery modules. A first solid state switch **S1 105** and a second solid state switch **S2 107** are coupled to form a half-bridge **129** and defining a first node **127**. Each switch **S1** and **S2** has a respective first terminal **131** and a respective second terminal **133**. The half-bridge **129** is formed by coupling the second terminal **133** of the first switch **S1** to the first terminal **131** of the second switch **S2** at the first node **127**. Each switch **S1** and **S2** includes a control terminal **135** for establishing an open or closed state between the respective first terminal **131** and second terminal **133**. Any suitable solid state device may be employed as switches **S1** and **S2** including, for example, solid state relays and transistors such as Si IGBTs, Si MOSFETs, SiC MOSFETs, GaN HEMTs, SiC JFETs, Diamond, Gallium Oxide and other Wide Band Gap (WBG) semiconductor-based power switch devices. Each switch **S1** and **S2** may also include a respective anti-parallel diode between the respective first and second terminals **131**, **133** either as a discrete component or integrated with each switch **S1**, **S2**. A capacitance **C 111** is coupled between the first switch **S1** first terminal **131** at a second node **128** and the second switch **S2** second terminal **133** at a third node **130**. The second terminal **133** of the second switch **S2** is coupled to a negative terminal **143** of the battery **103**. The node **127** is coupled to the positive terminal **141** of the battery **103** through an inductance and a switch. An inductance **L 109** is thereby coupled between the node **127** and the positive terminal **141** of the battery **103**. The inductance **L** may include any one or more of a component inductor, intrinsic internal battery inductance, and intrinsic inductance in the coupling (e.g., cable and/or busbar). In one embodiment, a switch **113** may enable selective coupling and decoupling of the node **127** from the battery **103**; however, the quasi-resonant circuit **101** is only operational to effect AC current through the battery **103** when node **127** is coupled to the battery. In one embodiment, a capacitor pre-charge circuit **119** may enable selective charging of the capacitance **C 111** connected across the node **128** and node **130** of the half-bridge comprised of **S1** and **S2** by coupling to the battery prior to the quasi-resonant circuit **101** operating to effect AC current through the battery **103**; however, the quasi-resonant circuit **101** is only operational to effect AC current through the battery **103** when the capacitance **C 111** is decoupled from the battery through the pre-charge circuit **119**. The pre-charge circuit in one embodiment may include a current limiting resistor in series with a controllable switch. Thus, it is appreciated that during operation of the quasi-resonant circuit **101** to effect AC current through the battery **103**, the node **127** is coupled to the positive terminal **141** of the battery **103** through the inductance **L 109** and the second node **128** is not directly coupled to the battery **103**.

(9) The quasi-resonant circuit **101** operates by placing the switch **S2** into an ON state and the switch **S1** into an OFF state for a period of time to allow the battery **103** to source current through the inductance **L 109**. Thereafter, the switch **S2** is placed into an OFF state and the switch **S1** is placed into an ON state thereby series coupling the inductance **L 109** and capacitance **C 111** and placing the series LC combination across the battery **103**. The switch **S2** is left in the OFF state and the switch **S1** is left in the ON state long enough for the circuit to oscillate wherein the current through the series LC combination reverses phase (i.e., direction) at least once.

(10) In one embodiment, a current controller **151** may provide a control signal **121** for switch **S2** from which a complementary control signal **121'** is derived. A high signal "1", which stands for a voltage that turns the switch fully ON (e.g., 15V at an IGBT or MOSFET gate terminal **135** with respect to the source **133** terminal), at the control terminals **135** puts the switches **S1**, **S2** into an ON state whereas a low signal "0", which stands for a voltage that turns the switch fully OFF (e.g., 0 to -5V for an IGBT or a MOSFET gate terminal **135** with respect to the source **133** terminal), at the control terminals **135** puts the switches **S1**, **S2** into an OFF state. Current controller **151** may be provided a reference current ( $I_{sub.Ref}$ ) **117** and a sensed battery current ( $I_{sub.Bat}$ ) **115** and provide a PWM signal having a preset or adjustable period and a pulse width of the control signal established by a comparison of the battery current ( $I_{sub.Bat}$ ) **115** to the reference current ( $I_{sub.Ref}$ ) **117**. When the battery current ( $I_{sub.Bat}$ ) **115** exceeds the reference current ( $I_{sub.Ref}$ ) **117**, the current controller **151** establishes the control signal **121** low (0) (switch **S2** to the OFF state) and the control signal **121'** high (1) (switch **S1** to the ON state) for the remainder of the PWM period whereafter the current controller **151** establishes the control signal **121** high (1) (switch **S2** to the ON state) and the control signal **121'** low (0) (switch **S1** to the OFF state). A short delay, known as dead time, may be introduced between the time either of the switches **S1**, **S2** is turned OFF and the other of the switches **S1**, **S2** is turned ON to prevent the capacitance **C 111** being short circuited by **S1** and **S2** being ON simultaneously. During such dead time, both switches **S1** and **S2** are open. In one embodiment, the dead time may be of the order of 0.5  $\mu$ s to 2  $\mu$ s depending on the rated voltage and current of the switches.

(11) Additional referenced is made to FIG. 2 which graphically illustrates the operation of one embodiment of a quasi-resonant circuit, for example quasi-resonant circuit **101** as shown in FIG. 1. Four graphs **201-207** are illustrated along a common horizontal timeline **209** and represent control and responses during operation of quasi-resonant circuit **101**. Graph **201** represents a PWM control signal **202** corresponding to control signal **121** for switch **S2** of FIG. 1. PWM control signal **202** has a period ( $P$ ) including a first pulse width duration ( $PW$ ) and a second ringing duration ( $R$ ). Graph **203** represents the battery current ( $I_{sub.Bat}$ ) **115** which varies in magnitude and phase (+/-). Graph **205** represents battery voltage ( $V_{bat}$ ). Graph **207** represents voltage across the capacitance **C 111** ( $V_{sub.C}$ ). Each pulse width is illustrated relative to a rising edge at time  $t_{sub.0}$  and a falling edge at time  $t_{sub.1}$ . Relative times just prior to  $t_{sub.0}$  are labeled  $t_{sub.0.sup.-}$  and relative times just subsequent to  $t_{sub.0}$  are labeled  $t_{sub.0.sup.+}$ . Similarly, relative times just prior to  $t_{sub.1}$  are labeled  $t_{sub.1.sup.-}$  and relative times just subsequent to  $t_{sub.1}$  are labeled  $t_{sub.1.sup.+}$ . At time  $t_{sub.1.sup.-}$  switch **S2** is in a closed state, switch **S1** is in an open state, and battery current ( $I_{sub.Bat}$ ) is positive. Battery current ( $I_{sub.Bat}$ ) direction through switch **S2** is labeled  $t_{sub.1.sup.-}$  in FIG. 1. At time  $t_{sub.1.sup.+}$  switch **S2** is in an open state, switch **S1** is in a closed state, and battery current ( $I_{sub.Bat}$ ) is positive. Battery current ( $I_{sub.Bat}$ ) direction through switch **S1** is labeled  $W_{in}$  in FIG. 1. The battery current ( $I_{sub.Bat}$ ) at the switching instant may flow through the anti-parallel diode of switch **S1** and thus the switching may be considered a zero voltage switching event for **S1**. During the ringing duration, the battery current ( $I_{sub.Bat}$ ) oscillates through the series LC combination thus reversing the phase of the battery current ( $I_{sub.Bat}$ ). At time  $t_{sub.0.sup.-}$  switch **S2** is in an open state, switch **S1** is in closed state, and battery current ( $I_{sub.Bat}$ ) is negative. Battery current ( $I_{sub.Bat}$ ) direction through switch **S1** is labeled  $t_{sub.0.sup.-}$  in FIG. 1. At time  $t_{sub.0.sup.+}$  switch **S2** is in a closed state, switch **S1** is in an open state, and battery current ( $I_{sub.Bat}$ ) is negative. Battery current ( $I_{sub.Bat}$ ) direction through switch **S2** is labeled  $t_{sub.0.sup.+}$  in FIG. 1. The battery current ( $I_{sub.Bat}$ ) at the switching instant may flow through the anti-parallel diode of switch **S2** and thus the switching may be considered a zero voltage switching event for **S2**.

(12) FIG. 3 illustrates another embodiment of a quasi-resonant circuit effecting AC current through a battery resulting in uniform heating thereof in an automotive application. FIG. 3 shows an embodiment of an exemplary vehicle **301**. The vehicle **301** may be any automobile, truck, aircraft,

construction equipment, farm equipment, factory equipment, etc. whether user or autonomously operated. Vehicle **301** includes an electric propulsion system **302** including a poly-phase AC traction motor **320**. Propulsion system **302** may include a control system **308** including one or more electronic control units (ECU), for example a vehicle controller **370**, a battery manager **371**, and an inverter controller **373**. The control system may be responsible for carrying out functions related to propulsion subsystem monitoring, control and diagnostics based upon a plurality of inputs. The vehicle controller **370** may include one or more ECUs and may be responsible as a supervisor for interpreting various user and environmental inputs, information arbitration, and developing and issuing control commands to various other ECUs including the battery manager **371** and the inverter controller **373** as illustrated by communication lines **342** and **348**. The battery manager may receive a plurality of inputs **340** related to the battery **303** including, for example, battery voltages, currents and temperatures. The inverter controller **373** may receive various inputs **352** used in the monitoring, control and diagnosis of the AC traction motor **320** and inverter **304**, including phase currents  $I_{sub.A}$ ,  $I_{sub.B}$  and  $I_{sub.C}$  from respective current sensors **360**, **361** and **363** and rotor position information from an encoder (not shown). The inverter controller may control the AC traction motor **320** by issuing conduction commands **354** to inverter switches **S1 305**, **S2 307**, **S3 315**, **S4 317**, **S5 335** and **S6 337**. In accordance with one embodiment, the battery manager **371** may provide a battery heating mode request **344** to the inverter controller **373** and provide battery current targets or setpoints **346**.

(13) The inverter **304** includes a positive DC rail **318**, a negative DC rail **322** and a plurality of phase legs therebetween. Phase legs in the exemplary 3-phase inverter **304** include switches **S1** and **S2** coupled at node **327** (phase leg A), Switches **S3** and **S4** coupled at node **328** (phase leg B), and switches **S5** and **S6** coupled at node **329** (phase leg C). Phase leg A node **327** couples to phase windings of the AC traction motor **320** via line **350**. Phase leg B node **328** couples to phase windings of the AC traction motor **320** via line **351**. And phase leg C node **329** couples to phase windings of the AC traction motor **320** via line **353**. Each line **350**, **351** and **353** may have an associated current sensor **360**, **361** and **363**, respectively, for sensing phase currents. High current disconnect switch **SW1 316** is controllable to couple and decouple the positive DC rail **318** and the positive battery terminal **341**. Likewise, high current disconnect switch **SW2 312** is controllable to couple and decouple the negative DC rail **322** and the negative battery terminal **343**. An inverter input filter capacitor **C 311** is coupled between the positive DC rail **318** and the negative DC rail **322**. Switch **314** is controllable to couple and decouple the node **327** of phase leg A to the positive battery terminal. Any leg of the inverter may be employed in the present embodiment as an active half-bridge operable in a quasi-resonant circuit as described. A capacitor pre-charge circuit **319** may enable selective charging of the capacitor **C 311** by coupling to the battery **303** prior to switch **SW1** closures. Similarly, in the present embodiment, the capacitor pre-charge circuit **319** may be employed to pre-charge the capacitor **C 311** prior to effecting AC current heating of the battery using one leg of the inverter **304** in a quasi-resonant circuit. As with the embodiment of FIG. 1, the capacitor **C 311** is decoupled from the battery **303** during AC current heating with the quasi-resonant circuit. The pre-charge circuit **319** in one embodiment may include a current limiting resistor in series with a controllable switch.

(14) When heating of the battery **303** by AC current is invoked, switches **SW1** is kept open and **SW2** is closed. Subsequent to any pre-charging of the capacitor **C 311**, the pre-charge circuit **319** is also opened. Switch **314** is closed to couple the node **327** of phase leg A to the positive battery terminal **341**. An inductance **L 309** is thereby coupled between the node **327** and the positive terminal **341** of the battery **303**. The inductance **L 309** may include any one or more of a component inductor, intrinsic internal battery inductance, and intrinsic inductance in the coupling. It is also envisioned to have the inductance placed between the switch **314** and the node **327** as in FIG. 1. The quasi-resonant circuit is only operational to effect AC current through the battery **303** when node **327** is coupled to the battery, switch **SW1** and pre-charge circuit **319** are opened, and

switch SW2 is closed. In the present embodiment, phase leg A current sensor **360** provides a measure of battery current ( $I_{sub.Bat}$ ) to inverter controller **373**. The inverter controller **373** may control the states of switches **S1** and **S2** in the same manner as described with respect to FIGS. **1** and **2** herein. Thus, it is appreciated that the quasi-resonant operation and AC current heating of the battery **303** may be effected without any added components, relying instead upon intrinsic inductance, existing inverter input filter capacitor **C 311**, and phase current sensor **360**. It is understood, however, that quasi-resonant circuit tuning may be accomplished via additional reactive components and switching networks as understood by one having ordinary skill in the art. (15) FIG. **4** illustrates another embodiment of a quasi-resonant circuit effecting AC current through a battery resulting in uniform heating thereof in an automotive application. FIG. **4** is not labeled as extensively as FIG. **3**; however, it is understood that unless specifically called out, the features of the embodiment of FIG. **3** are shared by the embodiment of FIG. **4**. FIG. **4** shows an embodiment of an exemplary vehicle **401**. The vehicle **401** may be any automobile, truck, aircraft, construction equipment, farm equipment, factory equipment, etc. whether user or autonomously operated. Vehicle **401** includes an electric propulsion system **402**. Thus, the electric propulsion system includes a polyphase AC traction motor, a control system **408** including for example a vehicle controller, a battery manager, and an inverter controller all as described herein with reference to the embodiment of FIG. **3**. The control system may be responsible for carrying out functions related to propulsion subsystem monitoring, control and diagnostics based upon a plurality of inputs all as described with reference to the embodiment of FIG. **3**.

(16) The inverter **404** includes a positive DC rail, a negative DC rail and a plurality of phase legs A, B and C therebetween. Phase legs in the exemplary 3-phase inverter **404** and respective current sensors. The propulsion system may also include a controllable high current disconnect switch **SW1** to couple and decouple the positive DC rail and the positive battery terminal. Likewise, a controllable high current disconnect switch **SW2** may couple and decouple the negative DC rail and the negative battery terminal. An inverter input filter capacitor **C** is coupled between the positive DC rail and the negative DC rail. A capacitor pre-charge circuit **419** may enable selective charging of the capacitor **C** by coupling to the battery prior to switch **SW1** closures. Switch **414** is controllable to individually and mutually exclusively couple and decouple the nodes **427**, **428** and **429** of phase legs A, B and C to the positive battery terminal. Any leg of the inverter may be employed in the present embodiment as an active half-bridge operable in a quasi-resonant circuit as described. In this embodiment, however, multiple phase legs may be employed simultaneously to effectively increase the current capacity of the AC resonant circuit. In this embodiment, the battery current ( $I_{sub.Bat}$ ) would be the equivalent of the summation of the measured phase current of each active half-bridge.

(17) FIG. **5** illustrates another embodiment of a quasi-resonant circuit effecting AC current through a battery resulting in uniform heating thereof in an automotive application. FIG. **5** is not labeled as extensively as FIG. **1**; however, it is understood that unless specifically called out, the features of the embodiment of FIG. **1** are shared by the embodiment of FIG. **5**. FIG. **5** shows an embodiment including a half-bridge **551** formed by coupling the first switch **S1** to the second switch **S2**. The half-bridge in the present embodiment is configured as a half-bridge inverter including a pair of equivalent series coupled capacitors **C1** and **C2**. A load **570** is coupled at one terminal between the capacitors **C1** and **C2** and at the other end the load **570** is selectively coupled to the half-bridge **551** by a switch **571**. A switch **513** selectively couples the positive terminal of the battery **503** to the half-bridge **551**. An inductance **L** is thereby coupled between the half-bridge **551** and the positive terminal of the battery **503**. The inductance **L** may include any one or more of a component inductor, intrinsic internal battery inductance, and intrinsic inductance in the coupling. A switch **521** selectively couples the positive terminal of the battery **503** to the positive DC rail of the half-bridge inverter **551**. The switch **513** enables selective coupling and decoupling of the half-bridge inverter **551** from the battery **503**; however, the quasi-resonant circuit is only operational to effect



AC current through the battery 503 when switch 513 is closed. In one embodiment, a capacitor pre-charge circuit 519 may enable selective charging of the capacitors C1 and C2 by coupling to the battery prior to the quasi-resonant circuit operating to effect AC current through the battery 503; however, the quasi-resonant circuit is only operational to effect AC current through the battery 503 when the pre-charge circuit 519 and switch 521 are open. The switch 521 is closed, the switch 513 is open, and the switch 571 is closed, when the half-bridge is operating in the inverter mode. The switch 521 is open, the switch 513 is closed, and the switch 571 is open, when the half-bridge is operating in the quasi-resonant, AC current heating mode.

(18) The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one more other features, integers, steps, operations, element components, and/or groups thereof.

(19) While the above disclosure has been described with reference to exemplary embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from its scope. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the disclosure without departing from the essential scope thereof. Therefore, it is intended that the present disclosure not be limited to the particular embodiments disclosed, but will include all embodiments falling within the scope thereof

## Claims

1. A heating apparatus for a battery, comprising: a first solid state switch having respective first and second terminals and a second solid state switch having respective first and second terminals, wherein the first solid state switch and the second solid state switch comprise one leg of an inverter coupled between a positive DC rail and a negative DC rail; the second terminal of the first solid state switch coupled to the first terminal of the second solid state switch at a first node; a coupling between a positive terminal of the battery and the first node with an inductance between the first node and the battery, wherein the inductance is switchably connected to the positive terminal of the battery by a third switch; a negative terminal of the battery coupled to the second terminal of the second solid state switch at a second node; a capacitance between the second node and the first terminal of the first solid state switch at a third node; and a controller repeatedly closing the second switch and opening the first switch for a first duration followed by opening the second switch and closing the first switch for a second duration.
2. A heating apparatus for a battery, comprising: a quasi-resonant circuit comprising an inductance, a capacitance, and a solid state half-bridge; and a controller alternating the circuit between a first configuration wherein the inductance is coupled directly across the battery and a second configuration wherein the inductance and the capacitance are in series coupled across the battery.
3. The heating apparatus of claim 2, wherein the solid state half-bridge comprises one leg of an inverter.
4. The heating apparatus of claim 2, wherein the inductance comprises an intrinsic inductance of the battery.
5. The heating apparatus of claim 2, wherein the capacitance comprises a capacitor coupled between a positive DC rail connected to a positive terminal of the battery and a negative DC rail connected to a negative terminal of the battery.
6. The heating apparatus of claim 5, wherein the inductance comprises an intrinsic inductance of the battery.

7. The heating apparatus of claim 1, wherein the capacitance comprises a capacitor coupled between the positive DC rail and the negative DC rail.
  8. The heating apparatus of claim 5, wherein the inverter comprises a half-bridge inverter.
  9. The heating apparatus of claim 5, wherein the inverter comprises an H-bridge inverter.
  10. The heating apparatus of claim 5, wherein the inverter comprises a polyphase inverter.
  11. The heating apparatus of claim 5, wherein the controller comprises an inverter controller.
  12. The heating apparatus of claim 5, wherein closing the switches occurs at zero-voltage conditions.
  13. A heating apparatus for a battery, comprising: a battery having a positive terminal and a negative terminal; an electric propulsion system comprising a polyphase electric machine and a polyphase power inverter, the inverter comprising a plurality of phase legs coupled between a positive DC rail and a negative DC rail, each phase leg including respective upper and lower switches and a respective phase pole therebetween, wherein each phase pole is coupled to a respective phase winding of the polyphase electric machine; a capacitor coupled between the positive DC rail and the negative DC rail; a coupling between the positive terminal of the battery and a corresponding phase pole of one of the phase legs with an inductance between the corresponding phase pole and the battery; the negative terminal of the battery coupled to the negative DC rail and the positive terminal of the battery decoupled from the positive DC rail; and a controller operating the lower switch of the one of the phase legs complementary to the upper switch of the one of the phase legs, wherein the lower switch is in a closed state while the upper switch is in an open state for a first duration and the lower switch is in an open state while the upper switch is in a closed state for a second duration.
  14. The heating apparatus of claim 13, wherein the inductance comprises an intrinsic inductance of the battery.
  15. The heating apparatus of claim 13, further comprising: a plurality of couplings between the positive terminal of the battery and respective phase poles of a corresponding plurality of phase legs with a respective inductance between the respective phase pole and the battery; and the controller operating the lower switches of the plurality of phase legs complementary to the upper switches of the plurality of phase legs, wherein the lower switches are in a closed state while the upper switches are in an open state for the first duration and the lower switches are in an open state while the upper switches are in a closed state for the second duration.
  16. The heating apparatus of claim 13, wherein closing the upper switch and the lower switch occurs at zero-voltage conditions.
  17. The heating apparatus of claim 15, wherein closing the upper switches and the lower switches occurs at zero-voltage conditions.
  18. The heating apparatus of claim 13, further comprising: a current sensor for sensing current through the battery; and the controller responsive to the current through the battery and a current setpoint to control the first duration.
  19. The heating apparatus of claim 18, wherein the current sensor comprises a phase winding current sensor corresponding to the one of the phase legs.
  20. The heating apparatus of claim 13, wherein the controller comprises an inverter controller.
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