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ACTIVE DISCHARGE OF AN ELECTRIC DRIVE SYSTEM

Abstract

A method for discharging a dc link capacitor coupled between a positive rail and a negative rail of an electric drive system. The method comprises generating an internal supply voltage with a relatively high value with respect to the negative rail, driving a control terminal of a power switch based on the internal supply voltage with the relatively high value, detecting a discharge command in the electric drive system, reducing the internal supply voltage from the relatively high value to a relatively lower value in response to the detected discharge command; and driving the control terminal of the power switch based on the internal supply voltage with the relatively lower value, and discharging the dc link capacitor through the power switch when the power switch is driven based on the relatively lower voltage value.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. application Ser. No. 17/665,249, filed Feb. 4, 2022 and currently allowed, which claims priority to European Patent Application No. 21157852.1, filed on Feb. 18, 2021. European Patent Application No. 21157852.1 and U.S. application Ser. No. 17/665,249 are hereby incorporated by reference in their entirety.

TECHNICAL FIELD
[0002] This invention relates to the active discharge of an electric drive system.
BACKGROUND
[0003] Electric drive systems are found in electric vehicles such as, e.g., electric cars and trucks, hybrid electric cars and trucks, and electric trains and trams. Electric vehicles generally include an inverter that converts a battery or other de output into an ac signal for driving an electric motor. In these vehicles, a relatively large and high current capacity energy storage capacitance is commonly used as an intermediate buffer between the battery and the inverter. These capacitances can be referred to as "DC link capacitors" or "smoothing capacitors." These capacitances smoothen the input voltage, provide low-inductive current paths to the inverter output stage, and to store energy
[0004] An electric drive system in a battery-powered electric vehicle will typically be shut down several thousand times over its operational lifespan. During a shutdown, the battery is isolated from the rest of the electric drive system. However, without further measures, the intermediate DC link capacitor will retain a charge after being disconnected from the battery. For safety reasons, regulatory agencies often require that this charge be dissipated reasonably soon after shut down. For example, a typical regulatory requirement would have the DC link capacitor discharged within 2 seconds to a voltage below 60 volts.
[0005] In some cases, a discharge switch and a resistor can be coupled across the DC link capacitor. After disconnection from the battery, this discharge switch is switched into conduction and the DC link capacitor is discharged through the resistor.

Description

DESCRIPTION OF DRAWINGS
[0006] Non-limiting and non-exhaustive embodiments of the present invention are described with reference to the following figures, wherein like reference numerals refer to like parts throughout the various views unless otherwise specified.
[0007] FIG. **1** is a schematic representation of an electric drive system.
[0008] FIG. **2** is a schematic representation of the portion responsible for controlling the provision of power to an electric motor via a single phase leg in the electric drive system of FIG. **1**.
[0009] FIG. **3** is a schematic representation of a supply regulator and the coupling between supply

regulator and the controller of FIG. **1**.

[0010] FIG. **4** is a graph that represents the output characteristics of an IGBT that is suitable for use in an inverter in an electric vehicle drive system.

[0011] FIG. **5** is a swim lane diagram that schematically represents a process for active discharge of a DC link capacitor.

[0012] FIG. **6** is a schematic representation of different waveforms in the electric drive system of FIG. **1**.

[0013] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0014] In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one having ordinary skill in the art that the specific detail need not be employed to practice the present invention. In other instances, well-known materials or methods have not been described in detail in order to avoid obscuring the present invention.

[0015] Reference throughout this specification to "one embodiment", "an embodiment", "one example" or "an example" means that a particular feature, structure or characteristic described in connection with the embodiment or example is included in at least one embodiment of the present invention. Thus, appearances of the phrases "in one embodiment", "in an embodiment", "one example" or "an example" in various places throughout this specification are not necessarily all referring to the same embodiment or example. Furthermore, the particular features, structures or characteristics may be combined in any suitable combinations and/or subcombinations in one or more embodiments or examples. Particular features, structures or characteristics may be included in an integrated circuit, an electronic circuit, a combinational logic circuit, or other suitable components that provide the described functionality. In addition, it is appreciated that the figures provided herewith are for explanation purposes to persons ordinarily skilled in the art and that the drawings are not necessarily drawn to scale.

[0016] As discussed above, regulatory agencies often require that the charge retained on a DC link capacitor after disconnection be dissipated reasonably soon after shut down.

[0017] In embodiments of the present disclosure, one or more of the power switches that drive the electric motor can be used to discharge the DC link capacitor. The amount of current conducted by the power switch is responsive to the difference between a control terminal voltage and a reference terminal voltage of the power switch. A gate drive unit controls the voltage difference between a control terminal and a reference terminal to turn ON and OFF the power switch and discharge the DC link capacitor In embodiments, the difference between the control terminal voltage and the reference terminal voltage may be varied to control current conduction by the power switch during discharge the DC link capacitor.

[0018] FIG. **1** is a schematic representation of an electric drive system **100**. Drive system **100** includes a battery **105** reversibly coupled between a high rail **110** and a low rail **115** by a switch **120**. Drive system **100** also includes an inverter **125**, an electric motor **130**, and a gate drive channel **150**. In operation, under the direction of gate drive channel **150**, inverter **125** converts the dc voltage supplied by battery **105** into an ac voltage and supplies electric motor **130** with power. A DC link capacitor **135** is coupled between rails **110**, **115**. When battery **105** is decoupled from rails **110**, **115** by switch **120**, DC link capacitor **135** is discharged through inverter **125**.

[0019] In more detail, switches **120** are typically mechanical switches and coupled to connect and disconnect battery **105** from rails **110**, **115**. Under normal conditions, battery **105** will be connected to rails **110**, **115** when the vehicle that includes drive system **100** is in operation, e.g., moving or ready to move. Battery **105** will be disconnected from rails **110**, **115** during shut-off or in the event of a sufficiently severe fault condition.

[0020] Upon connection of battery **105** to rails **110**, **115**, both DC link capacitor **135** and inverter **125** will be biased by battery **105**. The voltage developed across DC link capacitor **135** will tend

towards equality with the voltage provided by battery **105**. However, deviations from equality will occur since DC link capacitor **135** accepts and provides charge more quickly than battery **105**. In addition, the DC link capacitor **135** is generally placed closer to the power switches of inverter **125** and at some distance from the battery **105**. The cable inductance can lead to high transient voltage events. DC link capacitor **135** thus acts to smooth the voltage between rails **110**, **115** across inverter **125**.

[0021] Inverter **125** can include a collection of phase legs that are each formed by a pair of switching devices coupled in series between rails **110**, **115**. In general, the switching devices will be insulated-gate bipolar transistors (IGBT) or other power semiconductor devices. Other power semiconductor devices could include transistors such as a gallium nitride (GaN) based transistor, silicon (Si) based transistor, or silicon carbide (SiC) based transistor. Other transistors such as a metal-oxide-semiconductor field-effect transistor (MOSFET) or a bipolar junction transistor (BJT) may also be used. The switching of the switching devices is driven by gate driver circuitry **140** under the control of a controller **145**. Gate driver circuitry **140** is configured to appropriately bias the switching devices in inverter **125** in accordance with control signals received from controller **145**. Controller **145** is configured to generate the control signals in response to higher level control signals. Example of higher level control signals include, e.g., an indication that the vehicle's velocity is to be increased or decreased. In some implementations, the control signals from controller **145** can specify the switching pattern to be used by gate driver circuitry **140** to bias the switching devices in inverter **125**. For example, the control signals from controller **145** can be a pulse-width modulated switching pattern that is converted by gate driver circuitry **140** into a signal that is suitable for driving the switching devices in inverter **125**. In other implementations, the control signals generated by controller **145** are higher level and used by gate driver circuitry **140** to generate a switching pattern. Controller **145** can be implemented, e.g., as a microcontroller that is disposed on the same printed circuit board (PCB) as gate driver circuitry **140**. In other embodiments, controller **145** can be implemented as a microcontroller disposed on a separate PCB than the gate driver circuitry **140**. Like inverter **125**, gate driver circuitry **140** may be referenced to rail **115**. Controller **145** can also be referenced to rail **115**, can be referenced to another voltage, or can include some components that are referenced to rail **115** and other components that are referenced to another voltage.

[0022] In any case, gate driver circuitry **140** and controller **145** can be considered to be part of a gate drive channel **150** that controls the provision of power to electric motor **130** by appropriately driving switches in inverter **125** As discussed further below, controller **145** can also control the switching of one or more of the switching devices in inverter **125** to discharge DC link capacitor **135** when battery **105** is decoupled from rails **110**, **115** by switch **120**.

[0023] FIG. **2** is a schematic representation of a portion of the circuitry in electric drive system **100**, namely, a portion responsible for controlling the provision of power to electric motor **130** via a single phase leg.

[0024] In more detail, electric drive system **100** includes a supply **205**. In general, supply **205** is configured to generate an internal supply voltage (i.e., V.sub.ISO-V.sub.COM) between its output rails **210**. **212**. As shown, supply **205** receives input rails **350**, **355** to generate output rails **210**, **212**. In some implementations, high rail **110** and low rail **115** can act as input rails **350**, **355**, although this is not necessarily the case. For example, with reference to DIN 72552, contacts **30/31** can be coupled to input rails **350**, **355**.

[0025] In the illustrated low side portion of electric drive system **100**, an intermediate output with a voltage V.sub.EE that is in a range between V.sub.ISO and V.sub.COM is tied to low rail **115** of battery **115**. As an aside, in a corresponding high side portion of electric drive system **100** which controls the switching of IGBT **240**, the intermediate output of a second supply regulator will be tied to an intermediate node in phase leg **260** of inverter **125**, i.e., output node **250**.

[0026] Returning to the illustrated low side portion of electric drive system **100**, in one example

with the intermediate output **215** of supply **205** tied to low rail **115**, voltage V.sub.ISO **210** is in a voltage range suitable to drive power switch **245** and referenced to rail **115** Further, voltage V.sub.COM **212** is selected to accommodate the turn-off gate voltage of IGBT **245**. In one example voltage V.sub.COM **212** is low with respect to the voltage on rail **115**. In another embodiment, voltage V.sub.COM **212** may be substantially equal to voltage V.sub.EE **215**. By virtue of the conversion performed by supply **205**, the voltage differences between high supply rail **210** V.sub.ISO, low supply rail **212** V.sub.COM, and intermediate output **215** V.sub.EE can be fairly constant even in the face of changes of load conditions during operation of the vehicle. These load condition include the speed of the vehicle and can be reflected in the switching frequency of power switch **245**. Further, the magnitude of the voltage differences between V.sub.ISO, V.sub.EE, and V.sub.COM are selected to provide working the turn-on and turn-off voltages for IGBT **245**. Further, V.sub.ISO, V.sub.EE, and V.sub.COM can be utilized to provide working supply voltages to internal circuitry of gate driver **140**. For example, the voltage difference between V.sub.ISO and V.sub.COM can be between 15-30 V (e.g., 20 Volts). During vehicular driving, the voltage difference between V.sub.EE and V.sub.COM can be, e.g., 0-10 volts (e.g., 5 volts) so that the voltage V.sub.COM on rail **212** is equal to or below the voltage on low rail **115**.

[0027] As discussed further below, the voltage difference between rails **210**, **212** can be changed to discharge DC link capacitor **135** when battery **105** is decoupled from rails **110**, **115**. The change can be implemented by supply **205** under the direction of controller **145**. To this end, controller **145** is coupled to supply **205** by one or more signal lines **270** by which, e.g., controller **145** can signal initiation of the active discharge mode to supply **205** and supply **205** can provide information to controller regarding changes in the voltage difference between rails **210**, **212**.

[0028] Amongst the circuitry in drive system **100** that rails **210** and **212** supply is at least a portion of gate drive channel **150**. The illustrated implementation of a portion of gate drive channel **150** includes a gate driver **140**, a pull up transistor **225**, a pull down transistor **230**, and a single gate resistor **232**. Gate driver **140** is configured to receive control signals and controls transistors **225**, **230** in accordance with those control signals. Pull up transistor **225** is coupled between high supply rail **210** and an output node **235** of the gate drive channel. Pull down transistor **230** is coupled between output node **235** and low rail **212**. Gate resistor **232** conducts drive signals from output node **235** to IGBT **245**.

[0029] Other implementations of this portion of gate drive channel **150** are possible. For example, rather than including output node **235**, the gate of IGBT **245** can be pulled up and down using different channels that each include one transistor and one gate resistor and alternatively couple the gate of IGBT **245** to a respective rail.

[0030] The illustrated portion of electric drive system **100** also includes a single phase leg **260** of inverter **125**. Phase leg **260** includes a pair of IGBTs **240**, **245** coupled in series between positive rail **110** and low supply rail **115**. An output node **250** of inverter **125** is between IGBTs **240**, **245** and reversibly coupled to a single one of either positive rail **110** or low supply rail **115** when a respective one of IGBTs **240**, **245** is switched into conduction.

[0031] Note that the control terminal (i.e., gate) of each IGBT **240**, **245** is coupled to a respective portion of gate drive channel **150**, although only the coupling of IGBT **245** is shown in the schematic illustration. Further, inverter **125** includes additional phase legs (e.g., 3 or 4 phase legs in toto).

[0032] In operation, gate driver **140**—in conjunction with other portions of gate drive channel **150**—will coordinate the switching of IGBTs **240**, **245** and other switches in other legs of inverter **125** in order to power motor **130**. When IGBT **245** is to be biased into conduction, pull down transistor **230** is driven into a non-conductive state by gate driver **140** and pull up transistor **225** is driven into a conductive state. Conduction through pull up transistor **225** biases IGBT **245** positively with respect to low supply rail **215** and into conduction. Current can flow through motor **130** and IGBT **245** to low supply rail **115**. When IGBT **245** is to be biased into non-conduction, pull up transistor

225 is driven into a nonconductive state and pull down transistor **230** is driven into a conductive state by gate driver **140**. Conduction through pull down transistor **230** biases the gate of IGBT **245** negatively with respect to low supply rail **115** and out of conduction. Since supply **205** supplies the voltages V.sub.ISO, V.sub.EE, V.sub.COM, low rail **212** can negatively bias the gate of IGBT **245** and ensure a proper shut-off. However, as discussed above, in alternative implementations the voltage on rail **215** can be substantially equal to the voltage on rail **212**.

[0033] For example, assume that, during vehicular operation, supply **205** supplies a voltage difference of 20 Volts between V.sub.ISO of rail **210** and V.sub.COM of rail **212** with V.sub.EE about 5 volts above V.sub.COM. The voltage difference between V.sub.ISO and V.sub.EE is thus approximately 15 Volts. With pull down transistor **230** in conduction and pull up transistor **225** not conducting, the gate of IGBT **245** will be biased to five volts below V.sub.EE—and hence below the emitter of IGBT **245**. Turn-off of IGBT **245** is insured. With pull up transistor **225** in conduction and pull down transistor **230** not conducting, the gate of IGBT **245** will be biased 15 volts positively with respect to V.sub.EE—and 15 volts above the emitter of IGBT **245**. Turn-on of IGBT **245** is insured and IGBT **245** will conduct with a given transconductance.

[0034] FIG. **3** is a schematic representation of an implementation of a portion of supply **205** and the coupling between supply **205** and controller **145**. The illustrated implementation of supply **205** is a full bridge de/dc converter and includes a bridge controller **305**, a transistor bridge **310**, a transformer **315**, a capacitor **319** and a rectifier **320**. In particular, the supply **205** is shown as a full bridge LLC converter. Other dc/dc converter topologies are possible. Regardless of the particular dc/dc converter topology, supply **205** supplies an internal supply voltage V.sub.ISO-V.sub.COM between high supply rail **210** and low rail **212**. In some implementations, the internal supply voltage V.sub.ISO-V.sub.COM may be regulated, although this is not necessarily the case. As an aside, the voltage V.sub.EE at intermediate output **215** (not shown) can be set between voltages V.sub.ISO, V.sub.COM in a number of different ways including, e.g., a voltage divider that includes resistors, Zener diodes, and/or other elements coupled between rails **210**, **212**. In more detail, transistor bridge **310** includes transistors **330**, **335**, **340**, **345** coupled between a pair of dc supply rails **350**, **355**. DC supply rails **350**, **355** supply dc voltage at a level such that, given the turns ratio of transformer **315**, bridge controller **305** can generate internal supply voltage difference V.sub.ISO-V.sub.COM between high supply rail **210** and low rail **212** using transistor bridge **310** as a full bridge, e.g., in a voltage-mode control scheme. In one embodiment, bridge controller **305** and transistors **330**, **335**, **340**, **345** may be formed as part of an integrated circuit that is manufactured as either a hybrid or monolithic integrated circuit. As shown, transistors **330**, **335**, **340**, **345** are illustrated as n-type MOSFETs, however it should be appreciated that other transistors may be utilized.

[0035] In using bridge **310** as a full bridge, bridge controller **305** can switch transistors **335**, **340** into conduction while maintaining transistors **330**, **345** in a non-conductive state. This configuration applies the voltage difference between rails **350**, **355** minus the voltage across capacitor **319** across an input winding of transformer **315**. In other words, the voltage across the input winding is the voltage on rail **350** minus the voltage on rail **355** minus the voltage across capacitor **319** (assuming that the voltage drops across the switches are negligible). Later, bridge controller **305** can switch transistors **335**, **340** into a non-conductive state and switch transistors **330**, **345** into conduction. This configuration applies the voltage difference between rails **355**, **350** minus the voltage across capacitor **319** across the input winding. In other words, the voltage across the input winding becomes the voltage on rail **355** minus the voltage on rail **350** minus the voltage across capacitor **319** (again assuming the voltage drops across the switches are negligible). An alternating current series of positive and negative pulses is thus applied across the input winding and converted into corresponding ac signal on the output winding of transformer **315** according to the turns ratio and polarity of the windings. Rectifier **320** rectifies the ac signal on the output winding to generate an internal supply voltage difference V.sub.ISO-V.sub.COM, between high

supply rail **210** and low rail **212**.

[0036] Controller **145** is also configured to signal to bridge controller that DC link capacitor **135** is to be discharged. In response, bridge controller **305** can use bridge **310** as a half bridge. For example, bridge controller **305** can maintain one of transistors **330**, **335**, **340**, **345** in conduction and another out of conduction while alternatively switching whichever of transistors **330**, **335**, **340**, **345** are connected to the other terminal of the input winding of transformer **315**.

[0037] By way of example, suppose bridge controller **305** maintains transistor **340** in conduction and transistor **330** non-conductive. When transistor **345** is in a nonconductive state and transistor **335** is in a conductive state, the voltage difference between rails **350**, **355** minus the voltage across the capacitor **319** is applied across the input winding of transformer **315**. In other words, the voltage across the input winding is the voltage on rail **350** minus the voltage on rail **355** minus the voltage across the capacitor **319**. In half-bridge configuration, the voltage across the capacitor **319** and the inductor of transformer **315** settles to about half the voltage difference between rails **350**, **355**. This leads to a reduced voltage across the input winding of transformer **315** and a smaller difference generated between high supply rail **210** and low rail **212**. In contrast, when transistor **335** is in a nonconductive state and transistor **345** is in a conductive state, no voltage difference is applied across the capacitance and the input winding of transformer **315**. As such, positive pulses are converted into corresponding ac signal on the output winding of transformer **315** and, after rectification by rectifier **320**, a smaller difference is generated between high supply rail **210** and low rail **212**. In other words, the reduced voltage across the input winding of transformer **315** leads to a smaller difference generated between high supply rail **210** and low rail **212**.

[0038] As discussed above, controller **145** can direct gate driver **140** to coordinate the switching of the switches in the legs of inverter **125** in order to power motor **130**. However, controller **145** can also control gate driver **140** to coordinate the switching of the switches in the legs of inverter **125** to actively discharge DC link capacitor **135** (FIG. **1**).

[0039] Referring again to FIG. **2**, when IGBT **245** is to be switched into or out of conduction, alternating conduction through pull up transistor **225** and pull down transistor **230** biases the gate of IGBT **245** positively or negatively with respect to low supply rail **115**. The magnitude of the bias is the voltage difference between V.sub.ISO and V.sub.EE or the voltage difference between V.sub.EE and V.sub.COM.

[0040] When bridge controller **305** uses bridge **310** as a half bridge, voltage difference between V.sub.ISO and V.sub.COM decreases. The voltage V.sub.COM on low rail **212** remains below V.sub.EE and the gate of IGBT **245** is still negatively biased for effective turn-off. However, the voltage difference between V.sub.ISO and V.sub.EE—which is the voltage between the gate and the emitter of the IGBT (i.e., V.sub.GE)—changes the output characteristic of IGBT **245** so that the impedance of IGBT **245** increases and the current carried through IGBT **245** decreases.

[0041] This change in the output characteristic of IGBT **245** can be used to actively discharge DC link capacitor **135** without damage to IGBTs **240**, **245**. In particular, as discussed above, DC link capacitor **135**—and rails **110**, **115**—will retain a high voltage after being disconnected from the battery. If IGBTs **240**, **245** were driven with a high transconductance to discharge this high voltage, this could approximate a short circuit. The current could be relatively high and could damage IGBTs **240**, **245**. In contrast, by driving at least one of IGBTs **240**, **245** with a relatively lower voltage difference between V.sub.ISO and V.sub.EE and lower transconductance, the current can be maintained sufficiently low to avoid damage.

[0042] Please note that a variety of different approaches can be used to tailor the net impedance across phase leg **260** to actively discharge DC link capacitor **135**. For example, [0043] IGBT **240** can be kept conductive while IGBT **245** is actively switched with a relatively low transconductance and higher impedance output characteristic, [0044] IGBT **245** can be kept conductive while IGBT **240** is actively switched with a relatively low transconductance, or [0045] both IGBTs **240**, **245** can be actively switched, where at least one has a relatively low transconductance.

If both IGBTs **240**, **245** are actively switched, their switching will generally be synchronized so that IGBTs **240**, **245** open and close in unison. However, this is not necessarily the case. For example, IGBT **240** could begin transitioning into a more conductive ON state (i.e., a state that has either a relatively high or low transconductance) while IGBT **245** initially remains non-conductive. IGBT **245** can begin transitioning into a more conductive state either some time during or after IGBT **240′**s ON state transition to further tailor the next impedance across phase leg **260** to operational conditions. It is only necessary that a current flow path be formed between rails **110**, **115** with a relatively low transconductance.

[0046] Further, lest any doubt remain, other phase legs in an inverter **125** can correspondingly participate in the active discharge. In any case, with at least one IGBT acting as a more resistive element, a short circuit between rails **110**, **115** is avoided. However, that IGBT still provides a current flow pathway for active discharge of DC link capacitor **135**.

[0047] Further, as discussed below, the switching pattern of one or both of IGBTs **240**, **245** during active discharge can be specified by controller **145**, gate drive **140**, or both controller **145** and gate drive **140**.

[0048] FIG. **4** is a graph **400** that represents the output characteristics of an IGBT that is suitable for use in an inverter in an electric vehicle drive system, e.g., as IGBT's **240**, **245**. Position along the x-axis in graph **400** denotes the voltage difference between the collector and the emitter (i.e., V_{CE}) of the IGBT in volts. Position along the y-axis denotes the collector current (i.e., I_C) in amperes. The different curves **405**, **410**, **415**, **420**, **425**, **430** are each associated with a different voltage between the gate and the emitter of the IGBT (i.e., V_{GE}). For example, curve **405** shows the relationship between V_{CE} and I_C when V_{GE} is 19 Volts, curve **410** shows the relationship between V_{CE} and I_C when V_{GE} is **17** Volts, curve **415** shows the relationship between V_{CE} and I_C when V_{GE} is 15 Volts, curve **420** shows the relationship between V_{CE} and I_C when V_{GE} is 13 Volts, curve **425** shows the relationship between V_{CE} and I_C when V_{GE} is 11 Volts, and curve **430** shows the relationship between V_{CE} and I_C when V_{GE} is 9 Volts. As shown, as V_{GE} decreases, the slope of curves **405**, **410**, **415**, **420**, **425**, **430** decreases and the resistance of the IGBT increases.

[0049] In general, graphs like graph **400** are provided by the supplier of an IGBT can be readily used to tailor the voltages and the values of different components to a particular set of operational circumstances.

[0050] FIG. **5** is a swim lane diagram that schematically represents a process **500** for active discharge of a DC link capacitor. In the context of the electric drive system described above, the actions in the controller lane can be performed by controller **145**, the actions in the bridge controller lane by bridge controller **305**, and the actions in the gate driver lane by gate driver **140**. Although process **500** can be performed in the context of these particular components, process **500** can also be adapted to other electric drive systems. For example, in some implementations, a single physical device may provide the functionality attributed to different controllers. For example, a bridge controller and a gate driver can be implemented in a single printed circuit board. Nevertheless, the processes and/or logic can be considered individually.

[0051] In process **500**, the controller can signal initiation of an active discharge mode at **505**. The controller can signal the initiation of the active discharge mode in response to one or more higher level signals, e.g., a signal indicating that operation of the device is to end or signal(s) indicating that a sufficiently severe fault condition has arisen. The initiation of the active discharge mode can be signaled in a number of different ways. For example, a signal on a dedicated active discharge terminal can indicate the initiation.

[0052] As discussed above, in some implementations, the control signals from a controller can specify the switching pattern to be used by the gate driver to bias the switching devices in an inverter. In these implementations, such control signals are terminated prior to initiation of an

active discharge mode. In some implementations, termination of the switching pattern can signal the initiation of the active discharge mode.

[0053] In some implementations, the bridge controller and the gate driver can be implemented in a single physical device, e.g., they can be implemented on a single gate drive printed circuit board. In another implementation, the bridge controller and the gate driver may be formed as part of an integrated circuit that is manufactured as either a hybrid or monolithic integrated circuit. In such cases, initiation of the active discharge mode can be signaled using the same terminals that carry the control signals that specify how the switching devices in the inverter are to be biased. For example, after a suitable absence of control signals, a specialized active discharge mode initiation signal can be sent by the controller to the combined bridge controller/gate driver device.

[0054] In response to receipt of the signal indicating initiation of the active discharge mode, the bridge controller can switch from a full-bridge to half bridge driving of a transistor bridge at **510**. As discussed above, this will lead to a decrease in the output voltage of the dc/dc converter. The bridge controller can continue to drive the transistor bridge as a half bridge at **515**. In one example, the bridge controller can drive the transistor bridge as a half bridge while monitoring the output of the dc/dc converter. This monitoring can rely upon components in the de/dc converter that participate in output regulation, i.e., no additional components or modification of the dc/dc converter are needed.

[0055] Further, at **520**, the bridge controller can identify an undervoltage condition on the dc/dc converter output. In general, dc/dc converters will monitor for an undervoltage condition even without the need to actively discharge a DC link capacitor. This is done to identify a potential fault condition and ensure appropriate operation of the electric drive system. In some implementations, this same functionality can be relied upon in the active discharge mode and no additional components or modification of the dc/dc converter are needed. Although the time required for the output voltage of the dc/de converter to fall below an undervoltage threshold may vary amongst different dc/dc converters, typically the fall will require between 1 and 10 milliseconds.

[0056] At **525**, the controller **145** receives the signal indicative of the undervoltage condition. In response, the controller signals initiation of the active discharge switching to the gate drive at **530**. As discussed above, in some implementations, the control signals from a controller can specify a particular switching pattern to be used by gate driver circuitry. In such implementations, the controller can signal initiation of active discharge by transmitting an active discharge switching pattern. For example, the active discharge switching pattern can be a series of pulse-width modulated pulses. The pulses for active discharge may be higher frequency/shorter duration than pulses in the switching patterns used during operation of the vehicle.

[0057] As another example, in some implementations, the control signals generated by controller **145** are higher level and used by gate driver circuitry **140** to generate an active switching pattern during active discharge.

[0058] As yet another example, in some implementations, the active discharge switching pattern is determined in part by controller **145** and in part by gate driver circuitry **140** For example, controller **145** can transmit indications of when one or both of IGBTs **240**, **245** are to switch into conduction without associated indications of when the IGBT(s) **240**, **245** is to switch out of conduction. Rather, the timing when the IGBT(s) **240**, **245** is to switch out of conduction can be determined by gate driver circuitry **140**.

[0059] In some implementations, desaturation protection functionality in gate driver circuitry **140** can be used to specify when IGBT(s) **240**, **245** is/are to be switched out of conduction. In this context, desaturation protection is functionality implemented by gate driver circuitry to protect driven switches (e.g., IGBTs **240**, **245**) from currents that could, e.g., damage the device. An overcurrent or short circuit is detected in the protected device and the device is switched out of conduction in response. It is generally important that the device be switched out of conduction as quickly as possible. To this end, desaturation protection is commonly implemented by gate driver

circuitry that is directly coupled to the device and that can respond without delays.

[0060] In the present context of active discharge, gate driver circuitry **140** can implement desaturation protection and monitor the voltage across one or both of IGBTs **240**, **245**. Typically, driver circuitry **140** compares the voltage across one or both IGBT **240**, **245** with a threshold to determine whether a desaturation or short-circuit condition exists. If the voltage across IGBT **240**, **245** is greater than the threshold, the gate driver circuitry triggers protection of the IGBT and turns the IGBT off. This process can be used during active discharge to specify when IGBT(s) **240**, **245** is/are to be switched out of conduction. In particular, the gate driver circuitry **140** turns off IGBT(s) **240**, **245** in response to detection of the desaturation/short-circuit condition.

[0061] This approach can provide some advantages. For example, desaturation protection functionality is generally already present in modern gate driver circuitry Further, because desaturation protection relies on sensing currents or voltages within the driven switch, defining a portion of the active discharge switching pattern using desaturation protection inherently tailors the active discharge switching pattern not only to the driven switch but also to its operational state (e.g., temperature).

[0062] In any case, the process also continues to block **532**, in which the gate driver implements the active discharge switching pattern by driving turn on and turn off of transistors in accordance with the active discharge switching pattern.

[0063] Either or both of the controller and the gate driver can monitor the voltage across the DC link capacitor during active discharge. At **535**, it will be determined that the DC link capacitor has been sufficiently discharged. If the DC link capacitor has not been sufficiently discharge, controller **145** continues providing the active discharge switching pattern. If the DC link capacitor has been sufficiently discharged, an end to the active discharge mode will be signaled at **540**. In the illustrated implementation, the controller determines that the DC link capacitor has been sufficiently discharged and signals the end to the active discharge mode to both the bridge controller and the gate driver. In implementations in which the gate driver determines that the DC link capacitor has been sufficiently discharged, the gate driver signals the end to the active discharge mode to the bridge controller and the controller. In either case, the active discharge switching scheme at **550** is ended. Once the active discharge scheme is ended, at block **545** the bridge controller can switch from half bridge to full bridge for dc/dc conversion and generation of V.sub.ISO-V.sub.COM and the gate driver ends the control of the turn-on and turn-off transistors per the active discharge switching scheme.

[0064] FIG. **6** is a schematic representation of different waveforms in an electric drive system **100**. The waveforms are all presented as a function of time and span a window during which the voltage across DC link capacitor **135** is actively discharged. For example, the waveforms can span a short window during and shortly after shut down or a response to a sufficiently severe fault condition.

[0065] Waveform **605** represents the signal that initiates and ends active discharge mode. In the context of FIG. **2**, active discharge control signal(s) can be sent from controller **145** to supply **205**, e.g., over a communication line dedicated to carrying signal(s) that initiate and end the active discharge mode. Waveforms **610**, **615** represent the voltage applied by a bridge controller to the control terminals of two of the transistors in a transistor bridge which is both a full bridge (before T**2**) and a half-bridge (between T**2** and T**4**) operation. Waveform **620** represents the voltage difference between the voltage at high supply rail V.sub.ISO **210** and the voltage V.sub.COM at low rail **212**. Waveform **625** represents the voltage across DC link capacitor **135**. Waveform **630** represents the drive voltage applied to the control terminal of IGBT **245** (or other IGBT that participates in active discharge of DC link capacitor **135**).

[0066] Prior to time T**1**, waveform **605** indicates that the bridge controller is to operate the bridge as a full bridge, i.e., outside of active discharge mode. Consequently, the bridge controller operates the transistors in the transistor bridge as a full bridge. For example, waveform **610** can represent the drive signal applied to the control terminal of transistor **335** and waveform **615** can represent the

drive signal applied to the control terminal of transistor **345**. Transistors **335**, **345** are switched into and out of conduction in alternation and participate in generating an ac signal across transistor **315**. A regulated, and relatively high, voltage difference is generated between the voltage at high supply rail V.sub.ISO **210** and the voltage V.sub.COM at low rail **212**, as shown in waveform **620**. The gate-to-emitter voltage of IGBT **245** (or other IGBT that participates in active discharge of DC link capacitor **135**) is pulled up and down in in succession, as shown in waveform **630**. As shown, the driving of IGBT **245** need not be continuous. For example, motor **130** need not be driven when the electric vehicle is "idling."

[0067] At time T**1**, controller **145** initiates the active discharge mode, e.g., by transitioning waveform **605** into a high state. In the illustrated implementation, controller **145** holds waveform **605** in the high state throughout the entire active discharge mode. Other conventions for signaling the initiation and end of the active discharge mode are possible.

[0068] After a delay, the bridge controller begins operating the bridge as a half bridge, i.e., in active discharge mode. The transistor in the bridge driven by waveform **610** is held in conduction whereas the transistor driven by waveform **615** is held out of conduction. The other transistors in the bridge can be alternatively switched in a manner akin to the switching on waveforms **610**, **615** before T**1**

[0069] In response to the switch to operation as a half bridge, the magnitude of the voltage generated by the dc/dc converter (i.e., the voltage difference between the voltage at high supply rail V.sub.ISO **210** and the voltage V.sub.COM at low rail **212**) decreases. This also decreases the voltage difference between the voltage at high supply rail V.sub.ISO **210** and the voltage V.sub.EE at intermediate output **215**, i.e., the gate-to-emitter voltage of the voltage of IGBT **245** or other IGBT that participates in active discharge of DC link capacitor **135**.

[0070] By time T**3**, the voltage generated by the dc/dc converter has dropped below an undervoltage level **640**. In some implementations, undervoltage level **640** can be remain the same in both active discharge mode and in other (e.g., operational) modes The same functionality can be relied upon and no additional components or modification of the dc/dc converter are needed.

[0071] After the voltage generated by the dc/dc converter has fallen below the undervoltage level **640** at T**3**, the gate-to-emitter voltage of the IGBT, i.e., waveform **630**, is pulsed with a series of pulses **635** that each only suffice to bias IGBT **245** into conduction with a limited transconductance. The voltage across DC link capacitor **135**, i.e., waveform **625**, discharges. Subsequently, at time T**4**, the voltage across DC link capacitor **135** has fallen to a sufficiently low level that active discharge using pulses **635** can be ended. Controller **145** signals the end of active discharge mode, e.g., by transitioning waveform **605** into a low state.

[0072] After the active discharge mode has come to an end, the vehicle can, e.g., shut down completely or even restart operations. For example, to shut down, the bridge controller can allow operation of the transistor bridge to come to an end. In general, the voltage across DC link capacitor **135** can continue to fall over time due to power consumption by other components. Alternatively, to restart, bridge controller can resume operating the bridge as a full bridge.

[0073] As discussed above, waveforms **605**, **610**, **615**, **620**, **625**, **630** only span a short window during and shortly after shut down or a response to a sufficiently severe fault condition.

[0074] The above description of illustrated examples of the present invention, including what is described in the Abstract, are not intended to be exhaustive or to be limitation to the precise forms disclosed. While specific embodiments of, and examples for, the invention are described herein for illustrative purposes, various equivalent modifications are possible without departing from the broader spirit and scope of the present invention. Indeed, it is appreciated that the specific example voltages, currents, frequencies, power range values, times, etc., are provided for explanation purposes and that other values may also be employed in other embodiments and examples in accordance with the teachings of the present invention. For example, rather than controlling the impedance output characteristic of power switch in an inverter, the impedance output characteristic of a power switch in a dc/dc converter that is connected to rails **110**, **115** can be controlled and used

to discharge DC-link capacitor **135**. Such a dc/dc converter can be used to supply power to other components in the vehicle.

[0075] These modifications can be made to examples of the invention in light of the above detailed description. The terms used in the following claims should not be construed to limit the invention to the specific embodiments disclosed in the specification and the claims. Rather, the scope is to be determined entirely by the following claims, which are to be construed in accordance with established doctrines of claim interpretation. The present specification and figures are accordingly to be regarded as illustrative rather than restrictive.

Claims

1. A method for discharging a de link capacitor coupled between a positive rail and a negative rail of an electric drive system, the method comprises: generating an internal supply voltage with a relatively high value with respect to the negative rail; driving a control terminal of a power switch based on the internal supply voltage with the relatively high value; detecting a discharge command in the electric drive system; reducing the internal supply voltage from the relatively high value to a relatively lower value in response to the detected discharge command; driving the control terminal of the power switch based on the internal supply voltage with the relatively lower value; and discharging the de link capacitor through the power switch when the power switch is driven based on the relatively lower voltage value.

2. The method of claim 1, further comprising: initiating an active discharge mode in response to detecting the discharge command; and switching a dc/dc converter from a full bridge configuration to a half bridge configuration in response to the initiated active discharge mode, wherein switching the dc/dc converter to the half bridge configuration reduces the internal supply voltage from the relatively high value to the relatively lower value.

3. The method of claim 1, further comprising: identifying that the internal supply voltage has fallen below a threshold; and driving the control terminal of the power switch with an active discharge switching pattern.

4. The method of claim 3, wherein the active discharge switching pattern is a series of pulses which bias the power switch into conduction with limited transconductance.

5. The method of claim 3, wherein the active discharge switching pattern is a series of pulse-width modulated pulses having a relatively higher frequency than a series of pulses driving the control terminal of the power switch during operation of the electric drive system.

6. The method of claim 1, further comprising: determining if the de link capacitor is discharged below a threshold; signaling an end of an active discharge mode in response to determining the de link capacitor is discharged below the threshold; and switching a dc/de converter from a half bridge configuration to a full bridge configuration in response to the end of the active discharge mode, wherein switching the dc/dc converter to the full bridge configuration increases the internal supply voltage from the relatively lower value to the relatively high value.

7. An electric drive system configured to control conduction of a power switch to control a motor, the electric drive system comprising: a supply capacitor coupled between a positive rail and a negative rail of the electric drive system; a supply configured to generate an internal supply voltage, wherein the supply is configured to generate the internal supply voltage to have either a relatively high voltage difference or a relatively lower voltage difference with respect to the negative rail in response to a signal indicating the supply capacitor is to be discharged; and a gate drive channel configured to drive the power switch into conductance based on the internal supply voltage, wherein the gate drive channel is configured to control the power switch based on the internal supply voltage having the relatively low voltage difference a to discharge the supply capacitor through the power switch.

8. The electric drive system of claim 7, wherein the supply further comprises: a transistor bridge;

and a bridge controller coupled to receive the signal indicating the supply capacitor is to be discharged and, in response, configured to switch from driving the transistor bridge as a full bridge to driving the transistor bridge as a half bridge.

9. The electric drive system of claim 8, wherein the gate drive channel is configured to determine if the supply capacitor is discharged to below a threshold and output a signal to end active discharge mode.

10. The electric drive system of claim 9, wherein the supply is configured to receive the signal to end active discharge mode and, in response, configured to switch from driving the transistor bridge as the half bridge to driving the transistor bridge as the full bridge.

11. The electric drive system of claim 7, wherein the gate drive channel is configured to pulse the power switch with an active discharge switching pattern in response to the signal indicating the supply capacitor is to be discharged.

12. The electric drive system of claim 11, wherein the gate drive channel is configured to pulse the power switch with the active discharge switching pattern for a time duration to discharge the supply capacitor.

13. The electric drive system of claim 12, wherein the active discharge switching pattern is a series of pulses which bias the power switch into conduction with limited transconductance.

14. The electric drive system of claim 7, wherein the electric drive system is housed in a vehicle.

15. A control system configured to control a power switch that comprises a first terminal, a second terminal, and a control terminal, wherein conductance between the first and second terminals of the power switch is responsive to a voltage on the control terminal, wherein the control system comprises: a capacitor coupled between a positive rail and a negative rail of the control system; a supply configured to detect a discharge command in the control system, wherein the discharge command initiates active discharge of the capacitor, the supply configured to switch from generating an internal supply voltage with a relatively higher voltage with respect to the negative rail to generating the internal supply voltage with a relatively lower voltage, wherein the supply is configured to output a signal indicative of the internal supply voltage falling below a threshold; and a switch controller coupled to receive the signal indicative of the internal supply voltage falling below the threshold, wherein the switch controller is configured to control the voltage on the control terminal based on the internal supply voltage with the relatively lower voltage in response to the signal indicative of the internal supply voltage falling below the threshold.

16. The control system of claim 15, wherein the supply further comprises: a transistor bridge; and a bridge controller coupled to receive the discharge command and, in response, configured to switch from driving the transistor bridge as a full bridge to driving the transistor bridge as a half bridge.

17. The control system of claim 16, wherein the switch controller is configured to determine if the capacitor is discharged to below a reference and output a signal to end active discharge mode.

18. The control system of claim 17, wherein the supply is configured to receive the signal to end active discharge mode and, in response, configured to switch from driving the transistor bridge as the half bridge to driving the transistor bridge as the full bridge.

19. The control system of claim 15, wherein the switch controller is configured to provide an active discharge switching pattern for controlling the voltage on the control terminal of the power switch in response to the signal indicative of the internal supply voltage falling below the threshold.

20. The control system of claim 19, wherein the switch controller is configured to control the power switch with the active discharge switching pattern for a time duration to discharge the capacitor.

21. The control system of claim 19, wherein the active discharge switching pattern is a series of pulses which bias the power switch into conduction with limited transconductance.

22. The control system of claim 15, wherein the discharge command is a shut-down command or a fault command.

23. The control system of claim 15, wherein the control system is utilized by a vehicle.

24. An electric drive system for a vehicle, the electric drive system comprising: an inverter having at least one phase leg, wherein a first of the at least one phase leg includes a first power switch; a dc/dc converter configured to generate an internal supply voltage that is regulated with respect to a voltage on a rail configured to be coupled to a de power supply, wherein the dc/dc converter is configured to generate the internal supply voltage to have either a relatively high voltage difference with respect to the voltage on the rail or a relatively lower voltage difference in response to an indication of an active discharge mode, wherein the dc/dc converter is configured to output a signal indicative of the internal supply voltage falling below a threshold; and a gate drive channel configured to receive the signal indicative of the internal supply voltage falling below the threshold, and configured to drive the first power switch into conductance based on the relatively high voltage difference during operation of the vehicle and to drive the first power switch into conductance based on the relatively lower voltage difference in response to the signal indicative of the internal supply voltage falling below the threshold.

25. The electric drive system of claim 24, wherein the dc/dc converter further comprises: a transistor bridge; and a bridge controller coupled to receive the indication of the active discharge mode and, in response, configured to switch from driving the transistor bridge as a full bridge to driving the transistor bridge as a half bridge.

26. The electric drive system of claim 25, wherein the gate drive channel is configured to determine if a supply capacitor is discharged to below a reference and output a signal to end active discharge mode, and the dc/dc converter is configured to receive the signal to end active discharge mode and, in response, configured to switch from driving the transistor bridge as the half bridge to driving the transistor bridge as the full bridge.

27. The electric drive system of claim 24, wherein the gate drive channel is configured to control the first power switch with an active discharge switching pattern for a time duration to discharge a supply capacitor in response to the signal indicative of the internal supply voltage falling below the threshold.

28. The electric drive system of claim 27, wherein the active discharge switching pattern is a series of pulses which bias the first power switch into conduction with limited transconductance.