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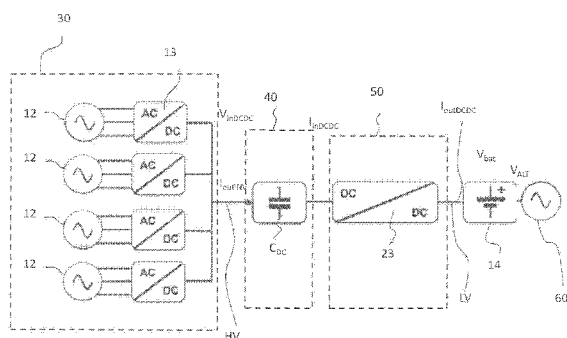


Fig. 2

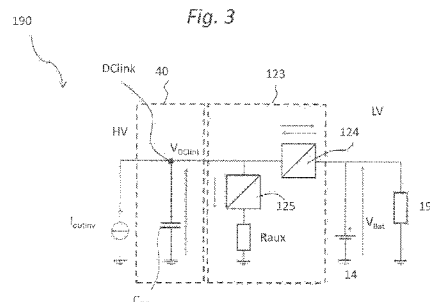


Fig. 3

(57) Abstract: A bidirectional energy-conversion apparatus of a DC-DC type operating between a low-voltage system (LV) and a high-voltage system (HV) of a vehicle comprising an energy-recovery stage (30), said low-voltage system (LV), which operates at a first voltage (V_{bat}), comprising a battery (14) that supplies said first voltage (V_{bat}) on a low-voltage bus (LV), said high-voltage system (HV), which operates at a second voltage (V_{inDCDC} , V_{DCLink}) higher than said first voltage (V_{bat}), comprising said energy-recovery stage (30) of the vehicle that supplies said second voltage (V_{inDCDC} , V_{DCLink}), said second voltage (V_{inDCDC} , V_{DCLink}) being supplied through an intermediate energy-storage system (40) to a DC-DC conversion module (23; 123), which converts said second voltage (V_{inDCDC} , V_{DCLink}) into said first voltage (V_{bat}) for said low-voltage bus (LV). The aforesaid DC-DC conversion module (123) comprises a bidirectional DC-DC converter (124) connected between the intermediate energy-storage stage (40) and the vehicle battery (14). Said apparatus is configured for selecting a direction of conversion of said bidirectional converter (124), from high voltage (HV) to low voltage (LV) or from low voltage (LV) to high voltage (HV) via a control circuit (140) as a function of the value of the voltage (V_{DCLink}) on the high-voltage bus (HV).

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BIDIRECTIONAL ENERGY-CONVERSION APPARATUS OF A DC-DC TYPE OPERATING
BETWEEN A LOW-VOLTAGE SYSTEM AND A HIGH-VOLTAGE SYSTEM OF A VEHICLE
COMPRISING AN ENERGY-RECOVERY STAGE, AND CORRESPONDING METHOD

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TEXT OF THE DESCRIPTION

The present invention relates to a bidirectional energy-conversion apparatus of a DC-DC type operating between a low-voltage system and a high-voltage system of a vehicle comprising an energy-recovery stage,

said low-voltage system, which operates at a first voltage, comprising a battery that supplies said first voltage on a low-voltage bus,

said high-voltage system, which operates at a second voltage higher than said first voltage, comprising said energy-recovery stage of the vehicle that supplies said second voltage,

said second voltage being supplied through an intermediate energy-storage system to a DC-DC conversion module, which converts said second voltage into said first voltage for said low-voltage bus.

In the automotive field, energy-recovery systems are known. In particular, energy-recovery systems are known that use regenerative shock absorbers, which convert movements of the shock absorber into electrical energy.

In this context, for example, of particular interest from the standpoint of efficiency of conversion are regenerative shock absorbers that envisage a conversion of the linear motion of the stem into a rotary motion of the shaft of an electric generator from which it is hence possible to recover in the form of electricity the energy that would otherwise be dissipated in heat. It is known to carry out this conversion using mechanical or hydraulic means in such

a way that the rotation of the shaft of the electric generator will occur always in the same direction of rotation, irrespective of the direction of the velocity of the stem. This enables a higher efficiency of energy conversion, from kinetic to electrical energy. The electric generator is usually a DC generator which supplies a DC voltage at output. If, instead, a synchronous generator is used, an inverter is employed. In either case, it is anyway necessary to use a DC-DC converter to match the output voltage of the electric generator to the battery of the vehicle, in particular a motor vehicle.

It is likewise known to use a stage for conversion from high voltage to low voltage, specifically a DC-DC converter that is controlled in output voltage, to be matched to the battery voltage, in a way similar to the regulator of an alternator.

Illustrated in Figure 1 is a diagram representing an electro-mechanical model of a known energy-recovery apparatus, designated as a whole by the reference number 10. Designated by 11 is a shaft of an electric generator 12, associated to which are an angular velocity ϕ and a torque τ . R_{og} denotes the output resistance of the electric generator 12, for example a DC generator, whereas R_e denotes the equivalent resistance of the circuits of the portion of apparatus downstream of the electric generator 12, i.e., the resistance seen by the electric generator 12, the equivalent resistance R_e being regulated, for example, by the aforementioned inverter. Denoted by V_{og} is the loadless voltage of the electric generator 12, denoted by I_g is the current of the generator 12, and denoted by V_{inDCDC} is the voltage that is set up on the equivalent resistance R_e .

Consequently, from what has been discussed so far,

it follows that it is possible to control damping of the shock absorber by acting on the equivalent resistance R_e seen by the electric generator 12, but the fact of having to act on the equivalent resistance R_e to control damping renders it, however, impossible to operate, as in other energy-harvesting systems, by matching the impedance seen by the generator, which, in particular, depends upon the inverter, to the output impedance of the electric generator 12 in order to maximize power transfer.

Illustrated in Figure 2 is a conversion apparatus designated as a whole by the reference number 90.

The above conversion apparatus 90 comprises an energy-recovery stage 30, which includes a plurality of regenerative shock absorbers 12, in particular four regenerative shock absorbers, associated to respective DC-DC converters in the form of inverters 13, the outputs of which are gathered in a single output node of the energy-recovery stage 30.

The output node of the energy-recovery stage 30 basically corresponds to a high-voltage bus HV, set up on which are a voltage V_{inDCDC} , which is the voltage on the DC side of the inverter 13 and an output current from the inverter I_{outINV} , which is the sum of the four currents at output from the inverters 13. The voltage V_{inDCDC} of the high-voltage bus HV is sent to the input of a high-voltage-to-low-voltage conversion stage 50, which in the example comprises a DC-DC converter 23, set in parallel on the input of which is a storage element, i.e., a capacitance, C_{DC} . In variant embodiments, the storage element may be a battery. Entering the DC-DC converter 23 is an input current I_{inDCDC} that is equal to the current at output from the inverter I_{outINV} minus the current that flows in the storage element C_{DC} . Of course, in the present context,

the voltage on the bus HV is defined high with respect to the voltage on the other end of the DC-DC converter 23, on the low-voltage bus LV, which is, instead, of a lower value and in general corresponds to the voltage of the electrical systems of the vehicle, usually 12 V.

In the systems as the one described in which a system at a higher voltage is connected, by means of a converter, to a system at lower voltage, in particular to the electrical systems connected to the vehicle battery, the bus on the DC side of the inverter, which is also the high-voltage side HV, is in what follows referred to as "DC-link bus", and the storage element C_{DC} is referred to as "DC-link capacitance". The DC-link capacitance corresponds in general to the capacitor connected to the input of the DC-DC converter 23, where the DC voltage to be converted to a lower voltage arrives. The DC-link capacitance is usually obtained via an electrolytic or film capacitor that decouples the input of the DC-DC converter.

The aforesaid DC-link capacitance C_{DC} , in the example described, provides an intermediate energy-storage stage 40 at the input of the DC-DC converter 23. The voltage of the DC-link bus has, for example, a value of 48 V.

Set between the intermediate energy-storage stage 40 and the low-voltage bus LV, on which the battery 14 is connected, is the bidirectional DC-DC converter 23, which converts the high voltage of the high-voltage bus HV into a low voltage on the low-voltage bus LV, for charging the battery 14, but, if need be, can operate in the other direction to convert the low voltage on the low-voltage bus LV into high voltage on the high-voltage bus HV. This bidirectionality is frequently required in hybrid or electric vehicles.

The battery 14 is also connected to an alternator

60, which applies thereto a charging voltage V_{ALT} .

A drawback of the aforesaid systems is the management of any excess energy produced, for example, by the energy-recovery system 30.

5 Known from the U.S. patent No. US8723490B2 is an apparatus for automatic regulation of the flow of power, which envisages, in order to determine the direction of operation of a bidirectional DC-DC converter, acquisition of the sign of the currents at
10 input and at output and consequent setting of the control. In the case where the devices connected to the bus are numerous (at least four controllers for the shock absorbers), this approach may be complex.

The object of the present invention is to provide
15 an improved apparatus and an improved method that will enable the drawbacks mentioned above to be overcome.

According to the present invention, the above object is achieved thanks to an apparatus, as well as to a corresponding method, having the characteristics
20 referred to specifically in the ensuing claims.

The invention will now be described with reference to the annexed drawings, which are provided purely by way of non-limiting example and in which:

- Figure 1 and 2 have already been described
25 previously;

- Figure 3 illustrates a principle diagram of a preferred embodiment of the apparatus described herein;

- Figure 4A shows a converter used by the apparatus described herein in a preferred embodiment;

30 - Figure 4B shows a converter used by the apparatus described herein in another embodiment;

- Figure 5A illustrates a regulation circuit for the preferred embodiment of the apparatus of Figure 4A;

35 - Figure 5B illustrates a regulation circuit for the preferred embodiment of the apparatus of Figure 4B;

- Figures 6, 7, and 8 illustrate implementations of the converter of Figure 4;

- Figures 9, 10, and 11 illustrate control signals and signals that are set up in the apparatus of Figure 3 in different configurations of operation of the apparatus.

In brief, the solution according to the invention regards a bidirectional energy-conversion apparatus of a DC-DC type operating between a low-voltage system and a high-voltage system of a vehicle comprising an energy-recovery stage,

said low-voltage system, which operates at a first voltage, comprising a battery that supplies said first voltage on a low-voltage bus,

said high-voltage system, which operates at a second voltage higher than said first voltage, comprising said energy-recovery stage of the vehicle that supplies said second voltage,

said second voltage being supplied through an intermediate energy-storage system to a DC-DC conversion module, which converts said second voltage into said first voltage (for said low-voltage bus),

According a main aspect of the solution described herein,

said DC-DC conversion module comprises a bidirectional DC-DC converter connected between the intermediate energy-storage stage and the vehicle battery

said apparatus is configured for selecting a direction of conversion of said bidirectional converter, from high voltage to low voltage or from low voltage to high voltage, via a control circuit as a function of the value of the voltage on the high-voltage bus.

In particular the first bidirectional converter

comprises a buck converter for conversion from high voltage to low voltage and a boost converter, the converters being selectable by said control circuit for operating, respectively, conversion from high voltage to low voltage or from low voltage to high voltage. The control circuit comprises a comparator with hysteresis with an upper hysteresis threshold and a lower hysteresis threshold configured for comparing the voltage on the bus with a reference voltage, and, if the voltage on the bus exceeds the upper threshold, a status signal is generated for enabling the operation of conversion from high voltage to low voltage, or buck mode, and, if the voltage on the bus drops below the lower threshold, a status signal is generated for enabling the operation of conversion from low voltage to high voltage, or boost mode.

In this connection, Figure 3 illustrates a bidirectional energy-conversion apparatus of a DC-DC type, designated by the reference 190, which comprises a bidirectional DC-DC conversion module 123, which comprises a first bidirectional DC-DC converter 124 connected between the intermediate energy-storage stage 40 and the vehicle battery 14 and a second auxiliary DC-DC converter 125 connected between the intermediate energy-storage stage 40 and an auxiliary load R_{aux} . As may be noted, for the rest the apparatus corresponds to the one described in the figure, where the energy-recovery system 30 is represented via a current generator, which generates the current at output from the inverter I_{outINV} . Represented connected in parallel to the battery 14, on which a battery voltage drop V_{bat} is present, is a generic electrical load 19, representing the electrical loads of the vehicle that are connected to the low-voltage bus LV (e.g., the heated rear window).

It is emphasized how the solution described herein is not, however, limited to an apparatus such as the apparatus 190 of Figure 3, but also regards a bidirectional energy-conversion apparatus of a DC-DC type 123, which comprises the first bidirectional DC-DC converter 124 connected between the intermediate energy-storage stage 40 and the vehicle battery 14, but not the second auxiliary DC-DC converter 125 connected between the intermediate energy-storage stage 40 and an auxiliary load R_{aux} .

In other words, the solution described herein also applies to a conversion apparatus that only carries out bidirectional conversion between a high voltage and a low voltage. This apparatus is exemplified in Figure 4B, whereas a corresponding regulation circuit is illustrated in Figure 5B.

Figure 4A illustrates, instead, a possible topology for providing the converter module 123. This topology, which is one of the simplest topologies for obtaining a bidirectional conversion and to which reference will be made in what follows for illustrating the solution described herein, comprises the bidirectional DC-DC converter 124 configured with buck topology, i.e., comprising a switch that connects (and disconnects) a series inductor to (from) the input, i.e., the voltage V_{DClink} that is the energy source, so that the inductor charges with magnetic energy and then discharges into the battery, in this circumstance a diode connected with its anode to ground enabling a path for the current from ground to the battery. The buck topology of the bidirectional converter 124, however, comprises in this case two switches, designated by Q_{Buck} and Q_{Boost} in Figure 4A, obtained for example via MOSFET transistors, for providing the characteristic of bidirectionality, in such a way one

implements, seen from the high-voltage terminals HV, the buck behaviour, and the other implements, seen from the low-voltage terminals LV, the boost behaviour. Each of the switches Q_{Buck} and Q_{Boost} is represented with a
5 diode in parallel connected so as to enable flow, when the switch Q_{Buck} or Q_{Boost} is open, of a current in a direction opposite to that in which the switch Q_{Buck} or Q_{Boost} causes flow of the current when it is closed. This may, for example, be obtained via the reverse
10 diode between the source and the drain that is normally present in the MOSFET. This diode completes in the case of the buck switch the boost scheme and in the case of the boost switch the buck scheme.

Hence, the bidirectional DC-DC converter 124
15 comprises an input capacitance C_{in} connected from the DC-link node to ground and a first switch Q_{Buck} connected to the node of the DC-link bus, with a reverse diode D_{Boost} in parallel with its cathode connected to the DC-link node, which separates the
20 latter from a series inductor L in which an inductor current I_L flows. The series inductor L is connected to an output node, which presents towards ground an output capacitor C_{out} , to which the battery 14 is connected in parallel. Connected to ground between the buck switch
25 Q_{Buck} and the series inductor L is a second switch, the boost switch Q_{Boost} . Seen from the terminals of the battery 14 said second switch Q_{Boost} with the series inductor L provides, in the direction of conversion from the low-voltage bus HV to the high-voltage bus LV,
30 a converter with boost topology.

Likewise connected to the DC-link node is the input of the unidirectional auxiliary converter 125, which also envisages, as has been said, a buck topology. Hence, the unidirectional auxiliary DC-DC
35 converter 125 comprises an auxiliary switch Q_{aux} ,

connected to the DC-link node, which separates the latter from an auxiliary series inductor L_{aux} in which an auxiliary-inductor current $I_{L_{aux}}$ flows. The auxiliary series inductor L_{aux} is connected to an output node, 5 which presents towards ground an auxiliary output capacitor C_{aux} , to which the auxiliary load R_{aux} is connected in parallel. In this case, since there is no dual boost switch as in the converter 124, a diode D_{aux} with its anode connected to ground and its cathode 10 connected between the auxiliary switch Q_{aux} and the auxiliary series inductor L_{aux} completes the buck-converter scheme of the converter 125.

According to the solution described herein, the two converters 124 and 125 are controlled in closed 15 loop in such a way that the controlled quantity is the DC-link voltage V_{DClink} , hence, the input voltage in the case of the first bidirectional DC-DC converter 124 in forward mode and of the second auxiliary DC-DC converter 125, and the output voltage in the case of 20 the first bidirectional DC-DC converter 124 in reverse mode. In this way, the regulation guarantees an extremely low voltage ripple and continuity of operation.

The second auxiliary DC-DC converter 125 enables 25 dissipation of the excess energy in a load at a higher voltage (up to that of the DC-link bus) with respect to the voltage of the battery 14, hence with lower currents, in addition to the advantage of not burdening the low-voltage system with a further load. Moreover, 30 also for this converter closed-loop (non-hysteretic) operation enables a better aspect ratio of the dissipated power.

The first bidirectional DC-DC converter 124 and the auxiliary DC-DC converter 125 are driven according 35 to different modes on the basis of the operating

conditions of the system, in particular of the voltage on the bus V_{DCLink} , and, possibly of a reference voltage V_{ref} , as described more fully hereinafter.

The bidirectional DC-DC converter 124 can be
5 activated in forward or reverse mode, according to the type of conversion required by the vehicle, whereas the second auxiliary DC-DC converter 125 is activated only in the condition in which there becomes necessary dissipation of excess energy in conversion from the
10 energy-recovery system 30 to the battery 14 (from the high-voltage bus HV to the low-voltage bus LV).

In order to determine the direction of operation of the bidirectional DC-DC converter 124, as has been said, it is envisaged to carry out substantially only
15 reading of the voltage on the bus V_{DCLink} with consequent determination of the direction of operation of the first bidirectional DC-DC converter 124 and possible activation of the second auxiliary converter 125.

This is obtained using a comparator with
20 hysteresis, designated by 141 in Figure 5, where represented in detail is a regulation module 140, which as a function of the voltage on the bus V_{DCLink} , is configured for generating PWM (Pulse-Width Modulation) driving signals PWM_{Buck} , $\text{PWM}_{\text{Boost}}$, and PWM_{Aux} to control
25 the switches Q_{Buck} , Q_{Boost} , and Q_{Aux} , respectively. The comparator with hysteresis 141 is configured with an upper hysteresis threshold V_{TH} and a lower hysteresis threshold V_{TL} . This DC-link voltage V_{DCLink} is compared with a reference voltage V_{ref} , the value of which is
30 intermediate between the value of the two hysteresis thresholds V_{TH} and V_{TL} and corresponds to a nominal voltage value of the high-voltage bus HV or, in any case, to a target voltage value. For example, the nominal voltage value of the high-voltage bus HV may be
35 48 V, the upper hysteresis threshold V_{TH} and the lower

hysteresis threshold V_{TL} may be 46V and 50V, respectively, and the reference voltage V_{ref} may be 48 V.

When the voltage on the bus V_{DClink} exceeds the upper threshold V_{TH} (for example, on account of an event of generation of energy by the shock absorbers 12) a (status) signal is generated for enabling operation in buck mode $Buck_mode$, so that the flow of energy will go from the DC-link bus to the battery 14 in order to cause a reduction of the DC-link voltage V_{DClink} on the DC-link bus.

Instead, if the DC-link voltage V_{DClink} becomes lower than the lower threshold V_{TL} (for example, on account of a demand for actuation) a (status) signal is generated for enabling the operation in boost mode $Boost_mode$, so that the flow of energy will go from the battery 14 to the DC-link bus in order to cause a rise of the DC-link voltage V_{DClink} on the DC-link bus.

If the voltage V_{DClink} remains within the two thresholds V_{TH} and V_{TL} the most recent setting is maintained. The target, or nominal, voltage of the DC-link bus does not change in the various operating modes, so that, within the two thresholds V_{TH} and V_{TL} , the bidirectional DC-DC converter 124 seeks to set the nominal voltage (or in any case the target voltage) whether it is in buck mode or in boost mode. Activation of the auxiliary converter 125 of a buck type is subordinate to the presence of the signal for enabling operation in buck mode $Buck_mode$ to prevent operation thereof during the boost operation of the bidirectional DC-DC converter 124 (this would amount to a transfer from the battery 14 to the high-voltage bus HV, with useless dissipation of energy). The reference voltages of the two converters 124 and 125 must be set so as to guarantee precedence of operation for the bidirectional

DC-DC converter 124, which is the main converter and generates recovery of energy, over operation of the auxiliary converter 125, which, instead, determines dissipation of energy. To guarantee this, two values of reference voltage are considered: the first is the reference voltage V_{ref} , which is used for regulating the bidirectional DC-DC converter 124, the second is a maximum overvoltage V_{max} , which is higher than the reference voltage V_{ref} and corresponds to the value of overvoltage accepted in conditions of excess regenerated energy, which is used for regulating the auxiliary DC-DC converter 125. If the bus voltage is lower than both of the values of the voltage references V_{ref} and V_{max} , the two converters 124 and 125, which are both in buck configuration, do not work; i.e., their operation is not enabled. With the bus voltage V_{DClink} comprised between the two voltage references V_{ref} and V_{max} operation only of the bidirectional DC-DC converter 124 is enabled. With a voltage higher than both of the voltage references V_{ref} and V_{max} both of the converters 124 and 125 are enabled and active.

Hence, Figure 5A illustrates an implementation of the regulation module 140 that comprises the voltage comparator with hysteresis 141, which receives on its inputs the bus voltage V_{DClink} and the reference voltage V_{ref} and generates at output a comparison logic signal HC, which is picked up to obtain a buck-mode-enable signal Buck_mode, and is in parallel picked up and inverted via an inverter 145 to obtain a boost-mode-enable signal Boost_mode.

The boost-mode-enable signal Boost_mode is sent to an AND logic gate 146 together with a boost PWM signal PWM_{Boost} originated by a boost regulation circuit 142, which regulates the pulse-width modulation that is used for controlling the boost switch Q_{Boost} so as to obtain

the desired voltage regulation V_{DCLink} , in a way in itself known to the person skilled in the branch, in particular by controlling the inductor current I_L , i.e., the input current, on the low-voltage vehicle side, i.e., on the battery, of the converter 124 when it operates in the above boost mode. The regulation circuit 142 also receives the reference voltage value V_{ref} , as control quantity of a voltage control loop, as described in greater detail in what follows. If the boost-mode-enable signal $Boost_mode$ is active, i.e., in the case illustrated has the value of a logic one, at output from the AND logic gate 146 there is the boost PWM signal PWM_{Boost} , which can be sent to the switch Q_{Boost} of the bidirectional DC-DC converter 124, as represented in greater detail in Figure 6.

The buck-mode-enable signal $Buck_mode$ at output from the inverter 145, is sent to an AND logic gate 147 together with a buck PWM signal PWM_{Buck} originated by a buck regulation circuit 143, which regulates the pulse-width modulation so as to obtain the desired voltage regulation V_{DCLink} , in a way in itself known to the person skilled in the branch, in particular by controlling the inductor current I_L , i.e., the output current of the converter 124 operating in forward mode (buck mode). The regulation circuit 143 also receives the reference voltage value V_{ref} , as control quantity of a voltage control loop, as described in greater detail in what follows. If the buck-mode-enable signal, $Buck_mode$, is active, i.e., in the case illustrated is a logic one, at output there is has the buck PWM signal PWM_{Buck} , which can be sent to the switch Q_{Buck} of the bidirectional DC-DC converter 124.

The buck-mode-enable signal $Buck_mode$ is also sent to an AND logic gate 148 together with a auxiliary PWM signal PWM_{aux} originated by an auxiliary regulation

circuit 144, which regulates the pulse-width modulation so as to obtain the desired voltage drop V_{DClink} , in particular by controlling the auxiliary-inductor current I_L , i.e., the output current of the converter 125. The regulation circuit 144 also receives the maximum overvoltage value V_{max} , as control quantity of a voltage control loop, as described in greater detail in what follows. It is clear how with this configuration if the buck-mode-enable signal `Buck_mode` is deactivated, i.e., it is a logic zero, the output of the logic gate 148 is always at zero, and hence operation of the converter 125 is inhibited, in so far as the auxiliary switch Q_{aux} remains open.

As mentioned, Figure 4B illustrates a bidirectional DC-DC energy-conversion apparatus 123', which comprises the first bidirectional DC-DC converter 124 connected between the intermediate energy-storage stage 40 and the vehicle battery 14, but not the second auxiliary DC-DC converter 125 connected between the intermediate energy-storage stage 40 and an auxiliary load R_{aux} . Figure 5B accordingly illustrates an embodiment of the control circuit 140' for the converter 123', which comprises just the bidirectional converter 124. Consequently, as compared to the circuit illustrated in Figure 5A, it does not comprise the AND logic gate 148 nor the auxiliary regulation circuit 143.

It is emphasized in this regard how the solution described herein refers in general to an apparatus for bidirectional conversion of energy between high and low voltage, which does not necessarily comprise circuits for dissipating energy overshooting by the high-voltage bus like the auxiliary converter of Figure 5A; i.e., it refers in general to a bidirectional energy-conversion apparatus of a DC-DC type operating between a low-

voltage system LV and a high-voltage system HV of a vehicle comprising an energy-recovery stage 30,

5 said low-voltage system LV, which operates at a first voltage V_{bat} , comprising a battery 14 that supplies said first voltage V_{bat} on a low-voltage bus LV ,

10 said high-voltage system HV, which operates at a second voltage V_{inDCDC} , V_{DClink} higher than said first voltage V_{bat} , comprising said energy-recovery stage 30 of the vehicle that supplies said second voltage V_{inDCDC} , V_{DClink} ,

15 said second voltage V_{inDCDC} , V_{DClink} being supplied through an intermediate energy-storage system 40 to a DC-DC conversion module 23; 123, which converts said second voltage V_{inDCDC} , V_{DClink} into said first voltage V_{bat} for said low-voltage bus LV, wherein said DC-DC conversion module 123 comprises a bidirectional DC-DC converter 124 connected between the intermediate energy-storage stage 40 and the vehicle battery 14, and
20 said apparatus is configured for selecting a direction of conversion of said bidirectional converter 124, from high voltage HV to low voltage LV or from low voltage LV to high voltage HV via a control circuit 140 as a function of the value of the voltage V_{DClink} on the high-
25 voltage bus HV.

The auxiliary load R_{aux} must be sized so as to guarantee the entire dissipation of the excess energy; i.e., it must have a resistive value not higher than, i.e., lower than or equal to, the value that would
30 cause a voltage drop across it equal to the voltage on the bus V_{DClink} in the presence of the maximum current deriving from the auxiliary DC-DC converter 125 of a buck type.

35 The operation described, in particular for the regulation circuit of Figure 5A, is obtained via the

use of the three regulation circuits 142, 143, 144, one for each mode, the boost mode, the buck mode, and the auxiliary mode, the latter mode being enabled only during buck-mode operation. Each regulation circuit
5 142, 143, 144 envisages a respective voltage control loop on the bus V_{DClink} and a pulse-width modulator, where this is understood as being a circuit that generates a PWM signal with a pulse-width modulation determined by one or more control signals, which
10 regulates an internal inductor-current loop (for example, a loop operating in Peak-Current Mode). The outputs of the three pulse-width modulators are enabled by the boost-mode-enable signal $Boost_mode$ or buck-mode-enable signal $Buck_mode$ described above and
15 directed to the switches Q_{Boost} , Q_{Buck} , Q_{Aux} (or to their drivers) for operating in the required configuration.

For example, with reference to Figure 6, the control loop comprises an adder 143a, which receives as control quantity, or setpoint, the reference voltage
20 V_{ref} , which it compares with the bus voltage V_{DClink} picked up on the input of the converter 123, to obtain an error signal that drives, through a compensation circuit 143b, an internal current loop 143c, which, for example, carries out a current limitation. The output
25 of the current loop is supplied as control signal to a pulse-width modulator 143d, which also receives also the current value I_L of the inductor L for controlling the pulse-width-modulation value and, as illustrated in Figure 5, supplies a signal PWM_{Buck} to the logic gate
30 147, which also receives the buck-mode-enable signal $Buck_mode$. At output from the logic gate 147 is the signal PWM_{buck} , which controls, preferably through drivers, opening and closing of the buck switch Q_{Buck} . The boost switch Q_{Boost} is kept open.

35 In Figure 7 the boost regulation circuit 142 is

similar, with an internal current loop 142c that carries out a current limitation of its own at a limit current value.

5 In Figure 8 the auxiliary regulation circuit 144 is similar, with an internal current loop 144c that carries out a current limitation of its own, and moreover the maximum overvoltage $V_{\max}$ is given as reference or setpoint value for limiting the voltage value.

10 Figure 9 illustrates diagrams that plot as a function of time the waveforms of signals of the apparatus described herein in a condition of turning-on and successive entry of excess energy on the bus.

The voltage on the bus V_{DClink} upon the turning-on
15 rises, while the converter 23 is operating in boost mode (signal Boost_mode at high level). When the voltage on the bus V_{DClink} exceeds the upper hysteresis threshold V_{TH} of the comparator 141, this switches its output, the boost-mode-enable signal Boost_mode drops
20 to the low logic level, and the buck-mode-enable signal Buck-mode goes to high logic level, enabling the bidirectional DC-DC converter 124 to function in buck mode converting the high voltage of the HV side into low voltage on the LV side. The auxiliary DC-DC
25 converter 125 is enabled if the voltage on the bus V_{DClink} has exceeded the maximum overvoltage $V_{\max}$ and the bidirectional converter 124 is in buck mode (the driving signal PWM_{aux} is issued). The auxiliary converter 125 is disabled when the voltage on the bus
30 V_{DClink} has dropped below the maximum overvoltage $V_{\max}$. When the voltage on the bus V_{DClink} drops below the lower hysteresis threshold V_{TL} of the comparator 141, the apparatus returns into boost mode.

In the more general case of the solution here
35 described of Figure 5B, the control circuit 140'

comprises the comparator with hysteresis 141 with an upper hysteresis threshold V_{TH} and a lower hysteresis threshold V_{TL} configured for comparing the voltage on the bus V_{DClink} with a reference voltage V_{ref} , and, if the voltage on the bus V_{DClink} exceeds the upper threshold V_{TH} , a status signal is generated for enabling the operation of conversion from high voltage to low voltage, or buck mode Buck_mode, and if the voltage on the bus V_{DClink} drops below the lower threshold V_{TL} , a status signal is generated for enabling the operation of conversion from low voltage to high voltage, or boost mode Boost_mode. The control circuit 140 only comprises the respective regulation circuits 142, 143 for the buck mode and the boost mode, which generate respective PWM driving signals PWM_{Buck} , PWM_{Boost} for driving respective switches Q_{Buck} , Q_{Boost} of said buck converter Q_{Buck} , L , D_{Buck} and boost converter Q_{Boost} , L , D_{Boost} , and just the logic circuits 147, 148 for selectively supplying at output from said regulation circuit 140 said PWM driving signals PWM_{Buck} , PWM_{Boost} to said respective switches Q_{Buck} , Q_{Boost} , under the control of said status signal for enabling the operation of conversion from high voltage to low voltage, Buck_mode, and said status signal for enabling the operation of conversion from low voltage to high voltage, Boost_mode.

Figure 10 illustrates diagrams that plot as a function of time the waveforms of signals of the apparatus in a condition in which the input energy, coming from the energy-recovery system 30 is in excess with respect to the energy that can be transferred into the battery 14.

In this case, the converter 123 is in buck mode; when the voltage on the bus V_{DClink} exceeds the maximum overvoltage V_{max} the auxiliary converter 125 is enabled

(the driving signal PWM_{aux} is issued).

Figure 11 illustrates diagrams that plot as a function of time the waveforms of signals of the apparatus in an additional condition that represents
5 the case where the maximum overvoltage V_{max} is set at a value higher than that of the other thresholds. In this mode, the voltage ripple increases, but a better mean energy transfer is obtained, in so far as dissipation of the excess energy is limited by storing it
10 temporarily in the storage element.

Also in this case, the converter 123, initially in buck mode with the bidirectional DC-DC converter 124 activated in buck mode to convert the high voltage into low voltage, activates the auxiliary DC-DC converter
15 125 when the voltage on the bus V_{DClink} exceeds the maximum overvoltage V_{max} and de-activates it, instead, when the voltage on the bus V_{DClink} subsequently drops below the maximum overvoltage V_{max} .

The solution proposed may be applied also in the
20 case in which is energy-management strategies are to be implemented by varying the voltage of the high-voltage bus (for example, in the presence of an energy-storage element such as supercapacitors or a Li-ion battery). In this case, the reference voltages V_{ref} , the threshold
25 hysteresis voltages V_{TH} , V_{TL} , and the maximum overvoltage V_{max} must be rendered settable in time.

Hence, from the foregoing description the advantages of the solution emerge clearly.

Advantageously, the apparatus and method described
30 enable regulation of the flow of power in an automatic way without requiring reading of the currents. Known solutions for determining the direction of operation of a bidirectional DC-DC converter envisage acquisition of the sign of the currents at input and output and
35 consequent setting of the control. In the case where

the devices connected to the bus are numerous (at least four controllers for the shock absorbers) this approach may be complex. The solution proposed envisages, instead, just reading of the voltage on the high-
5 voltage bus with consequent determination of the direction of operation of the first converter and possible activation of the second converter.

Of course, without prejudice to the principle of the invention, the details of construction and the
10 embodiments may vary widely with respect to what has been described and illustrated herein purely by way of example, without thereby departing from the scope of the present invention.

CLAIMS

1. A bidirectional energy-conversion apparatus of a DC-DC type operating between a low-voltage system (LV) and a high-voltage system (HV) of a vehicle comprising an energy-recovery stage (30),

said low-voltage system (LV), which operates at a first voltage (V_{bat}), comprising a battery (14) that supplies said first voltage (V_{bat}) on a low-voltage bus (LV),

said high-voltage system (HV), which operates at a second voltage (V_{inDCDC} , V_{DClink}) higher than said first voltage (V_{bat}), comprising said energy-recovery stage (30) of the vehicle that supplies said second voltage (V_{inDCDC} , V_{DClink}),

said second voltage (V_{inDCDC} , V_{DClink}) being supplied, through an intermediate energy-storage system (40), to a DC-DC conversion module (23; 123), which converts said second voltage (V_{inDCDC} , V_{DClink}) into said first voltage (V_{bat}) for said low-voltage bus (LV),

said apparatus being characterized in that:

said DC-DC conversion module (123) comprises a bidirectional DC-DC converter (124), connected between the intermediate energy-storage stage (40) and the vehicle battery (14); and

said apparatus is configured for selecting a direction of conversion of said bidirectional converter (124), from high voltage (HV) to low voltage (LV) or from low voltage (LV) to high voltage (HV), via a control circuit (140) as a function of the value of the voltage (V_{DClink}) on the high-voltage bus (HV).

2. The apparatus according to Claim 1, characterized in that said first bidirectional converter (124) is configured for operating in a buck-conversion mode (Q_{Buck} , L , D_{Buck}) from high voltage to

low voltage and a boost-conversion mode (Q_{Boost} , L , D_{Boost}), said modes being selectable by said control circuit (140) for operating, respectively, conversion from high voltage (HV) to low voltage (LV) or from low
5 voltage (LV) to high voltage (HV).

3. The apparatus according to Claim 2, characterized in that said control circuit (140) comprises a comparator with hysteresis (141) with an upper hysteresis threshold (V_{TH}) and a lower hysteresis
10 threshold (V_{TL}), which is configured for comparing the voltage on the bus (V_{DClink}) with a reference voltage V_{ref} , and, if the voltage on the bus (V_{DClink}) exceeds the upper threshold (V_{TH}), a status signal is generated for enabling the operation of conversion from high voltage
15 to low voltage, or buck mode (Buck_mode), and

if the voltage on the bus (V_{DClink}) drops below the lower threshold (V_{TL}), a status signal is generated for enabling the operation of conversion from low voltage to high voltage, or boost mode (Boost_mode).

20 4. The apparatus according to any one of the preceding claims, characterized in that said control circuit (140) comprises respective regulation circuits (142, 143) for the buck mode and the boost mode, which generate respective PWM (Pulse-Width Modulation)
25 driving signals (PWM_{Buck} , $\text{PWM}_{\text{Boost}}$) for driving respective switches (Q_{Buck} , Q_{Boost}) of said buck converter (Q_{Buck} , L , D_{Buck}) and said boost converter (Q_{Boost} , L , D_{Boost}), and logic circuits (147, 148) for selectively supplying at
30 output from said regulation circuit (140) said PWM driving signals (PWM_{Buck} , $\text{PWM}_{\text{Boost}}$) to said respective switches (Q_{Buck} , Q_{Boost}) under the control of said status signal for enabling the operation of conversion from high voltage to low voltage (Buck_mode) and said status
35 signal for enabling the operation of conversion from low voltage to high voltage (Boost_mode).

5 5. The apparatus according to any one of the preceding claims, characterized in that said apparatus (90; 190) comprises an auxiliary load (R_{aux}), in particular an external load, which can be connected in order to enable dissipation of the excess energy supplied by the energy-recovery system (30),

 said DC-DC conversion module (123) further comprising a bidirectional DC-DC converter (124) connected between the intermediate energy-storage stage (40) and the vehicle battery (14), and a second DC-DC converter (125) connected between the intermediate energy-storage stage (40) and said auxiliary load (R_{aux}).

15 6. The apparatus according to any one of the preceding claims, characterized in that said apparatus is configured for selecting a direction of conversion of the first bidirectional converter (124), from high voltage (HV) to low voltage (LV) or from low voltage (LV) to high voltage (HV)), and activation or
20 deactivation of said second auxiliary converter (124) via a control circuit (140) as a function of the value of the voltage (V_{DClink}) on the high-voltage bus (HV).

 7. The apparatus according to any one of the preceding claims, characterized in that said first
25 bidirectional converter (124) further comprises an auxiliary buck converter (Q_{Aux} , L_{Aux} , D_{Aux}), which can be selected if said one buck converter (Q_{Buck} , L , D_{Buck}) is selected active for conveying the bus voltage (V_{DClink}) on the auxiliary load (R_{aux}).

30 8. The apparatus according to any one of the preceding claims, characterized in that said control circuit (140) is configured for:

 disabling operation of the first converter (124) and of the second converter (125) if the bus voltage is
35 lower both than the reference voltage value (V_{ref}) and

than a maximum overvoltage value ($V_{\max}$),

enabling operation only of the bidirectional DC-DC converter (124) if the bus voltage (V_{DClink}) is comprised between the reference voltage value (V_{ref}) and the maximum overvoltage value ($V_{\max}$),

enabling operation of the first converter (124) and of the second converter (125) if the bus voltage (V_{DClink}) is higher both than a reference voltage value (V_{ref}) and than a maximum overvoltage value ($V_{\max}$).

9. A method for bidirectional energy conversion between a low-voltage system (LV) and a high-voltage system of a vehicle according to any one of Claims 1 to 8, said method comprising selecting a direction of conversion of the first bidirectional converter (124), from high voltage (HV) to low voltage (LV) or from low voltage (LV) to high voltage (HV)), as a function of the value of the voltage (V_{DClink}) on the high-voltage bus (HV).

10. The method according to Claim 9, characterized in that it comprises executing an operation of comparison with hysteresis (141) with an upper hysteresis threshold (V_{TH}) and a lower hysteresis threshold (V_{TL}), and, if the voltage on the bus (V_{DClink}) exceeds the upper threshold (V_{TH}), a status signal is generated for enabling the operation of conversion from high voltage to low voltage, or buck mode (Buck_mode), if the voltage on the bus (V_{DClink}) drops below the lower threshold (V_{TL}), a status signal is generated for enabling the operation of conversion from low voltage to high voltage, or boost mode (Boost_mode).

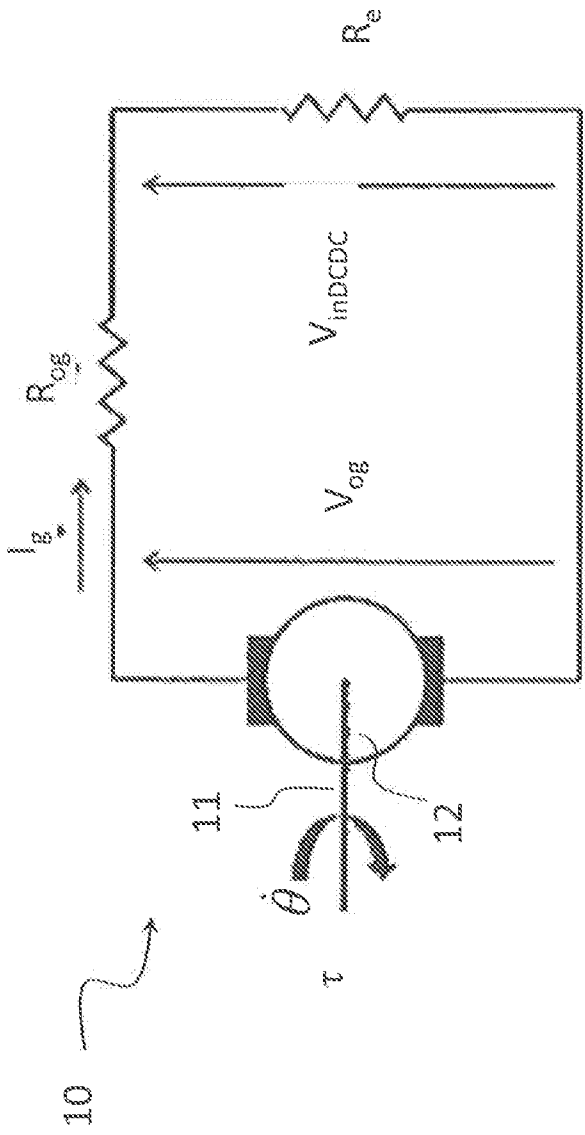


Fig. 1

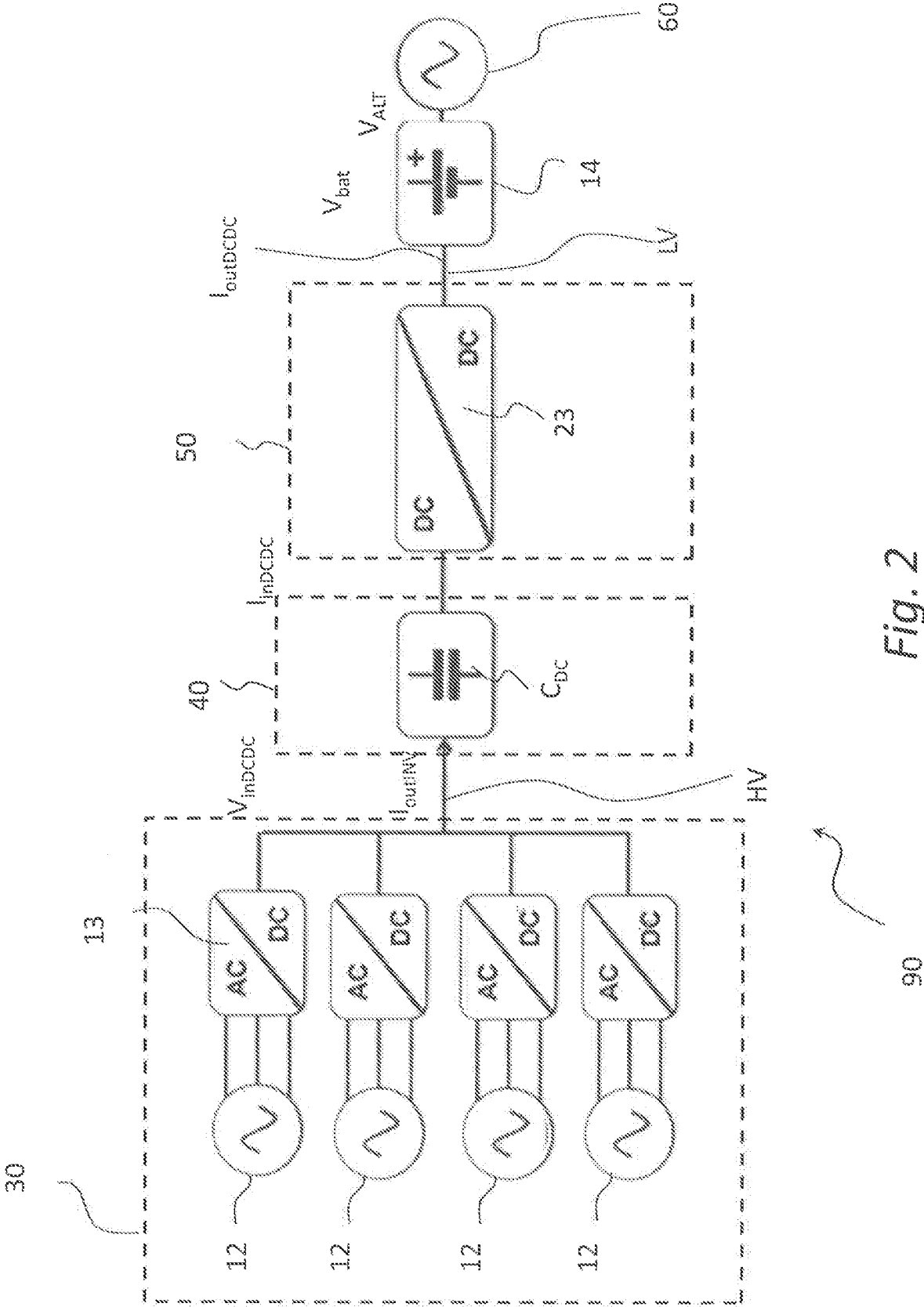


Fig. 2

3. 5. 4.

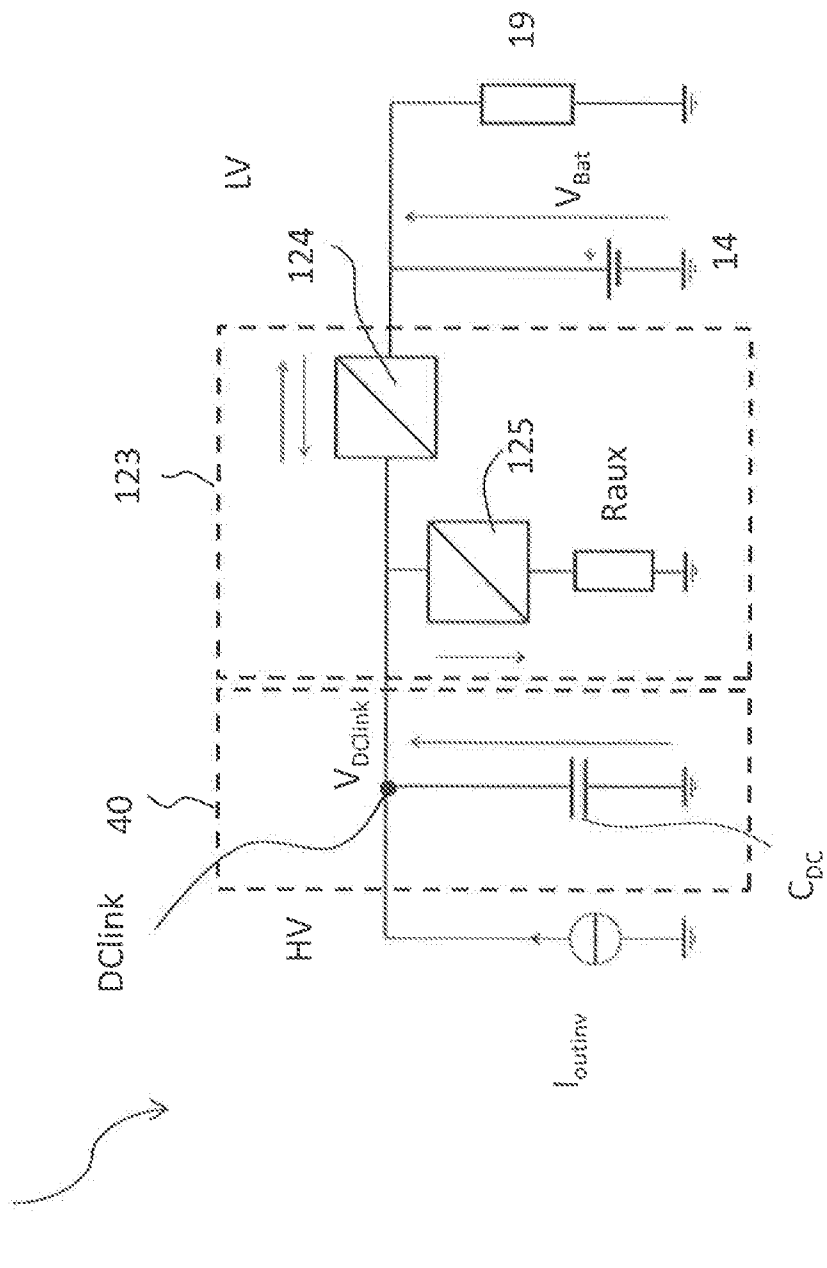


Fig. 4A

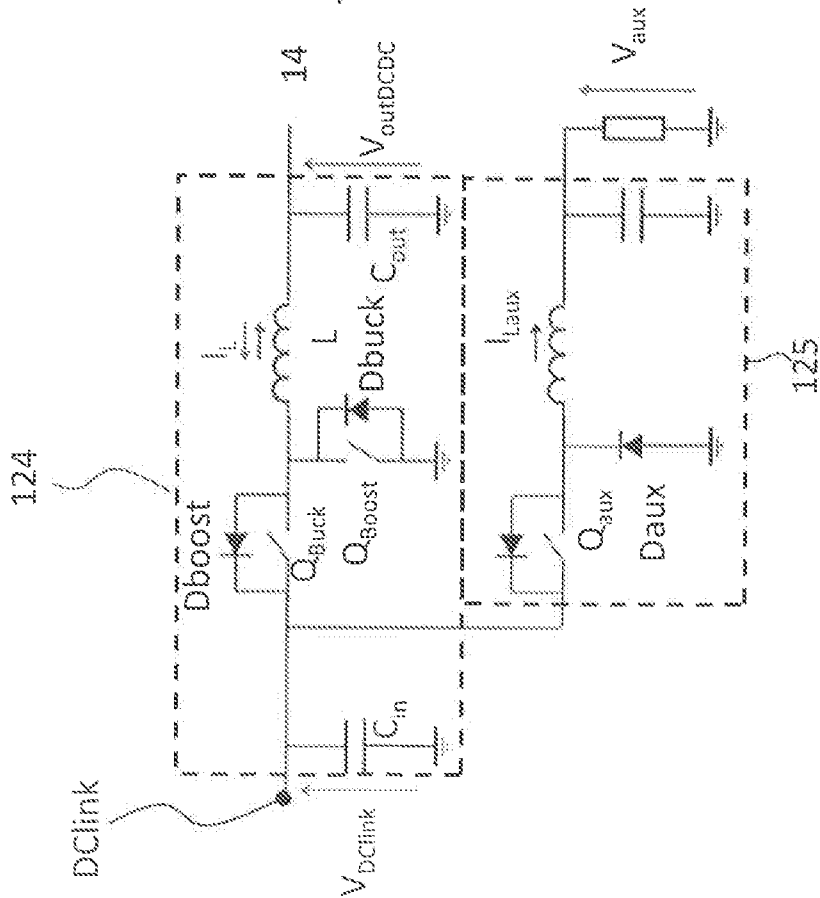
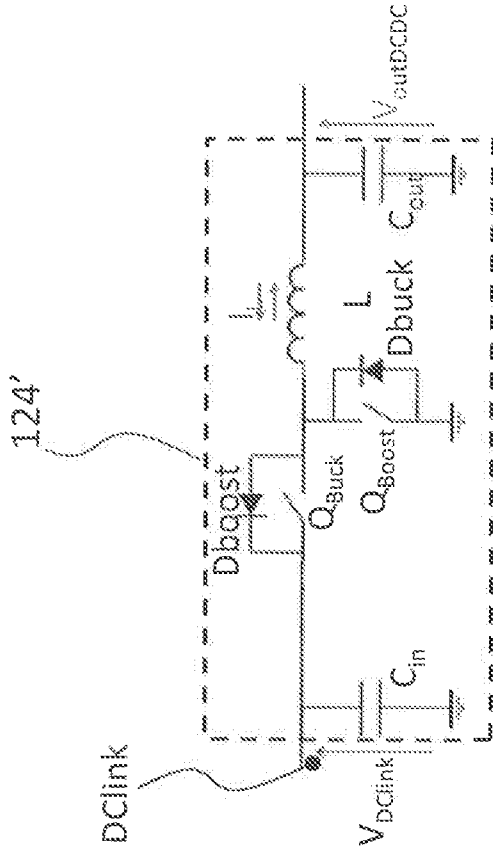


Fig. 4B



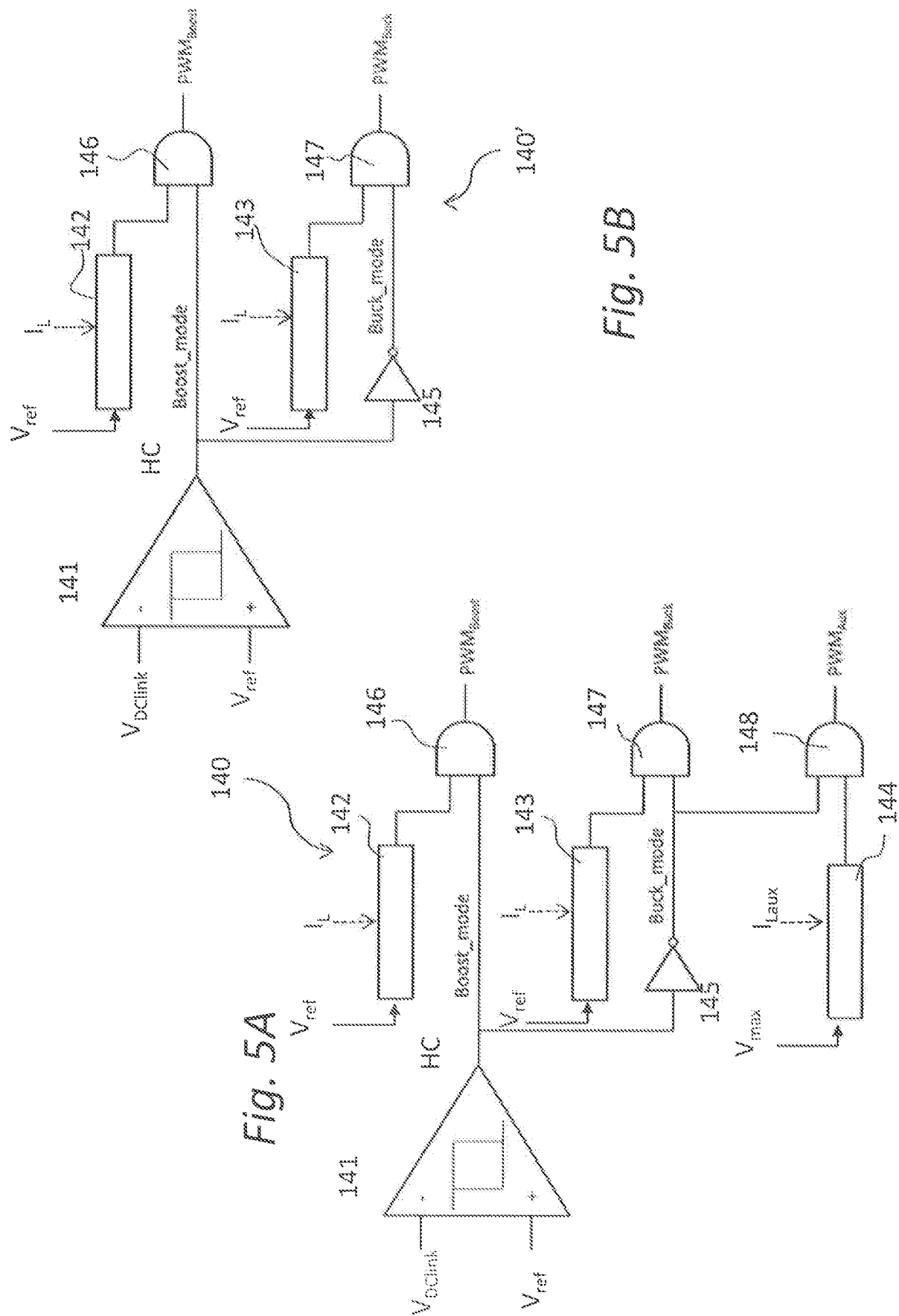


Fig. 5B

Fig. 6

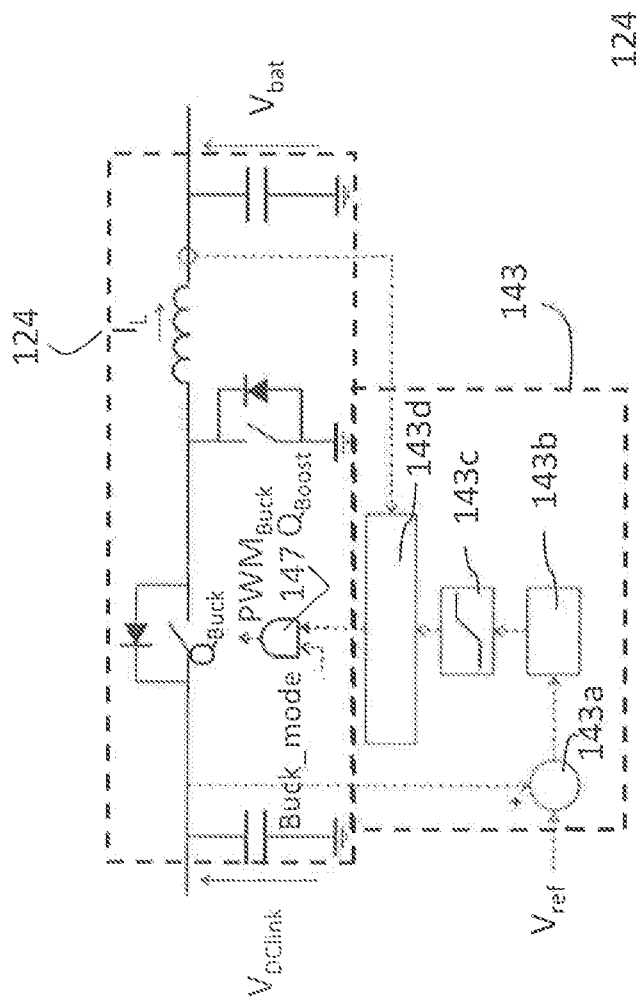


Fig. 7

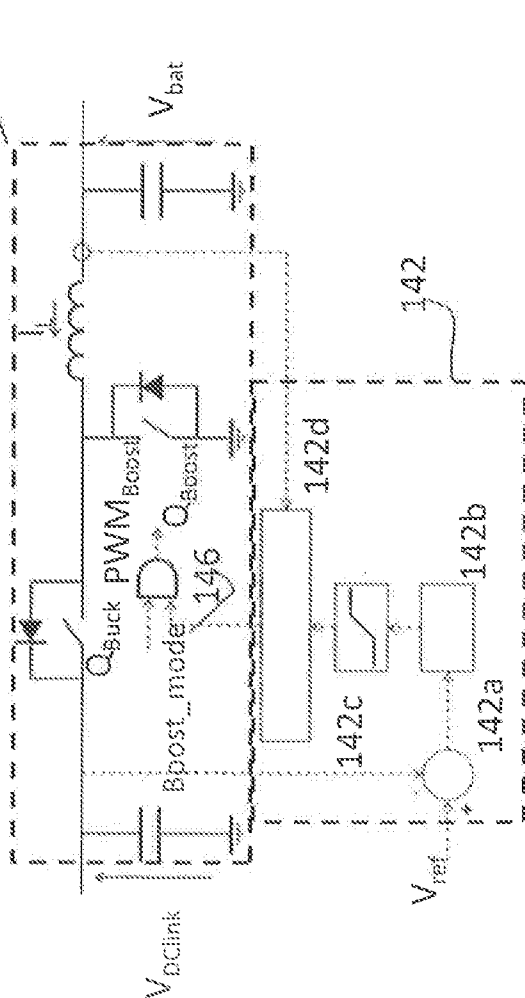
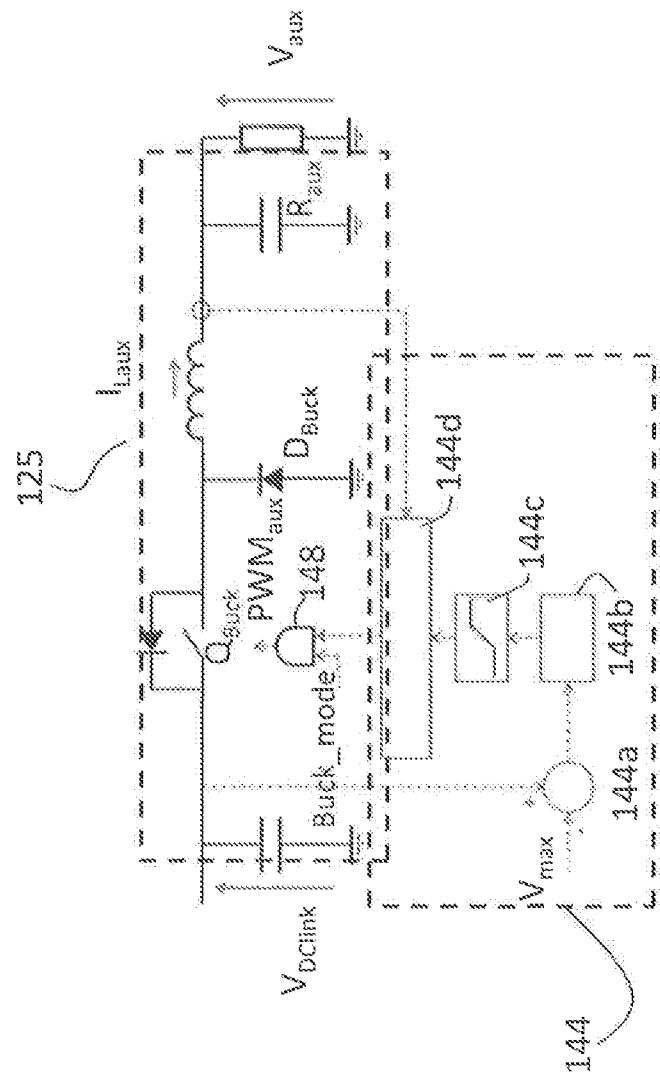


Fig. 8



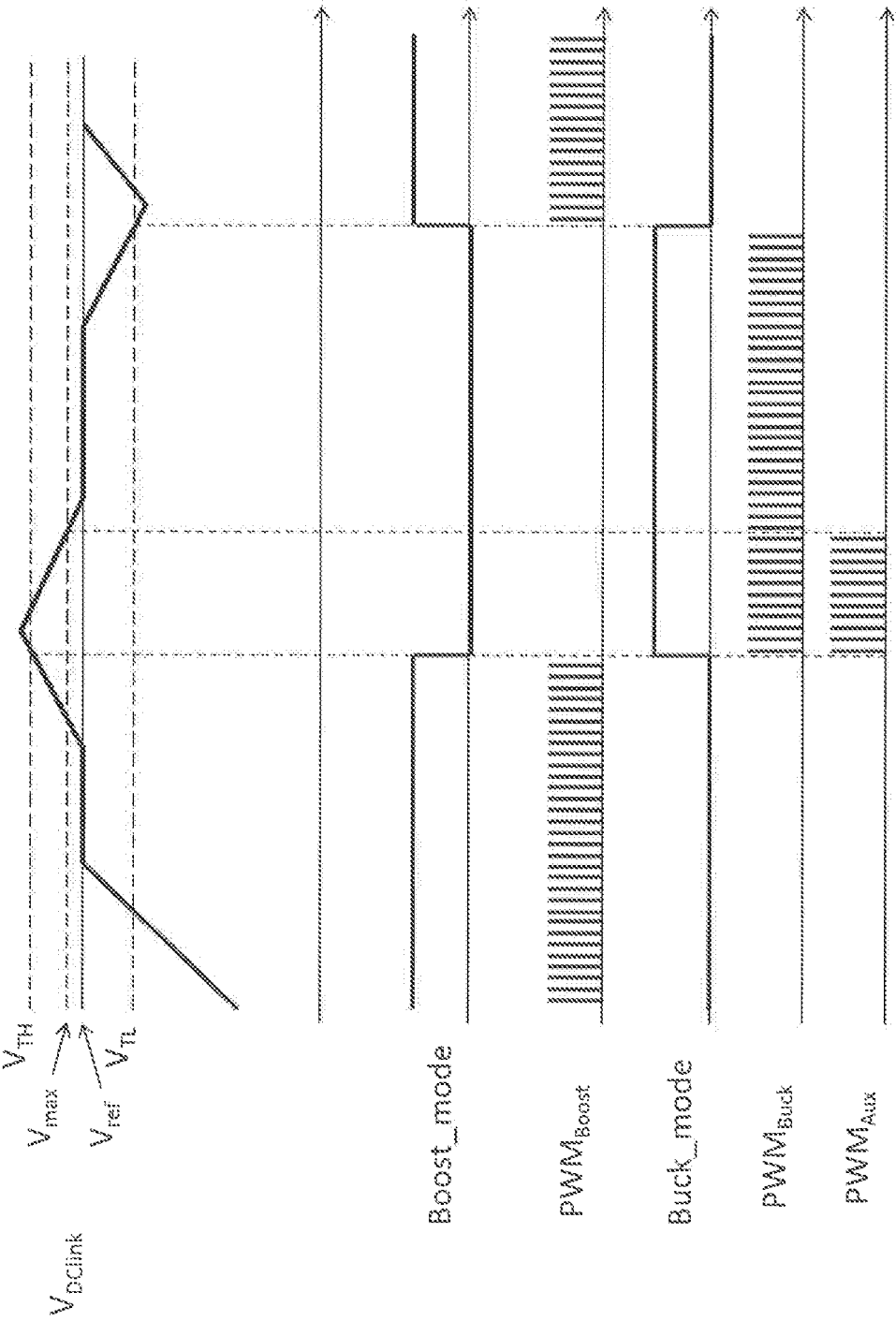


Fig. 9

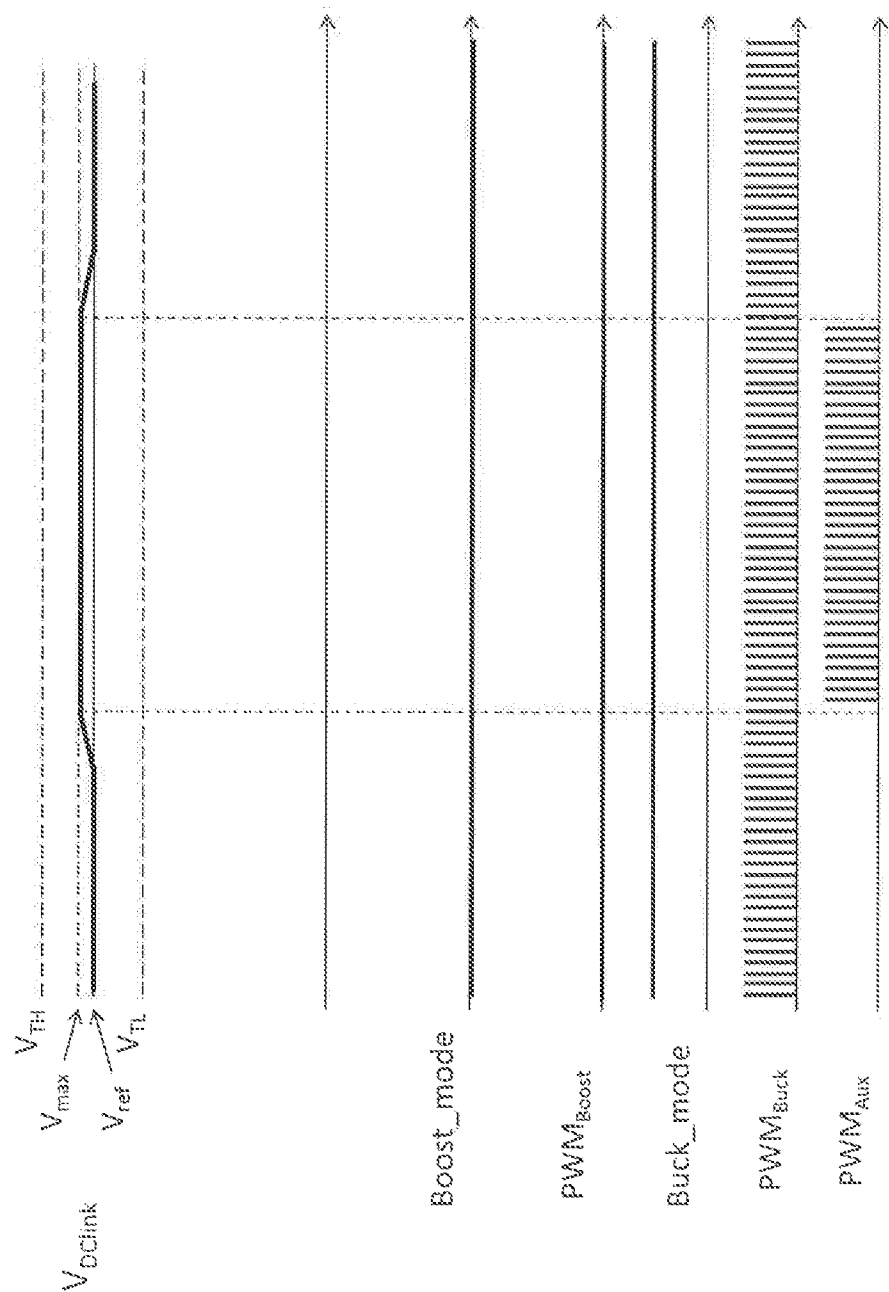


Fig. 10

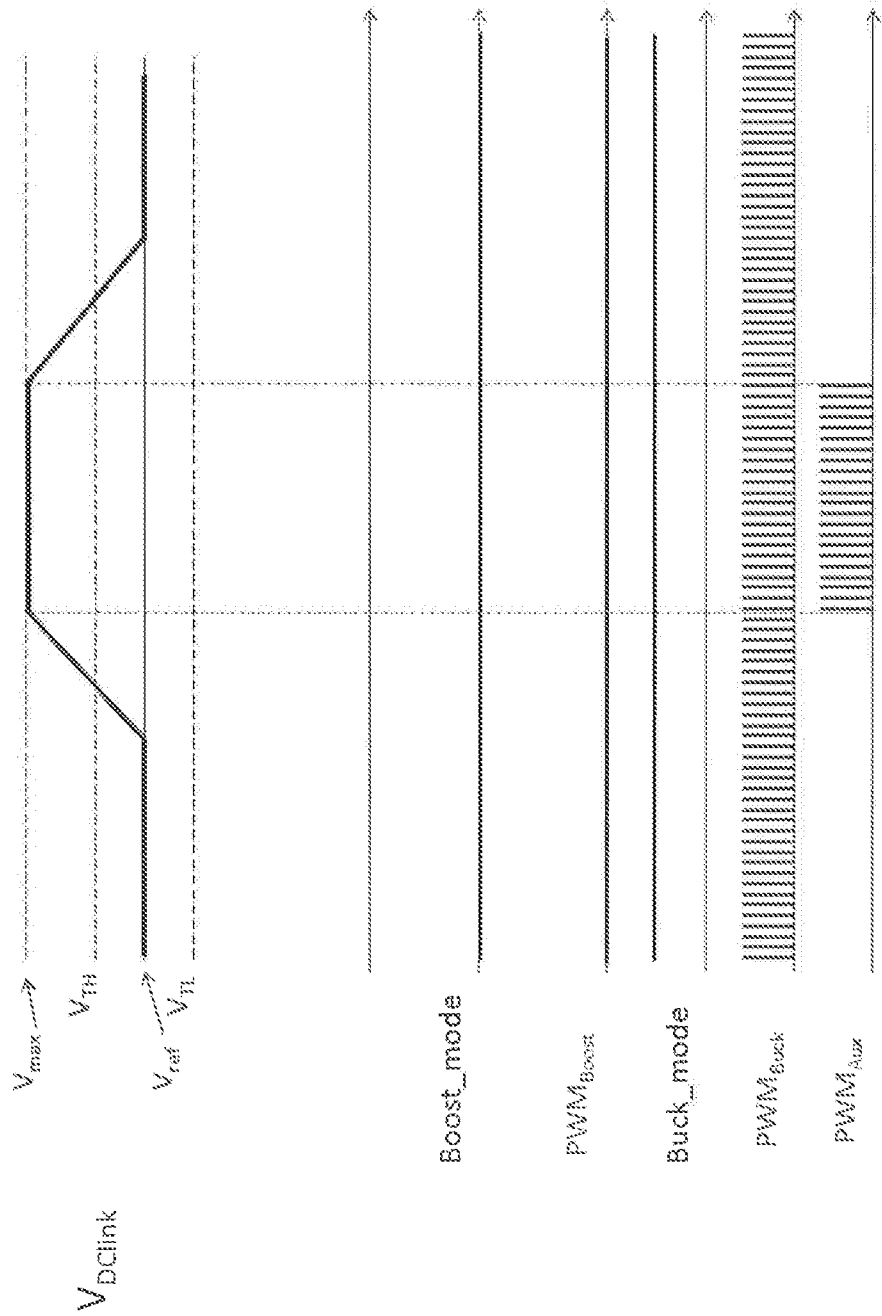


Fig. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2018/056674

A. CLASSIFICATION OF SUBJECT MATTER INV. H02M1/32 H02M3/158 B60G13/14 B60G17/0165 B60G17/06 ADD. H02M1/00		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) H02M B60G		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2014/145018 A2 (LEVANT POWER CORP [US]) 18 September 2014 (2014-09-18)	1,2,4-9
Y	abstract paragraphs [0001] - [0004], [1067], [1069] - [1071], [1074], [1075], [1089] - [1091], [1122]; figures 1-2, 3-2, 4-1, 4-9G	3,10
A	----- EP 2 821 265 A1 (MAGNETI MARELLI SPA [IT]; SISTEMI SOSPENSIONI SPA [IT]) 7 January 2015 (2015-01-07) abstract; figures 3, 4, 8, 10	1-10
A	----- EP 2 193 954 A1 (GEN ELECTRIC [US]) 9 June 2010 (2010-06-09) abstract paragraphs [0022], [0023], [0028]; figures 2-4 ----- -/-	1-10
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 7 November 2018		Date of mailing of the international search report 14/11/2018
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Van der Meer, Paul

INTERNATIONAL SEARCH REPORT

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Y	abstract; figure 3 -----	3,10
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