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King et al.

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(54) **APPARATUS AND METHOD FOR RAPID CHARGING USING SHARED POWER ELECTRONICS**

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US 2024/0157821 A1 May 16, 2024

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(63) Continuation of application No. 17/977,204, filed on Oct. 31, 2022, now Pat. No. 11,884,168, which is a

(Continued)

(51) **Int. Cl.**

H02J 7/00 (2006.01)
B60L 7/12 (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***B60L 53/14*** (2019.02); ***B60L 7/12*** (2013.01); ***B60L 7/14*** (2013.01); ***B60L 9/22*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC B60L 53/14; B60L 53/20; B60L 53/11; B60L 58/16; B60L 58/40; B60L 58/20; B60L 50/40; B60L 50/51

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(57) **ABSTRACT**

An apparatus comprises a power electronic energy conversion system comprising a first energy storage device configured to store DC energy and a first voltage converter configured to convert a second voltage from a remote power supply into a first charging voltage configured to charge the first energy storage device. The apparatus also includes a first controller configured to control the first voltage converter to convert the second voltage into the first charging voltage and to provide the first charging voltage to the first energy storage device during a charging mode of operation and communicate with a second controller located remotely from the power electronic energy conversion system to cause a second charging voltage to be provided to the first

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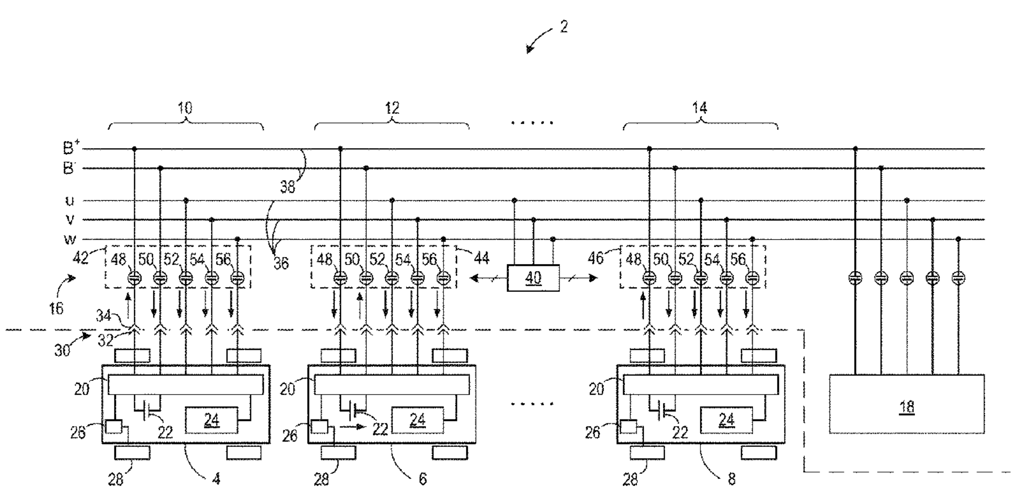

energy storage device during the charging mode of operation to rapidly charge the first energy storage device.

20 Claims, 10 Drawing Sheets

Related U.S. Application Data

continuation of application No. 17/873,357, filed on Jul. 26, 2022, now abandoned, which is a continuation of application No. 16/715,508, filed on Dec. 16, 2019, now Pat. No. 11,400,820, which is a continuation of application No. 16/278,379, filed on Feb. 18, 2019, now Pat. No. 10,543,755, which is a continuation of application No. 15/708,859, filed on Sep. 19, 2017, now Pat. No. 10,377,259, which is a continuation of application No. 14/219,201, filed on Mar. 19, 2014, now Pat. No. 9,789,780, which is a continuation of application No. 12/641,359, filed on Dec. 18, 2009, now Pat. No. 8,698,451.

(51) **Int. Cl.**

B60L 7/14	(2006.01)
B60L 9/22	(2006.01)
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B60L 50/40	(2019.01)
B60L 50/51	(2019.01)
B60L 50/52	(2019.01)
B60L 53/10	(2019.01)
B60L 53/14	(2019.01)
B60L 53/20	(2019.01)
B60L 58/16	(2019.01)
B60L 58/20	(2019.01)
B60L 58/40	(2019.01)
H02J 7/14	(2006.01)

(52) **U.S. Cl.**

CPC ***B60L 9/28*** (2013.01); ***B60L 50/30*** (2019.02); ***B60L 50/40*** (2019.02); ***B60L 50/51*** (2019.02); ***B60L 50/52*** (2019.02); ***B60L 53/11*** (2019.02); ***B60L 53/20*** (2019.02); ***B60L 58/16*** (2019.02); ***B60L 58/20*** (2019.02); ***B60L 58/40*** (2019.02); ***H02J 7/0013*** (2013.01); ***H02J 7/0029*** (2013.01); ***H02J 7/0045*** (2013.01); *B60L 2200/36* (2013.01); *B60L 2210/14* (2013.01); *B60L 2210/30* (2013.01); *B60L 2210/40* (2013.01); *B60L 2240/72* (2013.01); *H02J 2207/20* (2020.01); *H02J 2310/48* (2020.01); *Y02T 10/70* (2013.01); *Y02T 10/7072* (2013.01); *Y02T 10/72* (2013.01); *Y02T 90/12* (2013.01); *Y02T 90/14* (2013.01); *Y02T 90/16* (2013.01); *Y02T 90/167* (2013.01); *Y02T 90/40* (2013.01); *Y04S 30/12* (2013.01); *Y10S 903/903* (2013.01)

(58) **Field of Classification Search**

USPC 320/109

See application file for complete search history.

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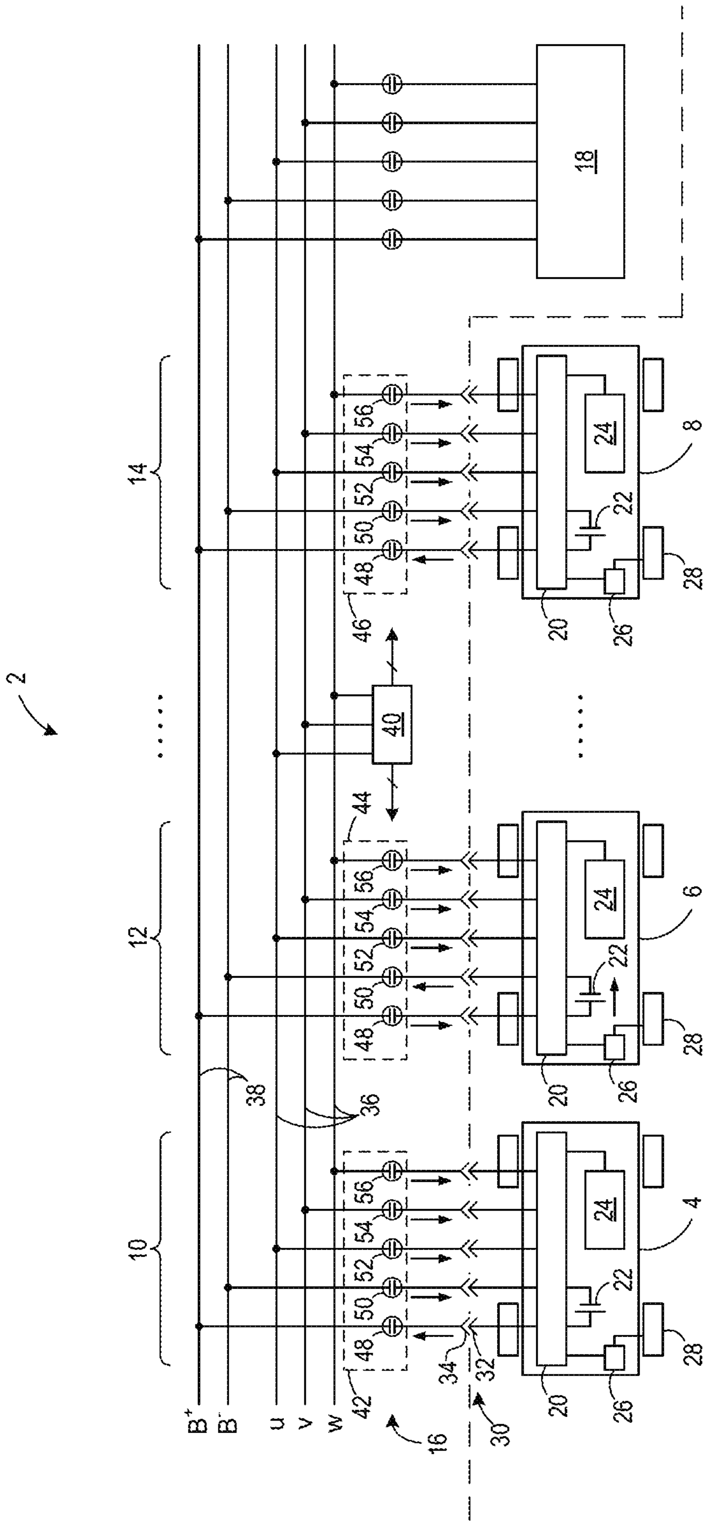

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FIG. 1

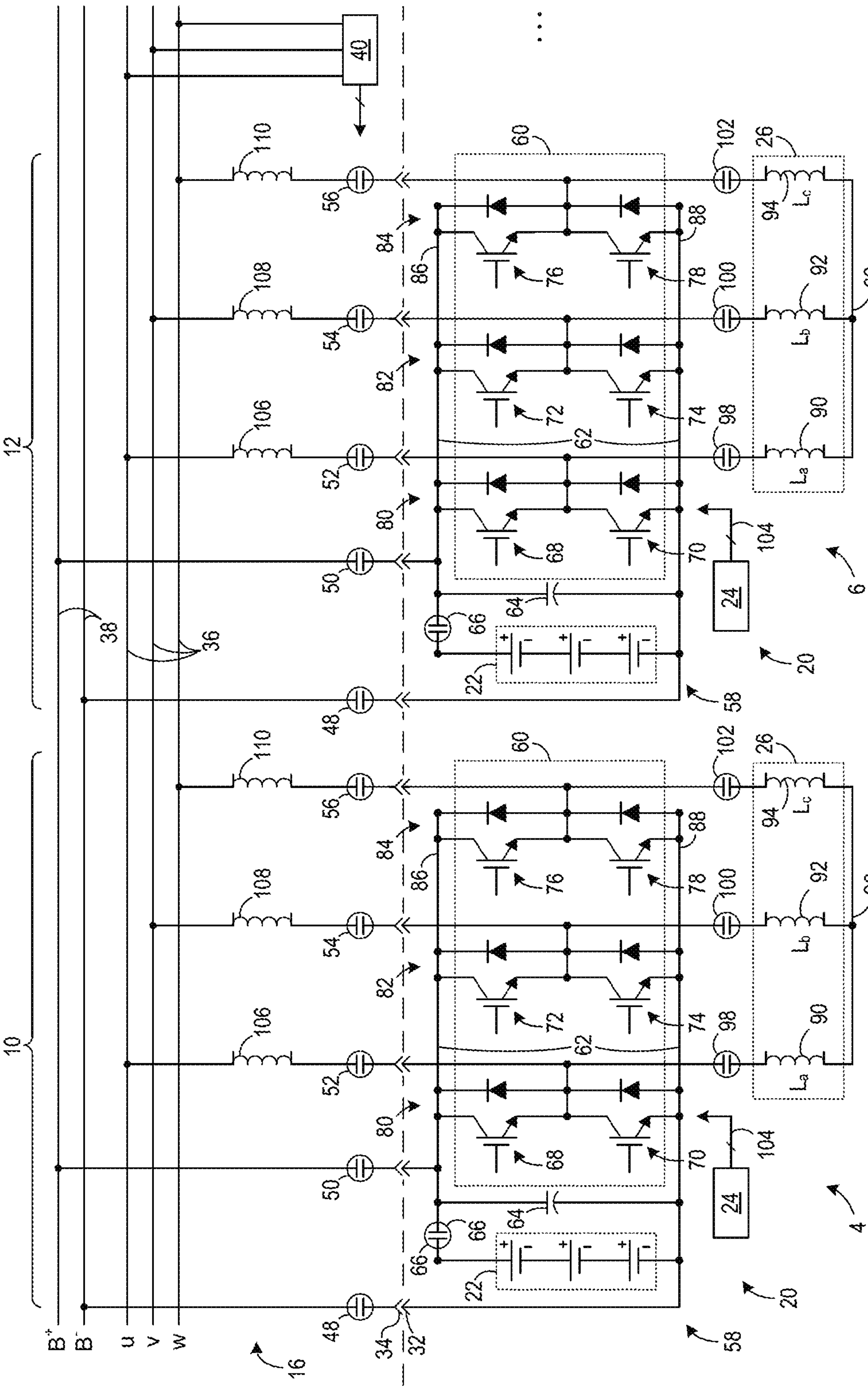

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FIG. 2

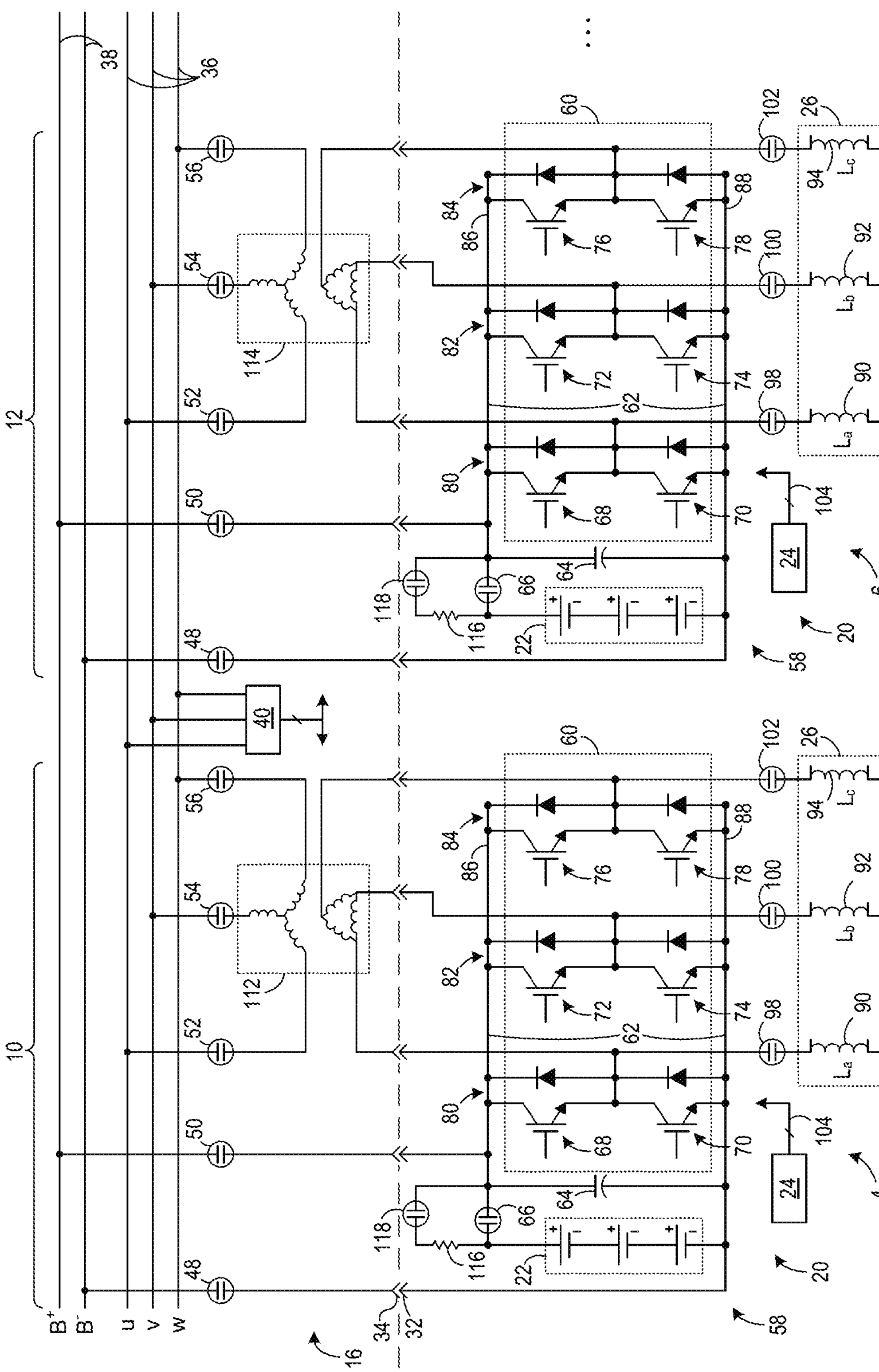

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FIG. 3

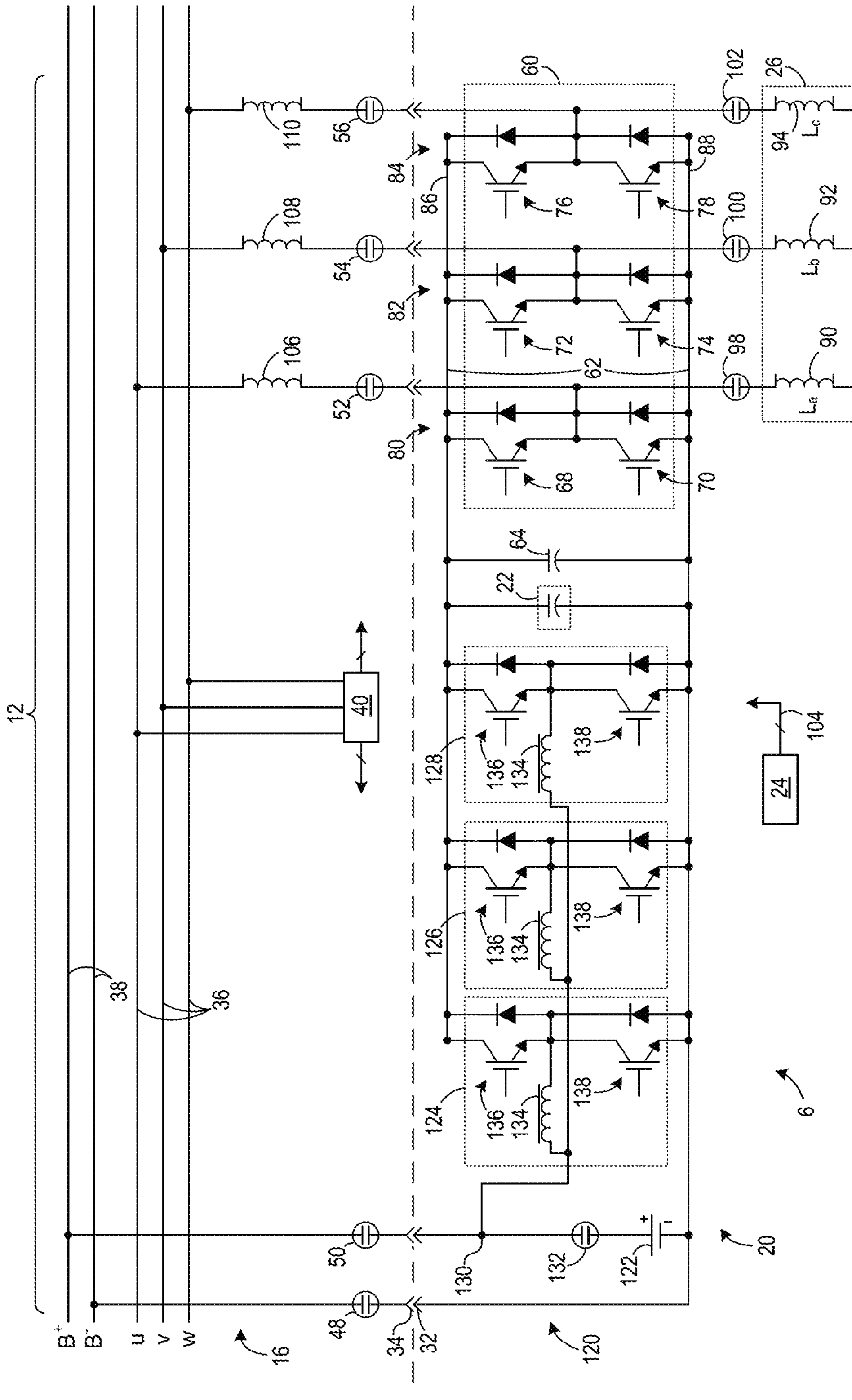

FIG. 4

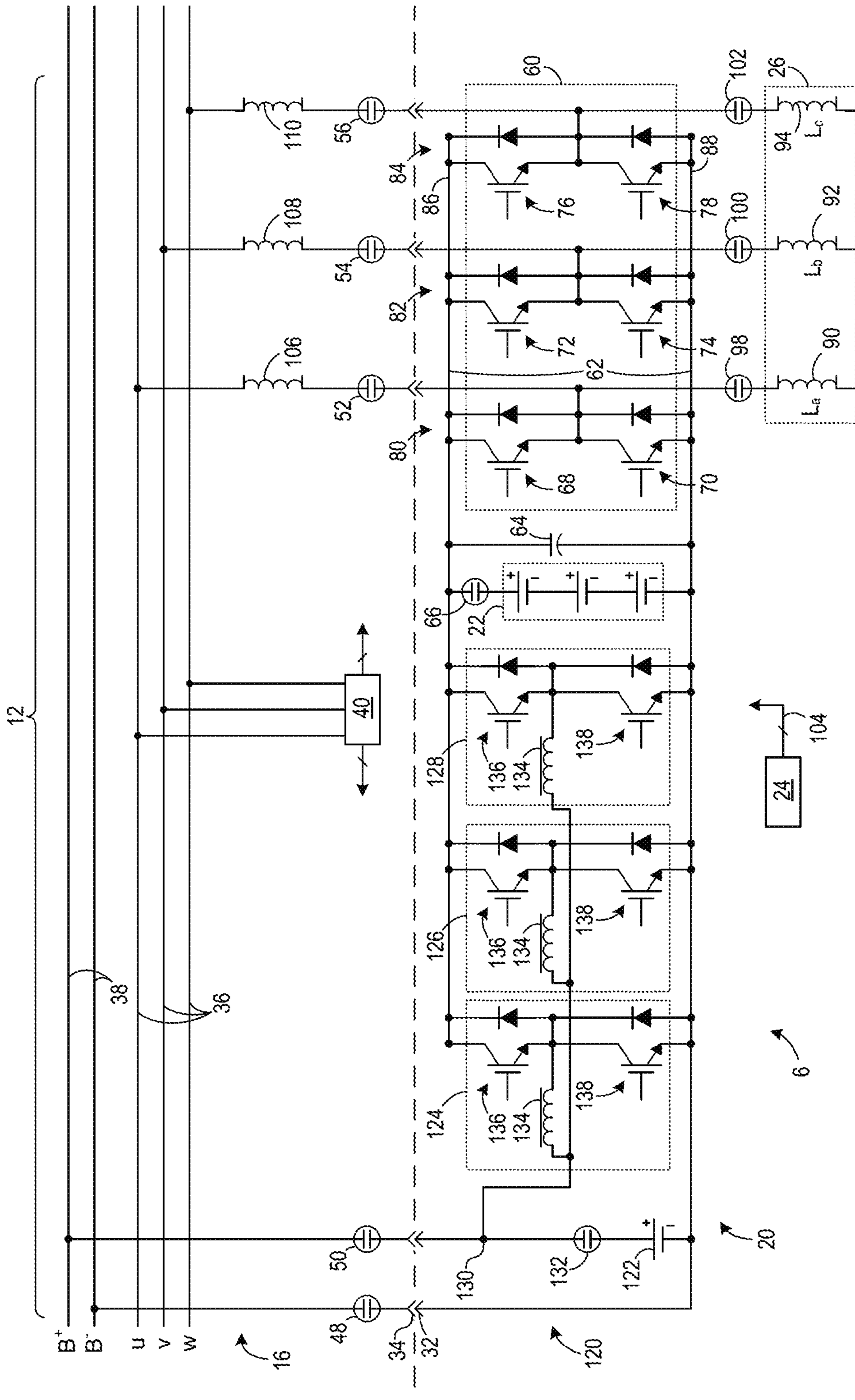
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FIG. 5

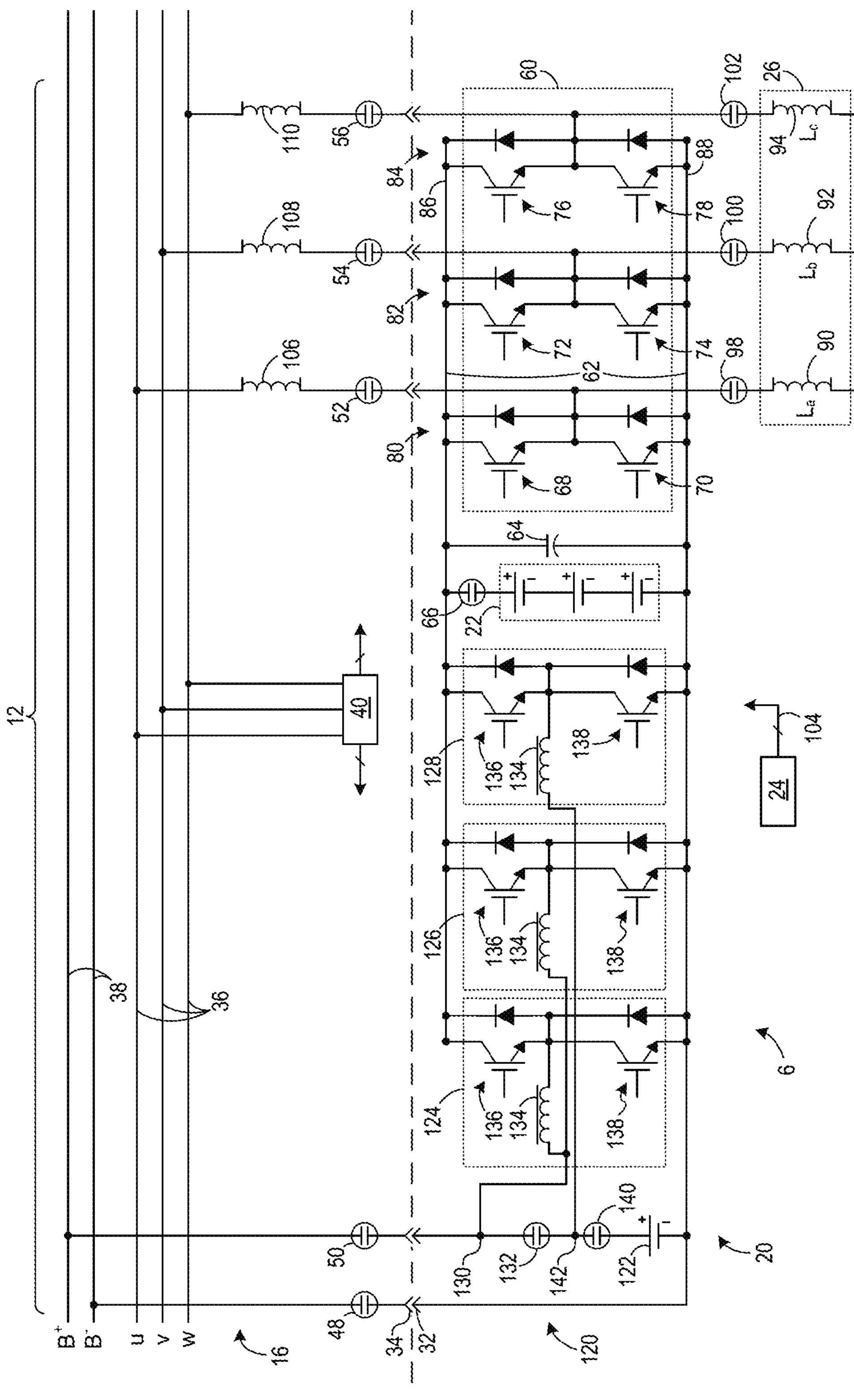
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FIG. 6

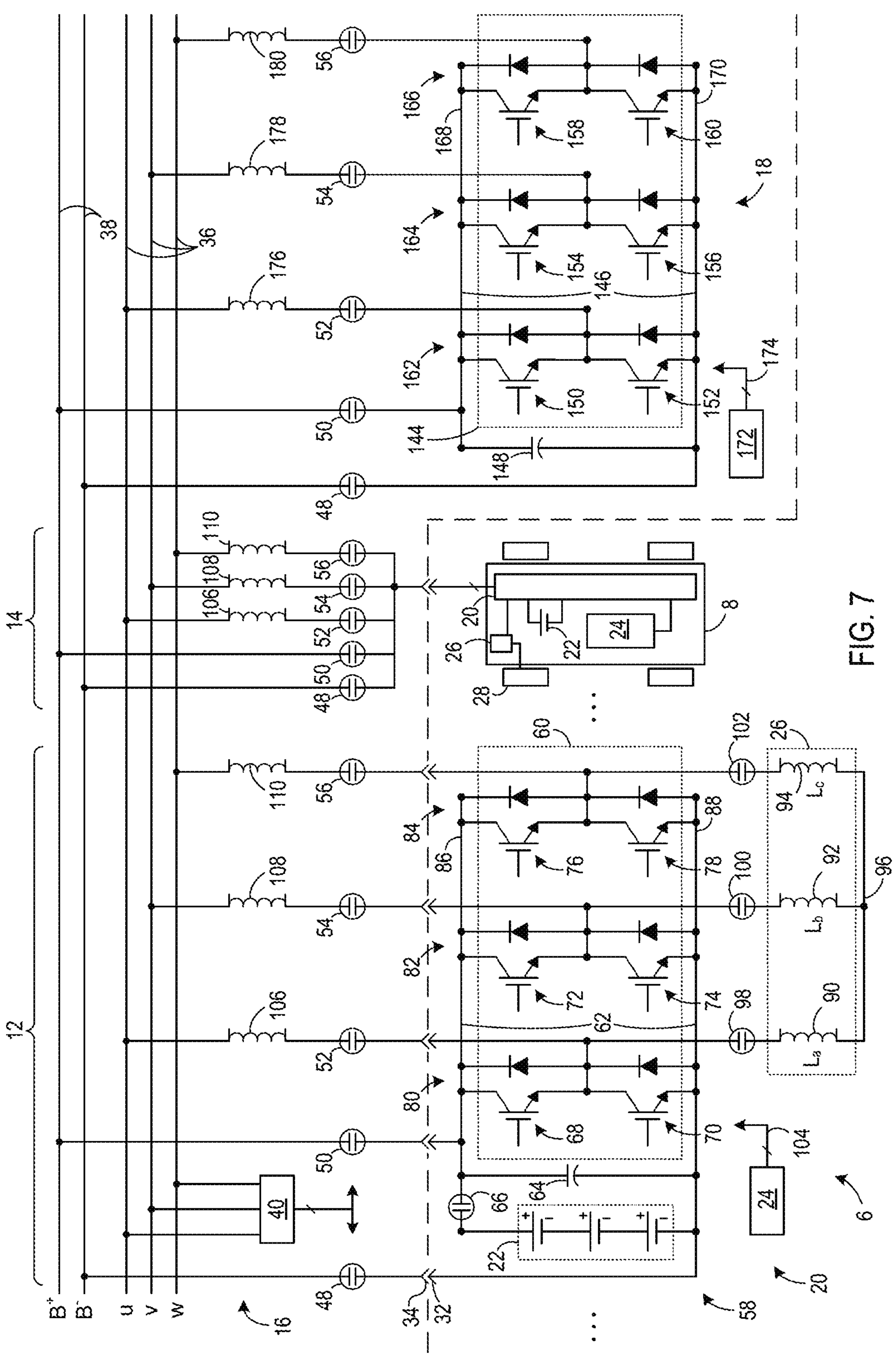
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FIG. 7

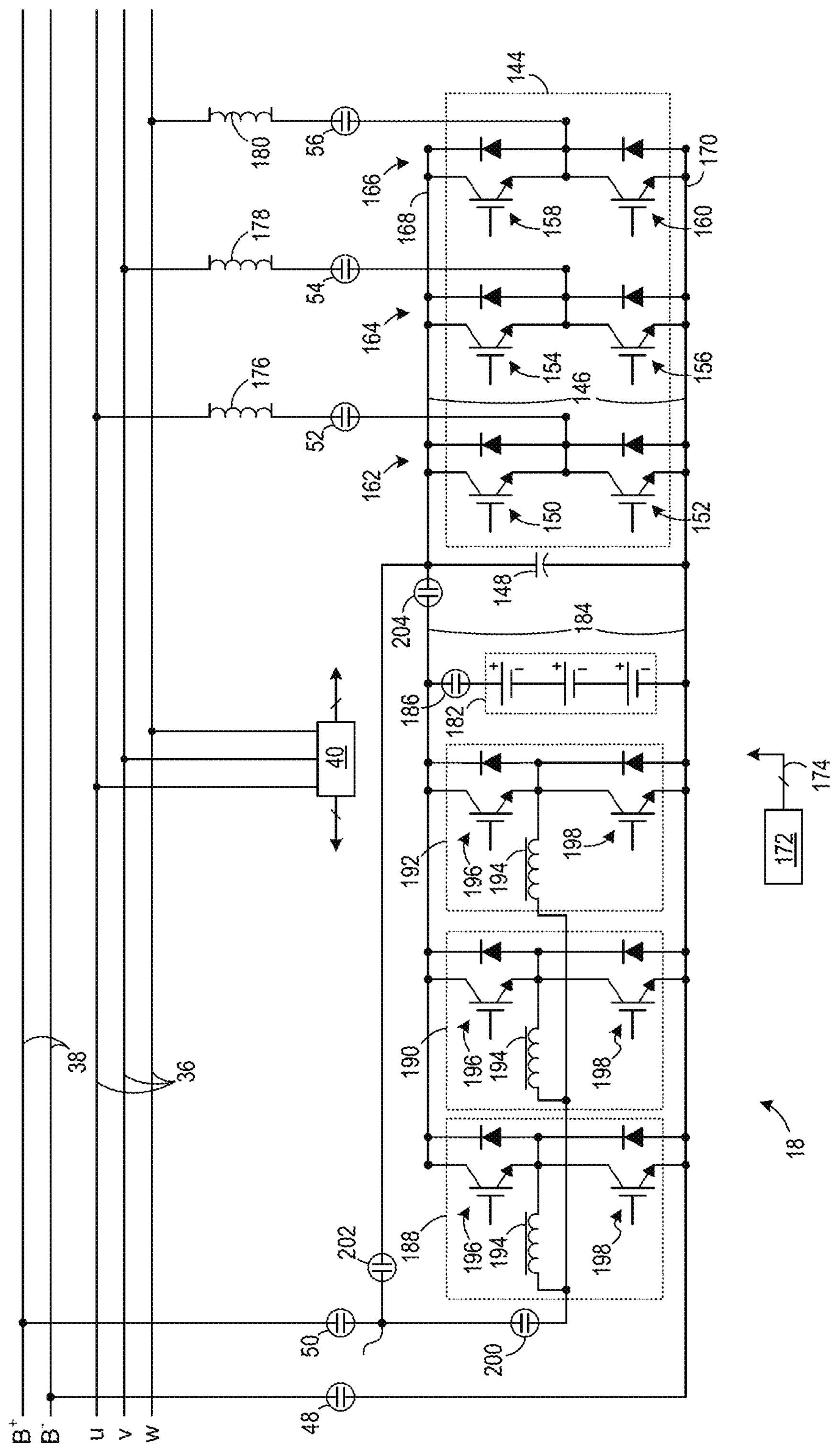
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FIG. 8

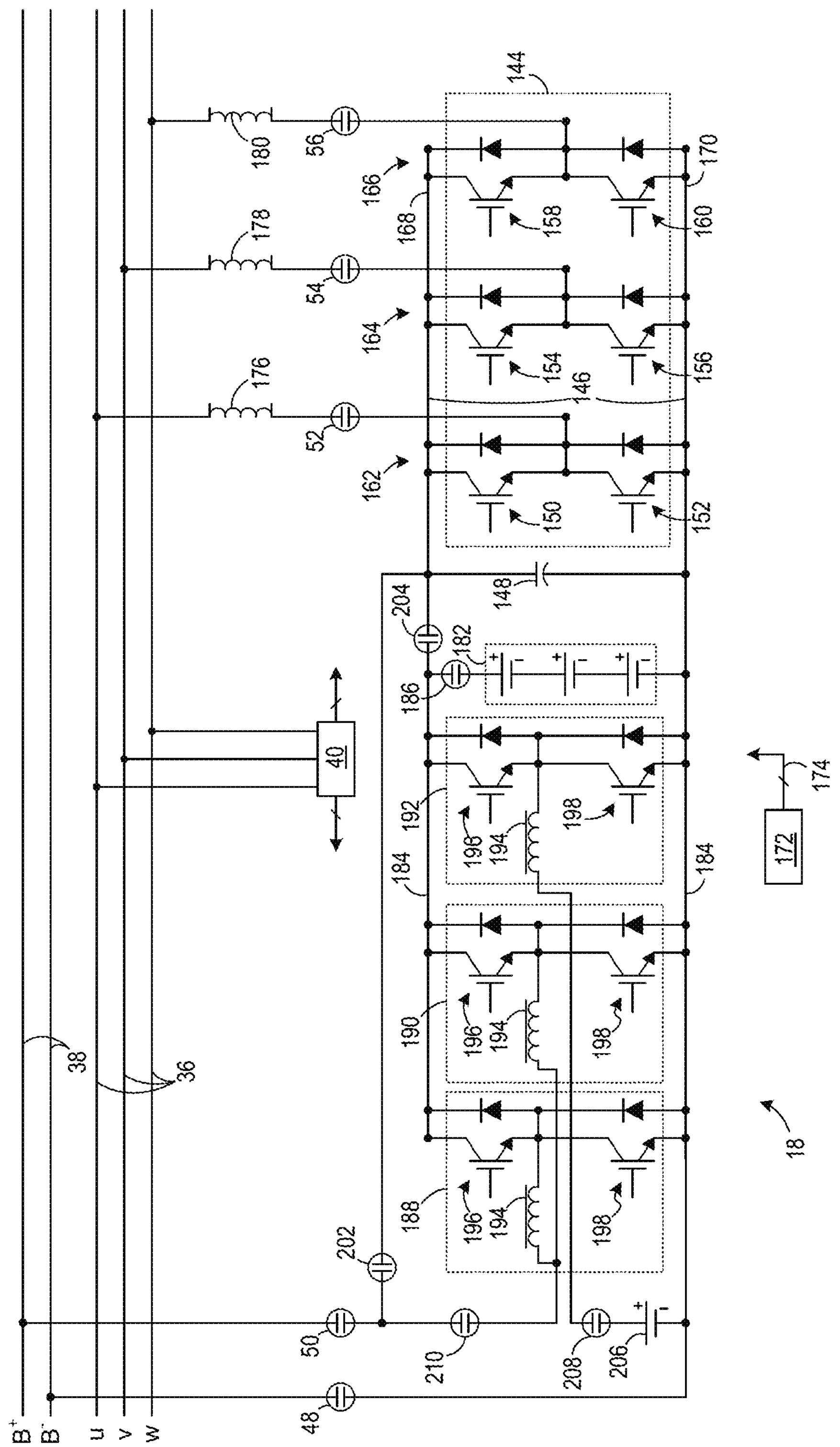

FIG. 9

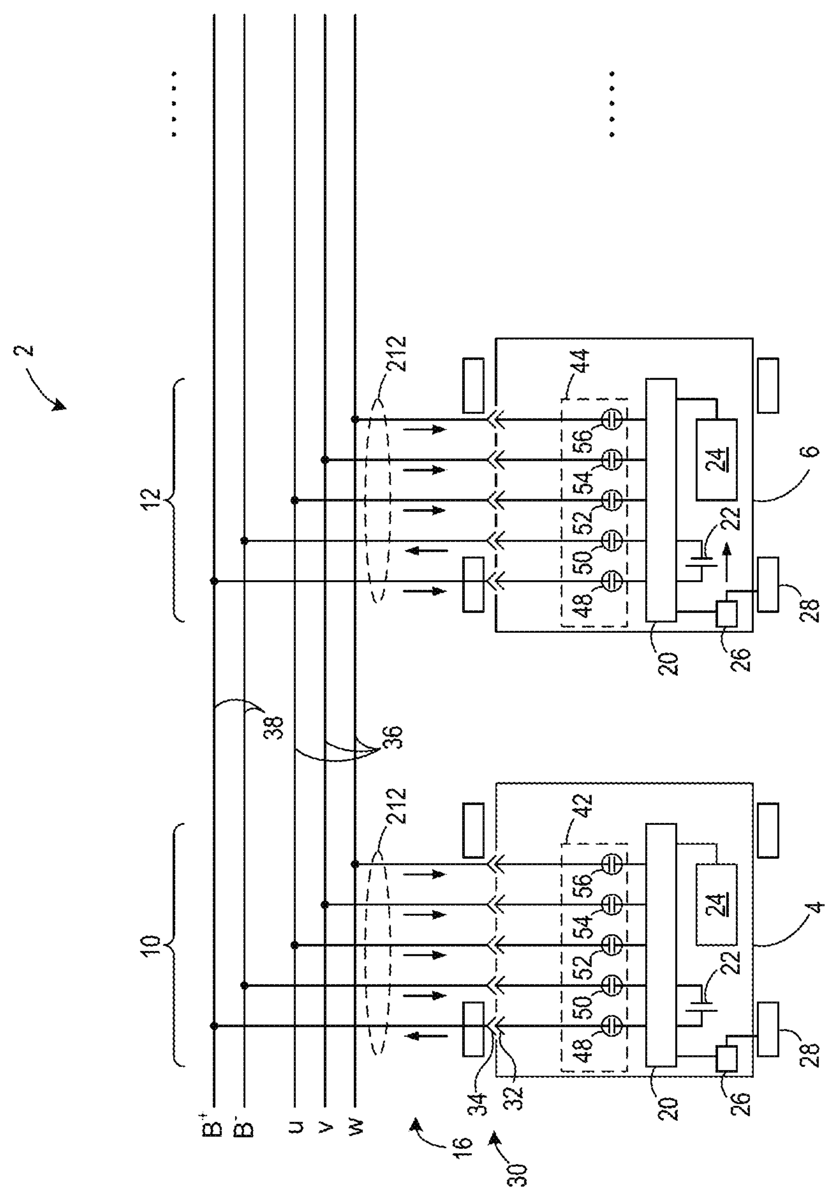
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FIG. 10

APPARATUS AND METHOD FOR RAPID CHARGING USING SHARED POWER ELECTRONICS

CROSS-REFERENCE TO RELATED APPLICATION

The present application is a continuation of U.S. application Ser. No. 17/977,204, filed on Oct. 31, 2022, which is a continuation of U.S. application Ser. No. 17/873,357, filed on Jul. 26, 2022, which is a continuation of U.S. application Ser. No. 16/715,508, filed on Dec. 16, 2019, now U.S. Pat. No. 11,400,820, issued on Aug. 2, 2022, which is a continuation of U.S. application Ser. No. 16/278,379, filed on Feb. 18, 2019, now U.S. Pat. No. 10,543,755, issued Jan. 28, 2020, which is a continuation of U.S. application Ser. No. 15/708,859, filed Sep. 19, 2017, now U.S. Pat. No. 10,377,259, issued Aug. 13, 2019, which is a continuation of U.S. application Ser. No. 14/219,201, filed Mar. 19, 2014, now U.S. Pat. No. 9,789,780, issued Oct. 17, 2017, which is a continuation of, and claims priority to, U.S. application Ser. No. 12/641,359, filed Dec. 18, 2009, now U.S. Pat. No. 8,698,451, issued Apr. 15, 2014, the disclosures of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

Embodiments of the invention relate generally to electric drive systems including hybrid and electric vehicles and, more particularly, to rapidly charging one electric drive system using shared power electronics of one or more additional electric drive systems.

Hybrid electric vehicles may combine an internal combustion engine and an electric motor powered by an energy storage device, such as a traction battery, to propel the vehicle. Such a combination may increase overall fuel efficiency by enabling the combustion engine and the electric motor to each operate in respective ranges of increased efficiency. Electric motors, for example, may be efficient at accelerating from a standing start, while combustion engines may be efficient during sustained periods of constant engine operation, such as in highway driving. Having an electric motor to boost initial acceleration allows combustion engines in hybrid vehicles to be smaller and more fuel efficient.

Purely electric vehicles use stored electrical energy to power an electric motor, which propels the vehicle and may also operate auxiliary drives. Purely electric vehicles may use one or more sources of stored electrical energy. For example, a first source of stored electrical energy may be used to provide longer-lasting energy while a second source of stored electrical energy may be used to provide higher-power energy for, for example, acceleration.

Plug-in electric vehicles, whether of the hybrid electric type or of the purely electric type, are configured to use electrical energy from an external source to recharge the traction battery. Such vehicles may include on-road and off-road vehicles, golf cars, neighborhood electric vehicles, forklifts, and utility trucks as examples. These vehicles may use either off-board stationary battery chargers, on-board battery chargers, or a combination of off-board stationary battery chargers and on-board battery chargers to transfer electrical energy from a utility grid or renewable energy source to the vehicle's on-board traction battery. Plug-in vehicles may include circuitry and connections to facilitate the recharging of the traction battery from the utility grid or other external source, for example. The battery charging circuitry, however, may include dedicated components such as boost converters, high-frequency filters, choppers, inductors, and other electrical components dedicated only to transferring energy between the on-board electrical storage device and the external source. These additional dedicated components add extra cost and weight to the vehicle.

In addition, the total current available for recharging the on-board electrical storage device using only the on-board battery charging circuitry of the vehicle is limited to the total current that the on-board battery charging circuitry can supply. The on-board electrical storage device, however, may be designed to accept a charging current much greater than the total current supplied by the on-board battery charging circuitry. Increasing the total current supplied by the on-board battery charging circuitry typically includes increasing the size and capacity of the circuitry components, which adds yet additional cost and weight to the vehicle.

It would therefore be desirable to provide an apparatus to facilitate the transfer of electrical energy from multiple external sources to the on-board electrical storage device of a plug-in vehicle that reduces the number of components dedicated only to transferring energy between the on-board electrical storage device and the external source and that increases the total current available for charging the on-board electrical storage device.

BRIEF DESCRIPTION OF THE INVENTION

According to one aspect of the invention, an apparatus comprises a power electronic energy conversion system comprising a first energy storage device configured to store DC energy and a first voltage converter configured to convert a stored voltage from the first energy storage device into a first voltage configured to drive an electromechanical device. The first voltage converter is also configured to convert a second voltage from a remote power supply into a first charging voltage configured to charge the first energy storage device. The apparatus also includes a first controller configured to control the first voltage converter to convert the second voltage into the first charging voltage and to provide the first charging voltage to the first energy storage device during a charging mode of operation and communicate with a second controller located remotely from the power electronic energy conversion system to cause a second charging voltage to be provided to the first energy storage device during the charging mode of operation to rapidly charge the first energy storage device.

In accordance with another aspect of the invention, a method comprises coupling a first energy storage device to a first voltage converter, wherein the first energy storage device is configured to store electrical energy and wherein the first voltage converter is configured to convert a stored voltage from the first energy storage device into a first voltage configured to drive a motor and to convert a second voltage from a first remote power supply into a first charging voltage configured to charge the first energy storage device. The method also comprises coupling a first controller to the first voltage converter and configuring the first controller to cause the first voltage converter to convert the second voltage into the first charging voltage and to provide the first charging voltage to the first energy storage device during a rapid charging mode of operation. The method further comprises configuring the first controller to cause a second charging voltage from a second remote power supply to be provided to the first energy storage device during the rapid charging mode of operation to rapidly charge the first energy storage device.

In accordance with yet another aspect of the invention, a system comprises a first power bus, a second power bus, and a first vehicle. The first vehicle comprises a first energy storage device configured to store DC energy, a first motor and a first voltage converter configured to convert a stored voltage from the first energy storage device into a motoring voltage configured to drive the first motor and to convert a first voltage from the first power bus into a first charging voltage configured to charge the first energy storage device. The first vehicle also comprises a first controller configured to control the first voltage converter to convert the first voltage into the first charging voltage and to provide the first charging voltage to the first energy storage device. The system also comprises a first energy conversion system located remotely from the first vehicle and comprising a second voltage converter configured to convert the first voltage from the first power bus into a second charging voltage configured to charge the first energy storage device of the first vehicle. The first energy conversion system further comprises a second controller configured to control the second voltage converter to convert the first voltage into the second charging voltage and to provide the second charging voltage to the second power bus and communicate with the first controller to cause the second charging voltage to be provided from the second power bus to the first energy storage device to rapidly charge the first energy storage device.

Various other features and advantages will be made apparent from the following detailed description and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings illustrate embodiments presently contemplated for carrying out the invention.

In the drawings:

FIG. **1** is a schematic block diagram of a charging system according to an embodiment of the invention.

FIG. **2** is a schematic diagram of a portion of the charging system of FIG. **1** according to an embodiment of the invention.

FIG. **3** is a schematic diagram of the charging system shown in FIG. **2** according to another embodiment of the invention.

FIG. **4** is a schematic diagram of another a portion of the charging system of FIG. **1** according to an embodiment of the invention.

FIG. **5** is a schematic diagram of another a portion of the charging system of FIG. **1** according to an embodiment of the invention.

FIG. **6** is a schematic diagram of another a portion of the charging system of FIG. **1** according to an embodiment of the invention.

FIG. **7** is a schematic diagram of another a portion of the charging system of FIG. **1** according to an embodiment of the invention.

FIG. **8** is a schematic diagram of the charging unit of FIG. **7** according to an embodiment of the invention.

FIG. **9** is a schematic diagram of the charging unit of FIG. **7** according to an embodiment of the invention.

FIG. **10** is a schematic diagram of another a portion of the charging system of FIG. **1** according to an embodiment of the invention.

DETAILED DESCRIPTION

FIG. **1** is a schematic block diagram of the infrastructure of a charging system **2** according to an embodiment of the invention. Charging system **2** illustrates a plurality of vehicles **4**, **6**, **8** coupled to a respective charging bay or socket **10**, **12**, **14** of a charging station **16**. Charging system **2** may include, in one embodiment, a non-vehicle charging unit **18** as described below with respect to FIGS. **7-9**. According to embodiments of the invention, vehicles **4-8** and charging station **16** are configured to cooperate together to share power electronics among the vehicles **4-8** and optional off-board charging unit **18** to provide a charging current to one of the vehicles, such as vehicle **6**, to augment and increase the charging current generated by the vehicle alone.

Each vehicle **4-8** includes a plurality of power electronics **20** coupled to a least one energy storage device **22**. During operation of vehicle **4-8**, a controller **24** causes a DC voltage from energy storage device **22** to be modified and delivered to an electromechanical device or motor **26** mechanically coupled to one or more driving wheels or axles **28** during a motoring mode of operation. In another embodiment, the DC voltage from energy storage device **22** may be modified and delivered to another load (not shown) such as air conditioning compressors, fans, pumps, or other auxiliary drives.

Vehicles **4-8** may include AC motors **26**, and controller **24** is configured to cause a DC voltage from energy storage device **22** to be inverted to an AC voltage via power electronics **20** for delivery to motor **26**. In this embodiment, vehicles **4-8** may be on-road and off-road vehicles or utility trucks, for example. In another embodiment, vehicles **4-8** may include DC motors **26**, and controller **24** is configured to cause a DC voltage from energy storage device **22** to be converted to a variable DC voltage via power electronics **20** for delivery to motor **26** during a motoring mode of operation. In this embodiment, vehicles **4-8** may be fork lift trucks, golf cars, or neighborhood electric vehicles, for example.

When a vehicle **4-8** is parked or not in use, it may be desirable to plug the vehicle into, for example, the utility grid or to a renewable energy source to refresh or recharge energy storage device **22**. Accordingly, vehicles **4-8** are coupleable to charging station **16** via a connection system **30** comprising mating contacts **32**, **34**. Charging station **16** includes a power bus **36** configured to supply or provide power to power electronics **20** of the vehicle **4-8**. In one embodiment, power bus **36** is a 3-phase AC power bus such as the utility grid. It is contemplated, however, that power bus **36** may include any number of phases and may supply or receive AC or DC power.

According to embodiments of the invention, charging station **16** includes a shared DC voltage bus **38** configured to augment and increase the charging current generated by one of the vehicles coupled to charging station **16**. Charging station **16** also includes a controller **40** coupled to a plurality of contactor groups **42**, **44**, **46** for each charging bay **10**, **12**, **14** available at charging station **16**. In one embodiment, each contactor group **42-46** has a pair of contactors **48**, **50** coupled to shared DC voltage bus **38** and a plurality of contactors **52**, **54**, **56** coupled to power bus **36**. Controller **40** is configured to control contactors **48-56** and to communicate with each vehicle controller **24** to direct and control charging of the vehicles coupled to charging station **16**. In one embodiment, controller **40** is configured to communicate with each vehicle controller **24** via power line communications over power bus **36**. However, other modes of communication, such as wireless communication or communication via a dedicated communication line, are also contemplated herein.

As illustrated in FIG. **1**, vehicles **4**-**8** are coupled to charging station **16**. According to the embodiment shown, vehicles **4** and **8** are using their power electronics **20** to provide power from power bus **36** to shared DC voltage bus **38** such that the charging power provided to the energy storage device **22** of vehicle **6** may augmented. That is, while vehicle **6** draws power from power bus **36** for conversion into a charging power provided to its energy storage device **22**, the additional charging power provided and controlled by vehicles **4** and **8** is also provided to the energy storage device **22** via shared DC voltage bus **38**, and the energy storage device **22** of vehicle **6** may accordingly be rapidly charged.

In one embodiment, the cost to a vehicle owner for plugging into charging station **16** and drawing charging power therefrom may vary per unit charge according to a level of charging mode desired. For example, charging station **16** may be configured to allow selection of a rapid/sharing charging mode, a non-rapid/non-sharing charging mode, and a non-rapid/sharing charging mode.

In the rapid/sharing charging mode, the vehicle is connected to charging station **16** and awaits its turn to rapidly charge its energy storage device **22**. In this mode, the respective contactors **48**, **50** are closed such that the vehicle's charging bus may be coupled to shared DC voltage bus **38**. While the vehicle is awaiting its turn for rapid charging and after its turn has been completed, its power electronics **20** are shared with other vehicles coupled to charging station **16** via the respective contactors **48**, **50** to charge another vehicle currently allowed to rapidly charge its energy storage device **22**.

In the non-rapid/non-sharing charging mode, the vehicle is connected to charging station **16** and begins to charge its energy storage device **22** only from the power electronics **20** on-board the vehicle without connection of its energy storage device **22** to the shared DC voltage bus **38**. That is, in this charging mode, the respective contactors **48**, **50** remain open, and the vehicle's energy storage device **22** is charged solely via the vehicle's on-board power electronics **20**.

In the non-rapid/sharing charging mode, the vehicle is connected to charging station **16**, and the respective contactors **48**, **50** are closed such that the vehicle's charging bus may be coupled to shared DC voltage bus **38**. In this charging mode, the vehicle participates in power electronics sharing while another vehicle is rapidly charging its energy storage device **22**. The vehicle, however, is disconnected from shared DC voltage bus **38** if no other vehicle is in a rapid charging mode, and the vehicle's power electronics **20** are used to charge the vehicle's energy storage device **22** solely via the vehicle's on-board power electronics **20**. When another vehicle later enters a rapid charging mode, the vehicle again participates in power electronics sharing during this time.

According to one embodiment, the rapid/sharing charging mode may result in the highest cost per charging unit for a vehicle owner/operator, and the non-rapid/sharing charging mode may result in the least cost per charging unit for a vehicle owner/operator. As such, the vehicle owner/operator may be charged at a premium rate, for example, for the ability to rapidly charge the vehicle's energy storage device **22** in the rapid/sharing charging mode, while the vehicle owner/operator may be charged at a reduced rate, for example, for sharing the vehicle's power electronics **20** in the non-rapid/sharing charging mode. For the non-rapid/non-sharing charging mode, the vehicle owner/operator may be charged at a rate, for example, between the premium rate and the reduced rate. The decision of which charging mode to select may be made by the vehicle owner/operator based on the need of the energy storage device **22** to receive a rapid charge and the comparative costs between the charging modes.

FIG. **2** is a schematic diagram of a portion of the charging system **2** of FIG. **1** according to an embodiment of the invention. FIG. **2** shows exemplary schematics for each vehicle **4**, **6**. Each vehicle **4**, **6** includes a traction system **58** that includes energy storage device **22** and power electronics **20**. Power electronics **20** include a bi-directional DC-to-AC voltage inverter **60** coupled to energy storage device **22** via a DC bus **62**. In one embodiment, energy storage device **22** is a high-voltage energy storage device and may be a battery, a flywheel system, fuel cell, an ultracapacitor, or the like. A DC link filter capacitor **64** is coupled across DC bus **62** to filter high-frequency currents on DC bus **62**. A contactor **66** coupled to DC bus **62** allows energy storage device **22** to be decoupled from DC bus **62**. Bi-directional DC-to-AC voltage inverter **60** is a voltage converter and includes six half phase modules **68**, **70**, **72**, **74**, **76**, and **78** that are paired to form three phases **80**, **82**, and **84**. Each phase **80**, **82**, **84** is coupled to a pair of conductors **86**, **88** of DC bus **62**.

Motor **26** is coupled to bi-directional DC-to-AC voltage inverter **60**. In one embodiment, motor **26** is a traction motor mechanically coupled to one or more driving wheels or axles **28** (shown in FIG. **1**) or other electrical apparatus including cranes, elevators, or lifts. Electromechanical device **26** includes a plurality of windings **90**, **92**, and **94** coupled to respective phases **80**, **82**, **84** of bi-directional DC-to-AC voltage inverter **60**. Windings **90**-**94** are also coupled together to form a node **96**. During the charging of energy storage device **22** via charging station **16** and after receiving communication and confirmation of charging mode from controller **40**, controller **24** causes a plurality of contactors **98**, **100**, **102** to respectively decouple windings **90**-**94** from bi-directional DC-to-AC voltage inverter **60** such that motor **26** remains unpowered.

Controller **24** is coupled to half phase modules **68**-**78** via a plurality of lines **104**. During use of vehicle **4**, **6** in a non-charging mode, controller **24** applies appropriate control of half phase modules **68**-**78** and controls bi-directional DC-to-AC voltage inverter **60** to convert a DC voltage or current on DC bus **62** to an AC voltage or current for supply to windings **90**-**94**. Accordingly, the DC voltage or current from energy storage device **22** may be converted into an AC voltage or current and delivered to motor **26** to drive wheels **28**. In other non-vehicle propulsion systems, the drive wheels **28** may be another type of load (not shown), including a pump, fan, winch, crane, elevator, or other motor driven loads. In a regenerative braking mode, electromechanical device **26** may be operated as a generator to brake wheels **28** or, for non-vehicle propulsion systems, other types of loads and to provide AC voltage or current to bi-directional DC-to-AC voltage inverter **60** for inversion into a DC voltage or current onto DC bus **62** that is suitable for recharging energy storage device **22**.

Contactors **48**, **50** are in the open state prior to coupling vehicles **4**, **6** to charging station **16**. Depending on the communication medium between controller **40** and the controllers **24** of vehicles **4**, **6**, contactors **52**-**56** may be in the open or closed state. For example, if controller **40** and the controllers **24** of vehicles **4**, **6** are configured to communicate over the power line, contactors **52**-**56** may be in the closed state to allow such communications when a vehicle **4**, **6** is coupled to charging station **16**. However, if controller **40** and the controllers **24** of vehicles **4**, **6** are configured to communicate via a different communication mode, contactors **52-56** may be in the open state. Contactors **98-102** are put into the open state prior to closing contactors **52-56** such that motor **26** remains unpowered during connection to charging station **16** as described above.

When a vehicle, such as vehicle **6**, is plugged into or coupled to charging station **16**, controller **40** establishes communication with the controller **24** of vehicle **6** to determine the desired charging mode and other parameters. The other parameters may include, for example, whether the DC nominal voltage of energy storage device **22** is within a given threshold and within minimum and maximum voltage limits of the charging station **16**. If the desired charging mode includes sharing power electronics and another vehicle is in the rapid charging mode, controller **40** closes contactors **48**, **50** and communicates with controller **24** of vehicle **6** that its power electronics **20** should convert power from power bus **36** for providing power to shared DC voltage bus **38**. If the desired charging mode includes rapidly charging the energy storage device **22** of vehicle **6**, controller **40** communicates with controller **24** of vehicle **6** when it is possible to close contactor **66** to begin the rapid charging of the energy storage device **22** of vehicle **6**.

The other parameters may also include a status of the energy storage device **22** currently being charged. For example, the controller **24** of vehicle **6** may be configured to monitor energy storage device **22** using known algorithms to prevent overcharge, etc. In another embodiment, the controller **24** of vehicle **6** may be configured to communicate commands through controller **40** to the controllers **24** of the other vehicles. These commands may be, for example, commands for the other vehicles to start ramping the current on shared DC voltage bus **38**, to hold the current on shared DC voltage bus **38** at the present value, or to start lowering the current on shared DC voltage bus **38** by a delta amount.

Controller **24** is configured to control half phase modules **68-78** to boost the voltage of the power supplied thereto from power bus **36** such that charging power may be provided to energy storage device **22** or to shared DC voltage bus **38** that is a voltage greater than that allowable through simple full-wave rectification of the power from power bus **36** without boosting. Respective pairs of half phase modules **68-70**, **72-74**, **76-78**, together with a plurality of respective inductors **106**, **108**, **110**, form individual boost converters that operate to boost the current and/or voltage of the power supplied thereto from power bus **36**. In one embodiment, inductors **106-110** are high frequency inductor components located in charging station **16** and are off board of vehicles **4**, **6**. In another embodiment, inductors **106-110** represent a leakage inductance of the line transformer of power bus **36**.

When one or more vehicles, such as vehicle **6** and/or vehicle **8**, is used to share its power electronics **20** with the power electronics **20** of vehicle **6** for the rapid charging of the energy storage device **22** of vehicle **6**, the bi-directional DC-to-AC voltage inverters **60** operate essentially in parallel.

After charging is complete or when a vehicle operator desires to unplug the vehicle from the charging station **16**, controller **40** establishes handshaking communication with the controller **24** of the vehicle, such as vehicle **6**, to confirm that the vehicle is in a non-charging mode and that the vehicle is disconnected from charging station **16**. In one embodiment, for example, contacts **32**, **34** of connection system **30** may be disengaged only after contactors **48-56** of the respective charging bay **10-14** have been opened and after the contacts **32**, **34** have been unlocked. An indicator (not shown) on the vehicle, the connection system **30**, or the charging station **16** may indicate a locked/unlocked status of the connection system **30**.

FIG. **3** is a schematic diagram of the charging system shown in FIG. **2** according to another embodiment of the invention. In addition to that shown with respect to FIG. **2**, charging station **16** includes a multi-phase transformer **112**, **114** for each charging bay **10**, **12** available at charging station **16**. Multi-phase transformers **112**, **114** provide electrical isolation of the power electronics **20** from power bus **36**. In addition, the outputs of the bi-directional DC-to-AC voltage inverters **60** via contactors **48**, **50** operate in parallel while the inputs to the bi-directional DC-to-AC voltage inverters **60** via contactors **52-56** are removed from parallel operation. While wye-delta three-phase transformers are shown, it is contemplated that other arrangements (such as a zigzag winding arrangement) could be used to achieve alternative waveform phase shifting to reduce harmonic currents on the utility. Multi-phase transformers **112**, **114** also allow selecting the most desired AC voltage for feeding the power electronics **20**.

Vehicles **4**, **6** also include a charge resistor **116** and a charge contactor **118**. In an embodiment of the invention, charge contactor **118** may be closed to limit current flowing into energy storage device **22** when its voltage is below a predetermined threshold during an initial charge of energy storage device **22**.

FIG. **4** shows a schematic diagram of a traction system **120** of vehicle **6** according to another embodiment of the invention. Elements and components common to traction systems **58** and **120** will be discussed relative to the same reference numbers as appropriate. In addition to the components common with traction system **58**, traction system **120** includes a second energy storage device **122** coupled to DC bus **62** to provide power to bi-directional DC-to-AC voltage inverter **60** to drive motor **26** and wheels **28** (shown in FIG. **1**). In one embodiment, second energy storage device **122** is a low-voltage energy storage device and may be a battery, a fuel cell, an ultracapacitor, or the like. First energy storage device **22** may be configured to provide a higher power than second energy storage device **122** to provide power during, for example, acceleration periods of the vehicle. Second energy storage device **122** may be configured to provide a higher energy than first energy storage device **22** to provide a longer-lasting power to the vehicle to increase a traveling distance thereof. As illustrated in FIG. **4**, in one embodiment, first energy storage device **22** is an ultracapacitor.

A plurality of bi-directional DC-to-DC voltage converters **124**, **126**, **128** are configured to convert one DC voltage into another DC voltage. Bi-directional DC-to-DC voltage converter **124-128** are coupleable to second energy storage device **122** via a node **130** coupled to a contactor **132** and are coupled to DC bus **62**. Each bi-directional DC-to-DC voltage converter **124-128** includes an inductor **134** coupled to a pair of half phase modules **136**, **138**. For illustrative purposes, half phase modules **136**, **138** are shown to include insulated gate bipolar transistors (IGBTs). However, embodiments of the invention are not limited to IGBTs. Any appropriate electronic switch can be used, such as, for example, metal oxide semiconductor field effect transistors (MOSFETs), Silicon Carbide (SiC) MOSFETs, bipolar junction transistors (BJTs), and metal oxide semiconductor controlled thyristors (MCTs).

Controller **24** is coupled to bi-directional DC-to-DC voltage converters **124-128** via lines **104**, and energy provided via second energy storage device **122** is boosted by control of bi-directional DC-to-DC voltage converters **124-128** to provide the higher voltage to DC bus **62**. The energy provided via second energy storage device **122** to DC bus **62** is inverted via bi-directional DC-to-AC voltage inverter **60** and provided to motor electromechanical device **26**. Similarly, energy generated during a regenerative braking mode may also be used to re-charge second energy storage device **122** via bi-directional DC-to-AC voltage inverter **60** and via bucking control of bi-directional DC-to-DC voltage converters **124-128**.

As shown in FIG. **4**, bi-directional DC-to-AC voltage inverter **60** of vehicle **6** is not coupled to second energy storage device **122** directly in parallel. Instead, as described above, power provided to DC bus **62** to charge second energy storage device **122** is controlled via bucking control of bi-directional DC-to-DC voltage converters **124-128**. In an embodiment of the invention, the voltage capacity of second energy storage device **122** is lower than a rectified voltage of the voltage on power bus **36**. Accordingly, bi-directional DC-to-AC voltage inverter **60** need not boost the voltage on power bus **36** but may be used to simply rectify the power bus voltage. That is, the switches in half phase modules **68-78** need not be switched or controlled via controller **24** in a charging operation of second energy storage device **122** using charging station **16**. While bi-directional DC-to-AC voltage inverter **60** need not boost the voltage on power bus **36**, it may nevertheless be controlled to do so. In addition, an isolation or multi-phase transformer, such as multi-phase transformer **112** shown in FIG. **3**, may be used as described above with charging station **16** shown in FIG. **4**. If switching control of half phase modules **68-78** is not used such that current from power bus **36** is not shaped via the switching control, harmonic currents may be reduced by employing various phase shifting arrangements of the isolation transformer to cancel harmonics.

To rapidly charge second energy storage device **122**, controllers **24** and **40** can cooperate together to close contactors **48**, **50** and contactor **132** of traction system **120** coupled to second energy storage device **122** such that the current from shared DC voltage bus **38** provided from other vehicles or from non-vehicle charging unit **18**, for example, may be joined with charging current provided by bi-directional DC-to-DC voltage converters **124-128**. Controllers **24** and **40** can also cooperate together to close contactors **48**, **50** and to open contactor **132** such that vehicle **6** can share its power electronics **20** for rapid charging of the energy storage device of another vehicle coupled to charging station **16**.

FIG. **5** shows a schematic diagram of traction system **120** of vehicle **6** according to another embodiment of the invention. As shown in FIG. **5**, first energy storage device **22** is a high-voltage energy storage device such as a battery, a fuel cell, or the like as described above and has a voltage capacity higher than a rectified voltage of the voltage on power bus **36**. Second energy storage device **122** may be configured, in an embodiment, to have a power limit that does not allow high power rapid charge as described above with respect to FIG. **4**. In this embodiment, charging current supplied through shared DC voltage bus **38** to vehicle **6** is directed, via boost control of bi-directional DC-to-DC voltage converters **124-128**, to DC bus **62** of vehicle **6** together with the charging current provided to DC bus **62** via boost control of phases **80-84** of bi-directional DC-to-AC voltage inverter **60**. The charging current on DC bus **62** is directed to energy storage device **22** through contactor **66** to rapidly charge energy storage device **22**. In this manner, six channels of the traction system **120** may be used to rapidly charge energy storage device **22**. In one embodiment, charging of second energy storage device **122** may be accomplished by opening contactors **48**, **50**, closing contactor **132**, and bucking charging current on DC bus **62** supplied thereto by either energy storage device **22** or by rectification of power from power bus **36**.

FIG. **6** shows a schematic diagram of traction system **120** of FIG. **5** according to another embodiment of the invention. A contactor **140** is coupled to a node **142** coupled between second energy storage device **122** and contactor **132**. As shown, bi-directional DC-to-DC voltage converter **128** is coupled to node **142**, while bi-directional DC-to-DC voltage converters **124**, **126** remain coupled to node **130**.

In this embodiment, it is possible to charge energy storage device **22** via six channels of traction system **120** as described above with respect to FIG. **5**. That is, by opening contactor **140** and by closing contactor **132**, bi-directional DC-to-DC voltage converters **124-128** and phases **80-84** of bi-directional DC-to-AC voltage inverter **60** may be controlled in a boosting mode to provide charging current to energy storage device **22** via DC bus **62** and contactor **66**.

Alternatively, it is possible to charge energy storage device **22** via five channels of traction system **120** while simultaneously charging second energy storage device **122** via one channel of traction system **120**. That is, controller **24** may open contactor **132** and cause bi-directional DC-to-DC voltage converters **124-126** and phases **80-84** of bi-directional DC-to-AC voltage inverter **60** in a boosting mode to provide charging current to DC bus **62**. Controller **24** may then close contactor **66** to control rapid charging of energy storage device **22**. In addition, controller **24** may also close contactor **140** and control bi-directional DC-to-DC voltage converter **128** in a bucking mode to charge second energy storage device **122**.

FIG. **7** is a schematic diagram of another portion of the charging system **2** of FIG. **1** according to an embodiment of the invention. FIG. **7** shows exemplary schematics for vehicle **6** and for non-vehicle charging unit **18**. Charging unit **18** includes an AC-to-DC voltage inverter **144** coupleable to shared DC voltage bus **38** via a DC bus **146** and via contactors **48**, **50**. A DC link filter capacitor **148** is coupled across DC bus **146**. AC-to-DC voltage inverter **144** includes six half phase modules **150**, **152**, **154**, **156**, **158**, and **160** that are paired to form three phases **162**, **164**, and **166**. Each phase **162**, **164**, **166** is coupled to a pair of conductors **168**, **170** of DC bus **146**. A controller **172** is coupled to half phase modules **150-160** via a plurality of lines **174** and controls respective pairs of half phase modules **150-152**, **154-156**, **158-160**, together with a plurality of respective inductors **176**, **178**, **180**, to boost the current and/or voltage of the power supplied thereto from power bus **36**. In one embodiment, inductors **176-180** are high frequency inductor components located in charging system **16**. In another embodiment, inductors **176-180** represent a leakage inductance of the line transformer of power bus **36**.

Charging unit **18** may be included in charging system **2** to further increase the power available for rapid charging of a single vehicle. In addition, charging unit **18** allows the rapid charging of the energy storage device **22** of vehicle **6** at a higher power levels than are available from the on-board power electronics **20** of vehicle **6** even when no other vehicle is coupled to charging station **16** or when no other vehicle is configured to share its power electronics. Combining the on-board power electronics **20** of vehicle **6** with the power electronics of charging unit **18** allows rapid charging of the energy storage device **22** of vehicle **6** from a lower cost, lower power rated, off-board charger versus rapid charging via using exclusively off-board power electronics. For example, if the on-board power electronics **20** of vehicle **6** are rated at 99 kW and the off-board power electronics of charging unit **18** are rated at 100 kW, then 199 kW of rapid charge power may be provided to energy storage device **22** of vehicle **6**. If two other vehicles, such as vehicles **4** and **8**, are also coupled to charging station **16** and configured to share their power electronics **20** rated at 99 kW each, then 397 kW of rapid charge power may be provided to energy storage device **22** of vehicle **6**. The power ratings specified in this example are merely exemplary, and other power ratings are contemplated. For example, charging unit **18** may be designed such that its power electronics are rated higher than 100 kW. The design of the power ratings of charging unit **18** may be based in part on the complexity and costs of the construction of charging system **2**.

FIG. **8** is a schematic diagram of charging unit **18** of FIG. **7** according to another embodiment of the invention. Elements and components common to the charging units **18** shown in FIGS. **7** and **8** will be discussed relative to the same reference numbers as appropriate. In addition to the components common with charging unit **18** of FIG. **7**, charging unit **18** of FIG. **8** includes an energy storage device **182** coupleable to a DC bus **184** via a contactor **186**. Energy storage device **182** is configured to provide additional power to shared DC voltage bus **38**. In one embodiment, energy storage device **182** is a high-voltage energy storage device and may be a battery, a flywheel system, fuel cell, an ultracapacitor, or the like.

A plurality of bi-directional DC-to-DC voltage converters **188**, **190**, **192** are configured to convert one DC voltage into another DC voltage. Bi-directional DC-to-DC voltage converter **188-192** are coupled to DC bus **184** and are coupleable to energy storage device **182** via contactor **186**. Each bi-directional DC-to-DC voltage converter **188-192** includes an inductor **194** coupled to a pair of half phase modules **196**, **198**. For illustrative purposes, half phase modules **196**, **198** are shown to include insulated gate bipolar transistors (IGBTs). However, embodiments of the invention are not limited to IGBTs. Any appropriate electronic switch can be used, such as, for example, metal oxide semiconductor field effect transistors (MOSFETs), Silicon Carbide (SiC) MOSFETs, bipolar junction transistors (BJTs), and metal oxide semiconductor controlled thyristors (MCTs). Bi-directional DC-to-DC voltage converter **188-192** are coupleable to contactor **50** via a contactor **200**, and DC bus **146** is coupleable to contactor **50** via a contactor **202**. A contactor **204** is configured to couple DC bus **146** to DC bus **184**. In addition, controller **172** is coupled to bi-directional DC-to-DC voltage converters **188-192** via lines **174**.

Energy storage device **182** allows the rapid charging of a vehicle energy storage device, such as energy storage device **22** of vehicle **6**, at a higher power levels than are available from AC-to-DC voltage inverter **144** alone. During a vehicle charging operation using both AC-to-DC voltage inverter **144** and energy storage device **182**, controller **172** causes contactor **204** to open and causes contactors **186**, **200**, and **202** to close. Controller **172** then controls respective pairs of half phase modules **150-152**, **154-156**, **158-160**, together with inductors **176-180** to boost the current and/or voltage of the power supplied thereto from power bus **36** and to deliver the boosted current/voltage to shared DC voltage bus **38**. In addition, controller **172** controls bi-directional DC-to-DC voltage converters **188-192** to buck a voltage from energy storage device **182** and to deliver the boosted current to shared DC voltage bus **38**. DC bus **146** and DC bus **184** may be independently controlled to provide energy to shared DC voltage bus **38**.

Energy storage device **182** may be charged by closing contactors **186**, **204** and by opening contactors **200**, **202**. In this manner, controller **172** controls respective pairs of half phase modules **150-152**, **154-156**, **158-160**, together with inductors **176-180** to boost the voltage of the power supplied thereto from power bus **36** and to deliver the boosted voltage to energy storage device **182**. In an embodiment of the invention, the charging of energy storage device **182** may be performed during periods of low demand or low cost, for example, for the power on power bus **36**. Energy storage device **182** may be used to augment the power provided to shared DC voltage bus **38** via AC-to-DC voltage inverter **144** during periods of high demand or high cost, for example, such as during high temperature days.

FIG. **9** is a schematic diagram of charging unit **18** of FIG. **8** according to another embodiment of the invention. Elements and components common to the charging units **18** shown in FIGS. **7-9** will be discussed relative to the same reference numbers as appropriate. In addition to the components common with charging unit **18** of FIGS. **7** and **8**, charging unit **18** of FIG. **9** includes a second energy storage device **206** coupleable to bi-directional DC-to-DC voltage converter **192** via a contactor **208**. In one embodiment, second energy storage device **206** is a low-voltage energy storage device and may be a battery, a fuel cell, an ultracapacitor, or the like. Energy storage device **182** may be configured to provide a higher power than second energy storage device **206**. Second energy storage device **206** may be configured to provide a higher energy than energy storage device **182**. Bi-directional DC-to-DC voltage converters **188**, **190** are coupleable to contactor **50** via a contactor **210**.

Second energy storage device **206** allows the rapid charging of a vehicle energy storage device, such as energy storage device **22** of vehicle **6**, at a higher power levels than are available from AC-to-DC voltage inverter **144** and energy storage device **182**. During a vehicle charging operation using AC-to-DC voltage inverter **144**, energy storage device **182**, and second energy storage device **206**, controller **172** causes contactor **204** to open and causes contactors **186**, **202**, **208**, and **210** to close. Controller **172** then controls respective pairs of half phase modules **150-152**, **154-156**, **158-160**, together with inductors **176-180** to boost the voltage of the power supplied thereto from power bus **36** and to deliver the boosted voltage to shared DC voltage bus **38**. Controller **172** controls bi-directional DC-to-DC voltage converter **192** to boost a voltage from second energy storage device **206** and to deliver the boosted voltage to DC bus **184**. Controller **172** also controls bi-directional DC-to-DC voltage converters **188-190** to buck a voltage from energy storage device **182** and the boosted voltage from second energy storage device **206** and to deliver the boosted current/voltage to shared DC voltage bus **38**. DC bus **146** and DC bus **184** may be independently controlled to provide energy to shared DC voltage bus **38**. In addition, contactors **186**, **208** and bi-directional DC-to-DC voltage converters **188-190** may be independently controlled to convert energy from either energy storage device **182** or second energy storage device **206** for delivery to shared DC voltage bus **38**.

Second energy storage device **206** may be charged by closing contactors **204**, **208** and by opening contactors **186**, **202**, **210**. In this manner, controller **172** controls respective pairs of half phase modules **150-152**, **154-156**, **158-160**, together with inductors **176-180** to boost the current and/or voltage of the power supplied thereto from power bus **36** and to deliver the boosted voltage to DC bus **184**. From DC bus **184**, current/voltage is provided to second energy storage device **206** via bucking control of bi-directional DC-to-DC voltage converter **192**. In another embodiment of the invention, the charging of energy storage device **182** may be performed during periods of low demand or low cost, for example, for the power on power bus **36**. Energy storage device **182** may be used to augment the power provided to shared DC voltage bus **38** via AC-to-DC voltage inverter **144** during periods of high demand or high cost, for example, such as during high temperature days. Controller **172** may open contactors **202**, **204**, **210** and close contactors **186 208** and control bi-directional DC-to-DC voltage converter **192** to buck energy provided to DC bus **184** from energy storage device **182**.

FIG. **10** is a schematic block diagram of charging system **2** according to another embodiment of the invention. As shown in FIG. **10**, contactor groups **42**, **44** are positioned on board vehicles **4**, **6**. According to an embodiment, controllers **24** of vehicles **4**, **6** are configured to control contactors **48-56** and to communicate with each other via power line communications over power bus **36** or via other modes of communication as described above. In this manner, charging station **16** only provides connections to power bus **36** and shared DC voltage bus **38** for charging, rapid charging, and sharing power electronics **20** between vehicles **4**, **6**. Controllers **24** of vehicles **4**, **6** are configured to communicate with each other regarding the rapid charging and power electronic sharing therebetween. While only vehicles **4** and **6** are illustrated in FIG. **10**, it is contemplated that more than two vehicles could be configured and coupled together in the manner shown.

FIG. **10** also shows an embodiment of connection system **30** coupled to vehicles **4**, **6**. In this manner, a cord or tether **212** coupled to mating contact **34** and coupling each vehicle **4**, **6** to charging station **16** may be extend from and be supplied by the charging station **16** rather than being provided on board vehicles **4**, **6** to reduce a cost and/or weight of vehicles **4**, **6**.

Embodiments of the invention thus use components such as inverters and converters already on-board a traction control system to charge one or more energy storage devices of the traction control system and to provide charging current to other traction control systems in a sharing mode. In this manner, these components may be used for the dual purposes of motoring and recharging the energy storage devices. Using the on-board components of one or more vehicles to rapidly charge the energy storage device of another vehicle allows for off-board charging stations to have a simple, low cost design. In addition, charging may be organized in a cost effective pricing schedule such that charging becomes more cost effective when the choice of sharing the power electronics of the vehicle for other vehicles is selected. Rapid, fast charging of the on-board energy storage devices may be thus accomplished through vehicle power electronics sharing such that off-board charging stations may be constructed and operated in a more cost effective manner than an off-board charging station built to provide high levels of current and power for rapid charging alone.

A technical contribution for the disclosed apparatus is that it provides for a controller implemented technique for rapidly charging one electric drive system using shared power electronics of one or more additional electric drive systems.

According to one embodiment of the invention, an apparatus comprises a power electronic energy conversion system comprising a first energy storage device configured to store DC energy and a first voltage converter configured to convert a stored voltage from the first energy storage device into a first voltage configured to drive an electromechanical

device. The first voltage converter is also configured to convert a second voltage from a remote power supply into a first charging voltage configured to charge the first energy storage device. The apparatus also includes a first controller configured to control the first voltage converter to convert the second voltage into the first charging voltage and to provide the first charging voltage to the first energy storage device during a charging mode of operation and communicate with a second controller located remotely from the power electronic energy conversion system to cause a second charging voltage to be provided to the first energy storage device during the charging mode of operation to rapidly charge the first energy storage device.

In accordance with another embodiment of the invention, a method comprises coupling a first energy storage device to a first voltage converter, wherein the first energy storage device is configured to store electrical energy and wherein the first voltage converter is configured to convert a stored voltage from the first energy storage device into a first voltage configured to drive a motor and to convert a second voltage from a first remote power supply into a first charging voltage configured to charge the first energy storage device. The method also comprises coupling a first controller to the first voltage converter and configuring the first controller to cause the first voltage converter to convert the second voltage into the first charging voltage and to provide the first charging voltage to the first energy storage device during a rapid charging mode of operation. The method further comprises configuring the first controller to cause a second charging voltage from a second remote power supply to be provided to the first energy storage device during the rapid charging mode of operation to rapidly charge the first energy storage device.

In accordance with yet another embodiment of the invention, a system comprises a first power bus, a second power bus, and a first vehicle. The first vehicle comprises a first energy storage device configured to store DC energy, a first motor and a first voltage converter configured to convert a stored voltage from the first energy storage device into a motoring voltage configured to drive the first motor and to convert a first voltage from the first power bus into a first charging voltage configured to charge the first energy storage device. The first vehicle also comprises a first controller configured to control the first voltage converter to convert the first voltage into the first charging voltage and to provide the first charging voltage to the first energy storage device. The system also comprises a first energy conversion system located remotely from the first vehicle and comprising a second voltage converter configured to convert the first voltage from the first power bus into a second charging voltage configured to charge the first energy storage device of the first vehicle. The first energy conversion system further comprises a second controller configured to control the second voltage converter to convert the first voltage into the second charging voltage and to provide the second charging voltage to the second power bus and communicate with the first controller to cause the second charging voltage to be provided from the second power bus to the first energy storage device to rapidly charge the first energy storage device.

While the invention has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the invention is not limited to such disclosed embodiments. Rather, the invention can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the invention. Additionally, while various embodiments of the invention have been described, it is to be understood that aspects of the invention may include only some of the described embodiments. Accordingly, the invention is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

What is claimed is:

1. An apparatus comprising:
a power electronic energy conversion system comprising:
a first energy storage device configured to store DC energy;
a first voltage converter configured to:
convert a stored voltage from the first energy storage device into a first voltage configured to drive an electromechanical device; and
convert a second voltage from a remote power supply into a first charging voltage configured to charge the first energy storage device; and
a first controller configured to:
control the first voltage converter to convert the second voltage into the first charging voltage and to provide the first charging voltage to the first energy storage device during a charging mode of operation;
communicate with a second controller located remotely from the power electronic energy conversion system to cause a second charging voltage to be provided to the first energy storage device during the charging mode of operation to rapidly charge the first energy storage device; and
control the first voltage converter to convert the second voltage into a shared charging voltage during a sharing mode of operation and to provide the shared charging voltage to a second energy storage device located remotely from the power electronic energy conversion system.

2. The apparatus of claim **1**, further comprising first contacts for providing the shared charging voltage to the second energy storage device during the sharing mode of operation, and second contacts for receiving the second voltage from the remote power supply.

3. The apparatus of claim **1**, further comprising first contacts operable between a closed position to provide the shared charging voltage to the second energy storage device during the sharing mode of operation, and an open position to not provide the shared charging voltage to the second energy storage device.

4. The apparatus of claim **1**, wherein the first voltage converter includes a bi-directional DC-to-AC voltage inverter coupled to the first energy storage device.

5. The apparatus of claim **4**, wherein the bi-directional DC-to-AC voltage inverter is decouplably coupled to the first energy storage device.

6. The apparatus of claim **5**, wherein the bi-directional DC-to-AC voltage inverter is a voltage converter and includes a plurality of half phase modules that are paired to form three phases.

7. The apparatus of claim **1**, wherein the electromechanical device is a motor.

8. The apparatus of claim **7**, wherein the motor is coupled to a bi-directional DC-to-AC voltage inverter of the first voltage converter.

9. The apparatus of claim **7**, wherein the motor is a traction motor mechanically coupled to one or more driving wheels or axles.

10. The apparatus of claim **7**, wherein the motor is a traction motor mechanically coupled to a pump, fan, winch, crane, elevator, or lift.

11. The apparatus of claim **7**, wherein the first controller is configured to cause the motor to be decoupled from the first voltage converter during the charging mode of operation.

12. The apparatus of claim **1**, wherein the first controller is further configured to communicate with the second controller to determine a desired mode of operation.

13. The apparatus of claim **1**, wherein the first controller is further configured to communicate with the second controller to confirm the apparatus is in a non-charging mode prior to unlocking a connection system by which the second voltage from the remote power supply is provided.

14. The apparatus of claim **1**, further comprising a second energy storage device coupled to the first voltage converter.

15. The apparatus of claim **14**, wherein the first energy storage device is configured to provide a higher power than the second energy storage device.

16. The apparatus of claim **14**, wherein the first voltage converter includes a DC-to-DC voltage converter, and the second energy storage device is coupled to the DC-to-DC voltage converter.

17. The apparatus of claim **14**, wherein the first voltage converter includes a bi-directional DC-to-AC voltage inverter, and the second energy storage device is configured to be rechargeable via the bi-directional DC-to-AC voltage inverter.

18. The apparatus of claim **1**, wherein the first energy storage device is a battery, and the first voltage converter is further configured to direct a first charging current associated with the first charging voltage together with a second charging current provided by a bi-directional DC-to-AC voltage inverter of the first voltage converter to charge the first energy storage device.

19. The apparatus of claim **18**, wherein the second charging current is provided to the first energy storage device via a contactor to a DC bus of the first voltage converter.

20. The apparatus of claim **18**, further comprising a second energy storage device coupled to the first voltage converter.

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