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Han et al.

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(54) **SERIES CONNECTED DC INPUT INVERTERS**

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(51) **Int. Cl.**

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H02P 5/74	(2006.01)
H02K 11/33	(2016.01)
H02M 1/00	(2006.01)

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

CPC ***H02M 7/49*** (2013.01); ***H02K 11/33*** (2016.01); ***H02P 5/74*** (2013.01); *H02M 2001/0074* (2013.01)

(58) **Field of Classification Search**

USPC 318/724

See application file for complete search history.

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(74) *Attorney, Agent, or Firm* — Bell & Manning, LLC

(57) **ABSTRACT**

A multi-level converter includes a first multi-phase inverter and a second multi-phase inverter. The first multi-phase inverter includes a first direct current (DC) positive line, a first DC negative line, and a first plurality of alternating current (AC) lines. Each AC line of the first plurality of AC lines is configured to be connected to a single phase winding of an electric machine. Each single phase winding is connected to a common neutral connector in a Y-winding configuration or between a pair of single phase windings in a Δ-winding configuration. The second multi-phase inverter includes a second DC positive line, a second DC negative line, and a second plurality of AC lines and is connected in

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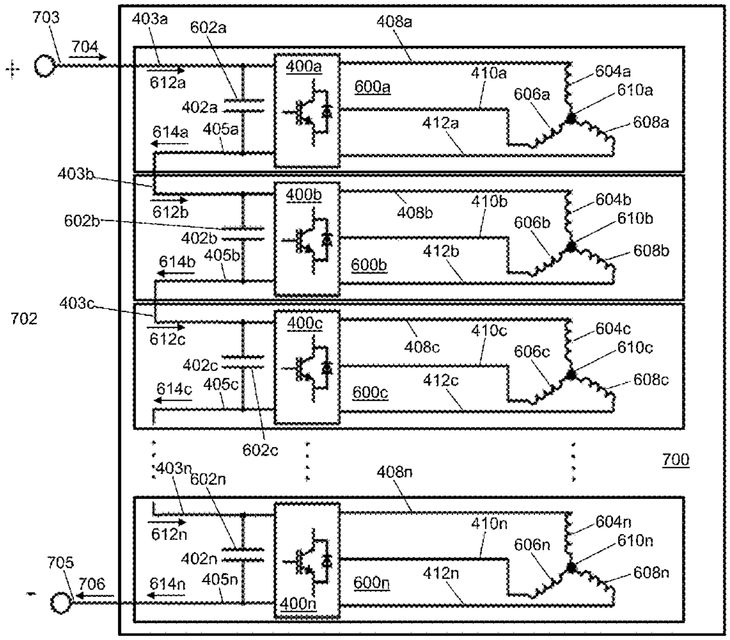

a similar manner to the first multi-phase inverter. The first DC negative line is electrically coupled to the second DC positive line to connect the first multi-phase inverter and the second multi-phase inverter in series.

18 Claims, 16 Drawing Sheets

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Power inverter, Downloaded from http://en.wikipedia.org/wiki/Inverter on Jan. 24, 2014, pp. 1-13.

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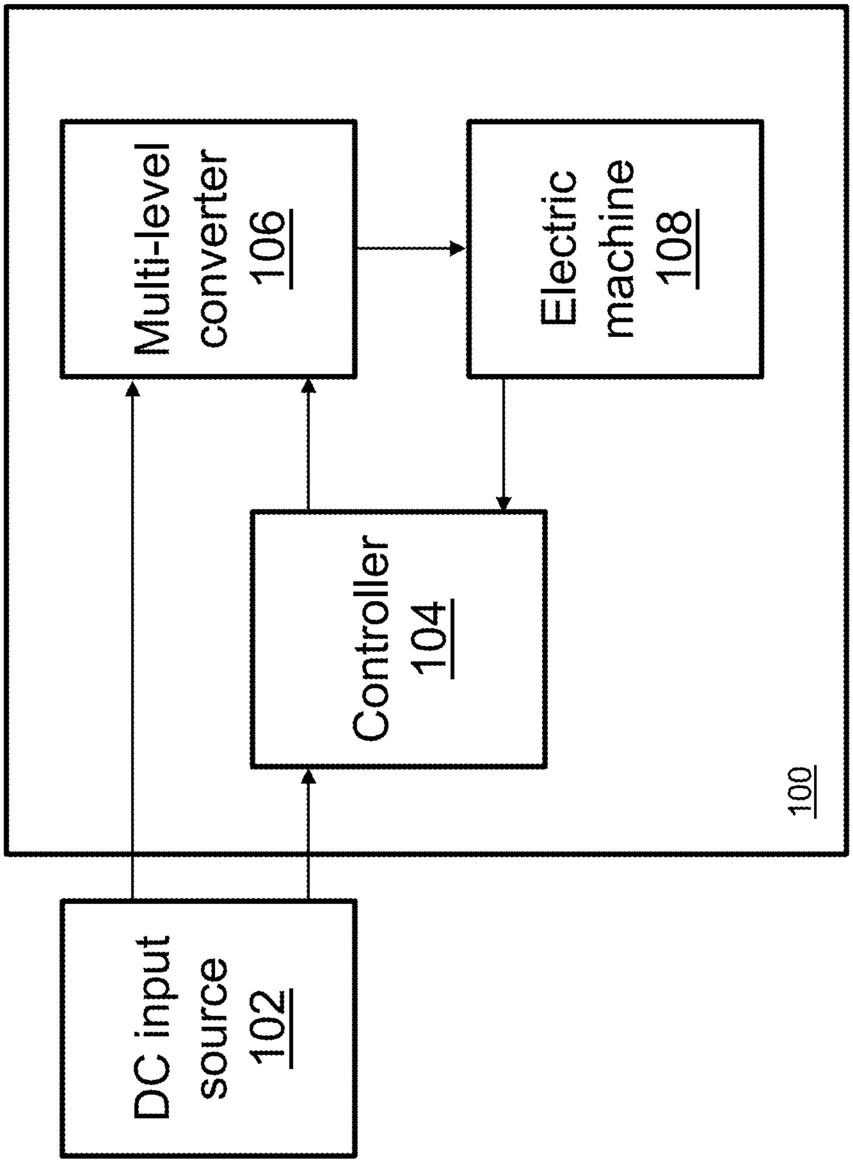

Multi-level converter 106
Electric machine 108
Controller 104
DC input source 102
100

Fig. 1

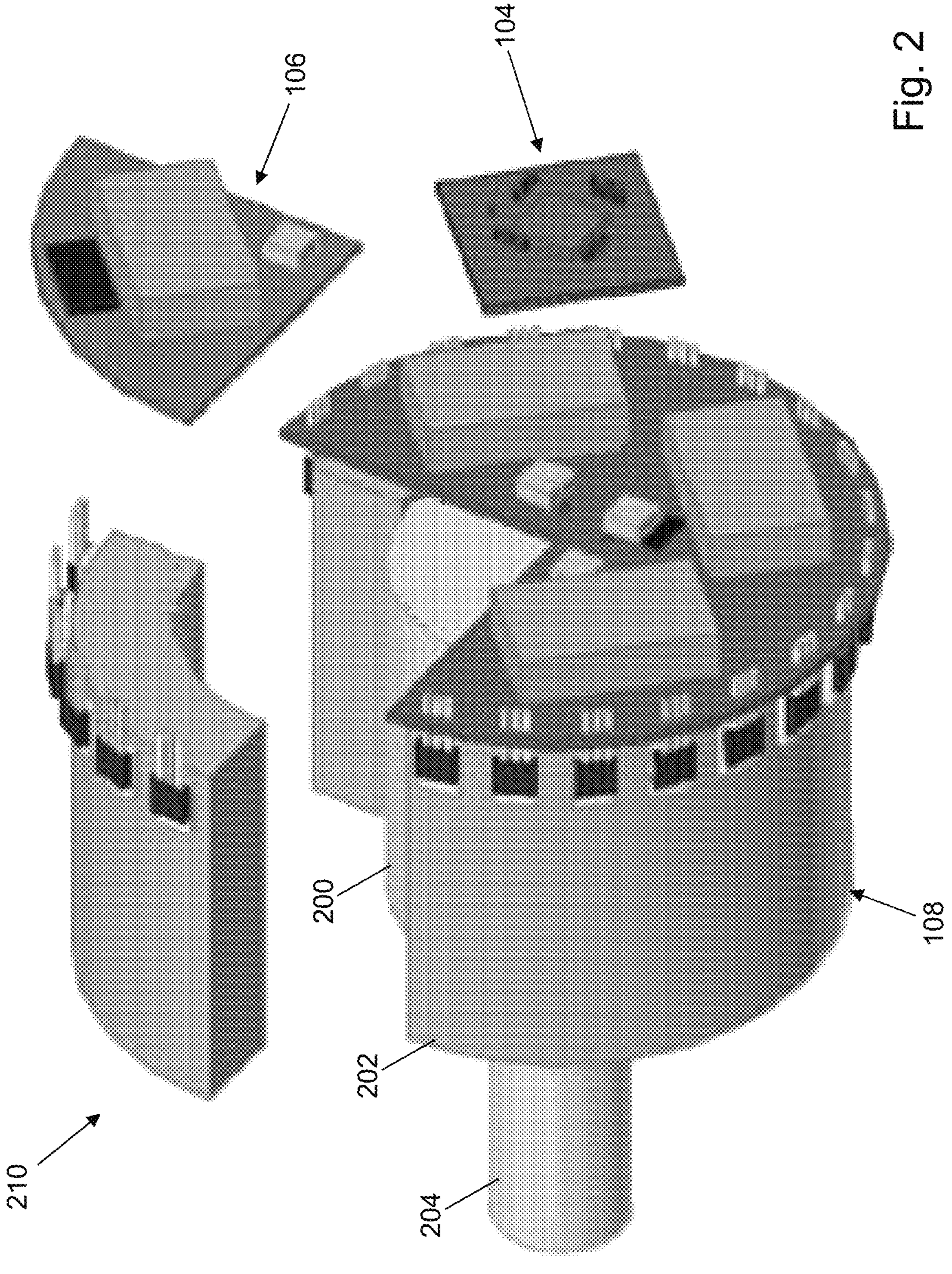


Fig. 2

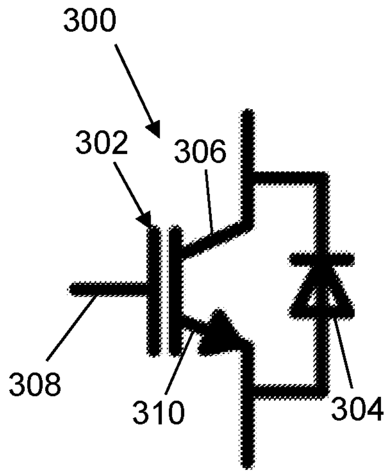

300
302
306
308
310
304

Fig. 3

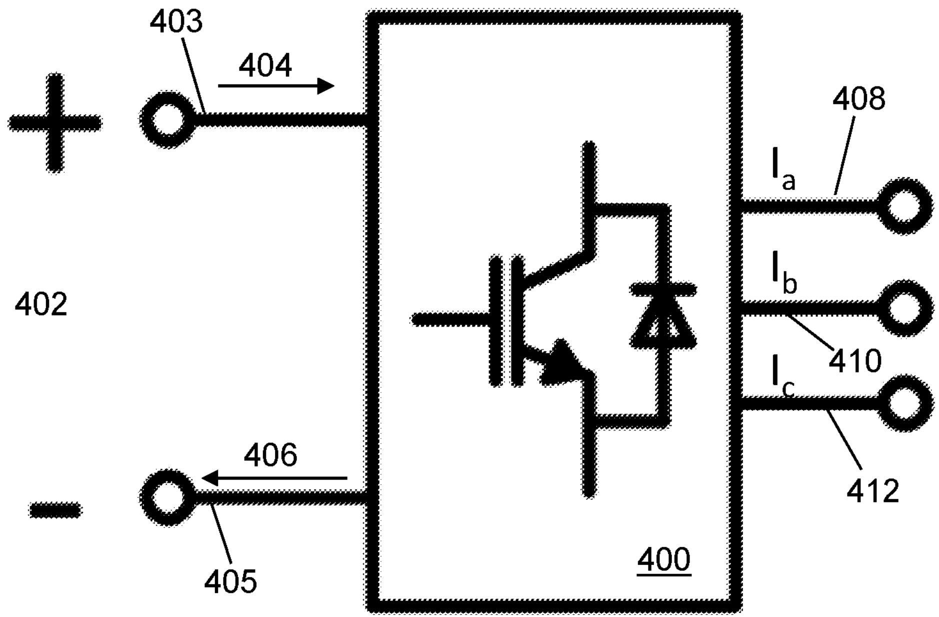

403
404
408
I_a
I_b
I_c
410
412
402
406
405
400

Fig. 4

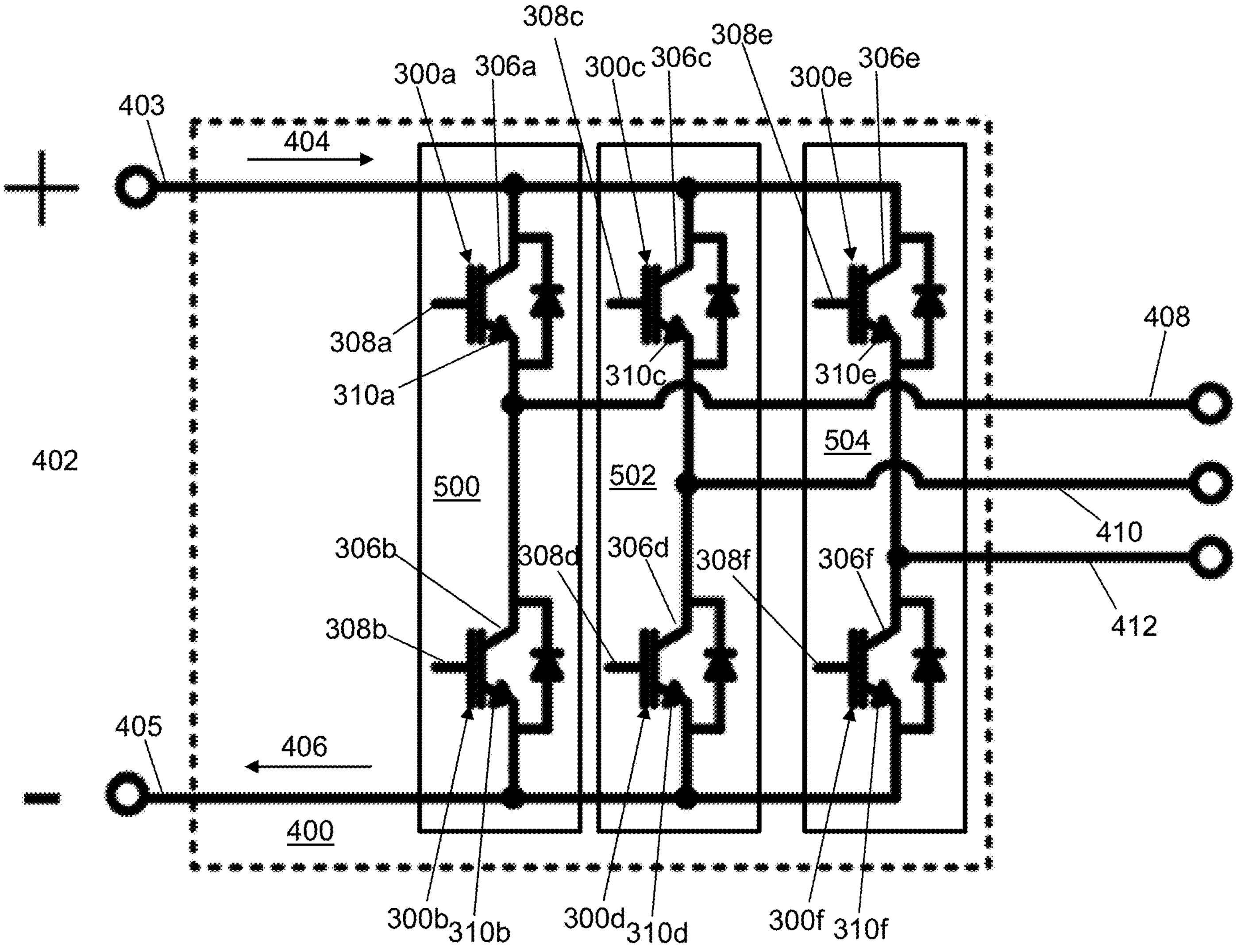

308c
308e
300a
306a
300c
306c
300e
306e
403
404
+
308a
310a
310c
310e
408
402
500
502
504
410
412
306b
308d
306d
308f
306f
308b
405
406
-
400
300b
310b
300d
310d
300f
310f

Fig. 5

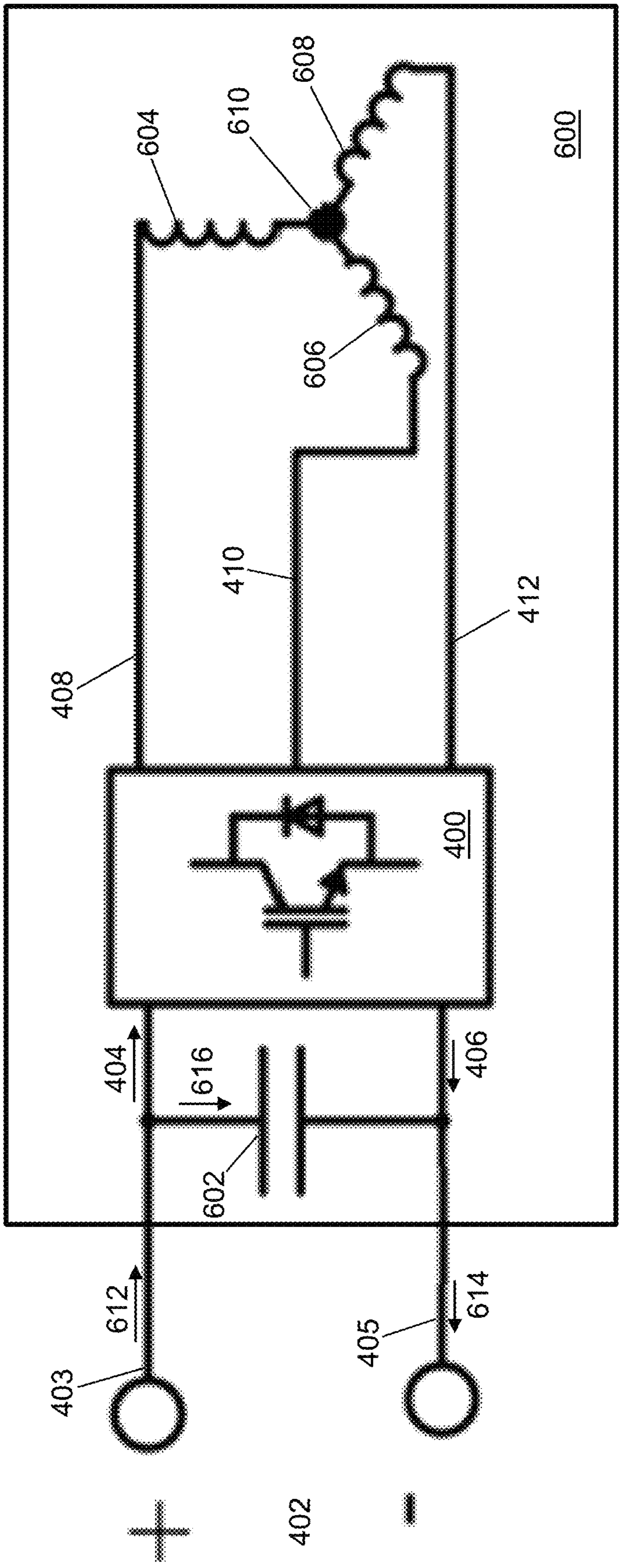
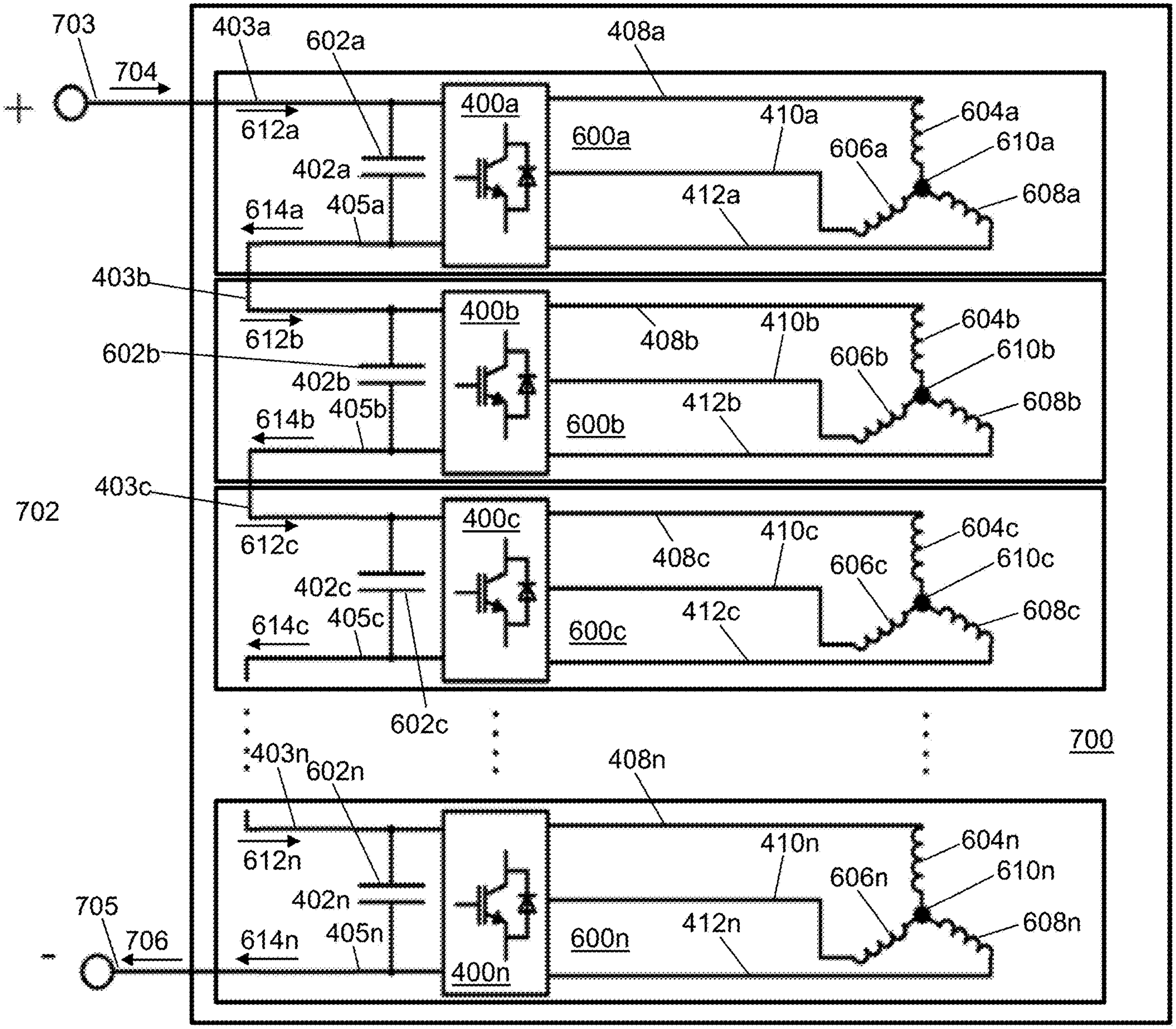

600
604
610
608
606
408
410
412
400
404
616
406
602
612
614
403
405
+
402
-

Fig. 6


703
704
+
403a
602a
408a
400a
612a
600a
410a
604a
610a
402a
606a
608a
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412a
403b
400b
612b
408b
410b
604b
610b
602b
402b
606b
608b
614b
405b
412b
600b
403c
702
400c
612c
408c
410c
604c
610c
402c
606c
608c
614c
405c
412c
600c
602c
700
403n
602n
408n
612n
410n
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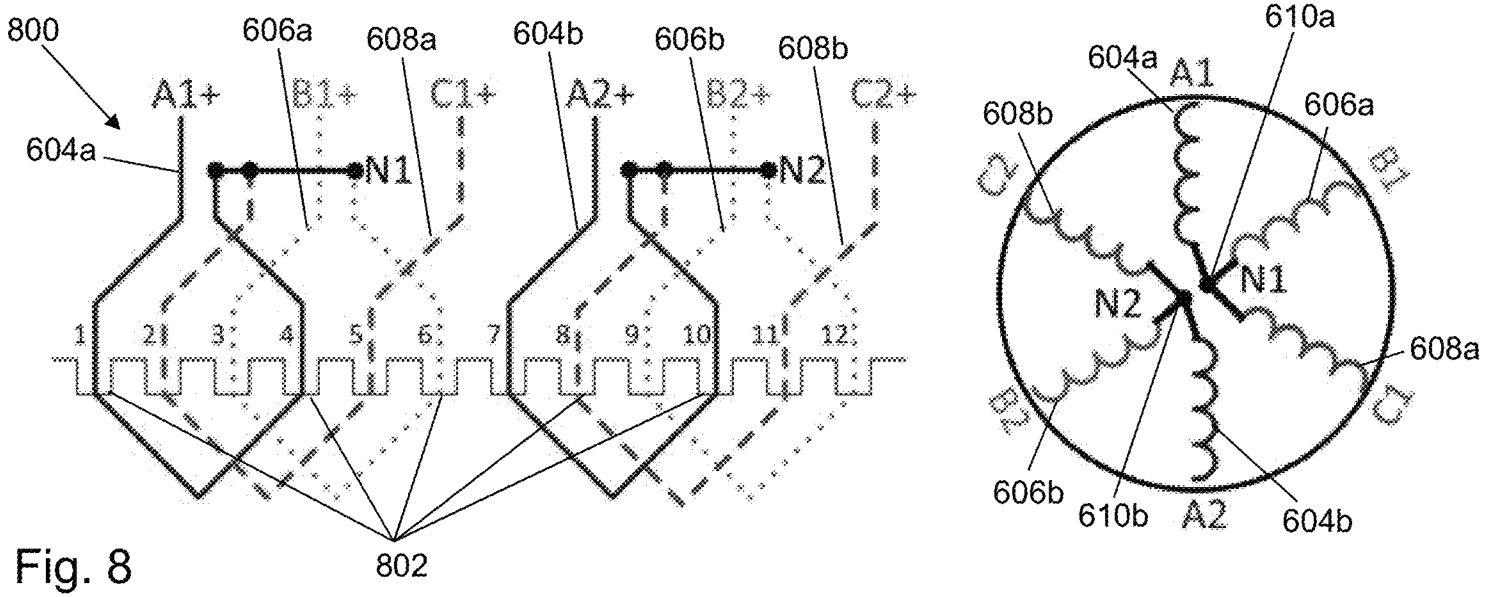
606n
402n
608n
705
706
-
614n
405n
412n
600n
400n

Fig. 7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608a
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606b
608b
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B1+
C1+
A2+
B2+
C2+
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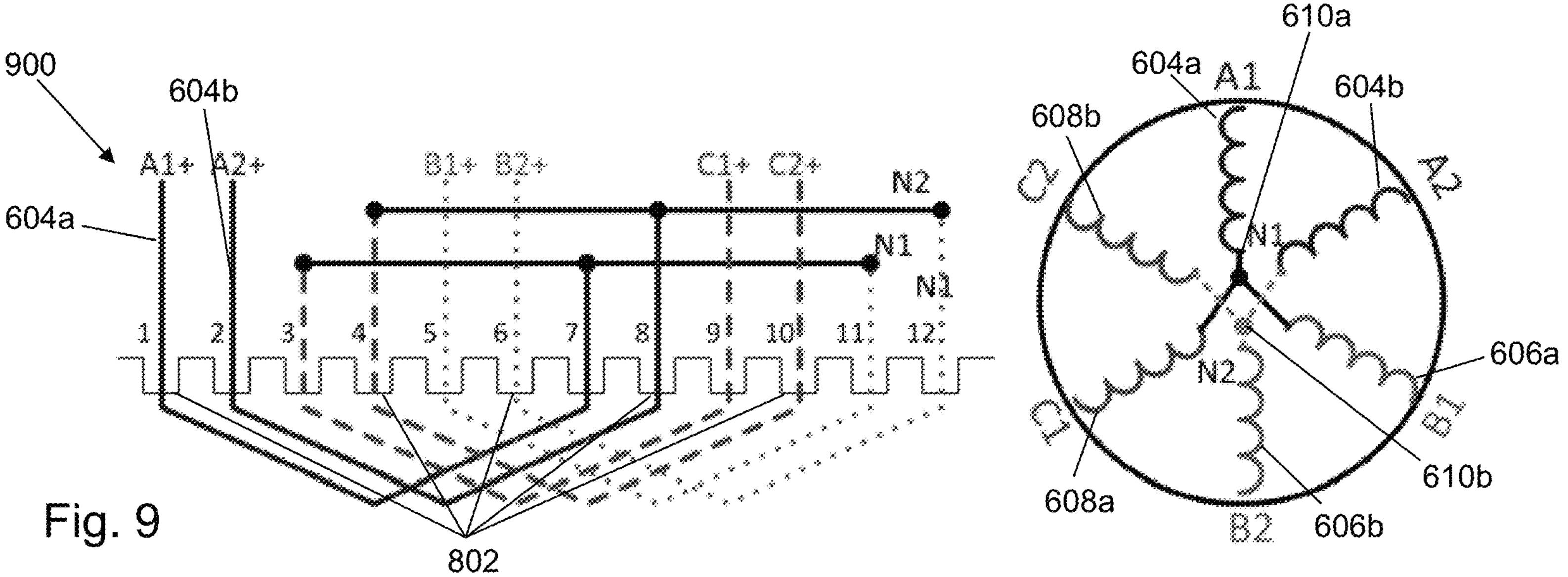
N2
1
2
3
4
5
6
7
8
9
10
11
12
802
610a
604a
A1
606a
608b
C2
B1
N1
N2
608a
C1
B2
606b
610b
A2
604b

Fig. 8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B1+
B2+
C1+
C2+
N2
N1
N1
1
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3
4
5
6
7
8
9
10
11
12
802
610a
604a
A1
604b
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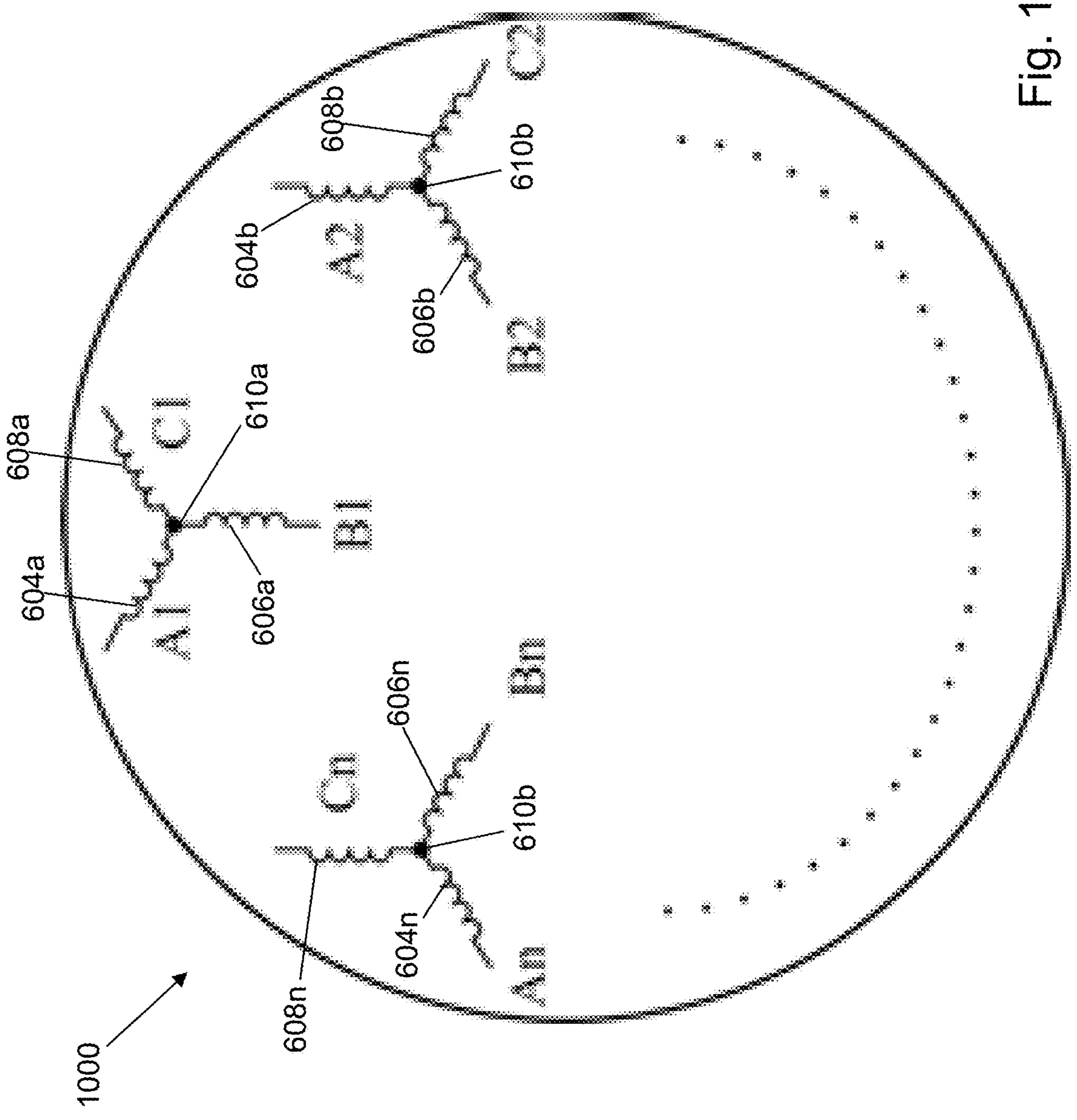
A2
C2
N1
606a
N2
B1
C1
610b
608a
606b
B2

Fig. 9


1000
608n
604n
An
610b
Cn
606n
Bn
604a
A1
606a
B1
610a
C1
608a
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606b
B2
610b
608b
C2

Fig. 10

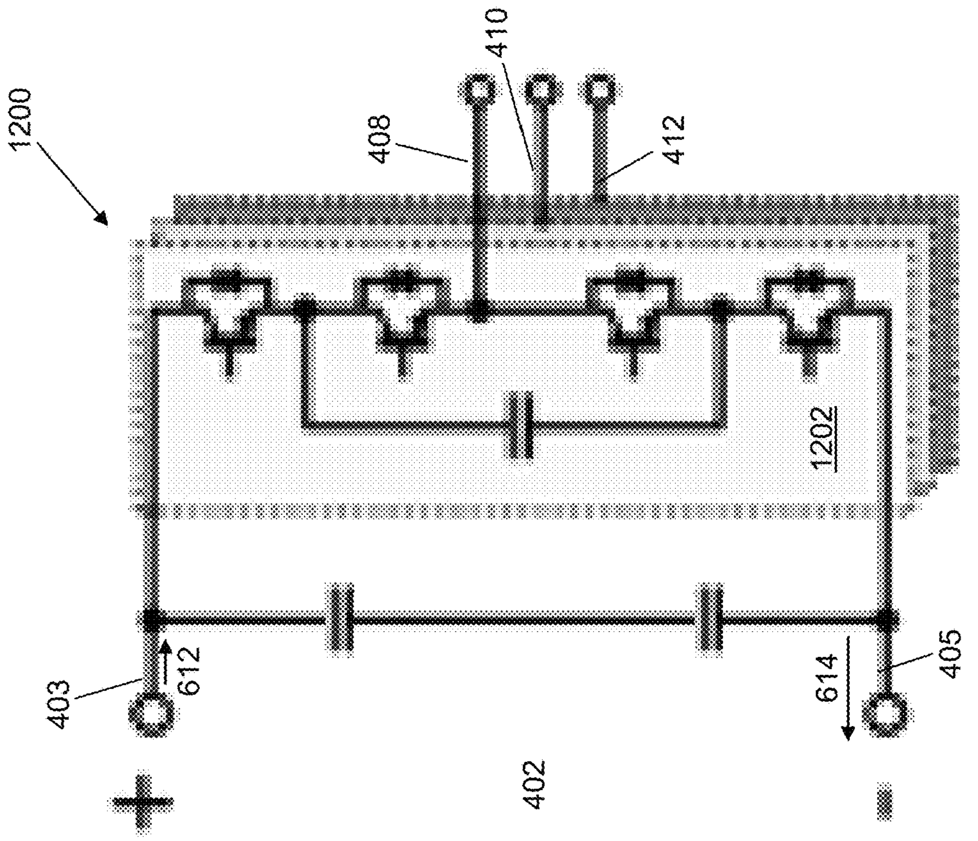
1200
408
410
412
1202
403
612
614
405
+
402
-

Fig. 12

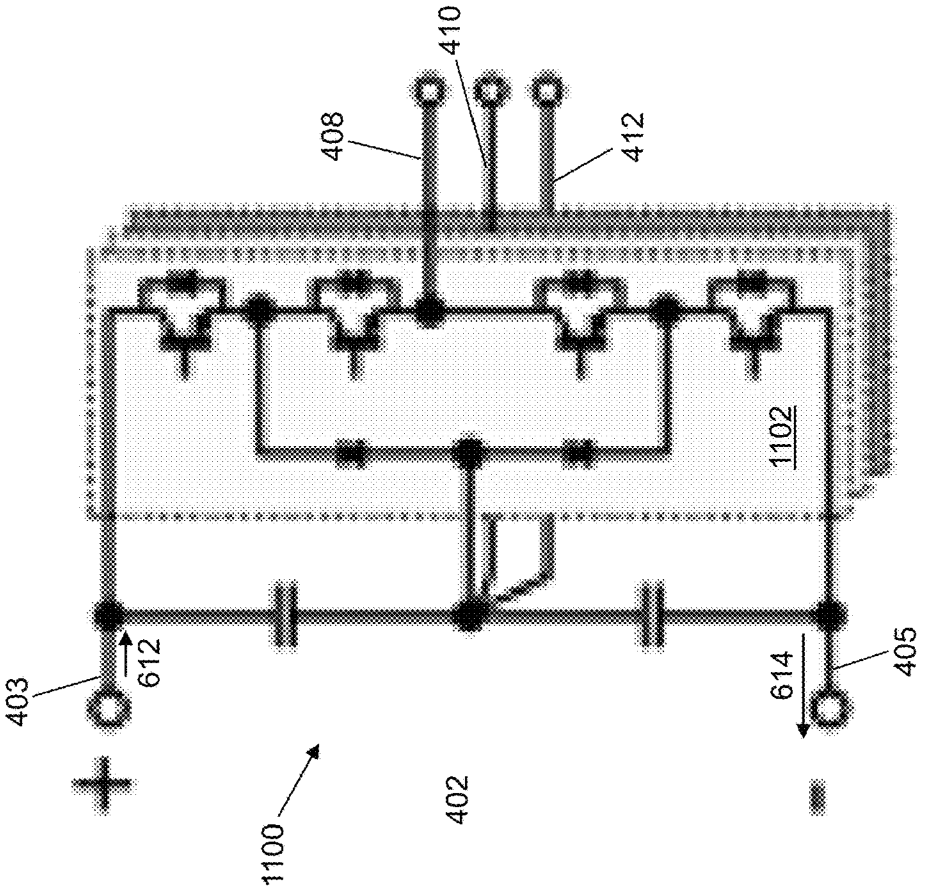
408
410
412
1102
403
612
614
405
+
402
-
1100

Fig. 11

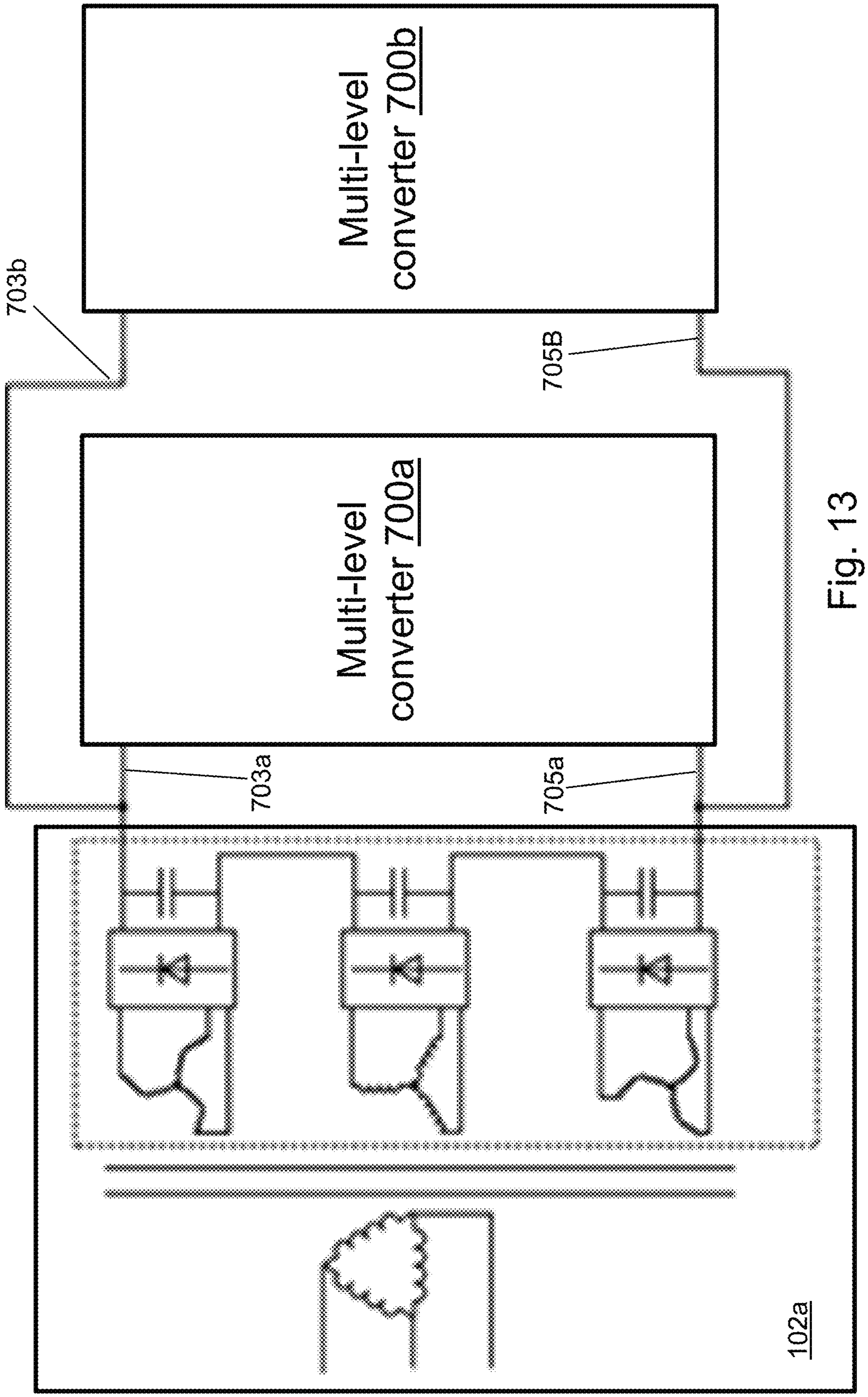
Multi-level converter 700b
703b
705B
Multi-level converter 700a
703a
705a
102a

Fig. 13

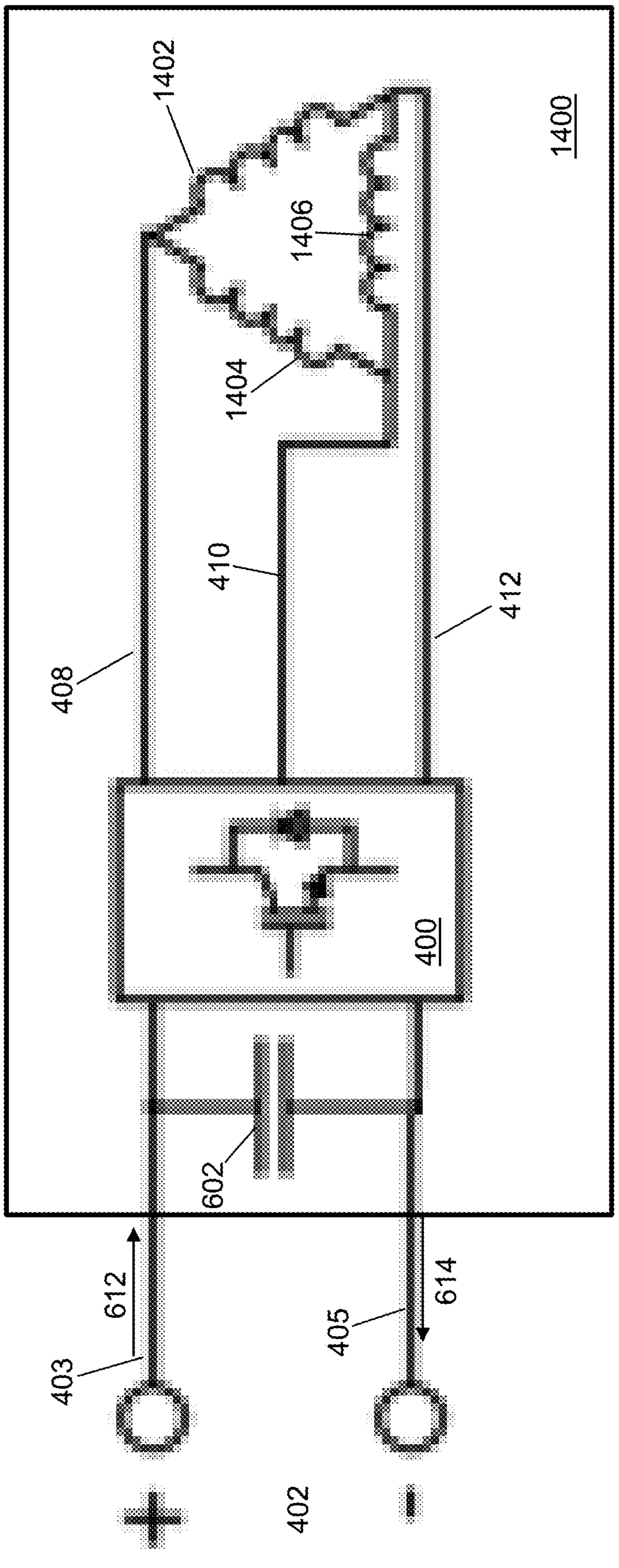

Fig. 14

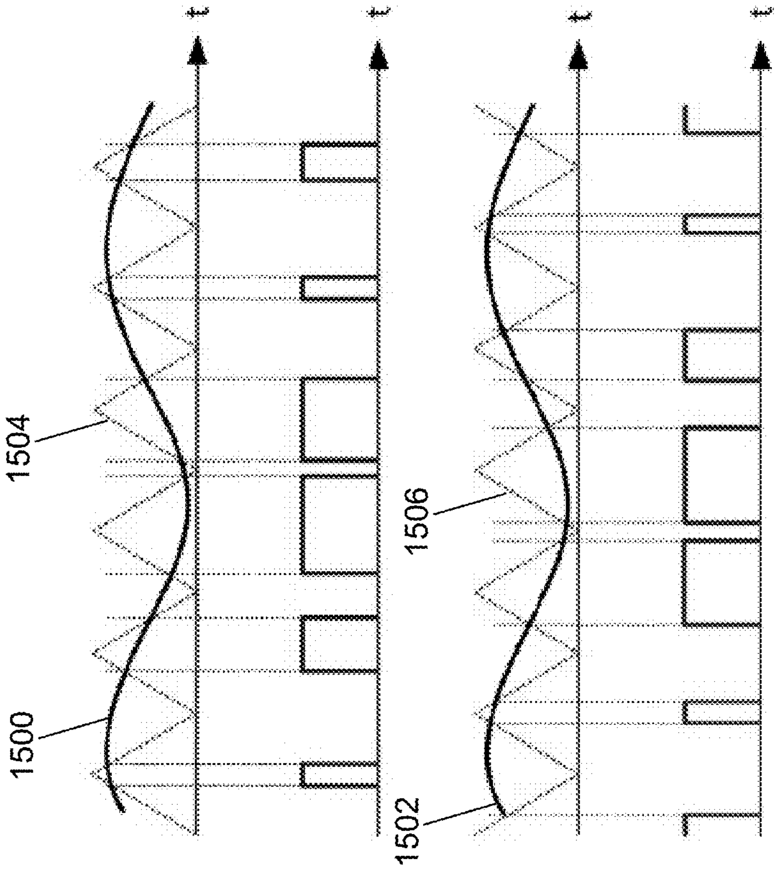

Fig. 15

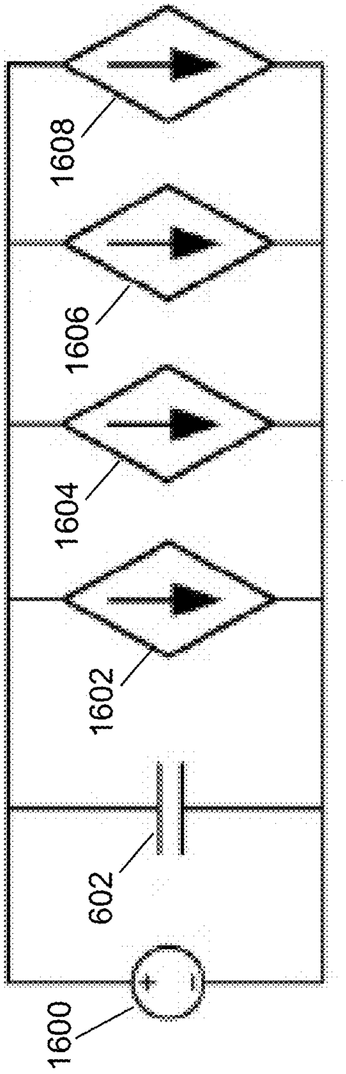

Fig. 16

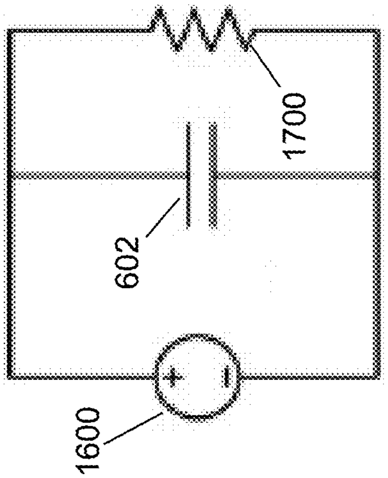

Fig. 17

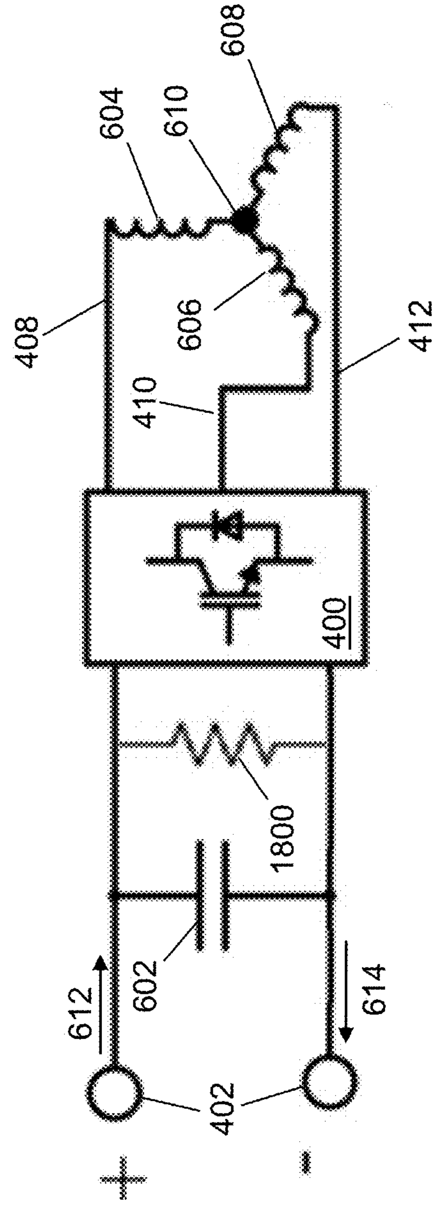

Fig. 18

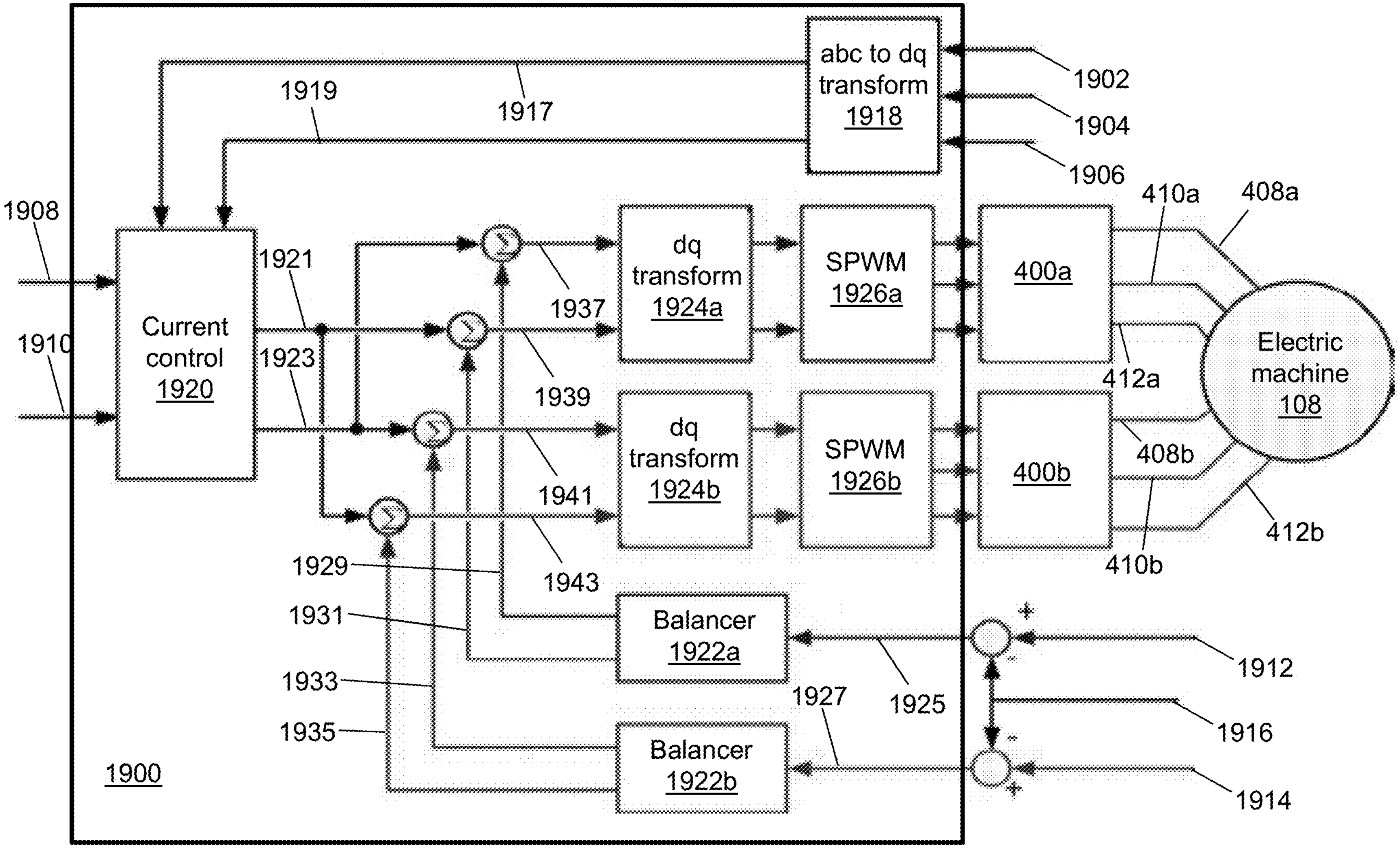
abc to dq transform 1918
1902
1904
1906
1917
1919
1908
1910
Current control 1920
1921
1923
1937
1939
1941
1943
dq transform 1924a
dq transform 1924b
SPWM 1926a
SPWM 1926b
400a
400b
410a
408a
412a
408b
410b
412b
Electric machine 108
1929
1931
1933
1935
Balancer 1922a
Balancer 1922b
1925
1927
1912
1916
1914
+
-
-
+
1900

Fig. 19

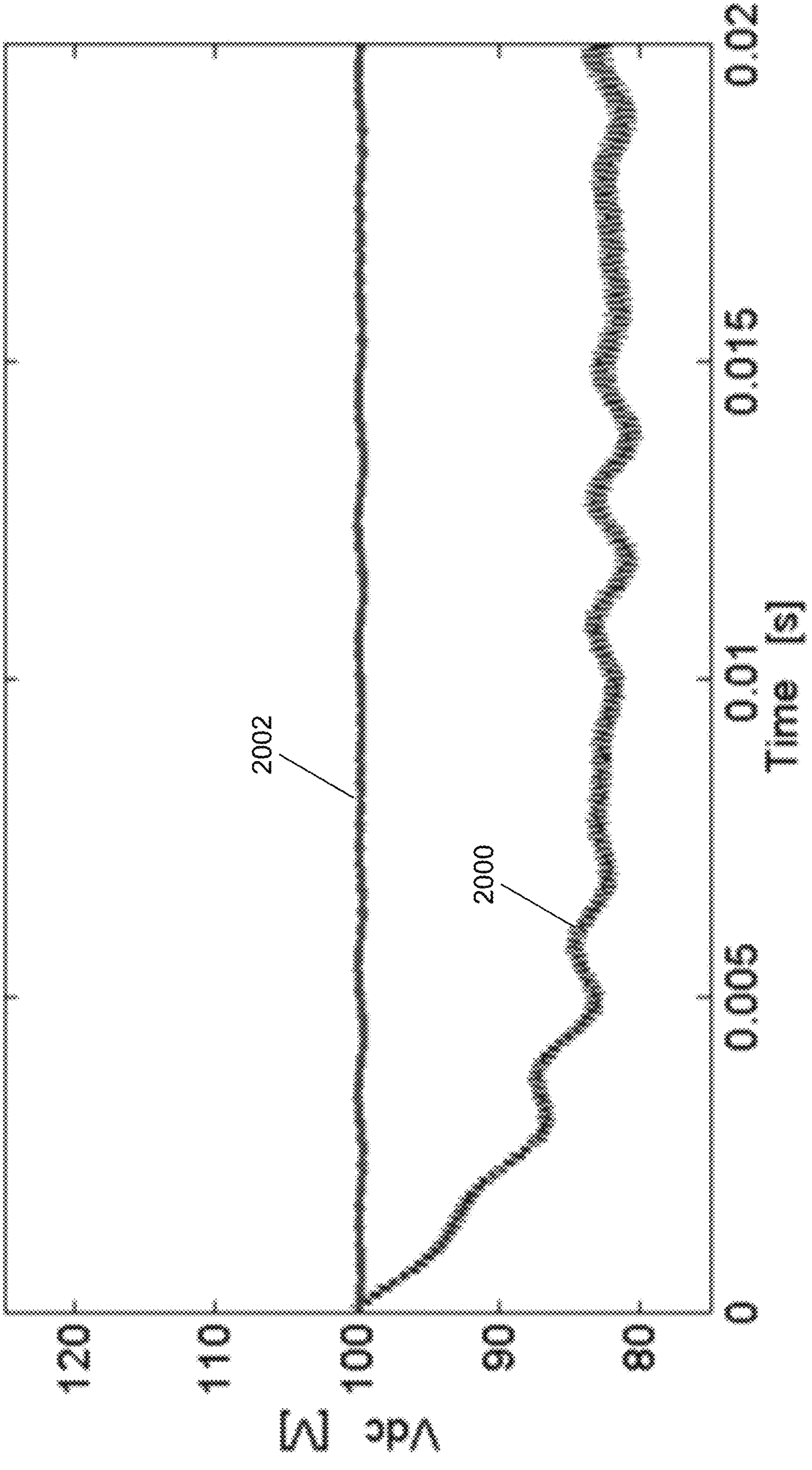

Fig. 20

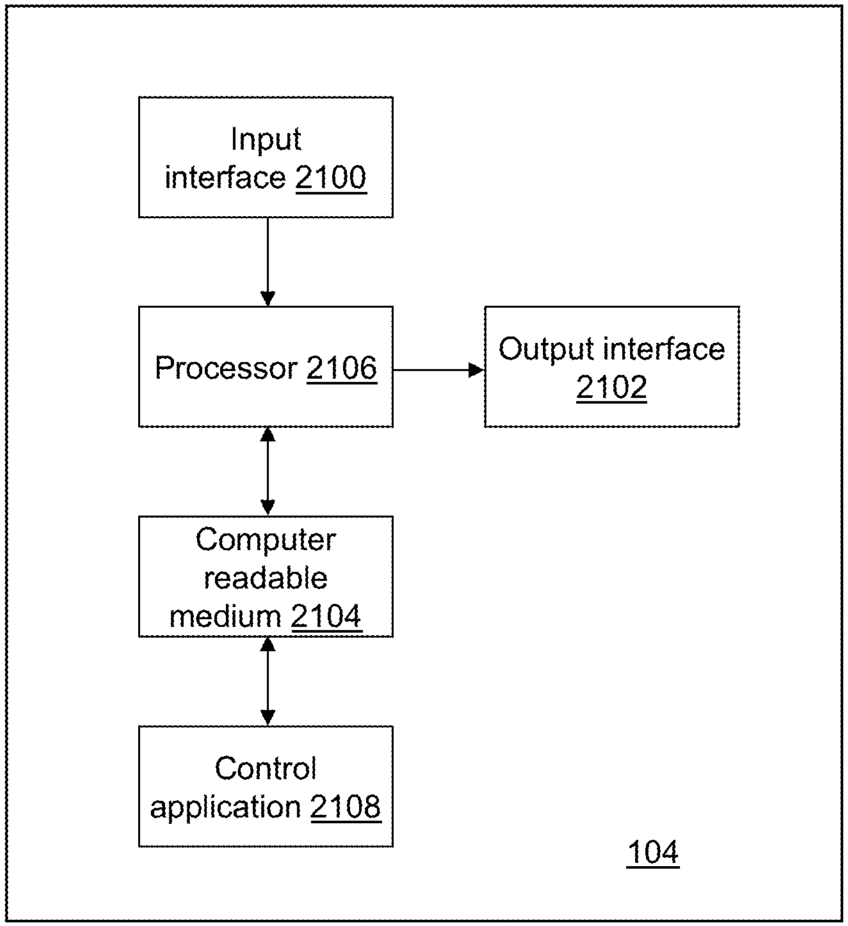
Input interface 2100
Processor 2106
Output interface 2102
Computer readable medium 2104
Control application 2108
104

Fig. 21

SERIES CONNECTED DC INPUT INVERTERS

BACKGROUND

There has been increasing attention given to the efficiency of energy conversion. Electric motors utilize 45 per cent of global electricity. Increased energy efficiency in electric motors will provide the U.S. with tremendous economic, environmental, human ecological, and security benefits.

An adjustable speed drive (ASD) is a power electronics device that controls the speed of machinery. ASDs also save energy for industry processes that require adjustable speed or control of flow from a fan or pump. ASDs have already replaced many conventional fixed speed drives in low-power and low-voltage applications such as air conditioners, washing machines, electric bicycles, and vehicles with stepless speed change. For high-power and medium-voltage (MV) applications, including industrial air compressors, water pumping stations, cooling fans, railway traction systems, steel rolling mills, marine propulsion, and renewable energy systems, ASDs are even more attractive because the cost saving of electric power is even more significant than it is in low-voltage and low-power applications.

SUMMARY

In an example embodiment, a converter is provided. The converter includes, but is not limited to, a first multi-phase inverter and a second multi-phase inverter. The first multi-phase inverter includes, but is not limited to, a first direct current (DC) positive line, a first DC negative line, and a first plurality of alternating current (AC) lines. Each AC line of the first plurality of AC lines is configured to be connected to a single phase winding of an electric machine. Each single phase winding is connected to a common neutral connector. The second multi-phase inverter includes, but is not limited to, a second DC positive line, a second DC negative line, and a second plurality of AC lines. Each AC line of the second plurality of AC lines is configured to be connected to a second single phase winding of the electric machine. Each second single phase winding is connected to a second common neutral connector. The common neutral connector is different from the second common neutral connector. The first DC negative line is electrically coupled to the second DC positive line to connect the first multi-phase inverter and the second multi-phase inverter in series.

In another example embodiment, a converter is provided. The converter includes, but is not limited to, a first multi-phase inverter and a second multi-phase inverter. The first multi-phase inverter includes, but is not limited to, a first DC positive line, a first DC negative line, and a first plurality of AC lines. Each AC line of the first plurality of AC lines is configured to be connected between a different pair of single phase windings of an electric machine. The second multi-phase inverter includes, but is not limited to, a second DC positive line, a second DC negative line, and a second plurality of AC lines. Each AC line of the second plurality of AC lines is configured to be connected between a different pair of second single phase windings of the electric machine. The first DC negative line is electrically coupled to the second DC positive line to connect the first multi-phase inverter and the second multi-phase inverter in series.

In yet another example embodiment, an electric machine is provided. The electric machine includes, but is not limited to, stator, a rotor configured to rotate, and at least four windings, a first multi-phase inverter, and a second multi-phase inverter. A first winding is connected between a first-phase line and a first neutral connector. A second winding is connected between a second-phase line and the first neutral connector. A third winding is connected between a second first-phase line and a second neutral connector. A fourth winding is connected between a second second-phase line and the second neutral connector. The first neutral connector is different from the second neutral connector. The first multi-phase inverter includes, but is not limited to, a first DC positive line, a first DC negative line, and at least the first-phase line and the second-phase line. The second multi-phase inverter includes, but is not limited to, a second DC positive line, a second DC negative line, and at least the second first-phase line and the second second-phase line. The first DC negative line is electrically coupled to the second DC positive line to connect the first multi-phase inverter and the second multi-phase inverter in series.

Other principal features of the disclosed subject matter will become apparent to those skilled in the art upon review of the following drawings, the detailed description, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Illustrative embodiments of the disclosed subject matter will hereafter be described referring to the accompanying drawings, wherein like numerals denote like elements.

FIG. **1** is a block diagram of an electric machine system connected to an input source in accordance with an illustrative embodiment.

FIG. **2** depicts the electric machine system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **3** depicts a switch-diode circuit in accordance with an illustrative embodiment.

FIG. **4** is a block diagram of a 3-phase inverter of the electric machine system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **5** is a circuit diagram of the 3-phase inverter of FIG. **4** in accordance with an illustrative embodiment.

FIG. **6** depicts a single converter module with a Y winding connection in accordance with an illustrative embodiment.

FIG. **7** depicts a multi-level converter module in accordance with an illustrative embodiment.

FIG. **8** depicts a first winding configuration of the electric machine system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **9** depicts a second winding configuration of the electric machine system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **10** depicts a general winding configuration of the electric machine system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **11** depicts a second 3-phase inverter of the electric machine system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **12** depicts a third 3-phase inverter of the electric machine system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **13** depicts feeding of two electric machine systems of FIG. **1** in accordance with an illustrative embodiment.

FIG. **14** depicts a single converter module with a Δ winding connection in accordance with an illustrative embodiment.

FIG. **15** shows a phase shifted signal input to a two-level converter in accordance with an illustrative embodiment.

FIG. **16** depicts a small signal model of the 3-phase inverter of FIG. **4** in accordance with an illustrative embodiment.

FIG. **17** depicts an equivalent small signal model of the 3-phase inverter of FIG. **4** with an active voltage balance virtual resistor in accordance with an illustrative embodiment.

FIG. **18** depicts the 3-phase inverter of FIG. **4** with a voltage balance resistor in accordance with an illustrative embodiment.

FIG. **19** depicts a block diagram of an active balancer controller of a two-level converter in accordance with an illustrative embodiment.

FIG. **20** shows a voltage comparison of with and without the active balancer controller of the two-level converter of FIG. **19** in accordance with an illustrative embodiment.

FIG. **21** depicts a block diagram of a controller of the electric machine system of FIG. **1** in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

Referring to FIG. **1**, an electric machine system **100** may include a controller **104**, a multi-level converter **106**, and an electric machine **108**. Electric machine **108** may be a motor such as an induction or a synchronous motor including permanent magnet machines. A direct current (DC) input source **102** is electrically connected to controller **104** and to multi-level converter **106**. DC input source **102** can be by one or more DC source. DC input source **102** may be a DC grid, batteries, a dc output of a single-phase or multi-phase passive or active rectifier, etc. that provides approximately constant instantaneous power flow.

DC input source **102** provides DC power and DC input source measured signals to controller **104**. DC input source **102** provides DC power to multi-level converter **106**. Multi-level converter **106** provides alternating current (AC) power to electric machine **108**.

Controller **104** is electrically connected to DC input source **102**, multi-level converter **106**, and electric machine **108**. Controller **104** controls the supply of power by multi-level converter **106** to electric machine **108** through command signals input to multi-level converter **106**. The command signals are generated by controller **104** based on the DC input source measured signals received from DC input source **102** and signals measured and received from electric machine **108**. In an illustrative embodiment, controller **104** implements a closed loop current control to determine the command signals.

Multi-level converter **106** converts DC power from DC input source **102** to the AC power supplied to electric machine **108**. Controller **104** and multi-level converter **106** can be incorporated inside a housing of electric machine **108**.

Referring to FIG. **2**, an AC motor **210** is shown in accordance with an illustrative embodiment. AC motor **210** is merely an example of electric machine **108**. AC motor **210** may include a rotor **200** and a stator **202** with associated windings (not shown) in various arrangements as understood by a person of skill in the art. AC motor **210** may be an AC electric motor in which the electric current in a rotor winding needed to produce torque is induced by electromagnetic induction from a magnetic field formed by a current in a stator winding. Rotor **200** of AC motor **210** may be either wound type, squirrel-cage type, etc. AC motor **210** further may be configured to have any size rating.

Referring to FIG. **3**, a switch-diode circuit **300** is shown in accordance with an illustrative embodiment. Switch-diode circuit **300** may include a transistor switch **302** and a diode **304**. Transistor switch **302** may include a drain **306**, a gate **308**, and a source **310** like a metal-oxide-semiconductor field-effect transistor (MOSFET) or include a collector **306**, a gate **308**, and an emitter **310** like an insulated-gate bipolar transistor (IGBT), or include a collector **306**, a base **308**, and an emitter **310** like a bipolar junction transistor. Depending on the switching logic and whether transistor switch **302** is an n-type or a p-type, drain **306** and source **310** may be reversed. A voltage applied to gate **308** determines a switching state of transistor switch **302**. Diode **304** is connected anti-parallel across source **310** and drain **306** of transistor switch **302**. In an illustrative embodiment, transistor switch **302** is an insulated-gate field-effect transistor such as a MOSFET, IGBT, Gallium Nitride (GaN) device, Silicon Carbide (SiC) device, or other type of power semiconductor switch.

Referring to FIG. **4**, a block diagram of a multi-phase inverter **400** is shown in accordance with an illustrative embodiment. ΔV_{dc} **402** is applied across a positive line **403** and a negative line **405**. An input current **404** is provided through positive line **403**, and an output current **406** is provided through negative line **405**. V_{dc} **402** represents the voltage from DC input source **102** if multi-level converter **106** included a single multi-phase inverter. In the illustrative embodiment, multi-phase inverter **400** outputs a first phase current I_a through a first-phase line **408**, a second phase current I_b through a second-phase line **410**, and a third phase current I_c through a third-phase line **412**. First-phase line **408**, second-phase line **410**, and third-phase line **412** are AC current lines that provide AC power to electric machine **108**. In the illustrative embodiment, multi-phase inverter **400** is a three-phase inverter though a different number of phases may be output from multi-phase inverter **400** in alternative embodiments. For example, multi-phase inverter **400** may output two- or four-phase currents.

Referring to FIG. **5**, a circuit diagram of multi-phase inverter **400** implemented as a three-phase inverter is shown in accordance with an illustrative embodiment. Multi-phase inverter **400** may include a first half-bridge **500**, a second half-bridge **502**, and a third half-bridge **504**. First half-bridge **500** includes a first switch-diode circuit **300*a*** and a second switch-diode circuit **300*b***. In the illustrative embodiment, source **310*a*** of first switch-diode circuit **300*a*** is connected to drain **306*b*** of second switch-diode circuit **300*b***. Drain **306*a*** of first switch-diode circuit **300*a*** is connected to positive line **403**. Source **310*b*** of second switch-diode circuit **300*b*** is connected to negative line **405**. Gate **308*a*** of first switch-diode circuit **300*a*** and gate **308*b*** of second switch-diode circuit **300*b*** are connected to controller **104** to receive gating signals to control a state of first switch-diode circuit **300*a*** and second switch-diode circuit **300*b***, respectively. First-phase line **408** is connected between source **310*a*** of first switch-diode circuit **300*a*** and drain **306*b*** of second switch-diode circuit **300*b***.

A half-bridge is included for each phase current output from multi-phase inverter **400**. Second half-bridge **502** is identical to first half-bridge **500** and includes a third switch-diode circuit **300*c*** and a fourth switch-diode circuit **300*d***. In the illustrative embodiment, source **310*c*** of third switch-diode circuit **300*c*** is connected to drain **306*d*** of fourth switch-diode circuit **300*d***. Drain **306*c*** of third switch-diode circuit **300*c*** is connected to positive line **403**. Source **310*d*** of fourth switch-diode circuit **300*d*** is connected to negative line **405**. Gate **308*c*** of third switch-diode circuit **300*c*** and gate **308***d* of fourth switch-diode circuit **300***d* are connected to controller **104** to receive gating signals to control a state of third switch-diode circuit **300***c* and fourth switch-diode circuit **300***d*, respectively. Second-phase line **410** is connected between source **310***c* of third switch-diode circuit **300***c* and drain **306***d* of fourth switch-diode circuit **300***d*.

Third half-bridge **504** is identical to first half-bridge **500** and includes a fifth switch-diode circuit **300***e* and a sixth switch-diode circuit **300***f*. In the illustrative embodiment, source **310***e* of fifth switch-diode circuit **300***e* is connected to drain **306***f* of sixth switch-diode circuit **300***f*. Drain **306***e* of fifth switch-diode circuit **300***e* is connected to positive line **403**. Source **310***f* of sixth switch-diode circuit **300***f* is connected to negative line **405**. Gate **308***e* of fifth switch-diode circuit **300***e* and gate **308***f* of sixth switch-diode circuit **300***f* are connected to controller **104** to receive gating signals to control a state of fifth switch-diode circuit **300***e* and sixth switch-diode circuit **300***f*, respectively. Third-phase line **412** is connected between source **310***e* of fifth switch-diode circuit **300***e* and drain **306***f* of sixth switch-diode circuit **300***f*.

Referring to FIG. **6**, a single converter module **600** is shown in accordance with an illustrative embodiment. Single converter module **600** may include a capacitor **602**, multi-phase inverter **400**, a first-phase machine winding **604**, a second-phase machine winding **606**, and a third-phase machine winding **608**. First-phase machine winding **604**, second-phase machine winding **606**, and third-phase machine winding **608** are windings of electric machine **108**. First-phase machine winding **604**, second-phase machine winding **606**, and third-phase machine winding **608** are connected in a Y-winding configuration. Capacitor **602** is connected across a DC side of multi-phase inverter **400** between positive line **403** and negative line **405**. Thus, capacitor **602** is connected in parallel with first half-bridge **500**, second half-bridge **502**, and third half-bridge **504**.

A first converter input current **612** is input to single converter module **600**. A capacitor current **616** is a first portion of first converter input current **612** that flows through capacitor **602**. Input current **404** is a remaining portion of first converter input current **612**. A first converter output current **614** is output from single converter module **600** and equals output current **406** and capacitor current **616** after flowing through capacitor **602**.

First-phase machine winding **604** is supplied I_a through first-phase line **408**. Second-phase machine winding **606** is supplied I_b through second-phase line **410**. Third-phase machine winding **608** is supplied I_c through third-phase line **412**.

First-phase machine winding **604**, second-phase machine winding **606**, and third-phase machine winding **608** are tied together at a connector **610**. Connector **610** is a common neutral connector between first-phase machine winding **604**, second-phase machine winding **606**, and third-phase machine winding **608**. As understood by a person of skill in the art, the currents applied to the machine windings are 360/m degrees out of phase with each other, where m represents a number of phases. Thus, I_a, I_b, and I_c are 120 degrees out of phase with each other.

Electric machine **108** is a magnetic component and its windings are magnetically coupled with inherent electrical isolation. Single converter module **600** can utilize the windings of electric machine **108**, stator or rotor as coupling transformers, inductors, or filters to achieve a multilevel output. The output ports can be connected to different machine windings. Thus, the output voltages are synthesized inside electric machine **108**.

Referring to FIG. **7**, a multi-level converter module **700** is shown in accordance with an illustrative embodiment. Multi-level converter module **700** may include a plurality of single converter modules. Multi-level converter module **700** may include any number of single converter modules. For example, multi-level converter module **700** may include a first single converter module **600***a*, a second single converter module **600***b*, a third single converter module **600***c*, . . . , and an N^{th} single converter module **600***n*. Identical gate signal commands can be applied to each single converter module enabling a fully modular design.

First single converter module **600***a* may include a first capacitor **602***a*, a first multi-phase inverter **400***a*, a first, first-phase machine winding **604***a*, a first, second-phase machine winding **606***a*, and a first, third-phase machine winding **608***a*. First capacitor **602***a* is connected across a DC side of first multi-phase inverter **400***a* between a first positive line **403***a* and a first negative line **405***a*. First, first-phase machine winding **604***a* is supplied I_a through a first, first-phase line **408***a*. First, second-phase machine winding **606***a* is supplied I_b through a first, second-phase line **410***a*. First, third-phase machine winding **608***a* is supplied I_c through a first, third-phase line **412***a*. First, first-phase machine winding **604***a*, first, second-phase machine winding **606***a*, and first, third-phase machine winding **608***a* are tied together at a first connector **610***a*. First, first-phase machine winding **604***a*, first, second-phase machine winding **606***a*, and first, third-phase machine winding **608***a* are windings of electric machine **108**.

Second single converter module **600***b* may include a second capacitor **602***b*, a second multi-phase inverter **400***b*, a second, first-phase machine winding **604***b*, a second, second-phase machine winding **606***b*, and a second, third-phase machine winding **608***b*. Second capacitor **602***b* is connected across a DC side of second multi-phase inverter **400***b* between a second positive line **403***b* and a second negative line **405***b*. Second, first-phase machine winding **604***b* is supplied I_a through a second, first-phase line **408***b*. Second, second-phase machine winding **606***b* is supplied I_b through a second, second-phase line **410***b*. Second, third-phase machine winding **608***b* is supplied I_c through a second, third-phase line **412***b*. Second, first-phase machine winding **604***b*, second, second-phase machine winding **606***b*, and second, third-phase machine winding **608***b* are tied together at a second connector **610***b*. Second, first-phase machine winding **604***b*, second, second-phase machine winding **606***b*, and second, third-phase machine winding **608***b* are windings of electric machine **108**.

Third single converter module **600***c* may include a third capacitor **602***c*, a third multi-phase inverter **400***c*, a third, first-phase machine winding **604***c*, a third, second-phase machine winding **606***c*, and a third, third-phase machine winding **608***c*. Third capacitor **602***c* is connected across a DC side of third multi-phase inverter **400***c* between a third positive line **403***c* and a third negative line **405***c*. Third, first-phase machine winding **604***c* is supplied I_a through a third, first-phase line **408***c*. Third, second-phase machine winding **606***c* is supplied I_b through a third, second-phase line **410***c*. Third, third-phase machine winding **608***c* is supplied I_c through a third, third-phase line **412***c*. Third, first-phase machine winding **604***c*, third, second-phase machine winding **606***c*, and third, third-phase machine winding **608***c* are tied together at a third connector **610***c*. Third, first-phase machine winding **604***c*, third, second-phase machine winding **606***c*, and third, third-phase machine winding **608***c* are windings of electric machine **108**.

N^{th} single converter module **600**n may include an N^{th} capacitor **602**n, an N^{th} multi-phase inverter **400**n, an N^{th}, first-phase machine winding **604**n, an N^{th}, second-phase machine winding **606**n, and an N^{th}, third-phase machine winding **608**n. N^{th} capacitor **602**n is connected across a DC side of N^{th} multi-phase inverter **400**n between an N^{th} positive line **403**n and an N^{th} negative line **405**n. N^{th}, first-phase machine winding **604**n is supplied I_a through an N^{th}, first-phase line **408**n. N^{th}, second-phase machine winding **606**n is supplied I_b through an N^{th}, second-phase line **410**n. N^{th}, third-phase machine winding **608**n is supplied I_c through an N^{th}, third-phase line **412**n. N^{th}, first-phase machine winding **604**n, N^{th}, second-phase machine winding **606**n, and N^{th}, third-phase machine winding **608**n are tied together at an N^{th} connector **610**n. N^{th}, first-phase machine winding **604**n, N^{th}, second-phase machine winding **606**n, and N^{th}, third-phase machine winding **608**n are windings of electric machine **108**.

A first V_{dc} **402**a is applied across first positive line **403**a and first negative line **405**a. A first input current **612**a is provided through first positive line **403**a to first single converter module **600**a, and a first output current **614**a is provided through first negative line **405**a from first single converter module **600**a. First V_{dc} **402**a represents the voltage from DC input source **102** applied to first single converter module **600**a.

A second V_{dc} **402**b is applied across second positive line **403**b and second negative line **405**b. A second input current **612**b is provided through second positive line **403**b to second single converter module **600**b, and a second output current **614**b is provided through second negative line **405**b from second single converter module **600**b. Second V_{dc} **402**b represents the voltage from DC input source **102** applied to second single converter module **600**b.

A third V_{dc} **402**c is applied across third positive line **403**c and third negative line **405**c. A third input current **612**c is provided through third positive line **403**c to third single converter module **600**c, and a third output current **614**c is provided through third negative line **405**c from third single converter module **600**c. Third V_{dc} **402**c represents the voltage from DC input source **102** applied to third single converter module **600**c.

A N^{th} V_{dc} **402**n is applied across N^{th} positive line **403**n and N^{th} negative line **405**n. A N^{th} input current **612**n is provided through N^{th} positive line **403**n to N^{th} single converter module **600**n, and a N^{th} output current **614**n is provided through N^{th} negative line **405**n from N^{th} single converter module **600**n. N^{th} V_{dc} **402**n represents the voltage from DC input source **102** applied to N^{th} single converter module **600**n.

An overall positive line **703** is connected to provide a total input current **704** to multi-level converter module **700**. Total input current **704** is input on first positive line **403**a. An overall negative line **705** is connected to provide a total output current **706** from multi-level converter module **700**. Total output current **706** is output on N^{th} negative line **405**n. An input voltage $V_{dc\text{-}tot}$ **702** is applied across multi-level converter module **700**. Input voltage $V_{dc\text{-}tot}$ **702** is a sum of first V_{dc} **402**a, second V_{dc} **402**b, third V_{dc} **402**c, . . . , and N^{th} V_{dc} **402**n because first single converter module **600**a, second single converter module **600**b, third single converter module **600**c, . . . , and N^{th} single converter module **600**n are connected in series. As a result, first output current **614**a of first single converter module **600**a is second input current **612**b of second single converter module **600**b; second output current **614**b of second single converter module **600**b is third input current **612**c of third single converter module **600**c; . . . , third output current **614**c of third single converter module **600**c is N^{th} input current **614**n of N^{th} single converter module **600**n. Input voltage $V_{dc\text{-}tot}$ **702** is provided by DC input source **102**.

Multi-level converter module **700** can accommodate a wide range of voltage levels and power ratings. The single converter modules are connected in series to reduce the input voltage, first V_{dc} **402**a, second V_{dc} **402**b, third V_{dc} **402**c, . . . , and N^{th} V_{dc} **402**n across each single converter module **600**a, **600**b, **600**c, . . . , **600**n to $V_{dc\text{-}tot}$/N, where N is a number of the plurality of single converter modules. This reduces the voltage stresses on the single converter modules allowing for the use of low-voltage, less-expensive circuit components. This further reduces the insulation burden between windings allowing electrical machine **108** to be smaller and less expensive. In an illustrative embodiment, $V_{dc\text{-}tot}$ is approximately constant.

Detection of machine faults in electric machine **108** can be determined quickly and accurately by measuring the inverter input or output voltage or current. When one single converter module **600** is in a fault condition, the voltage of this module drops to zero and the voltage of the remaining modules increases from $V_{dc\text{-}tot}/N$ to $V_{dc\text{-}tot}/(N-1)$, where $N-1$ is a number of the remaining modules. In this way, multi-level converter module **700** can operate without shutting down, despite electric machine **108** losing a winding group and possibly producing a reduced torque.

The AC lines from each multi-phase inverter **400**a, **400**b, **400**c, . . . , **400**n power different groups of machine windings of electric machine **108**, and a total output voltage of electric machine **108** is combined inside of electric machine **108**. Electric machine **108** may have a plurality of pole-pairs and a plurality of slots in each phase. Windings in these pole-pairs and slots can be split into several branches in accord with certain rules. Different branches may locate in different poles, or in the same pole, but different slots.

Two fundamental winding configurations suitable for electric machine **108** can be implemented for the windings of electric machine **108**. In alternative embodiments, these two configurations can be combined and formed into a more complicated winding configuration and implemented for the windings of electric machine **108** as understood by a person of skill in the art. Referring to FIGS. **8** and **9**, two winding groups are shown for the sake of simplification. Electric machine **108** includes N winding levels based on the number of the plurality of single converter modules. Machine manufacturers usually connect the machine windings in series, but the machine windings can be disconnected and reconnected into several winding groups. In an illustrative embodiment, individual machine winding groups have the same gauge, number of turns, and configuration as conventional ones.

Referring to FIG. **8**, a first winding configuration **800** is shown. First winding configuration **800** includes first, first-phase machine winding **604**a, first, second-phase machine winding **606**a, first, third-phase machine winding **608**a, second, first-phase machine winding **604**b, second, second-phase machine winding **606**b, and second, third-phase machine winding **608**b with each winding positioned in one of a plurality of slots **802**. First winding configuration **800** forms a three-phase, four-pole, and twelve slot (1 slot per pole per phase) winding configuration where the three-phase windings form different poles are separated and have their own neutral points indicated as first connector **610**a, and second connector **610**b.

Referring to FIG. **9**, a second winding configuration **900** is shown. Second winding configuration **900** includes first, first-phase machine winding **604**a, first, second-phase machine winding **606***a*, first, third-phase machine winding **608***a*, second, first-phase machine winding **604***b*, second, second-phase machine winding **606***b*, and second, third-phase machine winding **608***b* with each winding positioned in one of the plurality of slots **802**. Second winding configuration **900** forms a three-phase, two-pole, and twelve slot (2 slots per pole per phase) winding configuration where the three-phase windings form different poles are separated and have their own neutral points indicated as first connector **610***a* and second connector **610***b*. If electric machine **108** has 2P poles with 0 slots per phase in each pole, the windings can be split into P·O segments. The windings can also be split into any factor of P·O segments, e.g., if P·O=6, the windings can be split into 1, 2, 3, or 6 segments.

Referring to FIG. **10**, a third winding configuration **1000** is shown. Third winding configuration **1000** includes first, first-phase machine winding **604***a*, first, second-phase machine winding **606***a*, first, third-phase machine winding **608***a*, second, first-phase machine winding **604***b*, second, second-phase machine winding **606***b*, second, third-phase machine winding **608***b*, Nth, first-phase machine winding **604***n*, Nth, second-phase machine winding **606***n*, and Nth, third-phase machine winding **608***n*. Each grouping of windings is separated and has its own neutral point.

Referring to FIG. **11**, a block diagram of a second multi-phase inverter **1100** is shown in accordance with an illustrative embodiment. Second multi-phase inverter **1100** is similar to multi-phase inverter **400** except that each phase **1102** of second multi-phase inverter **1100** is formed using a neutral point clamped topology as understood by a person of skill in the art. Multi-level converter module **700** may be formed of a plurality of single converter modules based on second multi-phase inverter **1100**.

Referring to FIG. **12**, a block diagram of a third multi-phase inverter **1200** is shown in accordance with an illustrative embodiment. Third multi-phase inverter **1200** is similar to multi-phase inverter **400** except that each phase **1202** of third multi-phase inverter **1200** is formed using a flying capacitor topology as understood by a person of skill in the art. Multi-level converter module **700** may be formed of a plurality of single converter modules based on third multi-phase inverter **1200**.

Referring to FIG. **13**, a first input source **102***a* is connected to provide a DC current to a first multi-level converter module **700***a* and to a second multi-level converter module **700***b* connected in parallel to first input source **102***a*. First multi-level converter module **700***a* drives a first electric machine (not shown). Second multi-level converter module **700***b* drives a second electric machine (not shown). A first overall positive line **703***a* is connected to provide a total input current to first multi-level converter module **700***a*. A second overall positive line **703***b* is connected to provide a total input current to second multi-level converter module **700***b*. A first overall negative line **705***a* is connected to provide a total output current from first multi-level converter module **700***a*. A second overall negative line **705***b* is connected to provide a total output current from second multi-level converter module **700***b*.

In the illustrative embodiment, first input source **102***a* may include a front-end rectifier separated from and shared by first multi-level converter module **700***a* and from second multi-level converter module **700***b*. The voltage rating, power rating, and the number of front-end rectifiers can be distinct from first multi-level converter module **700***a* and from second multi-level converter module **700***b*.

Referring to FIG. **14**, a second single converter module **1400** is shown in accordance with an illustrative embodiment. Second single converter module **1400** may include capacitor **602**, multi-phase inverter **400**, a first-phase machine winding **1402**, a second-phase machine winding **1404**, and a third-phase machine winding **1406**. First-phase machine winding **1402**, second-phase machine winding **1404**, and third-phase machine winding **1406** are alternative windings of electric machine **108**. Unlike the Y-winding configuration of FIG. **6**, first-phase machine winding **1402**, second-phase machine winding **1404**, and third-phase machine winding **1406** are configured in a Δ-winding configuration as understood by a person of skill in the art. First-phase machine winding **1402** is connected between first-phase line **408** and third-phase line **412**. Second-phase machine winding **1404** is connected between first-phase line **408** and second-phase line **410**. Third-phase machine winding **1406** is connected between second-phase line **410** and third-phase line **412**. Any of the multi-level converter modules may be connected to electric machine **108** using a Δ-winding configuration instead of the Y-winding configuration of FIG. **6**.

A gate signal interleaving technique can be used to reduce a ripple voltage in input voltage $V_{dc\text{-}tot}$ **702**. Compared with a non-interleaving case, an input voltage and current ripple after interleaving has a higher frequency and a smaller amplitude. Thus interleaving supports the use of capacitor **602** having a smaller capacitance value, which stabilizes the DC-bus voltage and smoothes the input current, while maintaining the same amount of voltage/current ripple at the DC input. By shifting the gating signal to each single converter module **600** of multi-level converter module **700** by 360°/N, where N is the total number of modules, the module voltage ripple of each single converter module **600** is out of phase with each other and cancels out. The total voltage ripple amplitude is reduced and the equivalent frequency is at most N times the switching frequency.

The magnetic coupling between different winding groups influences an output current ripple of multi-level converter module **700**. The current ripple of a larger, negative coupling factor is less than the current ripple of a small, negative coupling factor, which is less than the current ripple of a zero coupling factor, which is less than the current ripple of a small, positive coupling factor, which is less than the current ripple of a large positive coupling factor. First winding configuration **800** benefits from the interleaving technique because it has a negative coupling factor. When the coupling factor is positive and not negligible, as may be the case for second winding configuration **900**, interleaving should also consider a leakage inductance or the ripple current may be increased instead of decreased.

Referring to FIG. **15**, a first duty ratio command **1500** in an αβ coordinate reference frame for first single converter module **600***a* and a second duty ratio command **1502** in the αβ coordinate reference frame for second single converter module **600***b* are identical, meaning that the output waveforms have the same fundamental frequency and amplitude. A first triangular carrier waveform **1504** of first single converter module **600***a* and a second triangular carrier waveform **1506** of second single converter module **600***b* are shifted by 180 degrees (360°/N, where N is the total number of modules). After the output voltage waveforms are added up, the second order harmonics and part of the higher order harmonics are canceled.

As discussed previously, multi-level converter **700** includes a plurality of single converter modules that are connected in series and drive machine windings independently. In a normal condition, the windings are balanced and consume the same amount of real power. Any mismatches between electric machine **108** and the modules of multi-level converter **700** may result in machine windings that have different electric properties causing DC input voltage V_{dc} **402** across the plurality of single converter modules to be unequal. To prevent this from happening, a control module may be applied to balance the input voltages. The voltages of series-connected capacitors may be balanced by passive resistors, which are in parallel with the capacitors.

Referring to FIG. **16**, an input small signal model for a three-phase inverter, where $\bar{V}_g$ **1600** is an unbalanced voltage error. The input small signal model includes four parallel circuit components, a first component **1602** equal to $3/2\Delta D_d I_d$, a second component **1604** $3/2\Delta D_q I_q$, a third component **1606** $3/2\Delta I_q D_q$, and a fourth component **1608** $3/2\Delta I_d D_d$, where the subscript 'd' references a direct axis component in a rotating direct-quadrature (d-q) coordinate reference frame, the subscript 'q' references a quadrature axis component in the rotating d-q coordinate reference frame, 'I' references a current, and 'D' references a duty ratio command such as duty ratio command **1500**. As in standard practice, the q-axis is assumed to be the axis containing the voltage vector $\bar{V}_g$, and the current in this direction is the real power component. The d-axis contains the component of the current normal to the voltage vector $\bar{V}_g$, and is the axis of the reactive power component. The small signal of current can be neglected because the current loop has a much slower dynamic response than a voltage balance resistor. As a result, third component **1606** $3/2\Delta I_q D_q$, and fourth component **1608** $3/2\Delta I_d D_d$ can be assumed to be zero.

To realize an active balance resistor, a duty ratio is manipulated to create a balancing current that is equivalent to a current consumed by a virtual resistor **1700** as shown with reference to FIG. **17**. In the control module, virtual resistor **1700** can be programmed to have a resistance value R_a. To achieve the same balancing results as virtual resistor **1700**, the equation

$$\frac{\tilde{V}_g}{R_a} = \frac{3}{2}\Delta D_d I_d + \frac{3}{2}\Delta D_q I_q$$

is satisfied. Referring to FIG. **18**, single converter module **600** is shown with a resistor **1800** that may be a passive (real) resistor or virtual (active) resistor **1700** mounted in parallel across the inputs of multi-phase inverter **400**.

Referring to FIG. **19**, a control module **1900** is shown in accordance with an illustrative embodiment. Control module **1900** implements an actively controlled virtual resistor to balance the module voltage. Merely for illustration, control module **1900** is an example for a two-level converter. Control module **1900** implements active voltage balance control allowing it to perform like resistor **1800** shown in FIG. **18**. Resistor **1800** can be programmed to a desired value. Control module **1900** generates updated values for

$$\Delta D_d = \frac{\tilde{V}_g}{\frac{3}{2}R_a\sqrt{I_d^2 + I_q^2}} I_d$$

and for

$$\Delta D_q = \frac{\tilde{V}_g}{\frac{3}{2}R_a\sqrt{I_d^2 + I_q^2}} I_q,$$

where $\Delta D_d^2 + \Delta D_q^2$ is minimum.

Inputs to control module **1900** include a summed first-phase current I_{ta} **1902**, a summed second-phase current I_{tb} **1904**, and a summed third-phase current I_{tc} **1906**. Summed first-phase current I_{ta} **1902** is a summation of the currents measured in first, first-phase line **408***a*, second, first-phase line **408***b*, third, first-phase line **408***c*, . . . , Nth, first-phase line **408***n*. Summed second-phase current I_{tb} **1904** is a summation of the currents measured in first, second-phase line **410***a*, second, second-phase line **410***b*, third, second-phase line **410***c*, . . . , Nth, second-phase line **410***n*. Summed third-phase current I_{tc} **1906** is a summation of the currents measured in first, third-phase line **412***a*, second, third-phase line **412***b*, third, third-phase line **412***c*, . . . , Nth, third-phase line **412***n*. Summed first-phase current I_{ta} **1902**, summed second-phase current I_{tb} **1904**, and summed third-first phase current I_{tc} **1906** are input to abc-to-d-q transform **1918** that converts the summed phase currents to the rotating d-q coordinate reference frame. Outputs from abc-to-d-q transform **1918** are a d measured current I_{dm} **1917** and a q measured current I_{qm} **1919**. d measured current I_{dm} **1917** and q measured current I_{qm} **1919** are input to a current control **1920**.

Inputs to control module **1900** further include a d reference current I_d **1908** and a q reference current I_q **1910**. d reference current I_d **1908** and q reference current I_q **1910** are input to current control **1920** as command inputs. Current control **1920** calculates $I_{derr}=I_d-I_{dm}$ and inputs the resulting I_{derr} into a first proportional-integral (PI) controller to generate a d-axis signal value that is compensated by a state feedback decoupling value determined based on a speed of electric machine **108** and a cross-coupling between the d-axis and q-axis. The compensated d-axis signal value is a d-axis voltage command, d voltage V_d **1921**, output from current control **1920**. Current control **1920** also calculates $I_{qerr}=I_a-I_{qm}$ and inputs the resulting I_{qerr} into a second PI controller to generate a q-axis signal value that is compensated by the state feedback decoupling value determined based on the speed of electric machine **108** and the cross-coupling between the d-axis and q-axis. The compensated q-axis signal value is a q-axis voltage command, q voltage V_q **1923**, output from current control **1920**.

Inputs to control module **1900** further include a first output voltage V_1 **1912** of first multi-phase inverter **400***a*, a second output voltage V_2 **1914** of second multi-phase inverter **400***b*, and a reference voltage V_r **1916**. First output voltage V_1 **1912** is first V_{dc} **402***a*. Second output voltage V_2 **1914** is second V_{dc} **402***b*. A first difference voltage **1925** is calculated as $\bar{V}_{g1}=V_1-V_r$ and input to first active balancer **1922***a*. A second difference voltage **1927** is calculated as $\bar{V}_{g2}=V_2-V_r$ and input to second active balancer **1922***b*.

Outputs from first active balancer **1922***a* are a first d difference voltage ΔV_{d1} **1929** and a first q difference voltage ΔV_{q1} **1931**. Outputs from second active balancer **1922***b* are a second d difference voltage ΔV_{d2} **1933** and a second q difference voltage ΔV_{q2}**1935**. $\Delta V_{d1}=\Delta D_{d1}*k_1$ and $\Delta V_{q1}=\Delta D_{q1}*k_1$, where k_1 is a constant that may be determined based on first V_{dc} **402***a* and a modulation method as understood by a person of skill in the art. $\Delta V_{d2}\Delta D_{d2}*k_2$ and

$\Delta V_{q2}=\Delta D_{q2}*k_2$, where k_2 is a constant that may be determined based on second V_{dc} **402***b* and the modulation method.

A first desired d voltage **1937** is calculated as $V_{dd}=V_d+\Delta V_{d1}$ and input to a first d-q transform **1924***a*. A first desired q voltage **1939** is calculated as $V_{qd}=V_q+\Delta V_{q1}$ and input to first d-q transform **1924***a*. First d-q transform **1924***a* converts first desired d voltage **1937** and first desired q voltage **1939** from the rotating d-q coordinate reference frame to a stationary d-q coordinate reference frame and inputs these voltages to a first sinusoidal pulse-width modulation (SPWM) modulator **1926***b*. First SPWM modulator **1926***b* translates the voltage duty cycle in the stationary d-q coordinate reference frame to a gating signal input to first multi-phase inverter **400***a*.

A second desired d voltage **1941** is calculated as $V_{dd}=V_d+\Delta V_{d2}$ and input to a second d-q transform **1924***b*. A second desired q voltage **1943** is calculated as $V_{qd}=V_q+\Delta V_{q2}$ and input to second d-q transform **1924***b*. Second d-q transform **1924***b* converts second desired d voltage **1941** and second desired q voltage **1943** from the rotating d-q coordinate reference frame to the stationary d-q coordinate reference frame and inputs these voltages to a second SPWM modulator **1926***b*. Second SPWM modulator **1926***b* translates the voltage duty cycle in the stationary d-q coordinate reference frame to a gating signal input to second multi-phase inverter **400***b*.

Referring to FIG. **20**, a simulated voltage comparison with and without control module **1900** is shown in accordance with an illustrative embodiment. In the simulation, the machine windings of first multi-phase inverter **400***a* have an unbalanced load, which causes the module DC input voltages to be out of balance. Without an active balancer, first multi-phase inverter **400***a* has the same duty ratio as second multi-phase inverter **400***b*. Since the loads are different, the load current of first multi-phase inverter **400***a* is larger than that of second multi-phase inverter **400***b*. The DC input voltage of first multi-phase inverter **400***a* drops until the load current is as the same as the load current in second multi-phase inverter **400***b* as shown by a first curve **2000**. First curve **2000** shows the DC input voltage of first multi-phase inverter **400***a* without control module **1900**. With control module **1900**, equal DC-bus voltages on first multi-phase inverter **400***a* and on second multi-phase inverter **400***b* are maintained as shown by a second curve **2002**. Second curve **200***s* shows the DC input voltage of first multi-phase inverter **400***a* with control module **1900**.

Referring to FIG. **21**, a block diagram of controller **104** is shown in accordance with an illustrative embodiment. Controller **104** may include an input interface **2100**, an output interface **2102**, a computer-readable medium **2104**, a processor **2106**, and a control application **2108**. Fewer, different, and additional components may be incorporated into controller **104**. Controller **104** further may include electrical circuit components connected to processor **2106** and/or computer-readable medium **2104**.

Input interface **2100** provides an interface for receiving information from the user or from other devices for entry into controller **104** as understood by those skilled in the art. Input interface **2100** may interface with various input technologies including, but not limited to, a keyboard, a mouse, a display, a track ball, a keypad, one or more buttons, etc. to allow the user to enter information into controller **104** or to make selections in a user interface displayed on the display. The same interface may support both input interface **2100** and output interface **2102**. For example, a touch screen display supports user input and presents output to the user. Controller **104** may have one or more input interfaces that use the same or a different input interface technology. Additional inputs to controller **104** may be summed first phase current I_{ta} **1902**, summed second phase current I_{tb} **1904**, third first phase current I_{tc} **1906**, d reference current I_d **1908**, q reference current I_q **1910**, first output voltage V_1 **1912** of first multi-phase inverter **400***a*, second output voltage V_2 **1914** of second multi-phase inverter **400***b*, and reference voltage V_r **1916**.

Output interface **2102** provides an interface for outputting information for review by a user of controller **104** and for input to another device. For example, output interface **2102** may interface with various output technologies including, but not limited to, the display and a printer, etc. Controller **104** may have one or more output interfaces that use the same or a different interface technology. Additional outputs from controller **104**, as discussed above, include.

Computer-readable medium **2104** is an electronic holding place or storage for information so the information can be accessed by processor **2106** as understood by those skilled in the art. Computer-readable medium **2104** can include, but is not limited to, any type of random access memory (RAM), any type of read only memory (ROM), any type of flash memory, etc. such as magnetic storage devices (e.g., hard disk, floppy disk, magnetic strips, . . .), optical disks (e.g., compact disc (CD), digital versatile disc (DVD), . . .), smart cards, flash memory devices, cache memory, etc. Controller **104** may have one or more computer-readable media that use the same or a different memory media technology. Controller **104** also may have one or more drives that support the loading of a memory media such as a CD or DVD.

Processor **2106** executes instructions as understood by those skilled in the art. The instructions may be carried out by a special purpose computer, logic circuits, or hardware circuits. Processor **2106** may be implemented in hardware and/or firmware, or any combination of these methods. The term "execution" is the process of running an application or the carrying out of the operation called for by an instruction. The instructions may be written using one or more programming language, scripting language, assembly language, etc. Processor **2106** executes an instruction, meaning it performs/controls the operations called for by that instruction. Processor **2106** operably couples with input interface **2100**, with output interface **2102**, and with computer-readable medium **2104** to receive, to send, and to process information. Processor **2106** may retrieve a set of instructions from a permanent memory device and copy the instructions in an executable form to a temporary memory device that is generally some form of RAM. Controller **104** may include a plurality of processors that use the same or a different processing technology.

Control application **2108** performs operations associated with implementing some or all of the closed loop control system as described with reference to FIG. **19**. The operations may be implemented using hardware, firmware, software, or any combination of these methods. Referring to the example embodiment of FIG. **21**, control application **2108** is implemented in software (comprised of computer-readable and/or computer-executable instructions) stored in computer-readable medium **2104** and accessible by processor **2106** for execution of the instructions that embody the operations of control application **2108**. Control application **2108** may be written using one or more programming languages, assembly languages, scripting languages, etc.

As used in this disclosure, the term "connect" includes join, unite, mount, couple, associate, insert, hang, hold, affix, attach, fasten, bind, paste, secure, bolt, screw, rivet, pin, nail, clasp, clamp, cement, fuse, solder, weld, glue, form over, slide together, layer, and other like terms. The phrases "connected on" and "connected to" include any interior or exterior portion of the element referenced. These phrases also encompass direct connection (in which the referenced elements are in direct contact) and indirect connection (in which the referenced elements are not in direct contact, but are mounted together via intermediate elements). Elements referenced as connected to each other herein may further be integrally formed together. As a result, elements described herein as being connected to each other need not be discrete structural elements. The elements may be connected permanently, removably, or releasably.

The word "illustrative" is used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as "illustrative" is not necessarily to be construed as preferred or advantageous over other aspects or designs. Further, for the purposes of this disclosure and unless otherwise specified, "a" or "an" means "one or more". Still further, using "and" or "or" is intended to include "and/or" unless specifically indicated otherwise.

The foregoing description of illustrative embodiments of the disclosed subject matter has been presented for purposes of illustration and of description. It is not intended to be exhaustive or to limit the disclosed subject matter to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the disclosed subject matter. The embodiments were chosen and described in order to explain the principles of the disclosed subject matter and as practical applications of the disclosed subject matter to enable one skilled in the art to utilize the disclosed subject matter in various embodiments and with various modifications as suited to the particular use contemplated. It is intended that the scope of the disclosed subject matter be defined by the claims appended hereto and their equivalents.

What is claimed is:

1. A converter comprising:

a first multi-phase inverter comprising

  a first plurality of switch-diode circuits for each phase of the first multi-phase inverter:

  a first direct current (DC) positive line;

  a first DC negative line, wherein the first plurality of switch-diode circuits are connected between the first DC positive line and the first DC negative line; and

  a first plurality of alternating current (AC) lines, wherein a first end of each AC line of the first plurality of AC lines is connected between a pair of the first plurality of switch-diode circuits for a respective phase of each AC line of the first plurality of AC lines, wherein each AC line of the first plurality of AC lines is configured to be connected at a second end to a single phase winding of an electric machine;

a second multi-phase inverter comprising

  a second plurality of switch-diode circuits for each phase of the second multi-phase inverter;

  a second DC positive line;

  a second DC negative line, wherein the second plurality of switch-diode circuits are connected between the second DC positive line and the second DC negative line; and

  a second plurality of AC lines, wherein a first end of each AC line of the second plurality of AC lines is connected between a pair of the second plurality of switch-diode circuits for a respective phase of each AC line of the second plurality of AC lines, wherein each AC line of the second plurality of AC lines is configured to be connected at a second end to a second single phase winding of the electric machine;

a first voltage balance control resistor connected in parallel with the first multi-phase inverter between the first DC positive line and the first DC negative line;

a first capacitor connected in parallel with the first multi-phase inverter between the first DC positive line and the first DC negative line;

a second voltage balance control resistor connected in parallel with the second multi-phase inverter between the second DC positive line and the second DC negative line; and

a second capacitor connected in parallel with the second multi-phase inverter between the second DC positive line and the second DC negative line,

wherein the first DC negative line is electrically coupled to the second DC positive line to connect the first multi-phase inverter and the second multi-phase inverter in series,

wherein each phase of the first multi-phase inverter is a first multilevel inverter, and each phase of the second multi-phase inverter is a second multilevel inverter.

2. The converter of claim **1**, wherein a number of the first plurality of AC lines is three, wherein a first AC line of the first plurality of AC lines is configured to be connected to a first phase winding of the electric machine, wherein a second AC line of the first plurality of AC lines is configured to be connected to a second phase winding of the electric machine, and wherein a third AC line of the first plurality of AC lines is configured to be connected to a third phase winding of the electric machine.

3. The converter of claim **1**, wherein a phase of a current input to the second multi-phase inverter is shifted relative to a current input to the first multi-phase inverter.

4. The converter of claim **3**, wherein the phase is determined based on a number of multi-phase inverters forming the converter.

5. The converter of claim **1**, wherein the first multilevel inverter of each phase is a neutral point clamped inverter, and the second multilevel inverter of each phase is a second neutral point clamped inverter.

6. The converter of claim **1**, wherein the first multilevel inverter of each phase is a flying capacitor inverter, and the second multilevel inverter of each phase is a second flying capacitor inverter.

7. The converter of claim **1**, wherein the first DC positive line and the second DC negative line are configured for connection to a single input voltage source.

8. The converter of claim **1**, further comprising:

a third multi-phase inverter comprising

  a third plurality of switch-diode circuits for each phase of the third multi-phase inverter;

  a third DC positive line;

  a third DC negative line, wherein the third plurality of switch-diode circuits are connected between the third DC positive line and the third DC negative line; and

  a third plurality of AC lines, wherein a first end of each AC line of the third plurality of AC lines is connected between a pair of the third plurality of switch-diode circuits for a respective phase of each AC line of the third plurality of AC lines, wherein each AC line of the third plurality of AC lines is configured to be connected at a second end to a third single phase winding of the electric machine; and a third capacitor connected in parallel with the third multi-phase inverter between the third DC positive line and the third DC negative line,

wherein the second DC negative line is electrically coupled to the third DC positive line to connect the second multi-phase inverter and the third multi-phase inverter in series.

9. The converter of claim **8**, wherein the first DC positive line and the third DC negative line are configured for connection to a single input voltage source.

10. A converter comprising:

a first multi-phase inverter comprising

a first plurality of switch-diode circuits for each phase of the first multi-phase inverter:

a first direct current (DC) positive line;

a first DC negative line, wherein the first plurality of switch-diode circuits are connected between the first DC positive line and the first DC negative line; and

a first plurality of alternating current (AC) lines, wherein a first end of each AC line of the first plurality of AC lines is connected between a pair of the first plurality of switch-diode circuits for a respective phase of each AC line of the first plurality of AC lines, wherein each AC line of the first plurality of AC lines is configured to be connected between a different pair of single phase windings of an electric machine;

a second multi-phase inverter comprising

a second plurality of switch-diode circuits for each phase of the second multi-phase inverter;

a second DC positive line;

a second DC negative line, wherein the second plurality of switch-diode circuits are connected between the second DC positive line and the second DC negative line; and

a second plurality of AC lines, wherein a first end of each AC line of the second plurality of AC lines is connected between a pair of the second plurality of switch-diode circuits for a respective phase of each AC line of the second plurality of AC lines, wherein each AC line of the second plurality of AC lines is configured to be connected between a different pair of second single phase windings of the electric machine:

a first capacitor connected in parallel with the first multi-phase inverter between the first DC positive line and the first DC negative line; and

a second capacitor connected in parallel with the second multi-phase inverter between the second DC positive line and the second DC negative line,

wherein the first DC negative line is electrically coupled to the second DC positive line to connect the first multi-phase inverter and the second multi-phase inverter in series,

wherein each phase of the first multi-phase inverter is a first multilevel inverter, and each phase of the second multi-phase inverter is a second multilevel inverter.

11. The converter of claim **10**, wherein a number of the first plurality of AC lines is three, wherein a first AC line of the first plurality of AC lines is configured to be connected between a first phase winding of the electric machine and a second phase winding of the electric machine, wherein a second AC line of the first plurality of AC lines is configured to be connected between the first phase winding of the electric machine and a third phase winding of the electric machine, and wherein a third AC line of the first plurality of AC lines is configured to be connected between the third phase winding of the electric machine and the second phase winding of the electric machine.

12. The converter of claim **10**, wherein a phase of a current input to the second multi-phase inverter is shifted relative to a current input to the first multi-phase inverter.

13. The converter of claim **10**, wherein the first multilevel inverter of each phase is a neutral point clamped inverter, and the second multilevel inverter of each phase is a second neutral point clamped inverter.

14. The converter of claim **10**, wherein the first multilevel inverter of each phase is a flying capacitor inverter, and the second multilevel inverter of each phase is a second flying capacitor inverter.

15. The converter of claim **10**, wherein the first DC positive line and the second DC negative line are configured for connection to a single input voltage source.

16. An electric machine system comprising:

an electric machine comprising

a stator;

a rotor configured to rotate; and

at least four windings, wherein a first winding is connected between a first-phase line and a first neutral connector, a second winding is connected between a second-phase line and the first neutral connector, a third winding is connected between a second first-phase line and a second neutral connector, a fourth winding is connected between a second second-phase line and the second neutral connector,

wherein the first neutral connector is different from the second neutral connector;

a first multi-phase inverter comprising

a first plurality of switch-diode circuits for each phase of the first multi-phase inverter;

a first direct current (DC) positive line;

a first DC negative line, wherein the first plurality of switch-diode circuits are connected between the first DC positive line and the first DC negative line; and

at least the first-phase line and the second-phase line, wherein a first end of the first-phase line is connected between a first pair of the first plurality of switch-diode circuits for a respective phase of the first-phase line, and a first end of the second-phase line is connected between a second pair of the first plurality of switch-diode circuits for a respective phase of the second-phase line;

a second multi-phase inverter comprising

a second plurality of switch-diode circuits for each phase of the second multi-phase inverter;

a second DC positive line;

a second DC negative line, wherein the second plurality of switch-diode circuits are connected between the second DC positive line and the second DC negative line; and

at least the second first-phase line and the second second-phase line, wherein a first end of the second first-phase line is connected between a first pair of the second plurality of switch-diode circuits for a respective phase of the second first-phase line, and a first end of the second second-phase line is connected between a first pair of the second plurality of switch-diode circuits for a respective phase of the second second-phase line;

a first capacitor connected in parallel with the first multi-phase inverter between the first DC positive line and the first DC negative line; and a second capacitor connected in parallel with the second multi-phase inverter between the second DC positive line and the second DC negative line,

wherein the first DC negative line is electrically coupled to the second DC positive line such that the first multi-phase inverter and the second multi-phase inverter are connected in series,

wherein each phase of the first multi-phase inverter is a first multilevel inverter, and each phase of the second multi-phase inverter is a second multilevel inverter.

17. The electric machine system of claim **16**, wherein the first DC positive line and the second DC negative line are configured for connection to a single input voltage source.

18. The electric machine system of claim **16**, further comprising:

a fifth winding is connected between a third first-phase line and a third neutral connector, a sixth winding is connected between a third second-phase line and the third neutral connector, wherein the third neutral connector is different from the first neutral connector and from the second neutral connector;

a third multi-phase inverter comprising

a third plurality of switch-diode circuits for each phase of the third multi-phase inverter;

a third DC positive line;

a third DC negative line, wherein the third plurality of switch-diode circuits are connected between the third DC positive line and the third DC negative line; and

a third plurality of AC, wherein a first end of the third first-phase line is connected between a first pair of the third plurality of switch-diode circuits for a respective phase of the third first-phase line, and a first end of the third second-phase line is connected between a first pair of the third plurality of switch-diode circuits for a respective phase of the third second-phase line; and

a third capacitor connected in parallel with the third multi-phase inverter between the third DC positive line and the third DC negative line;

wherein the second DC negative line is electrically coupled to the third DC positive line to connect the second multi-phase inverter and the third multi-phase inverter in series,

wherein the first DC positive line and the third DC negative line are configured for connection to a single input voltage source.

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