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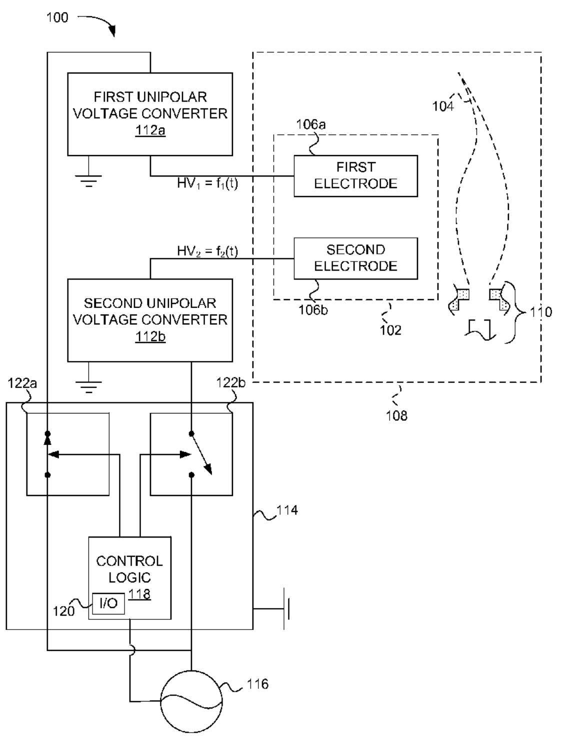
(54) Title: ELECTRICAL COMBUSTION CONTROL SYSTEM INCLUDING A COMPLEMENTARY ELECTRODE PAIR

FIG. 1



(57) Abstract: Two or more unipolar voltage generation systems may apply respective voltages to separate but complementary electrodes. The complementary electrodes may be disposed substantially congruently or analogously to one another to provide bipolar electrical effects on a combustion reaction.

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ELECTRICAL COMBUSTION CONTROL SYSTEM INCLUDING A COMPLEMENTARY ELECTRODE PAIR

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims priority benefit from U.S. Provisional Patent Application No. 61/745,540, entitled “ELECTRICAL COMBUSTION CONTROL SYSTEM INCLUDING A COMPLEMENTARY ELECTRODE PAIR”, filed December 21, 2012; which, to the extent not inconsistent with the disclosure herein, is incorporated by reference.

BACKGROUND

It has been found that the application of a high voltage to a combustion reaction can enhance the combustion reaction and/or drive the reaction, control or enhance heat derived therefrom, and/or cause flue gas derived therefrom to achieve a desirable parameter. In some embodiments, it may be desirable to drive an electrode assembly to a time-varying bipolar high voltage.

Efficiently driving a single electrode to an arbitrary high voltage bipolar waveform may present challenges to system cost, size, reliability, power consumption, etc. What is needed is an approach that can apply variable voltage or bipolar voltage to a combustion reaction-coupled electrode assembly while minimizing negatives.

SUMMARY

According to an embodiment, a system configured to apply time-varying electrical energy to a combustion reaction includes two electrodes including a first electrode and a second electrode operatively coupled to a combustion reaction in a combustion volume including or at least partly defined by a burner. A first unipolar voltage converter is operatively coupled to the first electrode and configured to output a first voltage for the first electrode. A second unipolar voltage converter is operatively coupled to the second electrode and configured to output a second voltage to the second electrode. A controller can be operatively coupled to the first and second unipolar voltage converters and configured to control when the first voltage is output by the first unipolar voltage converter for delivery to the first electrode and when the second voltage is output by the second unipolar voltage converter for delivery to the second electrode.

According to an embodiment, an electrode assembly for applying electrical energy to a combustion reaction includes a complementary electrode pair configured to apply a time-varying electrical waveform to a combustion reaction. The complementary electrode pair includes a first electrode configured to receive a first polarity voltage during a first time and a second electrode, electrically isolated from the first electrode, and configured to receive a second polarity voltage during a second time. The first and second electrodes are configured to cooperate to apply respective first and second polarities of electrical energy to the combustion reaction during respective first and second times.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram of a system configured to apply time-varying electrical energy to a combustion reaction, according to an embodiment.

FIG. 2 is a diagram of a system configured to apply a time-varying bipolar electric field to a combustion reaction, according to an embodiment.

FIG. 3 is a diagram of a system configured to apply a time-varying bipolar charge to a combustion reaction, according to an embodiment.

DETAILED DESCRIPTION

In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. Other embodiments may be used and/or other changes may be made without departing from the spirit or scope of the disclosure.

FIG. 1 is a diagram of a system 100 configured to apply time-varying electrical energy to a combustion reaction 104, according to an embodiment. The system 100 includes a complementary electrode pair 102. The complementary electrode pair includes a first electrode 106a and a second electrode 106b operatively coupled to a combustion reaction 104 in a combustion volume 108 including or at least partly defined by a burner 110.

The system 100 includes a first unipolar voltage converter 112a operatively coupled to the first electrode 106a and configured to output a first voltage for the first electrode 106a. A second unipolar voltage converter 112b is operatively coupled to the second electrode 106b and is configured to output a second voltage to the second electrode 106b.

An AC power source 116 can be operatively coupled to the first and second unipolar voltage converters 112a, 112b. A positive unipolar voltage converter 112a increases the voltage output by the AC power source 112 during positive portions of the AC waveform. A negative unipolar voltage converter 112b increases negative voltage output by the AC power source 112 during negative portions of the AC waveform. The first and second unipolar voltage converters 112a, 112b can each include a voltage multiplier, for example.

Optionally, a controller 114 is operatively coupled to the first and second unipolar voltage converters 112a, 112b and configured to control when the first voltage is output by the first unipolar voltage converter 112a for delivery to the first electrode 106a and when the second voltage is output by the second unipolar voltage converter 112b for delivery to the second electrode 106b. For embodiments including the controller 114, a DC power source can be substituted for an AC power source 116. Moreover, the controller 114 can increase a switching frequency applied to the first and second unipolar voltage converters 112a, 112b to a rate higher than the periodicity of an AC power source 116. The AC power source 116 (or optional DC power source) can optionally supply electrical power to operate the controller 114. Additionally or alternatively, the AC power source 116 can be operatively coupled to control logic 118 of the controller 114, for example to provide voltage signals for synchronization of the AC power source 116 with operation of the first and second unipolar voltage converters 112a, 112b.

The system 100 includes a burner 110. According to embodiments, at least the combustion volume 108 and the burner 110 comprise portions of a furnace, boiler, or process heater.

The first and second electrodes 106a, 106b of the complementary electrode pair 102 can be configured to apply electrical energy to the combustion reaction 104 from substantially congruent and/or analogous locations. Additionally and/or alternatively, the first and second electrodes 106a, 106b can be configured to respectively apply substantially antiparallel electric fields to the combustion reaction 104. Additionally and/or alternatively, the first and second electrodes 106a, 106b can be configured to at least intermittently cooperate to form an arc discharge selected to ignite the combustion reaction 104.

According to an embodiment, the first voltage output by the first unipolar voltage converter 112a is a positive voltage. The first voltage can be a positive polarity voltage having a value of greater than 1000 volts. For example, the first voltage can be a positive polarity voltage having a value of greater than 10,000 volts.

According to an embodiment, the first unipolar voltage converter 112a can include a voltage multiplier or a charge pump configured to output a positive voltage. The second unipolar voltage converter 112b can include a voltage multiplier or a charge pump configured to output a negative voltage.

The second voltage can be a negative voltage having a value of greater than -1000 volts negative magnitude. For example, the second voltage can be a negative voltage having a value of greater than -10,000 volts magnitude.

The system 100 can include at least one voltage source 116 that is selectively operatively coupled to the first and second unipolar voltage converters 112a, 112b. The at least one voltage source 116 can include an alternating polarity (AC) voltage source. Additionally and/or alternatively, the at least one voltage source 116 can include at least one constant polarity (DC) voltage source.

According to an embodiment, the controller 114 can be configured to control pump switching of a first polarity voltage from either an AC voltage source or at least one constant polarity (DC) voltage source to the first unipolar voltage converter 112a, and can control pump switching of a second polarity voltage from either an AC voltage source or at least one constant polarity (DC) voltage source to the second unipolar voltage converter 112b. The pump switching can be selected to cause stages of the first and second unipolar voltage sources 112a, 112b to increase the magnitudes of the first and second polarity voltages output by the one or more voltage sources 116 respectively to the first and second voltages output by the first and second unipolar voltage sources 112a, 112b.

The at least one voltage source can be set at different output levels for different embodiments. For example, according to one embodiment, the at least one voltage source 116 can be configured to output less than or equal to 1000 volts magnitude. According to another embodiment, the at least one voltage source 116 can be configured to output less than or equal to 230 volts magnitude. According to another embodiment, the at least one voltage source 116 can be configured to output less than or equal to 120 volts magnitude. According to another embodiment, the at least one voltage source 116 can be configured to output a safety extra-low voltage (SELV). For example, the at least one voltage source 116 can be configured to output less than or equal to 42.4 volts magnitude. According to another embodiment, the at least one voltage source 116 is configured to output less than or equal to 12 volts magnitude. According to another embodiment, the at least one voltage source 116 can be configured to output less than or equal to 5 volts magnitude.

The controller 114 can include a control logic circuit 118 configured to determine when to operatively couple at least one voltage source 116 to the first unipolar voltage converter 112a and when to operatively couple the at least one voltage source 116 to the second unipolar voltage converter 112b. According to an embodiment, the control logic circuit 118 can include or consist essentially of a timer. According to an embodiment, the control logic circuit 118 can include a microcontroller.

The control logic circuit 118 can include a data interface 120 configured to communicate with a human interface and/or an external computer-based control system, for example. A computer control system can be operatively coupled to a data interface portion of the control logic circuit 118. All or a portion of the computer control system can form a portion of the system 100.

According to an embodiment, the controller 114 can include at least one switching element 122a, 122b operatively coupled to the control logic circuit 118. The control logic circuit 118 can be configured to control the at least one switching element 122a, 122b to make electrical continuity between the at least one voltage source 116 and the first unipolar voltage converter 112a and break electrical continuity between the at least one voltage source 116 and the second unipolar voltage converter 112b during a first time segment. The control logic 118 can be configured to subsequently control the at least one switching element 122a, 122b to break electrical continuity between the at least one voltage source 116 and the first unipolar voltage converter 112a and make electrical continuity between the at least one voltage source 116 and the second unipolar voltage converter 112b during a second time segment. By repeating the complementary make-break cycle of powering the first unipolar voltage converter and then the second unipolar voltage converter, the first and second unipolar voltage converters 112a, 112b can cause the complementary electrode pair 102 to apply a bipolar voltage waveform to the combustion reaction 104. The first and second time segments together can form a bipolar electrical oscillation period applied to the first and second electrodes 106a, 106b.

In embodiments where one or more DC voltage sources 116 are selectively coupled to the first and second unipolar voltage converters 112a, 112b, the controller 114 can apply pumping switching to cause the voltage converters 112a, 112b to raise the input voltage provided by the voltage sources to high voltages applied to the first and second electrodes 106a, 106b. Such pump switching can typically occur at a relatively high frequency consistent with R-C time constants of the voltage converters 112a, 112b.

As used herein, *pump switching* refers to pumping a voltage converter 112a, 112b at a single polarity to cause the voltage converter 112a to multiply the input voltage. In contrast, *cycle switching* refers to switching the voltage converters 112a, 112b to change the polarity of voltage output by the electrode pair 102.

The cycle of making and breaking of continuity between the one or more voltage sources 116 and the voltage converters 112a, 112b typically occurs at a relatively low frequency consistent with the voltage converters 112a, 112b raising and holding their respective output voltage magnitudes for a substantial portion of each respective half cycle. For example, the first and second cycle switched time segments can be 5 times or more in duration than the pumping cycles. In another embodiment, the first and second time segments can be 10 times or more in duration than the pumping cycles. In another embodiment, the electrical oscillation period applied to the electrodes 106a, 106b can be about 100 times longer than the pumping period.

The bipolar electrical oscillation (cycle switching) frequency applied to the first and second electrodes can be between 200 and 300 Hertz, for example. Other bipolar electrical oscillation frequencies can be used according to the needs of a given combustion system and/or designer preferences.

According to an embodiment, the at least one switching element 122a, 122b can include a pair of relays and/or a double-throw relay. Additionally and/or alternatively, the at least one switching element 122a, 122b can include an electrically controlled single pole double throw (SPDT) switch.

The at least one switching element 122a, 122b can include one or more semiconductor devices. For example, the at least one switching element 122a, 122b can include an insulated gate bipolar transistor (IGBT), a field-effect transistor (FET), a Darlington transistor and/or at least two sets of transistors in series.

The system 100 includes an electrode assembly 102 for applying electrical energy to a combustion reaction 104, according to an embodiment. The system includes a complementary electrode pair 102 configured to apply a time-varying electrical waveform to a combustion reaction 104. The complementary electrode pair includes a first electrode 106a and a second electrode 106b. The first electrode106a is configured to receive a first polarity voltage during a first time interval. The second electrode 106b is electrically isolated from the first electrode 106a and is configured to receive a second polarity voltage during a second time interval.

The first and second electrodes 106a, 106b are configured to cooperate to apply respective first and second polarities of electrical energy to the combustion reaction 104 during respective first and second times.

Optionally, the first and second electrodes 106a, 106b can be driven to provide a combustion ignition spark by simultaneously driving the first electrode 106a to a high positive voltage and driving the second electrode 106b to a high negative voltage. Optionally, the system 100 includes a sensor (not shown) configured to sense a combustion condition in the combustion volume 108 and operatively coupled to the controller 114. The controller can drive the first and second unipolar voltage converters 112a, 112b to apply opposite polarity high voltages respectively to the first and second electrodes 106a, 106b responsive to a sensed condition corresponding to flame 104 blow-out or responsive to a sensed condition indicative of unstable combustion.

FIG. 2 is a diagram of a system 200 configured to apply a time-varying bipolar electric field to a combustion reaction, according to an embodiment. The system 200 includes first and second electrodes 106a, 106b. The first and second electrodes 106a, 106b can be configured to apply the electrical energy to the combustion reaction 104 from substantially congruent locations.

“Substantially congruent locations” is intended to mean locations resulting in electric fields caused by each electrode 106a, 106b of the complementary electrode pair 102 having a substantially equal and opposite effect on the combustion reaction 102. For example, in the embodiment 200 of **FIG.2**, each electrode 106a, 106b can be considered substantially congruent, because as a pair the electrodes 106a, 106b apply similar but opposite electric fields to the combustion reaction 104. Electrodes 106a, 106b in substantially congruent locations occupy regions of space that are close together, at least relative to the scale of the combustion volume 108 and/or the combustion reaction 104. Because opposite-sign voltages in close proximity can cause electrical arcing, closely-spaced complementary electrodes 106a, 106b can be placed sufficiently far apart to prevent arc discharge therebetween. A set of complementary electrodes 106a, 106b can be considered substantially congruent when they are placed close enough together to cause similar effect on the combustion reaction 104 (albeit with opposite polarity voltages) and far enough apart to substantially prevent electrical arc discharge between the electrodes 106a, 106b. Additionally or alternatively, the first and second electrodes 106a, 106b can include features that are placed sufficiently close together to support a spark discharge when the controller 122 causes the first and second unipolar voltage converters 112a, 112b to simultaneously apply opposite polarity voltages to the first and second electrodes 106a, 106b.

The first and second electrodes 106a, 106b can be configured as field electrodes capable of applying antiparallel electric fields to the combustion reaction 104. The first and second electrodes 106a, 106b can be toric, as shown in **FIG. 2**.

FIG. 3 is a diagram of a system 300 configured to apply a time-varying bipolar charge to a combustion reaction, according to an embodiment.

According to an embodiment, the first and second electrodes 106a, 106b can be configured to respectively eject oppositely charged ions for transmission to the combustion reaction 104. The system 300 illustrates first and second electrodes 106a, 106b configured to apply the electrical energy to the combustion reaction from analogous locations.

Analogous locations refers to locations from which each electrode 106a, 106b can produce the same effect on the combustion reaction, albeit with opposite polarity. For example, in the embodiment 300 of **FIG. 3**, two ion ejecting electrodes 106a, 106b are disposed near a combustion reaction 104, configured to respectively apply positive and negative ions to the combustion reaction. If the polarities of the voltages applied to the electrodes 106a and 106b were reversed, each would still function substantially identically, albeit with opposite polarities. For example, in the embodiment 300, an axis 302 can be defined by the burner 110 and the combustion reaction 104 (at least near the electrodes 106a, 106b). The analogous locations of the first and second electrodes 106a, 106b can be axisymmetric locations.

According to an embodiment, the first and second electrodes 106a, 106b can be ion-ejecting electrodes. For example, the first and second electrodes 106a, 106b can be configured to apply a respective opposite polarity majority charge to the combustion reaction 104.

Referring to **FIGS. 2 and 3,** an electrode support apparatus 204, 204a, 204b can be configured to support the electrodes 106a, 106b forming the complementary electrode pair 102. The electrode support apparatus 204, 204a, 204b can be configured to support at least the first and second electrodes 106a, 106b within a combustion volume 108. For example, as indicated in **FIG. 2**, a combustor wall 202 can define at least a portion of the combustion volume 108. The electrode support apparatus 204a, 204b support the electrodes 106a, 106b from the combustion volume wall 202. The electrode support apparatus 204, 204a, 204b can include at least one insulator 206a, 206b configured to insulate voltages placed on the electrodes 106a, 106b from one another. The at least one insulator 206a, 206b can be further configured to insulate voltages placed on the electrodes 106a, 106b from ground.

While various aspects and embodiments have been disclosed herein, other aspects and embodiments are contemplated. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

CLAIMS

What is claimed is:

1. A system configured to apply time-varying electrical energy to a combustion reaction, comprising:

at least two electrodes including a first electrode and a second electrode operatively coupled to a combustion reaction in a combustion volume including or at least partly defined by a burner;

a first unipolar voltage converter operatively coupled to the first electrode and configured to output a first voltage for the first electrode;

a second unipolar voltage converter operatively coupled to the second electrode and configured to output a second voltage to the second electrode; and

a controller operatively coupled to the first and second unipolar voltage converters and configured to control when the first voltage is output by the first unipolar voltage converter for delivery to the first electrode and when the second voltage is output by the second unipolar voltage converter for delivery to the second electrode.

2. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, further comprising the burner.

3. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein at least the combustion volume and the burner comprise portions of a furnace, boiler, or process heater.

4. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein the first and second electrodes are configured to apply the electrical energy to the combustion reaction from substantially congruent or analogous locations.

5. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein the first and second electrodes are configured to respectively apply substantially antiparallel electric fields to the combustion reaction.

6. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein the first and second electrodes are configured to respectively eject oppositely charged ions for transmission to the combustion reaction.

7. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein the first and second electrodes are configured to at least intermittently cooperate to form an arc discharge selected to ignite the combustion reaction.

8. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein the first voltage output by the first unipolar voltage converter is a positive voltage.

9. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein the first voltage is a positive polarity voltage having a value of greater than 1000 volts.

10. The system configured to apply time-varying electrical energy to a combustion reaction of claim 9, wherein the first voltage is a positive polarity voltage having a value of greater than 10,000 volts.

11. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein the first unipolar voltage converter includes a voltage multiplier or a charge pump configured to output a positive voltage.

12. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein the second voltage output by the second unipolar voltage converter is a negative voltage.

13. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein the second unipolar voltage converter includes a voltage multiplier or a charge pump configured to output a negative voltage.

14. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein the second voltage is a negative voltage having a value of greater than -1000 volts negative magnitude.

15. The system configured to apply time-varying electrical energy to a combustion reaction of claim 14, wherein the second voltage is a negative voltage having a value of greater than -10,000 volts negative magnitude.

16. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, further comprising at least one voltage source operatively coupled to the first and second unipolar voltage converters.

17. The system configured to apply time-varying electrical energy to a combustion reaction of claim 16, wherein the at least one voltage source includes an alternating polarity (AC) voltage source.

18. The system configured to apply time-varying electrical energy to a combustion reaction of claim 16, wherein the at least one voltage source includes at least one constant polarity (DC) voltage source;

wherein the controller is configured to control pump switching of a first polarity voltage from the at least one constant polarity (DC) voltage source to the first unipolar voltage converter, and to control pump switching of a second polarity voltage from the at least one constant polarity (DC) voltage source to the second unipolar voltage converter; and

wherein the pump switching is selected to cause stages of the first and second unipolar voltage sources to increase the magnitudes of the first and second polarity voltages output by the one or more voltage sources respectively to the first and second voltages output by the first and second unipolar voltage sources.

19. The system configured to apply time-varying electrical energy to a combustion reaction of claim 16, wherein the at least one voltage source is configured to output less than or equal to 1000 volts magnitude.

20. The system configured to apply time-varying electrical energy to a combustion reaction of claim 19, wherein the at least one voltage source is configured to output less than or equal to 230 volts magnitude.

21. The system configured to apply time-varying electrical energy to a combustion reaction of claim 20, wherein the at least one voltage source is configured to output less than or equal to 120 volts magnitude.

22. The system configured to apply time-varying electrical energy to a combustion reaction of claim 21, wherein the at least one voltage source is configured to output a safety extra-low voltage (SELV).

23. The system configured to apply time-varying electrical energy to a combustion reaction of claim 22, wherein the at least one voltage source is configured to output less than or equal to 42.4 volts magnitude.

24. The system configured to apply time-varying electrical energy to a combustion reaction of claim 23, wherein the at least one voltage source is configured to output less than or equal to 12 volts magnitude.

25. The system configured to apply time-varying electrical energy to a combustion reaction of claim 24, wherein the at least one voltage source is configured to output less than or equal to 5 volts magnitude.

26. The system configured to apply time-varying electrical energy to a combustion reaction of claim 1, wherein the controller includes a control logic circuit configured to determine when to operatively couple at least one voltage source to the first unipolar voltage converter and when to operatively couple the at least one voltage source to the second unipolar voltage converter.

27. The system configured to apply time-varying electrical energy to a combustion reaction of claim 26, wherein the control logic circuit comprises a timer.

28. The system configured to apply time-varying electrical energy to a combustion reaction of claim 26, wherein the control logic circuit comprises a microcontroller.

29. The system configured to apply time-varying electrical energy to a combustion reaction of claim 26, wherein the control logic circuit includes a data interface configured to communicate with a human interface or an external computer-based control system.

30. The system configured to apply time-varying electrical energy to a combustion reaction of claim 26, further comprising:

a computer control system operatively coupled to a data interface portion of the control logic circuit.

31. The system configured to apply time-varying electrical energy to a combustion reaction of claim 26, wherein the controller includes at least one switching element operatively coupled to the control logic circuit;

wherein the control logic is configured to:

control the at least one switching element to make electrical continuity between the at least one voltage source and the first unipolar voltage converter and break electrical continuity between the at least one voltage source and the second unipolar voltage converter during a first time segment, and

control the at least one switching element to break electrical continuity between the at least one voltage source and the first unipolar voltage converter and make electrical continuity between the at least one voltage source and the second unipolar voltage converter during a second time segment.

32. The system configured to apply time-varying electrical energy to a combustion reaction of claim 31, wherein the first and second time segments together form a bipolar electrical oscillation period applied to the first and second electrodes.

33. The system configured to apply time-varying electrical energy to a combustion reaction of claim 32, wherein a bipolar electrical oscillation frequency applied to the first and second electrodes is between 200 and 300 Hertz.

34. The system configured to apply time-varying electrical energy to a combustion reaction of claim 31, wherein the at least one switching element includes a pair of relays or a double-throw relay.

35. The system configured to apply time-varying electrical energy to a combustion reaction of claim 32, wherein the at least one switching element includes an electrically controlled single pole double throw (SPDT) switch.

36. The system configured to apply time-varying electrical energy to a combustion reaction of claim 32, wherein the at least one switching element includes one or more semiconductor devices.

37. The system configured to apply time-varying electrical energy to a combustion reaction of claim 36, wherein the at least one switching element includes an insulated gate bipolar transistor (IGBT).

38. The system configured to apply time-varying electrical energy to a combustion reaction of claim 36, wherein the at least one switching element includes a field-effect transistor (FET).

39. The system configured to apply time-varying electrical energy to a combustion reaction of claim 36, wherein the at least one switching element includes a Darlington transistor.

40. The system configured to apply time-varying electrical energy to a combustion reaction of claim 36, wherein the at least one switching element includes at least two sets of transistors in series.

41. An electrode assembly for applying electrical energy to a combustion reaction, comprising:

a complementary electrode pair configured to apply a time-varying electrical waveform to a combustion reaction, the complementary electrode pair including a first electrode configured to receive a first polarity voltage during a first time interval and a second electrode, electrically isolated from the first electrode and configured to receive a second polarity voltage during a second time interval;

wherein the first and second electrodes are configured to cooperate to apply respective first and second polarities of electrical energy to the combustion reaction during respective first and second times.

42. The electrode assembly for applying electrical energy to a combustion reaction of claim 41, wherein the first and second electrodes are configured to apply the electrical energy to the combustion reaction from substantially congruent locations.

43. The electrode assembly for applying electrical energy to a combustion reaction of claim 42, wherein the first and second electrodes are configured as field electrodes capable of applying antiparallel electric fields to the combustion reaction.

44. The electrode assembly for applying electrical energy to a combustion reaction of claim 42, wherein the first and second electrodes are toric.

45. The electrode assembly for applying electrical energy to a combustion reaction of claim 41, wherein the first and second electrodes are configured to apply the electrical energy to the combustion reaction from analogous locations.

46. The electrode assembly for applying electrical energy to a combustion reaction of claim 45, wherein the analogous locations of the first and second electrodes are axisymmetric locations.

47. The electrode assembly for applying electrical energy to a combustion reaction of claim 41, wherein the first and second electrodes are ion-ejecting electrodes.

48. The electrode assembly for applying electrical energy to a combustion reaction of claim 41, wherein the first and second electrodes are configured to apply a majority charge to the combustion reaction.

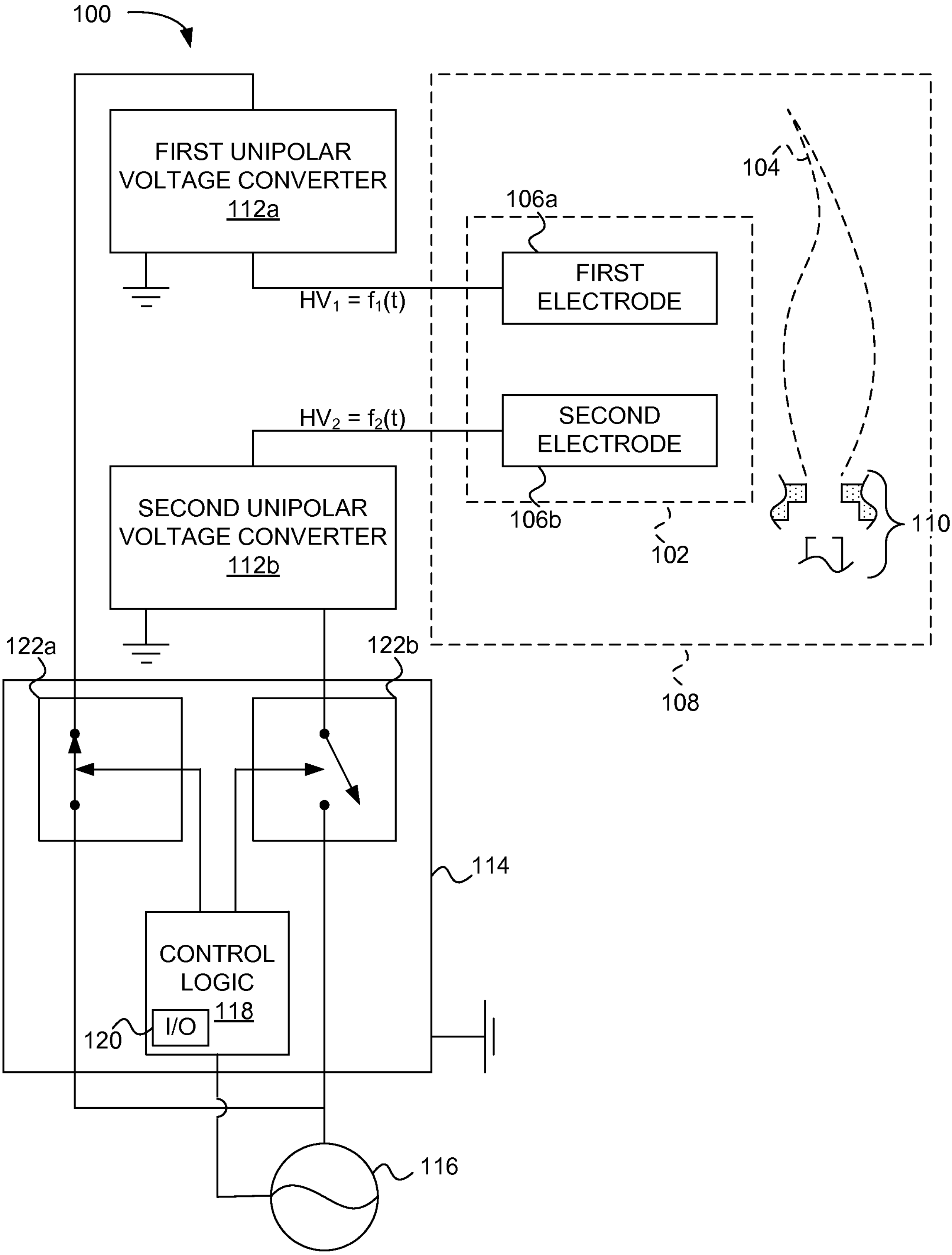
49. The electrode assembly for applying electrical energy to a combustion reaction of claim 41, further comprising:

an electrode support apparatus configured to support at least the first and second electrodes within a combustion volume.

50. The electrode assembly for applying electrical energy to a combustion reaction of claim 49, wherein the electrode support apparatus includes at least one insulator configured to insulate voltages placed on the electrodes from one another.

51. The electrode assembly for applying electrical energy to a combustion reaction of claim 49, wherein the electrode support apparatus includes at least one insulator configured to insulate voltages placed on the electrodes from ground.

FIG. 1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FIRST UNIPOLAR VOLTAGE CONVERTER 112a
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106a
104
$HV_2 = f_2(t)$
SECOND ELECTRODE
106b
102
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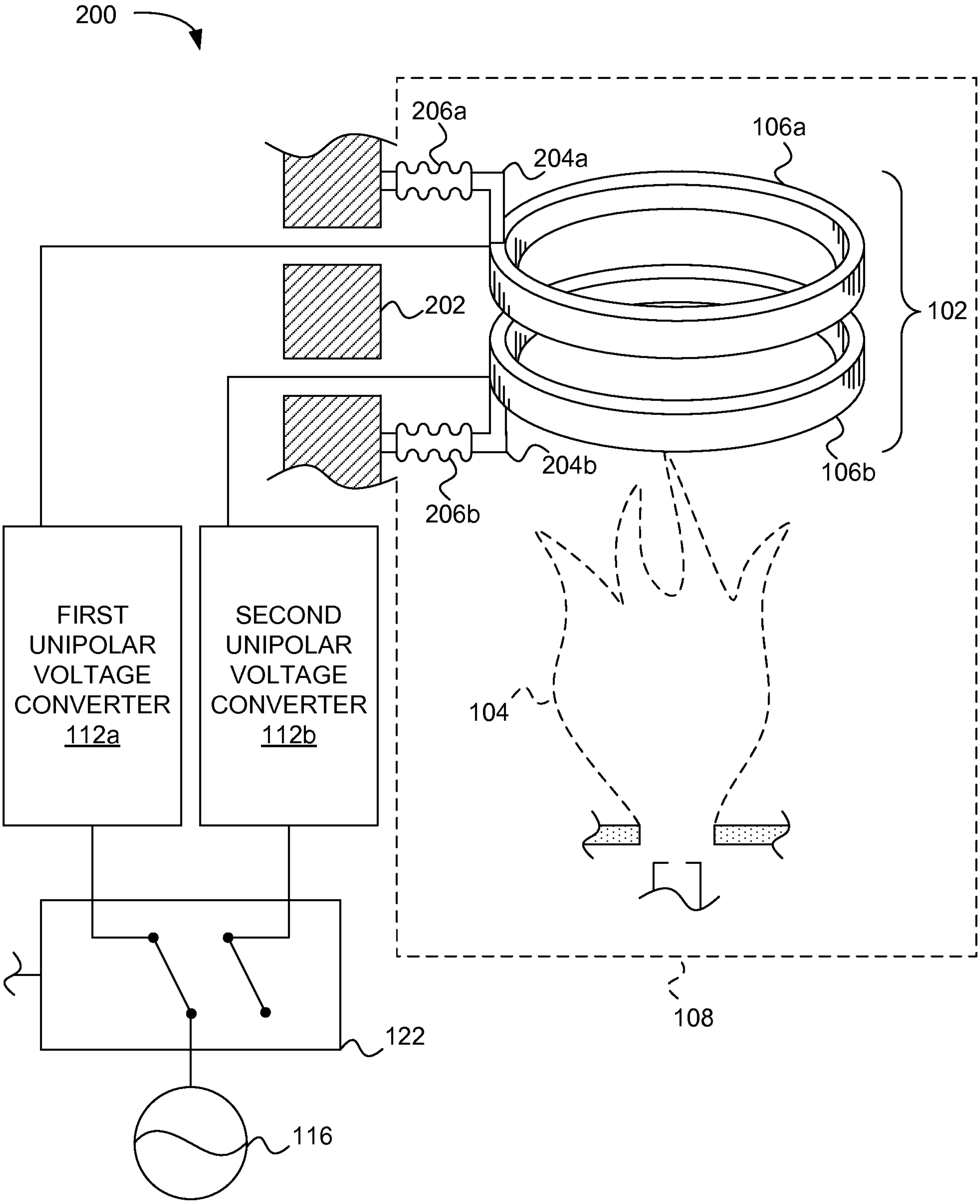
SECOND UNIPOLAR VOLTAGE CONVERTER 112b
122a
122b
108
114
CONTROL LOGIC 118
I/O
120
116

FIG. 2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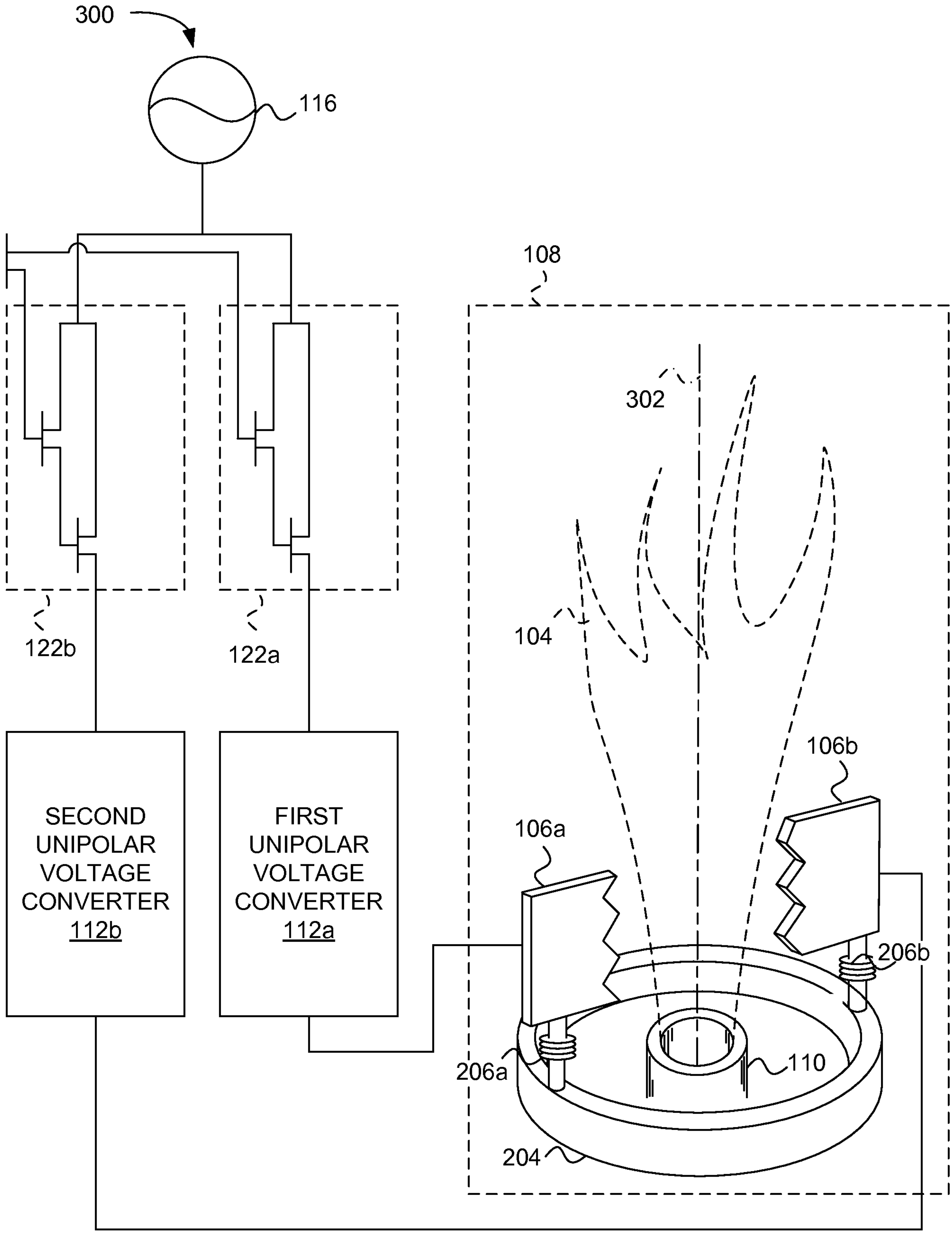
204a
102
202
204b
106b
206b
FIRST UNIPOLAR VOLTAGE CONVERTER 112a
SECOND UNIPOLAR VOLTAGE CONVERTER 112b
104
108
122
116

FIG. 3


300
116
108
302
104
122b
122a
106b
106a
SECOND UNIPOLAR VOLTAGE CONVERTER 112b
FIRST UNIPOLAR VOLTAGE CONVERTER 112a
206b
206a
110
204

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/070423

A. CLASSIFICATION OF SUBJECT MATTER

F23N 5/00(2006.01)i, F23N 5/10(2006.01)i, F23M 11/04(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F23N 5/00; F23L 15/00; F23C 5/00; F23C 11/04; F01K 13/00; F15B 21/00; F23D 14/46; F28F 13/00; F02C 1/00; F23N 5/10; F23M 11/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: combustion, electrode, converter, unipolar, polarity, and controller

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2005-0208442 A1 (HEILIGERS et al.) 22 September 2005 See abstract, paragraphs [0153]-[0169] and figures 3,5,6a,6b,12.	1-51
A	US 2012-0317985 A1 (HARTWICK et al.) 20 December 2012 See abstract, paragraphs [0014]-[0019],[0030],[0031] and figures 1-3.	1-51
A	US 2007-0020567 A1 (BRANSTON et al.) 25 January 2007 See abstract, paragraphs [0026]-[0032] and figures 1-3.	1-51
A	US 2007-0026354 A1 (BRANSTON et al.) 01 February 2007 See abstract, paragraphs [0028]-[0030],[0034] and figures 2-6.	1-51
A	US 2011-0203771 A1 (GOODSON et al.) 25 August 2011 See abstract, paragraphs [0019]-[0027],[0042],[0077]-[0080] and figures 1-8.	1-51

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 February 2014 (26.02.2014)	**26 February 2014 (26.02.2014)**

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2013/070423

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