US 20090045048A1

(19) **United States**

(12) **Patent Application Publication**

Bourcier et al.

(10) **Pub. No.: US 2009/0045048 A1**

(43) **Pub. Date: Feb. 19, 2009**

(54) **CAPACITIVE DEIONIZATION SYSTEM**

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(21) Appl. No.: **11/893,186**

(22) Filed: **Aug. 15, 2007**

Publication Classification

(51) **Int. Cl.**
C25B 9/00 (2006.01)

(52) **U.S. Cl.** **204/228.1**

(57) **ABSTRACT**

A capacitive deionization system comprising: a CDI device; a power supply device electrically connected with the CDI device, capable of providing a programmable voltage and/or a programmable current to the CDI device in response to an input signal; at least one of: (i) an electric current meter for measuring the electric current I flowing through the CDI device; and (ii) a voltage meter for measuring the voltage V supplied to the CDI device; an optional output stream sensor for monitoring the output stream and providing an optional output stream data DE; an optional input stream sensor for monitoring the input stream and providing an optional input stream data DI; a control device capable of sending an output signal to the power supply device to maintain or alter the voltage V and/or current I according to at least one of the results of I-ICREF, I-IDREF, V-VCREF, V-VDREF and optionally DE-DECREF and DE-DEDREF, wherein ICREF and IDREF are preset reference current data in the charge cycle and the discharge cycle, respectively, VCREF and VDREF are preset reference voltage data in the charge cycle and the discharge cycle, respectively, and DECREF and DEDREF are preset reference output stream data in the charge cycle and discharge cycle, respectively.

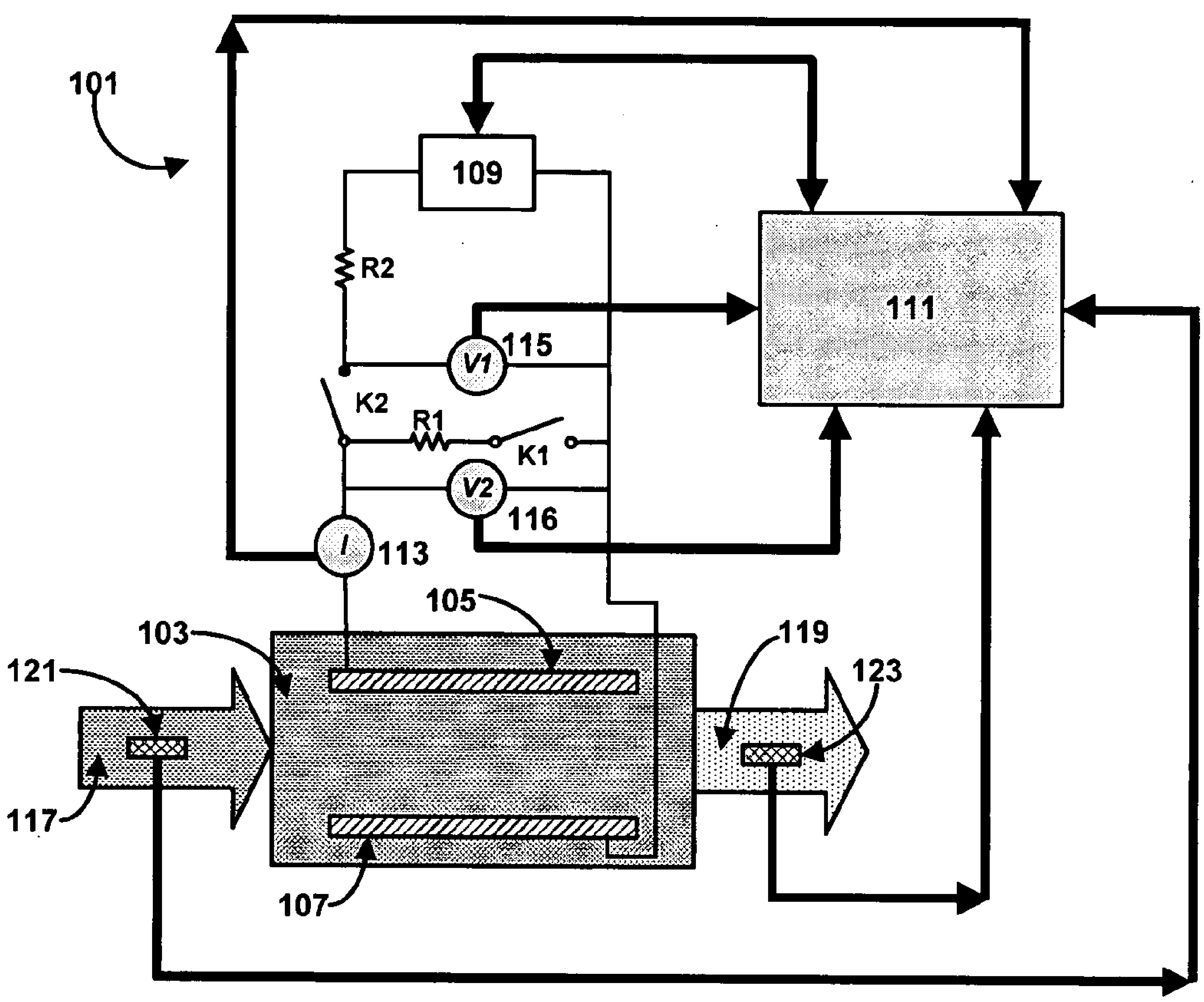


FIG. 1

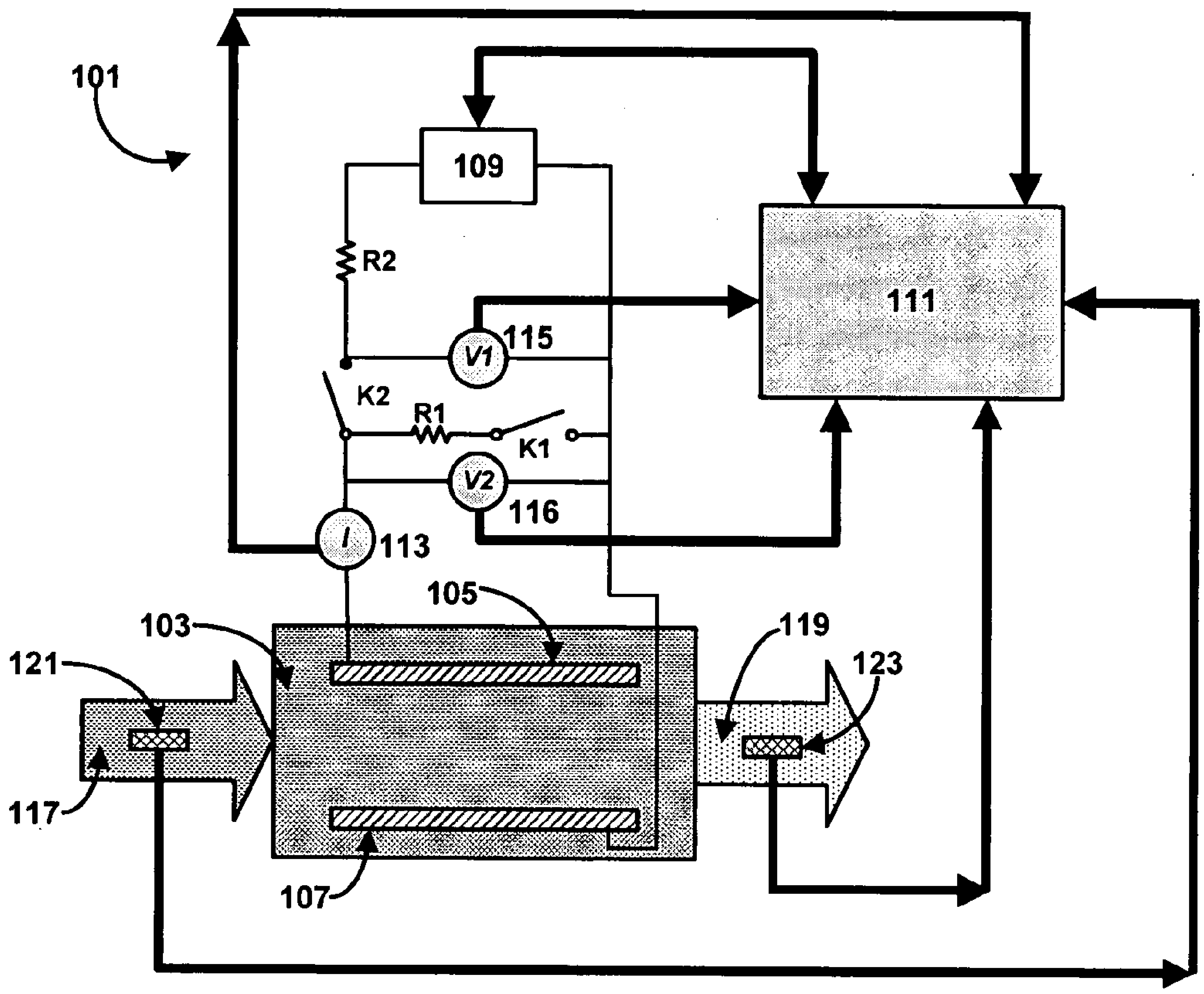

101
109
R2
V1
115
K2
R1
K1
V2
116
113
111
105
103
119
123
121
117
107

FIG. 4

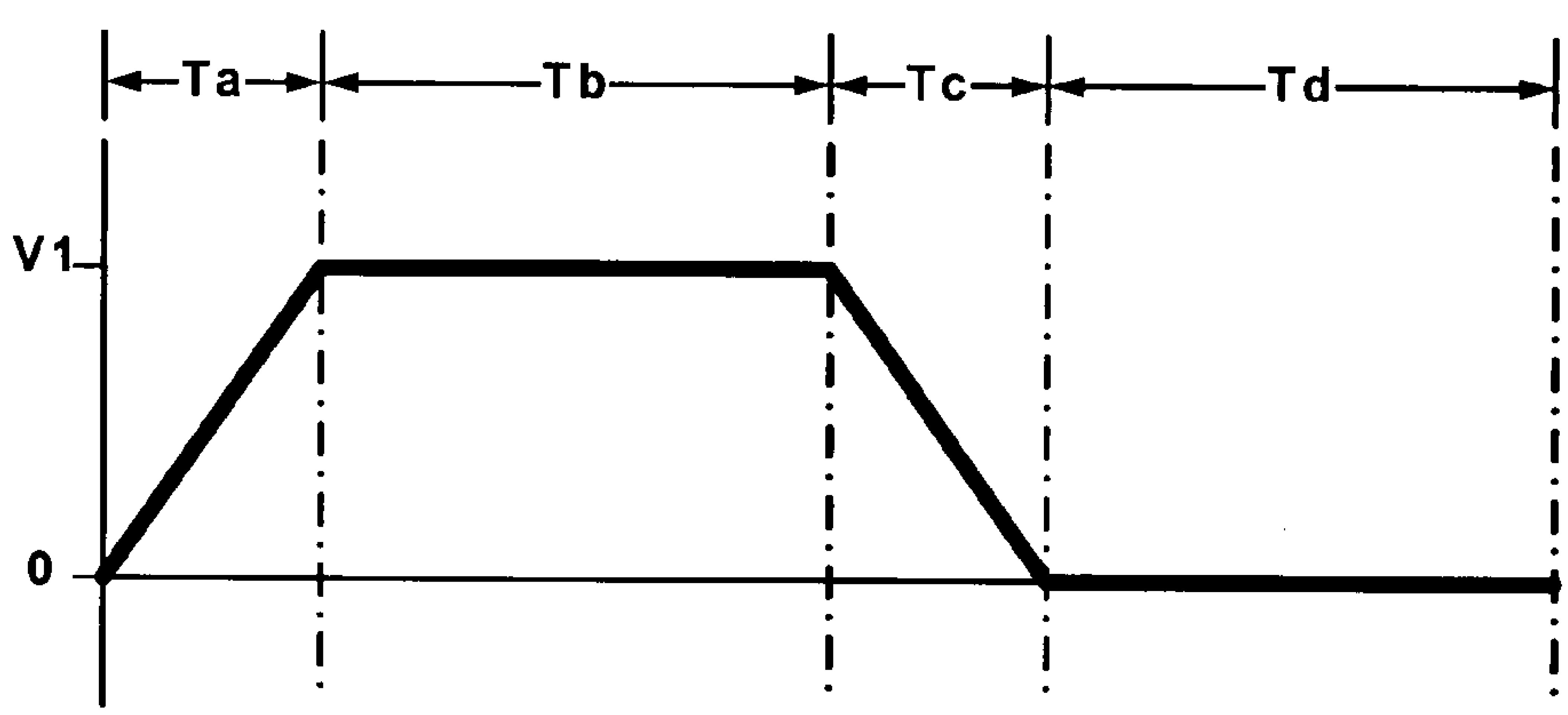

Ta
Tb
Tc
Td
V1
0

FIG. 2

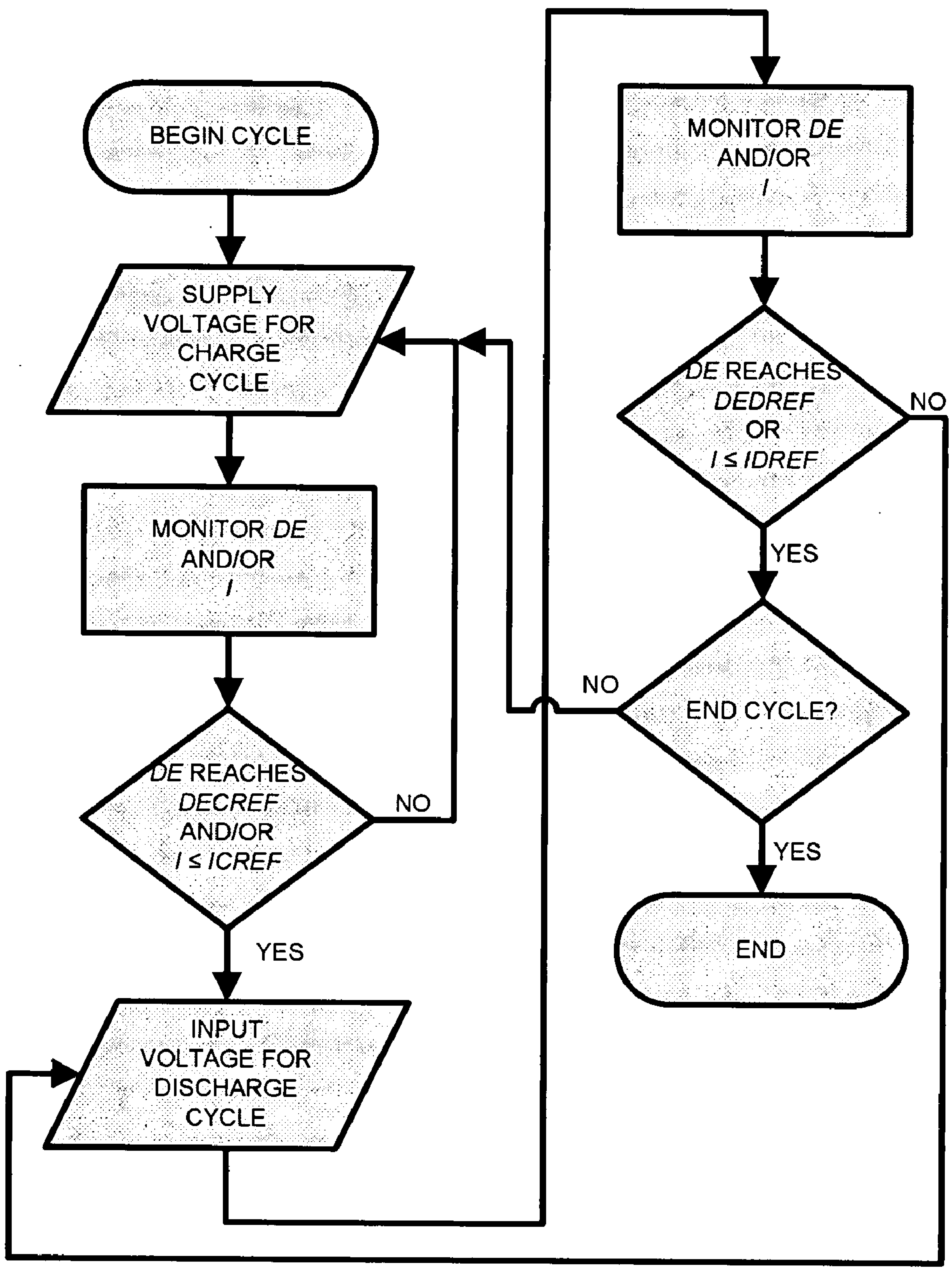

BEGIN CYCLE
SUPPLY VOLTAGE FOR CHARGE CYCLE
MONITOR DE AND/OR I
DE REACHES DECREF AND/OR I ≤ ICREF
NO
YES
INPUT VOLTAGE FOR DISCHARGE CYCLE
MONITOR DE AND/OR I
DE REACHES DEDREF OR I ≤ IDREF
NO
YES
END CYCLE?
NO
YES
END

FIG. 3

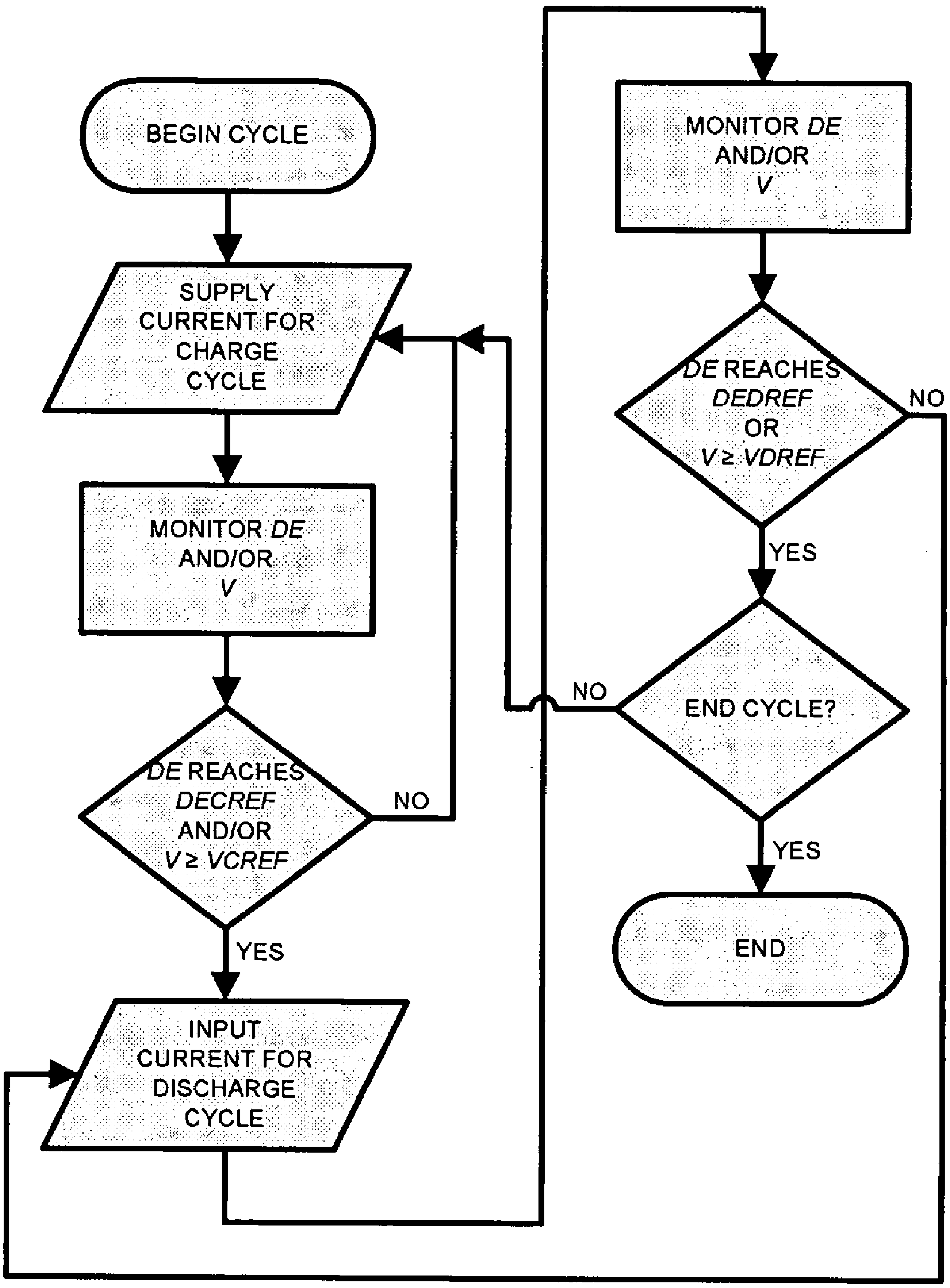

BEGIN CYCLE
SUPPLY CURRENT FOR CHARGE CYCLE
MONITOR DE AND/OR V
DE REACHES DECREF AND/OR V ≥ VCREF
NO
YES
INPUT CURRENT FOR DISCHARGE CYCLE
MONITOR DE AND/OR V
DE REACHES DEDREF OR V ≥ VDREF
NO
YES
END CYCLE?
NO
YES
END

FIG. 5

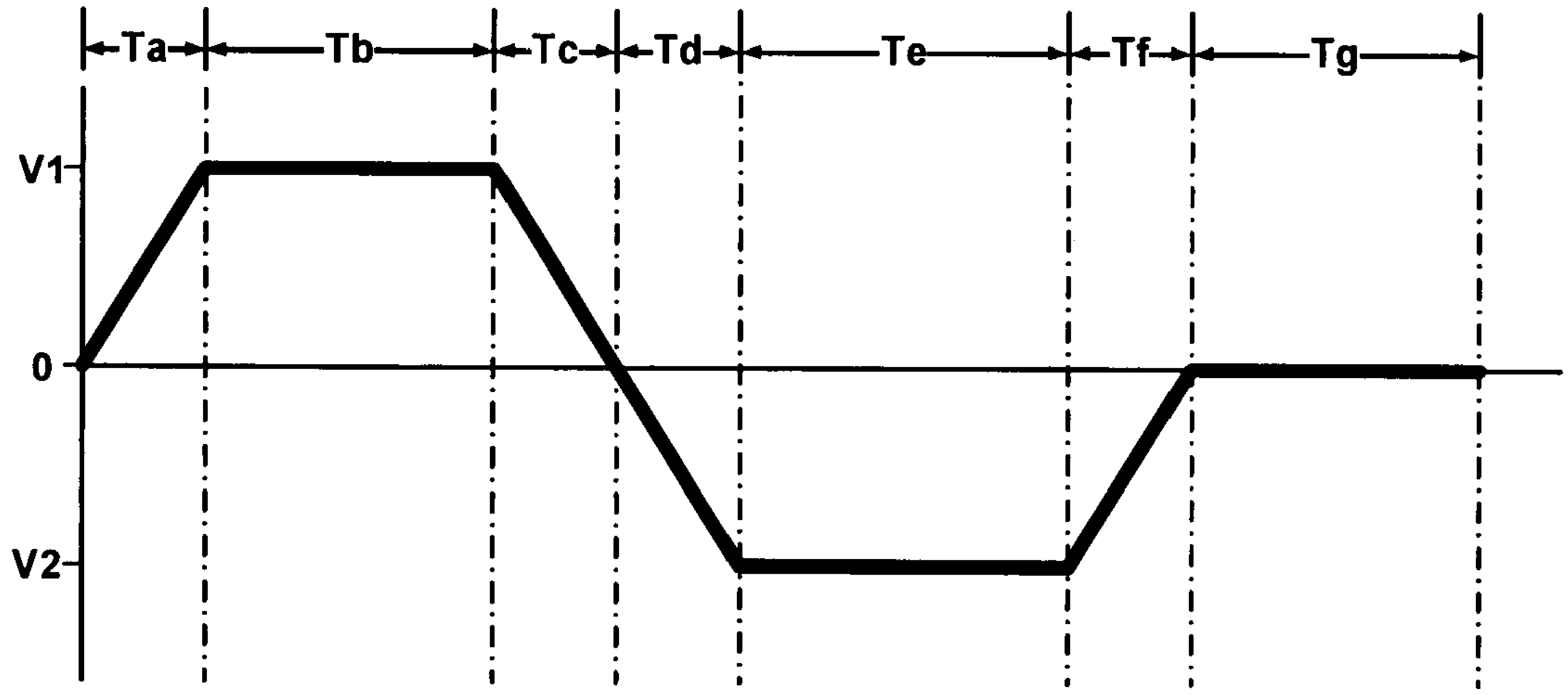


FIG. 6

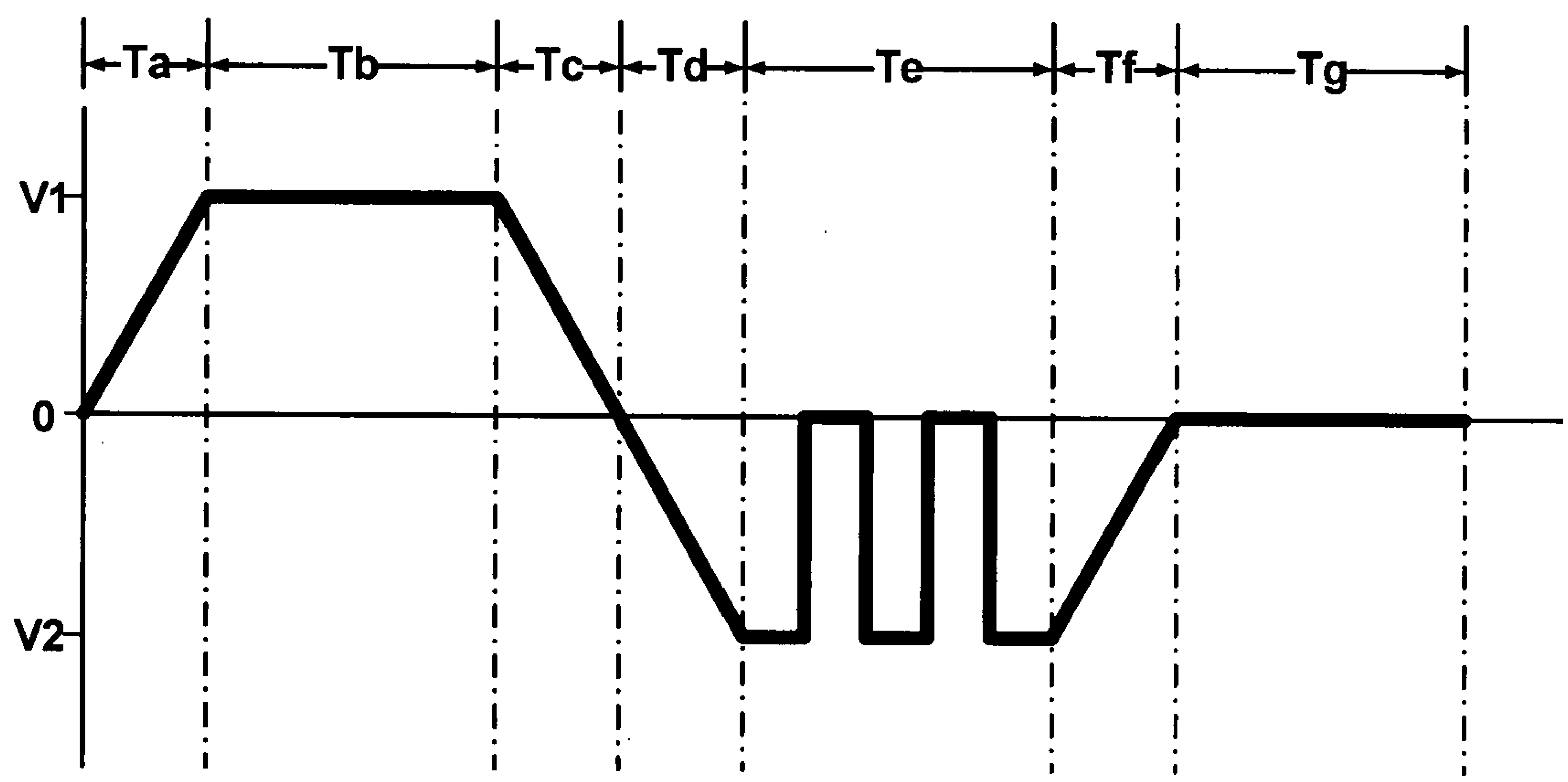
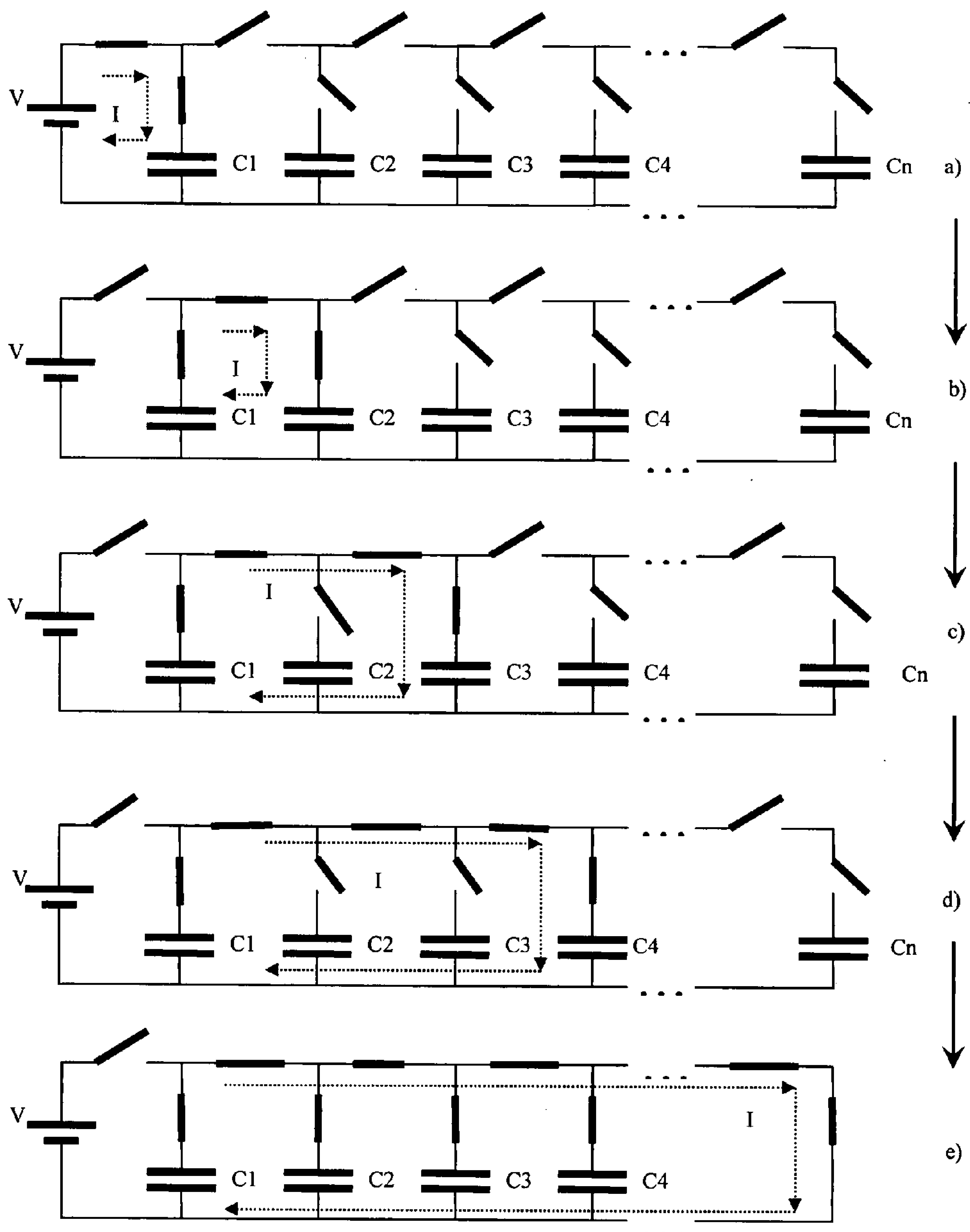


FIG. 7



CAPACITIVE DEIONIZATION SYSTEM

TECHNICAL FIELD

[0001] The present invention relates to capacitive deionization systems. In particular, the present invention relates to capacitive deionization systems with adjustable controls. The present invention is useful, e.g., for removing cations from aqueous solutions with selectable ion removal efficiency and/or energy efficiency.

BACKGROUND

[0002] Capacitive deionization (CDI) utilizes varying electrical field between the electrodes of a capacitor in contact with a liquid to be treated to redistribute the cations and anions in the liquid. If a stream or a bath of ion-containing liquid flows through the electric field, or is placed in the electric field, during the charge cycle, the electric field forces the ions to aggregate at locations close to the surfaces of the electrodes to form electrochemical double-layers, thus reducing the amount of ions present in the fluid distal to the electrodes before the capacitor is fully charged. The stream during the charge cycle exiting the electrical field would have a reduced amount of ions. In the discharge cycle, the electric field between the electrodes is allowed to decrease in intensity and/or reverse in direction, causing the capacitor to discharge and the ions in proximity to the electrodes to move away from the electrode surface, thus enriching the ion concentration in the stream flowing between the electrodes.

[0003] CDI devices have been proposed for removing undesired ions from water streams. For example, it was proposed for purifying municipal water supply, brackish water, and the like. CDI devices have the potential to remove all ions indiscriminately from a water source without using chemical agents. Thus, it is highly desirable in many applications. On the other hand, CDI devices can be used to enrich the concentration of ions in a liquid as well.

[0004] To achieve a commercially viable level of ion removal capability, the capacitor is desired to have a large capacitance. Thus it is typically desired that the CDI device comprises electrodes with a high surface area. Materials proposed for those electrodes include carbon areogel, activated carbon, and the like, which typically comprise large amounts of pores on the micrometer and nanometer scales. One of the factors impacting the overall performance of the CDI device is the ability of the ions to enter and exit the pores during the charge and discharge cycles.

[0005] Using CDI devices to remove ions from water and other liquids consumes electrical energy. When treating a large volume of liquid, such electrical energy consumption can be quite substantial. Achieving a desirable balance between the efficacy of ion removal/redistribution and energy efficiency would be interesting.

[0006] It would be advantageous to have a CDI system with desired ion removal efficacy and efficiency as well as an acceptable level of energy consumption.

SUMMARY

[0007] Accordingly, provided in the present invention is a system for treating an aqueous input stream to produce an output stream comprising redistributed ions, comprising:

[0008] a CDI device for the input stream to enter and the output stream to exit, capable of operating in a charge cycle and a discharge cycle;

[0009] a power supply device electrically connected with the CDI device, capable of providing a programmable voltage and/or a programmable current to the CDI device in response to an input signal;

[0010] at least one of: (i) an electric current meter for measuring the electric current I flowing through the CDI device; and (ii) a voltage meter for measuring the voltage supplied to the CDI device;

[0011] an optional output stream sensor for monitoring the output stream and providing an optional output stream data DE;

[0012] an optional input stream sensor for monitoring the input stream and providing an optional input stream data DI; and

[0013] a control device capable of sending an output signal to the power supply device to maintain or alter the voltage V and/or current I according to at least one of the results of I-ICREF, I-IDREF, V-VCREF, V-VDREF and optionally DE-DECREF and DE-DEDREF, wherein ICREF and IDREF are preset reference current data in the charge cycle and the discharge cycle, respectively, VCREF and VDREF are preset reference voltage data in the charge cycle and the discharge cycle, respectively, and DECREF and DEDREF are preset reference output stream data in the charge cycle and discharge cycle, respectively.

[0014] In certain embodiments of the present invention, the system comprises an output stream sensor comprising an electrical conductivity meter, and the data DE comprise output stream electrical conductivity data DEEC.

[0015] In certain embodiments of the present invention, the system comprises an input stream sensor comprising an electrical conductivity meter, and the input stream data comprise input stream electrical conductivity data DIEC.

[0016] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: the power supply device provides a programmable voltage to the CDI device; and during the charge cycle in which a charge voltage V is supplied to the CDI device wherein $V>0$, if $I\text{-}ICREF \leqq 0$, the control device sends a signal **S1** to the power supply device to change V to enable the discharge cycle such that V decreases to zero, and then maintain $V=0$ until $I\text{-}IDREF \leqq 0$ when the control device sends a signal S**2** to the power supply device to change V to enable the charge cycle.

[0017] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: the power supply device provides a programmable voltage to the CDI device; and during the charge cycle in which $V>0$, once $I\text{-}ICREF \leqq 0$, the control device sends a signal S**3** to the power supply device to change V to enable the discharge cycle such that $V<0$, and then maintain $V<0$ until $I\text{-}IDREF \leqq 0$ when the control device sends a signal S**3** to the power supply device to change V to enable the charge cycle.

[0018] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: the power supply device provides a programmable voltage to the CDI device; and during the charge cycle in which a charge voltage V is supplied to the CDI device wherein $V>0$, if DE reaches DECREF, the control device sends a signal S**1**A to the power supply device to change V to enable the discharge cycle such that V decreases to zero, and then maintain $V=0$ until DE reaches DEDREF when the control devices sends a signal S**2**A to the power supply device to change V to enable the charge cycle.

[0019] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: the power supply device provides a programmable voltage to the CDI device; and during the charge cycle in which V>0, once DE reaches DECREF, the control device sends a signal S3A to the power supply device to change V to enable the discharge cycle such that V<0, and then maintain V<0 until DE reaches DEDREF when the control device sends a signal S3A to the power supply device to change V to enable the charge cycle.

[0020] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: the power supply device provides a programmable current to the CDI device; and during the charge cycle in which a charge current I is supplied to the CDI device wherein V>0, if V-VCREF≧0 the control device sends a signal SV1 to the power supply device to change I to enable the discharge cycle such that V decreases to zero, and then maintain V=0 until I-IDREF≦0 when the control devices sends a signal SV2 to the power supply device to change I to enable the charge cycle.

[0021] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: the power supply device provides a programmable current to the CDI device; and during the charge cycle in which V>0, once V-VCREF≧0, the control device sends a signal SV3 to the power supply device to change I to enable the discharge cycle such that V<0, and then maintain V<0 until V-VDREF≦0 when the control device sends a signal SV3 to the power supply device to change I to enable the charge cycle.

[0022] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: the power supply device provides a programmable current to the CDI device; and during the charge cycle in which a charge current I and a charge voltage V are supplied to the CDI device wherein V>0, if DE reaches DECREF, the control device sends a signal S1A to the power supply device to change I to enable the discharge cycle such that V decreases to zero, and then maintain V=0 until DE reaches DEDREF when the control devices sends a signal SV2A to the power supply device to change I to enable the charge cycle.

[0023] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: the power supply device provides a programmable current to the CDI device; and during the charge cycle in which V>0, once DE reaches DECREF, the control device sends a signal S3A to the power supply device to change I to enable the discharge cycle such that V<0, and then maintain V<0 until DE reaches DEDREF when the control device sends a signal SV3A to the power supply device to change I to enable the charge cycle.

[0024] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: the discharge cycle starts with an initial discharge voltage VD1 supplied to the CDI device, followed by a discharge voltage V<VD1. In certain embodiments, assuming the average voltage supplied to the CDI device during the charge cycle is positive, the discharge cycle starts with an initial discharge voltage VD1<0.

[0025] In certain embodiments of the system of the present invention, the CDI device comprises a membrane M1 over the surface of an electrode to selectively allow essentially only cations to pass through, and a membrane M2 over the surface of the opposite electrode to selectively allow essentially only anions to pass through, during the operation of the CDI devices.

[0026] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: the control device collects and/or stores the data V, I, DE, DI, ICREF, IDREF, VCREF, VDREF, DECREF, DEDREF, and computes and stores the values I-ICREF, I-IDREF, V-VCREF, V-VDREF, DE-DECREF and DE-DECREF.

[0027] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: ICREF is preset to correspond to a charge current of the CDI device having operated for a time ranging from $\frac{1}{4}\cdot\tau$ to $4\cdot\tau$, where τ is the RC time constant of the CDI device.

[0028] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: IDREF is preset to correspond to a discharge current of the CDI device having operated for a time ranging from $\frac{1}{4}\cdot\tau$ to $4\cdot\tau$, where τ is the RC time constant of the CDI device.

[0029] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein the power supply device supplies an essentially constant voltage to the CDI device during the charge cycle of the CDI device.

[0030] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein the power supply device supplies a DC voltage which may range from 0.1 to 5.8 volts to the CDI device during the charge cycle thereof. In certain embodiments of the system of the present invention, the power supply device supplies an DC voltage from 1.2 to 5.8 volts to the CDI device.

[0031] In certain embodiments of the system of the present invention, the system is capable of operating in a mode wherein: the power supply device supplies a DC voltage with varying amplitude to the CDI device during the discharge cycle thereof In certain more specific operation modes, the power supply device supplies a negative DC voltage with varying amplitude to the CDI device during discharge cycle thereof

[0032] In certain embodiments of the system of the present invention, the CDI device comprises multiple CDI units.

[0033] In certain embodiments of the system of the present invention comprising multiple CDI units, the system is capable of operating in a mode wherein: the multiple CDI units are wired such that during the discharge cycle of some of the CDI units, some of the CDI units can work in the charge cycle.

[0034] In certain embodiments of the system of the present invention comprising multiple CDI units, the system is capable of operating in a mode wherein: the multiple CDI units are wired such that the discharge current of the some of the CDI units during the discharge cycle thereof charges some of CDI units sequentially or simultaneously during the charge cycle thereof.

[0035] In certain embodiments of the system of the present invention comprising multiple CDI units, the control device is capable of controlling the electric switches between and among the multiple CDI units.

[0036] In certain embodiments of the system of the present invention, the control device is further capable of controlling the flow rate of the input stream and/or the output stream.

[0037] One or more embodiments of the present invention has one or more of the following advantages. First, variable ion removal/redistribution efficacy, as well as variable level of energy efficiency, can be achieved by adjusting the values of one or more of I, V, ICREF, IDREF, VCREF, VDREF, and DECREF. Second, automatic control of the CDI system to achieve a desired level of ion removal efficacy and energy efficiency can be achieved. Third, the life cycle of the CDI units at a given work load can be optimized by adjusting the operation parameters of the system.

[0038] Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from the description or recognized by practicing the invention as described in the written description and claims hereof, as well as the appended drawings.

[0039] It is to be understood that the foregoing general description and the following detailed description are merely exemplary of the invention, and are intended to provide an overview or framework to understanding the nature and character of the invention as it is claimed.

[0040] The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification.

BRIEF DESCRIPTION OF THE DRAWINGS

[0041] In the accompanying drawings:

[0042] FIG. **1** is a schematic illustration of an embodiment of the system of the present invention.

[0043] FIG. **2** is a flow chart showing the control logic of an operation mode of an embodiment of the system of the present invention.

[0044] FIG. **3** is a flow chart showing the control logic of an opedration mode of another embodiment of the system of the present invention.

[0045] FIGS. **4**, **5** and **6** are diagrams showing the profiles of voltage applicable to the CDI devices according to various operation modes of various embodiments of the system of the present invention.

[0046] FIG. **7** is a diagram showing sequential charging and discharging of a plurality of CDI units according to an operation mode of an embodiment of the system of the present invention comprising a plurality of CDI units.

MODES OF CARRYING OUT THE INVENTION

[0047] Unless otherwise indicated, all numbers such as those expressing electric voltage, electric current, and values for certain physical properties used in the specification and claims are to be understood as being modified in all instances by the term "about." It should also be understood that the precise numerical values used in the specification and claims form additional embodiments of the invention. Efforts have been made to ensure the accuracy of the numerical values disclosed in the Examples. Any measured numerical value, however, can inherently contain certain errors resulting from the standard deviation found in its respective measuring technique.

[0048] As used herein, in describing and claiming the present invention, the use of the indefinite article "a" or "an" means "at least one," and should not be limited to "only one" unless explicitly indicated to the contrary. Thus, for example, reference to "a CDI device" includes embodiments comprising one or more CDI devices, unless the context clearly indicates otherwise.

[0049] A single "CDI unit" in the meaning of the present application comprises only two electrodes that can be electrically connected to a power supply device to be charged and discharged. A "CDI device" in the meaning of the present application can comprise one or multiple CDI units electrically connected serially, in parallel or in combination of both. A single CDI device typically comprises an array of interdigitated electrodes where both electrode faces are utilized.

[0050] A CDI device behaves in a manner similar to a standard capacitor, but not exactly the same. When a CDI device placed in a bath or stream of liquid is applied a charging voltage, the ions present in the liquid move in response to the electric field between the electrodes of the CDI device and aggregate in proximity to the surface area of the electrodes of the CDI device to form an electric double layer. Each electric double layer can be regarded as an equivalent to a conventional capacitor. Thus, a single CDI unit can be regarded as two conventional capacitors connected in series when in operation. The total capacitance of the two electric double layers can be regarded as the equivalent capacitance of the CDI unit.

[0051] To achieve a high ion redistribution capability, it is desired that the CDI unit has a high equivalent capacitance. To that end, the electrodes need to have a large effective surface area to form electric double layer with large areas, which can store large amounts of electric charges. Thus, it has been proposed that highly porous electrically conductive materials, such as activated carbon materials with large specific area, in certain cases as large as 400-2000 $m^2 \cdot g^{-1}$, be used as the electrode materials. For a CDI unit to function as intended, it is important that the ions can enter and exit the pores without substantial obstacles, so that ions can be redistributed in the fluid at large quantities at a reasonable speed.

[0052] U.S. Pat. No. 6,214,204 discloses a CDI device using monolithic activated carbon honeycomb as the electrode material, the content of which is incorporated herein by reference in its entirety. Multiple activated carbon honeycomb disks form an array of connected electrodes through which liquid stream can flow through. The device can comprise multiple CDI units packed together and connected in series, in parallel or in combination of both. Electrical leads in contact with the electrodes are typically called current collectors in a CDI device. Current collectors are typically made of corrosion-resistant electrically conductive materials, such as carbon, titanium, and precious metals, for example.

[0053] The material selected for the CDI electrodes, structure of the electrodes, surface area of the electrodes, the porosity of the electrodes, distances from the electrodes, packaging of the electrodes, and the like, are all factors internal to the CDI device that can impact the overall performance of the CDI devices. In addition to the CDI device itself, the design and operation of a CDI system which includes a CDI device with determined structural and electrical parameters can impact the overall performance and efficiency of an operating CDI device as well. The present invention provides a controllable CDI system with adjustable performance in terms of ion redistribution capability (such as load of liquid and ions, flow rate of the liquid, ion immobilization speed during the charge cycle of the CDI device, ion mobilization speed during the discharge cycle, and the like), energy efficiency, and the like.

[0054] The CDI system according to the present invention will now be described by referring to the embodiment illustrated in FIG. **1**. It should be noted, however, that FIG. **1** represents only a specific embodiment of the system of the present invention. One of ordinary skill in the art, upon reading the present application, will readily understand that other embodiments falling within the scope of the claimed invention but differing from that illustrated in FIG. **1** are possible.

[0055] The embodiment of the CDI system of the present invention (referenced as **101**) in FIG. **1** includes a CDI device **103** comprising two opposite electrodes **105** and **107** electrically connected with a power supply **109** capable of supplying a programmable voltage or current to the CDI device **103**. An electric current meter **113** monitors the current I flowing through the CDI device **103**, a voltage meter **116** monitors the voltage potential between the two electrodes **105** and **107** during the charge and discharge cycle. A voltage meter **115** monitors the voltage supplied by the power supply **109** and applied to the two electrodes **105** and **107** during the charge and discharge cycles. Switches K**1** and K**2** can be turned on or off to connect and disconnect the power supply **109** with the CDI device **103**, starting and/or terminating the charge and/or discharge cycles of the CDI device **103**. The resistors R**1** and R**2** in FIG. **1** represent the internal resistance of the CDI device, resistance introduced by the wirings, and resistance intentionally included in the electric loop in an effort to adjust the charge and discharge rate of the CDI device during certain operations.

[0056] During the operation of the CDI system, an input stream **117** is allowed to enter into the CDI device, where ions will be extracted from the fluid during a charge cycle and released into the fluid during a discharge cycle, resulting in an output stream **119** which exits the CDI device with a reduced ion concentration or enriched ion concentration, during a charge cycle and a discharge cycle, respectively. Shown in this figure are also the optional input stream sensor **121** which monitors the input stream and provides input stream data DI, and the optional output stream sensor **123** which monitors the output stream and provides output stream data DE. The sensors **121** and **123** can be electrical conductivity meters, ion concentration meters, and the like. Electric conductivity data of a fluid can be correlated to the ion concentration of the liquid by methods known in the art. For the convenience of description, in the description of certain embodiments illustrated by FIG. **1** below, DE and DI will represent the ion concentrations in the output stream and the input stream, respectively. However, it should be noted that DE and DI can comprise other data showing the characteristics of the output stream and input stream in other embodiments of the system of the present invention.

[0057] A control device, **111**, which may be a computer, collects the current data I from the electric current meter **113**, voltage data V from the voltage meters **115** and **116**, the input stream data DI and the output stream data DE, and sends an output signal to the power supply **109** according to various algorithms to be illustrated infra, to adjust the voltage and/or current supplied by the power supply to the electrodes **105** and **107** of the CDI device **103**. In addition, the control device **1 11** may also collect and store information of the switches K**1** and K**2**, and control the operations thereof. Such feedback/control relationship between the control device **111** and the switches are not shown in FIG. **1**. Thick lines with arrows in FIG. **1** illustrate direction of data flow in the system.

[0058] Moreover, in order to minimize the use of energy by the system, a stage with high inductance can be used to make the equivalent circuit store the energy of discharge and reuse it in subsequent cycles.

[0059] A prototype CDI device comprising two electrodes was measured in two experiments with differing discharge voltage profiles. In the first experiment, the pair of electrodes, fully discharged at the initiation of the experiments, were supplied with an essentially constant DC voltage of 1.2V by an external power supply. At the initial instant the capacitor was essentially fully discharged and a peak current appeared followed by an exponential decay that is related to the RC constant of the circuit, where R is the resistance of the circuit and C is the overall capacitance of the circuit. After a certain period of charging, the electrodes were discharged by reducing the external potential imposed on the electrodes to zero (0 Volts), effectively creating a virtual short circuit between the pair of electrodes (the set up is equivalent to that of FIG. **1** where K**2** is off and K**1** is on). At the beginning of the discharge cycle, a peak current was observed, followed by exponential decay determined by the RC constant of the RC circuit. It should be noted that even if the two electrodes were short-circuited without any intentionally included resistance between them, intrinsic resistance exists, leading to the decay current curve typical of a RC circuit.

[0060] In a second experiment, the electrodes were charged in essentially the same way as in the first experiment by a 1.2V DC power source. At the end of the charge cycle, the power supplied to the electrodes was revised in bias to −1.2V. Thus, the experimental set-up during the whole experiment corresponds to FIG. **1** where K**1** is off and K**2** remains on, but the power supply device **109** supplied +1.2V and −1.2V DC voltages to the electrodes **106** and **107** in the charge and discharge cycles, respectively. Higher initial discharge current was observed in this second experiment than in the first one, leading to faster discharging of the electrodes. Thus, in certain operation modes of various embodiments of the system of the present invention, in order to expedite the discharge process of the electrodes, a negatively biased voltage can be provided by the power supply device to the electrodes of the CDI device (assuming the voltage of the charge cycle is positive).

[0061] In the above two experiments, a power supply device supplying a programmable voltage was used. The present inventors have also used a power supply device supplying a programmable current in setting up a system that can be represented by FIG. **1**. The operating principles of the system remain the same irrespective of whether a voltage supply or a current supply is used. Understandably, the control of the current intensity and direction of the current in the circuit is effected by control of the voltage output of the power supply device. When using either type of power supply device, it is highly desired that the electric potential between the electrodes do not reach such an extent that electrolysis of water occurs significantly.

[0062] The faster the charge and discharge of the circuit, the more efficient in time is the removal of ions from the input stream. The amount of ions removed is closely related to the number of electronic charges accumulated in the electrodes, though some discrepancies may occur due to leakage of current in the contacts and electrode material. Various standard approaches are available for one of ordinary skill in the art to reduce such current leakage.

[0063] During various operation modes of various embodiments of the system of the present invention, where a power supply device providing a programmable voltage is utilized, the following various voltage profiles may be used during a complete operation cycle of the CDI device (including a charge cycle and a discharge cycle): (1) $V=VC>0$ during the charge cycle and $V=0$ during the discharge cycle; where VC is a constant DC voltage; (2) a voltage profile illustrated in FIG. **4**, comprising a charge cycle with constant positive voltage and a discharge cycle with $V=0$, including rising and falling slopes to minimize current surge, where the charge cycle comprises periods Ta, Tb and possibly part of Tc, and the discharge cycle comprises periods Td and possibly part of Tc; (3) a voltage profile illustrated in FIG. **5**, where the charge cycle comprises periods Ta, Tb and possibly part of Tc, and the discharge cycle comprises periods Td, Te, Tf, Tg and possibly part of Tc; (4) a voltage profile illustrated in FIG. **6**, where the charge cycle comprises periods Ta, Tb and possibly part of Tc, and the discharge cycle comprises periods Td, Te, Tf, Tg and possibly part of Tc, and during Te, the discharge voltage oscillates.

[0064] The inclusion of voltage slopes at the beginning and end of the charge cycle in profiles (2), (3), (4) and (5) described above may reduce the current surge at the beginning of the charge cycle and discharge cycle, thus is desired in various operation modes of various embodiments of the system of the present invention.

[0065] The time segment Tn (n=a, b, c, . . . f, g, . . .) described in the previous charge and discharge voltage profiles can be controlled by the control device **111** of the system as illustrated in FIG. **1**. Switching from one time segment to the next can be triggered by, e.g., data collected by the control device from the input stream sensor **121**, the output stream sensor **123**, the current meter **113**, and voltage meters **115** and **116** and the power supply device **109**.

[0066] FIG. **2** schematically illustrates the control logic of an operation mode of certain embodiments of the system of the present invention. According to FIG. **2**, data of the current passing through the CDI device and/or data of the output stream are collected by the control device. The process flow illustrated in this figure assumes a programmable voltage source is used as the power supply device. Those data are compared to preset values ICREF (reference charge current), IDREF (reference discharge current), DECREF (reference charge output stream data) and DEDREF (reference discharge output stream data). Once these threshold values are reached, the control device will trigger the change from one time segment to the next, and/or from the charge cycle to the discharge cycle, and vice versa. The output stream data DE, including DECREF and DEDREF, can be, e.g., electrical conductivity data measured by an electric conductivity meter, total ion concentration data measured by certain ion concentration meters, and the like. Data DE may be monitored and collected continuously or intermittently.

[0067] The preset reference threshold values can be determined arbitrarily, or calculated from the input stream data DI. For example, in certain embodiments where electric conductivity meters are used, an electric conductivity meter initially measures the solution of the input stream at the beginning of the cycle and stores its conductivity value. The control system selects an appropriate starting voltage depending on the input stream conductivity value to begin the charge cycle, then collects and monitors the rate of decay in conductivity of the output stream solution. Once the level or the rate of decay of the conductivity reaches (meaning, equals or goes beyond) a threshold value indicating that the electrodes are saturated or a desired level of salt removal has reached, the control device sends a signal to alter the power supplied to the CDI device to switch into the pre-determined profile of the next time segment, and/or to stop the charge cycle and/or start the discharge cycle. A complementary monitoring procedure can be also implemented with the current I. Once the current I or the gradient of the current reaches a certain level one can switch into the next time segment, and/or from the charge to the discharge cycle or vice versa. A negative voltage for the discharge cycle may be fixed or may be altered based on the conductivity measured. The charge-discharge cycles can be repeated for many times before an operation is terminated.

[0068] FIG. **3** schematically illustrates the control logic of another operation mode of certain embodiments of the system of the present invention. According to FIG. **3**, data of the voltage supplied by the power supply device and/or data of the output stream of are collected by the control device. The process flow illustrated in this figure assumes a programmable current source is used as the power supply device. Those data are compared to preset values VCREF (reference charge voltage), VDREF (reference discharge voltage), DECREF (reference charge output stream data) and DEDREF (reference discharge output stream data). Once these threshold values are reached, the control device will trigger the change from one time segment to the next, and/or the charge cycle to the discharge cycle, and vice versa.

[0069] The threshold reference V and I values, VCREF (reference charge voltage), VDREF (reference discharge voltage), DECREF (reference charge output stream data) and DEDREF (reference discharge output stream data), can be set by, e.g., using an analogy to a normal capacitor.

[0070] In operation modes of certain embodiments of the system of the present invention where a programmable voltage is supplied by the power supply device, by monitoring the gradient of the current one can decide where the charging time has reached approximately $T=\tau$, where $\tau=RC$, that corresponds to approximately 69% of a full charge of the capacitor or in this case the absorption of salt by the electrodes. Alternatively, depending on the requirements of the user, charging can be terminated at a time corresponding to $n\cdot\tau$, where n may be 0.5, 1.5, 2.0, 3.0, or any other arbitrary value, and $\tau=RC$. In certain operation modes of certain embodiments of the system of the present invention, ICREF is preset to correspond to a charge current of the CDI device at a time from $\frac{1}{4}\cdot\tau$ to $4\cdot\tau$, in certain other embodiments from 0.5τ to 3τ, in certain other embodiments from $0.5\cdot\tau$ to $2\cdot\tau$, where τ is the RC time constant of the CDI device.

[0071] In terms of discharge the same can be implemented where the discharge current can be monitored with the salt concentration until the overall time for discharge corresponds to approximately $T=RC$ or a recovery of salt is optimized without loss of efficiency in discharge due to the salt being attracted by the opposite plate. In certain operation modes of certain embodiments of the system of the present invention, IDREF is preset to correspond to a discharge current of the CDI device at a time from $\frac{1}{4}\cdot\tau$ to $4\cdot\tau$, in certain other embodiments from $0.5\cdot\tau$ to 3τ, in certain other embodiments from $0.5\cdot\tau$ to $2\cdot\tau$, where τ is the RC time constant of the CDI device.

[0072] It has been observed that, if one applies a negative bias for enough period of time during a discharge cycle of a CDI device, reverse charge may occur. Such reverse charge of the electrodes can be indicated as increasing current, falling electrical conductivity, and the like. During most operation modes of certain embodiments of the system of the present invention, this is undesired and should be generally avoided, as it can decrease the efficiency and efficacy of the discharge cycle. A solution to avoid this situation is to establish a closed loop control system, such as those described above, where the salt concentration in the input stream and/or output stream and the current flowing through the CDI device are monitored. By monitoring the salt concentration in the discharge cycle one can use the controls to switch from a negative voltage to zero volt when the salt concentration changes from increasing to reducing in the discharge cycle. Alternatively, it is possible to include a selective ion filter on the electrodes of the CDI devices, such that only positively charged ions can reach one electrode, and only negatively charged ions can reach the opposite electrode, in the same CDI unit.

[0073] The CDI devices of the system of the present invention behave in a way similar to a standard capacitor in any RC circuit. If the energy stored in the CDI devices during the charge cycle is allowed to be converted completely into thermal energy and dissipated through a RC circuit during the discharge cycle, the stored energy in the charged CDI devices would no longer be available for redistributing ions in the input stream. One approach to reduce energy consumption during the operation of a CDI system of the present invention is thus using the released energy stored in the charged CDI unit during discharge cycle thereof to charge another CDI unit having a lower electrical potential between the electrodes.

[0074] One possible way to reuse the energy of discharge cycles is RLC circuit tank design. For this approach, the resistive losses and leakage current of the device are desired to be small. An inductor can be employed in the circuit to store the electrical energy released during the discharge cycle of a charged CDI device. The inductor, the CDI device, and the resistance in the circuit together form a RLC circuit. By choosing the proper inductance of the inductor, one can utilize the energy obtained from an external power supply device during a single first charge cycle to enable multiple cycles of subsequent charge and discharge of CDI unit.

[0075] A second approach which could partially recover the energy stored in a CDI device is to use additional CDI devices to store the discharge of previous CDI devices in sequence.

[0076] In a normal RC circuit the discharge of a capacitor with charge Q to another, identical, completely discharged, capacitor results in both capacitors with a charge of Q/2 at equilibrium. A third CDI device can then be connected to the original CDI device while the second capacitor or CDI device is disconnected leaving the original CDI device with Q/4 charges left. A fourth CDI device if subjected to the same procedure could leave Q/8 charges and so on. As is indicated above, this assumes that all CDI devices to be charged by the first one have the same capacitance and zero initial charge.

[0077] This approach could reuse much of the energy in the initial capacitor and if implemented for the cycles of each CDI device could reduce the amount the energy required, albeit at the cost of a large number of switches and a switch control system.

[0078] A diagram describing an embodiment of such scheme is provided in FIG. **7**. For the sake of simplicity of illustration, the embodiment illustrated in FIG. **7** includes multiple CDI devices C**1**, C**2**, C**3**, . . . , Cn, all having essentially the same overall capacitance so that connecting a charged capacitor with another fully discharged CDI device leads to equal distribution of the charge between the two. In practice, however, the individual CDI devices may be different.

[0079] In step a) of FIG. **7**, CDI device C**1** is first charged via connection to voltage V of a power supply device indicated by the current flow from the power supply to C**1**. The total charge accumulated in C**1** is Q. While C**1** charges it extracts ions from the input stream solution.

[0080] Referring to step b) of FIG. **7**, after a period of time T**1** with storage of charges Q, C**1** is disconnected from the power supply device. Then C**1** is connected to CDI device C**2** where the charge Q is partially transferred to C**2** over a period of time. At the end of a period of time T**2**, C**1** and C**2** will have equal charges with value Q/2. While C**1** discharges it releases ions from the solution while C**2** is charging and absorbing ions from the solution.

[0081] Afterwards, in step c), C**1** is disconnected from C**2** and connected to CDI device C**3** that is initially completely discharged to charge C**3** with the residual charges retained in C**1**. After a period of time T**3**, C**1** and C**3** will have equal charges with value Q/4.

[0082] Again, in subsequent step d), C**1** is then disconnected from C**3** connected to CDI device C**4** that is initially completely discharged leading again to the charge of C**4** with the previous residual charges retained in C**1**. After a period of time T**4**, C**1** and C**4** will have equal charges with value Q/8.

[0083] The process may be repeated until a CDI device Cn is charged with $Q/2^n$ charge. See step e) of FIG. **7**. During this period of time the discharging CDI devices release ions into the output stream solutions while the charging CDI devices absorb ions from the input stream solutions.

[0084] By feeding the individual CDI devices with differing input streams, one can achieve the desired ion redistribution for these differing aqueous solution streams.

[0085] It is also possible to utilize multiple simultaneously discharging CDI devices to charge a single or multiple CDI devices. The switches between and among the multiple CDI devices can be electronically, mechanically or manually controlled. Automatic control of the switches may be implemented by the control device of the system of the present invention. Such control of switches can lead to an optimized connection between and among multiple CDI devices to achieve the desired ion removal performance and/or energy efficiency of the whole unit.

[0086] It will be apparent to those skilled in the art that various modifications and alterations can be made to the present invention without departing from the scope and spirit of the invention. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. A system for treating an aqueous input stream to produce an output stream comprising redistributed ions, comprising:

a CDI device for the input stream to enter and the output stream to exit, capable of operating in a charge cycle and a discharge cycle;

a power supply device electrically connected with the CDI device, capable of providing a programmable voltage and/or a programmable current to the CDI device in response to an input signal;

at least one of: (i) an electric current meter for measuring the electric current I flowing through the CDI device; and (ii) a voltage meter for measuring the voltage V supplied to the CDI device;

an optional output stream sensor for monitoring the output stream and providing an optional output stream data DE;

an optional input stream sensor for monitoring the input stream and providing an optional input stream data DI;

a control device capable of sending an output signal to the power supply device to maintain or alter the voltage V and/or current I according to at least one of the results of I-ICREF, I-IDREF, V-VCREF, V-VDREF and optionally DE-DECREF and DE-DEDREF, wherein ICREF and IDREF are preset reference current data in the charge cycle and the discharge cycle, respectively, VCREF and VDREF are preset reference voltage data in the charge cycle and the discharge cycle, respectively, and DECREF and DEDREF are preset reference output stream data in the charge cycle and discharge cycle, respectively.

2. A system according to claim **1**, wherein the output stream sensor comprises an electrical conductivity meter and the output stream data DE comprise output stream electrical conductivity data DEEC.

3. A system according to claim **1**, wherein the input stream sensor comprises an electrical conductivity sensor and the input stream data DI comprise input stream electrical conductivity data DIEC.

4. A system according to claim **1**, capable of operating in a mode wherein:

the power supply device provides a programmable voltage to the CDI device; and

during the charge cycle in which a charge voltage V is supplied to the CDI device wherein V>0, if I-ICREF≦0, the control device sends a signal S**1** to the power supply device to change V to enable the discharge cycle such that V decreases to 0, and then maintain V=0 until I-IDREF≦0 when the control device sends a signal S**2** to the power supply device to change V to enable the charge cycle.

5. A system according to claim **1**, capable of operating in a mode wherein:

the power supply device provides a programmable voltage to the CDI device; and

during the charge cycle in which V>0, once I-ICREF≦0, the control device sends a signal S**3** to the power supply device to change V to enable the discharge cycle such that V decreases to a value below 0, and then maintain V≦0 until I-IDREF≦0 when the control device sends a signal S**3** to the power supply device to change V to enable the charge cycle.

6. A system according to claim **1**, capable of operating in a mode wherein:

the power supply device provides a programmable voltage to the CDI device; and

during the charge cycle in which a charge voltage V is supplied to the CDI device wherein V>0, if DE reaches DECREF, the control device sends a signal S**1**A to the power supply device to change V to enable the discharge cycle such that V decreases to 0, and then maintain V=0 until DE reaches DEDREF when the control device sends a signal S**2**A to the power supply device to change V to enable the charge cycle.

7. A system according to claim **1**, capable of operating in a mode wherein:

the power supply device provides a programmable voltage to the CDI device; and

during the charge cycle in which V>0, once DE reaches DECREF, the control device sends a signal S**3**A to the power supply device to change V to enable the discharge cycle such that V decreases to a value below 0, and then maintain V≦0 until DE reaches DEDREF when the control device sends a signal S**3**A to the power supply device to change V to enable the charge cycle.

8. A system according to claim **1**, capable of operating in a mode wherein:

the power supply device provides a programmable current to the CDI device; and

during the charge cycle in which a charge current I is supplied to the CDI device wherein V>0, if V-VCREF≧0 the control device sends a signal SV**1** to the power supply device to change I to enable the discharge cycle such that V decreases to zero, and then maintain V=0 until I-IDREF≦0 when the control devices sends a signal SV**2** to the power supply device to change I to enable the charge cycle.

9. A system according to claim **1**, wherein:

the power supply device provides a programmable current to the CDI device; and

during the charge cycle in which V>0, once V-VCREF≧0 the control device sends a signal SV**3** to the power supply device to change I to enable the discharge cycle such that V decreases to a value below zero, and then maintain V≦0 until V-VDREF≦0 when the control device sends a signal SV**3** to the power supply device to change I to enable the charge cycle.

10. A system according to claim **1**, capable of operating in a mode wherein:

the power supply device provides a programmable current to the CDI device; and

during the charge cycle in which a charge current I and a charge voltage V are supplied to the CDI device wherein V>0, if DE reaches DECREF, the control device sends a signal S**1**A to the power supply device to change V to enable the discharge cycle such that V decreases to zero, and then maintain V=0 until DE reaches DEDREF when the control devices sends a signal SV**2**A to the power supply device to change I to enable the charge cycle.

11. A system according to claim **1**, capable of operating in a mode wherein:

the power supply device provides a programmable current to the CDI device; and

during the charge cycle in which V>0, once DE reaches DECREF, the control device sends a signal S**3**A to the power supply device to change V to enable the discharge cycle such that V decreases to a value below zero, and then maintain V≦0 until DE reaches DEDREF when the control device sends a signal SV**3**A to the power supply device to change I to enable the charge cycle.

12. A system according to claim **1**, capable of operating in a mode wherein the discharge cycle starts with an initial discharge voltage VD**1** supplied to the CDI device, followed by a discharge voltage V<VD**1**.

13. A system according to claim **1**, wherein the CDI device comprises a membrane Ml over the surface of an electrode to selectively allow essentially only cations to pass through, and a membrane M**2** over the surface of the opposite electrode to selectively allow essentially only anions to pass through, during the operation of the CDI device.

14. A system according to claim **1**, wherein the control device collects and/or stores data V, I, DE, DI, ICREF, IDREF, VCREF, VDREF, DECREF, DEDREF, and computes the values I-ICREF, I-IDREF, V-VCREF, V-VDREF, DE-DECREF and DE-DEDREF.

15. A system according to claim **1**, capable of operating in a mode wherein ICREF is preset to correspond to a charge current of the CDI device at a time from $\frac{1}{4}\cdot\tau$ to $4\cdot\tau$, where τ is the RC time constant of the CDI device.

16. A system according to claim **1**, capable of operating in a mode wherein IDREF is preset to correspond to a discharge current of the CDI device at a time from $\frac{1}{4}\cdot\tau$ to $4\cdot\tau$, where r is the RC time constant of the CDI device.

17. A system according to claim **1**, capable of operating in a mode wherein the power supply device supplies an essentially constant voltage to the CDI device during the charge cycle of the CDI device.

18. A system according to claim **17**, capable of operating in a mode wherein the power supply device supplies a DC voltage from 0.2 to 5.8 volts to the CDI device during the charge cycle thereof.

19. A system according to claim **1**, wherein the CDI device comprises multiple CDI units, and the multiple CDI units are wired such that the discharge current of the some of the CDI units during the discharge cycle thereof can charge some some of CDI units sequentially or simultaneously during the charge cycle thereof.

20. A system according to claim **18**, wherein the control device is capable of controlling the electric switches between and among the multiple CDI units.

21. A system according to claim **1**, wherein the control device is further capable of controlling the flow rate of the input stream and/or the output stream.

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