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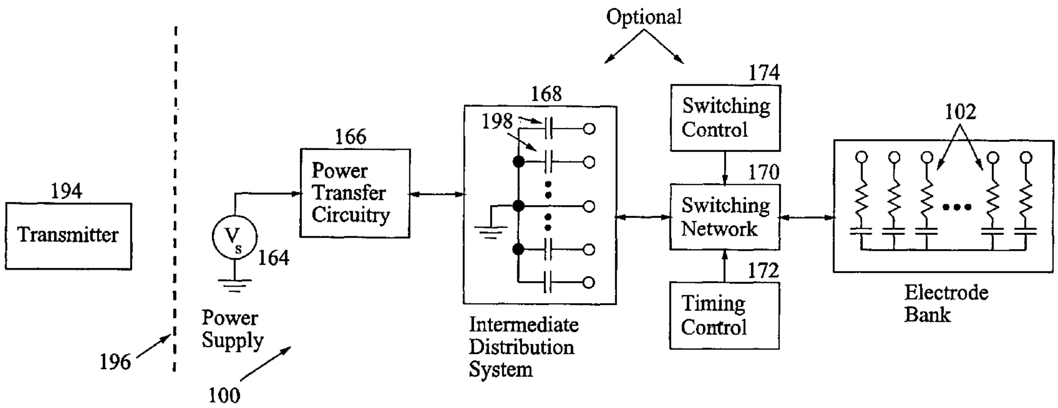
(54) Title: POWER SAVING SYSTEM FOR NEURAL IMPLANT DEVICES




(57) Abstract: Circuitry for and method of power efficient operation of, and energy recovery from, tissue-stimulating electrodes having high charge capacities. Post-stimulation energy is recovered from the electrodes through a variety of techniques into circuit elements such as other electrodes, an intermediate distribution system, a power supply or any other elements, through the use of sequential switching. Energy is also recoverable from the intermediate distribution system, which preferably is comprised of one or more storage capacitors operating a different voltages. Efficient power transfer among circuit elements is effected by transferring energy while limiting element- element voltage differences and/or voltage differences between the elements and the capacitances of the electrodes.

WO 03/030991 A1

# POWER SAVING SYSTEM FOR NEURAL IMPLANT DEVICES

This application claims the benefit of priority to U.S. Provisional Application No. 60/328,346 filed October 10, 2001.

## Field of the Invention

The present invention relates to the field of medical devices, and more particularly relates to medical devices capable of generation of tissue or nerve stimulating pulses. Even more particularly, the present invention relates to efficient power utilization in, and energy recovery from, electrodes of implantable prostheses, such as retinal or cochlear stimulators.

## Background of the Invention

Devices for electrically stimulating tissue, including cochlear implants, pacemakers, muscle and spinal cord stimulators, have been in use for decades. Retinal prostheses that might assist some of the estimated 10 million people worldwide who are blind as a result of degenerative retinal diseases, such as age-related macular degeneration and retinitis pigmentosa, are under development based on the concept of replacing photoreceptor function with an electronic nerve-stimulating device.

Many tissue-stimulating prostheses provide electrical signals to an implanted section, which then generates excitation signals to excite the tissue of a patient by means of appropriately positioned stimulation electrodes or arrays of electrodes. Common in some tissue stimulators is a two-part design, wherein an external section transmits RF energy that is inductively coupled by a transcutaneous RF link to the implanted section. The energy of the coupled RF electrical signals is rectified and stored by a power supply located in the internal section. It is that power supply that provides the energy required to power the internal section and to generate the stimulus signals.

To increase patient safety, to minimize the power requirements of a tissue stimulator, and because power dissipation losses are in proportion to the square of the voltage, it is desirable to operate the tissue stimulator at low voltages that are no greater than required. This is especially true in implantable stimulator electronics.

During stimulation, the electrodes of tissue stimulating devices are typically driven by a constant current source to a prescribed level of charge, resulting in storage of that charge, and therefore storage of energy, within the electrodes. To ensure charge balancing to avoid electroplating the electrodes, the same amount of charge is then driven in the opposite direction (changing polarity) until the electrodes are left uncharged. Typical circuit techniques are very inefficient when driving this type of electrode, often using more than twice the necessary energy during the first phase of current drive, and even more during the second phase.

U.S. Pat. No. 5,522,865 to Schulman, *et al.*, entitled "Voltage/Current Control System for a Human Tissue Stimulator" discloses a human tissue stimulating system that comprises an audio responsive system for artificially stimulating a cochlea to improve hearing for the hearing impaired. The implanted stimulator includes a power supply that extracts raw power from a data signal, a voltage downconverter for providing a number of output voltages from the extracted raw power signal, and a storage capacitor that serves as the power source for portions of the stimulator. One of the output voltages is applied to isolated refresh voltage capacitors, where it controls a voltage controlled current source that supplies output to the electrodes through a complex switch matrix. Energy is conserved by turning off and on various subsystems within a control processor, and by optimizing power dissipation of a conventional input switching regulator by controlling the RF power transmitted from an external source to the implanted stimulator based on a telemetered voltage drop across the regulator, indicating what power is required to be transmitted for just sufficient stimulator operation.

U.S. Pat. No. 5,876,425 to Gord, *et al.*, entitled "Power Control Loop for Implantable Tissue Stimulator" also describes a feedback power control loop utilizing back telemetry from the implantable device. The voltage level of a tank capacitor utilized as an internal rechargeable power source is transmitted to an external power supply processor for computation and delivery of an appropriate amount of power to maintain normal operation, while minimizing transmission of extra energy that might otherwise be dissipated.

U.S. Pat. No. 6,415,186 to Siu-Chor Chim, *et al.*, entitled "Active Feed Forward Power Control Loop" discloses a feed forward power control loop for providing power to the implanted part of a tissue stimulator. Power consumption is similarly kept low by transmitting across a wireless transcutaneous transmission link only the amount of power required by the implanted device, as predicted by the power control loop processor. The reference discloses the use of intermittent telemetry and predictive modeling to determine the appropriate amount of power to transmit.

Each of the references cited above approaches power transfer optimization by using tank capacitor voltage telemetry to determine power transmission. They address power consumption efficiency of the implanted circuitry, to a greater or lesser extent, by turning on and off circuit components, and otherwise treat conventionally the transfer of energy from the power supply to the electrodes. None address recovering energy from the electrodes and other components after stimulation has occurred.

U.S. Pat. No. 6,181,969 to Gord, entitled "Programmable Current Output Stimulus Stage for Implantable Device" discloses a programmable output current source for use within an implantable tissue or nerve stimulator. Each electrode node has parallel-connected P-FET current source sets permanently connected between it and a positive voltage rail, and parallel-connected N-FET current source sets permanently connected between it and a negative voltage rail. The higher power requirement of the PFET and NFET current sources is kept to a minimum by avoiding physically or electrically "switching" the electrode nodes between one or more circuit locations, or to different sides of a current or voltage source so as to change the polarity of the current flowing through the node. Rather, the P-FET sources "source" current to the node, and the N-FET sources receive, or "sink", current from the node. Such a non-switching approach is achieved at the cost of more circuit components.

Accordingly, there is a continuing need for greater power utilization and delivery efficiency in tissue stimulating devices. The present invention satisfies such needs.

## Summary of the Invention

The present invention provides a variety of circuits and techniques for power-efficient operation of, and energy recovery from, tissue-stimulating electrodes. The invention takes advantage of recent advances in electrical properties of the electrodes to reduce the power required for effective stimulation.

The present invention finds particular relevance with implantable tissue stimulators, wherein optimal power efficiency can prolong the life of the device and decrease the risk of patient harm. The use of iridium oxide and other types of electrodes that have vastly higher charge-capacity properties than platinum or other electrode materials used in the past makes the present invention feasible. The principles of the systems and methods described below are applicable to any tissue stimulation device (*e.g.*, retinal and cochlear implants, cortical stimulator, spinal stimulator, cardiac pacemaker, etc.) employing electrodes having a series capacitance.

As used herein, the term "power supply" refers to the portion of a tissue stimulator responsible for, in the case of an implanted stimulator, receiving energy from an external power-transmitting unit and at least temporarily storing the energy for use by other portions of the stimulator for generating electrical stimulation signals. The power supply employed is dependent upon the nature of the tissue stimulator. In a retinal stimulator, for example, the power supply may comprise a secondary coil for coupling AC magnetic fields transmitted from outside the patient's body. In larger tissue stimulators, the power supply may comprise a battery.

In one aspect, the present invention provides systems and methods for recovering energy from tissue stimulating electrodes post-stimulation. As discussed in the previous section, this energy has, in the past, been wasted. As will be described below, there is residual energy in the capacitance of post-stimulated electrodes. The recovered energy may be utilized in driving one or more other electrodes to be used in subsequent stimulation. In other embodiments, the recovered energy is transferred to other circuit elements within the tissue stimulator

In another aspect, the present invention provides systems and methods for the efficient transfer of energy within a tissue stimulator.

In one embodiment, a system in accordance with the invention includes one or more tissue stimulating electrodes, a power supply, and transfer circuitry coupled to the power supply and the electrodes that provides energy to the electrodes directly from the power supply while limiting voltage differences between the power supply and the capacitance of the electrodes to which the power supply is to be connected. The transfer circuitry may also operate so as to remove energy from one or more previously stimulated electrodes and return the energy directly or indirectly to the power supply.

In another embodiment, the system may have an intermediate distribution system (IDS) disposed between the electrodes and the power supply. The IDS provides one or more voltage sources to the electrodes to be driven, and may be fed from the power supply through power transfer circuitry. The power transfer circuitry maintains the voltage sources at the desired, preferably DC, voltages by providing energy from the power supply while limiting voltage differences between the power supply and the voltage sources to which the power supply is to be connected. In certain embodiments, the power transfer circuitry may include a synchronous switching rectifier for directly supplying power to or recovering power from the voltage sources. A switching network provides energy to the electrodes from the voltage sources while limiting voltage differences between the voltage sources and the capacitance of the electrodes to which the voltage sources are to be connected.

In certain embodiments, the IDS is comprised of a plurality of storage capacitors among which one or more electrodes, or groups of electrodes, are appropriately switched. Single capacitor embodiments of the IDS are also possible by driving a constant current into a single capacitor via the power transfer circuitry, thereby creating a psuedo-ramping voltage source. This ramping capacitor is connected to the electrodes during a single constant-current phase. There will be some ripple in the voltage ramp, but it can be limited.

In another embodiment, a system for power-recovery in a tissue stimulator comprises one or more previously stimulated electrodes, one or more elements into which energy from the one or more previously stimulated electrodes will be recovered, and a switching network that provides sequential connections from the one or more previously stimulated electrodes to the one or more elements. The one or more elements are preferably electrodes to be used in subsequent stimulation, or groups thereof, but could be any electrical element capable of utilizing the recovered energy. The electrodes to be used in subsequent stimulation may be completely uncharged prior to energy transfer, but, as will be described below, optimal energy efficiency is achieved through a method of partially pre-charging the electrodes that will be transferred the recovered energy.

The system components described above may be designed to operate based on pre-set timing intervals. Alternatively, they may be responsive to monitored electrical parameters of the system. For example, the power transfer circuitry may be responsive to the difference between the voltage of the capacitance of the previously stimulated electrodes and the voltage of the power supply. Or, the switching network may be responsive to the difference between the voltage(s) of the capacitances of the previously stimulated electrodes and the voltage(s) of the voltage sources to which the previously stimulated electrodes are to be connected, or between the capacitances of the previously-stimulated electrodes and the capacitances of uncharged and/or partially charged electrodes to be stimulated.

In preferred embodiments, the switching network provides sequential connections from one or more storage capacitors (of an IDS) to one or more of the electrodes to be stimulated while limiting voltage differences between the storage capacitors and the capacitances of the one or more electrodes to which the one or more storage capacitors are to be connected. A judicious selection of connection sequences results in progressive addition to or removal of energy from the capacitances of the electrodes being connected.

## Brief Description of the Drawing

**Figure 1** is an electrical schematic of a power-efficient energy transfer system in accordance with the invention.

**Figure 2** is an electrical schematic diagram of circuit equivalent model of a tissue stimulating electrode.

**Figures 3A, 3B** are plots of ideal constant current and associated voltage waveforms for optimally driving a tissue stimulating electrode.

**Figure 4** is an electrical schematic diagram of a simple circuit segment illustrating the concept of charge sharing between a charged electrode and an uncharged electrode.

**Figure 5A, 5B** are illustrations provided for the purpose of analogizing electrode charge states to the volume of water in hypothetical water buckets.

**Figures 6A, 6B** are plots of electrode voltage waveforms demonstrating recoverable and non-recoverable post-stimulation energy.

**Figure 7** is an electrical schematic diagram of a first embodiment of a switching supply source in accordance with the present invention.

**Figures 8A, 8B** are plots illustrating optimal and realistic current and voltage waveforms across an electrode in accordance with the first embodiment of the switching supply source.

**Figure 9** is an electrical schematic diagram of a second embodiment of a switching supply source in accordance with the present invention.

**Figure 10** is a plot illustrating potential switch timing for the second embodiment of the switching supply source.

**Figures 11A, 11B** are plots illustrating optimal and realistic current and voltage waveforms across an electrode in accordance with the second embodiment of the switching supply source.

**Figure 12** is an electrical schematic diagram illustrating an embodiment of a switching network in accordance with the present invention.

## Detailed Description of Certain Preferred Embodiments of the Invention

Preferred embodiments of the invention will now be described with reference to the accompanying drawings. The circuitry shown in the drawings and described below is simplified in that not all of the components utilized in the system are shown, but sufficient components are shown to clearly teach the novel aspects of the present invention.

The present invention provides a variety of circuits and techniques for power-efficient operation of, and energy recovery from, tissue-stimulating electrodes. The invention takes advantage of recent advances in electrical properties of the electrodes to reduce the power required for effective stimulation.

*ELECTRODES*

With reference to **Figure 1**, the present invention provides a system **100** for efficient energy transfer in a tissue stimulator utilizing one or more tissue stimulating electrodes **102.** The electrodes **102** are preferably manufactured from oxidized iridium or other material with a high charge capacity. Fabrication of the electrodes can be performed using any techniques known to those skilled in the art, such as electrodeposition or infusion of molten metal under pressure. In a preferred embodiment of a retinal tissue stimulator employing the systems and methods in accordance with the present invention, the electrodes used may include 400 um diameter iridium oxide electrodes. As shown in **Figure 2**, each of the electrodes **102** can be modeled as a modest resistive element **104** (about 1 KOhm) in series with a very large capacitance **106** (300 nF to 3 uF, depending on the oxidation process). This simple model has some limitations (a significant conducting path in parallel with the capacitance forms at high enough voltage), and is not exact, but is sufficient for modeling the response to currents and voltages typically seen during tissue stimulation.

The usual method of stimulation, as shown in **Figure 3A** and discussed in further detail below, is a constant current drive $-I_d$ **108** for a fixed time *T/2* **110**. This deposits a charge on the capacitance **106** of electrode **102**, resulting in a voltage across the electrode and stimulation of the nerve or muscle tissue near the electrode. If left open-circuited for typical times of interest (several milliseconds or tens of milliseconds), the charge of the capacitance **106** will not leak off electrode **102**, and can be thought of as stored energy. The process is then reversed by driving an opposite current $+I_d$ **112** through electrode **102** for the same time *T/2* **114**, leaving electrode **102** uncharged and ready for the next stimulation.

*BASIC METHOD OF ENERGY RECYCLING*

As shown in **Figure 4A**, after a charge $Q_0$ **114** has been driven onto an electrode $E_1$ **116**, resulting in stimulation of adjacent tissue, that electrode's capacitance **118** contains stored energy. Furthermore, the charge $Q_0$ **114** on electrode $E_1$ **116** must be removed to prevent electroplating and to prepare for future stimulations. The simplest method for energy recycling, as shown in **Figure 4B**, involves connecting charged electrode $E_1$**116** to an uncharged electrode $E_2$**120**, allowing them to share charge $Q_0$ **114**. In a final step, as shown in **Figure 4C**, electrode $E_1$ **116** is shorted to ground **124** to continue its discharge, while $E_2$ **120** is fully charged by some type of supply source **122**. More complicated procedures increase the efficiency of this technique.

*MORE EFFICIENT CHARGE RECYCLING*

**Figures 5A and 5B** are useful in visualizing the electrodes $E_1$ **116,** $E_2$ **120** as buckets of water, wherein the charges of their capacitances are equivalent to one or more volumes **124,126** of water, their voltages are equivalent to the heights **128,130** of the water volumes, and their energies are proportional to the products **132,134** of the two. **Figure 5A** illustrates the simple recycling scheme, while **Figure 5B** shows a more efficient scheme involving partially pre-filling the empty bucket (*i.e.*, partially pre-charging electrode $E_2$ **120**). As can be seen, one drawback of the simple method is its inefficiency. Assuming that the *RC* time constant of electrode $E_1$ **116** is much shorter than the time *t* that the electrodes are connected, half the charge V **124** will be transferred to electrode $E_2$ **120,** giving it half the voltage H **128** originally on the electrode $E_1$ **116.** But since the energy stored on a capacitor is proportional to the product of charge and voltage, electrode $E_2$ **120** now has only 1/4 of the energy U **132** originally stored on $E_1$ **116,** and the other 3/4 of the required energy must be supplied by the supply source **122.**

In **Figure 5B,** a more efficient way to transfer charge between the two electrodes $E_1$ **116',** $E_2$ **120'** is demonstrated. The unstimulated electrode $E_2$ **120'** is partially pre-charged, then connected to previously stimulated electrode $E_1$ **116',** and finally driven by supply source **122** to complete the required charge. This method can recover as much as 1/3 of the energy U **136** from the previously stimulated electrode

$E_1$ **116'**. More energy can additionally be recovered by connecting the uncharged electrode $E_2$ **120** to a series of previously stimulated electrodes, but the complexity of control circuitry required grows significantly and the charging times required would limit stimulation frequencies that could be utilized.

In a direct electrode-to-electrode transfer, at best 1/3 of the energy can be recovered because the electrodes are at such different voltages when they are shorted together. This means that a large voltage develops across the electrode resistances, burning power. This drawback leads to a more sophisticated way of recovering energy from the electrodes, and an optimal method of delivering energy to them.

*RESPONSE OF ELECTRODES TO DRIVE CURRENT*

**Figure 3B** shows the voltage waveform across any tissue stimulating electrode **102** in response to the constant current drives **108,112** with a negative pulse during the first phase T/2 **110**, a typical configuration. The resistive element **104** of electrode **102** is responsible for the steps (**136,138,140**) in the voltage waveform, and the capacitance **106** of electrode **102** is responsible for the ramps (**142,144**).

The first voltage step **136** and last voltage step **140** in the waveform shown have magnitude

$$V_R = I_d R \qquad \textbf{Eq. 1}$$

The middle voltage step **138** is twice that value, since the change in drive current at that moment is twice the magnitude. The magnitude of each ramp segment **142,144** is

$$V_C = \frac{Q}{C} = \frac{I_d T}{2C} \qquad \textbf{Eq. 2}$$

The power into the electrode at any moment in time is

$$P(t) = I(t)V(t) \qquad \textbf{Eq. 3}$$

In the first phase T/2 **110**, the product of the negative current $-I_d$ and the negative voltage is positive power into electrode **102**. The energy into electrode **102** during the first phase T/2 **110** (between $t_1$ **150** and $t_2$ **152**), $U_1$, is the integral of the power over time T, or the product of the constant current $I_d$ and the area under the voltage waveform:

$$U_1 = \int_0^T P(t)dt = (-I_d)(-\frac{T}{2}V_R - \frac{1}{2}\frac{T}{2}V_C) = I_d^2(\frac{RT}{2} + \frac{T^2}{8C}) \quad \textbf{Eq. 4}$$

The energy into the resistive element **104** of electrode **102** is lost to heat, but the energy into the capacitance **106** is stored, and potentially recoverable. During the second phase T/2 **114** (between $t_2$ **152** and $t_4$ **156**), some of this stored capacitive energy is lost in the resistance, but some is returned from electrode **102**, as illustrated in **Figure 3B**.

Note that for a short time, between $t_2$ **152** and $t_3$ **154**, the current is positive but the voltage is negative, meaning the power into electrode **102** is negative. Put another way, the electrode is "supplying power". In traditional systems, this power is not recovered into the supply where it may be used again. Rather, it is burned in the current source circuitry. The present invention recovers and reuses some of that returned energy.

The total energy into electrode **102** during the second phase T/2 **114** (between $t_2$ **152** and $t_4$ **156**) is calculated in the same way as in **Eq. 4**, and is:

$$U_2 = (I_d)(\frac{T}{2}V_R - \frac{1}{2}\frac{T}{2}V_C) = I_d^2(\frac{RT}{2} - \frac{T^2}{8C}) \quad \textbf{Eq. 5}$$

The returned energy can be seen in the negative sign in **Eq. 5**. The total energy into electrode **102** over both phases **110,114** is

$$U_{Tot} = U_1 + U_2 = I_d^2 RT \quad \textbf{Eq. 6}$$

This is the familiar power relation for a resistor, $P = I^2 R$, integrated over the total biphasic pulse time T. In other words, the capacitance **106** of electrode **102** does not burn any power, it merely stores energy and then returns it.

*CONDITIONS FOR ENERGY RECOVERY*

As stated above, the capacitance **106** of electrode **102** cannot burn power. It merely stores the energy, to be returned during the second phase **114**. The energy is in the form of electric charge held at an electric potential (voltage). When the charge is removed from the capacitance **106** during the second phase **114**, it necessarily passes through the resistive element **104**, which burns power, converting some of the energy to heat. The degree to which this occurs determines whether usable energy may be recovered from the capacitive part of the electrode.

**Figures 6A, 6B** show two illustrative cases of the voltage across electrode **102** in response to the same current drive as depicted in **Figure 3A**. In the waveform of **Figure 6A**, the second phase ($t_2$ **152** to $t_4$ **156**) has exactly half its area **162** below zero and half above. In this case, energy is returned early in the second phase (between $t_2$ **152** and $t_3$ **154**), and lost late in the second phase (between $t_3$ **154** and $t_4$ **156**). Over the whole second phase, no net energy is recovered or lost. That is, the amount of energy burned in the resistive element **104** during the second phase is the same as the amount of energy that had been stored in the capacitance **106**. The waveform of **Figure 6B** shows a more extreme case, in which at no time during the second phase (between $t_6$ **160** and $t_7$ **161**) is energy recovered from the capacitance **106**. The differences between the two illustrated waveforms are determined by the relation between the *RC* product, or respective time constants, of the electrodes, and the pulse duration T/2.

For the waveform of **Figure 6A**, no net energy is recovered or lost, and the condition derives from **Eq. 5**,

$$U_2 = I_d^2\left(\frac{RT}{2} - \frac{T^2}{8C}\right) = 0$$

$$RC = \frac{T}{4}$$

**Eq. 7**

For the waveform of **Figure 6B**, no energy is recovered at any time, the condition derives from **Eqs. 1** and **2**,

$$V_R = V_C$$
$$RC = \frac{T}{2}$$

**Eq. 8**

Thus if the biphasic pulse time T can be made longer than twice the *RC* time constant of an electrode **102**, instantaneous power can be returned from the capacitance **106**. If T is made longer than four *RC* time constants, net energy is recoverable over the second phase (between $t_6$ **160** and $t_7$ **161**). Electrodes currently used in retinal implants, for example, have *RC* time constants that are far less than any expected pulse duration, so energy should be recoverable from the electrodes.

*OPTIMAL DRIVE*

Regardless of whether energy can be returned from the capacitance **106** of one or more electrodes **102**, the technique described below will approach the minimum level of energy required to drive the electrodes.

In order to store charge (and therefore energy) in the capacitance and then remove it, the charge must be moved through the resistive element **104**, and through any resistive element in series between a power supply **164** and one or more electrodes **102**.

*POWER BURNED WITHIN THE ELECTRODE*

The resistive element **104** of the electrodes cannot be removed, so the power burned in it must be minimized. Since a prescribed amount of charge must be driven through the resistive elements in a prescribed pulse time, the only variable is the current waveform used to deliver this charge. The typical current waveform, using a constant current $I_d$ over the pulse duration, as shown in **Figure 3A**, is the optimal waveform to minimize power burned in the electrode resistance, given the constraint of delivering a prescribed charge in a fixed time.

A slightly varied current waveform will use more energy to deliver the same charge in the same time. Take for example a current waveform with the current level set slightly below $I_d$, or $I_d - \delta$, for the first phase **110** of the pulse duration, and slightly above $I_d$, or $I_d + \delta$, for the second phase **114**. Since power burned in a resistor is $P = I^2 R$, the energy burned in the resistance in the optimal, constant-current waveform in one phase is:

$$U_{pot} = I_d^2 \frac{RT}{2}$$

**Eq. 9**

The energy used in this example waveform is:

$$U = (I_d + \delta)^2 R \frac{T}{4} + (I_d - \delta)^2 R \frac{T}{4}$$
$$U = R \frac{T}{4} (I_d^2 + 2 I_d \delta + \delta^2 + I_d^2 - 2 I_d \delta + \delta^2)$$
$$U = I_d^2 R \frac{T}{2} (1 + (\frac{\delta}{I_d})^2)$$

**Eq. 10**

The energy used by this example waveform is greater than the energy used by the constant-current waveform of **Figure 3A**. Furthermore, it can be shown with variational calculus that the constant-current waveform uses less energy than any other waveform delivering the same charge in the same time, and therefore, that the constant-current waveform burns the least amount of energy possible in the resistance within the electrode.

The resistive elements **104** of electrodes **102** cannot be removed, so the power burned in them must be minimized. The power is minimized, as shown in the previous document, by driving a constant current through the electrodes.

*POWER BURNED OUTSIDE THE ELECTRODES*

The typical implementation of a constant-current source involves a voltage supply that is higher than the highest voltage reached by the electrodes, with some variable resistive element (usually transistor-based circuitry) in series to control the current. The problem with this approach is that the series resistive element burns power as it supplies charge to the electrode. The present invention solves this problem by removing the series resistance.

If the series resistance is removed, the voltage supply itself must adapt to maintain a constant current. This task is very difficult unless the load impedance is well known, as it is in this case. The load impedance of a variety of tissues can be and has been well characterized. An ideal current driver, with no power dissipation in the source, can be made if the voltage being supplied to the electrodes "tracks" the electrode voltage waveforms shown in **Figures 6A** or **6B**, that is, if the voltage difference between the capacitance of the electrodes and the voltage source supplying the stimulating energy are limited to a minimum. This keeps the voltage across the resistive portion **104** of the electrodes **102** constant, generating a constant current, the minimum power dissipation in the electrode resistance, and no power dissipation in the supply.

*POWER EFFICIENT ELECTRODE SUPPLY: FIRST EMBODIMENT*

In reality, a voltage supply that follows the step-ramp pattern in **Figures 6A** or **6B** is very difficult to build. But an approximation to those patterns can be made by switching between a number of different voltage supplies **176A-C**, as shown schematically in **Figure 7**. A typical implementation for a power efficient voltage supply **175**, as shown, might use three voltage sources **176A-C** for each phase **110, 114**. The total number of voltage sources in that case could be held to four if the middle voltage source **176B** were used in both phases. This is shown in the waveforms of **Figures 8A** and **8B**, with three negative voltages and one positive voltage. The use of a greater number of voltage levels will yield a closer approximation to the minimum required power, but at a cost of increased system complexity. The dashed lines represent the optimal electrode voltage **178** and optimal current **180** waveforms for minimal power dissipation. One of the solid lines illustrates a four-level voltage approximation waveform **182** of this embodiment, and the resultant electrode current **184**.

*POWER EFFICIENT ELECTRODE SUPPLY: SECOND EMBODIMENT*

Another embodiment of a power efficient electrode supply **175** is illustrated in **Figure 9**. In this configuration, a ramping voltage **163** may be made available to charge electrode **102** (or multiple electrodes not shown) by driving a constant current from a power supply **164** into a storage capacitor **165** by means of power transfer circuitry **166**. Capacitor **165** comprises a portion of an intermediate distribution system (IDS) **168**, which is represented in **Figure 1** as a bank of storage capacitors. Storage capacitor **165** will be the *only* capacitor connected to the electrode being stimulated during a single constant-current phase. Switch network **170** establishes and interrupts connections between the ramping capacitor **165** and the electrodes **102** to be stimulated. Capacitor **165** can be charged to give a pseudo-ramping voltage by power transfer circuitry **166**. There will be some ripple in the ramp, but it can be kept small.

Power transfer circuitry **166** and switch network **170** are each depicted as switches in **Figure 9**. Switch network **170** in this embodiment connects the one or more electrodes **102** to the storage capacitor **165** for the duration of one phase T/2 of stimulation. Power transfer circuitry **166** switches as the power supply **164** sine wave changes, driving charge onto storage capacitor **165** to achieve the waveform shown in **Figure 10**.

This description relates to one phase of biphasic current stimulus. The other phase can be achieved by quickly stepping storage capacitor **165** to a different voltage to represent the step that occurs at time $t_2$ **152** in **Figure 3B**, but such a step of voltage on a capacitor cannot be done efficiently. Another way to achieve such a voltage step to start the second current phase **114** is to switch the electrode(s) **102** away from the storage capacitor that has been used, to a different storage capacitor operating at the desired voltage. This second storage capacitor may then be ramped, in the same manner, in the opposite direction to generate the opposite current.

The power transfer circuit **166** charges the storage capacitor **165** to achieve a ramping waveform, by connecting the capacitor to a sinusoidal power supply **164** with a period much shorter than the pulse width of the stimulus current. **Figure 10** illustrates the timing for half of a sine wave cycle of the power supply voltage **180**. Power transfer circuit **166** is turned on at time **182** when the power supply voltage **180** is larger in magnitude than the voltage of the storage capacitor, $V_{cap}$**184** but close enough to $V_{cap}$**184** to minimize losses in the power transfer.

**Figures 11A** and **11B** illustrate the ideal and realistic electrode current and voltage waveforms that may be attained employing the circuit described above. The dashed lines represent the optimal electrode voltage **186** and current **188** waveforms for minimal power dissipation. The solid lines illustrate a representation of the voltage **190** and current **192** waveforms utilizing the ramping capacitor solution. In reality, the ripple on the voltage and current waveforms would be much higher frequency, and smaller in magnitude than depicted.

*COMPLETE CIRCUIT IMPLEMENTATION*

**Figure 1** is a block diagram of a system **100** in accordance with the present invention, including means for efficiently transferring energy and for recovering energy from one or more electrodes **102** following stimulation.

A power supply **164** that receives energy wirelessly, such as in the form of a coupled AC magnetic field, from an external power transmitter **194** is preferable in implanted tissue stimulators, due to the decreased risk of patient infection and increased mobility of the patient. To transmit power to the power supply **164**, external power transmitter **194** is placed against the outside of a patient's skin **196** over the implanted tissue stimulator. The ac magnetic fields from the external power transmitter **194** induce ac currents in a secondary coil comprising the power supply **164**. Power supply **164** may either be directly connected to the electrodes **102** or to power transfer circuitry **166** that rectifies the ac current to produce dc current for charging the one or more voltage sources **198** in IDS **168** to their desired voltages.

The voltage sources **198** are preferably implemented using storage capacitors, as previously described. The voltage sources **198** are maintained at their prescribed voltage level by power transfer circuitry **166**, charging from whatever power supply **164** is being used for the implant (battery, RF coil, etc.).

**Figure 1** shows a block diagram of a multi-source system, with a bank of capacitors **198** forming part of IDS **168** charged from power supply **164**, and driving the electrodes **102** as described above, through switch network **170**. Switching control **174** receives whatever data is required to determine which electrodes need to be driven, and the switching network **170** connects each electrode to an appropriate sequence among voltage sources **198** to create the waveforms portrayed in **Figures 11A** and **11B**.

The power transfer circuitry **166** may be comprised of a synchronous switching rectifier for repeatedly causing a rectified ac voltage to accumulate across the voltage sources **198** in a step-wise fashion.

The charging of the voltage sources **198** may occur according to a predetermined timing or pulse-counting routine. Alternatively, power transfer circuitry **166** may monitor the voltage difference(s) between the power supply **164** and the voltage(s) of the one or more voltage sources **198**, perhaps through the use of a voltage comparator. With this knowledge, power transfer circuitry **166** may determine the appropriate connection sequence between the power supply **164** and the voltage sources **198**.

**Figure 12** is a functional block diagram of a portion of the present system that illustrates switching control between a plurality of voltage sources **198** and one or more electrodes **102**. The voltage sources **198** of the IDS **168** are connected to a plurality of switches **200** that will typically be implemented using solid state switching devices as are known in the art, and whose operation is controlled jointly by digital timing control **172** and electrode switching control **174**. In the circuit shown, CMOS Field effect transistors serve as the switches **200** for individually coupling one or more of the storage capacitors to one or more of the electrodes **102** based on signals asserted by digital timing control **172** and electrode switching control **174**. Although timing intervals may determine the operation of the switches **200**, alternatively the connections can be made in response to monitored between the various voltage sources **198** and the one or more electrodes **102** are determined either open-loop by the timing circuitry or by a more complicated feedback system measuring either electrode voltage or supplied current.

Other embodiments of the invention will be apparent to those skilled in the art from a consideration of the specification or practice of the invention disclosed herein. It is intended that the specification and examples be considered as exemplary only, with the true scope and spirit of the invention being indicated by the following claims.

We claim:

1. A system for power-recovery in a tissue stimulator, comprising:

one or more tissue stimulating electrodes, each having a capacitance; and

means for recovering post-stimulation energy from the electrodes.

2. The system of claim 1, wherein the recovered energy is recovered from the capacitance of the electrodes.

3. The system of claim 1, wherein the recovered energy is utilized in driving one or more electrodes to be used in subsequent stimulation.

4. The system of claim 1, further comprising:

a power supply; and

power transfer circuitry, coupled to the power supply and the electrodes, that provides energy to the electrodes directly from the power supply while limiting voltage differences between the power supply and the capacitance of the electrodes to which the power supply is to be connected.

5. The system of claim 1, further comprising:

a power supply;

an intermediate distribution network including one or more storage capacitors;

a switching network, coupled to the one or more electrodes and the intermediate distribution system, that provides energy to the electrodes from the one or more storage capacitors while limiting voltage differences between the storage capacitors and the capacitance of the electrodes to which the storage capacitors are to be connected; and

power transfer circuitry, coupled to the power supply and the intermediate distribution system, that provides energy to the storage capacitors from the power supply while limiting voltage differences between the power supply and the storage capacitors to which the power supply is to be connected.

6. A system for power-recovery in a tissue stimulator, comprising::

one or more previously stimulated electrodes;

one or more elements into which energy from the one or more previously stimulated electrodes will be recovered; and

a switching network that provides connection for the one or more previously stimulated electrodes to the one or more elements.

7. The system of claim 6, wherein the one or more elements comprise one or more electrodes to be used in subsequent stimulation.

8. The system of claim 6, wherein the switching network is responsive to timing intervals.

9. The system of claim 7, wherein the one or more electrodes to be used in subsequent stimulation are uncharged.

10. The system of claims 4 or 5, wherein the energy recovery means further comprises transfer circuitry that removes energy from one or more previously stimulated electrodes and returns said energy directly to the power supply.

11. The system of claim 4 or 5, wherein the energy recovery means further comprises transfer circuitry that removes energy from one or more previously stimulated electrodes and returns said energy to the power supply through an intermediate circuit.

12. The system of claims 10 or 11, wherein the energy recovery means comprises a synchronous switching rectifier.

13. The system of claims 10 or 11, wherein the energy recovery means is responsive to timing intervals.

14. The system of claim 6, wherein the switching network is responsive to the difference between the voltage of the capacitance of the previously stimulated electrodes and the voltage of the one or more elements

15. The system of claim 10, wherein the transfer circuitry is responsive to the difference between the voltage of the capacitance of the previously stimulated electrodes and the voltage of the power supply.

16. The system of claim 7, wherein one or more of the electrodes to be used in subsequent stimulation have a pre-charge before being connected to the one or more previously stimulated electrodes.

17. The system of claim 7, wherein the switching network is responsive to a voltage differential between the one or more previously stimulated electrodes and the one or more electrodes to be used in subsequent stimulation.

18. The system of claim 7, wherein the one or more electrodes to be used in subsequent stimulation are sequentially connectable to a series of two or more groups of electrodes, each group comprising one or more previously stimulated electrodes.

19. A system for power-recovery in a tissue stimulator, comprising:

a power supply;

an intermediate distribution system including one or more storage capacitors;

power transfer circuitry, coupled to the power supply and the intermediate distribution system, that recovers energy from the storage capacitors to the power supply while limiting voltage differences between the power supply and the storage capacitors to which the power supply is to be connected;

one or more tissue stimulating electrodes, each having a capacitance; and

a switching network, coupled to the one or more electrodes and the intermediate distribution system, that provides sequential connections for the one or more storage capacitors to one or more of the electrodes while limiting voltage differences between the storage capacitors and the capacitances of the one or more electrodes to which the one or more storage capacitors are to be connected.

20. The system of claim 19, wherein the connection sequence results in progressive removal of energy from the one or more electrodes being connected.

21. The system of claim 19, wherein the switching network is responsive to differences between the voltages of the one or more storage capacitors and the voltage of the capacitances of the one or more electrodes to which the one or more storage capacitors are to be connected.

22. The system of claim 19, wherein the intermediate distribution system includes two or more storage capacitors operating at different DC voltages.

23. The system of claim 22, wherein:

the one or more tissue stimulating electrodes includes one or more previously stimulated electrodes; and

the switching network provides sequential connections from the one or more previously stimulated electrodes to the storage capacitors to progressively lower the energy in the electrode.

24. The system of claim 19, wherein the one or more storage capacitors comprises a single capacitor having a controllably ramping voltage.

25. The system of claim 24, wherein:

the one or more tissue stimulating electrodes includes one or more previously stimulated electrodes; and

the switching network provides intermittent sequential connection from the capacitor to the one or more previously stimulated electrodes.

26. A system as in any one of claims 14-25, wherein the switching network is responsive to timing intervals.

27. The system of claims 4, 5 or 19, wherein the power transfer circuitry further comprises a synchronous switching rectifier for directly recovering power from the one or more storage capacitors.

28. The system of claims 27, wherein the power transfer circuitry is responsive to timing intervals.

29. A system for implementing power-efficient energy transfer in a tissue stimulator,

comprising:

a power supply;

one or more tissue stimulating electrodes, each having a capacitance; and

power transfer circuitry, coupled to the power supply and the electrodes, that provides energy to the electrodes directly from the power supply while limiting voltage differences between the power supply and the capacitance of the electrodes to which the power supply is to be connected.

30. A system for implementing power-efficient energy transfer in a tissue stimulator, comprising:

a power supply;

one or more tissue stimulating electrodes, each having a capacitance;

an intermediate distribution network including one or more storage capacitors;

a switching network, coupled to the one or more electrodes and the intermediate distribution system, that provides energy from the one or more storage capacitors to the electrodes while limiting voltage differences between the storage capacitors and the capacitance of the electrodes to which the storage capacitors are to be connected; and

power transfer circuitry, coupled to the power supply and the intermediate distribution system, that provides energy from the power supply to the storage capacitors while limiting voltage differences between the power supply and the storage capacitors to which the power supply is to be connected.

31. The system of claim 30, wherein the power transfer circuitry further comprises means for monitoring the voltage differences between the power supply and one or more storage capacitors to which the power supply is to be connected.

32. The system of claim 31, wherein the power transfer circuitry is responsive to the monitored voltage differential between the power supply and the one or more storage capacitors to which the power supply is to be connected.

33. The system of claims 29 or 30, wherein the power transfer circuitry further comprises a synchronous switching rectifier.

34. The system of claim 30, wherein the switching network provides sequential connections from the one or more storage capacitors to the one or more electrodes being connected.

35. The system of claim 30, wherein the switching network is responsive to differences between the voltages of the one or more storage capacitors and the voltage of the capacitances of the one or more electrodes to which the one or more storage capacitors are to be connected.

36. The system of claim 30, wherein the intermediate distribution system comprises two or more storage capacitors operating at different DC voltages.

37. The system of claim 36, wherein the switching network provides sequential connections from the one or more electrodes to be used in subsequent stimulation to storage capacitors of progressively higher energy.

38. The system of claim 30, wherein the one or more storage capacitors of the intermediate distribution system have controllably ramping voltages.

39. The system of claim 38, the switching network provides sequential connections from the one or more storage capacitors of controllably ramping voltages to the one or more electrodes to drive energy efficiently into the one or more electrodes.

40. A system as in any one of claims 29-39, wherein the power transfer circuitry is responsive to timing intervals.

41. A system as in any one of claims 30-39, wherein the switching network is responsive to timing intervals.

42. The system of claims 4, 10-13, 15, or 19-39, further comprising

power transmission means including a primary coil that generates AC magnetic fields; and wherein the power supply further comprises a secondary coil that couples the AC magnetic fields.

43. The system as in any of the preceding claims, wherein the electrodes are comprised of oxidized iridium.

44. The system as in any of claims 1-41, wherein the system is implantable.

45. The system as in any of the preceding claims, wherein the system stimulates human tissue.

46. The system as in any of the preceding claims, wherein the system stimulates human retinal tissue.

47. A method of using the system of claim 1 in recovering post-stimulation energy from one or more tissue-stimulating electrodes, comprising the steps of:

driving currents into one or more of the electrodes; and

recovering post-stimulation energy from the one or more driven electrodes.

48. The method of claim 47, wherein the driving step further comprises directly driving the currents from the power supply via a synchronous switching rectifier.

49. A method for recovering post-stimulation energy from one or more tissue stimulating electrodes in a tissue stimulator, comprising the steps of:

driving currents into one or more tissue stimulating electrodes; and

connecting the one or more previously stimulated electrodes to one or more uncharged electrodes to be used in subsequent stimulation.

50. A method for recovering post-stimulation energy from one or more tissue stimulating electrodes in a tissue stimulator, comprising the steps of:

driving currents into one or more tissue stimulating electrodes;

partially charging one or more electrodes to be used in subsequent stimulation; and

connecting the one or more previously stimulated electrodes to one or more of the partially charged electrodes.

51. The method of claims 49 or 50, further comprising the step of determining, based on one or more timing intervals, when to connect the one or more previously stimulated electrodes to the one or more electrodes to be used in subsequent stimulation.

52. The method of claims 49 or 50, further comprising the step of:

monitoring one or more voltage differences between the voltage of the capacitances of one or more previously stimulated electrodes and the voltage of the capacitances of one or more electrodes to be used in subsequent stimulation; and

determining, based on the voltage differences, when to connect the one or more previously stimulated electrodes to the one or more electrodes to be used in subsequent stimulation.

53. The method of claims 49 or 50, further comprising the step of:

monitoring one or more voltage differences between the voltage of the capacitances of one or more previously stimulated electrodes and the voltage of the capacitances of one or more electrodes to be used in subsequent stimulation; and

determining, based on the voltage differences, which one or more previously stimulated electrodes to connect to the one or more electrodes to be used in subsequent stimulation.

54. A method of using the system of claims 19 or 30 in efficiently transferring energy in a tissue stimulator, comprising the steps of:

sequentially connecting one or more of the electrodes to one or more of the storage capacitors such that energy is progressively added to the capacitances of the electrodes to which the storage capacitors are to be connected.

55. A method of using the system of claims 19 or 30 in efficiently transferring energy in a tissue stimulator, comprising the steps of:

sequentially connecting post-stimulation one or more previously stimulated electrodes to one or more of the storage capacitors such that energy is progressively recovered from the capacitances of the one or more previously stimulated electrodes.

56. The method of claims 54 or 55, further comprising the step of:

monitoring one or more voltage differences between the one or more storage capacitors and the voltages of the capacitances of the one or more electrodes to be connected; and

determining, based on the monitored voltage differences, when to connect the one or more electrodes to the one or more storage capacitors.

57. A method of using the system of claims 19 or 30 in efficiently transferring energy in a tissue stimulator, comprising the steps of:

charging the one or more storage capacitors to the different voltages by sequentially connecting the power supply to the one or more storage capacitors while limiting voltage differences between the power supply and the one or more storage capacitors to which the power supply will be connected.

58. The method of claim 57, further comprising the step of:

determining, based on one or more timing intervals, when to connect the power supply to the one or more storage capacitors.

59. The method of claim 57, further comprising the step of:

monitoring one or more voltage differences between the power supply and the one or more storage capacitors voltage sources; and

determining, based on the monitored voltage differences, when to connect the power supply to the one or more storage capacitors.

60. The method as in any one of claims 57-59, wherein the power transfer circuitry further includes a switching rectifier for directly driving the storage capacitors from the power supply.

61. The method as in any one of claims 47-50 or 57-60, further comprising the step of:

generating AC magnetic fields in a primary coil comprising a transmitting means; and

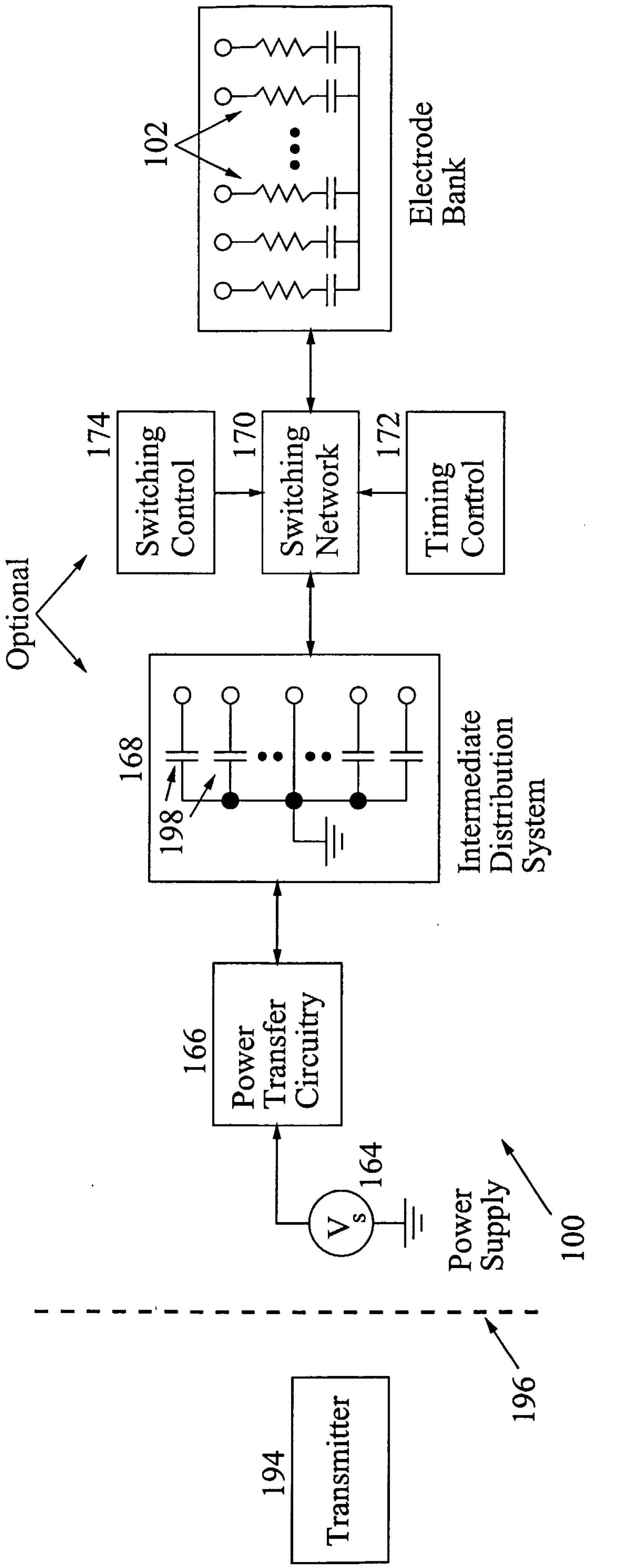
coupling the generated AC magnetic fields in a secondary coil comprising the power supply.

62. The method as in any one of claims 47-56, wherein the electrodes are comprised of oxidized iridium.

63. The method as in any one of claims 47-62, wherein the tissue stimulator is implantable.

64. The method as in any one of claims 47-62, wherein the tissue stimulator is adapted to stimulate human tissue.

65. The method as in any one of claims 47-62, wherein the tissue stimulator is adapted to stimulate human retinal tissue.



102
Electrode Bank
174
Switching Control
170
Switching Network
172
Timing Control
Optional
168
198
Intermediate Distribution System
166
Power Transfer Circuitry
164
$V_s$
Power Supply
100
196
194
Transmitter


Figure 1

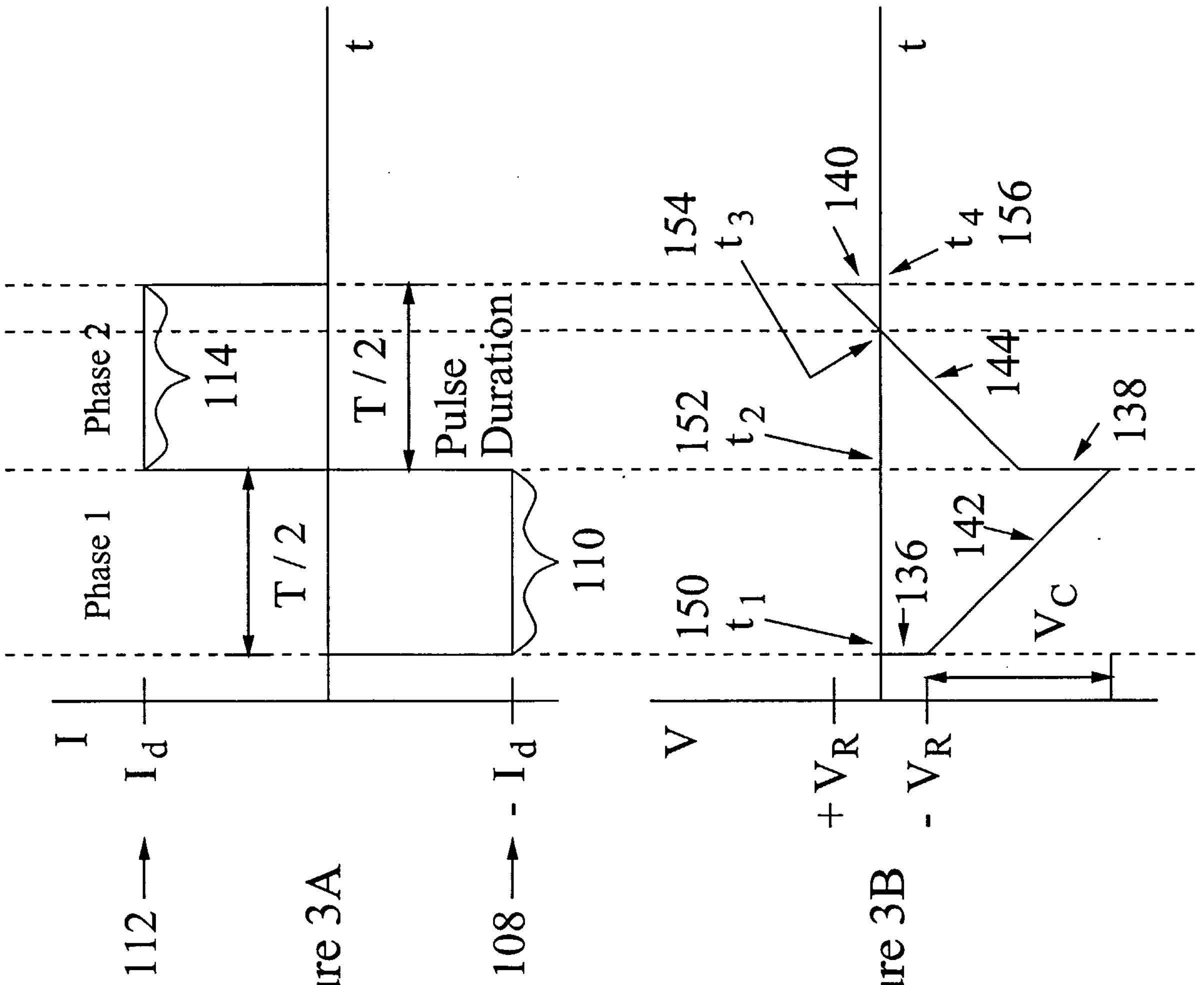



Figure 3A

Figure 3B

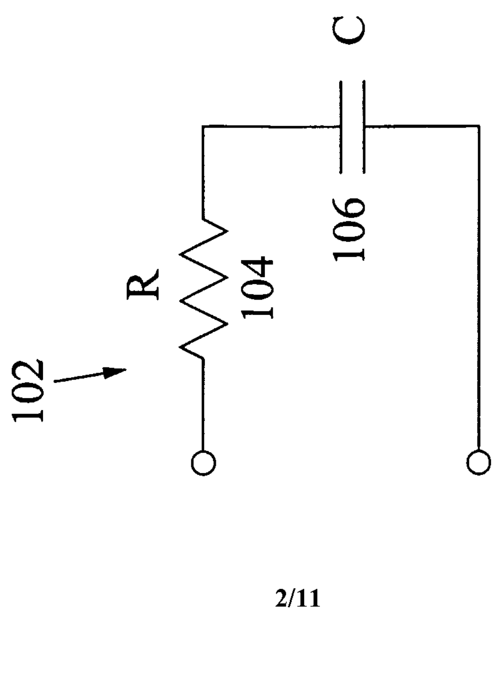



Figure 2

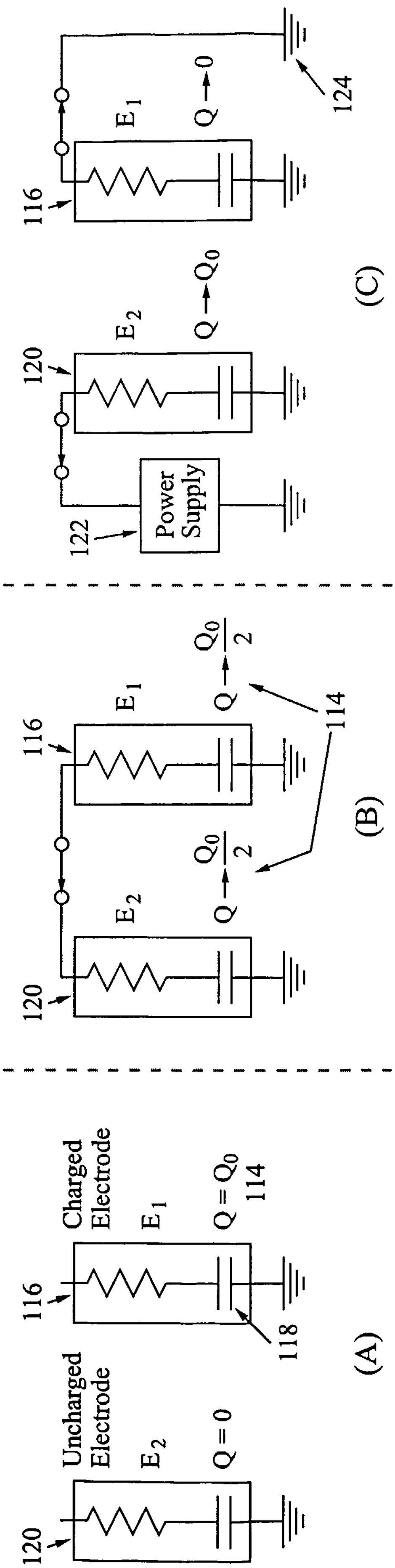

120
Uncharged
Electrode
$E_2$
Q = 0
116
Charged
Electrode
$E_1$
Q = $Q_0$
114
118
(A)
120
$E_2$
Q → $\frac{Q_0}{2}$
116
$E_1$
Q → $\frac{Q_0}{2}$
114
(B)
122
Power
Supply
120
$E_2$
Q → $Q_0$
(C)
116
$E_1$
Q → 0
124

Figure 4

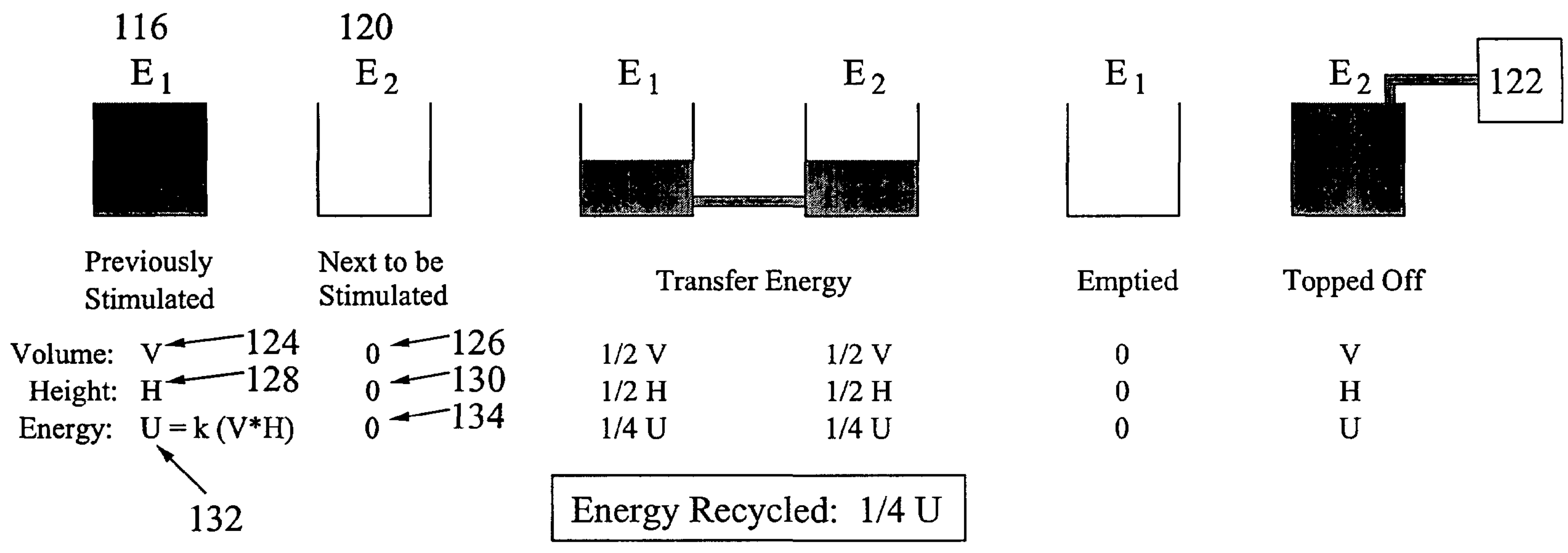



Figure 5A

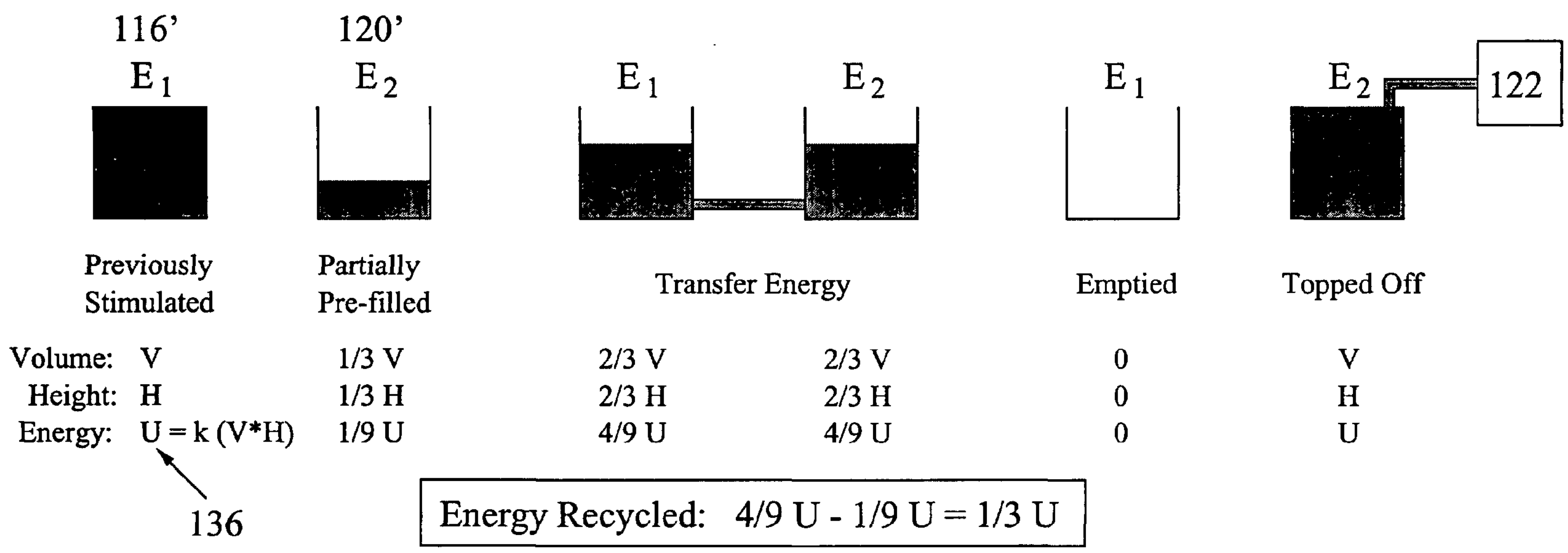



Figure 5B

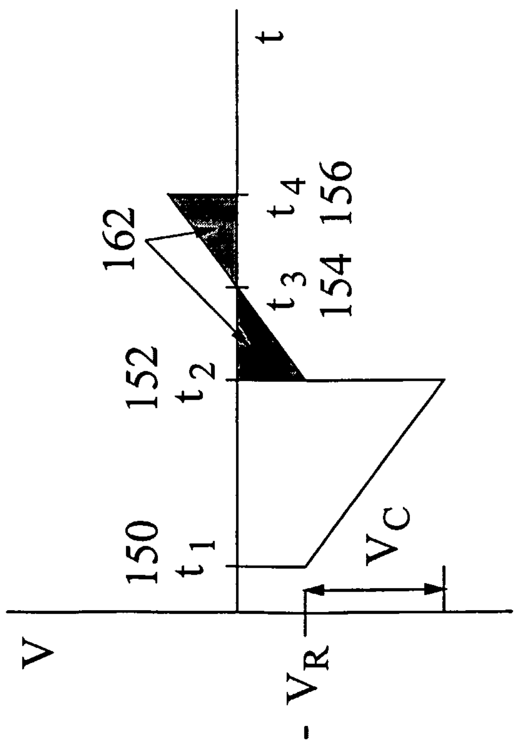



Figure 6A

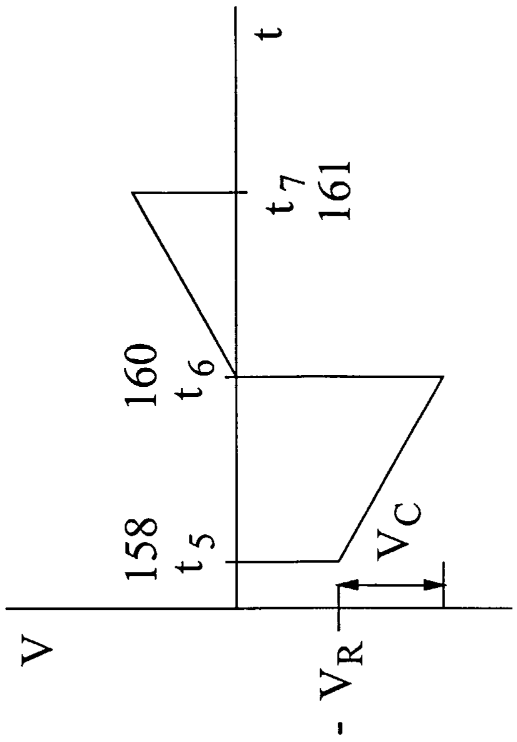



Figure 6B

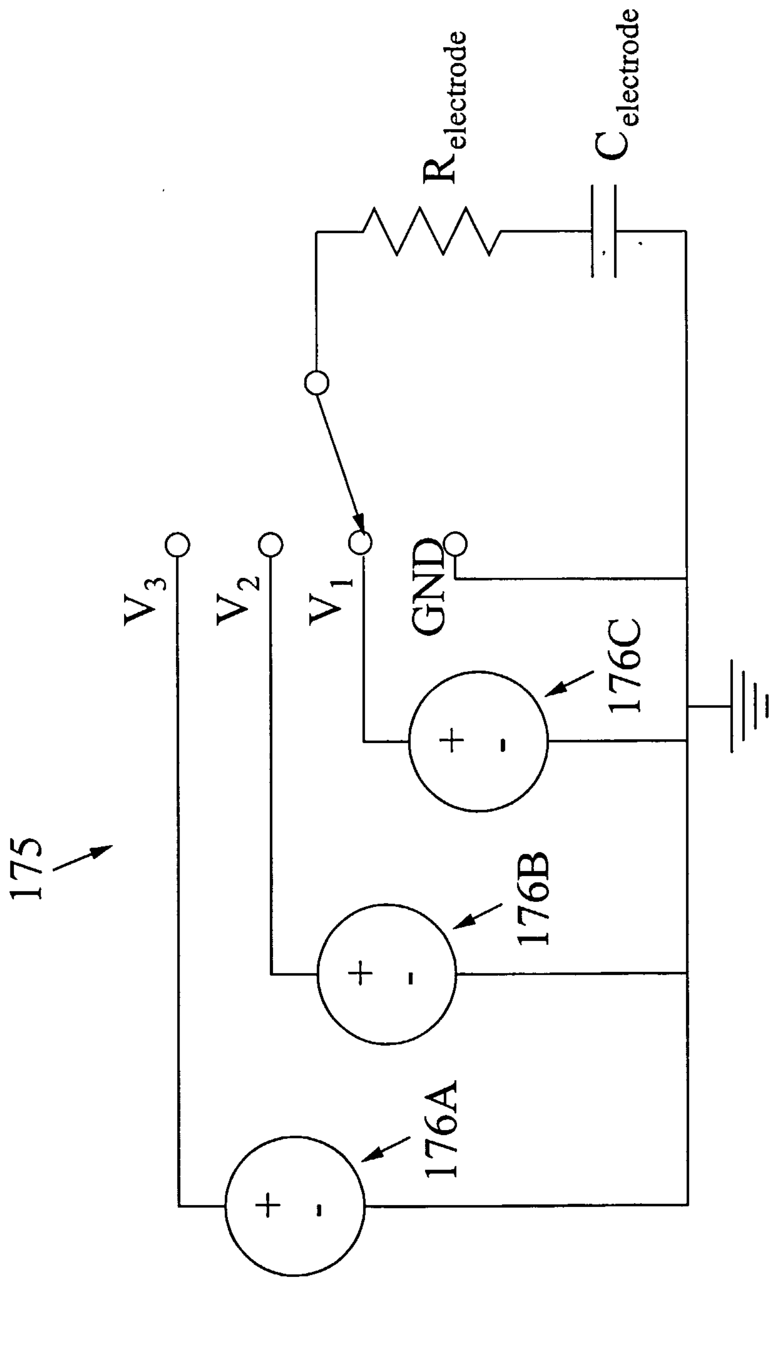



Figure 7

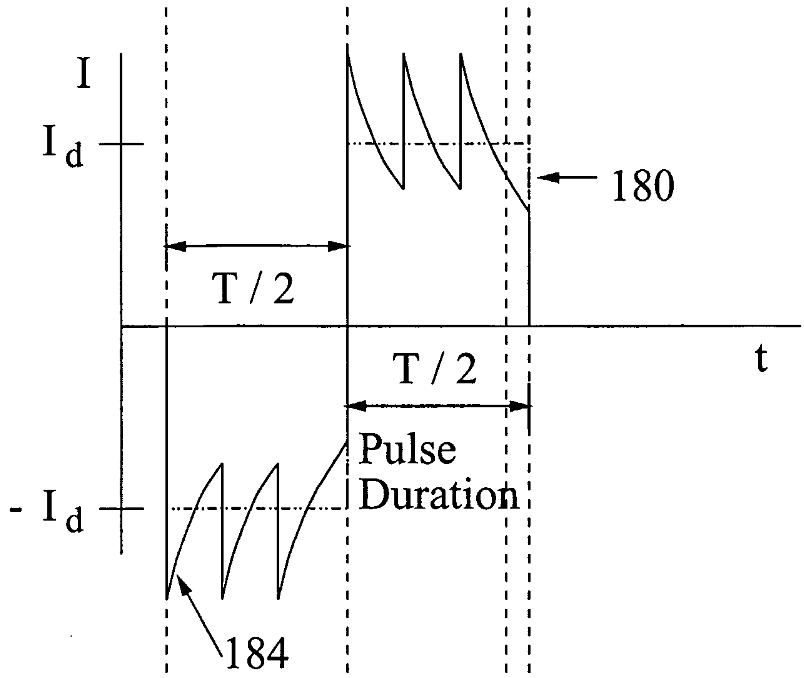



Figure 8A

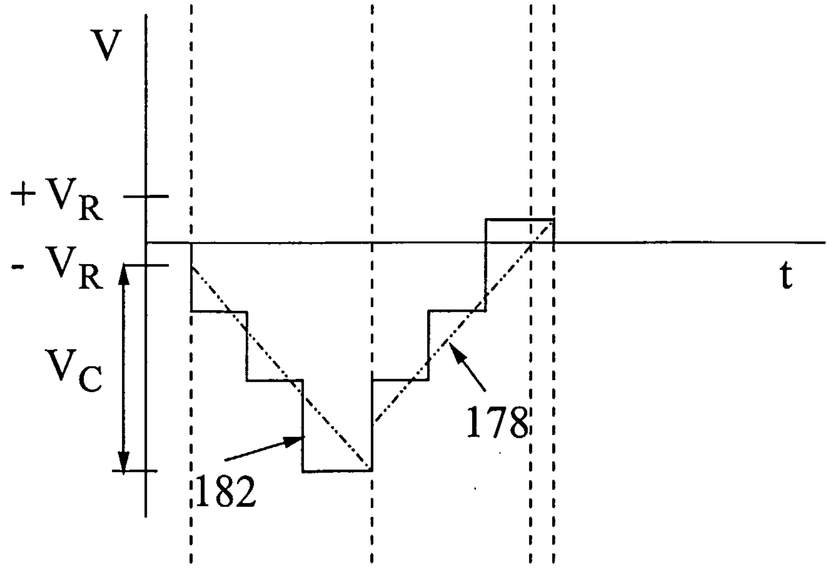



Figure 8B

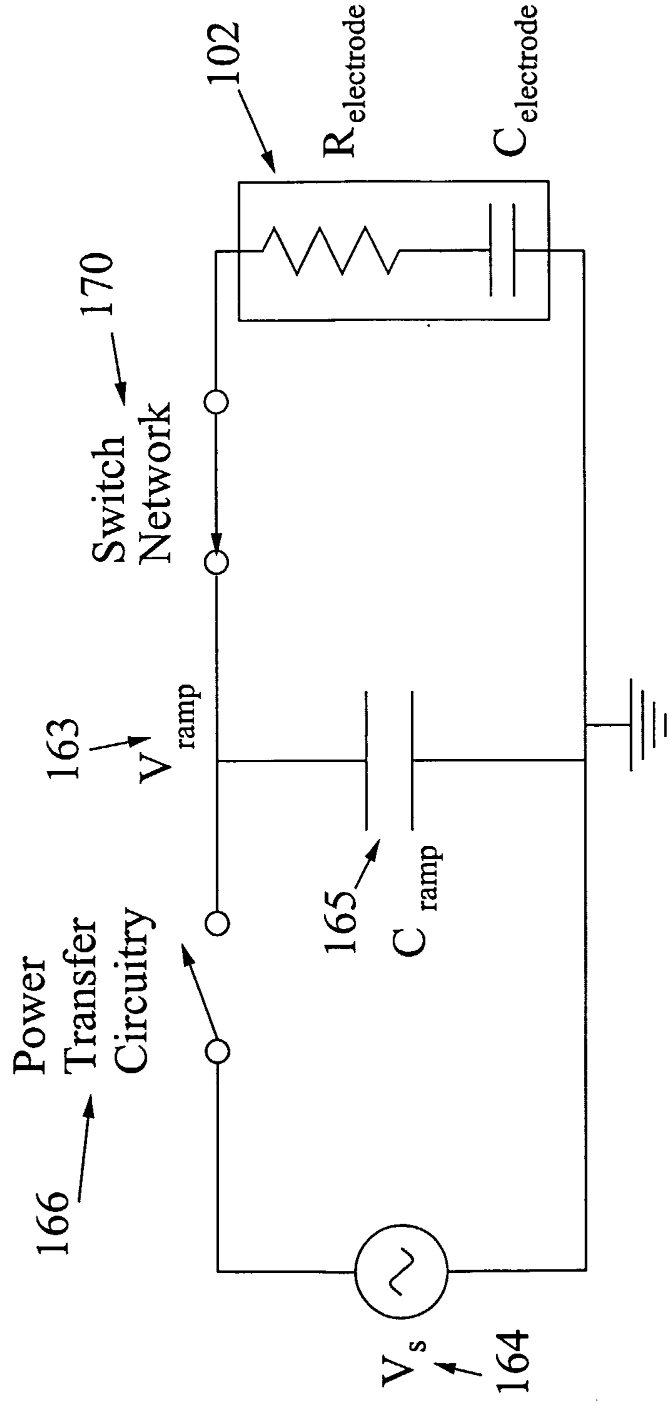

102
$R_{electrode}$
$C_{electrode}$
170
Switch Network
163
$V_{ramp}$
165
$C_{ramp}$
166
Power Transfer Circuitry
$V_s$
164

Figure 9

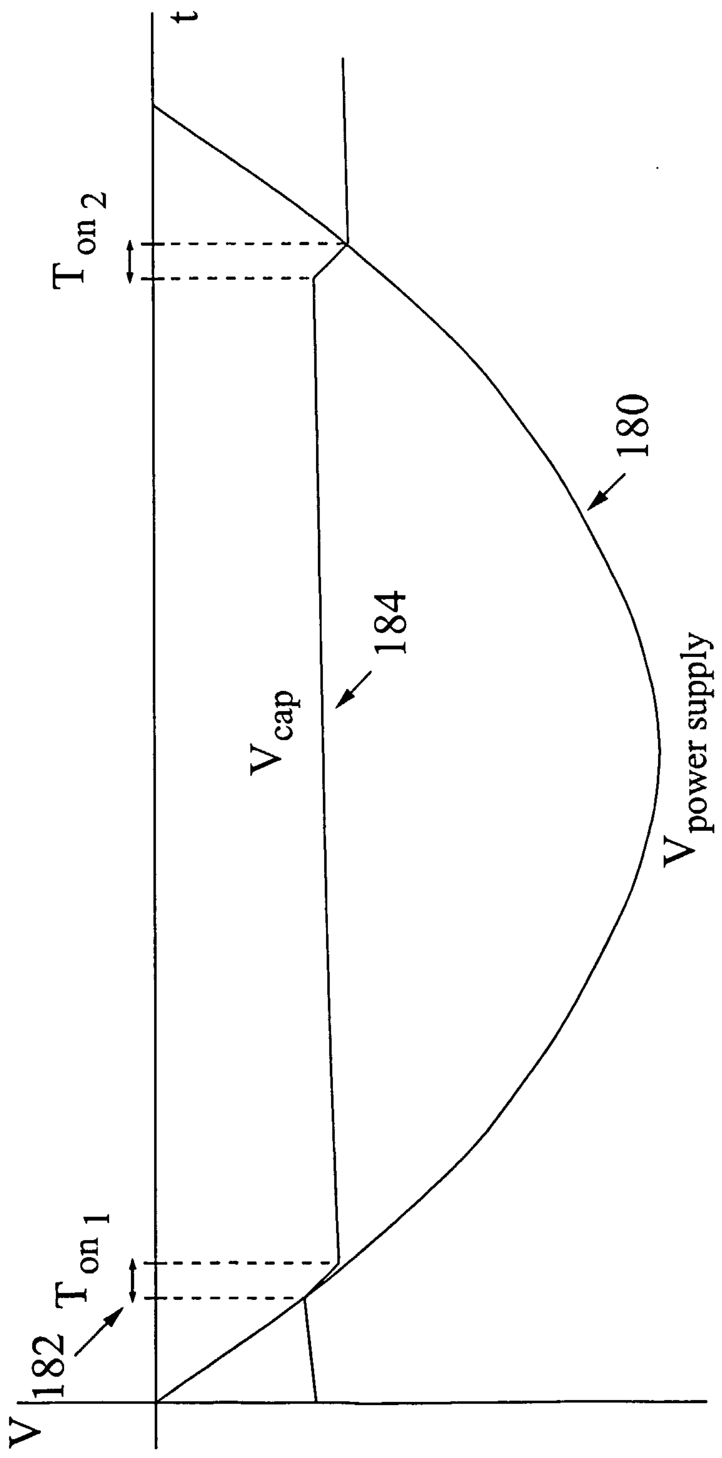



Figure 10

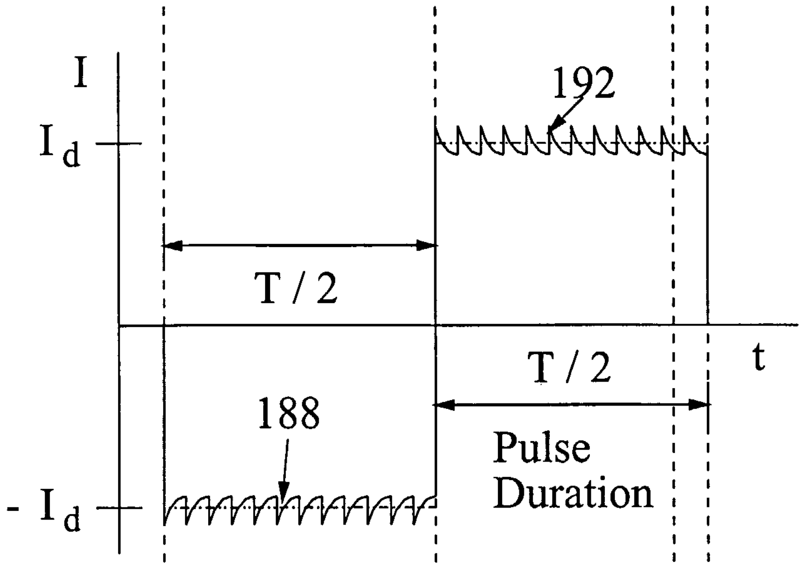



Figure 11A

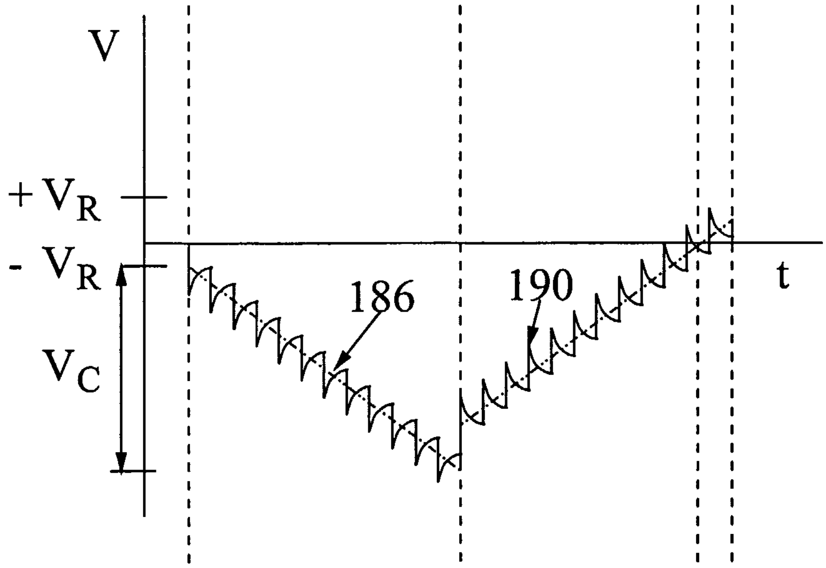



Figure 11B

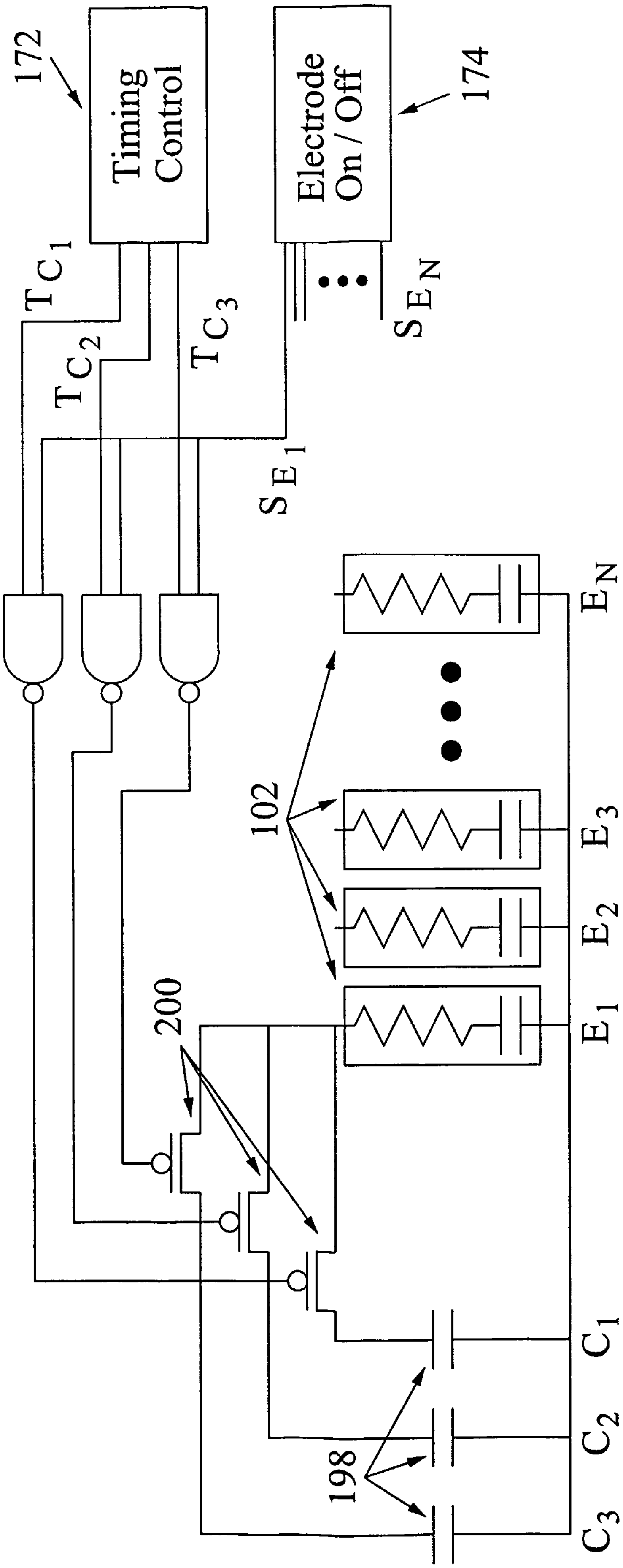

172
Timing Control
174
Electrode On / Off
$TC_1$
$TC_2$
$TC_3$
$S_{E_1}$
$S_{E_N}$
102
200
198
$E_1$
$E_2$
$E_3$
$E_N$
$C_1$
$C_2$
$C_3$

Figure 12

# INTERNATIONAL SEARCH REPORT

Internati    pplication No
PCT/US 02/32509

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 7 A61N1/378 A61N1/36 A61N1/08 A61N1/05

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)
IPC 7 A61N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category ° | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | US 5 312 439 A (LOEB GERALD E) 17 May 1994 (1994-05-17) | 1,2,4-6, 8,10,13, 29,30, 33,34, 42-45 |
| | column 3, line 1 - line 56<br>column 4, line 39 -column 5, line 60<br>column 6, line 45 -column 7, line 33; figures 1,5,6 | |
| A | | 19-24 |
| | --- | |
| | -/-- | |

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in 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 document 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 |
|---|---|
| 20 January 2003 | 28/01/2003 |

| Name and mailing address of the ISA | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL – 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,<br>Fax: (+31-70) 340-3016 | Artikis, T |

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

| Category ° | Citation of document, with indication,where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | US 4 399 818 A (MONEY DAVID K) 23 August 1983 (1983-08-23) | 1,2,5-8, 10,11, 13,16, 26,29, 30,34, 36,40, 41,44,45 |
| | column 1, line 1 - line 40<br>column 2, line 8 -column 3, line 68<br>column 4, line 55 -column 5, line 17<br>column 6, line 1 -column 7, line 48<br>column 8, line 24 -column 9, line 28;<br>figures 1,2 | |
| X | US 6 035 237 A (SCHULMAN JOSEPH H ET AL) 7 March 2000 (2000-03-07) | 1,2,4,6, 8,16,29, 44,45 |
| | column 1, line 50 -column 2, line 35<br>column 3, line 58 -column 5, line 8<br>column 6, line 22 - line 42 | |
| Y | column 12, line 12 -column 14, line 17;<br>figures 1,3,4,10 | 42 |
| Y | US 4 082 097 A (SCHULMAN JOSEPH H ET AL) 4 April 1978 (1978-04-04) | 42 |
| A | column 4, line 17 - line 56; figure 1 | 33 |
| A | US 4 114 627 A (LEWYN LANNY LOUIS ET AL) 19 September 1978 (1978-09-19)<br>abstract; figure 1 | 1,6,29, 30 |

**FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210**

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-28,42-46

   Systems for recovering post-stimulation energy from one or more electrodes of a tissue stimulator

2. Claims: 29-41

   Systems for efficiently transferring energy from the power supply of a tissue stimulator to its electrodes

# INTERNATIONAL SEARCH REPORT

**Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)**

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [X] Claims Nos.: 47-65
because they relate to subject matter not required to be searched by this Authority, namely:

Rule 39.1(iv) PCT - Method for treatment of the human or animal body by therapy

2. [ ] Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. [ ] Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. [ ] As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. [X] As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

**Remark on Protest**

[ ] The additional search fees were accompanied by the applicant's protest.

[ ] No protest accompanied the payment of additional search fees.

# INTERNATIONAL SEARCH REPORT

In. ation on patent family members

Internatic ıpplication No
PCT/US 02/32509

| Patent document cited in search report | | Publication date | Patent family member(s) | | | Publication date |
|---|---|---|---|---|---|---|
| US 5312439 | A | 17-05-1994 | NONE | | | |
| US 4399818 | A | 23-08-1983 | NONE | | | |
| US 6035237 | A | 07-03-2000 | NONE | | | |
| US 4082097 | A | 04-04-1978 | NONE | | | |
| US 4114627 | A | 19-09-1978 | BE | 861850 | A1 | 31-03-1978 |
| | | | DE | 2755706 | A1 | 15-06-1978 |
| | | | FR | 2374023 | A1 | 13-07-1978 |
| | | | JP | 53092582 | A | 14-08-1978 |
| | | | NL | 7713726 | A | 16-06-1978 |