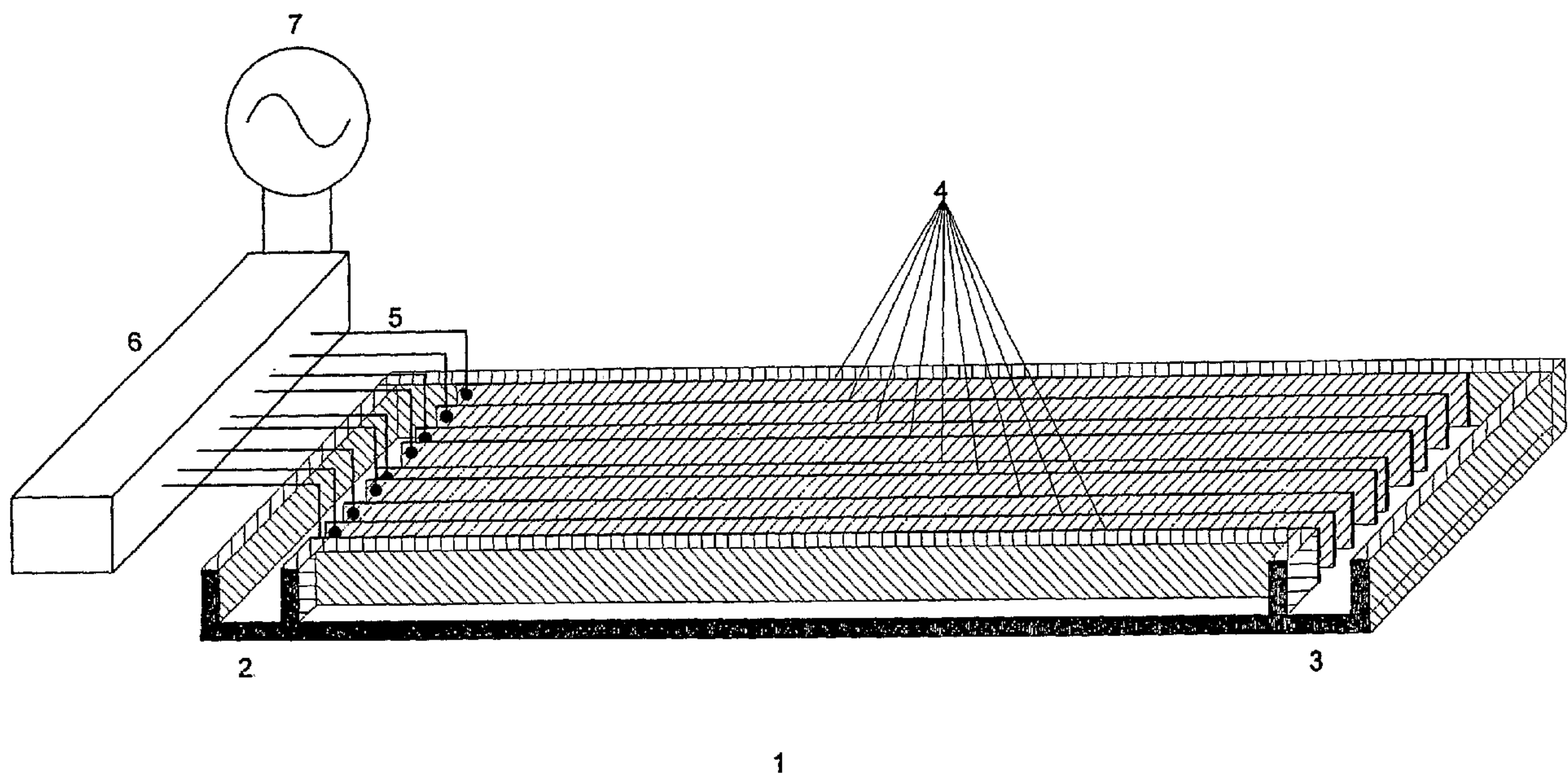




(86) Date de dépôt PCT/PCT Filing Date: 2006/05/03  
(87) Date publication PCT/PCT Publication Date: 2006/11/09  
(45) Date de délivrance/Issue Date: 2014/01/14  
(85) Entrée phase nationale/National Entry: 2007/11/02  
(86) N° demande PCT/PCT Application No.: US 2006/017172  
(87) N° publication PCT/PCT Publication No.: 2006/119440  
(30) Priorités/Priorities: 2005/05/04 (US60/677,552);  
2005/08/19 (US60/709,528); 2005/10/13 (US60/726,473);  
2006/02/10 (US11/352,184)

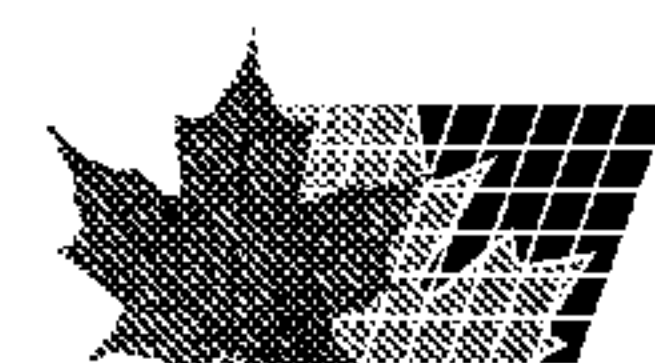
(51) Cl.Int./Int.Cl. *H05B 7/144* (2006.01)  
(72) Inventeurs/Inventors:  
CALLAHAN, JEREMIAH M., US;  
BARZYK, JAMES, US;  
BOWERS, JOHN HENRY, US  
(73) Propriétaire/Owner:  
ISI TECHNOLOGY, LLC, US  
(74) Agent: BORDEN LADNER GERVAIS LLP

(54) Titre : DISPOSITIF DE CHAUFFAGE DE LIQUIDE A RESISTANCE ELECTRIQUE  
(54) Title: DIRECT ELECTRIC RESISTANCE LIQUID HEATER



(57) Abrégé/Abstract:

The Direct Electric Resistance Liquid Heater comprises a liquid heating chamber containing a plurality of electrodes. The electrodes are spaced apart to create a plurality of channels through which the liquid to be heated passes. The electrodes are each connected to a power supply by one or more switches. A controller controls the switches based upon data received from a temperature sensor, sensing the temperature of the liquid, and/or an electric current sensor, sensing the current utilized by the liquid heater. Selection of the number and spacing of the electrodes, and the number of switches, provides the controller with various current levels options to apply to the liquid to be heated. The current levels available due to the number and spacing of the electrodes and the number of switches, span the range from minimum current to maximum current such that the controller can incrementally increase or decrease the current applied to the liquid to be heated without disrupting other users of the same power source.





## (12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
9 November 2006 (09.11.2006)

PCT

(10) International Publication Number  
**WO 2006/119440 A2**

(51) International Patent Classification:  
**H05B 7/144** (2006.01)

(21) International Application Number:  
PCT/US2006/017172

(22) International Filing Date: 3 May 2006 (03.05.2006)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

|            |                               |    |
|------------|-------------------------------|----|
| 60/677,552 | 4 May 2005 (04.05.2005)       | US |
| 60/709,528 | 19 August 2005 (19.08.2005)   | US |
| 60/726,473 | 13 October 2005 (13.10.2005)  | US |
| 11/352,184 | 10 February 2006 (10.02.2006) | US |

(71) Applicants and

(72) Inventors: **CALLAHAN, Jeremiah, M.** [US/US]; 1655 Middle Street, Sullivan's Island, South Carolina 29482-8739 (US). **BARZYK, James** [US/US]; 844 Woodlawn Avenue, Naperville, Illinois 60540 (US).

(74) Agent: **DARDEN, Allen, D.**; P.O. Box 4412, Baton Rouge, LA 70821-4412 (US).

(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

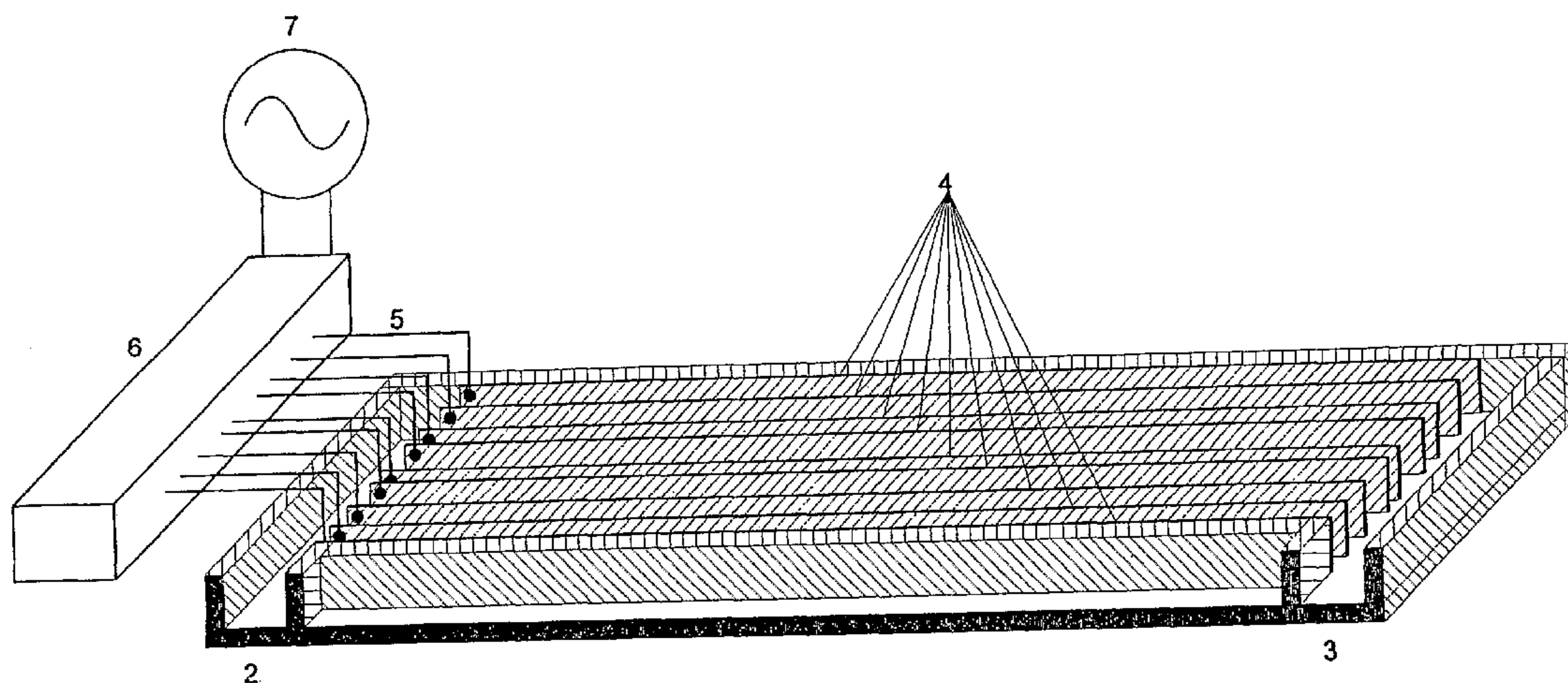
(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

**Published:**

— *without international search report and to be republished upon receipt of that report*

*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

(54) Title: DIRECT ELECTRIC RESISTANCE LIQUID HEATER



(57) Abstract: The Direct Electric Resistance Liquid Heater comprises a liquid heating chamber containing a plurality of electrodes. The electrodes are spaced apart to create a plurality of channels through which the liquid to be heated passes. The electrodes are each connected to a power supply by one or more switches. A controller controls the switches based upon data received from a temperature sensor, sensing the temperature of the liquid, and/or an electric current sensor, sensing the current utilized by the liquid heater. Selection of the number and spacing of the electrodes, and the number of switches, provides the controller with various current levels options to apply to the liquid to be heated. The current levels available due to the number and spacing of the electrodes and the number of switches, span the range from minimum current to maximum current such that the controller can incrementally increase or decrease the current applied to the liquid to be heated without disrupting other users of the same power source.

WO 2006/119440 A2



## Direct Electric Resistance Liquid Heater

### 1 Field of Invention

2 This invention is directed towards an electrically powered tankless electrically  
3 conductive liquid heater that provides instant, on demand heating of the liquid.

### 4 Background of the Invention and Prior Art

5 The objectives of an electrically powered tankless liquid heating device include, at a  
6 minimum, provision of the heated liquid on demand, regulation of the temperature of the  
7 heated liquid so as not to exceed a maximum temperature set point, operation below a  
8 maximum electrical current set-point, safety of operation, minimal disturbance to the power  
9 supply and low cost to manufacture. Prior art liquid heating devices have attempted to  
10 achieve these objectives, but have been only partially able to do so.

11 Most prior art electrically powered tankless liquid heating devices use resistance type  
12 electrical heating elements to heat the liquid. Although the use of electrical heating elements  
13 is well known and widely practiced, in tankless liquid heating devices, they suffer from  
14 considerable disadvantages. One of the most important of these is the occurrence of “dry  
15 firing”, i.e., operation of the heating element when it is not completely immersed in the  
16 liquid, or when excessive deposits are formed along the surface of the heating element, thus  
17 enabling operation of the heating element outside of its safe temperature range and  
18 introducing the possibility of shortened life span, element failure, system meltdown, or even  
19 fire. Additional functional and costly components are required to address this. Maus, in US  
20 Patent 4,900,896, provides an example of such a heater. A flow detection switch (which  
21 must carry the entire electrical current consumed by the heating elements) detects the  
22 condition of no water flow, thus preventing dry firing of the heating elements where there is  
23 insufficient water in the heating chamber. However, when the heating element is covered  
24 with deposits that are relatively thermally non-conducting, the thermostat is not thermally



1 connected to the heating element and thus the thermostat does nothing to prevent overheating  
2 of the electric heating element. Other tankless water heaters using electric heating elements  
3 that suffer the same disadvantage and the mechanisms to address it are described in US  
4 Patents 5,216,743 issued to Seitz, 5,325,822 issued to Fernandez, 5,408,578 issued to  
5 Bolivar, 5,479,558 White, Jr. et al, 5,866,880 issued to Seitz et al, 6,080,971 issued to Seitz  
6 et al, US 6,246,831 issued to Seitz et al, and 6,834,160 issued to Chen-Lung et al. The  
7 primary mechanism in '743 is an automatic vapor release outlet to ensure that the  
8 temperature sensors sense liquid temperature. This mechanism clearly does not function  
9 after the heater has been drained for servicing or for periods of no use. In '822, liquid level  
10 sensors are used. However, these are only effective in one mounting orientation of the  
11 heater. '578 provides two ports between two heating chambers to ensure that water enters the  
12 two chambers more or less equally, thereby preventing that one of the heating elements in  
13 one of the chambers can overheat while the other is filling with water. A flow-sensing switch  
14 is also used to prevent application of power unless water flow is detected. However, a flow-  
15 sensing switch is generally expensive and not reliable. '558 uses the combination of a  
16 sophisticated flow detector and thermal sensors, one for regulating temperature, the other for  
17 sensing an over temperature condition. The flow detector uses a plunger that is constrained  
18 to move vertically, thus constraining the heater to installation in only one orientation.  
19 Besides, as described, it is subject to binding and getting stuck in one position, including  
20 possibly a position that indicates the existence of water flow when there is none. This  
21 solution is expensive, unreliable, and suffers the same problems as '896. '880 provides high  
22 temperature limit switches. These are inoperative when there is not a high thermal  
23 conductivity thermal path between heaters and the switches, such as when the heater is  
24 without water. The '971 and '831 patents provide over temperature switches thereby  
25 suffering the previously mentioned disadvantages.



1 Another disadvantage of liquid heaters that utilize resistance type electric heating  
2 elements is that the elements themselves have substantial thermal mass and thermal  
3 resistance. This creates the problem of how to manage the latent heat (the heat which has not  
4 yet escaped) of the elements when the liquid flow rate is abruptly reduced to near zero or  
5 zero. This latent heat must be absorbed by the liquid surrounding the elements. However,  
6 doing so increases the temperature of the surrounding liquid, possibly to an undesirable  
7 extent. Thus, the volume of the heating chambers must be made larger to avoid overheating  
8 of the liquid, for example, to prevent scalding if the liquid heater is a domestic hot water  
9 heater. This is also necessary to stabilize the operation of any temperature control loop or  
10 else high variations in temperature of the heated liquid will occur. However, these larger  
11 heating chambers make it difficult to respond to demand changes, especially when the water  
12 flow rate starts from zero.

13 As previously mentioned, deposits tend to form on the heating elements. Seitz  
14 discloses that the amount of mineral deposition is a function of the maximum heating element  
15 temperature in '880, and thus the desirability of providing power to the heating elements as a  
16 function of the power needed to heat the water passing through the disclosed heater to  
17 minimize such depositions. In the '558 patent, White, Jr. also identifies a different reason for  
18 doing this – to minimize power supply voltage fluctuations due to heater power demands that  
19 can cause flickering of lights. Unfortunately, the best semiconductor devices for controlling  
20 current to electrically powered water heaters are essentially switches (they can be opened and  
21 closed, but they don't provide a means for regulating current), thus making this a significant  
22 problem. White Jr. addresses this by incorporating multiple equally sized heating elements.  
23 However, this only reduces the magnitude of the potential power supply voltage variations by  
24 a factor of the number of heating elements, in the case of his example, four. The '880 patent  
25 echoes this approach. Seitz, in the '971 and '831 patents, discloses various methods for



1 minimizing the power supply variations caused by variations in the heater power demand and  
2 the visible flickering of lights and electrical interference that results there from. These  
3 methods generally relate to the use of multiple heat elements and the timing of the  
4 application of power to them so as to minimize power supply current fluctuations, or to make  
5 these power supply fluctuations such that they are not readily perceived. These lead to a  
6 relatively high level of design complexity and a correspondingly high manufacturing cost.

7 The predominant alternative to using heating elements to heat the liquid is to pass an  
8 electrical current through the liquid by passing it between two electrodes between which a  
9 voltage exists. The voltage is preferably an AC voltage so as to avoid electrolysis of the  
10 liquid. This method is known as direct electrical resistance (DER) heating. Probably the  
11 most common application of this approach (although relatively crude) is in vaporizers used to  
12 humidify room environments. One reason for the popularity of the approach is that it is  
13 intrinsically safe: no electrical current can flow if there is no liquid between the electrodes.

14 One example of a DER liquid heater is disclosed in US patent 6,130,990 issued to  
15 Herrick et al for use in a beverage dispenser. The advantages of "rapid and efficient transfer  
16 of electrical energy into the water as thermal energy while reducing the energy loss  
17 associated with indirect heating methods" are disclosed. One of the disadvantages of the  
18 DER method, however, is that the amount of electrical current drawn by the liquid between  
19 the electrodes, and therefore the amount of heat delivered to the liquid, is determined by the  
20 electrical conductivity of the liquid, a parameter that can vary quite widely, for example 10 to  
21 1. One method of controlling the temperature contemplated in this patent is by varying the  
22 water flow rate. Another is by varying the electrical power delivered to the water, which  
23 would require varying the power supply voltage. A third involves mechanically adjusting the  
24 distance between the electrodes. It is evident that accommodating such wide range of liquid  
25 conductivities by any of these methods is quite difficult. In fact, the inventors contemplate



1 the possibility of treating the water with minerals prior to passing it through the heater in  
2 order to increase the water conductivity. In US patent 6,522,834 also issued to Herrick et al,  
3 which is a continuation in part of the '990 patent, a new element, a power supplier, is  
4 introduced specifically to overcome this issue. Essentially, it is a power converter that  
5 receives power from a convention power supply (for example, 220VAC @ 60Hz), and  
6 converts it such that the output voltage is adjustable and which may have a frequency range  
7 from 50Hz to 200KHz. This was apparently driven by the need to accommodate the large  
8 range of water conductivities and the inadequacy of the other previously mentioned methods.  
9 US patent 6,640,048 issued Novotny et al discloses a DER liquid heater that provides another  
10 adjustment mechanism that addresses the wide range of liquid conductivities. It  
11 mechanically varies the area of the electrodes (and the effective distance between them) by  
12 adjustably interposing an electrically non-conducting current gating plate between the  
13 electrodes, thus adjusting the electrical conductance of the heating zone comprising the  
14 electrodes and the liquid between them. However, no disclosure of the range of adjustability  
15 of the device is disclosed. Furthermore, the mechanical adjustment involves the translation  
16 of motion across a liquid to air barrier, something that is difficult to achieve reliably and at  
17 low cost.

18 DER liquid heaters must also address other difficulties that are in common with  
19 heaters utilizing resistance type electrical heating elements. An example of these is the use of  
20 a flow switch to control the application of power to the heater. Flow switches are generally  
21 characterized by a flow rate threshold, below which they do not indicate a flow, although a  
22 low flow may be present. This allows for unheated liquid to leave the heater at low flow  
23 rates (unlike conventional tank type heaters), and it tends to generate a delay between the  
24 time liquid flow is demanded and the time fully heated liquid is finally delivered thus  
25 creating a wastage of liquid. This, together with the presence of orientation limitations,



1 unreliable functioning and cost must be overcome in a tankless liquid heating device that  
2 meets the objectives cited above. Additionally, the previously mentioned difficulties  
3 associated with latent heat management, the design and operation of temperature control  
4 loops, formation of deposits, and minimization of power supply variations and the  
5 corresponding light flicker must be overcome.

## 6 **Brief Description of the Invention**

7 In the present invention these and other difficulties, as will become apparent, are  
8 overcome in a direct electrical resistance liquid heater having many unique and previously  
9 undisclosed aspects. In one aspect, the invention comprises a liquid heating chamber with a  
10 liquid inlet and a liquid outlet in which a plurality of thin, spaced apart electrodes comprise  
11 an electrode array, the electrodes defining a plurality of channels, the spaces between the  
12 electrodes, through each of which liquid flows from the inlet to the outlet, and in which the  
13 liquid is heated when a voltage is connected between one or more pairs of electrodes. The  
14 use of thin electrodes avoids the creation of significant amounts of latent heat thus helping to  
15 minimize the potential response time to liquid flow rate or conductivity changes.

16 In a second aspect, the invention provides electrically operable switches connected  
17 between the electrodes and an AC power supply, the switches operated by a controller that  
18 selectively opens or closes the switches according the heating demand. The switches are  
19 closed for periods comprising one or more full AC cycles

20 In a third aspect of the invention, the switches can connect the power supply to one or  
21 more pairs of electrodes with one or more unconnected electrodes between a connected pair,  
22 or alternatively, according to signals provided by the controller to the switches and the  
23 configuration of connections determined by it to provide the necessary power, can connect  
24 the power supply to adjacent electrodes alternately (adjacent electrodes are connected to



1 opposite sides of the power supply and all electrodes are connected) such that the maximum  
2 current flows through every channel defined by the electrodes.

3 In a fourth aspect of the invention, the spacing between the electrodes is non-uniform,  
4 i.e., each and every channel width is different from the other channel widths.

5 In a fifth aspect of the invention, choice of electrode spacings or channel widths is  
6 such that a maximum number of more or less logarithmically spaced electrical current or  
7 power levels can be achieved with the appropriate selection switch connection  
8 configurations.

9 In a sixth aspect of the invention, an adequate number of current levels are defined,  
10 over a full range of liquid conductivities, to enable good operation of a temperature control  
11 loop and to provide current control such that a preset maximum current is not exceeded but is  
12 closely approached.

13 In a seventh aspect of the invention, the electrode spacings are chosen so as to cause a  
14 maximum semiconductor switch current that is minimized or selected so as to be able to  
15 utilize low cost semiconductor switches.

16 In an eighth aspect, the invention provides a thermal sensing element comprising a  
17 highly thermally conductive temperature sensing plate disposed at the hot end of the heating  
18 chamber within a short distance of the electrodes such that it is orthogonal to the liquid flow  
19 and such that the liquid passes through perforations in the temperature sensing plate, the  
20 temperature sensing plate thereby providing a good indication of the liquid temperature at the  
21 hot end of the heating chamber.

22 In a ninth aspect, a temperature sensor is thermally coupled to the sensing plate, the  
23 temperature sensor being a semiconductor junction such as that in a diode or bipolar  
24 transistor. The performance of these is highly repeatable.



1 In a tenth aspect of the invention, the controller senses and acts upon at least the  
2 temperature as measured by the temperature sensor and its rate of change.

3 In an eleventh aspect of the invention, the controller adjusts a maximum of one  
4 current level step every AC cycle. This together with the relatively small size of the current  
5 level steps provided by the invention avoids rapid changes in the current drawn from the  
6 power supply and eliminates light flicker.

7 In a twelfth aspect of the invention, the electrically operable switches are  
8 semiconductor switches the packages of which are both electrically and thermally coupled to  
9 the electrodes such that transfer of electrical energy and thermal energy occurs from the  
10 semiconductor switch to the electrode. The electrode is used to cool the semiconductor  
11 switch.

12 In a thirteenth aspect of the invention, the electrodes comprise the combination of  
13 oriented graphite and a small percentage of polymer and/or elastomer that acts to bind the  
14 graphite into a solid piece. This makes the electrodes mechanically robust and virtually  
15 eliminates problems with corrosion. These electrodes are also highly electrically and  
16 thermally conductive within the plane of the electrodes.

17 In a fourteenth aspect of the invention, the average rate of liquid flow is chosen to be  
18 such that it is approximately at the point at which turbulence begins. This tends to resist the  
19 formation of deposits on the electrodes. The selection of channel dimensions is a function of  
20 both the turbulence properties of the liquid flow and the electrical properties of the heating  
21 chamber, as described above. This results in a unique range of channel dimensions that  
22 simultaneously satisfy all of the requirements once the relative proportions of the channel  
23 widths have been established.

24 In a fifteenth aspect, the invention provides electrical current leakage current  
25 electrodes, one between the inlet and the heating chamber and the other between the



1 temperature sensor and the outlet. These electrodes are connected to each other and to an  
2 electrically neutral voltage source.

3 In a sixteenth aspect, the invention provides a direct electric resistance liquid heater  
4 that does not incorporate a flow switch and is orientation independent. Control of heating  
5 power is determined strictly by the liquid temperature at the end of the heating chamber and a  
6 maximum current setpoint.

7 Details of the invention are provided below with reference to the accompanying  
8 Figures.

## 9 **Brief Description of the Drawings**

10 Figure 1 is a schematic drawing of the DER liquid heating chamber, including the inlet,  
11 outlet, electrode array and the channels through which the liquid passes. The power source  
12 and switch matrix are also shown.

13 Figure 2 is a more detailed schematic of switch matrix.

14 Figure 3 is a graph showing the distribution of relative electrical current levels for various  
15 switch matrix configurations when the electrodes are equally spaced.

16 Figure 4 is a graph that shows relative current levels for a selection of switch matrix  
17 configurations with optimally spaced electrodes.

18 Figure 5 is a functional block diagram of the DER liquid heater including a current sensor,  
19 temperature sensing element, and controller.

## 20 **Detailed Description of the Invention**

21 Figure 1 shows essential elements of the present invention. A liquid heating chamber  
22 1 is shown comprising a liquid inlet 2, a plurality of electrodes 4 (the electrode array), the  
23 electrodes defining a plurality of channels, the spaces between the electrodes, through each of  
24 which liquid flows from the liquid inlet 2 to the liquid outlet 3, the liquid being heated when



1 it flows through the channels and a voltage is applied between electrodes. For clarity, the  
2 liquid heating chamber is shown with a bottom but without a top so that the electrodes and  
3 the channels defined by them can more clearly be seen. The electrodes 4 are shown in Figure  
4 1 as having a non-uniform or unequal spacing, which will be explained later. The electrodes  
5 4 are connected via connections 5 to switch matrix 6 via which AC electrical power 7 is  
6 communicated to the electrodes. The electrodes 4 are thin relative to the width of the  
7 channels. The electrodes 4 are preferably thinner than the width of the narrowest channel.  
8 This minimizes the amount of latent heat that can be stored in the electrodes and provides  
9 some balancing of the heating in the heating chamber in that heat created in one channel can  
10 be communicated through the electrodes to adjacent channels.

11 Figure 1 also shows some aspects that are exemplary and not to be construed as  
12 limiting. For example, the electrodes are shown as planar and parallel. This is not a limit to  
13 the scope of the invention. For example, the electrodes may be sections of cones of different  
14 radii coaxially located such that the required plurality of channels is formed (in this case the  
15 channels will also be conical) and be within the scope of the present invention. Any  
16 geometric configuration of electrically unconnected electrodes that defines a plurality of  
17 channels through each of which a liquid may be passed from the liquid inlet 2 to the liquid  
18 outlet 3 and which provides an electrically conductive path between the two endmost  
19 electrodes when an electrically conductive liquid is in the channels and the interposed  
20 electrodes are electrically unconnected is within the scope of the present invention.

21 Figure 2 shows the details of the switch matrix 6 and its connections to power supply  
22 7. Shown are two switches 8 for each connection 5 to the electrodes, one of the two switches  
23 connected to one side or phase of the AC power supply 7 and the other of the two switches  
24 connected to the second side or phase of the AC power supply 7. However, a multiple phase  
25 power supply be used with as many switches per connection 5 as exist phases of the power



1 supply. For example, with a three-phase power supply, there may be up to three switches per  
2 connection 5. All of the switches 8 are individually operable by their respective control  
3 signals 9. The switches 8 are any kind of electrically operable switch, i.e., a switch that  
4 utilizes an electrical input signal to operate the switch. Examples of suitable switches include  
5 relays and, more preferably, semiconductor switches such as triacs.

6 In operation, the switches are selectively closed by a controller, thereby placing the  
7 power supply voltage between electrodes. The power delivered to heat the liquid between  
8 the electrodes, generally proportional to the current drawn from the power supply, is a  
9 function of 1) the spacing between the electrodes and 2) the number of electrode pairs to  
10 which power is applied through switches 7. The switch matrix 6 of the present invention  
11 provides great flexibility in this regard. For example, when the minimum current is required,  
12 one of the switches 8 electrically connected to a first endmost electrode 4 (one of the two that  
13 define only one channel) is closed, thereby connecting the electrode to a first side of the  
14 power supply and one of the switches 8 electrically connected to the opposite endmost  
15 electrode (the electrode most distant from the first endmost electrode) is closed such that it is  
16 connected to a second side of the power supply. All of the other switches 8 remain open and  
17 therefore the electrodes 4 interposed between the endmost electrodes remain electrically  
18 unconnected. This places the maximum distance between the electrodes to which the voltage  
19 source can be connected, thereby causing the electrical conductance between the cells to be  
20 minimized and likewise the electrical current and therefore the power delivered to the liquid  
21 for heating to be likewise minimized. It is possible to increase the electrical current by  
22 connecting the power supply to an electrode via one of the switches 8 that is physically and  
23 closer to the first electrode. Thus, the present invention provides for adjusting the current,  
24 and power delivered for heating, according to the separation between the electrodes to which  
25 voltage is applied.



1       Applying the voltage of power supply 7 via switches 8 between two adjacent  
2 electrodes maximizes the amount of electrical current that is passed through the channel  
3 defined by them. It is also possible to adjust the liquid heating power by applying the voltage  
4 of power supply 7 power to one or more pairs of adjacent electrodes. Thus, in addition to the  
5 liquid heating power adjustment based upon distance between the electrodes to which voltage  
6 is applied, the present invention provides for adjustment of the total liquid heating power by  
7 controlling the number of pairs of electrodes that are simultaneously connected to the power  
8 supply through switch matrix 6. The concurrent use of both methods for controlling the  
9 heating power provides a much larger range of control of liquid heating power than can be  
10 achieved by either method by itself and therefore provides a way in which overcome the  
11 difficulty of a large range of liquid electrical conductivities and liquid flow rates.

12       It will be apparent to those skilled in the art that there are a large number of possible  
13 combinations of switch positions or switch configurations, i.e., 2 raised to the power of the  
14 number of switches. It is also apparent that some of these switch configurations are not  
15 useful. For example, it not useful to close a switch connected to an electrode that causes it to  
16 be connected to the same side of the power supply that electrodes on both sides of it are  
17 connected to, as this performs no useful function because there is no electrical field generated  
18 between the electrodes and therefore no current will flow through the switch connected  
19 electrode. Additionally, it is not useful to simultaneously close two switches connected to the  
20 same electrode as this will simply short the power supply. Switches are also relatively  
21 expensive components, so it is desirable to minimize their number. In a preferred  
22 embodiment of the invention, therefore, it is desirable to minimize the number of switches  
23 and switch combinations used. Most preferably, there is one switch per electrode, the  
24 switches connecting the electrodes to different terminals of the power supply in a round robin  
25 pattern, or if there are only two power supply terminals, in an alternating pattern.



1 Comprising switch matrix 6 with one switch per electrode can normally provide an adequate  
2 number of switch configurations and corresponding current levels. However, there may be  
3 situations where the increase in the number of switch configurations is sufficiently  
4 worthwhile to justify more fully or fully populating the switch matrix 6 with more or all of  
5 the possible number of switches for making electrical connection between the electrodes and  
6 the power supply.

7 Although the use of a plurality of electrodes 4, the plurality of channels, and the  
8 associated switch matrix 6 has been demonstrated to provide a large ratio between the  
9 maximum and minimum currents and power levels for heating, this is still not sufficient to  
10 make a DER liquid heater that meets the objectives of this invention. Provision of uniform  
11 spacing between the electrodes 4 (provision of equal channel widths) does not yield  
12 uniformly spaced current operating points between switch matrix configurations. Figure 3  
13 shows the distribution of relative current levels for a DER liquid heater comprising 17  
14 electrodes with equal spacings between the electrodes 4. Although a more than adequate  
15 250:1 range of currents is achieved, there is a large portion of this range for which no switch  
16 configuration exists that can yield an intermediate current. In this example, there is a 20 to 1  
17 range of currents for which for which no switch configuration is available. It is impossible to  
18 obtain, for example, a current that is 25% of the maximum current. This current level is one  
19 that could be quite useful if the liquid flow rate is reduced to 25% or if the liquid conductivity  
20 is four times that of the minimum liquid conductivity. Not having this current level means  
21 that the average 25% current level has to be achieved by cycling between two current levels  
22 that are quite different and which therefore can create power supply fluctuations and  
23 accordingly light flickering. Thus, the use of uniformly spaced electrodes does not satisfy the  
24 objectives of this invention.



Utilization of non-uniformly spaced electrodes overcomes this difficulty. Selection of the spacing between electrodes can be such that a selection of switch matrix configurations that yield more or less logarithmically uniformly spaced current steps can be achieved. An example of such spacings is discussed later in the description of a preferred embodiment of the invention. The inventors do not know of any method by which the optimum electrode spacings can be analytically calculated and are therefore unable to present such a method. Suitable electrode spacings were "discovered" using a genetic optimization algorithm that had as its objective to minimize the ratio of currents of the largest current step. Other methods for determining an adequate set of electrode spacings also exist. It is the inventors' opinion that adequate electrode spacings should preferably yield a maximum current step size of 10% or less of the maximum current, and a maximum ratio between the two current levels of any step of 1.2, whichever is smaller, between selected switch matrix configurations with optimum electrode spacings. However, any set of electrode spacings and current steps that meet the objectives of the invention are intended to be within its scope.

The electrically operable switches preferably comprise semiconductor switches and most preferably comprise triacs. Given their number, it is likely that the cost of the triacs will comprise a significant portion of the parts cost of the liquid heater. The cost of triacs is related to the maximum current that they can handle: higher current capacity triacs cost more. It is therefore desirable to minimize the maximum current requirements for the triacs. The inventors have found that just optimizing the electrode spacing for current step size does not automatically yield a set of electrode spacings that also yields the lowest maximum triac current. However, the inventors have discovered that, using the same genetic optimization algorithm, by adding the additional objective of a maximum triac current, it is possible to generate electrode spacings that simultaneously satisfy the current step size requirements and the maximum triac current requirements. Accordingly, in a most preferred embodiment of



1 the invention, a maximum triac current requirement (so that the lowest cost triac may be  
2 used) and current step size requirements are simultaneously satisfied by selection of the  
3 electrode spacings. Figure 4 shows the relative currents achieved from a selection of switch  
4 configurations with an optimized set of electrode spacings. With these spacings, the  
5 constraint of a maximum triac current has been achieved, the range of currents provided is  
6 308 to 1, and the average current step ratio is approximately 1.10 and the maximum current  
7 step ratio is 1.22. The current control range and the step sizes are more than adequate to  
8 closely control the temperature of the heated liquid without causing excessive power supply  
9 load changes and corresponding light flickering. Additionally, the electrode spacings make  
10 possible the operation of the liquid heater at a current that is quite close (5% nominally, 10%  
11 worst case) to a current set-point, the current set-point being the maximum current that the  
12 liquid heater can draw, without having to rapidly switch between quite different current  
13 levels (in order to achieve the set-point current by averaging) and thereby cause the  
14 aforementioned light flickering.

15 An example of the invention will now be discussed. The DER heater of this example  
16 was designed to heat water with conductivities of 200 $\mu$ S/cm to 1500 $\mu$ S/cm at flow rates of  
17 0.6 gallons per minute to 2.5 gallons per minute and operate from a 220VAC power supply.  
18 It was a standard point of use water heater for domestic applications. It comprised 17  
19 electrodes that were 0.9mm thick by 340mm long. The channel height, i.e., the height of the  
20 electrodes exposed to the liquid (which may be less than the actual physical height of the  
21 electrodes in order to accommodate mounting of them) was 8.6mm. The electrode array  
22 comprised sequentially numbered electrodes having the following inter-electrode spacings:

23  
5.49mm  
1.49mm  
5.76mm  
6.22mm  
1.19mm



5.77mm  
3.82mm  
5.04mm  
5.37mm  
3.15mm  
6.78mm  
6.12mm  
5.49mm  
6.91mm  
3.69mm  
5.11mm

1  
2 between electrodes numbered 1 and 2, 2 and 3, 3 and 4 respectively through electrodes  
3 numbered 16 and 17. These electrode dimensions and spacings resulted in a DER liquid  
4 heater having the current control points shown in Figure 4 where the maximum total current  
5 was 55A and the maximum triac current was 15.5A when the liquid conductivity was  
6 between 200 $\mu$ S/cm and 1500 $\mu$ S/cm with a 220VAC power supply.

7 A preferred embodiment of the invention has additional aspects and features that  
8 make the invention even more useful. Referring now to Figure 5, a current measurement  
9 device 11 is made part of the liquid heater. AC power 7 is communicated to switch matrix 6  
10 via current measurement device 11. A current signal 13, indicative of the current measured  
11 by the current measurement device 11, is communicated to the controller 10. The current  
12 measurement device 11 and the current signal 13 are used by the controller 10 to respond to  
13 the measured current by adjusting switch matrix 6 configuration such that the measured  
14 current does not exceed the current set-point. In this way, the maximum current drawn by the  
15 DER liquid heater can be controlled, independently of the liquid conductivity or temperature.

16 Additionally, a temperature-sensing element 12 is disposed at the end of the heating  
17 chamber, prior to outlet 3, and generates a temperature signal 14 indicative of the heated  
18 liquid temperature. The heated liquid temperature signal 14 is communicated to controller 10  
19 which responds to it by adjusting the configuration of switch matrix 6 such that the water  
20 temperature is maintained as close as possible to a temperature set-point, but which, in any



case, does not exceed it. The matrix switch configuration is always set such that current set-point takes priority over the temperature set-point. In other words, regardless of the demand for power to heat the liquid to the temperature set-point, the controller prevents drawing more current from the AC power supply 7 than the current set-point.

A power supply (not shown) of well known art for converting the high voltage AC from power supply 7 to a low voltage DC supply suitable for providing power to the controller 10 and other electronic control elements, as required, is also provided. These elements are sufficient to implement a DER liquid heater that meets all of the objectives of the invention.

More details of the example of the invention will now be described for purposes of clarification and to elucidate further improvements of the invention. The switch matrix comprised triacs, one per electrode, connected to the power supply in alternating fashion, i.e., adjacent electrodes were connected to opposite terminals of a two terminal power supply.

The controller comprised a counter to control the power level, in other words, a power level counter, the value of which determined the power level to be applied to the electrodes 4 via the switch matrix 6. The operation of the power level counter was according to the following algorithm that was executed once every cycle of the power supply waveform:

```

if current signal >= current set-point then decrement the power level counter
else
    if temperature signal = temperature set-point then don't change the power level counter
    else
        if temperature signal > temperature set-point then decrement the power level counter
        else
            increment the power level counter

```

This algorithm is strictly exemplary and any method of achieving the same operative results is within the scope of the present invention. The counter had a range of values corresponding to power levels between zero power and a maximum power level. The algorithm also incorporated a mechanism to ensure that the operating range of the counter was not exceeded.



1 The values of the counter are converted to switch matrix control signals 9 by any suitable  
 2 means. For the present example, the following look-up table was used:

3

| power level | SW17 | SW16 | SW15 | SW14 | SW13 | SW12 | SW11 | SW10 | SW9 | SW8 | SW7 | SW6 | SW5 | SW4 | SW3 | SW2 | SW1 |
|-------------|------|------|------|------|------|------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0           | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 1           | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0   |
| 2           | 0    | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 0   |
| 3           | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 0    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   |
| 4           | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 0   |
| 5           | 0    | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   |
| 6           | 0    | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0   |
| 7           | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 8           | 0    | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 0   |
| 9           | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   |
| 10          | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 1    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 11          | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 1   | 0   |
| 12          | 0    | 0    | 0    | 0    | 0    | 1    | 0    | 0    | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   |
| 13          | 0    | 1    | 0    | 0    | 0    | 0    | 1    | 0    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 14          | 0    | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 15          | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 1    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   |
| 16          | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 1    | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 0   |
| 17          | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 1    | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 0   |
| 18          | 0    | 0    | 1    | 0    | 0    | 0    | 0    | 1    | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 0   |
| 19          | 0    | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 1   | 0   |
| 20          | 0    | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 1   |
| 21          | 1    | 0    | 0    | 0    | 0    | 1    | 0    | 0    | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   |
| 22          | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 1    | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   |
| 23          | 0    | 1    | 0    | 0    | 0    | 0    | 1    | 0    | 1   | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 0   |
| 24          | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 0    | 1   | 0   | 1   | 0   | 0   | 0   | 0   | 1   | 0   |
| 25          | 0    | 1    | 0    | 0    | 1    | 0    | 1    | 0    | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 0   |
| 26          | 0    | 0    | 0    | 1    | 0    | 0    | 1    | 0    | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 1   | 0   |
| 27          | 1    | 0    | 0    | 0    | 0    | 1    | 0    | 0    | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 1   |
| 28          | 0    | 0    | 1    | 0    | 0    | 0    | 0    | 1    | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 1   |
| 29          | 0    | 0    | 0    | 1    | 0    | 0    | 1    | 0    | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 1   | 0   |
| 30          | 0    | 1    | 0    | 0    | 1    | 0    | 0    | 0    | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 1   |
| 31          | 0    | 0    | 0    | 1    | 0    | 1    | 0    | 0    | 1   | 0   | 1   | 0   | 0   | 0   | 0   | 1   | 0   |
| 32          | 0    | 1    | 0    | 0    | 0    | 0    | 0    | 1    | 0   | 0   | 1   | 0   | 1   | 0   | 0   | 1   | 0   |
| 33          | 0    | 1    | 0    | 0    | 1    | 0    | 1    | 0    | 0   | 0   | 0   | 1   | 0   | 0   | 1   | 0   | 0   |
| 34          | 1    | 0    | 0    | 1    | 0    | 0    | 1    | 0    | 1   | 0   | 0   | 0   | 0   | 1   | 0   | 1   | 0   |
| 35          | 0    | 0    | 1    | 0    | 0    | 0    | 0    | 1    | 0   | 1   | 0   | 0   | 0   | 1   | 0   | 0   | 1   |
| 36          | 0    | 1    | 0    | 0    | 1    | 0    | 0    | 0    | 0   | 1   | 0   | 0   | 0   | 1   | 0   | 0   | 1   |
| 37          | 1    | 0    | 0    | 1    | 0    | 0    | 0    | 0    | 1   | 0   | 1   | 0   | 0   | 1   | 0   | 0   | 1   |
| 38          | 1    | 0    | 0    | 1    | 0    | 1    | 0    | 0    | 1   | 0   | 1   | 0   | 0   | 1   | 0   | 0   | 0   |
| 39          | 0    | 1    | 0    | 0    | 1    | 0    | 0    | 0    | 1   | 0   | 0   | 1   | 0   | 1   | 0   | 0   | 1   |
| 40          | 1    | 0    | 0    | 1    | 0    | 1    | 0    | 1    | 0   | 0   | 1   | 0   | 1   | 0   | 0   | 1   | 0   |
| 41          | 0    | 0    | 1    | 1    | 0    | 1    | 1    | 0    | 1   | 0   | 0   | 0   | 0   | 1   | 0   | 1   | 0   |



|    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|----|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 42 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 43 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 |
| 44 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| 45 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 |
| 46 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| 47 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 48 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 |
| 49 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| 50 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| 51 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| 52 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| 53 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 |
| 54 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 |
| 55 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 |
| 56 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |
| 57 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 |
| 58 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 |
| 59 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 |
| 60 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| 61 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 |
| 62 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 |
| 63 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| 64 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 65 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

1  
2 where '0' means that the switch was operatively open and '1' means that the switch was  
3 operatively closed and SW1 through SW17 refer to the switches connected to electrodes 1  
4 through 17 respectively. At power level 0, all of the switches 6 were open and no power was  
5 applied for heating the liquid. At power level 65, all of the switches 6 were closed and  
6 maximum power was applied for heating liquid. The intermediate power levels correspond  
7 to the relative current levels shown in Figure 4. For many of the power levels, the selection  
8 of switch matrix 6 configuration is not unique. There sometimes exist other switch matrix  
9 configurations that yield identical or similar currents. In fact, the choice of relative current  
10 for any power level is somewhat arbitrary in that, for many power levels, there exist lower or  
11 higher power levels that can be achieved with other switch combinations that are so close to  
12 the selected power level so as to be essentially equivalent. In general, the choices that were  
13 made in the exemplary table were driven by the desire to involve as many electrodes as



1 possible in heating the liquid at any given power level or to involve the greatest width of the  
2 heating zone as defined by the distance between the two electrodes to which power is  
3 applied. However, other trade-offs may also apply to the choice of power levels and switch  
4 configurations that could change the selection of entries in the look up table. Furthermore, it  
5 is also possible that a power level in the look-up table to correspond to more than one entry,  
6 such as in a linked list. In this case, it is possible for the controller to cycle through the  
7 various entries for a given power level so as to possibly more evenly distribute the heating  
8 within the heating chamber. Thus, the above look up table is meant to be purely exemplary.

9 In a broader view of the invention, a power level value is increased or decreased  
10 according to the measured current and measured temperature such that the measured current  
11 is maintained at a level below or equal to the current set-point, and that, when possible, the  
12 measured liquid temperature is maintained at the temperature set-point and the power level  
13 value is converted into switch matrix 6 configurations so as to deliver the desired heating  
14 power to the liquid. The power level value may be any electronically representable value, for  
15 example, a digital number, an analog voltage or analog current, and the translation of the  
16 power level value to switch matrix configuration is by any suitable mechanism.

17 The algorithm was executed once per every cycle of the AC power supply 7 and thus  
18 caused the maximum rate of change of the load to the power supply to be nominally 10% per  
19 cycle in this example of the invention. It took 65 cycles to effect a change of current from  
20 zero current to maximum current (over 1 second for a 50Hz or 60Hz power supply). This  
21 slow rate of change essentially eliminated power supply voltage fluctuations that can lead to  
22 flickering of lights, yet, because of the small current step ratios which enable the system to  
23 find an optimum power level, it was more than fast enough to regulate the temperature of the  
24 liquid. In addition, the triacs were operatively closed at the zero crossing of the power supply  
25 waveform, as is known and customary, thereby creating virtually no electromagnetic or radio



1 frequency interference, and eliminating the need for additional filtering components.

2 Additionally, an optimal resistive load was always presented to the power supply.

3 In a preferred embodiment of the invention, the temperature-sensing element 12  
4 comprises a perforated thermally conductive temperature sensing plate, a semiconductor  
5 junction based temperature sensor, and a temperature signal conditioner. The plate is placed  
6 as close as practicable to the end of the heating chamber and perpendicular to the flow of the  
7 liquid such that the liquid leaving the heating chamber must pass through the perforations in  
8 the temperature sensing plate. Assuming that the plate is electrically conductive, the limit to  
9 how close the plate can be placed to the ends of the electrodes is based upon non-interference  
10 of the plate with normal heating operation of the electrodes. A suitable non-electrically  
11 conductive plate may be used. In this case, it may be desirable to align the perforations of the  
12 plate with channels defined by the electrodes 4 and place it immediately at the exit end of the  
13 channels defined by them. There are two objectives that the design of the temperature  
14 sensing plate and its placement achieves. The first is that the temperature of the liquid in the  
15 heating chamber is accurately sensed, even when there is no liquid flow. The second is that,  
16 even in the presence of gas bubbles and independent of heater orientation, the temperature of  
17 the liquid that flows from the outlet 3 is accurately sensed.

18 Although thermistors or thermocouple junctions may suitably be used as the  
19 temperature sensor of the present invention, a semiconductor junction, such as a diode or the  
20 base-emitter junction of a transistor is preferred for reasons of low cost, easy availability and  
21 a high degree of repeatability that eliminates the need for calibration. The semiconductor  
22 junction may be a separate component or incorporated as part of a larger integrated circuit  
23 that may also contain some or all of the temperature signal conditioner. The temperature  
24 signal conditioner converts the voltages from the temperature sensor to a temperature signal  
25 suitable for the controller. Additionally, it at least partially compensates for the thermal lag



1 or delay seen between the temperature of the heated liquid and that sensed by the thermal  
2 sensor because of the combination of thermal resistance of the thermal plate and packaging of  
3 the thermal sensor and the thermal mass of them. This conditioning is well known art and  
4 typically involves creating a signal representative of the rate of change of the temperature as  
5 measured by the temperature sensor and summing this with the signal representing the  
6 temperature as measured by the temperature. This compensation helps to stabilize the  
7 operation of the temperature control loop. The temperature signal conditioner may also  
8 partially or wholly exist within the controller if that is more suitable. In any case, it is most  
9 desirable that the temperature signal communicated to the portion of the controller that  
10 implements the method for selecting the power level be as accurate an indication of actual  
11 liquid temperature as possible.

12 In another feature of the example, the semiconductor switches 8 were connected  
13 electrically and thermally to the electrodes 4 so as to simultaneously provide connections 5  
14 for both electrical current from the semiconductor switches 8 to the electrodes 4 and for the  
15 heat generated within the semiconductor switches 8 to the incoming liquid via the electrodes  
16 4. Each connection 5 was placed at or near the end of the electrode closest to the inlet 2  
17 where the liquid is relatively cool. This required electrodes 4 that are both highly electrically  
18 conductive and thermally conductive. Preferably, the electrical and thermal conductivities of  
19 the electrodes are equal to or greater than those of aluminum. The semiconductor switches 8  
20 were packaged in a package that has a thermally and electrically conductive surface that can  
21 be applied directly to the electrode or a feature of the electrode to make the connection 5, in  
22 this example, the JEDEC TO-220 package. This package provided a relatively large flat  
23 surface that has been designed to communicate heat generated by the semiconductor device  
24 packaged inside of it to a heat sink to which it is generally attached. In many instances, and a  
25 requirement of this feature, the flat heat conducting surface of the TO-220 package (or any



1 other suitable package) also is connected to a main terminal of the semiconductor switch 8, a  
2 main terminal being a terminal not dedicated to controlling the operation of the switch 8, but  
3 rather one through which the switchable current passes. The connection is made in any  
4 suitable manner such that the electrical and thermal conductances across the connection 5 are  
5 adequate for good performance. A connection that is under mechanical compression is most  
6 preferred. In the present example, the mechanical compression was effected with a spring  
7 clamp and the connections made between the TO-220 packages and tabs of the electrodes  
8 that came through the housing of the heating chamber for purpose of making the connections  
9 5 to the switch matrix 6.

10 For reasons of maximizing the operating life of the heater, the electrodes are  
11 mechanically robust and resistant to corrosion. Preferably the electrodes comprise carbon.  
12 Most preferably, the electrodes comprise a combination of graphite and polymer and/or  
13 elastomer. The polymer and/or elastomer comprises only a small percentage of the total  
14 volume of the electrode and is used primarily for purposes of binding the graphite. The  
15 graphite is most preferably oriented graphite with an orientation such that it has highest  
16 electrical and thermal conductivity within the plane of the electrode. This electrode  
17 composition satisfies the electrical and thermal conductivity needs and also provides and  
18 electrode that is largely immune to electrochemical corrosion. Such electrodes may be  
19 fabricated by any suitable method. Metallic electrodes, though not preferred because of the  
20 poor corrosion resistance, are within the scope of the invention. Current art conductive  
21 plastic electrodes are not suitable because they do not achieve the required electrical and  
22 thermal conductivities. However, this may change in the future and, as such, electrodes of  
23 such composition are within the scope of the invention if they provide adequate electrical and  
24 thermal conductivities and resistance to degradation in the presence of the liquid. The



1 electrodes may comprise additional elements or materials so as to provide all of the  
2 properties required for good performance and lifetime.

3 It will be appreciated by those skilled in the art that for a given set of electrode  
4 spacings and a desired electrode channel defining area, which sets the electrical conductances  
5 of the channels, there exists an infinite range of electrode dimensions that would simply heat  
6 the liquid and meet the already cited requirements. An additional objective, however, is to  
7 minimize the formation of deposits on the electrodes, thereby extending the operating life of  
8 the heater. This is accomplished by setting the average velocity of the liquid flow in the  
9 channels such that it is at the onset of turbulence. The method of calculation of the velocity  
10 of the onset of turbulence for a channel of defined dimensions and cross-section is well  
11 known and will not be discussed here. The liquid flow velocity is a function of the channel  
12 height with smaller heights giving higher liquid flow velocities for a given volumetric flow  
13 rate. Thus, satisfying the constraints of the electrode height, for reasons of obtaining the  
14 requisite liquid flow velocity for a desired volumetric flow rate, and the electrode channel  
15 defining area, in order to achieve the desired channel electrical conductance, sets the  
16 optimum electrode dimensions. These electrode dimensions are unique in that there are no  
17 other electrode dimensions that simultaneously satisfy all of the requirements of a preferred  
18 embodiment of the invention. The electrode dimensions of the example satisfy these  
19 requirements. It is noted, however, that the velocity for the onset of turbulence is not a  
20 singular number, but a range, since turbulence itself is not strictly a binary quantity or  
21 quality. Thus, in a preferred embodiment, the optimum electrode dimensions fall within a  
22 narrow range determined both by the range of velocities associated with the onset of  
23 turbulence and the other parameters associated with the overall design of the liquid heater.

24 It is known in DER heaters that, absent electrodes to collect it, electrical leakage  
25 current can be created. Generally, this is of a small magnitude, but for reasons of safety, it



1 should be essentially eliminated. A preferred embodiment of the invention also includes two  
2 leakage current collecting electrodes, one between the liquid inlet 2 and the heating chamber,  
3 and the other between the heating chamber and liquid outlet 3. They are electrically  
4 connected to an electrically neutral voltage. These electrodes may be of similar design as the  
5 electrodes used to heat the liquid or comprise any electrical conductor that is suitably  
6 corrosion resistant. They are designed and located so as to maximize the surface area of  
7 contact between the liquid and the electrodes and preferably centered in any channel defined  
8 by the heater vessel walls associated with the inlet 2 and outlet 3. The length of the leakage  
9 current electrodes is at least twice and preferably 10 or more times the largest distance  
10 between the electrode and the vessel wall along a line drawn between the electrode and  
11 vessel wall perpendicular to the leakage current electrode. The inventors have found that  
12 provision of such leakage current electrodes can reduce the current leakage current to below  
13 1 $\mu$ A, well below a value that is considered to be hazardous to human beings. Other leakage  
14 current electrode configurations that achieve this are also suitable.

15 No flow measurement device is mentioned as part of this invention. In preferred  
16 embodiments of the invention, it is specifically absent. The combination of the preferred  
17 temperature sensing element 12, the optimally spaced electrodes 4 which provide a wide  
18 current control range and fine adjustability of power, the switch matrix 6 and the controller  
19 10 are sufficient to control the liquid temperature for all flow velocities, including zero, and  
20 for all orientations of the DER liquid heater. Furthermore, the DER liquid heater of this  
21 invention is able to provide virtually instant heated liquid availability because it maintains the  
22 small reservoir of liquid within its heating chamber at or close to the temperature set-point  
23 and is able to respond very quickly to liquid flow rate changes due to the very small latent  
24 heat associated with the electrodes 4 and a rapid response by the temperature sensing element  
25 12. Thus, wastage of liquid due to the delivery of unheated liquid is largely eliminated.



1           The scope of the claims should not be limited by particular embodiments set forth herein,  
2   but should be construed in a manner consistent with the specification as a whole.



**CLAIMS:**

## 1. A liquid heater comprising:

a chamber having an inlet and an outlet, and at least three electrodes within said chamber defining a plurality of adjacent channels for liquid flow from said inlet to said outlet whereby the liquid flow is divided between the channels and wherein the liquid is heated by electrical current flow through the liquid between two or more of said at least three electrodes;

an electrical power supply connection; and

at least one switch for each of said electrodes, the at least one switch being arranged to removably connect each of said electrodes to the power supply connection independent of the remaining ones of said electrodes, the electrodes being non-uniformly spaced apart from one another with different distances between different pairs of mutually-adjacent ones of the electrodes, so that connection of different sets of the electrodes to the electrical power supply connection provides different levels of current passing through the liquid, the levels of current including levels defining a stepwise progression between zero current when none of the electrodes are connected and a maximum current when all of the electrodes are connected, the progression having substantially uniform ratios between the currents of adjacent steps with non-zero current levels.

2. A liquid heater as in claim 1, further comprising a controller controlling the operation of the at least one switch for each of the electrodes and thereby controlling connection of said electrodes to the electrical power supply connection.

3. A liquid heater as in claim 2, further comprising a temperature sensor sensing the temperature of the liquid, wherein the controller controls the operation of said at least one switch based upon information received from the temperature sensor.

4. A liquid heater as in claim 2, further comprising a temperature sensor sensing the temperature of the liquid after it passes through the channels, wherein the controller controls the operation of said at least one switch based upon information received from the temperature sensor.



5. A liquid heater as in claim 1, wherein said at least one switch for each of said electrodes are physically attached to said electrodes to facilitate the removal of generated heat from said switch, into said electrode, and into the liquid to be heated.
6. A liquid heater as in claim 2, further comprising an electric current sensor sensing the amount of electric current being utilized by the liquid heater, wherein said controller controls the operation of said at least one switch for each of said electrodes, based upon information received from said electric current sensor.
7. A liquid heater as in claim 2, further comprising a temperature sensor sensing the temperature of the liquid, and an electric current sensor sensing the amount of electric current being utilized by the liquid heater, wherein said controller controls the operation of said at least one switch for each of said electrodes, based upon information received from said temperature sensor and from said electric current sensor.
8. A liquid heater as in claim 1, further comprising a pair of electric current leakage electrodes, one located in said chamber adjacent said inlet, and the other located in said chamber adjacent said outlet, both of said electric current leakage electrodes connected to each other and to an electrically neutral voltage source.
9. A liquid heater as in claim 1, wherein said at least three electrodes are manufactured from a combination of oriented graphite and polymer binder.
10. A liquid heater as in claim 1, wherein there is one switch for each of said electrodes, and the power supply connection has two opposite terminals, and wherein said switches removably connect mutually-adjacent ones of said electrodes to opposite terminals of the power supply connection.



11. A liquid heater as in claim 1, wherein said power supply connection is a three-phase connection having three terminals and said at least one switch for each of said electrodes removably connects each of said electrodes to one of the terminals of the three phase connection.
12. A liquid heater as in claim 1, wherein said power supply connection is a three-phase connection having three terminals and the at least one switch for each of the electrodes includes three switches for each of said electrodes, said switches removably connecting each of said electrodes to each terminal of the three phase connection.
13. A liquid heater as in claim 1, wherein the power supply connection has two opposite terminals and said at least one switch for each of said electrodes connects each of said electrodes to one or the other terminal of the power supply connection.
14. A liquid heater as in claim 1, wherein said controller can connect and disconnect any combination of said electrodes to the power supply connection by operating said switches.
15. A liquid heater as in claim 2, wherein said controller is operative to control the switches so as to cycle through different combinations of said electrodes that yield similar current levels, whereby the current applied to the liquid is more evenly distributed throughout the liquid and said electrodes are more evenly utilized.
16. A liquid heater as in claim 1, wherein a greatest difference between the levels of current in any two adjacent steps of the progression is no greater than 10% of the maximum current.
17. A liquid heater as in claim 1, wherein a greatest ratio between the currents in any two adjacent steps of the progression having non-zero currents is no more than 1.22:1.
18. A liquid heater as in claim 17, wherein the greatest ratio is no more than 1.1:1.
19. A liquid heater as in claim 1, wherein a greatest difference between the levels of current in any two adjacent steps of the progression is no greater than 5% of the maximum current.

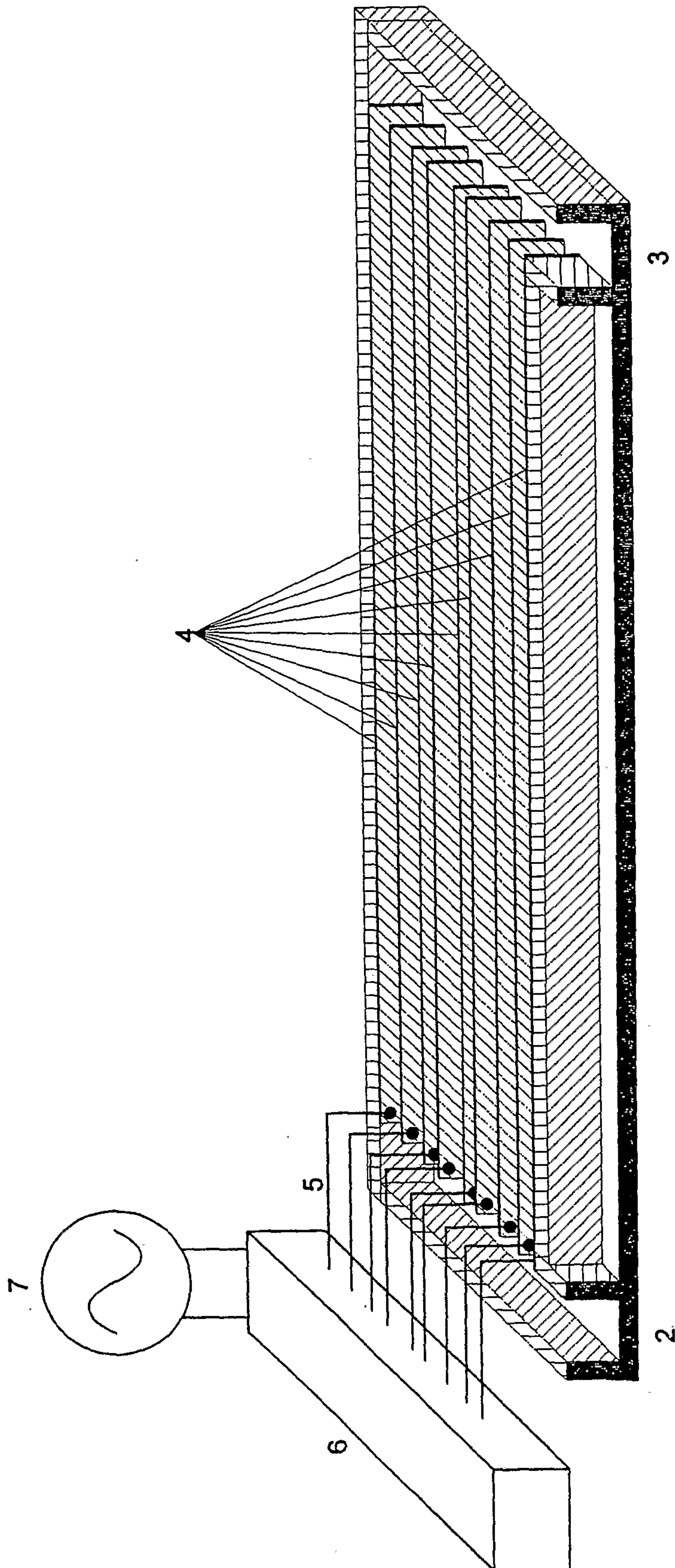


20. A liquid heater as in claim 1, wherein the number of said electrodes, the number of said switches, and the spacing of said electrodes is sufficient to provide at least 60 different current levels in said stepwise progression.
21. A liquid heater as in claim 4, wherein said controller controls the application of electrical power to said electrodes based upon the temperature sensed by said temperature sensor and the rate of change of the temperature sensed by said temperature sensor.
22. A liquid heater as claimed in claim 4, wherein said controller periodically determines if the combination of said electrodes connected to the power supply connection needs to be changed to raise or lower the current level applied to the liquid to be heated, based upon information received from said temperature sensor and a desired liquid temperature at said chamber outlet.
23. A liquid heater as in claim 22, wherein said controller limits the rate of change of electrical current applied to said electrodes, thereby limiting surges in power levels that could impact other users of the power source used by the liquid heater.
24. A liquid heater as in claim 23, wherein said controller limits the rate of change of electrical current applied to said electrodes, by adjusting the current applied to said electrodes only to the next highest or lowest available current level provided by a combination of said electrodes, each time said controller periodically determines if there needs to be a change in the current level applied to the liquid to be heated.
25. A liquid heater as in claim 24, wherein said controller limits the rate of change of electrical current applied to said electrodes by only determining if the combination of said electrodes connected to a power supply needs to be changed once every cycle of an alternating current supplied to the power supply connection.
26. A liquid heater as in claim 1, wherein said electrodes are planar, thin, and rectangular.



27. A liquid heater as in claim 1, wherein said chamber and said electrodes are sized and spaced such that the design rate of liquid flow through the channels between said electrodes is in the range of transition between laminar flow and turbulent flow.
28. A liquid heater as in claim 1, wherein a ratio between the maximum current and a minimum non-zero current in said progression is at least 250:1.





# Figure 1



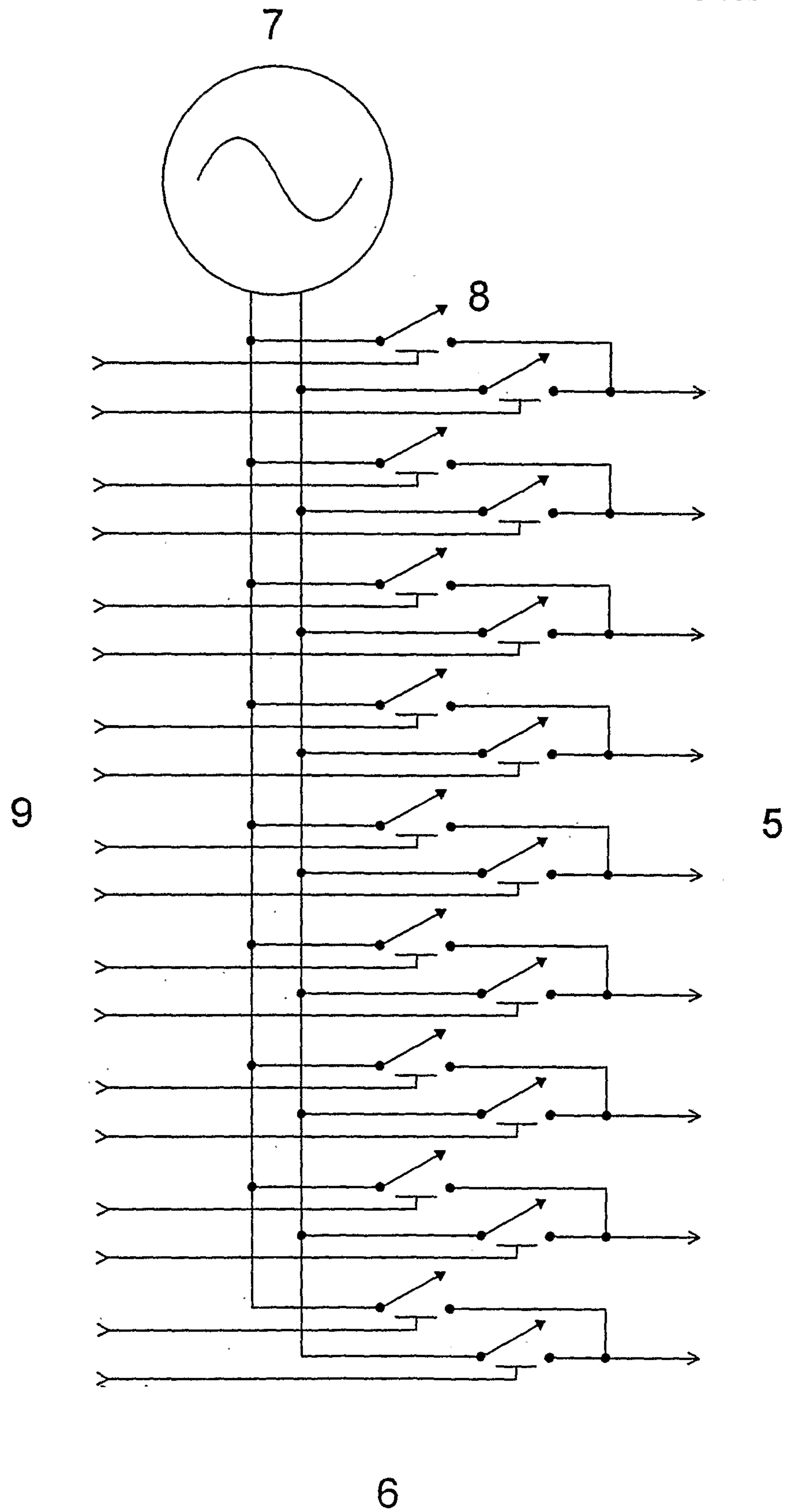
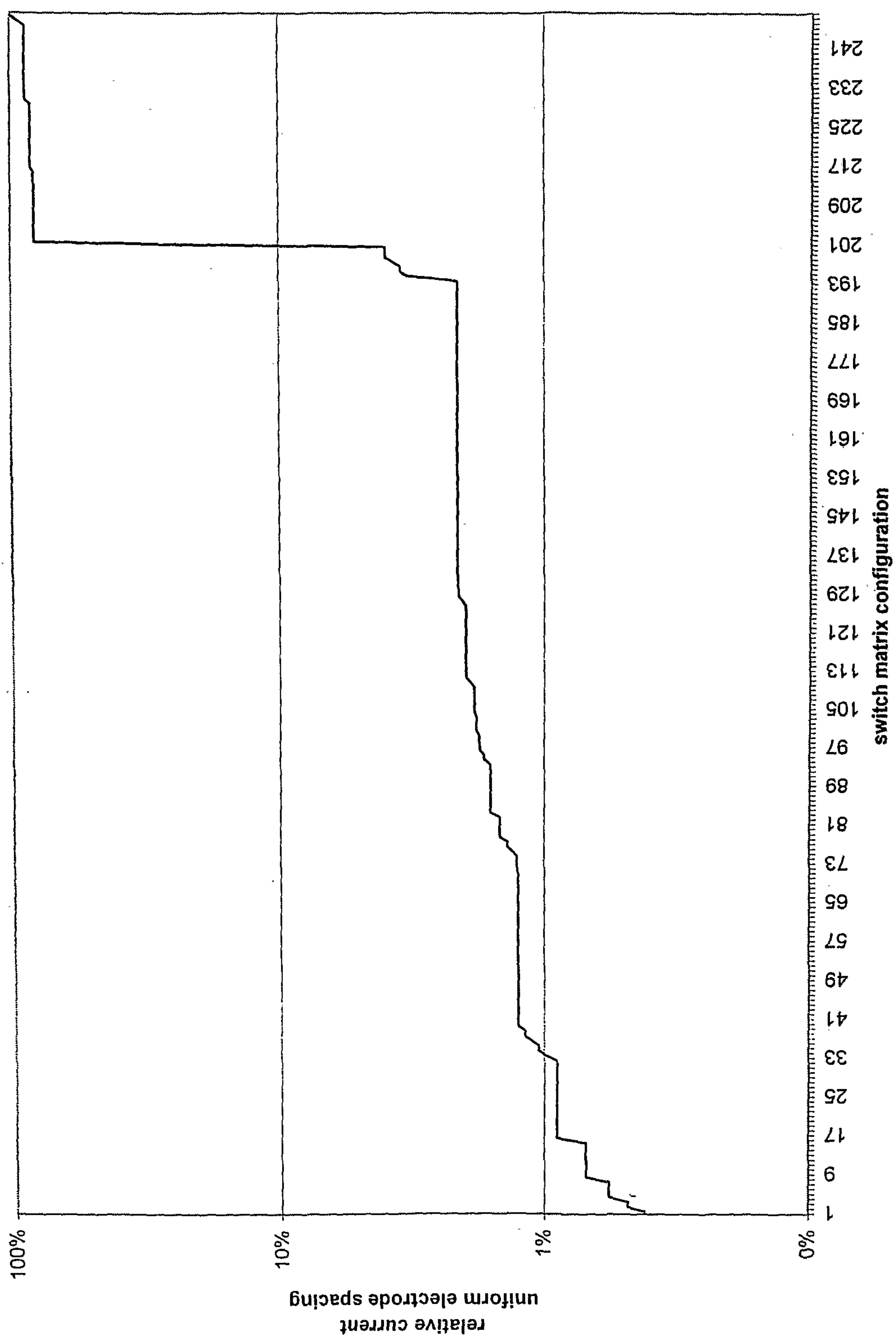
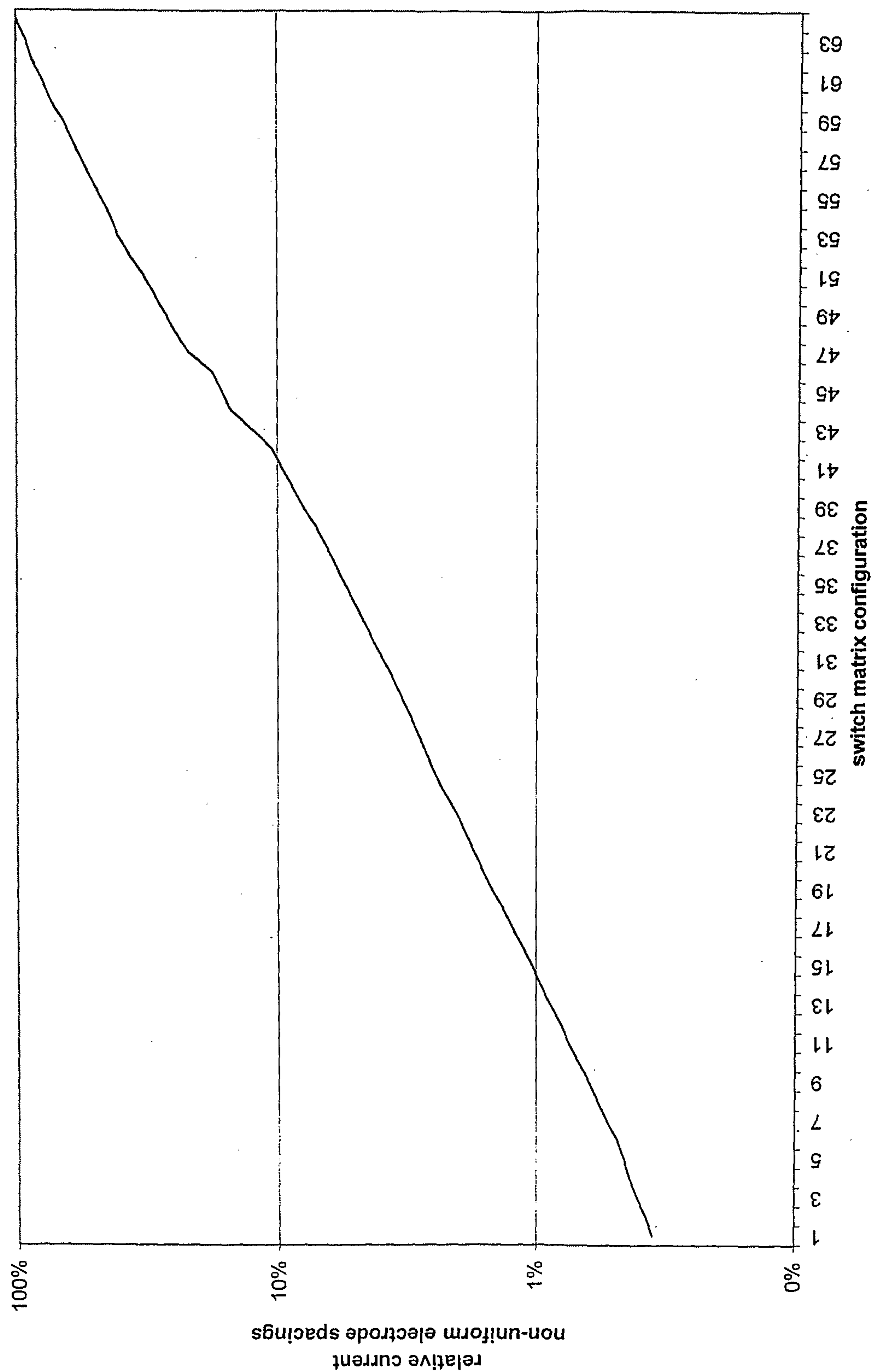


Figure 2



**Figure 3**



**Figure 4**



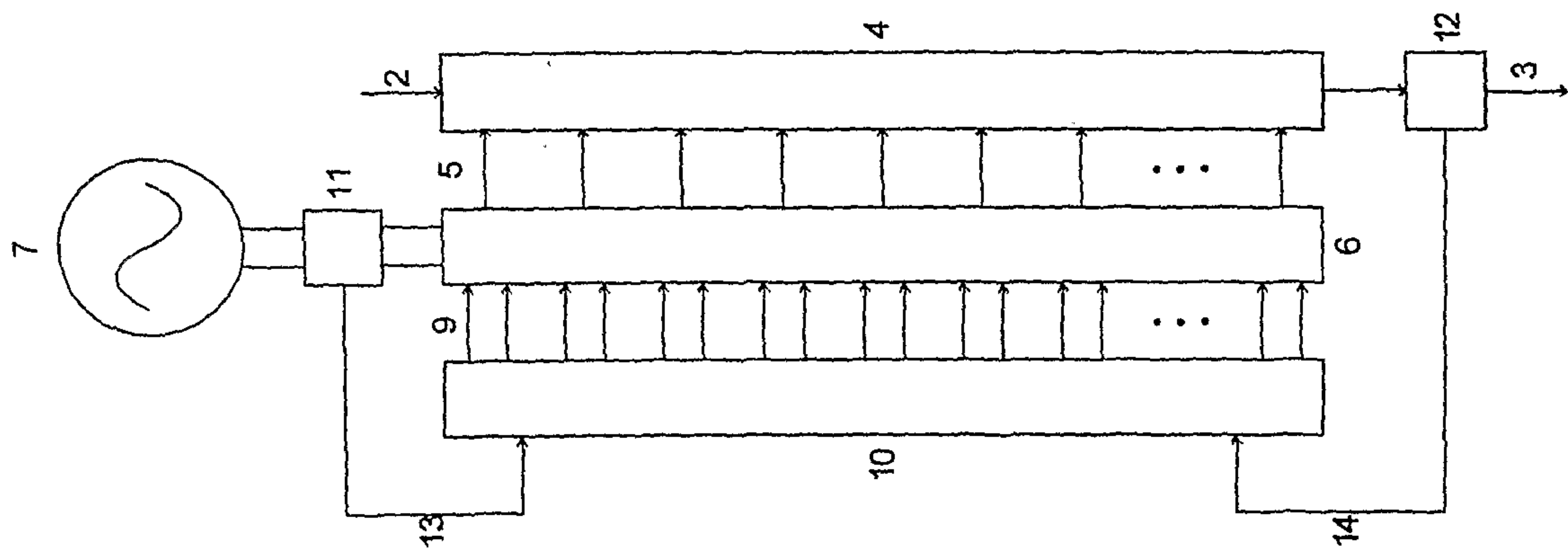


Figure 5



