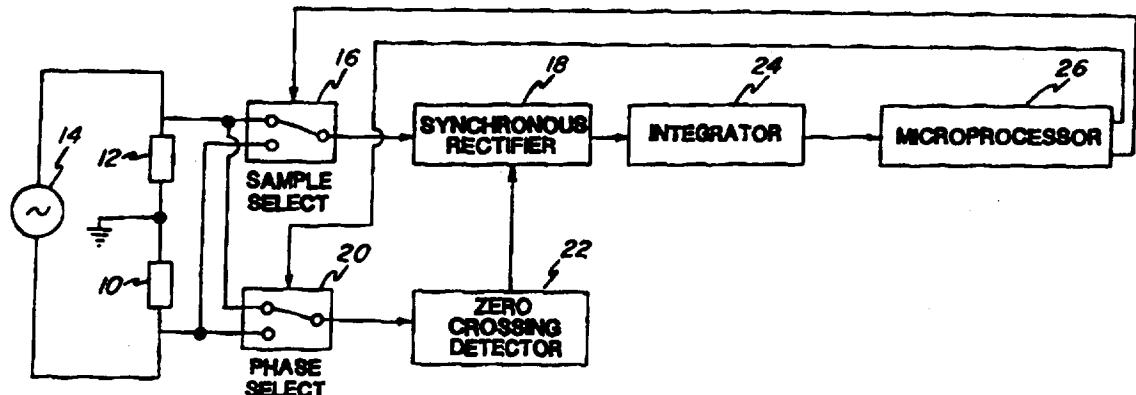




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(54) Title: CONDUCTIVITY MEASURING APPARATUS AND METHOD



## (57) Abstract

An improved apparatus for measuring conductivity or resistivity compensates for series capacitance (Cs) and parallel capacitance (Cp). A sine-wave potential excitation (14) is applied to a reference resistance (12) and a conductivity cell (10) connected in series. The voltages across the resistance (12) and the cell (10) are sampled. To compensate for series capacitance, both sampled voltages are synchronously rectified with respect to the phase of the sampled resistance voltage. To compensate for parallel capacitance, both sampled voltages are synchronously rectified with respect to the phase of the sampled cell voltage. The rectified voltages are integrated and the cell conductivity or resistivity is calculated from the ratio of the integrated voltages.

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## CONDUCTIVITY MEASURING APPARATUS AND METHOD

### BACKGROUND OF THE INVENTION

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#### Field of the Invention

This invention relates to an improved apparatus and method for measuring electrical conductivity or resistivity in liquids, and more particularly, it relates to a conductivity measuring apparatus having a phase-synchronous rectifier and integrator for accurately measuring electrical conductivity in the presence of parasitic 10 capacitance.

#### Background of the Invention

The measurement of conductivity or resistivity is desired in a number of applications. For example, in the pharmaceutical industry, many processes require 15 the use of ultra-pure water. Conductivity measurements yield an indication of ionic concentrations in water. Ultra-pure water has a conductivity below a given level. Conductivity measurements can therefore be used to reliably and accurately determine the purity of water.

Another application where it is desirable to measure the conductivity of a 20 liquid is the determination of the concentration of total dissolved solids in water. For example, investigators desiring to determine the level of pollution in river water want to know the concentration of total dissolved solids in the water. The higher the concentration of total dissolved solids in the water, the higher the conductivity, or inversely, the lower the resistivity of the water.

25

The volume conductivity, or just "conductivity", is defined as the conductance of one cubic centimeter of a liquid at a specific temperature. Conductivity is typically measured in mhos/cm ( $\Omega/cm$ ), or Siemens/cm ( $S/cm$ ), and micro mhos/cm ( $\mu\Omega/cm$ ), or micro Siemens/cm ( $\mu S/cm$ ). Ultra-pure water typically has a conductivity of 0.2 micro mhos/cm or less. Volume resistivity ("resistivity") is 30 the inverse of conductivity and is typically measured in ohm-cm ( $\Omega\text{-cm}$ ), or megohm-cm ( $M\Omega\text{-cm}$ ). Ultra-pure water typically has a resistivity of 5 megohms-cm or greater.

Conductivity of a liquid is typically measured by immersing two electrodes

contained in a conductivity cell in the liquid, applying an excitation to the liquid, and measuring the resultant voltage  $v_c$  between the electrodes and the current  $i_c$  flowing through the electrodes. Because a direct current ("DC") excitation can cause ions present in the liquid to migrate to the electrodes, interfering with the conductivity measurement, an alternating current ("AC") excitation of sufficiently low amplitude and sufficiently high frequency is often used.

Measurements of conductivity and resistivity vary depending upon the cell used to make the measurements, the temperature of the liquid being measured, and the concentration of ions or other electrically conductive material in the liquid. A 10 cell with fixed dimensions and configuration is typically used. For a given fixed cell, a cell constant K may be defined as a function of conductive cell surface area and conductive path length. For a cell with two flat parallel plates of area A and separation distance L, the cell constant K is found to be the length L of the conductive path between the electrodes, divided by the conducting area A of the 15 electrodes, so that  $K = L/A$ .

For a given cell, the conductivity and resistivity of a liquid are then given by

$$\sigma = \frac{Ki_c}{v_c} \quad (\text{eq. 1})$$

and

$$\rho = \frac{1}{\sigma} = \frac{v_c}{Ki_c} \quad (\text{eq. 2})$$

Where:

$i_c$  = the electric current flowing between the cell 20 electrodes, in Amperes,

$v_c$  = the voltage across the cell electrodes, in Volts,

and

$K$  = the cell constant, in  $\text{cm}^{-1}$ .

The conductivity cell immersed in liquid may be electrically modeled as a

resistor  $R_c$  with value equal to the resistivity  $\rho$  times the cell constant  $K$ , such that

$$R_c = K\rho . \quad (\text{eq. 3})$$

However, accurate measurement of  $R_c$  is difficult when an AC excitation is used due to capacitive effects of the cell, as well as capacitive effects of the lead wires to the cell. At the interface between each cell electrode and the liquid is a 5 series capacitance  $C_s$ . Between each electrode is a capacitance in parallel with the resistance  $R_c$ , represented by  $C_p$ . Including the capacitive effects, the cell may be electrically modeled as a parallel capacitance  $C_p$  in parallel with liquid resistance  $R_c$ , both in series connection with series capacitance  $C_s$ , as shown in Figure 1. Lead wire cabling capacitance (not shown) would appear as a capacitance in parallel across the 10 circuit of Figure 1.

The cell capacitances  $C_p$  and  $C_s$  exhibit impedances to an AC excitation which vary inversely as a function of the excitation frequency  $f$  (measured in cycles/second or Hertz). For a relatively low frequency  $f$ , the impedances of  $C_p$  and  $C_s$  can be quite large for fixed values of  $C_p$  and  $C_s$ . For small values of  $R_c$ , the 15 impedance of series capacitance  $C_s$  can be large compared to  $R_c$ , thus giving rise to an erroneously large measured value for  $R_c$ . For large values of  $R_c$ , the impedance of parallel capacitance  $C_p$  can be small relative to  $R_c$ , thus giving rise to erroneously small measured values of  $R_c$ .

For a relatively high excitation frequency  $f$ , the impedances of  $C_p$  and  $C_s$  can 20 be quite small for fixed values of  $C_p$  and  $C_s$ . For small values of  $R_c$ , the impedance of series capacitance  $C_s$  can be large compared to  $R_c$ , thus giving rise to an erroneously large measured value for  $R_c$ . For large values of  $R_c$ , the impedance of parallel capacitance  $C_p$  can be small relative to  $R_c$ , thus giving rise to an erroneously small measured value for  $R_c$ .

25 In general, at a given frequency  $f$  and fixed  $C_s$  and  $C_p$ , as the resistivity of a sampled liquid increases, the impedance due to series capacitance  $C_s$  can be ignored, while the impedance of parallel capacitance  $C_p$  causes an erroneously small value for  $R_c$  to be measured. Conversely, as the resistivity of a sampled liquid decreases, the

impedance due to parallel capacitance  $C_p$  can be ignored, while the impedance of series capacitance  $C_s$  causes an erroneously large value for  $R_c$  to be measured.

Thus, for large values of cell resistance  $R_c$ , the measurement error is largely due to the presence of parallel capacitance  $C_p$ . For small values of cell resistance  $R_c$ ,  
5 the primary source of measurement error is due to the presence of series capacitance  $C_s$ .

Various efforts to measure conductivity in the presence of capacitive effects are known in the prior art. An early method uses an AC conductance bridge, wherein different reactances are inserted into the arms of the bridge to compensate either or  
10 both  $C_s$  and  $C_p$ . While this method is effective, it is generally slow and not easily automated.

Another measurement technique uses square-wave excitation and center-sampling of the voltage waveform across the cell. The parallel capacitance is charged to saturation during the first part of the square-wave cycle. The cell voltage  
15 is then sampled during a later portion of the cycle during which the series capacitance is charging in a linear fashion. The value of the series capacitance can be determined from the rate of charge of the capacitance and mathematically subtracted from the output based on the cell voltage to determine the cell resistance. This measurement technique suffers from the disadvantage of relying upon the use of  
20 a second-order polynomial to approximate the amount of measurement error. Thus, this prior art method does not eliminate the source of error itself, the voltage due to the series capacitance.

#### Summary of the Invention

25 These disadvantages and others are met by means of the present invention embodied in a circuit and method for measuring the conductivity sensed by a cell wherein the effects of series and parallel capacitance inherent in cells are minimized.

In the present invention, a periodic time-varying excitation is applied across a known reference resistance series-connected to a cell sensor. The voltages across the  
30 reference resistance and the cell sensor are synchronously sampled with respect to a predetermined signal phase. The synchronous sampled voltages are then integrated

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with respect to a predetermined signal phase to provide DC values representative of their RMS values. By sampling and integrating the signals synchronously, voltage components due to cell capacitance are substantially eliminated, leaving the voltage components due to cell resistance. The cell resistance is then found as a product of 5 the reference resistance and the ratio of the RMS value of the synchronous sampled cell signal to the RMS value of the synchronous sampled reference resistance voltage.

Therefore, it is one object of the invention to provide a measurement of the conductivity of liquids reliably and accurately, even when parasitic cell capacitances 10 are present. This and other objects, features and advantages of the present invention will be described in further detail in connection with preferred embodiments of the invention shown in the accompanying drawings, wherein:

#### BRIEF DESCRIPTION OF THE DRAWINGS

15 Fig. 1 is an electrical schematic of a conductivity cell immersed in a liquid;

Fig. 2 is an electrical schematic of a conductivity cell immersed in a liquid modeled as a parallel RC circuit;

Fig. 3 is an electrical schematic of a conductivity measuring circuit modeled as a series circuit;

20 Fig. 4 is an electrical schematic of a conductivity measuring circuit modeled as a parallel circuit;

Fig. 5 is a block diagram of a conductivity measuring circuit;

Fig. 6 is a set of electrical waveforms illustrating the operation of a conductivity measuring circuit;

25 Figs. 7a, 7b, and 7c are a detailed circuit schematic diagram of a preferred embodiment of the invention; and

Fig. 8 is a block diagram of a conductivity meter incorporating the present invention.

Detailed Description of the Preferred Embodiments

As discussed above, the resistance of a liquid the conductivity of which is desired is not an ideal resistance. As shown in Figure 1, a conductivity cell immersed in a liquid may be modeled as a cell resistance  $R_c$  in parallel with a 5 capacitance  $C_p$ , both in series with a capacitance  $C_s$ .

Series capacitance  $C_s$  is caused by liquid-electrode interface capacitance and is a function of the resistivity of the liquid under measurement and the available surface area of the cell electrodes. Values for series capacitance  $C_s$  typically range from as low as  $.1 \mu\text{F}$  to in excess of  $100 \mu\text{F}$ . For example, platinum electrodes 10 plated with highly porous platinum black generally have  $C_s > 1 \mu\text{F}$ , while titanium-palladium electrodes may typically have  $C_s \approx 0.1 \mu\text{F}$ .

Parallel capacitance  $C_p$  is caused by interelectrode capacitance, which is a function of cell geometry and electrode separation distance, as well as lead wire cabling capacitance. Cabling capacitance can dominate interelectrode capacitance by 15 a factor of ten times or more. Values for  $C_p$  typically may vary from a low of  $10 \text{ pF}$  to a high of  $2500 \text{ pF}$ .

For large values of resistance  $R_c$ , the principal source of measurement error is due to the presence of parallel capacitance  $C_p$  while measurement error due to the presence of series capacitance  $C_s$  may be ignored. For small values of resistance  $R_c$ , 20 the principal source of measurement error is due to the presence of series capacitance  $C_s$  while measurement error due to the presence of parallel capacitance  $C_p$  may be ignored.

By way of illustration, assume typical values for  $C_s$  and  $C_p$  such that  $C_s = 1 \mu\text{F}$  and  $C_p = 600 \text{ pF}$ . At a driving frequency  $f = 70 \text{ Hz}$ ,  $C_s$  and  $C_p$  will exhibit 25 reactances  $X_s$  and  $X_p$  given by

$$X = \frac{1}{2\pi f C} \quad (\text{eq. 4})$$

such that  $X_s \approx 2.274 \text{ k}\Omega$  and  $X_p \approx 3.789 \text{ M}\Omega$ . The measured cell resistance  $R_m$  will then be given by

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$$R_m = X_s + X_p \parallel R_c = X_s + \frac{1}{\frac{1}{R_c} + \frac{1}{X_p}} . \quad (\text{eq. 5})$$

For the given values, and a required degree of accuracy, a range of values for which  $R_m$  exhibits the required degree of accuracy for  $R_c$  can be determined. In this example, for a required measurement accuracy of  $\pm .25\%$ , the range over which  $R_c$  may be accurately measured extends from a low value of  $R_c \approx 89.18 \text{ k}\Omega$  to a high 5 value of  $R_c \approx 99.01 \text{ k}\Omega$ , with minimal error at  $R_c \approx 93.96 \text{ k}\Omega$ .

Now, assuming that  $R_c$  and  $X_p$  are much larger than  $X_s$  ( $R_c \gg X_s$  and  $X_p \gg X_s$ ), the electrical model of Figure 1 can be approximated by the simple parallel circuit of  $R_c$  in parallel with  $C_p$ , as shown in Figure 2. Provided that some means can be used to substantially compensate the effect of the parallel capacitance  $C_p$ , then the 10 accuracy of the measurement of  $R_c$  is limited only by the presence of  $C_s$ . For example, the measured resistance  $R_m$  as given above reduces to

$$R_m = X_s + R_c . \quad (\text{eq. 6})$$

Thus, for a required accuracy of  $\pm .25\%$ , the range for  $R_c$  now extends from a low value of  $R_c \approx 909.6 \text{ k}\Omega$  to an arbitrarily large value limited only by the sensitivity of the measurement apparatus. For these large values of  $R_c$ ,  $R_c \geq 400X_s$ , 15 and  $X_p \geq 1600X_s$ , thus verifying the assumptions that  $R_c \gg X_s$  and  $X_p \gg X_s$  are valid. Therefore, large values of cell resistance can be accurately measured using a parallel capacitance model, provided that some means is used to substantially compensate the effects of parallel capacitance  $C_p$ .

The inventor has observed that for the series model shown in Figure 3,

$$V_{ab} = iR_{ref} \quad (\text{eq. 7})$$

20 and

$$V_{bd} = V_{bc} + V_{cd} = iR_c + V_{cd} . \quad (\text{eq. 8})$$

If both sides of the equations are integrated, then

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$$\int v_{ab} dt = R_{ref} \int i dt \quad (\text{eq. 9})$$

and

$$\int v_{bd} dt = R_c \int i dt + \int v_{cd} dt . \quad (\text{eq. 10})$$

Solving for  $\int i dt$  in eq. 9 and substituting the result in eq. 10, then

$$\int v_{bd} dt = \frac{R_c}{R_{ref}} \int v_{ab} dt + \int v_{cd} dt . \quad (\text{eq. 11})$$

For periodic time-varying excitation  $v_{cd}$ , limits  $l_1, l_2$  can be chosen such that

$$\int_{l_1}^{l_2} v_{cd} dt = 0 . \quad (\text{eq. 12})$$

5 By way of example,  $l_1$  and  $l_2$  may have values:

$$l_1 = -\frac{\pi}{2\omega} , \quad l_2 = \frac{\pi}{2\omega}$$

where  $\omega$  is the angular frequency of the driving signal and the times  $l_1$  and  $l_2$  are measured with reference to the instant of zero crossover for the signal  $v_{cd}$ . It will be observed that the voltage  $v_{cd}$  may not be measured, but it is known to be 90 degrees out of phase with  $v_{ab}$ . Therefore, the limits  $l_1$  and  $l_2$  may be set with respect to the 10 peak value of  $v_{ab}$ , in which case they are equal to zero-crossings of  $v_{ab}$ .

Then, substituting eq. 12 in eq. 11 and solving for  $R_c$

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$$R_c = R_{ref} \frac{\frac{l_2}{\int v_{bd} dt}}{\frac{l_1}{\int v_{ab} dt}} . \quad (\text{eq. 13})$$

Thus, the unknown resistance  $R_c$  can be found by multiplying the value of the reference resistance by the ratio of the integral of the sampled cell voltage to the integral of the sampled reference voltage. The value of the unknown resistance  $R_c$  5 can thereby be found despite the presence of unknown series capacitance  $C_s$ . However, it should be noted that  $l_2 - l_1$  may not have a value of  $2\pi/\omega$ , because such a condition causes Equation 13 to become indeterminate.

Similarly, for the parallel capacitance model shown in Figure 4, the inventor has observed that

$$v_{ab} = i_1 R_{ref} = R_{ref} (i_2 + i_3) \quad (\text{eq. 14})$$

10 and

$$v_{bc} = i_2 R_c . \quad (\text{eq. 15})$$

Integrating both sides of equations 14 and 15 yields

$$\int v_{ab} dt = R_{ref} \int i_2 dt + R_{ref} \int i_3 dt \quad (\text{eq. 16})$$

and

$$\int v_{bc} dt = R_c \int i_2 dt . \quad (\text{eq. 17})$$

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Solving eq. 17 for  $\int i_2 dt$  and substituting the result in eq. 16 gives

$$\int v_{ab} dt = \frac{R_{ref}}{R_c} \int v_{bc} dt + R_{ref} \int i_3 dt . \quad (\text{eq. 18})$$

For a periodic time-varying excitation  $v_{ac}$ ,  $i_3$  is also periodic and limits  $l_3$ ,  $l_4$  can be chosen such that

$$\int_{l_3}^{l_4} i_3 dt = 0 . \quad (\text{eq. 19})$$

5 By way of example,  $l_3$  and  $l_4$  may have values:

$$l_3 = -\frac{\pi}{2\omega} , \quad l_4 = \frac{\pi}{2\omega}$$

where  $\omega$  is the angular frequency of the driving signal and the times  $l_3$  and  $l_4$  are measured with reference to the instant of zero crossover for the signal  $i_3$ . It will be observed that the current  $i_3$  may not be measured, but it is known to be 90 degrees out of phase with current  $i_2$  and voltage  $v_{bc}$ . Therefore, the limits  $l_3$  and  $l_4$  may be set 10 with respect to the peak value of  $v_{bc}$ , in which case they are equal to zero-crossings of  $v_{bc}$ .

Substituting eq. 19 into eq. 18 and solving for  $R_c$  yields

$$R_c = R_{ref} \frac{\int_{l_3}^{l_4} v_{bc} dt}{\int_{l_3}^{l_4} v_{ab} dt} . \quad (\text{eq. 20})$$

Note the similarity of eq. 20 to eq. 13. Thus, the unknown resistance  $R_c$  can be found by multiplying the value of the reference resistance  $R_{ref}$  by the ratio of the integral of the sampled cell voltage  $v_{bc}$  to the integral of the sampled reference voltage  $v_{ab}$ . The value of the unknown resistance  $R_c$  can thereby be found despite the 5 presence of unknown parallel capacitance  $C_p$ . However, it should be noted that  $I_4 - I_3$  may not have a value of  $2\pi/\omega$ , because such a condition causes Equation 20 to become indeterminate.

It can be shown that the ratio of the integrals given in Equations 13 and 20 is equal to the ratio of the peak voltages divided by the cosine of the phase angle 10 between the two voltage signals being monitored. Thus, if the peak voltage ratio is determined and is divided by the ratio of the integrals, it becomes possible to determine the phase angle and hence the value of the unknown capacitance.

Turning now to an examination of an apparatus which compensates for unknown capacitance when measuring unknown resistance, Figure 5 shows a 15 simplified block diagram of a circuit according to one embodiment of the invention. A liquid (not shown), the conductivity of which is to be measured, is disposed between electrodes (not shown) in a cell 10. Connected to one electrode of the cell 10 is a reference resistance 12. A sinusoidal voltage driving source 14 is connected across the reference resistance 12 and the cell 10 to form a series electrical circuit.

20 A sample signal select switch 16, controlled by a microprocessor 26, is connected so as to be able to connect either the voltage across the reference resistance 12, or the voltage across the cell 10, depending upon which signal voltage is to be sampled, to a synchronous rectifier 18. A phase signal select switch 20, controlled by the microprocessor 26, is connected so as to be able to connect either 25 the voltage across the reference resistance 12, or the voltage across the cell 10, depending upon which signal voltage is to be the input to a zero-crossing detector 22.

The zero-crossing detector 22 provides a zero-crossing detect signal to the synchronous rectifier 18 each time the input signal to the zero-crossing detector 22 passes through zero Volts. Preferably, the synchronous rectifier 18 provides, at its 30 output, in response to the zero-crossing detect signal, a non-inverted version of the sample signal at its input whenever the input voltage to the zero-crossing detector 22

is positive. When the input voltage to the zero-crossing detector 22 is negative, the synchronous rectifier 18 preferably provides at its output an inverted version of the sample signal at its input. Alternatively, the polarity of the output from synchronous rectifier 18 may be reversed without affecting the conductivity measurement. Then, 5 when the input voltage to zero-crossing detector 22 is positive, the output from rectifier 18 is an inverted version of its input, while when the input voltage to detector 22 is negative, the output from rectifier 18 is a non-inverted version of its input.

The output of the synchronous rectifier 18 is provided to the input of an 10 integrator 24. The integrator 24 produces a DC output voltage which is representative of the RMS value of the input voltage. The output of the integrator 24 is provided to the microprocessor 26 which calculates the value of the cell resistance by multiplying the value of the reference resistance 12 times the ratio of the integrated synchronously-rectified sampled cell voltage to the integrated 15 synchronously-rectified sampled reference resistance voltage.

Thus, the zero-crossing detector 22 supplies the proper limits of integration so as to compensate for the effects of unknown capacitance present in combination with the unknown resistance being measured.

The operation of the synchronous rectifier 18 may be more clearly understood 20 by referring to the voltage waveforms shown in Figure 6. The waveforms share a common vertical axis which represents voltage. The horizontal axes represent time. Voltage  $V_D$  represents the driving voltage from signal source 14. Voltage  $V_R$  represents the sampled voltage from reference resistor 12. Voltage  $V_C$  represents the sampled cell voltage from cell 10. For the sake of clarity, all three voltages  $V_D$ ,  $V_C$ , 25 and  $V_R$  are shown as having equal amplitude. Also,  $V_R$  is shown with a phase angle of 30 degrees with respect to  $V_D$ , and  $V_C$  is shown with a phase angle of -30 degrees with respect to  $V_D$ .

To illustrate the case where the resistivity is high and it is desired to remove 30 the effects of parallel capacitance, synchronous rectification with respect to cell voltage  $V_C$  is shown. Voltage  $V_{CR}$  is the output of the synchronous rectifier 18 when  $V_C$  is the input to synchronous rectifier 18 and zero-crossing detector 22. The

vertical dashed lines in Figure 6 show the timing relationship of the voltage waveforms with respect to the zero crossings of  $V_C$ . As can be seen,  $V_{CR}$  is a full-wave rectified version of  $V_C$ .

Voltage  $V_{RR}$  is the output of synchronous rectifier 18 when  $V_R$  is the input to 5 the synchronous rectifier 18 and  $V_C$  is the input to the zero-crossing detector 22. During the time between zero crossings of  $V_C$  when  $V_C$  is positive,  $V_{RR}$  is a non-inverted version of  $V_R$ . However, during the time between zero crossings of  $V_C$  when  $V_C$  is negative,  $V_{RR}$  is an inverted version of  $V_R$ . Thus,  $V_R$  is synchronously rectified with respect to  $V_C$ .

10 Voltage  $INT_R$  represents the output of integrator 24 when the input is  $V_{RR}$ . Voltage  $INT_C$  represents the output of integrator 24 when the input is  $V_{CR}$ . Because  $V_{CR}$  is always a non-negative voltage,  $INT_C$  steadily increases over time as additional cycles of  $V_{CR}$  are integrated. Because  $V_{RR}$  may be negative,  $INT_R$  may show dips in 15 amplitude at the zero crossings of  $V_C$ . If  $V_R$  were exactly in phase with  $V_C$ , then  $V_{RR}$  would match  $V_{CR}$ , and  $INT_R$  would match  $INT_C$ . At the other extreme, if  $V_R$  were exactly 90 degrees out of phase with  $V_C$ , then  $INT_R$  would dip to zero at the zero crossings of  $V_C$ .

Thus, while the in-phase portion of  $V_R$  due to current through the cell 20 resistance integrates to some positive value, the 90 degree out-of-phase portion of  $V_R$  due to current through the cell parallel capacitance integrates to a zero value. For the case of series cell capacitance, the same principles may be demonstrated by exchanging the voltages and viewing  $V_R$  as the sampled cell voltage,  $V_C$  as the sampled reference resistance voltage,  $V_{RR}$  as the synchronously rectified cell voltage,  $V_{CR}$  as the synchronously rectified reference voltage,  $INT_R$  as the integrated cell 25 voltage, and  $INT_C$  as the integrated reference voltage.

Figures 7a, 7b, and 7c show a preferred embodiment of the present invention. A programmable sine-wave generator 30 receives inputs from the microprocessor 26 (Fig. 5) and produces a sine-wave output of fixed amplitude. One such 30 programmable sine-wave generator 30 is the Micro Linear ML2035, which is programmable from DC to 25 kHz. The sine-wave generator 30 provides a highly stable source of sine-wave excitation at a frequency determined by the inputs from

the microprocessor.

The output of sine-wave generator 30 passes through series-limiting resistor 32 and DC-blocking capacitor 34 to resistor 36 and the non-inverting input of op amp 38. Op amps 38 and 40, and resistors 42, 44, and 46, buffer the sine-wave signal and provide sufficient current to drive a primary winding 50 of isolation transformer 48. The sine-wave input to isolation transformer 48 is inductively coupled to two secondary windings 52 and 54 of the transformer 48.

The secondary windings 52, 54 are series-connected. Capacitors 56 and 58 are series-connected across the output of secondary windings 52, 54. The common 10 tap of windings 52, 54 is connected to switch 60. The other tap of winding 52 is connected to switches 62 and 64. Range selection signals RANGE\_1, RANGE\_2, and RANGE\_3, from the microprocessor 26 (Fig. 5), pass through series-limiting resistors 66, 68, and 70, to switches 60, 62, and 64, respectively. Reference resistors 72, 74, and 76 are connected in series with one end of resistor 72 tied to ground. The 15 output of switch 60 is connected to the common tie point of resistors 72 and 74. The output of switch 62 is connected to the common tie point of resistors 74 and 76. The output of switch 64 is connected to the other lead of resistor 76.

In response to range selection signals RANGE\_1, RANGE\_2, and RANGE\_3, from the microprocessor 26 (Fig. 5), the switches 60, 62, 64 may be 20 turned on or off. A low range selection signal turns a switch on while a high range selection signal turns a switch off. When turned on, the switches 60, 62, 64 have very low resistance and couple the sine-wave signal from one of the windings 52, 54 to the reference resistors 72, 74, 76. When the switches 60, 62, 64 are off, they exhibit very high input impedance to provide isolation between the inputs to the 25 switches 60, 62, 64 and the reference resistors 72, 74, 76. Switches which may be used for this purpose are Photo-MOS relay switches made by Aromat. Switches 62, 64 may be Aromat AQV210EA switches which typically exhibit  $10^{10}\Omega$  off resistance and  $30\text{--}100\Omega$  on resistance. Switch 60 may be an Aromat AQV215A which typically exhibits  $10^8\Omega$  off resistance and about  $5\Omega$  on resistance.

30 Resistors 72, 74, and 76 preferably are precision resistors that exhibit superior stability over time and a wide range of operating conditions. Values for resistors 72,

74, and 76 preferably are 10Ω, 1kΩ, and 100kΩ. Preferably, resistor 72 will have the smallest value and resistor 76 will have the largest value.

In operation, when the resistance being measured is small, RANGE\_3 is low, RANGE\_1 and RANGE\_2 are high, switch 60 is on, switches 62 and 64 are off, and

5 sine-wave excitation is coupled from the common tie point of windings 52 and 54 to the common tie point of resistors 72 and 74. When the resistance being measured is of some intermediate value, RANGE\_2 is low, RANGE\_1 and RANGE\_3 are high, switch 62 is on, switches 60 and 64 are off, and sine-wave excitation is coupled from winding 52 to the common tie point of resistors 74 and 76. When the resistance

10 being measured is large, RANGE\_1 is low, RANGE\_2 and RANGE\_3 are high, switch 64 is on, switches 60 and 62 are off, and sine-wave excitation is coupled from winding 52 to resistor 76.

Secondary winding 54 is further connected to cell 10 and resistor 78. Preferably, cell 10 is a four-wire, four-element cell. Alternatively, cell 10 may be a

15 four-wire, two-element cell. A four-wire, four-element cell 10 has electrodes 80, 82, 84, and 86. Electrodes 80 and 86 are drive electrodes and receive the sine-wave excitation from winding 54. Electrode 80 is the DRIVE2 input and is connected to winding 54, while electrode 86 is the DRIVE1 input and is tied to ground to complete a drive circuit path through cell 10. Electrodes 82 and 84 are sense

20 electrodes to detect the voltage across and the current through cell 10. Electrode 82 is the SENSE2 electrode, while electrode 84 is the SENSE1 electrode. Resistor 78 is connected between DRIVE2 electrode 80 and SENSE2 electrode 82, while resistor 88 is connected between SENSE1 electrode 84 of cell 10 and ground. Resistors 78 and 88 preferably are of equal value and act to keep circuit parameters stable when

25 cell 10 is disconnected from the circuit.

In a typical four-wire, four-element cell, an excitation is applied to drive electrodes 80 and 86. Sense electrode 82 is positioned sufficiently close to drive electrode 80 so as to be substantially at the same electrical potential as drive electrode 80. Similarly, sense electrode 84 is positioned sufficiently close to drive

30 electrode 86 so as to be substantially at the same electrical potential as drive electrode 86. Sense electrodes 82 and 84 are preferably disposed substantially within

the current flow path through the cell 10 between drive electrodes 80 and 86. In a typical four-wire, two-element cell, drive electrode 80 is electrically short-circuited to sense electrode 82, and drive electrode 86 is electrically short-circuited to sense electrode 84.

5        In operation, a complete circuit path is traversed from one side of winding 52, through one of the switches 60, 62, and 64, through resistors 72, 74, and 76, to ground. From ground, the circuit path continues to electrode 86 of cell 10, through cell 10 to electrode 80, then through winding 54 to the other side of winding 52, thus completing the circuit path. The values of the range selection signals determine  
10 whether one, two, or all three of resistors 72, 74, and 76 are in the circuit path. Thus, it can be seen that, as shown in Figure 5, the signal source 14, reference resistance 12, and cell 10 form a series circuit.

Turning to Figure 7b, the tie point of switch 64 and resistor 76 (Fig. 7a) is connected to the non-inverting input of op amp 100, while the tie point of switch 62 and resistors 74 and 76 (Fig. 7a) is connected to the non-inverting input of op amp 102. Op amps 100 and 102 are unity-gain buffer amplifiers that buffer the voltages XA, XB, respectively, from the reference resistors 72, 74, and 76 (Fig. 7a). The outputs of op amps 100 and 102 are connected to inputs Y and X, respectively, of analog switch 104B. Switch 104B is one of three switches, along with switches  
20 104A and 104C, contained in a single integrated circuit package. A preferred analog switch that features low sine-wave distortion and low crosstalk between switches is the HC4053 triple 2-channel analog multiplexer/demultiplexer made by SGS-Thomson Microelectronics.

From the microprocessor 26 (Fig. 5), a standard select signal, STD\_SEL, is  
25 connected to input B of switch 104B. The value of STD\_SEL determines which input, X or Y, is connected to output BO/I. When RANGE\_1 is low and switch 64 (Fig. 7a) is on, then STD\_SEL is high, input Y is connected to output BO/I, and reference resistance voltage XA is present at output BO/I of switch 104B. When either RANGE\_2 or RANGE\_3 is low, then STD\_SEL is low, input X is connected  
30 to output BO/I, and reference resistance voltage XB is present at output BO/I of switch 104B.

The tie point of electrode 82 and resistor 78 (Fig. 7a) is connected, through series-limiting resistor 106, to the non-inverting input of unity-gain buffer op amp 108. The tie point of electrode 84 and resistor 88 is connected, through series-limiting resistor 110, to the non-inverting input of unity-gain buffer op amp 112.

- 5 The output of op amp 108 is connected to the inverting input of unity-gain differential amplifier 114, while the output of op amp 112 is connected to the non-inverting input of unity-gain differential amplifier 114.

In the preferred embodiment, differential amplifier 114 is a Precision Monolithics AMP-03 is used due to its high (70-80 dB) common-mode rejection ratio ("CMRR"). The unity-gain differential amplifier 114 eliminates common mode voltages from the cell sense potentials XC and XD. For low unknown resistances, the resistance in the lead wires going to and from the cell 10 (Fig. 7a) may be sufficiently large relative to the cell resistance so as to induce relatively large measurement errors. Using four lead wires to the cell, in combination with unity-gain differential amplifier 114, effectively eliminates lead wire resistance as a source of measurement error.

The output of unity-gain differential amplifier 114 is connected to input Y of switch 104A and input Y of switch 104C. Output BO/I of switch 104B is connected to potentiometer 116, capacitor 118, and input X of switch 104C. The wiper arm of potentiometer 116 is connected to input X of switch 104A. Potentiometer 116, capacitor 118, and resistor 120 form a low-frequency compensation circuit. Potentiometer 116 may be adjusted to ensure that zero crossings are accurately detected for low frequency sine-wave excitations.

From the microprocessor 26 (Fig. 5), a phase select signal, PHASE\_SEL, is connected to input C of switch 104C, and determines whether input X or Y is connected to output CO/I of switch 104C. When the unknown cell resistance is high, PHASE\_SEL is high, input Y of switch 104C is connected to output CO/I so that the sampled cell voltage at the output of differential amplifier 114 appears at output CO/I of switch 104C, and synchronous rectification takes place with respect to the cell voltage to eliminate parallel capacitance effects. When the unknown cell resistance is low, PHASE\_SEL is low, input X of switch 104C is connected to output CO/I so

that the sampled reference resistance voltage at the output BO/I of switch 104B appears at the output CO/I of switch 104C, and synchronous rectification takes place with respect to the reference resistance voltage to eliminate series capacitance effects.

5        Also from the microprocessor 26 (Fig. 5), an amplitude select signal, AMPL\_SEL, is connected to input A of switch 104A, and determines whether input X or Y is connected to output AO/I of switch 104A. When it is desired to integrate the sampled reference resistance voltage, then AMPL\_SEL is low, input X of switch 104A is connected to output AO/I, and the sampled reference resistance voltage at 10 output BO/I of switch 104B is present at output AO/I of switch 104A. When it is desired to integrate the sampled cell voltage, then AMPL\_SEL is high, input Y of switch 104A is connected to output AO/I, and the sampled cell voltage at the output of differential amplifier 114 is present at output AO/I of switch 104A.

Output CO/I of switch 104C is connected to capacitor 122. Capacitor 122 is 15 a DC blocking capacitor that couples the sampled voltage which is to be used as the phase synchronization reference to resistor 124 and the non-inverting input of op amp 126. Op amp 126 is a unity-gain buffer amplifier that couples the signal to potentiometer 128 and capacitor 130. Potentiometer 128 is in turn connected to resistor 132. The signal is then coupled from resistor 132 to the inverting input of op 20 amp 134, back-to-back diode 136, and capacitor 138.

Capacitor 130 is further connected to back-to-back diodes 136 and 140. Back-to-back diode 140 is then connected to resistors 142 and 144. The other lead of resistor 142 is tied to  $V_{EE}$ , the negative supply voltage. The other lead of resistor 144 is connected to the output of op amp 134 and capacitor 138. The non-inverting input 25 of op amp 134 is tied to ground. The output of op amp 134 is further connected to series-limiting resistor 146. Series-limiting resistor 146 couples the output from op amp 134 to the base of transistor 148. Transistor 148 is an NPN-type transistor with input to the base, emitter tied to ground, and output at the collector. The output at the collector is an inverted and amplified version of the signal input to the base. The 30 collector of transistor 148 is connected to resistors 150, 152, and 154. The other lead of resistor 150 is tied to  $V_{CC}$ , the positive supply voltage, and provides collector

current to transistor 148. The output of transistor 148 is the zero-crossing signal PHASE\_I. PHASE\_I is a square wave signal in phase with the sine-wave input to the zero-crossing detector 22 (Fig. 5) and has amplitude from about zero Volts to about five Volts.

5        Capacitors 122, 130, and 138, resistors 124, 128, 132, 144, 142, 146, 150, 152, and 154, op amps 126 and 134, back-to-back diodes 136 and 140, and transistor 148 collectively comprise the zero-crossing detector 22 (Fig. 5). In the preferred embodiment, the op amps 126 and 134 are MC34182 op amps, the back-to-back diodes 136 and 140 are MMBD7000L diodes, and transistor 148 is an

10      MMBT3904LT1 general-purpose NPN silicon transistor, all manufactured by Motorola, Inc.

The signal that supplies the reference phase is coupled into the detector 22 (Fig. 5) through blocking capacitor 122 and buffer op amp 126. The input to detector 22 is typically a sine-wave voltage of from about  $50\text{mV}_{\text{RMS}}$  to about  $2.0\text{V}_{\text{RMS}}$ . The 15 signal is then coupled through potentiometer 128 and resistor 132 to the inverting input of op amp 134. The signal level at the inverting input of op amp 134 is compared to the ground level at the non-inverting input of op amp 134 and the difference is amplified. Because of the large open-loop gain of op amp 134, the output of op amp 134 is driven toward  $V_{\text{CC}}$  when the input signal is negative, and 20 toward  $V_{\text{EE}}$  when the input signal is positive. Thus, for a sine-wave input, the output of op amp 134 is an inverted square wave.

Resistors 142 and 144 provide the proper DC level at the output of op amp 134 and proper DC bias for back-to-back diodes 136 and 140. To prevent op amp 134 from being driven into saturation, back-to-back diodes 136 and 140 provide 25 feedback from the output of op amp 134 to the inverting input of op amp 134 so as to cause op amp 134 to operate in current mode, thereby limiting the gain of op amp 134. The values of resistors 142 and 144 preferably are such that the output of op amp 134 is a square wave of amplitude from about  $-0.5\text{V}$  to about  $+1.5\text{V}$  with midpoint about equal to the forward conductance voltage  $V_{\text{BE}}$  of transistor 148.

30      Capacitor 138 provides feedback from the output of op amp 134 to the inverting input of op amp 134 to ensure more stable switching of the op amp 134

output for input voltage levels substantially equal to zero volts by damping high-frequency oscillations at the output of op amp 134. Capacitor 130 provides a small amount of leading phase angle to compensate for a small amount of lagging phase angle induced by off-state capacitance of the back-to-back diodes 136 and 140.

5 Resistor 132 provides series current limiting of the input signal to op amp 134 while potentiometer 128 provides a means for compensating the phase angle of high-frequency input signals for small zero-crossing detection errors.

Output AO/I of switch 104A is connected to the non-inverting input of unity-gain buffer op amp 156. The output of op amp 156 is connected to resistor 158 and 10 input Y of analog switch 160B. In the preferred embodiment, switch 160B is one switch of an HC4053 triple 2-channel analog multiplexer/demultiplexer manufactured by SGS-Thomson Microelectronics. Op amp 162, resistors 158, 164, and 166 comprise a unity-gain inverting amplifier such that the voltage waveform at the output of op amp 162 is a mirror-image of the voltage waveform at the output of 15 op amp 156. Preferably, resistors 158 and 164 are precision resistors of equal value, and resistor 166 has value approximately half that of resistors 158 and 164. The output of op amp 162 is connected to input X of switch 160B. The output of transistor 148 is coupled through series-limiting resistor 152 to input B of switch 160B.

20 Input B of switch 160B determines whether input X or input Y is connected to output BO/I. When the input to zero-crossing detector 22 (Fig. 5) is positive, PHASE\_I is high, input Y of switch 160B is connected to output BO/I, and the non-inverted version of the input voltage to the synchronous rectifier 18 (Fig. 5) is present at the output BO/I of switch 160B. When the input to zero-crossing detector 25 22 is negative, PHASE\_I is low, input X of switch 160B is connected to output BO/I, and the inverted version of the input voltage to the synchronous rectifier 18 is present at the output BO/I of switch 160B.

Output BO/I of switch 160B is connected to a switch-capacitor low-pass filter comprised of resistor 168 and capacitors 170 and 172. Capacitor 170 is connected to 30 input Y of switch 160A, and capacitor 172 is connected to input X of switch 160A. Amplitude signal select line AMPL\_SEL, from the microprocessor 26 (Fig.5), is

connected to input A of switch 160A. The signal AMPL\_SEL determines whether capacitor 170 or 172 is connected to ground through output AO/I of switch 160A. When AMPL\_SEL is low, input X of switch 160A is connected to output AO/I, and capacitor 172 is connected to ground. When AMPL\_SEL is high, input Y of switch 5 160A is connected to output AO/I, and capacitor 170 is connected to ground. Thus, capacitor 170 is switched into the low-pass filter when the synchronously-rectified sampled cell voltage is being integrated, and capacitor 172 is switched into the low-pass filter when the synchronously-rectified sampled reference resistance voltage is being integrated. Using two separate capacitors 170 and 172 for filtering the output 10 of synchronous rectifier 18 permits faster switching between input signals to the integrator 24 (Fig. 5).

The BO/I output of switch 160B passes through resistor 168 to the VIN+ input of integrating analog-to-digital converter 174 (Figure 7c). Analog-to-digital converter 174, in the preferred embodiment, is a TC500A integrating converter 15 analog processor manufactured by Teledyne Components. Converter 174 is a microprocessor-controlled dual-slope integrating converter. Capacitor 176 and resistors 178 and 180 provide a reference voltage to input REFH of converter 174. The reference voltage of the preferred embodiment is about 200mV, but the absolute 20 value is not critical so long as the voltage remains stable from one conversion to the next. Inputs REFL and ACOM are tied to ground. Connected to input BUF is resistor 182. Capacitor 184 is connected to input CAZ and capacitor 186 is connected to input CINT. The other ends of resistor 182 and capacitors 184 and 186 are tied together. Capacitor 188 is connected between inputs CREF+ and CREF-. From the microprocessor 26 (Fig. 5), two control signals, A and B, are connected to 25 inputs A and B, respectively. The output of the converter 174 appears at output COUT as output signal COMP.

When the control signals AB to converter 174 are set to 01, converter 174 is in its resting state (i.e. not converting). On instruction from the microprocessor 26, control signals AB are set to 10 to begin the integration process. Integration is set to 30 begin and end on zero crossings detected by the zero-crossing detector 22 (Fig. 5), with a minimum integration time as determined by the microprocessor 26 such that

an even number of half-cycles will always be integrated. Integrating over an even number of half-cycles helps to eliminate error due to possible DC levels present in the signal to be integrated. Also, to enhance resolution of low voltage signals, the integration time may be lengthened. During the signal integration period, the 5 microprocessor 26 counts the number of microprocessor clock cycles to determine the actual integration time.

At the end of the signal integration period, microprocessor 26 sets control signals AB to 11 to start deintegration. Converter 174 then integrates the reference voltage at input REFH so as to drive the output at COUT back toward zero. The 10 microprocessor 26 counts microprocessor clock cycles during the deintegration period. When the COMP output signal goes low, deintegration is complete, and the microprocessor 26 sets control signals AB to 01 to zero the converter 174 COMP output until the next conversion period.

The microprocessor 26 then uses the integration time, deintegration time, and 15 known reference voltage to compute a DC voltage value for the signal voltage applied to the converter 174 VIN+ input during the integration time period. The larger the input voltage to converter 174 is relative to the reference voltage at VREF+, the longer it takes to deintegrate the COMP output back to a low level. The computed DC voltage value represents the RMS voltage value for the input voltage 20 and is computed by multiplying the known reference voltage times the ratio of the deintegration time to the integration time.

Turning now to Figure 8, a conductivity meter incorporating the preferred embodiment of the invention can be seen. Microprocessor 26 is connected to a keypad 202 and buzzer 204 through keypad controller 206. An operator can enter 25 information into the meter and select different modes of operation through keypad 202. The microprocessor 26 can generate a tone from buzzer 204 when desired. Watchdog timer 208 monitors microprocessor 26 and provides a reset signal to microprocessor 26 if no microprocessor 26 activity is detected for a predetermined 30 interval of time. Real time clock 210 provides external timing information to microprocessor 26. Microprocessor 26 is connected through serial port interface 212 to an RS-232 port 214 to permit communication with external peripheral devices.

Programmable read-only memory ("ROM") 216 contains the software instructions which control the operation of the meter and are executed by microprocessor 26. Random-access memory ("RAM") 218 is used by microprocessor 26 to store information. Microprocessor 26 addresses ROM 216 and RAM 218 via address bus 220. Data is communicated among the microprocessor 26, ROM 216, RAM 218, display 222, and data latch 224 via data bus 226. Display 222 is preferably a liquid-crystal display, but may be any means suitable for visually displaying information. Data latch 224 holds the various control signals used by the different parts of the meter.

10 Microprocessor 26 controls the operation of sine-wave generator 30 to produce sine-wave excitation of predetermined frequency and amplitude. Sine-wave excitation is coupled by means of switches 64, 62, and 60, in response to range select signals RANGE\_1, RANGE\_2, and RANGE\_3, respectively, from data latch 224, to reference resistors 76, 74, and 72. Sine-wave excitation is also coupled from sine-wave generator 30 to cell 10. Range select signal RANGE\_1 is also coupled to platinizing circuit 226, which is coupled to cell 10 via switch 228 in response to a platinizing signal PLAT from data latch 224. Platinizing circuit 226 provides a reversible 30mA current to cell 10 to permit deposition of platinum black on the cell electrodes (not shown).

15 20 In response to standard select signal STD\_SEL from latch 224, switch 104B provides the appropriate reference resistance sample voltage to switches 104A and 104C. The sampled cell voltages from cell 10 are applied to differential amplifier 114, then to switches 104A and 104C. In response to phase select signal PHASE\_SEL from latch 224, switch 104C passes the appropriate sample voltage to 25 zero-crossing detector 22. The zero-crossing detector 22 output signal PHASE\_I is provided to microprocessor 26 and synchronous rectifier 18.

20 30 In response to amplitude select signal AMPL\_SEL, switch 104A passes the appropriate sample voltage to synchronous rectifier 18. The synchronously-rectified output from rectifier 18 is coupled to the switched-capacitor low-pass filter comprised of resistor 168 and capacitors 170 and 172. The appropriate capacitor 170 or 172 is connected to ground by switch 160A in response to signal AMPL\_SEL

from latch 224.

Cell 10 may contain a built-in thermistor (not shown) which provides an output through external thermistor jack 230 to switch 160C. Temperature information from the built-in thermistor, or alternatively from an external thermistor 5 (not shown), is coupled from jack 230 to switch 160. In response to a signal A/D\_SEL from latch 224, switch 160 passes either a synchronously-rectified sample voltage or a thermistor voltage to integrator 24. The output from integrator 24 is provided to microprocessor 26 for calculation of the appropriate parameters.

Although the present invention has been described with reference to preferred 10 embodiments, it is to be understood that various modifications may be made without departing from the spirit and scope of the invention. Moreover, the invention is not limited to the particular form or arrangement described herein except to the extent that such limitations are found in the claims.

--CLAIMS--

1. An apparatus for providing an output representative of a conductivity of a liquid sensed by a cell which produces a cell signal which is affected by a capacitance, comprising:
  - 5 excitation means for producing periodic time-varying excitation, said excitation means coupled to the cell;
    - a reference resistance, said reference resistance coupled to the excitation means and the cell in series electrical connection;
    - sampling means coupled to the cell and to the reference resistance for
  - 10 sampling whole half-cycles of the cell signal and a reference signal produced by the reference resistance; and
  - measurement means coupled to the sampling means for measuring the cell signal as sampled and for measuring the reference signal as sampled and providing the output substantially corrected for the effect of the capacitance.
2. A conductivity measuring apparatus comprising:
  - a periodic time-varying excitation source;
  - a sensor electrically coupled to said source and producing a sensor signal;
  - 5 a reference resistance having a resistance value and electrically connected in series with said source and said sensor and producing a reference signal;
  - a phase-synchronous sampling means electrically coupled to said sensor and to said resistance for producing a synchronized sampled sensor signal and
- 10 a synchronized sampled reference signal synchronized with a predetermined signal phase; and
- measurement means electrically coupled to the sampling means for providing a measure of conductivity in response to the synchronized sampled sensor signal and the synchronized sampled reference signal.

3. The conductivity measuring apparatus of claim 2 wherein:  
the measurement means includes integrator means for producing DC levels representative of the RMS values of the synchronized sampled sensor signal and the synchronized sampled reference signal.
4. The conductivity measuring apparatus of claim 2 wherein:  
the periodic time-varying excitation source is a means for producing substantially sinusoidal excitation.
5. The conductivity measuring apparatus of claim 2 wherein:  
the sensor is a conductance cell immersed in a liquid the conductivity of which is desired.
6. The conductivity measuring apparatus of claim 2 wherein:  
the reference resistance is a plurality of resistances which may be selectively included so as to provide a plurality of ranges of conductivity measurements.
7. The conductivity measuring apparatus of claim 2 wherein:  
the sampling means includes zero-crossing detector means for producing a zero-crossing detect signal in response to the predetermined signal phase amplitude being substantially zero;  
5 inverting means for providing an inverted sampled signal in response to either a sensor signal or a reference signal;  
non-inverting means for providing a non-inverted sampled signal in response to either a sensor signal or a reference signal; and  
switching means for providing either the inverted sampled signal or  
10 the non-inverted sampled signal in response to the zero-crossing detect signal.

8. A method for determining conductivity comprising:
  - applying a time-varying excitation to a reference resistance and a conductivity cell in series connection, said cell having a cell resistance, a cell series capacitance, and a cell parallel capacitance;
  - 5 sampling a resistance voltage across the reference resistance and a cell voltage across the conductivity cell;
  - synchronously rectifying both the resistance voltage and the cell voltage with respect to the phase of the resistance voltage;
  - integrating both the synchronously rectified resistance voltage and the
  - 10 synchronously rectified cell voltage;
  - calculating the value of the cell resistance by multiplying the value of the reference resistance by the ratio of the integrated synchronously rectified cell voltage to the integrated synchronously rectified resistance voltage.
9. A method for determining conductivity comprising:
  - applying a time-varying excitation to a reference resistance and a conductivity cell in series connection, said cell having a cell resistance, a cell series capacitance, and a cell parallel capacitance;
  - 5 sampling a resistance voltage across the reference resistance and a cell voltage across the conductivity cell;
  - synchronously rectifying both the resistance voltage and the cell voltage with respect to the phase of the cell voltage;
  - integrating both the synchronously rectified resistance voltage and the
  - 10 synchronously rectified cell voltage;
  - calculating the value of the cell resistance by multiplying the value of the reference resistance by the ratio of the integrated synchronously rectified cell voltage to the integrated synchronously rectified resistance voltage.

10. A method for determining conductivity comprising:
  - applying a time-varying periodic excitation to an unknown impedance and a reference resistance in series electrical connection, said unknown impedance having an unknown resistance;
  - 5 integrating the voltage across the unknown impedance over a time period during which the aggregate contribution of any unknown capacitance is zero;
  - integrated the voltage across the reference resistance over the same time period;
  - calculating the ratio of the two integrated voltages; and
- 10 using the integral ratio and a known value of the reference resistance to calculate the value of the unknown resistance.

11. A method for determining conductivity comprising:
  - applying a time-varying periodic excitation to an unknown impedance and a reference resistance in series electrical connection, said unknown impedance having an unknown resistance;
  - 5 integrating the voltage across the reference resistance over a time period during which the aggregate contribution of any unknown capacitance is zero;
  - integrated the voltage across the unknown impedance over the same time period;
  - calculating the ratio of the two integrated voltages; and
- 10 using the integral ratio and a known value of the reference resistance to calculate the value of the unknown resistance.

12. An apparatus for determining the conductivity of an unknown impedance having an unknown resistance comprising:

excitation means for applying a time-varying periodic excitation to the unknown impedance;

5 a reference resistance in series electrical connection with said unknown impedance and said excitation means;

means for integrating the voltage across the unknown impedance over a time period during which the aggregate contribution of any unknown capacitance is zero;

10 means for integrating the voltage across the reference resistance over the same time period;

means for calculating the ratio of the two integrated voltages; and

means for using the integral ratio and a known value of the reference resistance to calculate the value of the unknown resistance.

13. The apparatus according to claim 12 wherein:

said means for integrating the voltage across the unknown impedance further comprises means for detecting zero-crossings of the voltage across the reference resistance;

5 means for rectifying the voltage across the unknown impedance responsive to said means for detecting zero-crossings of the voltage across the reference resistance; and

means for integrating the voltage across the reference resistance further comprises means for detecting zero-crossings of the voltage across the

10 reference resistance; and

means for rectifying the voltage across the reference resistance responsive to said means for detecting zero-crossings of the voltage across the reference resistance.

14. An apparatus for determining the conductivity of an unknown impedance having an unknown resistance comprising:

excitation means for applying a time-varying periodic excitation to the unknown impedance;

5 a reference resistance in series electrical connection with said unknown impedance and said excitation means;

means for integrating the voltage across the reference resistance over a time period during which the aggregate contribution of any unknown capacitance is zero;

10 means for integrating the voltage across the unknown impedance over the same time period;

means for calculating the ratio of the two integrated voltages; and

means for using the integral ratio and a known value of the reference resistance to calculate the value of the unknown resistance.

15. The apparatus according to claim 14 wherein:

said means for integrating the voltage across the reference resistance further comprises means for detecting zero-crossings of the voltage across the unknown impedance;

5 means for rectifying the voltage across the reference resistance responsive to said means for detecting zero-crossings of the voltage across the unknown impedance; and

means for integrating the voltage across the unknown impedance further comprises means for detecting zero-crossings of the voltage across the

10 unknown impedance; and

means for rectifying the voltage across the unknown impedance responsive to said means for detecting zero-crossings of the voltage across the unknown impedance.

16. The method according to claim 10 wherein:  
the step of integrating the voltage across the unknown impedance  
includes the steps of detecting zero-crossings of the voltage across the reference  
resistance;

5 rectifying the voltage across the unknown impedance responsive to  
said detected zero-crossings; and  
the step of integrating the voltage across the reference resistance  
includes the steps of detecting zero-crossings of the voltage across the reference  
resistance; and

10 rectifying the voltage across the reference resistance responsive to  
said detected zero-crossings.

17. The method according to claim 11 wherein:  
the step of integrating the voltage across the reference resistance  
includes the steps of detecting zero-crossings of the voltage across the unknown  
impedance;

5 rectifying the voltage across the reference resistance responsive to  
said detected zero-crossings; and  
the step of integrating the voltage across the unknown impedance  
includes the steps of detecting zero-crossings of the voltage across the unknown  
impedance; and

10 rectifying the voltage across the unknown impedance responsive to  
said detected zero-crossings.

18. The apparatus according to claim 1 wherein:  
said sampling means includes means for detecting zero-crossings of  
the reference signal;  
means for rectifying the cell signal synchronously with said detected  
5 zero-crossings; and  
means for rectifying the reference signal synchronously with said  
detected zero-crossings.

19. The apparatus according to claim 1 wherein:  
said sampling means includes means for detecting zero-crossings of  
the cell signal;  
means for rectifying the cell signal synchronously with said detected  
5 zero-crossings; and  
means for rectifying the reference signal synchronously with said  
detected zero-crossings.

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FIG - 1

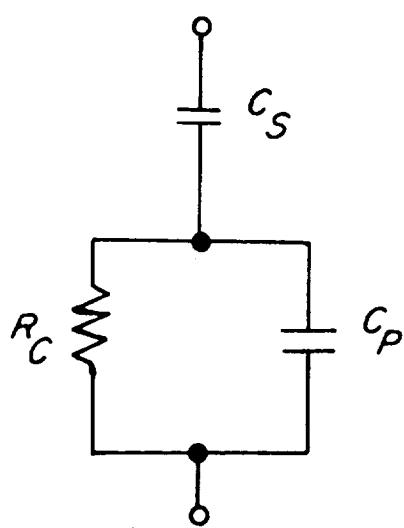


FIG - 2

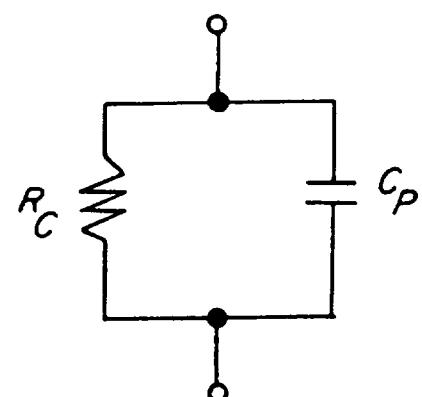


FIG - 3

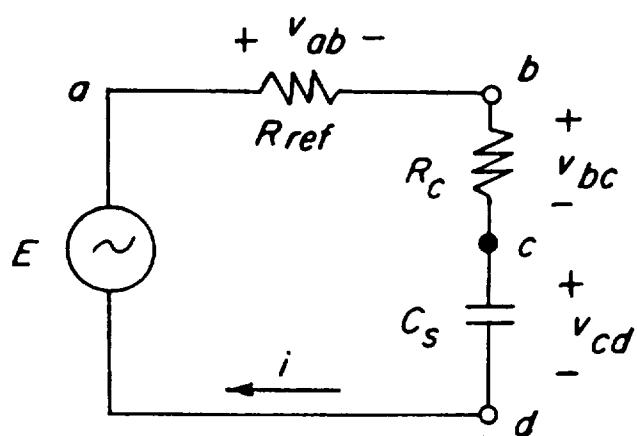


FIG - 4

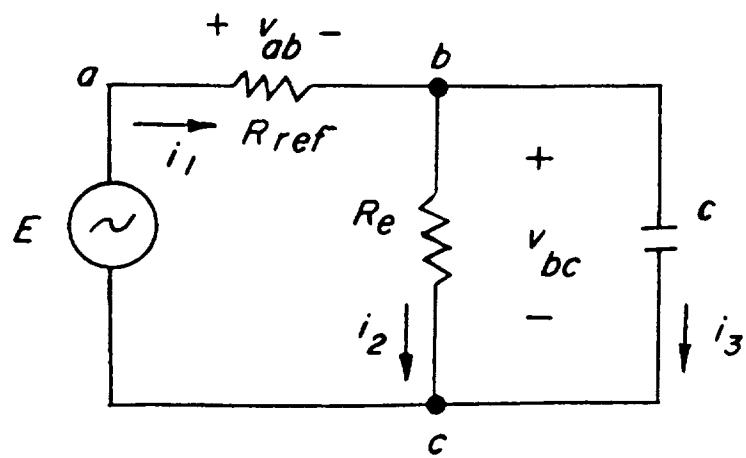
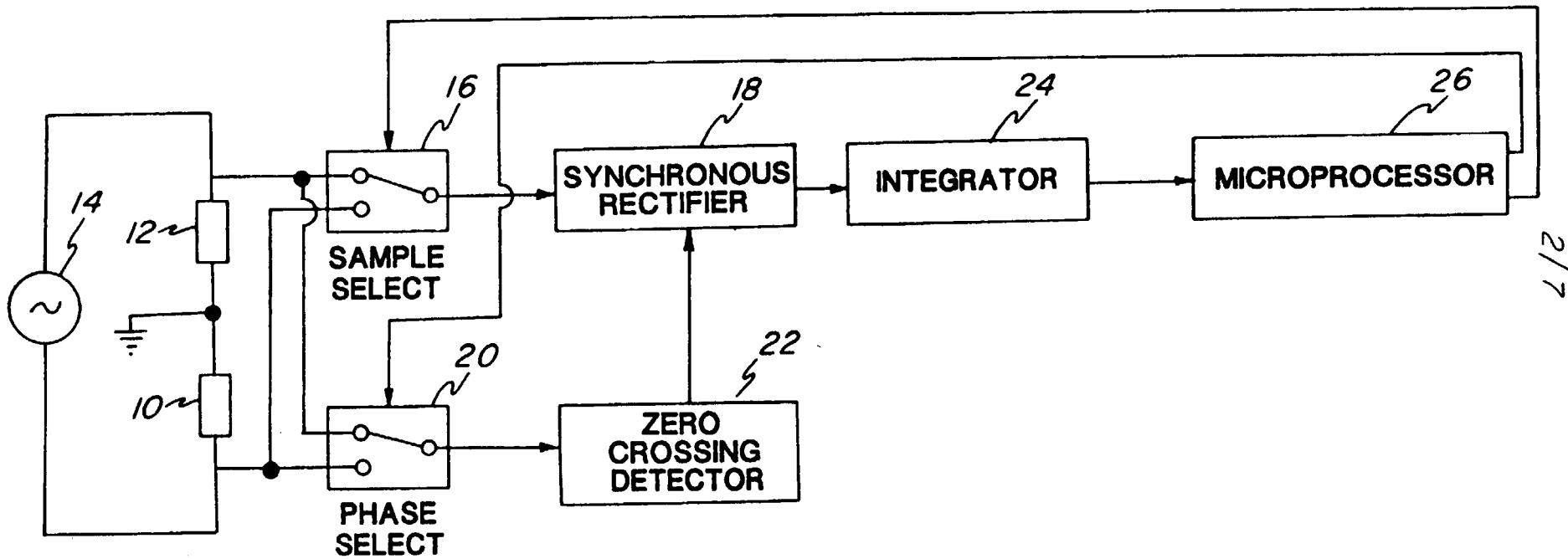


FIG. 5



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FIG. 6

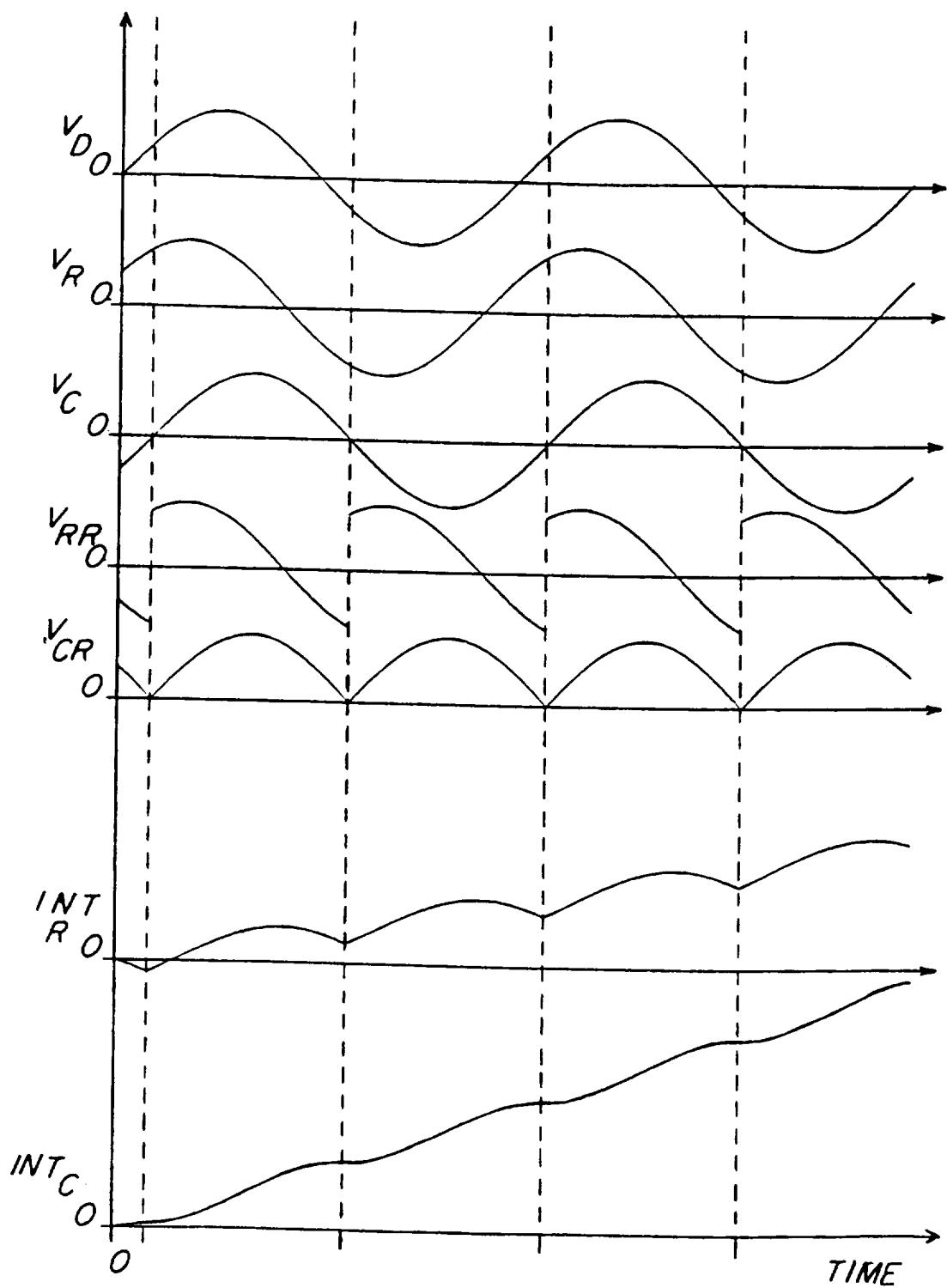


FIG - 70

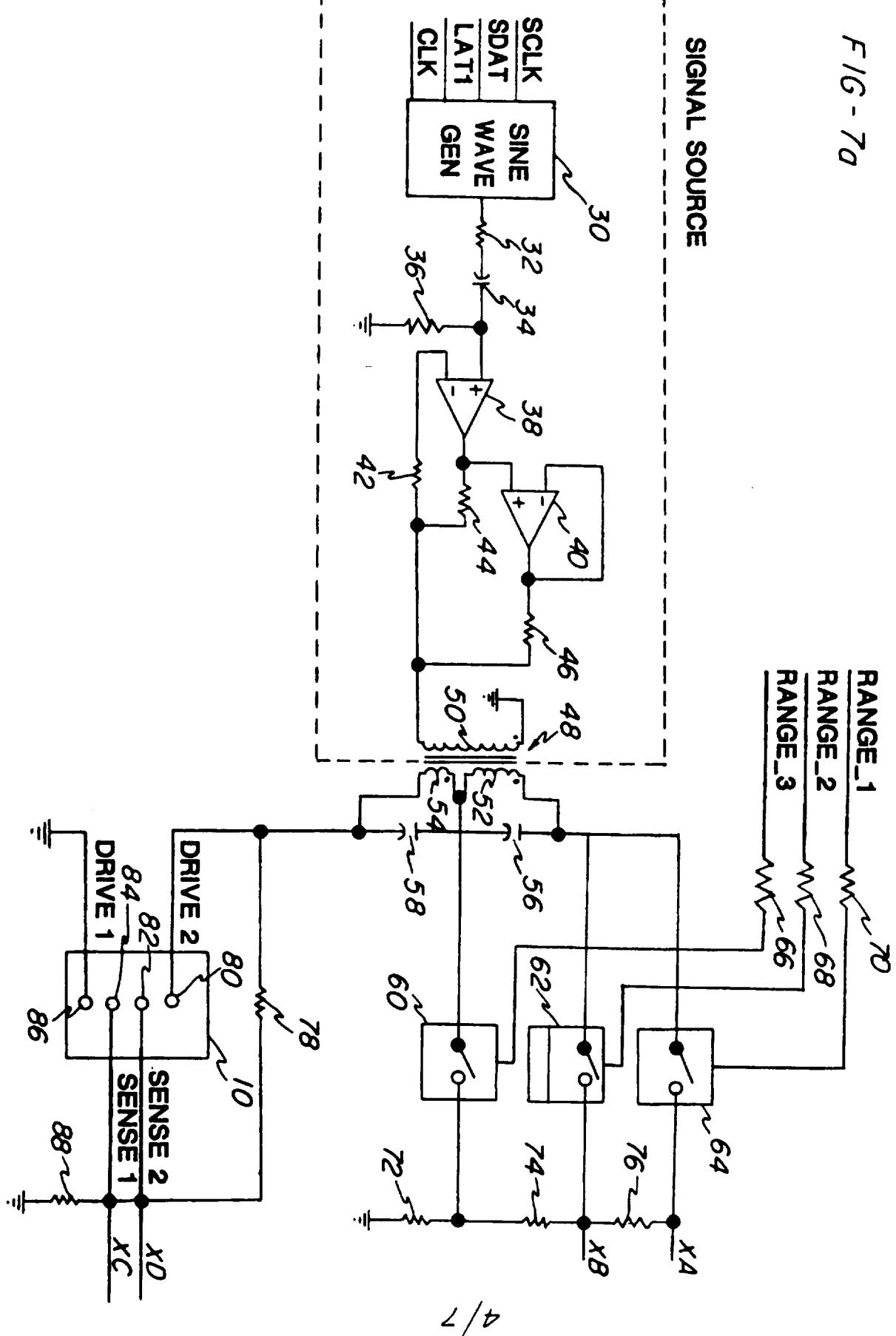
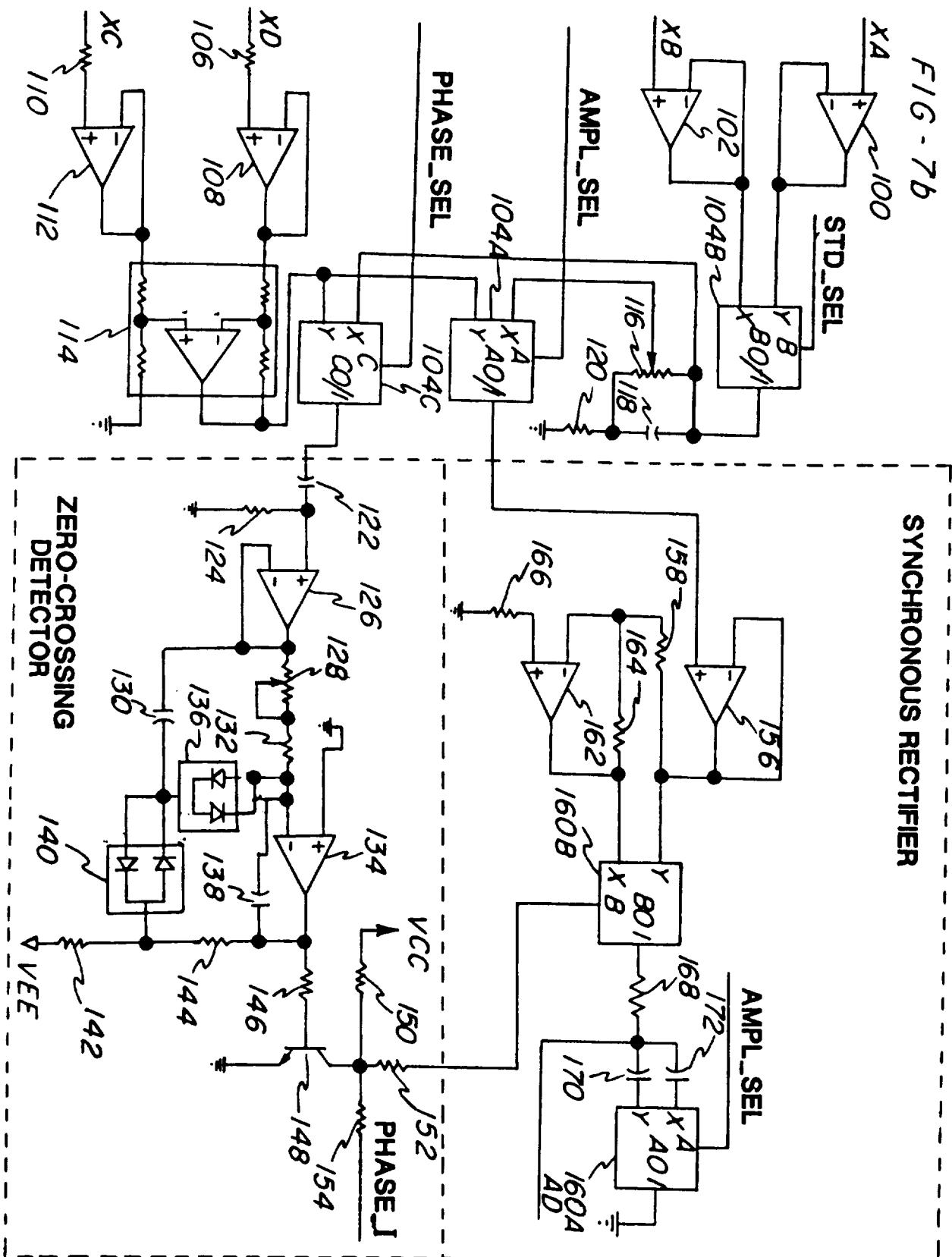


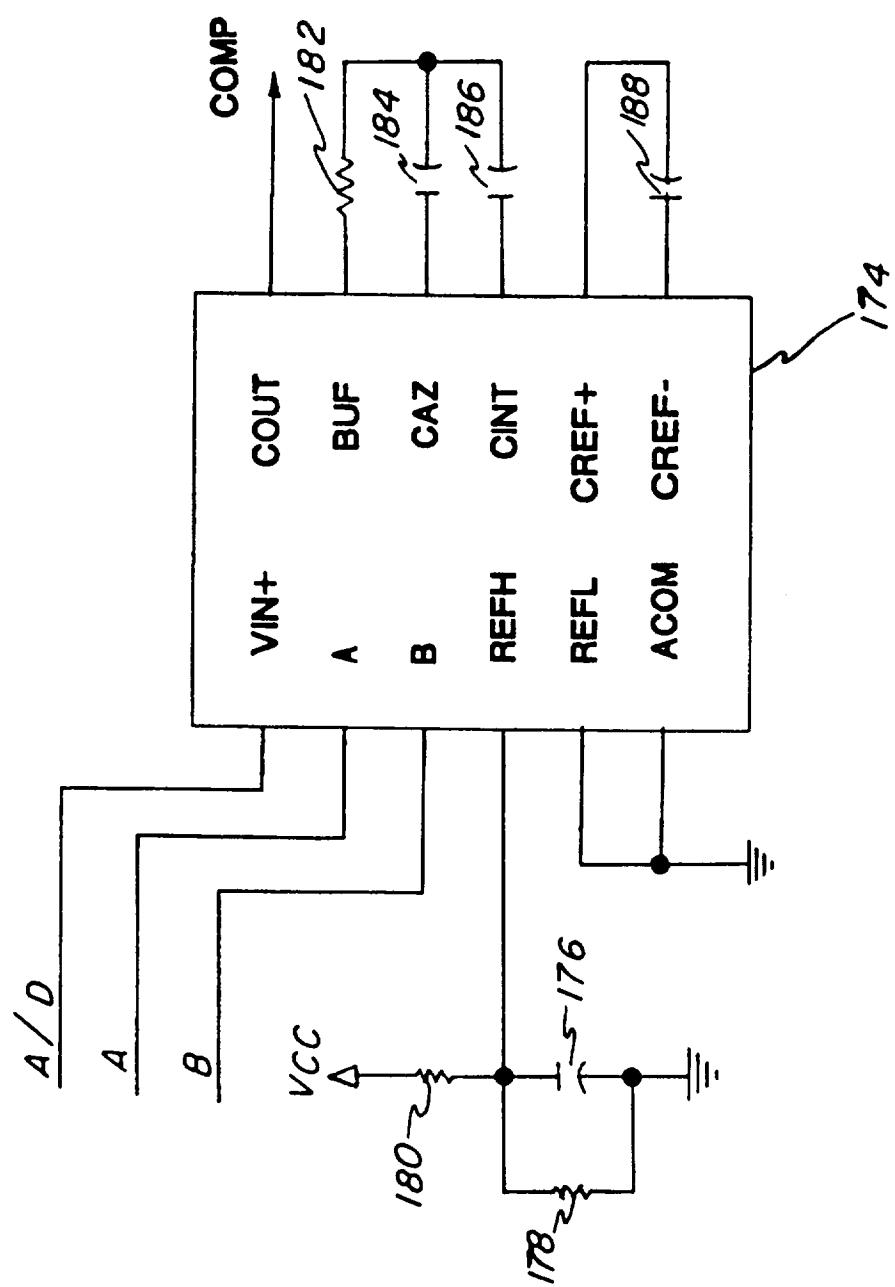
FIG - 7b

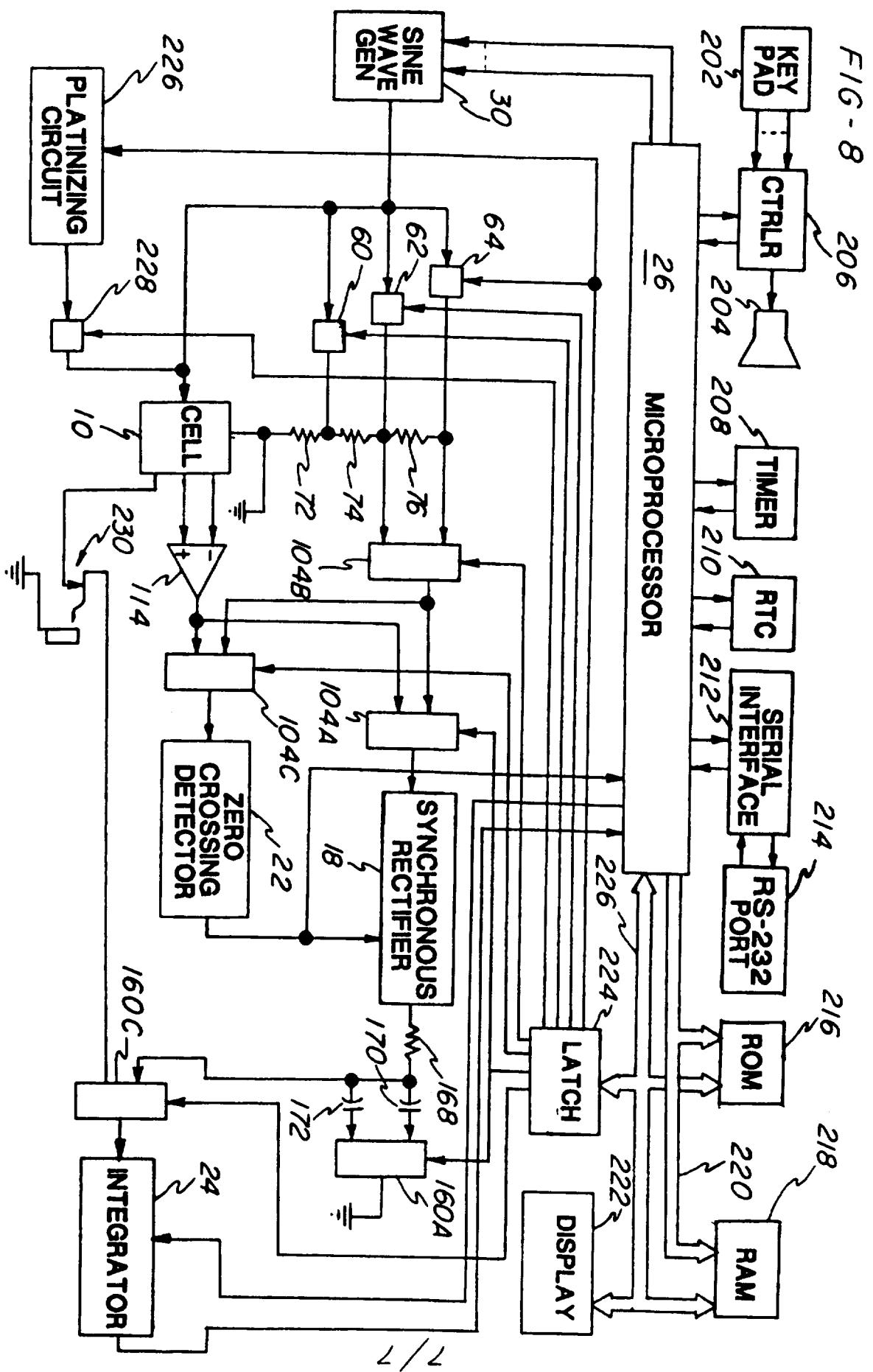
## SYNCHRONOUS RECTIFIER



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FIG - 7c





## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US97/17237

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G01R 27/22; G01N 27/06  
US CL :324/439, 693, 704, 709 713

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)

U.S. : 324/439, 442, 446, 691, 693, 694, 704, 709 713, 722; 204/400, 402, 406, 407

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched  
noneElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
none

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,334,940 A (BLADES) 02 August 1994, Fig. 10.	1-19
A	US 5,260,663 A (BLADES) 09 November 1993, Fig. 10.	1-19
A	US 4,808,930 A (KAISER) 28 February 1989, Figs. 1 and 5.	1-19
A	US 3,906,353 A (MURDOCK) 16 September 1975, Fig. 7.	1-19

 Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:	
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*O* document referring to an oral disclosure, use, exhibition or other means	*&* document member of the same patent family
*P* document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

19 NOVEMBER 1997

Date of mailing of the international search report

17 MAR 1998

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