CAPACITANCE-MEASURING TECHNIQUE

Original Filed April 14, 1969 3 Sheets-Sheet 1

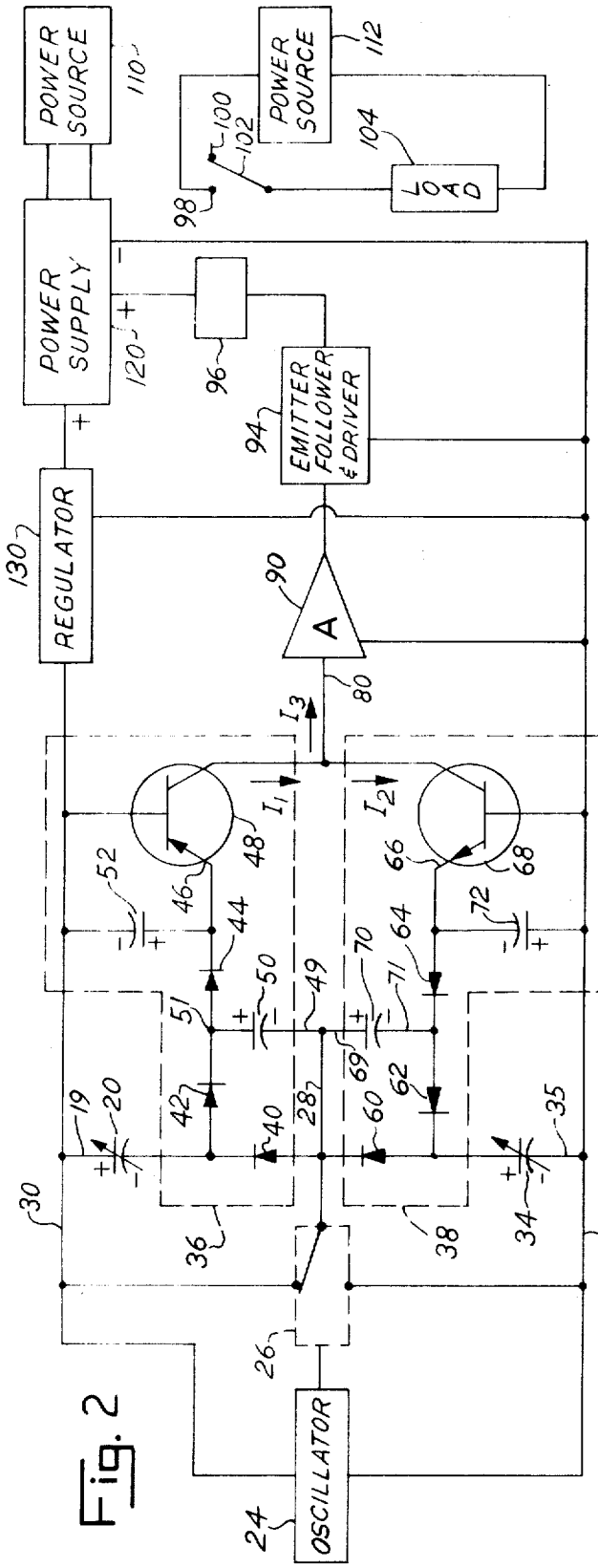


Fig. 2

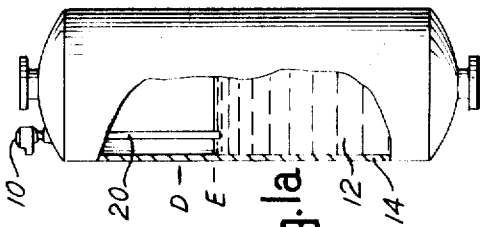


Fig. 1a

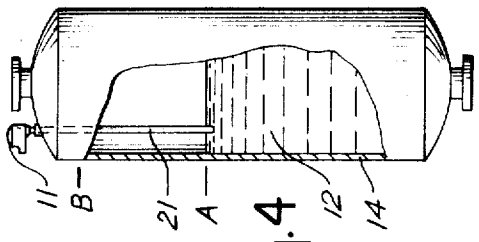


Fig. 4

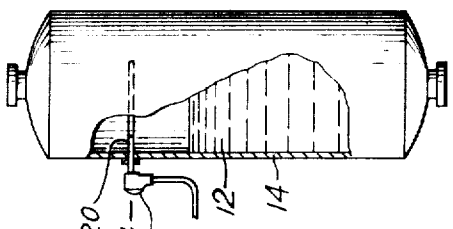


Fig. 1

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CAPACITANCE-MEASURING TECHNIQUE

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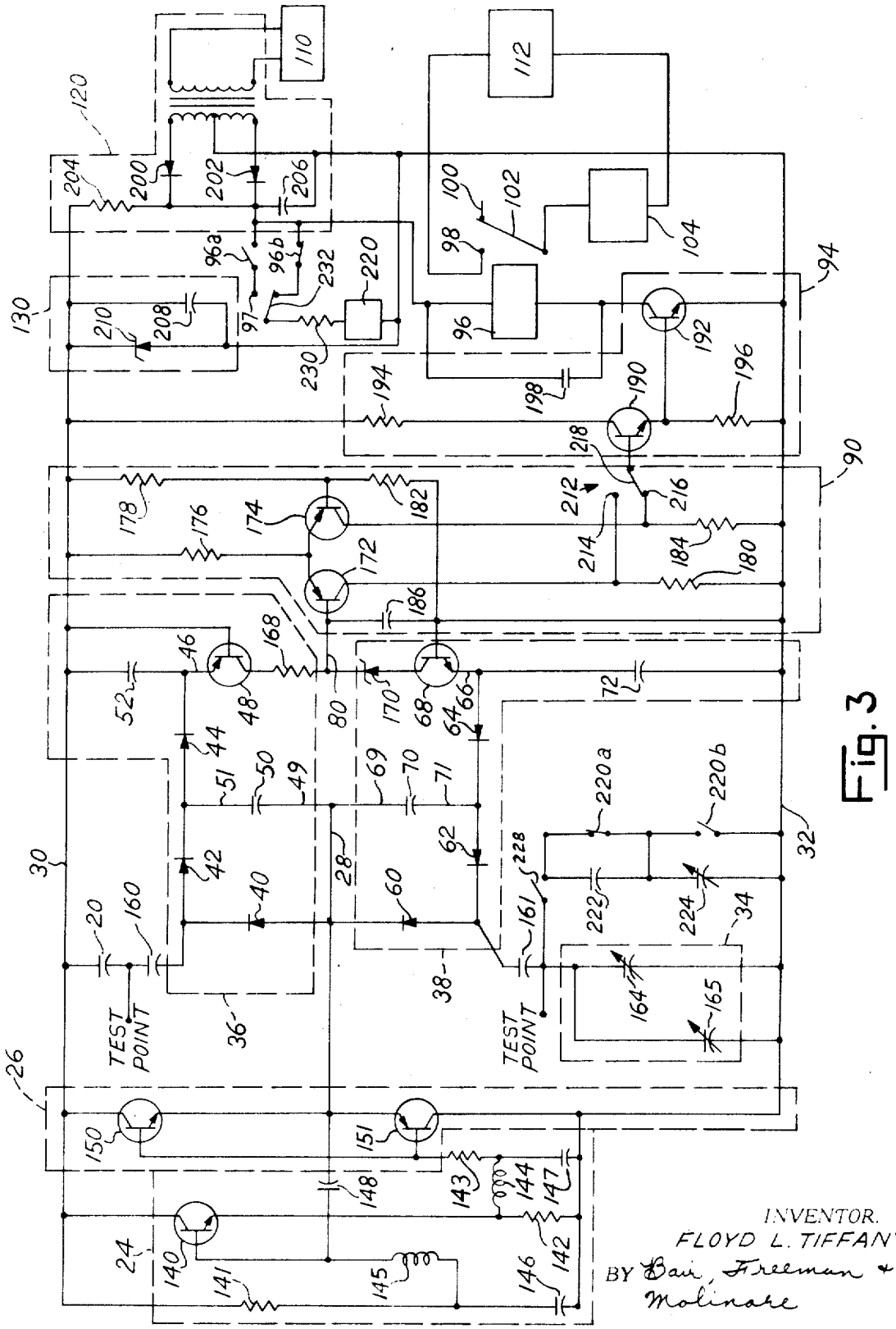


Fig. 3

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CAPACITANCE-MEASURING TECHNIQUE

Original Filed April 14, 1969 3 Sheets-Sheet 3

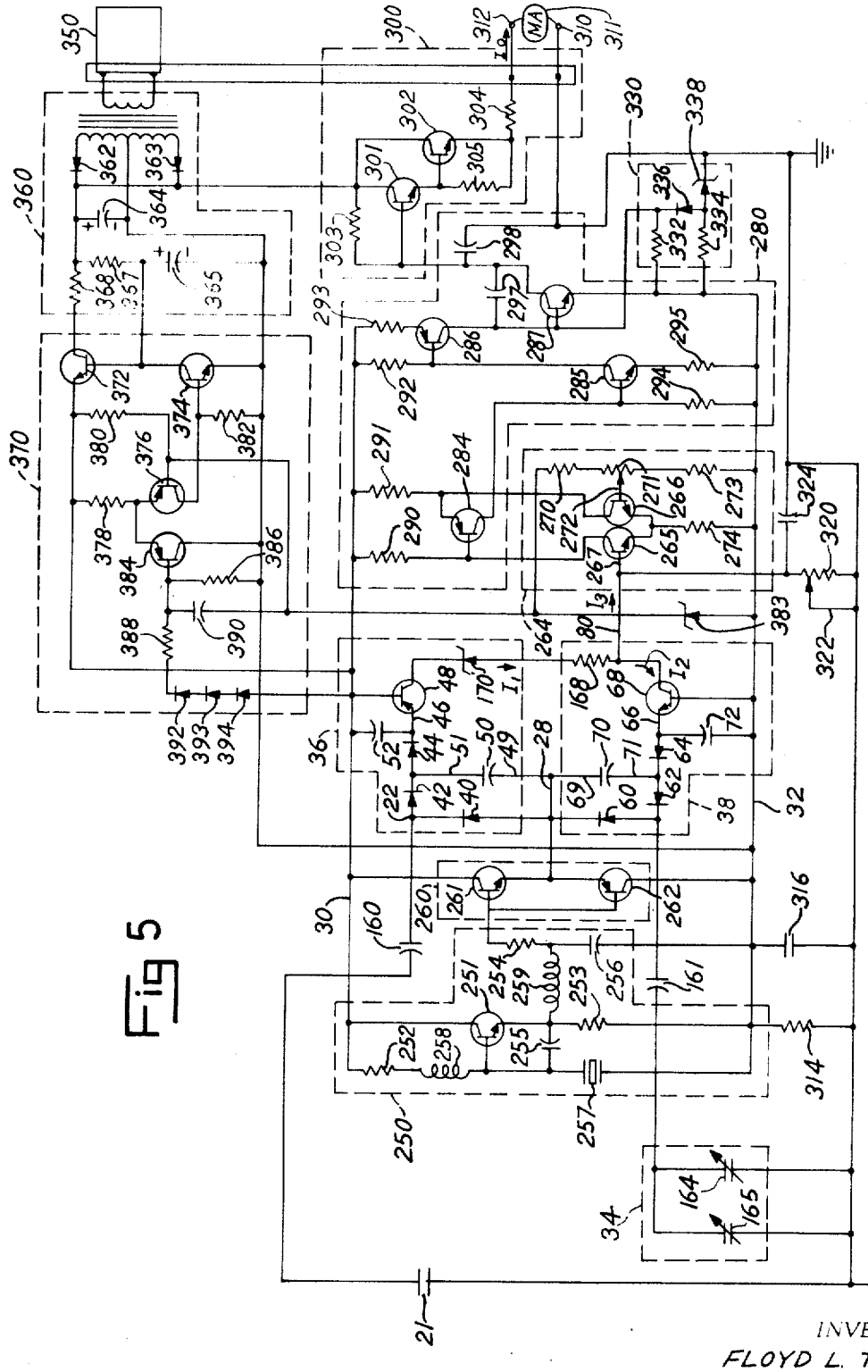


Fig 5

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Re. 27,829
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27,829

CAPACITANCE-MEASURING TECHNIQUES

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Original No. 3,543,046, dated Nov. 24, 1970, Ser. No. 815,795, Apr. 14, 1969. Application for reissue Sept. 21, 1972, Ser. No. 291,052

Int. Cl. G01f *31/00*

U.S. Cl. 307—118 24 Claims

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

ABSTRACT OF THE DISCLOSURE

The relative capacitance of a first capacitor may be accurately measured by providing a second reference capacitor and a switch that cyclically charges and discharges the first and second capacitors at a predetermined rate. The cyclical charging and discharging of the first capacitor produces a first current that is amplified by a first amplifier. The cyclical charging and discharging of the second reference capacitor produces a second current that is amplified by a second amplifier. The first and second currents are algebraically summed and conducted to a comparison device that indicates the relative difference between the capacitance of the first and second capacitors by sensing the magnitude of the summed currents.

BACKGROUND AND SUMMARY OF THE INVENTION

This invention relates to capacitance-measuring techniques, and it is more particularly directed to capacitance-type level-measuring and control devices.

Devices generally capable of monitoring and controlling the level of a liquid or granular substance held in a tank or bin have been used to advantage for many years. In one class of such devices, the level of the substance is monitored by placing a probe comprising a variable capacitor into the tank. If the probe is mounted horizontally at a particular level, the capacitance of the probe changes abruptly as the level of the substance rises and covers the probe. By sensing the change in capacitance, the presence of the substance at the particular level may be detected. If the probe is mounted vertically, the capacitance of the probe is gradually altered as the level rises and covers an increasingly larger proportion of the probe. By sensing the gradual change in capacitance, the level of the substance may be continuously monitored.

A typical circuit presently used to detect a change in probe capacitance comprises an oscillator that has the probe electrically connected to its input circuit. As the probe capacitance changes, the magnitude of the input voltage to the oscillator is varied, and the magnitude of the oscillator output voltage is altered accordingly. The oscillator output voltage is rectified and is used to drive a relay circuit that is energized when the voltage level reaches a predetermined value. Alternatively, the rectified output voltage may be used to operate a meter or other indicating device. A device of the foregoing type is illustrated in U.S. Reissue Pat. No. 25,977 (Rosso—1966).

Although devices of the foregoing type have been somewhat useful for certain applications, they have been deficient in sensitivity, linearity, temperature stability, and the ability to detect changes in capacitance that occur over a wide range of values.

It has been surprisingly discovered that each of the foregoing qualities lacking in the prior art devices may

be achieved by providing a reference capacitor for use in connection with the probe capacitor and a switch means that cyclically charges and discharges the reference and probe capacitors. The cyclical charging and discharging of the probe capacitor produces a first current that depends on the capacitance value thereof. A second independent current is created by the charging and discharging of the reference capacitor. As the capacitance of the probe is altered due to changes in the level of the substance being measured, the magnitude of the first current is varied accordingly. Since the reference capacitor is not affected by level changes in the tank, the second current remains relatively constant. By comparing the first and second currents, the relative change in probe capacitance due to changes in tank level may be measured with a degree of accuracy, sensitivity, and linearity unattained by prior art devices. Moreover, environmental factors such as changes in temperature and line voltage have an insignificant effect on the operation of the invention during normal usage.

Accordingly, it is a primary object of the present invention to provide a level-detecting device in which the capacitance of a probe capacitor is compared with the capacitance of a reference capacitor.

It is another related object of the present invention to provide a device of the foregoing type in which the probe capacitor and reference capacitor are periodically charged and discharged.

It is yet another object of the present invention to provide means for producing currents the magnitude of which are respectively related to the capacitances of the probe and reference capacitors.

It is yet another object of the present invention to provide a device of the foregonig type in which the currents produced by the charging and discharging of the probe and reference capacitors are compared in order to determine the relative capacitance of the probe and reference capacitors.

Yet another object of the present invention is to provide a device of the foregoing type in which the sensitivity thereof may be adjusted without altering the minimum output current produced by the device.

DESCRIPTION OF THE DRAWINGS

These and other objects and advantages of the present invention will be pointed out for purposes of illustration, but not of limitation, in the accompanying drawings in which like reference numerals refer to like parts throughout, and in which:

FIG. 1 illustrates a preferred means of horizontally mounting a probe capacitor used in connection with the present invention;

FIG. 1a illustrates a preferred means of vertically mounting the probe capacitor shown in FIG. 1 for two-point and single-point control applications;

FIG. 2 is a block diagram, schematic drawing of a preferred form of capacitance-measuring device made in accordance with the present invention and intended for use in connection with the probe capacitor illustrated in FIG. 1 or FIG. 1a;

FIG. 3 is a detailed schematic drawing of the device shown in FIG. 2, together with an additional control circuit;

FIG. 4 illustrates a preferred means of vertically mounting a probe capacitor used in connection with the present invention for proportional control or indication; and

FIG. 5 is a detailed schematic drawing of a capacitance-measuring device made in accordance with the present invention and intended for use in connection with the probe capacitor illustrated in FIG. 4.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

As best shown in FIG. 1 and FIG. 1a, a capacitance-measuring circuit **10** made in accordance with the present invention may be used to indicate or control the level of a liquid **12** held in a tank **14**. The tank is fitted with a probe capacitor **20** which has a capacitance that depends on the presence or absence of liquid surrounding the probe. The probe may be mounted either vertically or horizontally. A capacitance-measuring circuit **10** is mounted on the probe capacitor in order to detect any changes in the capacitance thereof, thereby indicating whether the liquid level is above or below a set point level such as level C.

Referring to FIG. 2, a preferred form of capacitance-measuring circuit **10** basically comprises an oscillator **24** that operates a switch **26** at a predetermined rate, such as 200 kilocycles. Switch **26** alternately applies to a conductor **28**, a positive supply voltage from a conductor **30** or a negative supply voltage from a conductor **32**. The operation of switch **26** alternately charges and discharges probe capacitor **20**, a reference capacitor **34**, and certain components of detecting circuits **36** and **38** (indicated by dotted lines).

Detecting circuit **36** is used to produce a current I_1 (flowing in the direction indicated) that is proportional to the change of voltage created across capacitor **20** due to the cyclical charging and discharging thereof. The circuit comprises diodes **40**, **42**, and **44** that are connected in series between conductor **28** and an emitter lead **46** of an amplifier transistor **48**. The circuit also includes a capacitor **50** having terminals **49** and **51** connected between conductor **28** and the junction of diodes **42** and **44**, and a capacitor **52** that is connected between a base lead and the emitter lead **46** of transistor **48** (i.e., between the input terminals of transistor **48**).

Detecting circuit **38** produces a current I_2 (flowing in the direction indicated) that is proportional to the change of voltage created across capacitor **34** due to the cyclical charging and discharging thereof. The circuit comprises diodes **60**, **62**, and **64** that are connected in series between conductor **28** and an emitter lead **66** of an amplifier transistor **68**. The circuit also includes a capacitor **70** having terminals **69** and **71** connected between conductor **28** and the junction of diodes **62**, **64**, and a capacitor **72** that is connected between a base lead and the emitter lead **66** of transistor **68** (i.e., between the input terminals of transistor **68**).

The collector leads of transistors **48** and **68** are connected through a conductor **80** to an amplifier **90**. As a result, current I_3 (flowing in the direction indicated) in conductor **80** represents the difference between the magnitude of current I_1 flowing in the collector lead of transistor **48** and current I_2 flowing in the collector lead of transistor **68**. Current I_3 is amplified in amplifier **90** and is passed through an emitter follower and driver arrangement **94** to the coil of a relay **96**. Relay **96** has contacts **98**, **100**, and a contact arm **102**. Contact arm **102**, in turn, is connected through a load **104** to a power source **112**. Load **104** preferably comprises an indicating device as a light bulb.

Power is supplied to the circuit through a source of AC power **110**. The AC power is converted to DC current in power supply **120** and is maintained at a predetermined value by a regulator **130**. A DC power source may be used to replace the AC power source **110** and the power supply **120**.

The operation of the apparatus shown in FIG. 2 is described as follows. Basically, switch **26** is used to simutlaneously charge capacitor **20** and discharge capacitor **34**, and conversely to simultaneously charge capacitor **34** and discharge capacitor **20** on alternate cycles of operation. The charging and discharging of the capacitors creates corresponding current that charge capacitors **52** and **72** until the forward conducting voltage across the

emitter to base junction of transistors **48** and **68**, respectively, is reached. Transistors **48** and **68** then conduct and establish currents I_1 and I_2 in their respective collector leads. The magnitudes of currents I_1 and I_2 depend on the capacitance of probe capacitor **20** and reference capacitor **34**, respectively.

In order to adjust the circuit, the level of liquid in tank **14** is raised to an adjustment level at the midpoint of probe **20** (i.e., to level C, FIG. 1) or to any desired adjustment level on a vetrical probe such as level D, (FIG. 1a). Capacitor **34** is then adjusted so that it is equal in magnitude to capacitor **20**. As a result, currents I_1 and I_2 are substantially equal and current I_3 has a low value that is insufficient to operate relay **96**. If the level of liquid decreases, I_1 decreases and current I_3 becomes negative. However, as soon as the level increases above the adjustment level, the capacitance of probe **20** becomes slightly greater than the capacitance developed during adjustment, and current I_1 thereby increases. The extreme sensitivity of the circuit enables current I_1 to be significantly increased even though the capacitance of probe **20** increases by only about .01 picofarad. An increase in current I_1 also increases current I_3. Accordingly, current I_3 is amplified by amplifier **90** to operate relay **96**, and load **104** is connected to the power source **112** through contact **98** when the liquid in tank **14** rises slightly above the adjustment level.

The foregoing mode of operation is achieved when terminal **19** of capacitor **20** is connected to the positive supply voltage and teminal **35** of capacitor **34** is connected to the negative supply voltage. However, it should be noted that the same basic mode of operation may be achieved when terminal **19** is connected to any source of positive or negative DC voltage within the breakdown limits of the components. Likewise, terminal **35** may be connected to any source of positive or negative DC voltage without altering the overall operating charatceristics of the circuitry. The probe and reference capacitors may be connected in the manner described as long as an AC bypass path is provided between the DC voltage supply terminals to which the subject capacitors are connected.

The operation of detecting circuit **36** and probe capacitor **20** will now be described in more detail assuming that switch **26** is connecting conductor **28** to negative supply conductor **32**. With switch **26** in the position described, diodes **40** and **44** are reverse biasesd and capacitors **20** and **50** are charged through diode **42**. Since capacitor **50** is normally at least 100 times larger than capacitor **20**, most of the voltage drop during the charging process occurs across capacitor **20**. Accordingly, capacitor **50** is charged to a relatively small positive voltage that depends on the relative capacitance of the two capacitors.

When switch **26** is reversed so that it connects conductor **28** to conductor **30**, the positive supply voltage is conducted to capacitor **20** through diode **40** and is directly conducted to terminal **49** of capacitor **50**.

Since the voltage on terminal **49** of capacitor **50** changes by the magnitude of the supply voltage as the switch reverses, the voltage at terminal **51** of capacitor **50** changes by a like amount. Accordingly, when the switch is reversed in the manner described, the voltage at terminal **51** increases by the magnitude of the supply voltage plus the magnitude of the voltage to which capacitor **50** was previously charged. The change in voltage at terminal **51** forward biases diode **44** and transfers a quantity of charge to capacitor **52**. As the switch is reversed during succeeding cycles of operation, capacitor **52** continues to charge in the foregoing manner until the forward conducting voltage of the emitter-base junction of transistor **48** is attained. Thereafter, transistor **48** begins to conduct and produces current I_1 that is proportional to the change of voltage created across capacitor **20** during each charging and discharging cycle thereof.

The magnitude of current I_1 ultimately depends on the capacitance value of capacitor **20**. For example, if

the capacitance of capacitor **20** increases, the voltage to which capacitor **50** is charged increases and the voltage to which terminal **51** is raised when the switch connecting conductors **28** and **30** is increased accordingly. As a result, capacitor **52** tends to be charged to a higher voltage and transistor **48** conducts more current through its collector lead (i.e., current I_1 increases).

The operation of detecting circuit **38** and reference capacitor **34** will now be described in detail assuming that switch **26** is connecting conductor **28** to positive supply conductor **30**. With switch **26** in the position indicated, diodes **60** and **64** are reverse biased and capacitors **70** and **34** are charged through diode **62**. Since capacitor **70** is normally at least 100 times larger than capacitor **34**, most of the voltage drop during the charging process occurs across capacitor **34**, and terminal **71** of capacitor **70** is charged to a relatively high voltage (i.e., a voltage relatively close to the positive supply voltage). When switch **26** is reversed so that conductor **28** is connected to conductor **32**, the voltage on terminal **69** of capacitor **70** is reduced by the amount of the supply voltage and the voltage at terminal **71** is reduced by a like amount. The negative supply voltage is also effectively connected to capacitor **34** through forward biased diode **60**. Since terminal **71** was already charged to a voltage slightly below the positive supply voltage, the operation of the switch reduces the instantaneous voltage at terminal **71** to a voltage lower than the negative supply voltage. As a result, diode **64** is forward biased and a quantity of charge is removed from capacitor **72**. During succeeding operating cycles of switch **26**, additional charge is removed from capacitor **72** until the voltage on emitter lead **66** equals the forward emitter-base voltage of transistor **68**. Thereafter, transistor **68** conducts and current I_2 is established in the collector lead thereof. Since the capacitance of reference capacitor **34** remains relatively constant, the magnitude of current I_2 does not appreciably change after it has reached its steady state value.

The circuit is adjusted in the manner previously described. Thereafter, if the liquid level rises slightly above the adjustment level, the capacitance of probe **20** becomes slightly greater than the capacitance of capacitor **34**, and currents I_1 and I_3 increase. Current I_3 is then amplified and used to activate relay **96**. When relay **96** is activated, arm **102** is moved into contact with contact **98** so that load **104** is connected to the power source **112**.

When capacitors **20** and **34** are substantially equal, any variations in the forwarding conducting voltage drop across diodes **40**, **42**, and **44** due to temperature variation is balanced by a similar voltage drop across diodes **60**, **62**, and **64**. Since the liquid level is detected when capacitor **20** is only slightly larger than capacitor **34**, the circuit achieves remarkable temperature stability.

When the liquid has receded below the adjustment level, the capacitance of probe **20** decreases and the magnitude of currents I_1 and I_3 are reduced accordingly. Relay **96** is then deenergized and the load is disconnected from the power source **112**.

The power source **112** may be connected to contact **100** instead of contact **98** to achieve reversal of load activation.

The apparatus described in FIG. 2 offers a number of advantages. The apparatus is capable of detecting very small capacitance differences between capacitors **20** and **34**, and is therefore extremely accurate. Moreover, the apparatus is capable of operating under adverse environmental conditions since variations in the frequency of the oscillator or the line voltage have very little effect on the operating characteristics. The portions of the apparatus shown in block diagram form in FIG. 2 are illustrated in more detail in FIG. 3.

In order to fully disclose the circuit illustrated in FIG. 3, specific values for the components thereof will be identified in the following chart.

CHART OF VALUES OF COMPONENTS SHOWN IN FIG. 3

Oscillator **24**:
- Transistor **140** ---- Type 2N3710.
- Resistor **141** ---- 2.2K ohms.
- Resistor **142** ---- 2.2K ohms.
- Resistor **143** ---- 4.7K ohms.
- Inductor **144** ---- 1200 microhenries.
- Inductor **145** ---- 4700 microhenries.
- Capacitor **146** ---- 0.01 microfarad.
- Capacitor **147** ---- 200 picofarads.
- Capacitor **148** ---- 100 picofarads.

Switch **26**:
- Transistor **150** ---- Type 2N3710.
- Transistor **151** ---- Type 2N4061.

Probe capacitor **20**: Stainless steel construction having a capacitance of 15–530 picofarads.

Capacitor **160**—0.1 microfarad

Capacitor **161**—0.1 microfarad

Reference capacitor **34**:
- Capacitor **164** adjustable from 0–500 picofarads
- Capacitor **165** adjustable from 0–60 picofarads

Detecting circuit **36**:
- Diode **40** ---- Type 1N914A.
- Diode **42** ---- Type 1N914A.
- Diode **44** ---- Type 1N914A.
- Capacitor **50** ---- 0.1 microfarad.
- Capacitor **52** ---- 0.1 microfarad.
- Transistor **48** ---- Type 2N4061.
- Resistor **168** ---- 1K ohms.

Detecting circuit **38**:
- Diode **60** ---- Type 1N914A.
- Diode **62** ---- Type 1N914A.
- Diode **64** ---- Type 1N914A.
- Diode **170** ---- 4.7 volt Zener Type.
- Capacitor **70** ---- 0.1 microfarad.
- Capacitor **72** ---- 0.1 microfarad.
- Transistor **68** ---- Type 2N3710.

Amplifier **90**:
- Transistor **172** ---- Type 2N4061.
- Transistor **174** ---- Type 2N4061.
- Resistor **176** ---- 150K ohms.
- Resistor **178** ---- 15K ohms.
- Resistor **180** ---- 47K ohms.
- Resistor **182** ---- 15K ohms.
- Resistor **184** ---- 47K ohms.
- Capacitor **186** ---- 0.1 microfarad.

Emitter follower **94**:
- Transistor **190** ---- Type 2N3710.
- Transistor **192** ---- Type 2N1711.
- Resistor **194** ---- 15K ohms.
- Resistor **196** ---- 22K ohms.
- Capacitor **198** ---- 43 microfarads.

Power supply **120**:
- Diode **200** ---- Type 1N645.
- Diode **202** ---- Type 1N645.
- Resistor **204** ---- 1K ohms.
- Capacitor **206** ---- 43 microfarads.

Regulator **130**:
- Capacitor **208** ---- 4.7 microfarads.
- Diode **210** ---- 15 volt Zener Type.

With reference to FIG. 3, oscillator **24** uses a transistor **140** with an inductance-capacitance feedback network. The oscillator operates a switch **26** comprising transistors **150** and **151**. When transistor **150** is conducting, conductor **28** is effectively connected to positive supply conductor **30**, and conversely, when transistor **151** is conducting, conductor **28** is effectively connected to the negative supply conductor **32**.

Capacitors **160** and **161** are included in the circuit to provide DC isolation of the probe and reference capacitors for safety considerations. Since capacitors **160** and

161 are much larger in value than the probe and reference capacitors and are in series therewith, their effect on circuit operation and performance is negligible.

Detecting circuits **36** and **38** were described in detail in connection with FIG. 2. However, the more detailed illustration in FIG. 3 also includes a resistor **168** that limits the current flow in transistors **48** and **68**, and a Zener diode **170** that maintains the base of transistor **172** at a positive voltage in order to prevent excessive saturation.

Amplifier **90** basically comprises a difference amplifier including transistors **172** and **174**. The collectors of these transistors are connected to a switch **212** that includes a terminal **214**, a terminal **216**, and an arm **218** that operates between the terminals. When the arm is in the position shown in FIG. 3, the apparatus is in its fail-safe low-level mode and operates in the manner described in connection with FIG. 2. That is, relay **96** is energized when the liquid in tank **14** exceeds the adjustment level, and is deenergized when the liquid is below the adjustment level. However, when arm **218** is moved into contact with terminal **214**, the apparatus is in its fail-safe high-level mode. In this mode of operation, relay **96** is energized when the liquid in tank **14** is below the adjustment level, and is deenergized when the liquid exceeds the adjustment level.

The operation of emitter follower and driver **94**, power supply **120**, and regulator **130** will be readily understood by those skilled in the art by reference to FIG. 3.

The apparatus described in FIG. 3 may be adapted to provide a two-point control system by moving switch **228** to its closed position and by relocating probe **20** in a vertical position as shown in FIG. 1a. By placing probe **20** in the position indicated, the level of liquid in tank **14** may be mantained between any two levels such as levels D and E.

When switch **228** is in the closed position, capacitors **222** and **224** are interconnected with the circuit in the manner shown in FIG. 3. Capacitor **224** preferably comprises fine and coarse adjustable capacitors that may be varied up to about 560 picofarads. Capacitor **222** has a value that equals (or slightly exceeds) the minimum capacitance to which capacitor **224** can be adjusted (generally about 6–7 picofarads). The operation of capacitors **222** and **224** is controlled by contacts **220a** and **220b**, respectively, that are, in turn, operated by relay coil **220**. Relay coil **220** is energized through a resistor **230**, a switch **232** (that is ganged with switch **212**), and contacts **96a** and **96b** that are operated by relay coil **96**. Switch **232** is shown in its fail-safe low-level position and may be moved to a fail-safe high-level position in contact with terminal **97**. When transistor **192** is in its nonconductive state (i.e., when relay coil **96** is deenergized), relay contacts **220a**, **220b**, **96a**, and **96b** are located in the positions shown in FIG. 3. That is, contacts **220a** and **96b** are closed and contacts **220b** and **96a** are open, when switches **212** and **232** are in the positions shown in FIG.3.

Liquid **12** is maintained between levels D and E as follows. Assuming relay coil **96** is deenergized as the liquid level rises toward level D from the position shown, coil **220** is energized through closed contact **96b**. As a result, contact **220a** is closed and contact **220b** is open, thereby short-circuiting and disabling capacitor **222** and placing variable capacitor **224** in parallel with reference capacitor **34**. Capacitor **224** is adjusted so that the combined capacitances of capacitors **34** and **224** substantially equal the capacitance of the probe when the liquid rises to level D. As the liquid reaches level D, relay **96** is energized in the manner previously described, and relay coil **220** is deenergized. Accordingly, relay contact **220a** is opened and contact **220b** is closed so that capacitor **224** is short-circuited and disabled, and capacitor **222** is connected in parallel with capacitor **34**. At the same time, load **104** is connected to the power source **112** through contact **98** in order to perform a control function that begins to decrease the level of liquid in the tank. Since capacitor **222** has a relatively small value, the capacitance of the probe is much greater than the capacitance of capacitors **34** and **222** combined, as long as the liquid remains near level D. As a result, relay **96** continues to be energized.

As the level of liquid in the tank decreases, relay **96** continues to be energized until the probe capacitance becomes less than the capacitance of capacitors **34** and **222** combined. Capacitor **34** is adjusted so that this condition is met at level E. When the probe capacitor has decreased in value in the manner indicated, relay **96** is deenergized in the manner previously described and relay **220** is again energized to establish the conditions initially described. In addition, load **104** is again disconnected from the power source **112** in order to perform a control function that raises the level of liquid in the tank.

Due to the unique arrangement of relay contacts **220a** and **220b**, the difference between the upper and lower levels of liquid maintained in tank **14** may be very small. Normally, this mode of operation would be impossible since capacitor **224** could not be adjusted to have a zero capacitance. Adjustable capacitors inherently exhibit a few picofarads of capacitance between their input and output terminals irrespective of the manner in which they are adjusted. As a result, the minimum difference in liquid levels that the system could maintain would be dictated by the inherent capacitance of capacitor **224**. This difficulty is eliminated by relay contact **220b** that short-circuits capacitor **224** during a portion of the operating cycle and by capacitor **222** that has a value equal to the minimum capacitance of capacitor **224**. As a result, the capacitance value connected in parallel with capacitor **34** can be approximately equal whether the liquid is rising or falling, so that the liquid level can be controlled within a small differential between levels D and E.

The present invention may also be adapted to continuously indicate the precise level of liquid stored in a tank. An example of such usage is illustrated in FIG. 4 wherein the precise level of liquid **12** between positions A and B is sensed by a vertically oriented probe capacitor **21**. As the liquid rises from level A to level B, the capacitance of probe **21** is increased, and a capacitance-measuring circuit **11** produces an output signal that is proportional to the change in capacitance. The output signal may be conducted through a meter that continuously indicates the level of the liquid, or through a control device that continuously adjusts the level of liquid in the tank.

A circuit of the foregoing type made in accordance with the present invention is illustrated in detail in FIG. 5. In order to fully describe the circuit, values are assigned to the components identified in FIG. 5 according to the following chart.

CHART OF VALUES OF COMPONENTS SHOWN IN FIG. 5

Oscillator **250**:

Resistor **251**	Type 2N3710.
Resistor **252**	220K ohms.
Resistor **253**	2.2K ohms.
Resistor **254**	4.7K ohms.
Capacitor **255**	0.01 microfarad.
Capacitor **256**	180 picofarads.
Crystal **257**	Designed to operate at about 200 kilohertz.
Inductor **258**	33 millihenries.
Inductor **259**	1.5 millihenries.

Switch **260**:

Transistor **261**	Type T1S60M.
Transistor **262**	Type T1S61M.

Detecting circuits **36** and **38**.—All components are identical to the corresponding components shown in FIG. 3 except as follows: Diode **170'**—13 volt Zener Type

Difference amplifier **264**:
- Transistor **265** ——— Type 2N3707.
- Transistor **266** ——— Type 2N3707.
- Resistor **270** ——— 3.32K ohms.
- Resistor **271** ——— 2K ohm potentiometer.
- Resistor **273** ——— 1K ohms.
- Resistor **274** ——— 47K ohms.

Amplifier **280**:
- Transistor **284** ——— Type 2N4061.
- Transistor **285** ——— Type 2N3710.
- Transistor **286** ——— Type 2N4061.
- Transistor **287** ——— Type 2N1711.
- Resistor **290** ——— 100K ohms.
- Resistor **291** ——— 100K ohms.
- Resistor **292** ——— 100K ohms.
- Resistor **293** ——— 15K ohms.
- Resistor **294** ——— 47K ohms.
- Resistor **295** ——— 4.7K ohms.
- Capacitor **297** ——— 0.25 microfarad.
- Capacitor **298** ——— 4.7 microfarads.

Emitter follower **300**:
- Transistor **301** ——— Type 2N1711.
- Transistor **302** ——— Type 2N3054.
- Resistor **303** ——— 22K ohms.
- Resistor **304** ——— 75 ohms for 4 to 20 milliamps output current.
- Resistor **305** ——— 15K ohms.

Load components:
- Resistor **315** ——— 510 ohms for 4 to 20 milliamps output current.
- Capacitor **316** ——— 43 microfarads.

Feedback resistor **320**—10,000 ohms.

Capacitor **324**—0.1 microfarad.

Overload protection circuit **330**:
- Resistor **332** ——— 22K ohms.
- Resistor **334** ——— 1K ohm.
- Diode **336** ——— Type 1N461
- Diode **338** ——— 13 volt Zener type.

Power source **350**—120 volt, 50 or 60 cycle AC

Power Supply **360**:
- Diode **362** ——— Type 1N645.
- Diode **363** ——— Type 1N645.
- Capacitor **364** ——— 43 microfarads.
- Capacitor **365** ——— 4.7 microfarads.
- Resistor **367** ——— 10K ohms.
- Resistor **368** ——— 300 ohms.

Regulator **370**:
- Transistor **372** ——— Type 2N3054.
- Transistor **374** ——— Type 2N3710.
- Transistor **376** ——— Type 2N4061.
- Resistor **378** ——— 47K ohms.
- Resistor **380** ——— 2K ohms.
- Resistor **382** ——— 47K ohms.
- Diode **383** ——— Type 1N821.
- Transistor **384** ——— Type 2N4061.
- Resistor **386** ——— 4.99 K ohms.
- Resistor **388** ——— 13.3K ohms.
- Capacitor **390** ——— 0.25 microfarads.
- Diode **392** ——— Type 1N461.
- Diode **393** ——— Do.
- Diode **394** ——— Do.

Referring to FIG. 5, a preferred form of the present invention capable of measuring changes in the capacitance of probe capacitor **21** basically comprises an oscillator **250**, a switch circuit **260**, detecting circuits **36** and **38**, a reference capacitor **34**, a difference amplifier **264**, an amplifier **280**, an emitter follower circuit **300**, a feedback resistor **320**, an overload protection circuit **330**, a power source **350**, a power supply **360**, and a regulator **370**.

Oscillator **250** is controlled by a crystal **257** that is designed to operate at 200 kilocycles over a wide range of temperatures.

Switch **260** and detecting circuits **36** and **38** are constructed in a manner similar to the corresponding components shown in FIG. 3 and may be understood with reference thereto.

Difference amplifier **264** includes a unique balancing circuit used in connection with transistor **266** that enables the adjustment of the maximum output current without affecting the adjustment of the minimum output produced by the circuit (at terminals **310** and **312**).

Amplifier **280** increases the magnitude of the signal produced by transistor **265** and emitter follower circuit **300** impedance-matches the signal to the load connected between output terminals **310** and **312**. In the present embodiment of the invention, the load consists of a DC milliammeter that indicates the level of liquid held in tank **14**, and a resistor **314** that is connected between the negative side of the load and the negative supply conductor **32**.

Overload protection circuit **330** comprises a unique arrangement of components whereby excessive current is prevented from flowing through the load. As soon as the current through the load is reduced to a safe level, the overload protection circuit automatically resets, and the entire circuit is returned to its normal mode of operation.

Regulator **370** comprises a conventional series regulating circuit including transistors **372**, **374**, **376**, and **384**, and a unique temperature compensating circuit that utilizes the forward conducting voltaged drop of diodes **392–394**. These diodes compensate for changes in the forward conducting voltage drop across the diodes in detecting circuits **36** and **38** due to temperature changes. The entire arrangement results in a capacitance-measuring circuit that is extremely stable over wide ranges of temperature variations.

The operation of the apparatus illustrated in FIG. 5 will now be discussed in detail. Oscillator **250** produces a 200 kilocycle signal that operates switch **260** in a manner described in connection with FIG. 3. That is, during the positive half-cycle of the signal produced by oscillator **250**, transistor **261** conducts current so that conductor **28** is effectively connected to the positive supply conductor **30**. Conversely, on the negative half-cycle of the signal produced by oscillator **250**, transistor **262** conducts so that conductor **28** is effectively connected to the negative supply conductor **32**.

The operation of detecting circuits **36** and **38** are somewhat different from the analogous circuits shown in FIG. 3 due to the slight change in the manner in which probe capacitor **21** and reference capacitor **34** are connected. However, the overall effect of the operation is the same.

The operation of detecting circuit **36** will be explained assuming that switch **260** is operated so that conductor **28** is effectively connected to the negative supply conductor **32**. With switch **260** operated in the manner indicated, diodes **40** and **44** are reverse biased and the charge maintained at terminal **22** of detecting circuit **36** is discharged along two paths. The first path extends from terminal **22** over capacitor **160**, probe capacitor **21**, and the parallel combination of resistor **314** and capacitor **316** to the negative supply. The second path extends over diode **42**, capacitor **50**, and switch **260** to the negative supply. The charge built up at terminal **22** due to preceding cycles of operation is discharged along the described paths, the resulting voltage across capacitor **50** depending primarily on the relative values of the capacitors in the paths. For example, if the capacitance of probe capacitor **21** is increased, charge is held at terminal **22** for a longer period of time during the discharge cycle so that the voltage retained across capacitor **50** increases.

Assuming the switch is reversed so that conductor **28** is effectively connected to conductor **30**, the positive supply voltage is directly connected to terminal **49** of capacitor **50** and is connected to terminal **22** through diode **40**. Accordingly, as the switch reverses, capacitor **21** begins to charge and the voltage on terminal **49** changes by the amount of the supply voltage. As a result, the

voltage at terminal **51** increases by a like amount so that the total instantaneous voltage present at terminal **51** approximately equals the supply voltage plus the voltage retained on capacitor **50** during the discharge portion of the operating cycle. The increased voltage at terminal **51** forward biases diode **44** so that capacitor **52** receives a quantity of charge. During succeeding cycles of operation, capacitor **52** receives additional charge until the voltage across the capacitor equals the forward conducting voltage of the emitter-base junction of transistor **48**. Transistor **48** then conducts in order to produce current I_1. Those skilled in the art will appreciate that the steady state magnitude of I_1 ultimately depends on the change of voltage across probe capacitor **21** due to the charging and discharging thereof. This voltage change, in turn depends on the relative capacitance of probe capacitor **21**.

The operation of detecting circuit **38** will now be explained assuming that switch **260** is effecively connecting conductor **28** to the positive supply conductor **30**. When switch **260** is operated in the manner indicated, diodes **60** and **64** are reverse biased, and reference capacitor **34** and capacitor **70** are charged through diode **62**, capacitor **161**, and the parallel combination of resistor **314** and capacitor **316**. Since capacitor **70** is at least 100 times larger than capacitor **34**, most of the voltage drop due to the charging of the capacitors occurs across capacitor **34**. As a result, terminal **71** of capacitor **70** is charged to a voltage slightly lower than the positive supply voltage. Assuming switch **260** is reversed so that conductor **28** is effectively connected to conductor **32**, the charge held on capacitor **34** is discharged through diode **60** and the voltage on terminal **69** of capacitor **70** is instantaneously reduced to the negative supply voltage. Accordingly, the voltage on terminal **71** of capacitor **70** is reduced by a like amount so that the instantaneous resulting voltage on terminal **71** approximately equals the negative supply voltage minus the voltage existing across capacitor **70** during the charging phase of the operating cycle. As a result, diode **64** is forward biased so that a quantity of charge is removed from capacitor **72**. During succeeding cycles of operation, additional quantities of charge are removed from capacitor **72** until the voltage across the capacitor equals the forward conducting voltage of the emitter-base junction of transistor **68**. Transistor **68** then begins to conduct current I_2. As previously stated, I_2 is proportional to the change in voltage occurring across the reference capacitor **34** during each cycle of operation. After the capacitance of reference capacitor **34** is initially adjusted, current I_2 normally does not change substantially during the operation of the circuit.

It should be noted that the probe and reference capacitors used in the apparatus illustrated in FIG. 5 are simultaneously charged and discharged as switch **260** is reverse. This mode of operation is the converse of the operation exhibited by the apparatus shown in FIG. 3, wherein the probe capacitor is charged as the reference capacitor is discharged and vice versa. It will also be observed that the paths through which the probe and reference capacitors are charged and discharged are somewhate different in the FIG. 3 and FIG. 5 embodiments. Nonetheless, both embodiments achieve the same end result. That is, currents I_1 and I_2 are proportional to the change in voltage across the probe and reference capacitors, respectively, during each operating cycle.

As in the case of the FIG. 3 embodiment, current I_3 flowing in conductor **80** (FIG. 5) equals the difference between currents I_1 and I_2. Current I_3 is amplified in difference amplifier **264** and amplifier **280** in a manner well-known to those skilled in the art. The resulting current is then conducted to an emitter follower arrangement **300**. The DC output current then flows through terminal **312**, DC milliammeter **311**, terminal **310** and load resistor **314** to the negative voltage supply.

The operation of the temperature-compensating section of regulator **370** will now be described in detail. The section compensates for the change in forward conducting voltage drop across the diodes in detecting circuits **36** and **38** due to changes in temperature. Those skilled in the art will appreciate that the forward conducting voltage drop across diodes **40**, **42**, and **44** decreases with increasing temperature. This decrease in voltage drop has the effect of raising the change of voltage across probe capacitor **21** as the capacitor is charged and discharged. This change of voltage across the probe capacitor can be eliminated by reducing the supply voltage by an appropriate amount.

Assuming an increasing temperature, the supply voltage is reduced by the temperature compensating section of regulator **370** in the following manner. As the temperature increases, the forward conducting voltage drop across diodes **392–394** decreases so that the voltage on the base lead of transistor **384** increases. An increased voltage on its base lead causes transistor **384** to conduct less current. As a result, less current is drawn through resistor **378**, and the voltage on the emitter lead of transistor **376** is thereby increased. Transistor **376** then conducts more current, thereby increasing the voltage on the base lead of transistor **374**. Transistor **374** conducts additional current so that the voltage on the base lead of transistor **372** is reduced. Transistor **372** then conducts less current so that the voltage at positive supply conductor **30** is reduced. The foregoing operation of regulator **370** results in a circuit that is extremely stable and capable of linear operation over a wide range of temperature.

The apparatus shown in FIG. 5 is adjusted as follows. The level of liquid in tank **14** is reduced to position A, and capacitors **164** and **165** that comprise reference capacitor **34** are adjusted until current I_3 attains the minimum value. (Even when the capacitances of the probe and reference capacitors are the same, current I_3 will have a small value due to the bias current required in order to operate transistors **48** and **68**.) After reference capacitor **34** is adjusted, adjusting arm **272** of potentiometer **271** is adjusted until the base lead **267** of transistor **265** is at ground potential. After the foregoing adjustment is made no current flows through feedback resistor **320**, so that its resistance value has no effect on the minimum current produced by the circuit (i.e., the current produced by the circuit when the probe and reference capacitors are approximately equal in capacitance).

When current I_3 is adjusted to its minimum value, output current I_0 is also at its minimum value. The minimum value of I_0 may be adjusted by altering the value of resistor **304** and resistor **314**. In the embodiment disclosed herein, current I_0 at its minimum value equals approximately 4 milliamps.

Following the foregoing adjustments, the level of liquid in tank **14** is raised to position B and currents I_1, I_3, and I_0 increase as previously described. Arm **322** of resistor **320** is then adjusted until a desired maximum current flows through milliammeter **311**. The maximum current may be adjusted to a variety of values (i.e., 20 milliamps). As previously explained, the adjustment of resistor **320** in no way affects the minimum current produced by the circuit when the level of liquid is at positive A. This unique feature enables the circuit to provide a variety of maximum current values without requiring readjustment of the minimum value.

By properly calibrating milliammeter **311** between the maximum and minimum output current values, the circuit produces a continuous indication of the upper level of liquid between positions A and B. Due to the sensitivity and linearity of the circuit shown in FIG. 5, the level is indicated with extreme accuracy over a wide temperature range.

Those skilled in the art will appreciate that the features

of the present invention may be used for a number of capacitance-measuring applications other than the detection of changes in liquid levels. For example, by choosing an appropriate probe, the quality of liquid (e.g., moisture content) may also be detected. Moreover, it should be understood that the embodiments shown herein are merely exemplary of the preferred practices of the invention and that additional changes in structure and modes of operation may be achieved without departing from the spirit and scope of the invention.

I claim:

1. In a system for measuring the relative capacitance of a first capacitor, apparatus comprising:

a second reference capacitor;

switch means for cyclically charging and discharging said first capacitor and said second capacitor;

[first detecting means for producing a first current proportional to the change of voltage created across said first capacitor by the cyclical charging and discharging thereof;

second detecting means for producing a second current proportional to the change of voltage created across said second capacitor by the cyclical charging and discharging thereof; and]

first detecting means for detecting a pulsating signal generated by the cyclical charging and discharging of the first capacitor to produce a first detected signal having a DC value proportional to the capacitance of the first capacitor and for amplifying the first detected signal to produce a first current;

second detecting means for detecting a pulating signal generated by the cyclical charging and discharging of the second capacitor to produce a second detected signal having a DC value proportional to the capacitance of the second capacitor and for amplifying the second detected signal to produce a second current; and

comparison means for comparing said first and second currents, whereby the relative capacitance of said first capacitor in relationship to said second capacitor may be determined.

2. [Apparatus as claimed in claim **1**, wherein said switch means comprises:] *In a system for measuring the relative capacitance of a first capacitor, apparatus comprising:*

a second reference capacitor;

switch means for cyclically charging and discharging said first capacitor and said second capacitor[;], *said switch means comprising*

a switch that alternately connects said first and second capacitors to a source of positive voltage and a source of negative voltage[;], and

an oscilator that operates the switch at a predetermined cyclical rate[.];

first detecting means for producing a first current proportional to the change of voltage created across said first capacitor by the cyclical charging and discharging thereof;

second detecting means for producing a second current proportional to the change of voltage created across said second capactor by the cyclical charging and discharging thereof; and

comparison means for comparing said first and second currents, whereby the relative capacitance of said first capacitor in relationship to said second capacitor may be determined.

3. [Apparatus, as claimed in claim **1**, wherein said first detecting means comprises:] *In a system for measuring the relative capacitance of a first capacitor, apparatus comprising:*

a second reference capacitor;

switch means for cyclically charging and discharging said first capacitor and said second capacitor;

first detecting means for producing a first current proportional to the change of voltage created across said first capacitor by the cyclical charging and discharging thereof[;], *said first detecting means comprising,*

a first amplifier having first and second input terminals[;], *and* a third capacitor connected between said first and second input terminals for storing a quantity of charge resulting from the change of voltage across said first capacitor so that the first amplifier is enabled to produce said first current[.];

second detecting means for producing a second current proportional to the change of voltage created across said second capacitor by the cyclical charging and discharging thereof; and

comparison means for comparing said first and second currents, whereby the relative capacitance of said first capacitor in relationship to said second capacitor may be determined.

4. Apparatus, as claimed in claim **3**, wherein said first detecting means further comprises:

a fourth capacitor having a first terminal connected to said switch means and also having a second terminal;

a first diode connected between said first capacitor and said second terminal of the fourth capacitor; and

a second diode connected between said third capacitor and said second terminal of the fourth capacitor.

5. Apparatus, as claimed in claim **3**, wherein said second detecting means comprises:

a second amplifier having first and second input terminals; and

a fifth capacitor connected between said first and second input terminals for storing a quantity of charge resulting from the change of voltage across said second reference capacitor so that the second amplifier is enabled to produce said second current.

6. Apparatus as claimed in claim **5**, wherein said second detecting means further comprises:

a sixth capacitor having a first terminal connected to said switch means and also having a second terminal;

a third diode connected between said second reference capacitor and said second terminal of the sixth capacitor; and

a fourth diode connected between said fifth capacitor and said second terminal of the sixth capacitor.

7. Apparatus, as claimed in claim **6**, wherein the first and second amplifiers have similar parameters, wherein the capacitance of said third and fifth capacitors are equal, wherein the capacitances of said fourth and sixth capacitors are equal, wherein the first and third diodes have similar parameters, and wherein the second and fourth diodes have similar parameters.

8. Apparatus, as claimed in claim **6**, and further comprising:

a source of positive voltage; and

means for [altetring] *altering* the magnitude of said positive voltage in order to compensate for the changes in forward conducting voltage across said diodes due to changes in temperature.

9. [Apparatus, as claimed in claim **1**, wherein the comparison means comprises:] *In a system for measuring the relative capacitance of a first capacitor, apparatus comprising:*

a second reference capacitor;

switch means for cyclically charging and discharging said first capacitor and said second capacitor;

first detecting means for producing a first current proportional to the change of voltage created across said first capacitor by the cyclical charging and discharging thereof;

second detecting means for producing a second current proportional to the change of voltage created across said second capacitor by the cyclical charging and discharging thereof; and

comparison means for comparing said first and second currents, whereby the relative capacitance of said first capacitor in relationship to said second capaci-

tor may be determined[.], *said comparison means comprising*

means for algebraically summing the first and second currents to produce a third current that represents the difference between said first and second currents;

a third amplifier wherein said third current is amplified to produce an output current; and

an indicating device that is operated whenever the output current exceeds a predetermined value.

10. Apparatus, as claimed in claim **9**, and further comprising a feedback network connected to said third amplifier, for adjusting the gain of the third amplifier, said feedback network comprising a variable resistor.

11. Apparatus, as claimed in claim **10**, and further comprising means for eliminating current flow through said variable resistor when the output current is at a minimum value, so that the gain of the third amplifier may be altered without changing the minimum value of the output current.

12. Apparatus, as claimed in claim **11**, wherein said means for eliminating current flow comprises a differential amplifier that includes:

a first amplifying device having an input terminal to which said varaible resistor is attached; and

a second amplifier for adjusting the voltage at said input terminal.

13. In a system for maintaining liquid in a tank between a first level and a second level, apparatus comprising in combination:

a first capacitor located in said liquid between the first and second levels, said first capacitor being adapted to change its capacitance in response to the changes in the level of said liquid;

a second reference capacitor;

an adjustable third capacitor;

a fourth capacitor;

first means for adjusting the second capacitor so that the combined capacitance of the second and third capacitors equals the capacitance of the first capacitor when the liquid is at the first level, and for adjusting the second capacitor so that the combined capacitance of the second and fourth capacitors equals the capacitance of the first capacitor when the liquid is at the second level;

second means for disabling the fourth capacitor and interconnecting the third capacitor with the second capacitor when the level of the liquid attempts to recede below the second level; and

third means for disabling the third capacitor and interconnecting the fourth capacitor with the second capacitor when the level of the liquid attempts to rise above the first level so that the minimum capacitance to which the third capacitor may be adjusted has no effect on the proximity within which the first and second levels can be maintained.

14. Apparatus, as claimed in claim **13**, wherein the fourth capacitor has a value equal to the minimum capacitance to which the third capacitor may be adjusted.

15. Apparatus, as claimed in claim **13**, wherein the second and third means each comprise contacts controlled by a relay.

16. Apparatus, as claimed in claim **13**, wherein said second means and third means comprise:

switch means for periodically charging and discharging said first, second, third, and fourth capacitors;

fourth detecting means for producing a first current proportional to the change of voltage created across said first capacitor by the charging and discharging thereof;

fifth detecting means for producing a second current proportional to the change of voltage created across whichever of the second, third, or fourth capacitors are charged and discharged by the switch means; and

comparison means for comparing the first and second currents.

17. A process for determining the relative difference in capacitance of a first capacitor and a second capacitor comprising the steps of:

cyclically charging and discharging the first capacitor;

[producing a first current proportional to the change of voltage created across the first capacitor due to the charging and discharging thereof;

cyclically charging and discharging the first capacitor;

producing a second current proportional to the change of voltage created across the second capacitor due to the charging and discharging thereof; and]

detecting a pulsating signal generated by the cyclical charging and discharging of the first capacitor;

producing a first detected signal having a DC value proportional to the capacitance of the first capacitor;

amplifying the first detected signal to produce a first current;

detecting a pulsating signal generated by the cyclical charging and discharging of the second capacitor;

producing a second detected signal having a DC value proportional to the capacitance of the second capacitor;

amplifying the second detected signal to produce a second current; and

comparing the first current and the second current, whereby the capacitance of the first capacitor in relationship to the second capacitor may be determined.

18. A process as claimed in claim **17**, wherein the first and second currents are compared by algebraically adding the magnitudes thereof.

19. Apparatus, as claimed in claim 1, wherein the first detecting means comprises:

a first amplifier having an input terminal;

first means for cyclically accumulating a first quantity of charge proportional to the capacitance of the first capacitor to produce a first pulsating signal having a first peak voltage proportional to the value of the first capacitor;

first means for cyclically transferring at least a portion of said first quantity of charge to the input terminal of the first amplifier in one direction only; and

wherein said second detecting means comprises:

a second amplifier having an input terminal;

second means for cyclically accumulating a second quantity of charge proportional to the capacitance of the second capacitor to produce a second pulsating signal having a second peak voltage proportional to the value of the second capacitor; and

second means for cyclically transferring at least a portion of the second quantity of charge to the input terminal of the second amplifier in one direction only.

20. Apparatus, as claimed in claim 19, and further comprising:

means for storing at least a portion of the charge transferred by the first means for transferring; and

means for storing at least a portion of the charge transferred by the second means for transferring.

21. Apparatus, as claimed in claim 20, wherein the first means for transferring comprises a first detector means for detecting the first peak voltage and wherein the second means for transferring comprises a second detector means for detecting the second peak voltage.

22. Apparatus, as claimed in claim 21, wherein the first detector means comprises a capacitor and a diode each connected to the input terminal of the first amplifier and wherein the second detector means comprises a capacitor and a diode each connected to the input terminal of the second amplifier.

23. Apparatus, as claimed in claim 19, wherein said switch means comprises:

a first switch directly connected to a source of a first DC voltage;

a second switch directly connected to a source of a second DC voltage; and

an oscillator that operates the first and second switches at a predetermined cyclical rate.

24. Apparatus, as claimed in claim 23, wherein the first means for cyclically accumulating is connected to the first switch, whereby the first means for cyclically accumulating generates a first peak voltage greater than the first DC voltage during each cycle of switch operation and wherein the second means for cyclically accumulating is connected to the second switch whereby the second means for cyclically accumulating generates a second peak voltage less than the second DC voltage during each cycle of switch operation.

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