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Cherng et al.

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[54] METHOD AND APPARATUS FOR CHARGING A LEAD-ACID BATTERY

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[*] Notice: The term of this patent shall not extend beyond the expiration date of Pat. No. 5,469,043.

[21] Appl. No.: 425,181

[22] Filed: Apr. 19, 1995

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 272,997, Jul. 14, 1994, Pat. No. 5,469,043, which is a continuation of Ser. No. 960,583, Oct. 13, 1992, abandoned.

[51] Int. Cl.⁶ H01M 10/44

[52] U.S. Cl. 320/31; 320/39

[58] Field of Search 320/5, 21, 22, 320/23, 24, 29, 30, 31, 39, 40, 43, 48; 324/426; 340/635, 636; 429/90, 61

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Primary Examiner—Edward Tso

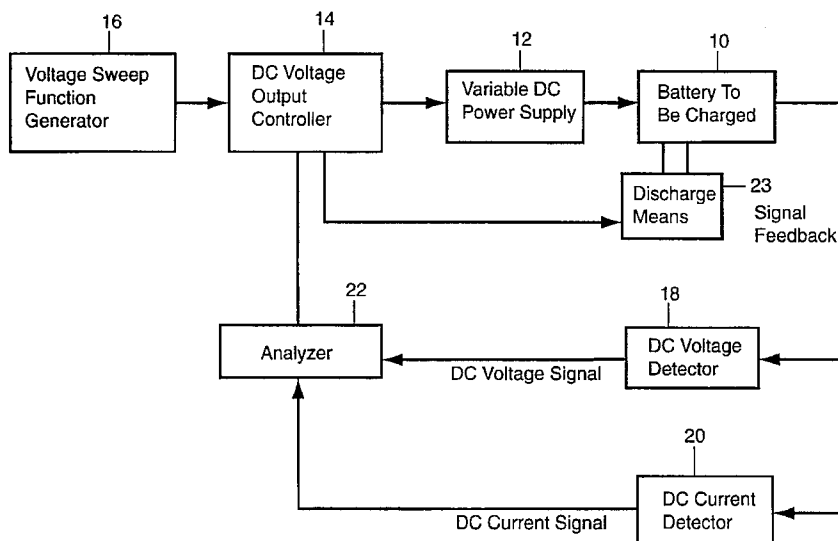
Attorney, Agent, or Firm—Leydig, Voit & Mayer, Ltd.

[57]

ABSTRACT

A method and apparatus is disclosed for charging lead-acid batteries which includes periodic voltage sweeps to determine the charging voltage that should be used for the battery and then adjusting the charging voltage in accordance with that voltage sweep information so as to ensure that a highly efficient charging process is achieved which avoids undue gassing and inherently compensates for factors such as the temperature, type and service life history of the battery and resistance due to the interactive nature of the technique and apparatus.

34 Claims, 21 Drawing Sheets



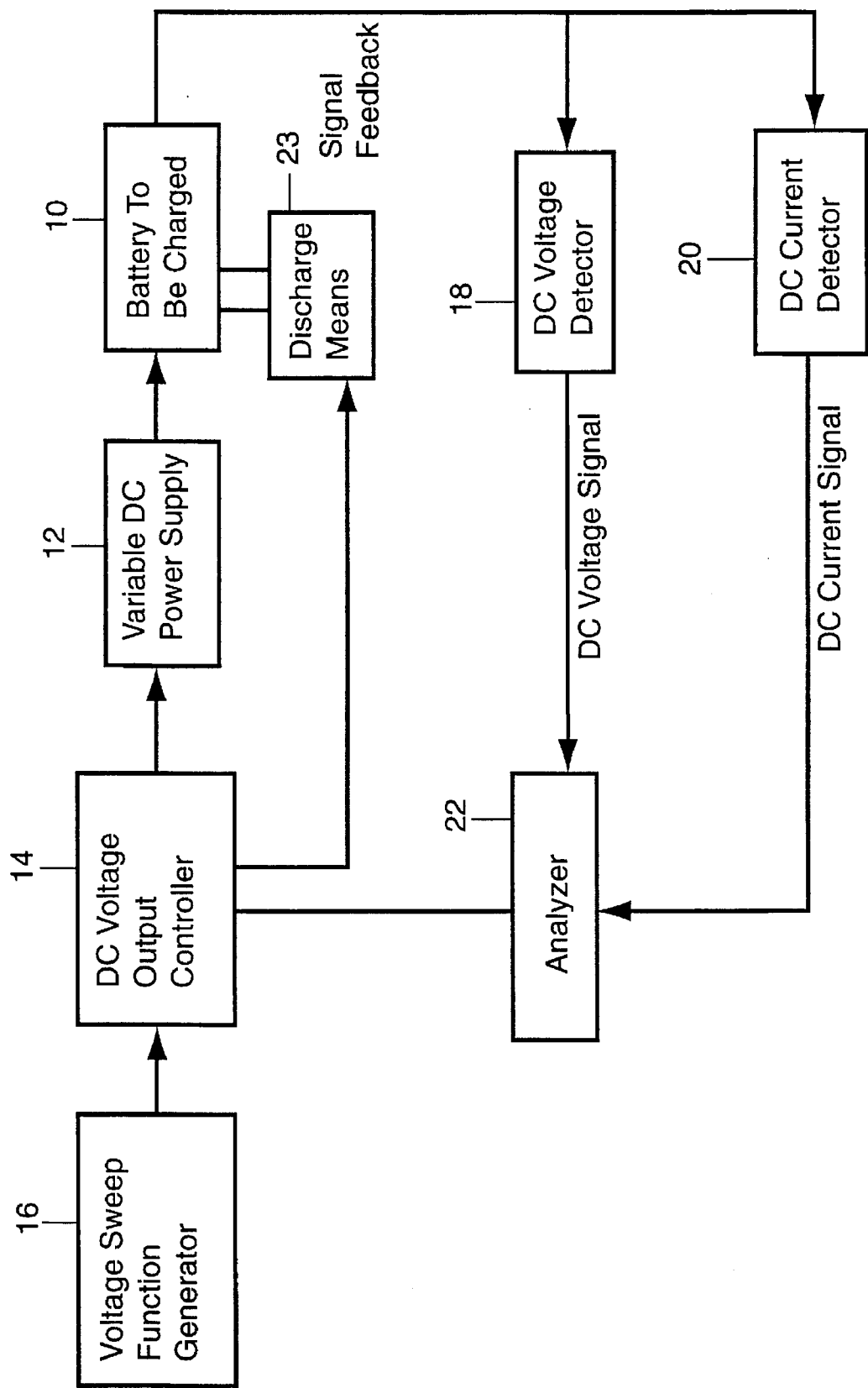


FIG. 1

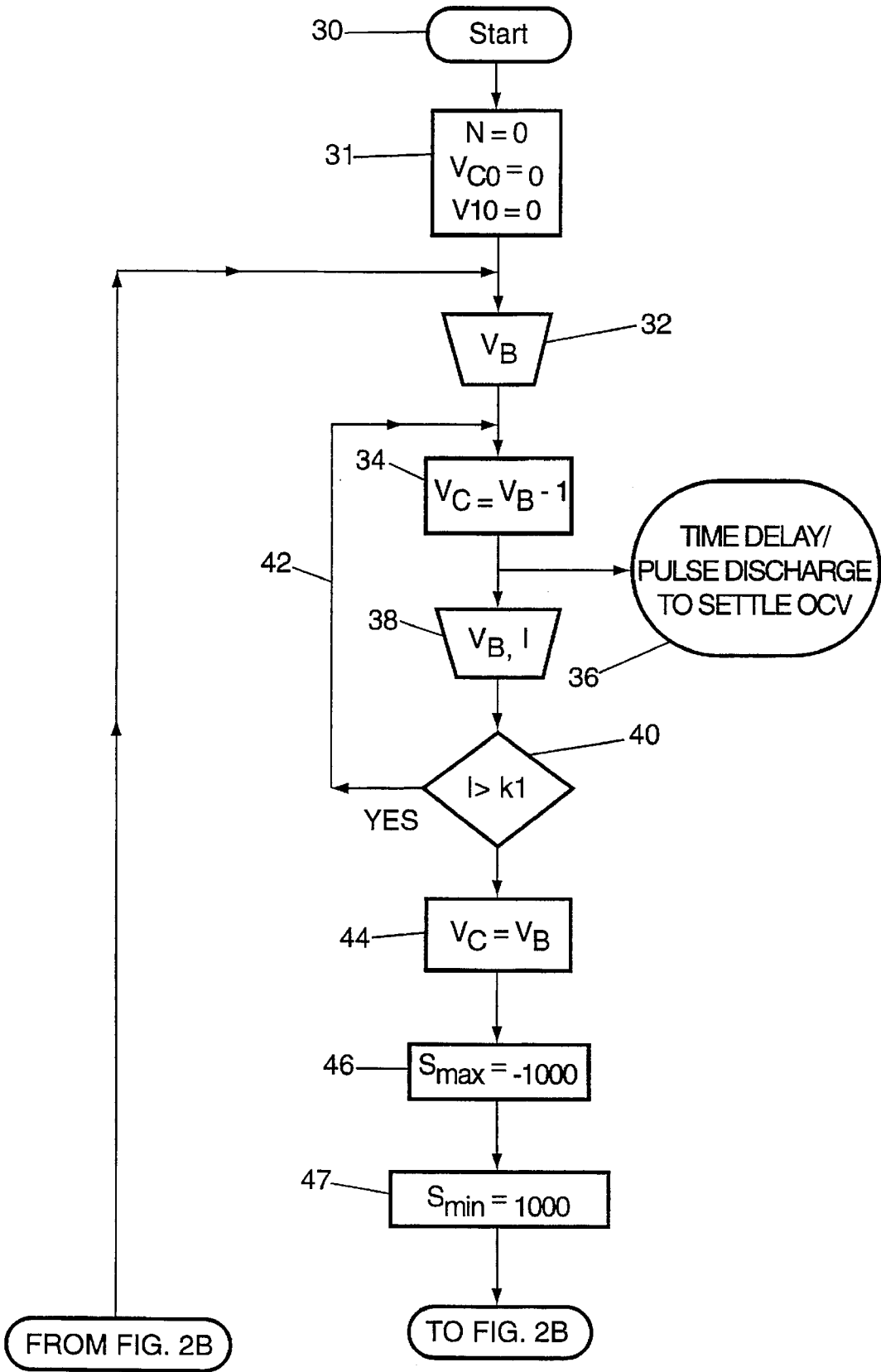


FIG. 2A

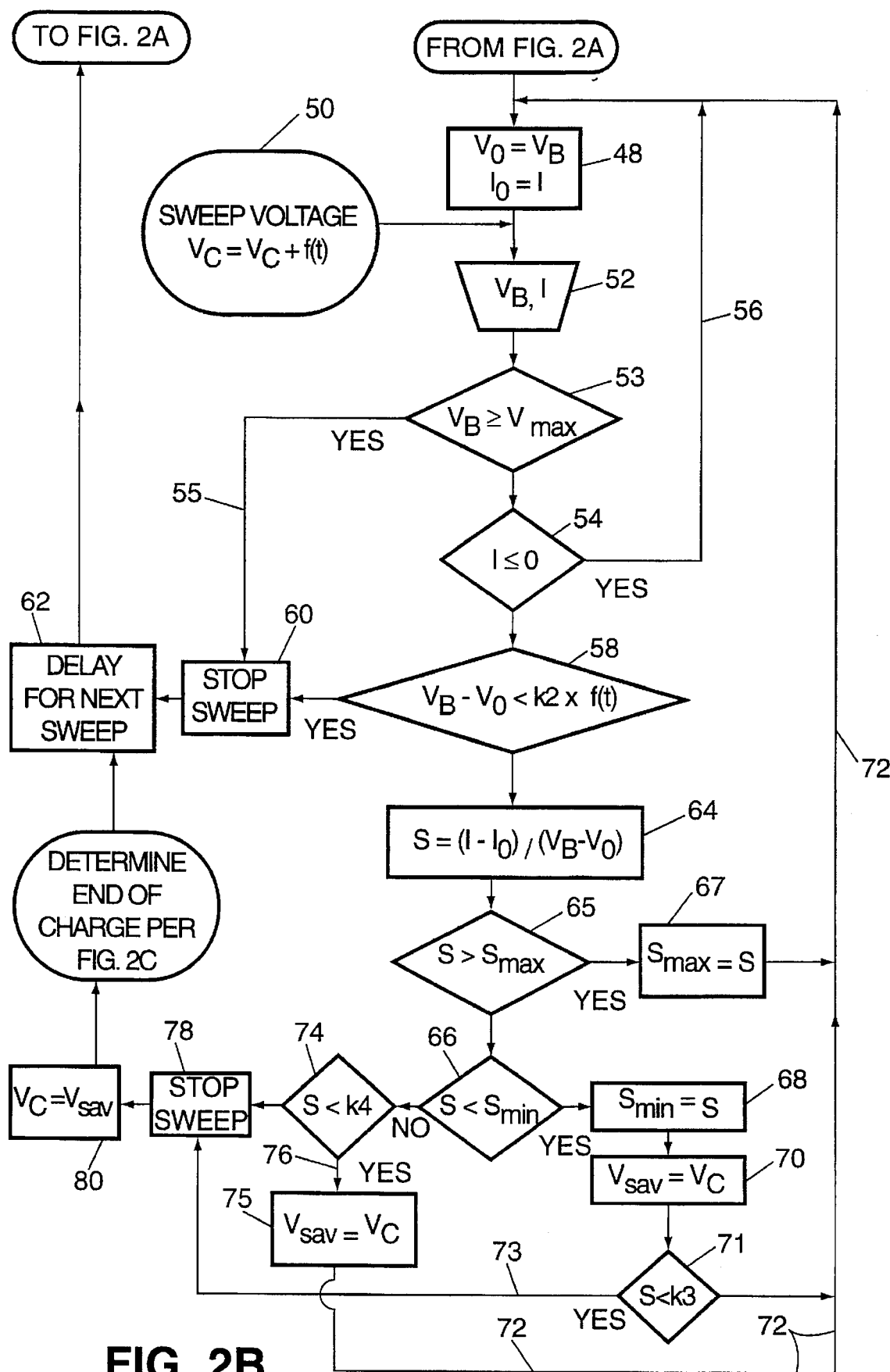


FIG. 2B

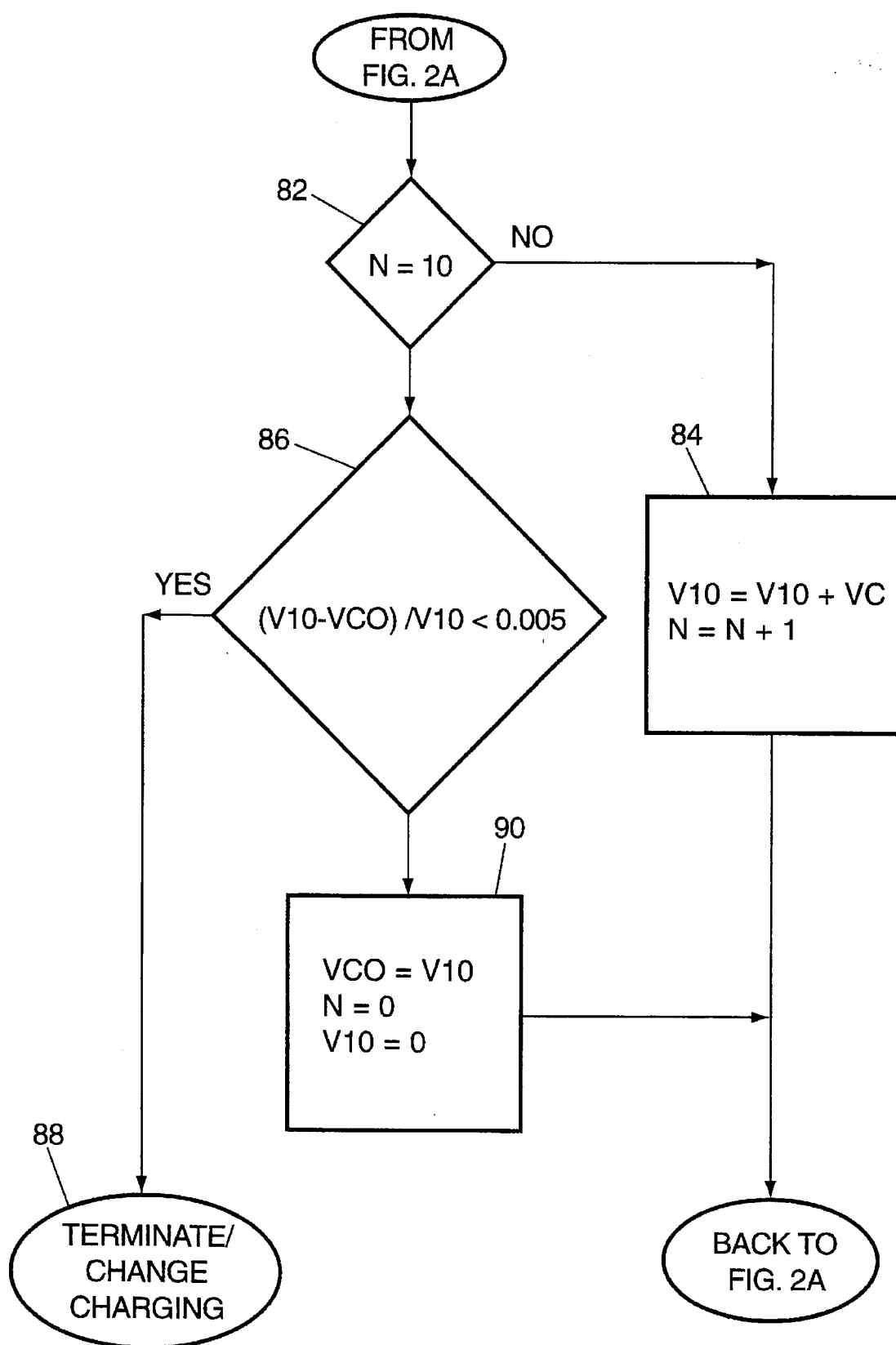


FIG. 2C

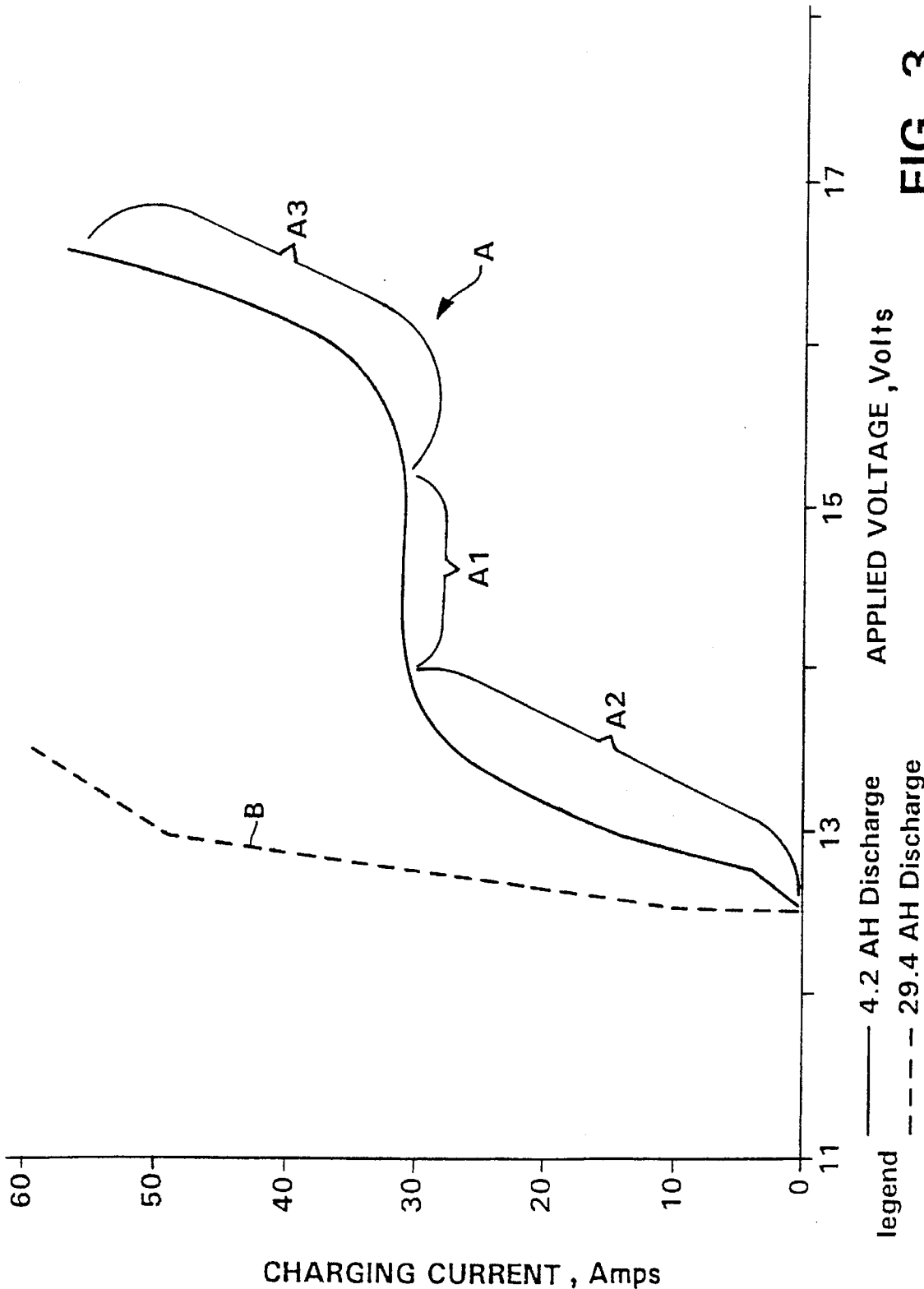


FIG. 3

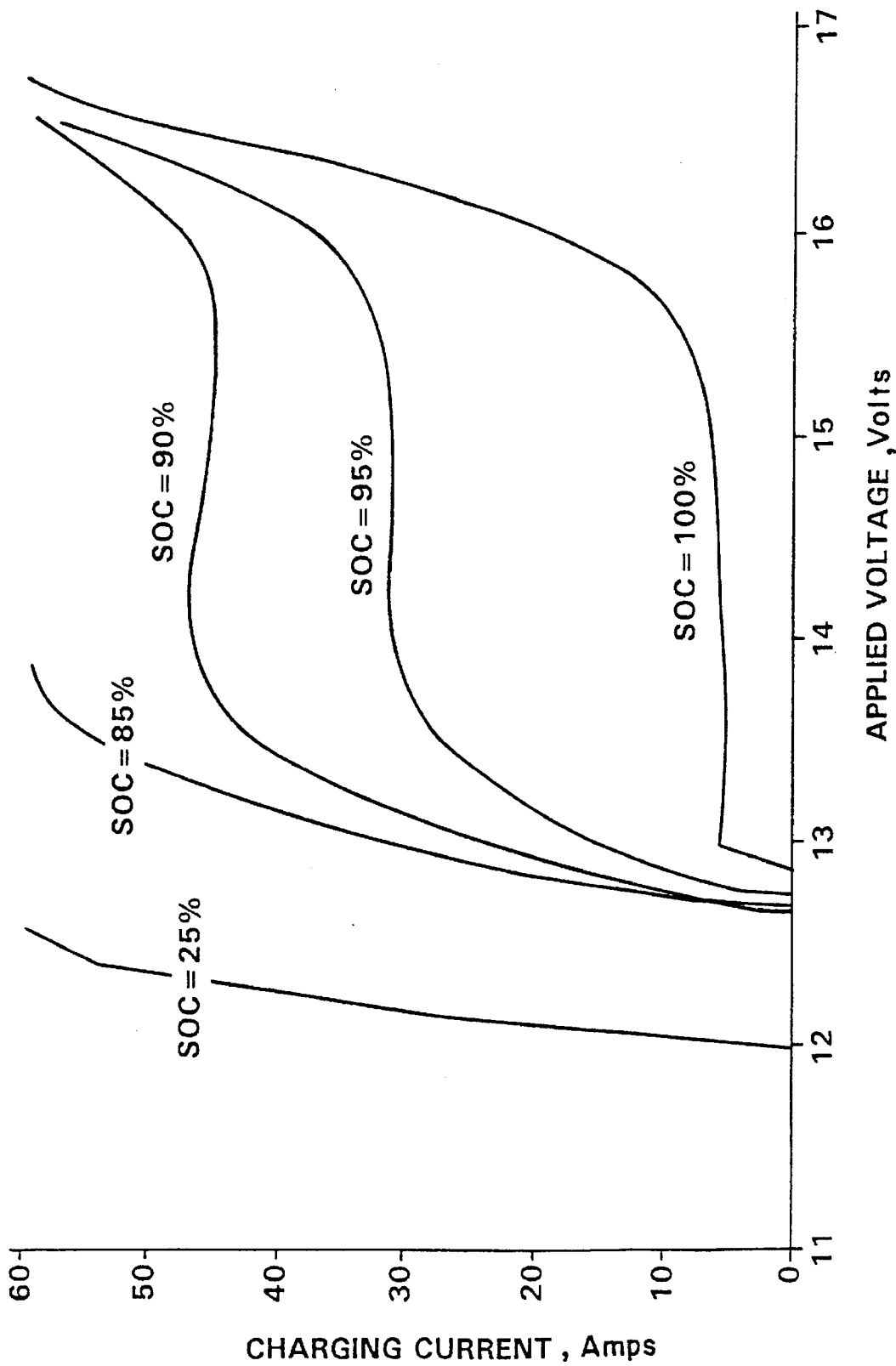


FIG. 4

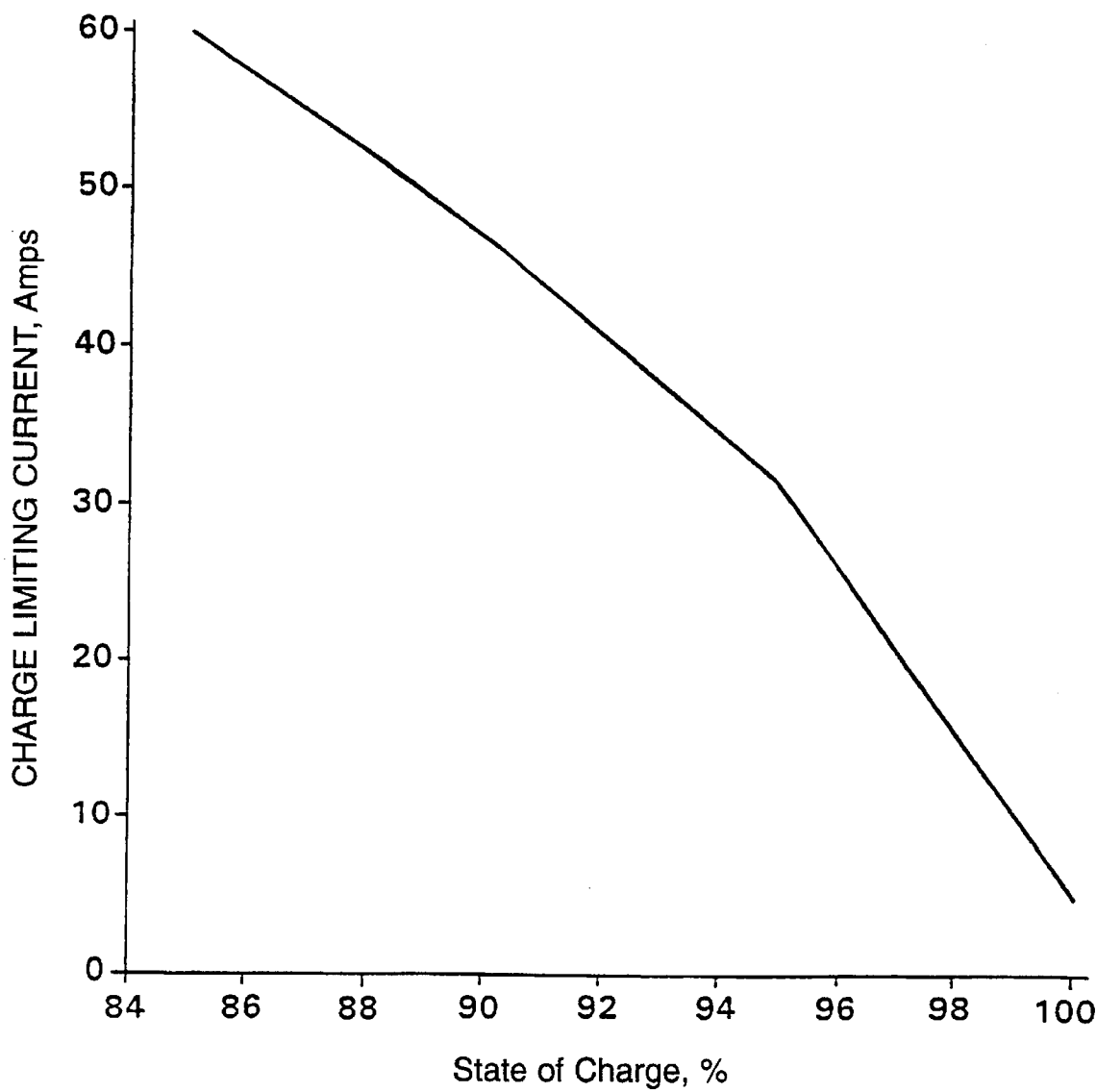


FIG. 5

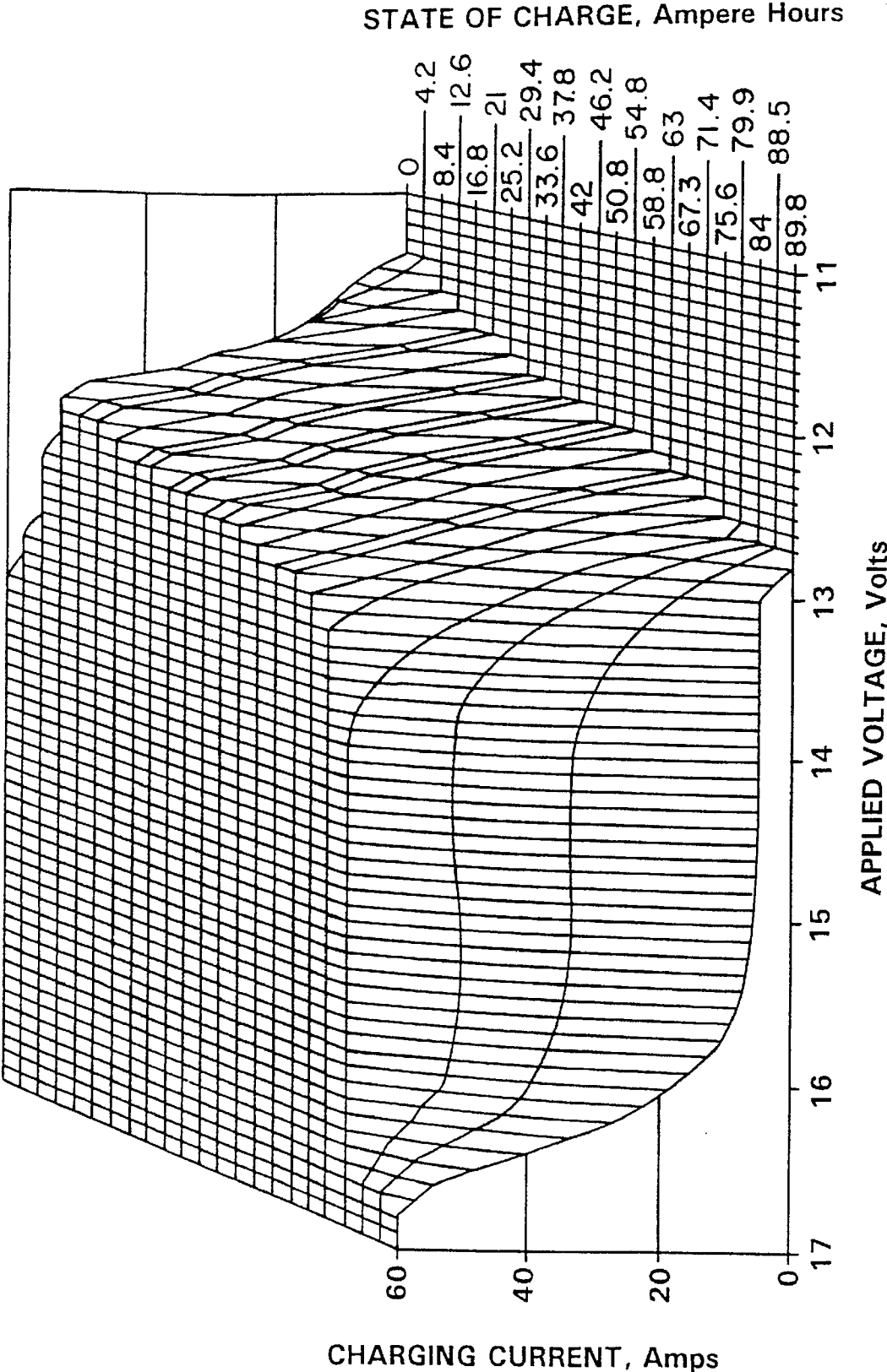


FIG. 6

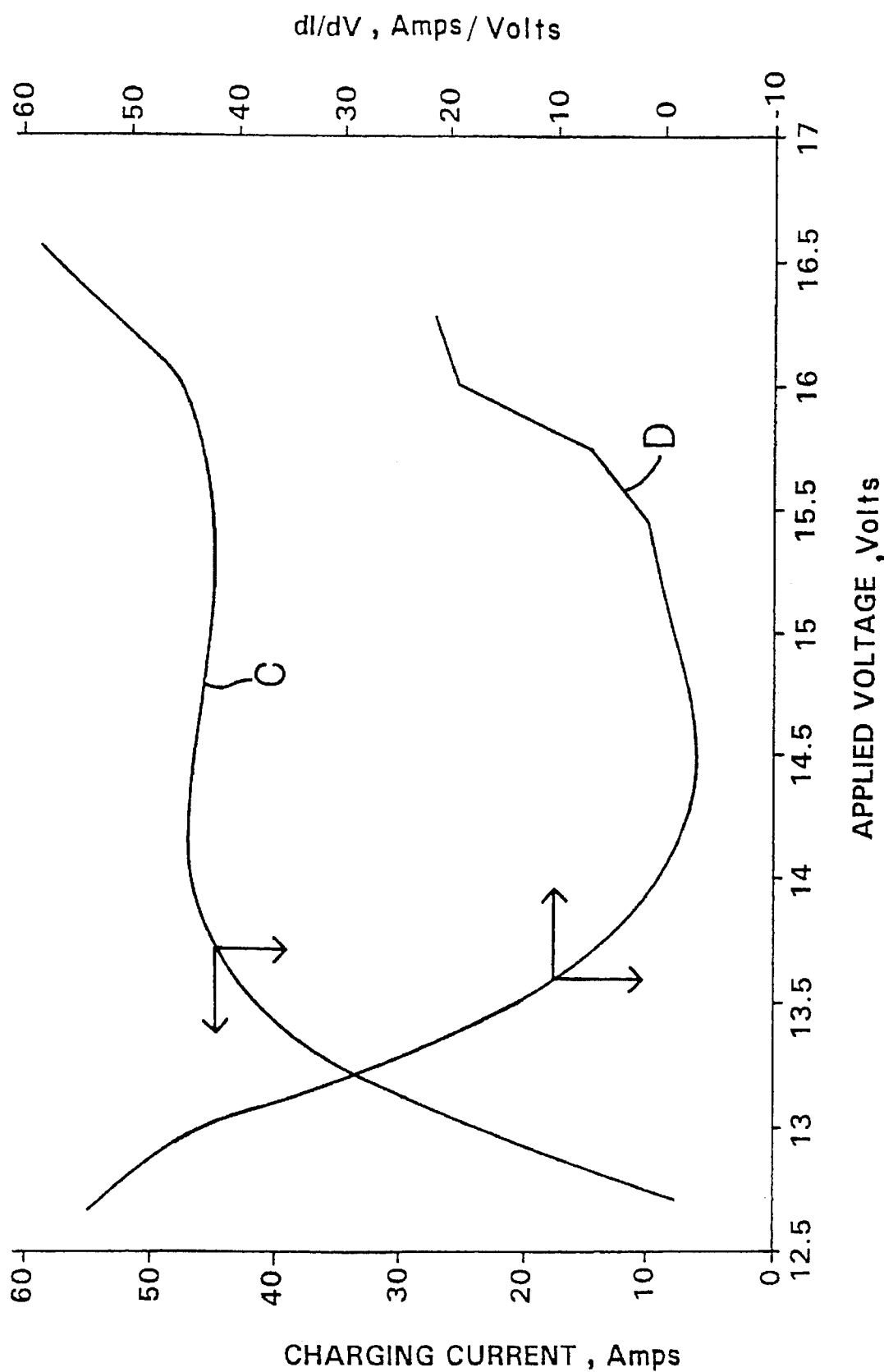


FIG. 7

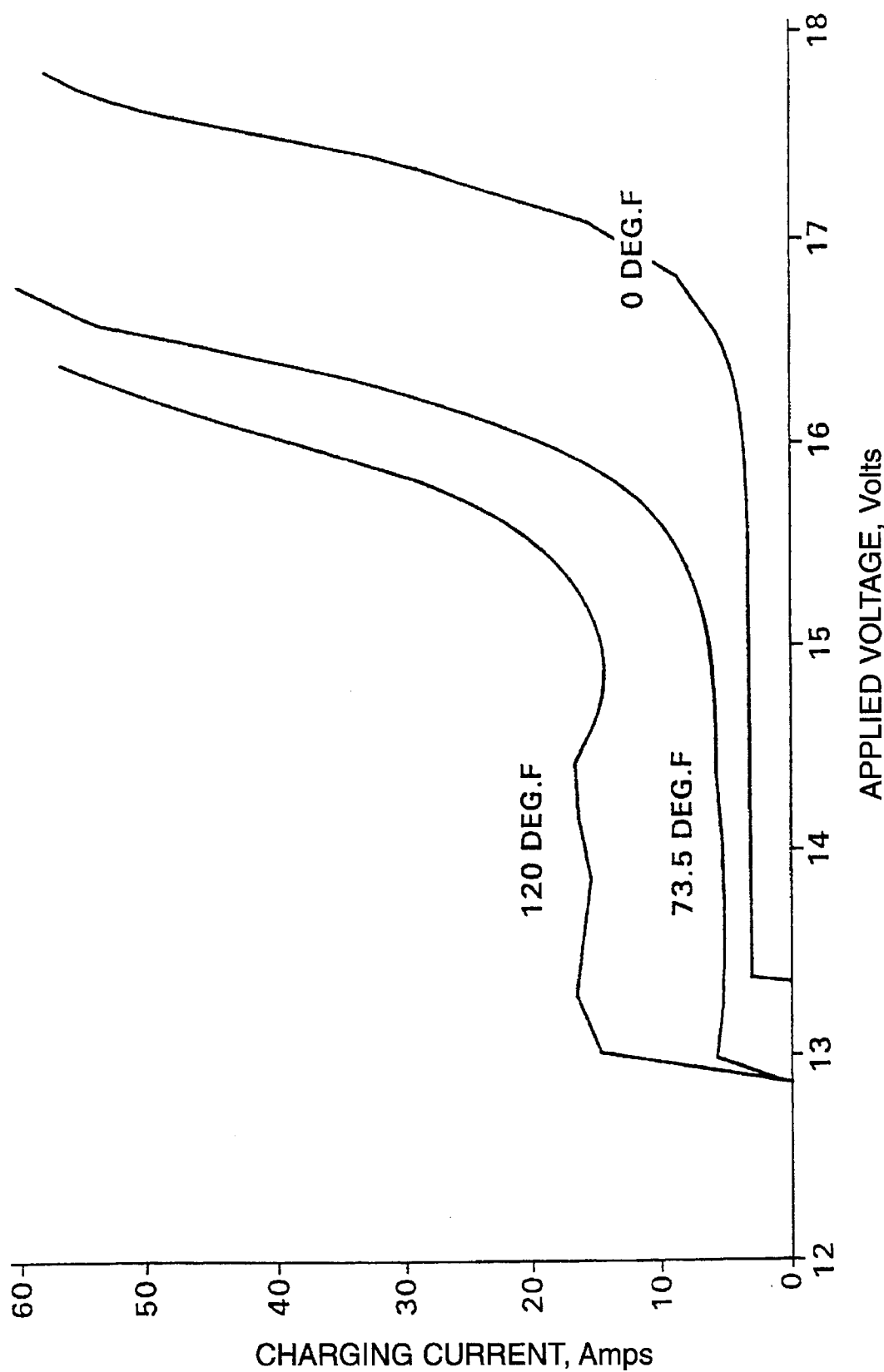


FIG. 8

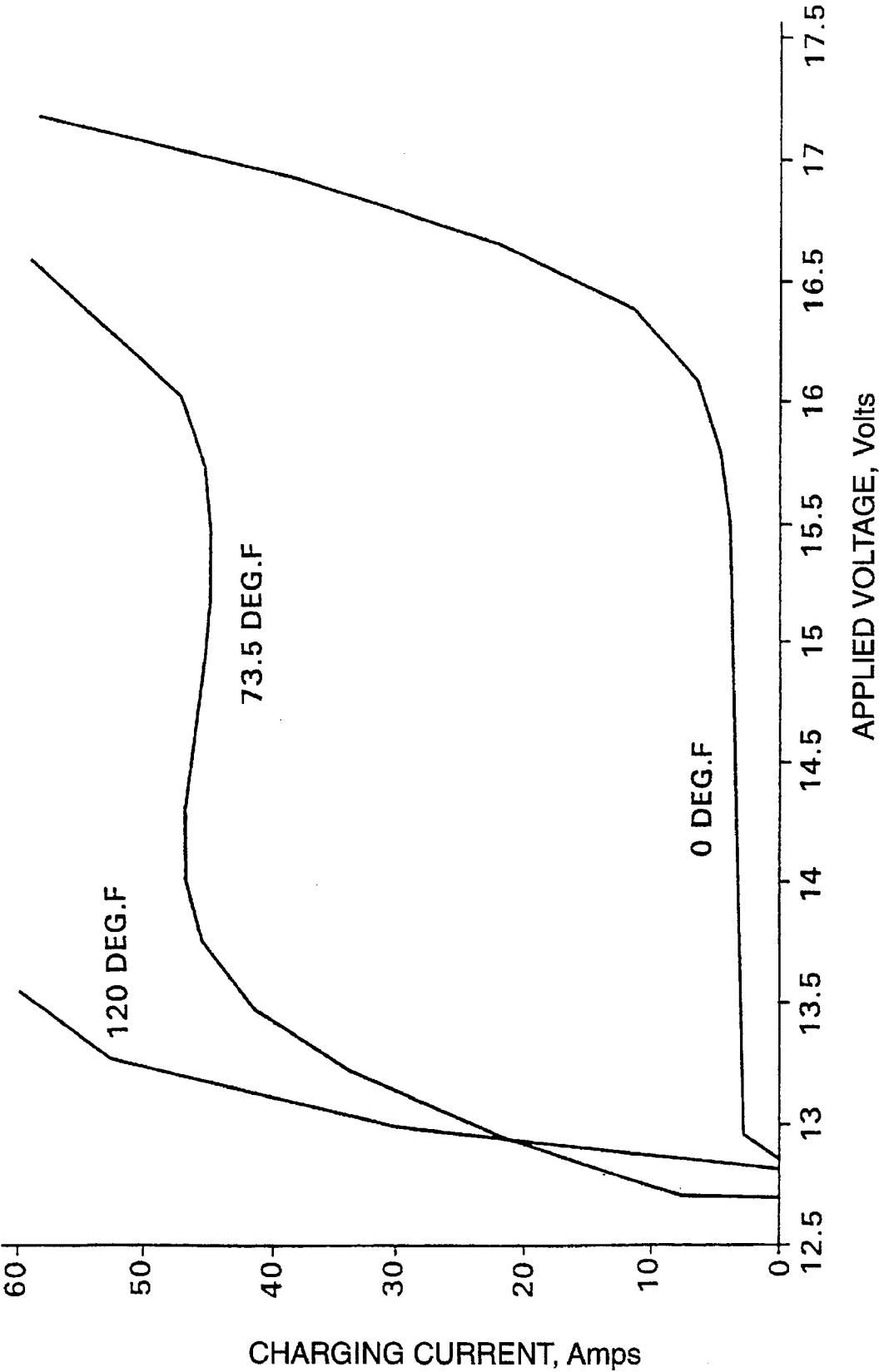


FIG. 9

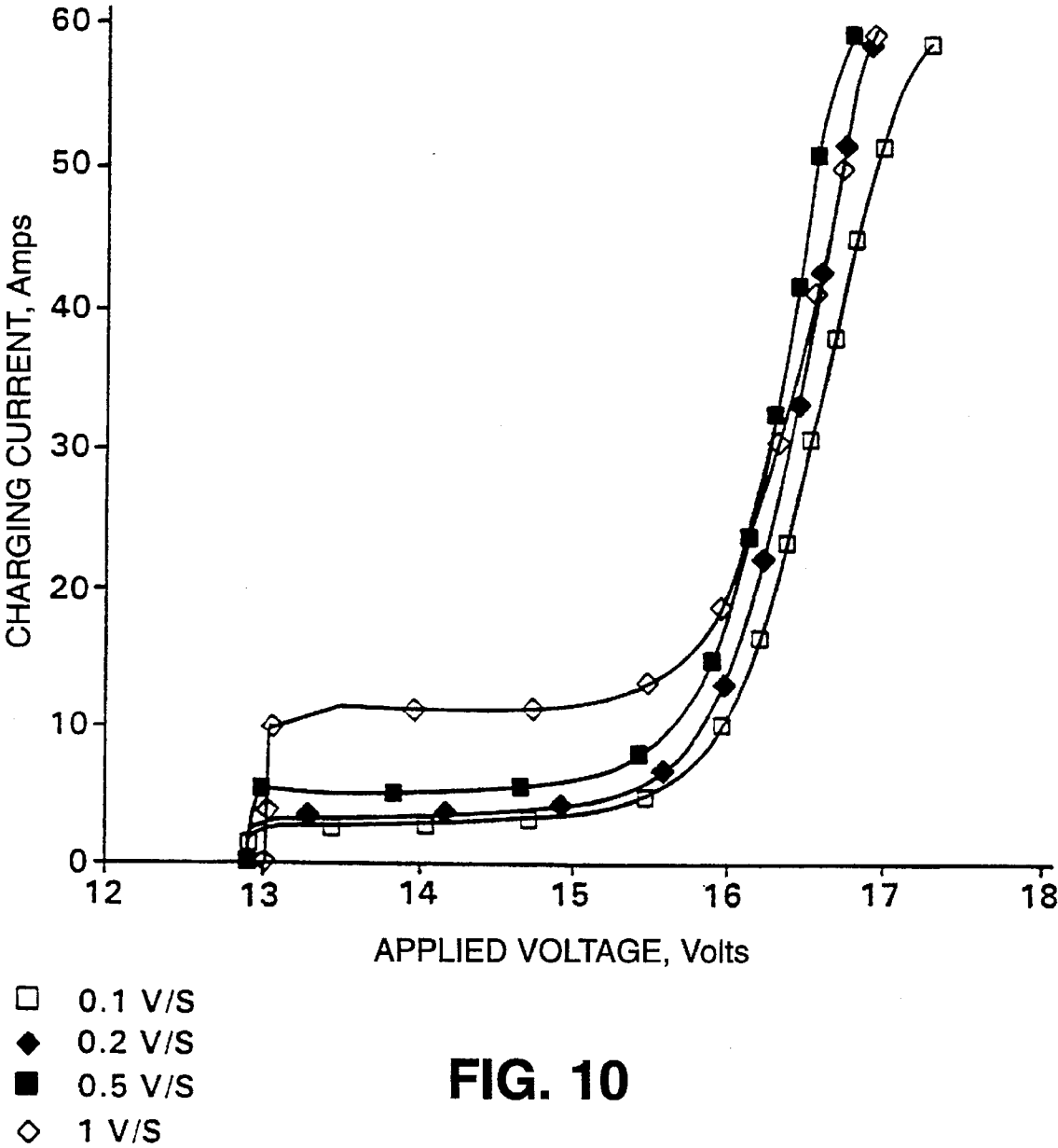


FIG. 10

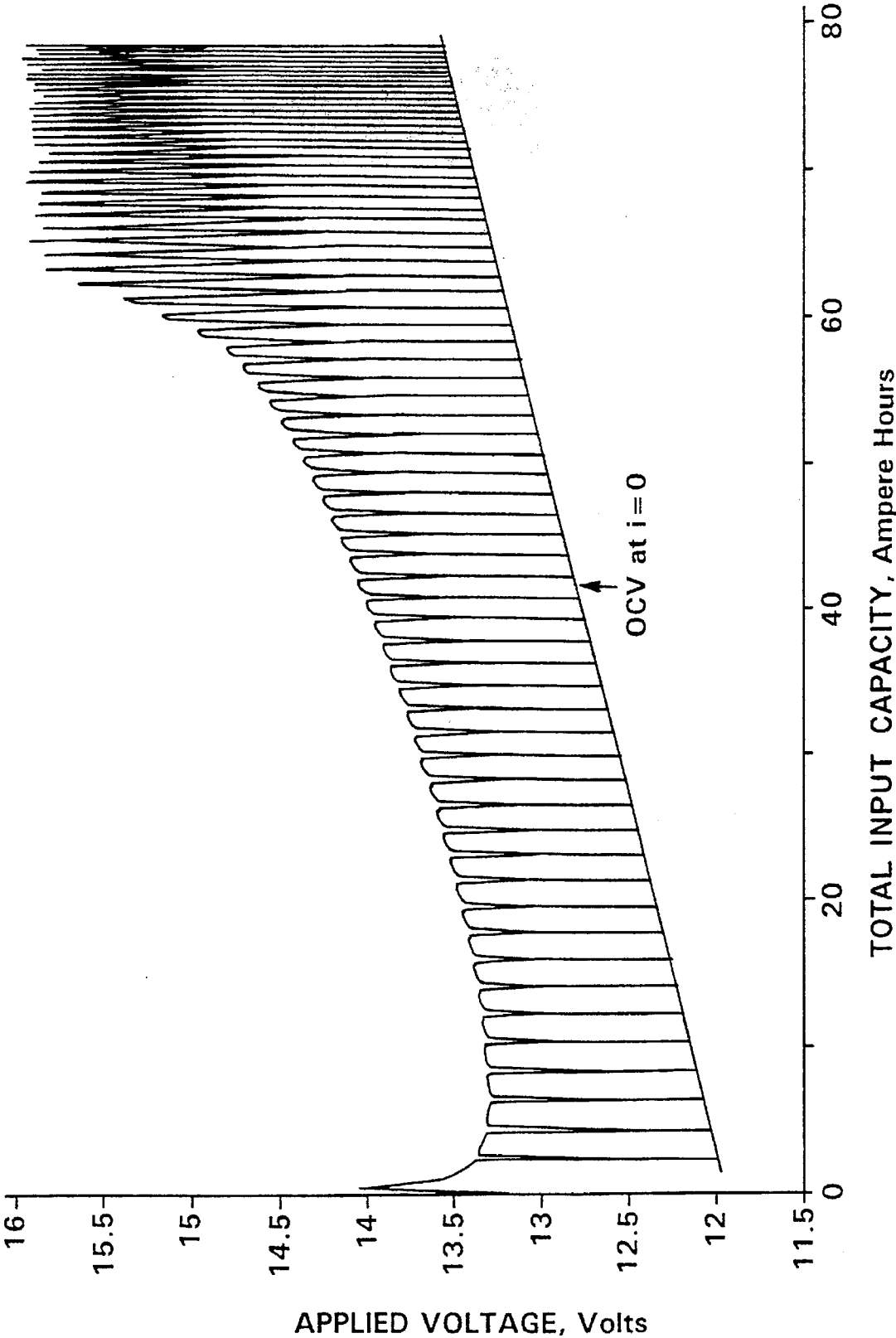


FIG. 11

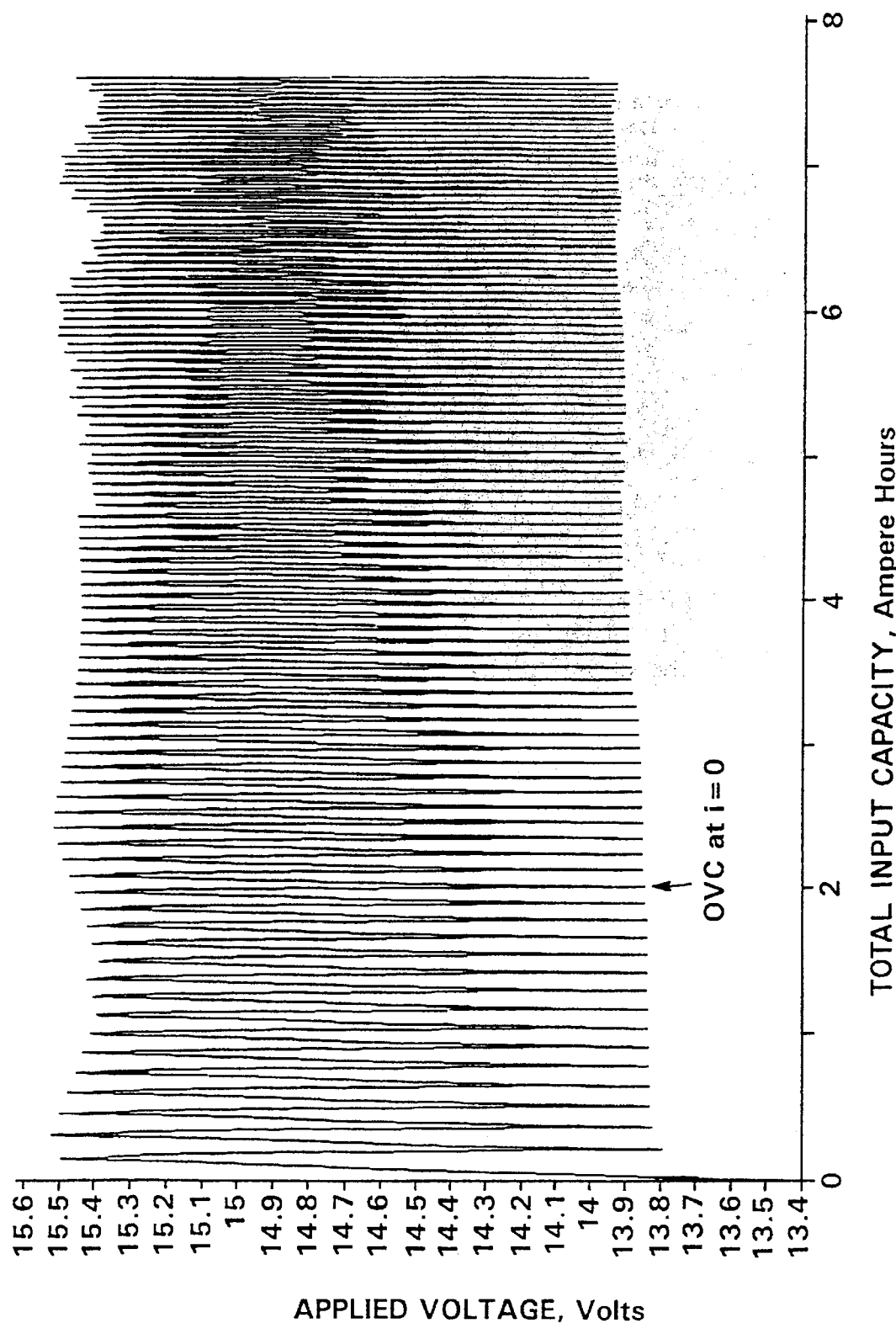


FIG. 12

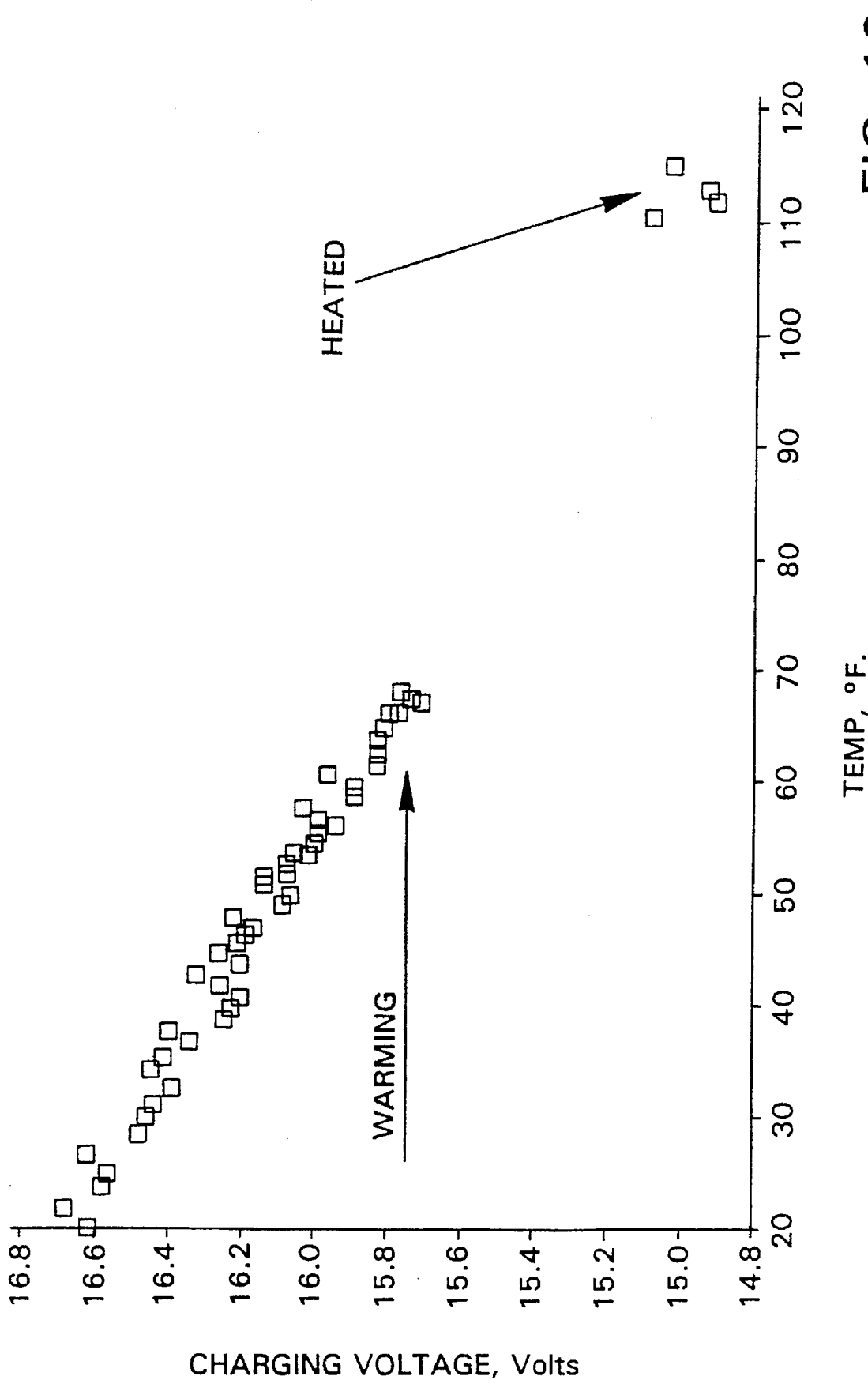


FIG. 13

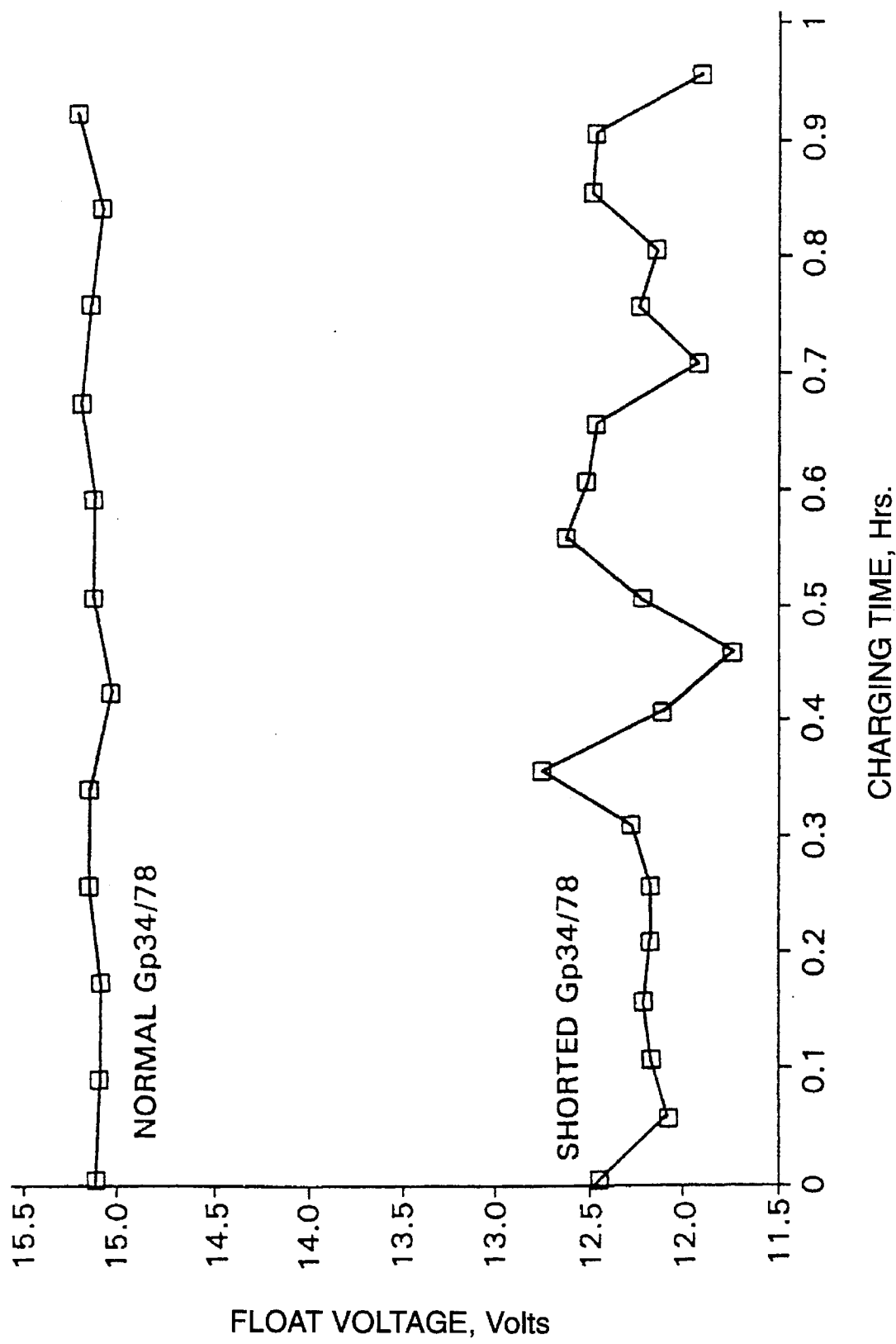


FIG. 14

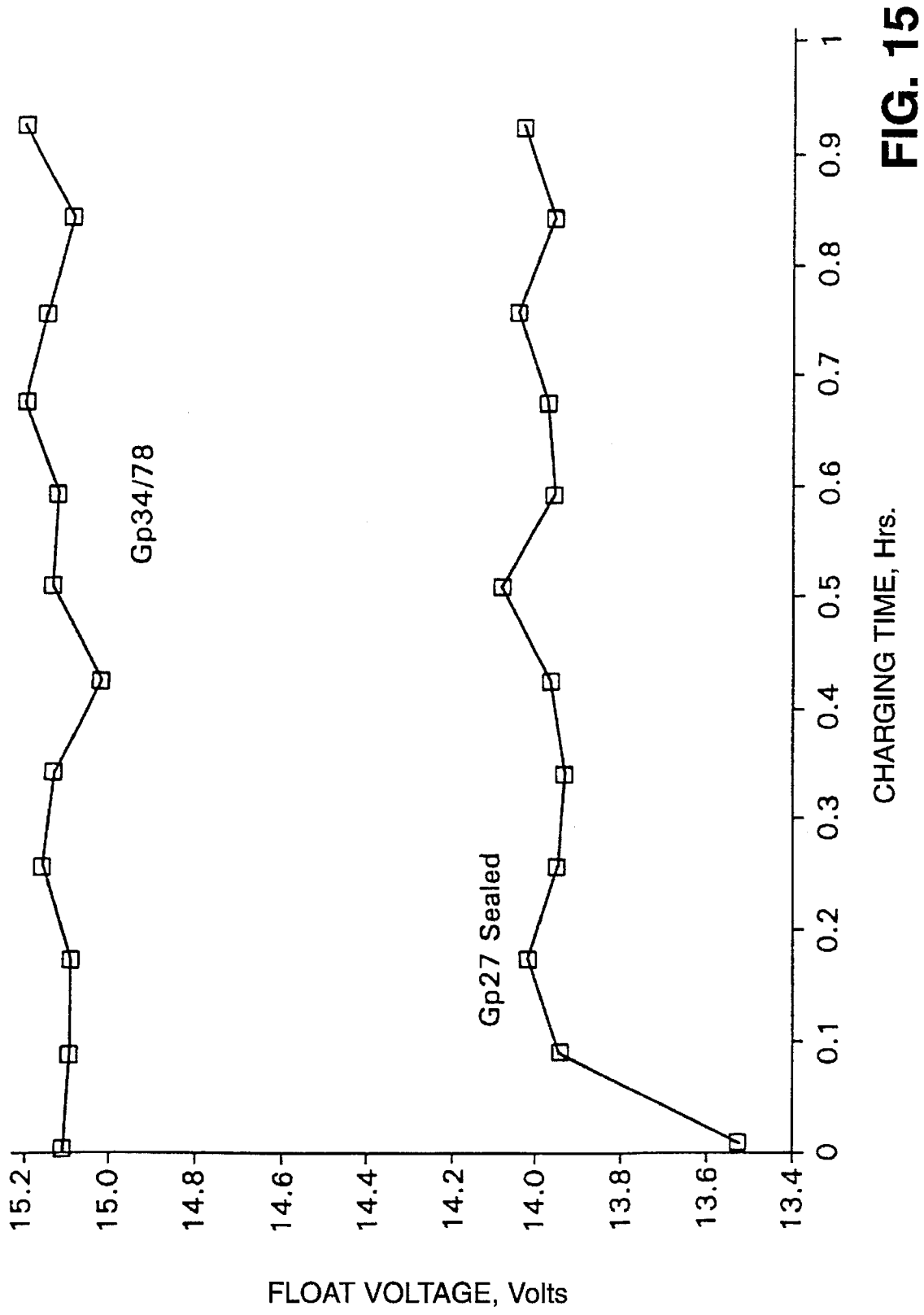


FIG. 15

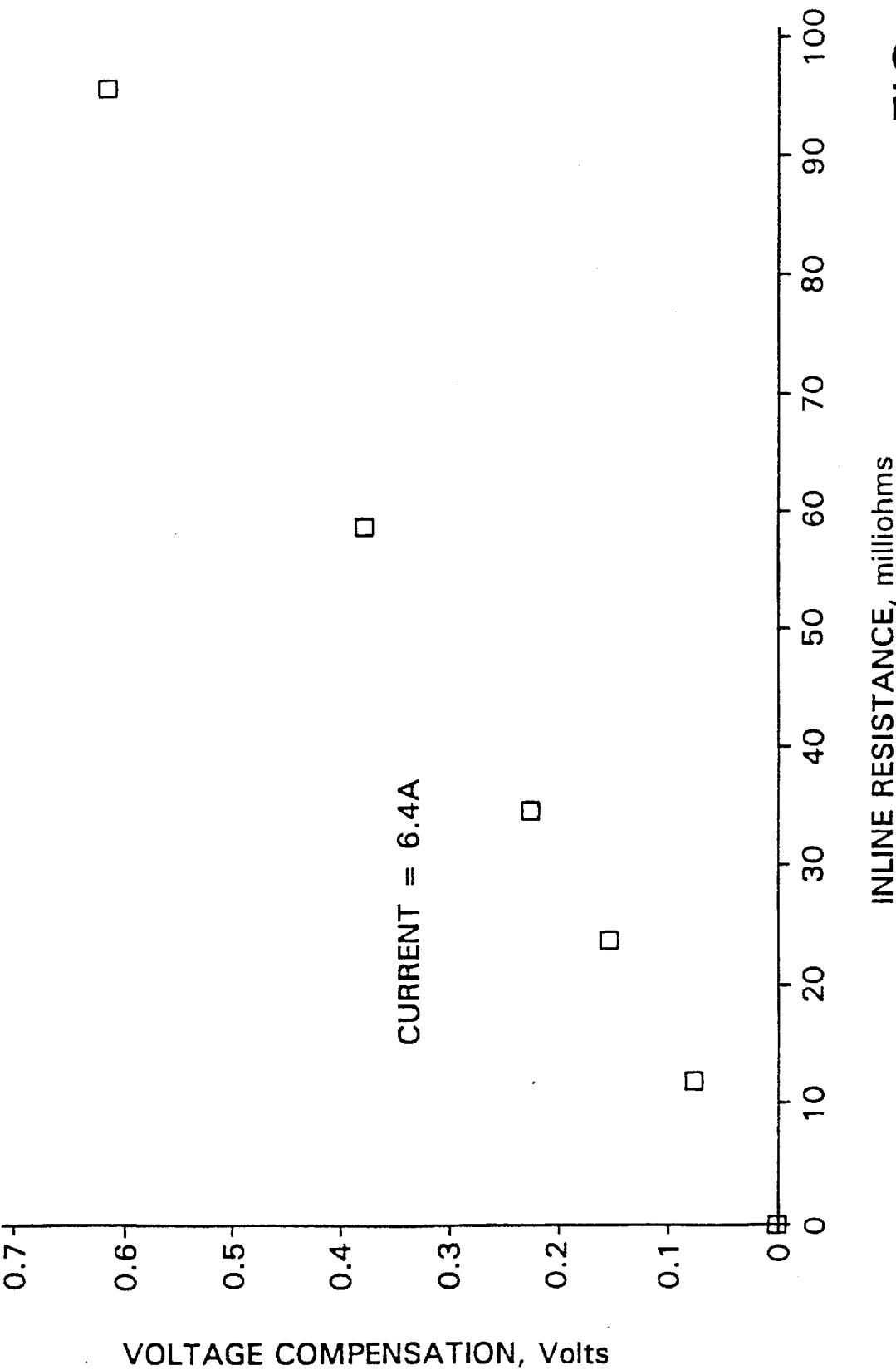


FIG. 16

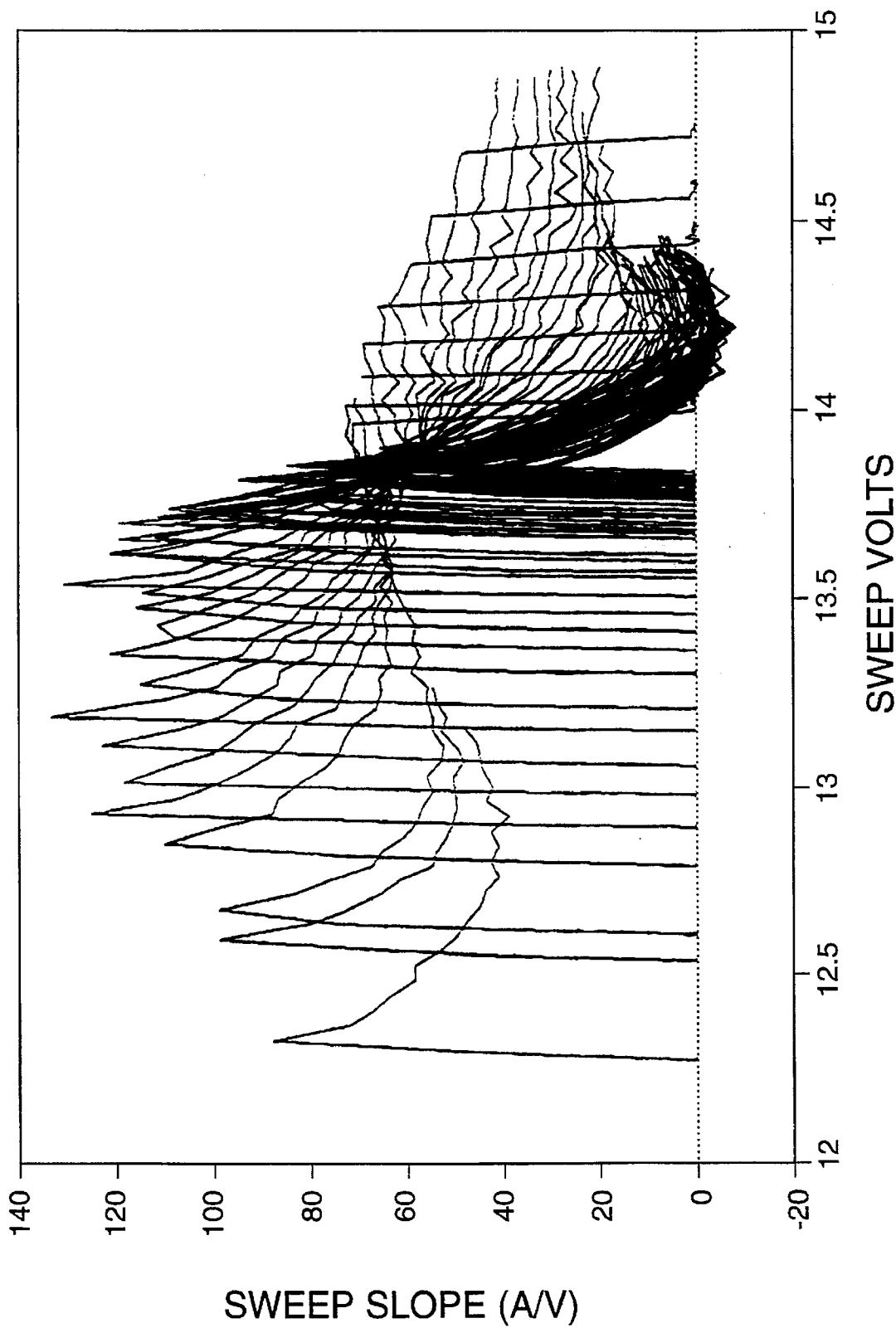


FIG. 17

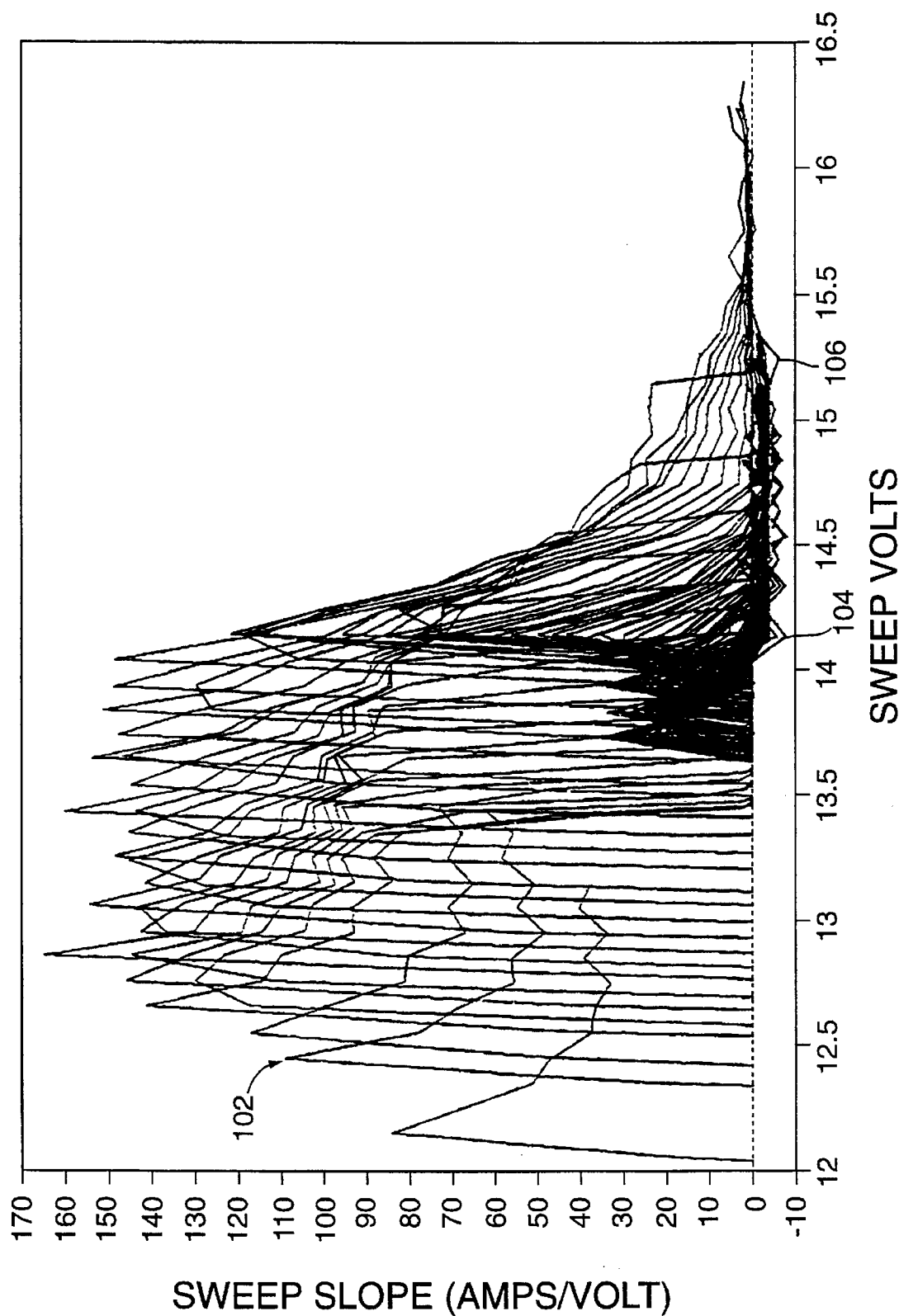


FIG. 18

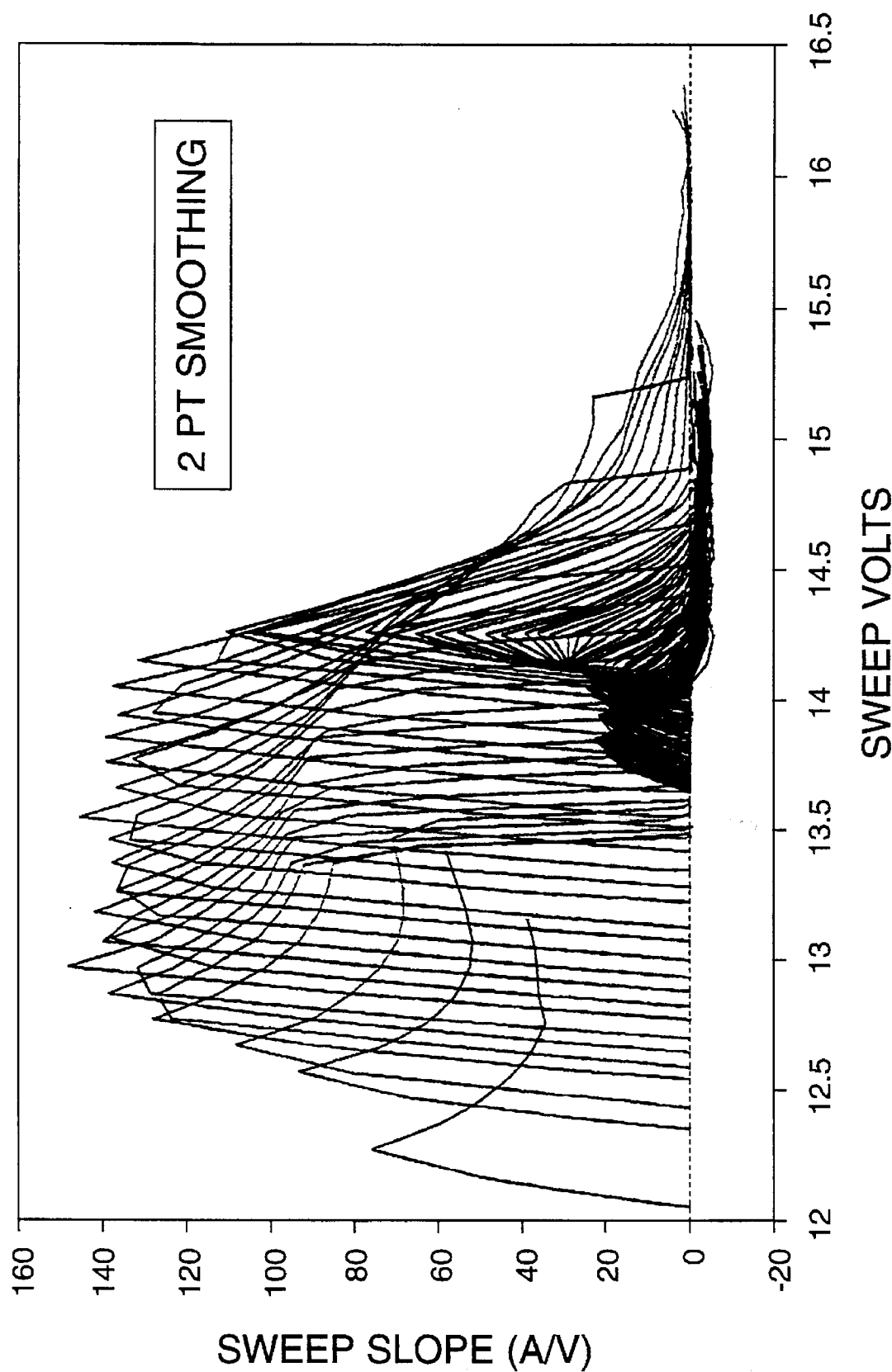


FIG. 19

METHOD AND APPARATUS FOR CHARGING A LEAD-ACID BATTERY

This application is a continuation-in-part of U.S. patent application Ser. No. 08/272,997 filed Jul. 14, 1994 (now U.S. Pat. No. 5,469,043), which is a continuation of U.S. patent application Ser. No. 07/960,583 filed Oct. 13, 1992, now abandoned.

FIELD OF THE INVENTION

This invention relates to lead-acid batteries and, more particularly, to a method and apparatus which may be utilized in charging such batteries.

BACKGROUND OF THE INVENTION

Lead-acid batteries have been used for many diverse applications. Such applications include use as a starting, lighting and ignition power source for vehicles (SLI), use in marine batteries for starting, lighting and other auxiliary power requirements, as a motive power source for use in golf carts and other vehicles and other applications of this sort. In addition, lead-acid batteries have been employed in a variety of stand-by power applications to provide a power source when the main power source becomes inoperable, as by, for example, interruption of electricity. Lead-acid batteries have also been employed in many other applications, e.g., uniform power distribution, power damping applications, and even for small electronic devices such as video cameras and cassette players.

While the extent of discharge and the particular cycling requirements of a lead-acid battery for a specific application vary widely, one criterion remains constant: it is important to ensure that proper charging of such batteries is carried out. Thus, on the one hand, undercharging such lead-acid batteries can result in less than optimum output and service life. Undercharging can result in perhaps permanent sulfation of part of the active materials, as well as stratification of the electrolyte and uneven use of the active materials.

On the other hand, undue overcharging of lead-acid batteries likewise creates problems. Overcharging of lead-acid batteries thus can result in permanent damage of the batteries as well as presenting potential safety hazards caused by, for example, boiling the electrolyte of the battery. Further, overcharging lead-acid batteries can accelerate positive grid corrosion and even lead to bulging and/or buckling of the battery plates. Among other undesirable aspects of undue overcharging are the undesirable increase in the specific gravity of the electrolyte, possible oxidation of the separators and the undue heat generated that can accelerate various problems.

The time and manner in which lead-acid batteries are charged is also important for other reasons. Thus, many applications require charging within a relatively short period of time so that it is important to optimize the current or voltage used, while, at the same time, avoiding the use of excessively high currents that will result in gassing and the like.

Further, the design of a suitable charger for lead-acid batteries that will allow optimization of the charging procedure is extremely complex. Typically, the state-of-charge (or state-of-discharge) of the battery requiring charging is not known. Also unknown are such factors as the specific use history of the particular battery, as well as the age and maintenance history, all of which can affect the optimum charging requirements. Similarly, the internal temperature of the battery is either unknown, or, if known, the ability to

compensate for the particular internal temperature in the charging process is quite difficult.

Another important factor complicating battery charger design is the type of battery being charged. Commercially used lead-acid batteries thus represent a broad spectrum of widely varying designs, ranging from flooded-type batteries (both maintenance-free and batteries requiring maintenance during service life) to valve-regulated recombinant sealed lead-acid batteries (where essentially all of the electrolyte is retained in the plates and separators and charging gas is recombined to water within the battery).

The size of the battery or cell being charged must also be taken into account. The requirements for charging a 12-volt battery are different from those requirements for a 6-volt battery or for a single lead-acid cell.

Additional factors that must be taken into account in determining the charging regime include the rate at which the battery was discharged and the stand time since discharge. The composition of the battery grids will affect the charging regime as will the presence of electrochemical impurities.

Another important factor that must be considered is the safety aspects of a battery charger. There is the potentiality for fumes, fire, explosion or thermal runaway when a battery such as an internally shorted battery or a sealed valve regulated recombinant battery is over-charged with typical fixed voltage chargers.

Still further, a stand-alone battery charger configuration may allow design considerations that could not be tolerated in a vehicle charging apparatus. Thus, in a vehicle, the dynamics of the battery utilization must be considered, viz., the charging regime may be taking place alternatively while the battery could be called on to deliver power due to a myriad of conditions.

For these and other reasons, it is not surprising that there has been considerable effort over a period of many years to provide battery chargers suitable for lead-acid batteries that overcome one or more of the problems involved. Thus, U.S. Pat. No. 3,421,067 to Wilson et al. discloses a battery charger control circuit which includes a coulometer to accurately measure the state-of-charge of the battery. That coulometer measurement is then used to cause the battery to be charged at the maximum available current rate until a charge exactly equal to the previous discharge has been accomplished.

U.S. Pat. No. 3,424,969 to Barry shows a battery charge control which includes sensing the rate of rise of voltage of the battery while fast-charging the battery. This fast-charging is terminated upon sensing a rate of rise that exceeds a predetermined rate.

U.S. Pat. No. 3,517,293 to Burkett et al. discloses charging a battery by imposing an increasing charge on the battery by charging during certain intervals and by providing discharge intervals interspersed with the charge intervals.

U.S. Pat. No. 3,816,806 to Mas involves discharging the battery periodically during the charging process.

U.S. Pat. No. 3,816,807 to Taylor notes that, in attempts to overcome the effects of temperature and age, efforts have turned to using the gas evolution rate as a more direct indication of the charge acceptance. It is stated that such systems appear to be unstable and have battery aging problems. Taylor discloses a charging sequence using the battery impedance as a charge control parameter.

U.S. Pat. No. 4,629,965 to Fallon et al. shows a charger for a battery which includes an initial charge carried out at

a maximum rate of current which tapers in magnitude until the battery attains a certain voltage. Thereafter, the battery is charged with a continuous reduction of current until termination.

U.S. Pat. No. 4,742,920 to Sutphin et al. discloses a microprocessor-directed battery charger which utilizes a dV/dt sensing. A timed finishing charge is used to enable a quicker and more efficient charging.

U.S. Pat. No. 4,829,225 to Podrazhansky et al. discloses a method and a device for rapidly charging a battery by providing a charge pulse to the battery, followed immediately by a depolarization pulse created by allowing the battery to discharge across a load and followed by a stabilization period. The sequence is cyclically repeated until the battery is charged.

U.S. Pat. No. 4,956,597 to Heavey et al. discloses a battery control circuit that first monitors the battery charge during a charge cycle until the charge voltage approaches the voltage range where the gassing point of the battery is anticipated to occur. As the charging voltage reaches the first voltage threshold level, a pulsed loading circuit is activated which periodically places a load across the battery and accurately measures the true output voltage. When the measured pulsed load voltage exceeds the threshold voltage predetermined to be indicative of the entry of the battery into the gassing phase, a timing network is activated and charging is continued for only a predetermined time.

U.S. Pat. No. 5,049,804 to Hutchings discloses what is considered to be a universal battery charger. This charger includes a microprocessor which receives inputs from current, voltage and temperature sensors for controlling the battery-charging profile.

It has further been proposed to use a microprocessor-based device to test the status of a battery using the battery starting characteristics. The battery status monitor determines the battery characteristics from two sets of data. One set of data is collected during normal usage of the battery, while the second set of data is taken during a specialized test profile typically in conditions like highway driving.

The test cycle involves imposing linearly increasing current or voltage ramp onto the battery terminals and then measuring the corresponding voltage or current response of the battery. The presence of a maximum in the dV/dI versus I_{ramp} or a minimum in the dI/dV versus the V_{ramp} indicates the gas point.

It was also found that the current at which the gas point occurs in the ramp-up direction is proportional to the battery capacity. The current at which the gas point occurs in the ramp-down direction reaches the lowest possible value when the battery is fully charged. Thus, the battery capacity can be determined from the former, and the state-of-charge from the latter parameter.

Despite all of the considerable effort evident in this field, there still exists the need for a method and apparatus that allows lead-acid batteries to be efficiently recharged. It is accordingly an object of the present invention to provide a method and apparatus for charging a lead-acid battery which is interactive with the battery being charged so the charging will inherently take into account, and compensate for, such factors as the service life history of the specific battery being charged so as to allow the charging profile to be capable of being optimized for that specific battery.

Another object of this invention is to provide a method and apparatus for recognizing an optimized charging current and voltage to achieve charging at a very high efficiency, while minimizing or controlling the amount of gassing.

A further object lies in the provision of a battery charger which inherently compensates for the internal temperature of the battery.

Yet another and more specific object of the present invention is to provide a method and apparatus for recognizing the state-of-charge of the battery so as to allow control of the end charge of the battery.

A still further object provides a method and apparatus for compensating for battery flaws such as imbalance from one cell to another as well as internal shorts and the like.

An additional object is to provide a battery charger that is capable of efficiently charging any size of cell or battery.

Other objects and advantages of the present invention will become apparent as the following description proceeds.

SUMMARY OF THE INVENTION

The present invention is predicated on the discovery that the use of periodic voltage sweeps to generate current-voltage information can be effectively utilized to provide a battery charger that is truly interactive, as the charging of the battery is varied based upon the voltage sweep information derived from the battery itself. The present invention thus inherently takes into account the internal temperature of the battery, internal battery resistance, charging circuit resistance and other service life and history factors that can alter the charging requirements.

To this end, utilizing such voltage sweeps detects the charge acceptance of the battery being charged as well as the gassing regions. Based upon the information detected, an optimum charging voltage can be employed, inherently providing the optimum IR, temperature and cell voltage compensation.

The voltage sweeps utilized involve increasing the applied voltage across the batteries to generate current-voltage information over the period of time involved in carrying out the sweep. Such voltage sweeps are then periodically repeated selecting charging voltages that adjust optimally to the needs of the battery as the charge progresses. In this fashion, the charging of the lead-acid batteries can be optimized by avoiding use of a voltage level that would either result in unduly overcharging the battery during the charging sequence or, on the other hand, would provide undercharging.

It is also possible to utilize the voltage information generated as an indication of when the charging cycle should be terminated. Thus, when charging has been completed, the appropriate voltages remain constant over time; and this condition can be utilized to dictate termination of the charging cycle.

The versatility of the present invention is such that the charging cycle is suitably altered as is required by the type of battery being charged, as well as providing a charging regime that will accommodate conditions such as a partial shorting of the battery, or the like.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram illustrating an exemplary lead-battery charger according to the present invention which utilizes voltage sweeping to alter the charging regime;

FIGS. 2A-2C comprise a logic diagram showing one embodiment of how the voltage sweep information can be detected so as to allow utilization in controlling the battery charging regime;

FIG. 3 is a graph of the current supplied versus the applied voltage for two batteries that were recharged after having been discharged to differing levels;

5

FIG. 4 is a graph similar to FIG. 3 except showing the results of voltage sweeps as the lead-acid battery is being recharged and the state-of-charge increases from 25 to 100%;

FIG. 5 is a graph of the sweep charge limiting current versus the state-of-charge and illustrating the relationship as the state-of-charge is increased to 100%;

FIG. 6 is a graph of the charging current versus the applied voltage similar to FIG. 4 except showing the voltage at relative states of charge;

FIG. 7 is a graph similar to FIG. 4 except also showing how the slope of the current-voltage curve changes during the voltage sweep;

FIG. 8 is a graph similar to FIG. 4 and showing the voltage sweep information when the temperature of the battery is varied;

FIG. 9 is a graph similar to FIG. 7 except showing the voltage sweep information obtained at a different state-of-charge;

FIG. 10 is a graph similar to FIG. 4 except showing voltage sweep information determined at varying sweeping rates;

FIG. 11 is a graph similar to FIG. 4 except showing the results of a sweep-up and back and the linear change of the open circuit voltage as the state-of-charge is increased;

FIG. 12 is a graph similar to FIG. 11 except showing voltage sweeps, up and back, after the battery has reached full charge;

FIG. 13 is a graph of voltage versus temperature and showing a temperature compensation effect resulting from utilizing the method and apparatus of the present invention;

FIG. 14 is a graph of charging time versus applied voltage and illustrating that the use of the present invention inherently compensates when charging a partially defective battery compared to a normal maintenance-free battery;

FIG. 15 is a graph similar to FIG. 14 except showing how the use of the present invention can be utilized with a sealed recombinant lead-acid battery versus a standard maintenance-free battery;

FIG. 16 is a graph showing the inherent resistance compensation effect of the present invention in charging of a standard maintenance-free lead-acid battery;

FIG. 17 is a graph showing the slope dI/dV versus voltage over a number of sweeps for a battery suitable for use in electric vehicles;

FIG. 18 is a graph showing the slope dI/dV versus voltage over a number of sweeps for a flooded battery; and

FIG. 19 is a graph showing the slope dI/dV versus voltage over a number of sweeps for the flooded battery of FIG. 18 using a two point moving averaging technique to smooth the curves.

While the present invention is susceptible of various modifications and alternative forms, the specific embodiments thereof will hereinafter be described in detail. It should be understood, however, that it is not intended to limit the invention to the particular forms disclosed, but, on the contrary, the invention is to cover all modifications, equivalents and alternatives falling within the scope of the invention as expressed in the appended claims. Thus, the method and apparatus of the present invention are described herein in connection with the charging of lead-acid batteries and cells. However, while the present invention does indeed provide substantial advantages in charging lead-acid batteries, it should be appreciated that the present invention

6

can likewise be advantageously used for charging other electrochemical systems that possess similar electrochemical characteristics, i.e., voltage sweep information which allows selection of an optimum charging voltage based upon the sweep charge limiting current as described herein. As illustrative examples, it is contemplated that the present invention can advantageously be used with nickel-cadmium, nickel-iron and nickel-zinc systems. Further, while the voltage sweeps described herein generally involve increasing the voltage to generate the current-voltage information, it should be appreciated that it is within the scope of the present invention to carry out the voltage sweeps by starting out at an appropriately high voltage and then decreasing the voltage to generate the necessary current-voltage information.

DETAILED DESCRIPTION OF THE INVENTION

Turning now to FIG. 1, there is shown an apparatus in accordance with the present invention for charging lead-acid batteries. As is schematically illustrated, the battery to be charged is shown at 10.

A variable DC power supply 12 is provided to charge the battery 10. Any of the power supplies used for charging lead-acid batteries can be employed so long as such power supplies can provide a variable voltage (and thus current) to the battery over the usual range of voltages, i.e., up to 17 volts or more. As one illustration, a variable DC power supply that can be used comprises an AC transformer, rectifier and filtering capacitors with current and voltage regulators. The power supply employed should, of course, provide a sufficiently stable voltage and current so as to allow appropriately accurate voltage sweep information to be developed as described herein.

A DC voltage output controller 14 serves to adjust the voltage, and, thus, the current the power supply 12 provides. Suitable microprocessors and electronic controls for serving as output controllers are well known.

In accordance with the present invention, voltage sweep function generator means are provided which are capable in the broadest aspects of this invention of causing the voltage applied by the power supply to sweep through a range that has been predetermined so as to allow, as will be more particularly discussed hereinafter, an analysis of the current versus voltage information over the predetermined range. A voltage sweep function generator 16 thus serves to periodically cause the DC voltage output controller 14 to interrupt the charging sequence and to sweep the voltage through the predetermined range so that the sweep curve can be evaluated to determine if any adjustment is needed to optimize the charging voltage. Devices capable of serving as the voltage sweep function generator are known and include, as for example, RC circuits with analog integrated circuitry (e.g., voltage scan generator, Wenking Model USG72 by Brinkmann Co.).

The frequency at which the voltage sweep is carried out can be varied as desired. As an illustrative example, the frequency of the voltage sweeps can vary from one sweep every 30 seconds to one sweep every two minutes. Of course, the frequency employed in a particular situation can be varied as desired. Indeed, the frequency can be varied within a single charge as the charge progresses.

Regarding the rate of sweep, the size of the power supply in relation to the battery being charged should be kept in mind. Also, the rate should not be so fast as to prevent accurate current-voltage information from being satisfacto-

rily determined. Further, in a dynamic environment, such as in a vehicle, it will, of course, be generally preferred to carry out the sweep as quickly as is consistent with obtaining accurate data. As illustrative examples, it has been found suitable to carry out the sweep at a rate of from about 0.05 volt/second up to about 2 volts/second or so for a 12-volt lead-acid battery.

To simplify data generation and particularly analysis, it will be generally preferred to carry out the voltage sweep at a constant rate. This allows data analysis using either time or voltage, as these two parameters are synonymous for analysis purposes with a constant sweep rate. Of course, if desired for some reason, the sweep could be carried out at other than a constant rate. Further, the current-voltage information can be generated by increasing the voltage in incremental fashion, rather than continuously increasing the voltage. Finally, it can be appreciated that the current-voltage information can be generated by sweeping with an increasing or decreasing current, rather than a voltage. Accordingly, as used herein, the terms "sweep" or "voltage sweep" are intended to include both continuously and incrementally changing the voltage or current, in either an increasing or decreasing direction.

The predetermined range over which the voltage sweep is carried out can be varied as desired to fit the requirements for the particular application. Functionally, as a minimum, the predetermined range for the voltage sweep need only cover the voltage range that allows an optimum charging voltage to be determined. In many applications, an optimum charging voltage will be the maximum voltage that can be applied to the specific battery at the particular stage in the charging sequence without undue gassing. However, as may be appreciated, one aspect of the present invention is that the current-voltage information generated from the periodic voltage sweeps can be utilized to accomplish whatever objectives are desired. Thus, for example, when the desired charging has been completed, the current-voltage information can be employed to select an applied voltage that will accomplish an acid mixing step.

Of course, the voltage sweep range can be much longer than the functional minimum range discussed, if desired. It has been found convenient to utilize a range that starts at or near the open circuit voltage of the battery being charged and terminates at an applied voltage just above that value which provides the desired optimum charging voltage.

Pursuant to another aspect of the present invention, voltage and current detection means are provided. Thus, as shown, the voltage applied to battery 10 is determined by DC voltage detector 18 while the current is detected by a DC current detector 20. Any of a variety of suitable DC voltage and current detectors are known and may be used. As illustrative examples, analog-to-digital converters connected to microprocessors or voltage comparator circuits may be used.

The present invention further involves analyzing the current versus voltage sweep curves so as to vary the charging voltage as is required to optimize the charging sequence. As is illustrated, an analyzer 22 functions to generate and analyze the current-voltage sweep data so that the voltage applied by variable DC power supply 12 can be adjusted if necessary.

The analysis and adjustment of the voltage sweep data can be carried out by any of a variety of techniques. It has thus been found suitable, as one example, to analyze the slope of the current versus voltage sweep curve so as to determine certain slope values or changes in values. The logic diagram

for carrying out such a dI/dV determination is shown in FIGS. 2A-2C. Certain aspects of the logic diagram concern a more preferred aspect of this invention (viz., detecting the end-of-charge condition of the battery being charged) and will be discussed later.

As shown in FIG. 2A, the start of the voltage sweep, shown at 30, involves measuring the battery voltage designated as V_B at 32, and the voltage of the charger, V_C , is set at a lower voltage than V_B as indicated at 34. The amount the charger voltage is decreased (e.g., one volt as shown in FIG. 2A) is arbitrary. In effect, the voltage decrease can be viewed as turning off the charger.

The battery voltage is then reduced as shown at 36 by whatever means desired, as, for example, by providing a settling time and/or a discharge pulse. It has thus been found necessary to provide a voltage reduction adequate to reduce polarization effects, which insures that the battery voltage, V_B , will be below an optimum charging voltage and that an optimum charging voltage will be detected during the sweep. Moreover, lowering the battery voltage ensures sufficient chargeable species in batteries near the end-of-charge, so that accurate slope detection is enabled during subsequent sweeps. This enables the system to properly govern the charging behavior near the end-of-charge. Further, while it will be desired to decrease the voltage of the battery to the level desired as promptly as possible where the charger is to be used in a vehicle as opposed to a stand-alone charger, the voltage settling time varies with state-of-charge, temperature and other factors.

Thus, a discharge pulse is preferred because it is much faster and more consistent than waiting for the battery voltage to settle on its own before the sweep, and because it provides chargeable species. To accomplish the discharge pulse, a discharge means 23 typically comprising a relay or the like in combination with a resistive load (e.g., one to five ohms) may be selectively switched in by the output controller 14 to draw current from the battery when desired. A discharge pulse drawing approximately two to twelve amperes of current for approximately two seconds has been found to provide the desired voltage reduction in prototype charging systems.

After V_C and V_B have been decreased, as at 34 and 36, the current value, I and the battery voltage V_B are measured as shown at 38. If current, I , is greater than an arbitrary value $k1$ as determined at 40, the logic loops back to decrease the voltage of the charger V_C as shown at 42 until a current is registered that satisfies the condition at 40. The arbitrary value, $k1$, can appropriately be set at whatever value is desired. Generally, $k1$ will be zero or a minimal current when compared to the charging current provided by the applied voltage.

Once a beginning voltage or minimal current is obtained (viz., the criteria at 40 is satisfied), the charger voltage, V_C , is set to this beginning voltage, V_B , as shown at 44, and a value of the slope of the current-voltage sweep is assigned. In the illustrative embodiment, a maximum slope, indicated at 46, is set at an extremely low number so that the first slope determined is greater than the initial S_{max} . As an example, it is suitable to set S_{max} as -1.000 Amps/volt. Similarly, a minimum slope, S_{min} , indicated at 47, is set at an extremely high number so that the first slope determined is less than the initial S_{min} . As an example, it is suitable to set S_{min} as 1,000 Amps/volt. Previously measured values of current and voltage at this time (i.e., V_B and I are retained as V_0 and I_0) are saved as shown at 48.

Continuing to FIG. 2B, the voltage augmentation is then initiated, increasing the voltage of the charger as a function

of time as shown at 50. As an example, the charger voltage, V_C , can be increased at a selected constant rate with time (e.g., where the rate constant is 0.05 to 2 volts/second for a 12-volt lead-acid battery). New values for the battery current and voltage are then determined as the voltage sweep continues as shown at 52.

Although not necessary to the invention, the battery voltage V_B is compared against a predetermined maximum charging voltage V_{max} at step 53 to ensure that the battery voltage V_B has not increased to an excessive level. The maximum voltage check is performed for safety purposes or to further control or moderate the gassing rate, e.g., if the power supply output is very large with respect to the battery. If the battery V_B voltage exceeds the predetermined maximum value V_{max} , as shown at 55 the sweep is halted at step 60, and charging continues at V_C . Of course, the power supply 12 or DC voltage controller 14 may be arranged to limit the charging voltage as an additional (or alternative) precaution.

As with the other parameters described herein (e.g., constants k1-k4), V_{max} may be manually or otherwise input to the charger. For example, V_{max} may be manually input as 15 volts for a 12-volt battery, 8 volts for a 6-volt battery, and so on. Alternatively, V_{max} and/or the other parameters may be coded into the software, or determined in some other manner, such as by accessing a software look-up table in accordance with a particular battery type entered to determine one or more of the optimal parameters for that battery.

Provided that the charging voltage is at an acceptable level, as shown at step 54 the current (measured at step 52) is evaluated. If the value of the current is less than, or equal to, zero, as shown at 54, the procedure loops back as shown at 56 until the sweep voltage has increased sufficiently so that a positive current is registered.

Next, as shown at 58, it is determined whether the difference in the battery voltage is substantially less than the rate at which the charger voltage has been augmented. The purpose of this determination is to ascertain whether the battery charger has reached its maximum current where little further change in battery voltage will occur even though the applied voltage continues to increase. If the maximum current has been reached, the charger voltage can remain at or somewhat above that point and charging continued. At this point, the voltage sweep would be terminated as shown at 60, and a delay would occur, as at 62, until the next sweep is initiated.

If the power supply has not been fully loaded (i.e., the maximum current has not been reached), a slope value is determined. This is indicated by the formula in the box indicated as 64. The slope is indicated as the quantity of change in the current divided by the change in the voltage.

As the sweep voltage increases during the voltage sweep, the slope tends to initially increase, reach a peak and then decrease as the slope levels off. Such a situation is exemplified in the slope versus voltage curve of FIG. 18, wherein the peak is denoted as 102, and also is evident in the graphs of FIGS. 17 and 19. It is in the region beyond this peak, where the slope is leveling off, that an optimal charging voltage generally resides, i.e., in a critical region.

To ensure that the desired charging voltage is obtained in the critical region, and not in the non-critical region wherein the initial slope initially rises, the slope is evaluated to determine when it has peaked. To this end, the measured (and calculated) slope value S is compared against the maximum slope value, S_{max} at step 65 to determine if the slope has indeed peaked and is leveling off. If S is greater

than S_{max} , indicating that the slope is rising, then S_{max} is set to S at step 67, and, as shown at 72 loops back to step 48. As described above, the initial value of S_{max} is set to a very low value (e.g., -1,000 V/A at step 46) so that the first time through, the comparison at step 65 will branch to step 67 whereby the maximum slope S_{max} will be set to the initial measured slope.

Conversely, if S is not greater than S_{max} , then the slope is decreasing and leveling off, and the process to determine the desired charging voltage via the slope calculation continues to step 66. As can be appreciated, this ensures that the measured slope value is not compared with the desired slope value until after a peak has been detected.

According to one aspect of the invention, once the critical region has been reached, the value of the slope is then evaluated to determine an optimal charging voltage. An optimal charging voltage may be either at the voltage where the slope is at a minimum, or above or below this value, generally depending on the type of battery to be charged, as described in more detail below. For example, recombinant batteries are preferably charged at voltages that are below the voltage that corresponds to the minimum slope, in order to minimize gassing. Conversely, flooded batteries are preferably charged above the voltage corresponding to the minimum slope voltage to encourage a controlled amount of gassing.

Moreover, it has been found that the charger setting is more consistent away from the minimum slope with certain batteries that have approximately the same minimum slope over a wide range of voltages. For example, as shown in FIG. 18, slope values at or near the minimum slope are found over a wide range of voltages, i.e., from approximately point 104 to point 106. Because of this, it is likely that the voltage corresponding to the slope detected as the minimum for one sweep may differ from the voltage corresponding to the minimum slope for another sweep. This creates difficulties when attempting to terminate the charge based on the stabilizing of the input voltage or current, because the charging voltage may be frequently adjusted, thus failing to remain sufficiently stable to reliably determine the end of charge.

To find the desired charging voltage, two variables, k3 and k4, which may be input as parameters, are provided. As described below, k3 may be used to find an optimal charging voltage that is less than the charging voltage at the minimum slope, while k4 may be used to find an optimal charging voltage that is greater than the charging voltage at the minimum slope.

Considering first k3, at step 66 the slope is compared against the minimum slope S_{min} , which initially is set to 1,000 Amperes/Volt. The slope will be less than this value the first time, and will thus branch to step 68 where S_{min} is set to the current slope, and step 70 where the voltage is recorded. At step 71, the slope is compared against k3. If the slope (which is just beginning to decrease after its peak) is below this value, then the desired slope has been detected, however this ordinarily will not happen until several iterations through the loop have taken place. If the desired slope has not been detected, then as shown at 72, the process loops back to step 48.

As the sweep voltage increases, the slope decreases towards its minimum. If k3 is between the peak slope value and the minimum slope value, eventually the slope falls below k3 and as shown at 73, the sweep is stopped, and at step 80 the charging voltage is set to V_{sav} which is the battery voltage (step 70) at this point. If K3 is less than the

S_{min} voltage, the sweep continues until a slope value of $k4$ is encountered. Unless the end-of-charge feature is being utilized, a predetermined delay occurs as indicated at 62.

As the battery approaches full charge, the slope drops below $k3$ at a voltage that is lower than the voltage that corresponds to the minimum slope. As can be appreciated, the actual charging voltage is determined by where the desired slope $k3$ fits with respect to the peak slope and the minimum slope S_{min} . However, if it is instead desired to utilize a charging voltage that is greater than the charging voltage at the minimum slope, $k3$ is input as (or otherwise set to) a value that is very low, e.g., -1,000 Amps/Volt. This ensures that step 71 will never stop the sweep.

To accomplish the higher charging voltage, $k3$ is thus set so as to never satisfy the comparison of step 71. As a result, at step 66, once the slope has reached its minimum and is again rising, S will be greater than or equal to S_{min} and thus branch to step 74. Assuming that $k4$ is set to a value above the minimum, as shown at 76 the process preserves the voltage (step 70) and, since step 71 is not satisfied, loops back to step 48. As the sweep voltage increases, the slope continues to increase until it exceeds $k4$. At this point, the sweep is stopped, and at step 80 the charging voltage is set to V_{sav} , which was the battery voltage of the previous loop. In this manner, the slope first exceeds the desired slope $k4$ at a voltage that is above or equal to the voltage that corresponded to the minimum slope. Unless the end-of-charge feature is being utilized, a predetermined delay occurs as indicated at 62.

The procedure is thereafter repeated until the charging of the battery is completed. While a timer may be used, it is preferable to employ logic to determine the end-of-charge condition. The logic for detecting the end-of-charge condition using the voltage or current information will be described later.

Although not necessary to the invention, one or more of the measurements and comparisons described above may be performed multiple times to ensure that any readings obtained accurately represent the state or condition of the battery on charge. For example, a counter may be kept in combination with each of the comparison routines so that a plurality of voltage and current readings obtained over a plurality of voltage augmentations are available before a branching decision is made. In this manner, potential problems arising from the use of single readings (which due to noise or the like may be erroneous) are minimized.

By way of example, before a comparison of the measured slope S with a desired value $k3$ is made at step 71, it is desirable to ensure that the measured slope is accurate, since the measured slope value is used to determine whether to stop the sweep. To ensure accuracy, a counter may be incremented and evaluated at step 71, such that until step 71 is reached a suitable number of times in a row, the decision is bypassed and more readings are obtained. Each time through, the readings may be analyzed with respect to one another using any number of techniques, thereby eliminating doubtful readings. Note that the voltage reading corresponding to the first iteration through step 71 is preserved, so that if the slope at that voltage had in fact achieved the desired value $k3$, the voltage corresponding to that slope reading is known for setting the appropriate charging voltage.

If desired, averaging or other suitable analysis techniques may be utilized with these multiple values to eliminate spurious readings. For example, FIG. 19 shows how the dI/dV curves are smoothed out using a two-point moving averaging technique on the voltage and current data detected

when compared against the dI/dV curves of FIG. 18 with the same current and voltage data. The curves are further smoothed using three- and four-point moving averaging. Using moving averaging may change and shift relative values, but these values may be corrected accordingly.

In any event, when the battery approaches full charge, the values of $k3$ and $k4$ are thus utilized for detection such that the charging voltage is fine-tuned somewhat above or somewhat below the voltage corresponding to the minimum slope. As can be readily appreciated, in the event that the slope value does not achieve either $k3$ or $k4$ during a sweep, either the voltage cap at step 53 or the detection of maximum power supply current at step 58 will stop the sweep.

The method of charging in accordance with the present invention can be illustrated by reference to a current-voltage sweep curve. As is shown in FIG. 3, sweep Curves A and B illustrate typical sweep curves at various states of charge. These curves were generated using a sweep rate at which the voltage was increased at a rate of 0.5 volts/second (the temperature being 73° F.). The fully charged battery in Curve B had been subjected to a discharge of 29.4 Ampere Hours while the battery in Curve A was a battery that had been discharged by only 4.2 Ampere Hours.

By way of illustration, the method of the present invention involves determining an optimum charging voltage of the battery as that voltage changes as the battery is being recharged. In the state-of-charge indicated at Curve B, the battery being charged can accept a current in excess of about 60 Amps so that a battery charger (as used in this illustration) that can only provide about 58 Amps or so can be set at the applied voltage (greater than 13.5 volts) that will yield its maximum current (i.e., 58 Amps) at this stage. However, as that battery becomes more fully charged, illustrated by Curve A, the sweep current for optimum charging efficiency drops well below 58 Amps. Thus, to achieve optimum charging performance, a charging voltage applied should be in the flat portion of the Curve A, namely A1 (14 to 15 volts). While the charging voltage used could, of course, be less than the level determined in the area A1, of Curve A, this would involve utilizing less than optimum charging since such lower voltage would be associated with the first upward portion of Curve A, namely A2. On the other hand, utilizing voltages well above that in the flat portion of Curve A will result in excessive gassing. Thus, use of voltages associated with the second upward part of Curve A, namely A3, would result in undue gassing and, accordingly, less than optimum charging performance.

However, as may be appreciated, one aspect of the significant benefits derived from the present invention is the versatility. The current-voltage information may thus be utilized in whatever fashion desired to control the charging sequence to achieve whatever objectives have been established.

What is important is that the current-voltage information provides a clear picture of the condition of the battery being charged at that time so that those established objectives can be met with that clear picture in hand. Thus, for example, it may be desirable for many applications to control the charging sequence by determining where the charging voltage should be set with respect to the inflection point of the curve, as occurs when the slope S equals S_{min} as shown at 66. If it is desired that the charging voltage is less than or equal to the voltage at S_{min} , then the step at 74 may be eliminated, either actually or effectively (the latter occurring by setting $k4$ at a very negative value). When $k3$ is set at zero or a low positive value, the applied charge voltage will be at

or somewhat to the left of the inflection point of the current versus voltage curve of FIG. 3, but will still be within the flat portion of the curve (e.g., A1 of Curve A).

On the other hand, if some gassing is desired or if enhanced temperature sensitivity is desired, k_4 can be set at an appropriate value that will correspond to a higher gassing condition, e.g., somewhere on the upper portion of A1 or even on A3 of Curve A in FIG. 3. Thus, when the latter objective is important, it has been found desirable in accordance with the present invention to utilize the overcharge or gassing portion of the curve since this portion of the current-voltage sweep curve has been found to be much more sensitive to temperature changes than the other portions of the sweep curve, especially when the battery approaches a full state-of-charge condition. Yet, this temperature sensitivity can be achieved while also using an applied voltage for charging that does not result in undue gassing. This condition can thus be achieved by setting the charger voltage, V_C , in step 80 not as V_{sav} , but at a voltage level sufficiently below V_{sav} so as to be in the region where undue gassing does not occur. For example, the charger voltage, V_C , may be set at a value between V_{sav} and the voltage at the point of maximum slope (e.g., portion A1 and potentially part of A2 of Curve A).

As has been described herein, the method of the present invention achieves many and significant benefits in charging lead-acid batteries. The truly interactive nature of this charging method and apparatus inherently compensates for temperature, service life history and the array of other factors that can alter the charging regime, including batteries that are in a partially malfunctioning state. The present invention is applicable to any type of a lead-acid battery and suitably alters the charging regime to fit the type of battery being charged. Yet, the method and apparatus used are straightforward and may be readily applied using available chargers and other available equipment.

Perhaps a particularly useful application will involve controlling the charging apparatus in automobiles and the like. This should minimize, if not wholly obviate, any problems due to frequently undercharging so long as adequate charging capacity is available, as are becoming a concern to the automobile industry, as well as obviating undue gassing as is also an important concern.

Determining the desired charging voltage by using the slope or change in slope of the current-voltage curve (or dI/dt where a constant voltage sweep rate is used) is a facile technique. However, any other technique desired can be employed to determine the charging voltage considered appropriate for the objectives wanted.

Indeed, if desired, more sophisticated methods for determining the characteristics of the current-voltage curve can be utilized. For example, electrical circuitry which directly measures values proportional to slope can be used.

Also, while a two-point regression analysis of slope has been illustrated, it should be appreciated that a three-point analysis (or even more) could be used. This could be accomplished by storing the current and time of a data point immediately prior to the other two data points used in the illustrative embodiments. Sequentially, the three point regression would involve as a first point (I_{01} at voltage V_{01}), a second point (I_0 at voltage V_0) and a third point (I at voltage V). The slope S then becomes

$$(I - 2I_0 + I_{01}) / (V - 2V_0 + V_{01}).$$

Still further, pursuant to another and preferred aspect of this invention, the point at which the charging sequence is

completed and can be terminated, if desired, can be determined from the voltage or current data being developed as the charging regime proceeds. Thus, when the battery has reached its full state of charge, the applied voltage or current becomes constant over a period of time. This condition can be used as the signal to terminate charging, to provide an acid-mixing step in those batteries where acid stratification so requires, or to adjust the current to that needed to provide a trickle charge, or whatever else may be desired.

To this end, and referring to FIG. 2A using voltage stability criteria, when the initial sweep cycle is started, a value for V_{C0} , V_{10} and for N are set as indicated at 31. (V_{C0} is a variable to store a previously generated average voltage value. V_{10} is an accumulator for a new average voltage value and, as indicated here, N is the number of sweep cycles.) As shown, V_{C0} , V_{10} and N are set at zero as a starting point to insure, as will become apparent, that the charging regime is not prematurely terminated. Moreover, these values are maintained at or reset to zero during the initial charging of the battery to differentiate the steady voltage detected at the end-of-charge from the steady voltage that exists when the power supply is at its maximum output. To this end, a simple evaluation of the amount of current flow may be performed such that the end-of-charge determination is only performed at low current flows.

After the value for V_C for the charger has been set equal to V_{sav} as shown at 80 in FIG. 2B (or some value above or lower than V_{sav} , as the case may be), a determination is made as shown at 82 in FIG. 2C as to whether $N=10$. If N does not equal 10, V_{10} is augmented by V_C and N is reset as being equal to $N+1$ as shown at 84; and the procedure is delayed until the next sweep.

The selection of 10 as the number of sweep cycles to determine whether charging should be continued is somewhat arbitrary. The number of sweep cycles should be such to ensure that the end-of-charge conditions have actually been met, and 10 cycles is certainly adequate for that purpose. The number of cycles used to determine whether the end-of-charge condition has been reached could be somewhat less and, of course, could be well in excess of 10 should that be desired.

If the number of sweep cycles has reached 10, then a determination is made as to whether the end-of-charge conditions have been reached. The criterion is that set at 86. More specifically, if the ratio of the difference between the accumulated charger voltage V_{10} in the current sweep cycle and V_{C0} (the previous accumulated voltage value when N was zero) to V_{10} is less than 0.005, the charging is terminated as indicated at 88.

As may be appreciated, charging cannot be terminated in the illustrative embodiment until at least 20 sweep cycles have been carried out. More specifically, since V_{C0} was set at 0 at the start, the criteria set forth at 86 cannot be met after the first 10 cycles, i.e., the ratio of $(V_{10} - V_{C0})/V_{10}$ will be 1.

The criterion set at 86 is somewhat arbitrary. The criterion should be substantially less than 1, but should be a positive value to accurately signal the end-of-charge condition by allowing for some variance in the voltage.

In the event that the voltage criterion is not met and charging is not terminated, the step at 31 is adjusted when the next sweep cycle begins after the delay indicated at 62. If the criterion set is not met, V_{C0} is set at the accumulated charging voltage and V_{10} and N are reset at zero as shown at 90. These values are stored until the initiation of the next cycle and then the procedure is repeated until the end-of-charge condition is detected.

Alternatively, the current may be evaluated to determine when it has stabilized sufficiently to indicate the end of charge, i.e., the fully-charged condition is detected by a substantially constant average output level. For example, current averaging may be performed in a manner that is similar to the voltage averaging technique of FIG. 2C. Moreover, using the criterion of little or no continuing current drop to detect the end of charge further prevents the occurrence of thermal runaway. As with the steady voltage detection, it can be appreciated that there is a need to differentiate the steady current flow that exists at the end-of-charge from the steady current flow that results during the maximum power supply output.

The following Examples are exemplary of the present invention, but not in limitation thereof. Unless otherwise indicated, the state-of-charge measurements were based upon how many Ampere Hours were required to completely discharge the battery (complete discharge being defined as the battery having a discharge voltage of 10.5 volts). Thus, for example, if 100 Ampere Hours had been determined to completely discharge a particular battery, a discharge of 10 Ampere Hours would mean that the state of charge would be 90%. Also, unless otherwise indicated, the voltage sweeps described were carried out by continuously increasing the voltage as opposed to incremented increases. Further, as used in these Examples, the terminology "sweep charge limiting current" refers to the current associated with the flat portion of the sweep curve (e.g., A1 in FIG. 3).

EXAMPLE 1

This Example illustrates how the sweep curves generated vary as the battery approaches a full state-of-charge.

Commercial Group 65 lead-acid batteries were used. These batteries were fully charged and were then discharged to various states at a rate of 4 Amps. Thereafter, a voltage sweep from 12.5 Volts to 16.5 Volts was applied at a sweep rate of 0.5 volts/second. The temperature of the batteries was about 73.5° F. FIG. 4 shows the current-voltage sweep curves. The charger utilized provided a maximum current of about 58 Amps. As can be seen from FIG. 4, the sweep charge limiting current decreased to about 32 Amps or so as the state-of-charge increased from an 85% state-of-charge to a 95% state-of-charge.

FIG. 5 shows the appropriate sweep charge limiting current for the specific batteries tested as the state-of-charge increases to 100%. FIG. 6 is a three-dimensional plot showing the relationship between the state-of-charge (Ampere Hours) versus applied voltage and sweep current.

FIG. 7 shows the voltage sweep curve (indicated as Curve C) when the state-of-charge of the battery was at 90%. Curve D is a plot of the slope of that curve (dI/dV) and shows how the slope minimum corresponds with the inflection point of Curve C where the sweep charge limiting current occurs.

EXAMPLE 2

This Example shows the use of the present invention at various temperatures and at various sweep rates.

Commercially available Group 65 lead-acid batteries were fully charged, and some were then discharged to a 90% state of discharge at a rate of 4 Amps. The batteries were maintained at a temperature of either 0° F., 73.5° F., or 120° F., and voltage sweeps were carried out at a rate of 0.5 volts/second. The results are shown in FIGS. 8 (100% state-of-charge) and 9 (90% state-of-charge).

As can be seen, the various temperatures at which the batteries were maintained did change the position of the

voltage sweep curve. However, the fundamental characteristics of the sweep curves did not change. Thus, the sweep curves used in this invention can be utilized to appropriately adjust the battery charging conditions whatever the temperature.

A series of the commercially available Group 65 lead-acid batteries were also subjected to various sweep rates. These batteries, maintained at a temperature of 73.5° F., and a state-of-charge of 100% were subjected to sweep rates of 0.1, 0.2, 0.5 and 1 Volt/Second. The results are shown in FIG. 10. As can be seen, the characteristic curves are developed at all sweep rates. The sweep charge limiting currents vary with the sweep rate used, but the curve characteristics for obtaining an optimum charging voltage remains essentially the same.

EXAMPLE 3

This Example shows that the use of sweep curves to assist in determining when battery charging, for example, can be terminated.

A commercially available Group 65 lead-acid battery was fully discharged to 10.5 Volts at a rate of 4 Amps. The first half of each cycle involved a sweep rate at a constant rate of 0.05 volts/second for about 42 seconds; the other half of the cycle involved a sweep back at a constant rate of 0.05 volts/second for about 42 seconds. The results are shown in FIG. 11. As can be seen, the voltage at zero current varied linearly using the cycling regime described herein.

After the batteries have been fully charged, additional current (calculated as Ampere Hours) was supplied to the battery for a period of time. FIG. 12 shows the results. As can be seen, the voltage at which the applied voltage resulted in zero current being provided to the battery stabilized at about 13.8 to 13.9 volts.

Accordingly, based upon this data, the voltage sweep data can be employed to provide an indication of the battery state-of-charge for a given type of battery. Based upon the information in this Example, the equation for the state-of-charge (determined as Ampere Hours) is as follows:

$$\text{Ampere Hours} = 47.62 \times (\text{OCV} - 11.92).$$

Further, this Example demonstrates that the voltage data can be used to indicate the end-of-charge condition.

EXAMPLE 4

This Example illustrates that the charging method of the present invention inherently compensates for temperature.

A fully charged, commercially available Group 58 lead-acid battery was used. The battery was first cooled down to temperatures well below ambient and then warmed as a function of charging time. A thermocouple was placed in one cell of the battery in contact with the electrolyte to determine the temperature of the battery. Thereafter, the battery was further charged in accordance with the present invention, utilizing an incremental sweep rate of 0.2 volts/second and a sweep frequency of 1/minute. Some data points were also developed by heating the battery to temperatures well above ambient and then determining the charging voltage by the procedure described herein.

FIG. 13 is a graph of the charging voltage versus the battery temperature. The temperature measured was for reference only and was not used to set the charging voltage. The charging voltage selected was determined solely by the sweep technique of the present invention using a value of 1 volt below a slope of 4 amps/volt after a minimum slope was

detected (i.e., k4 at 74 in FIG. 2B was 4 Amps/volt and V_C at 80 was set equal to: $V_{sav}-1$ and k3 was set to a highly negative value). As can be seen, the charging voltage determined in accordance with the present invention varies with temperature in essentially a linear or direct manner.

Based upon this data, the use of the present invention can compensate for the temperature of the battery as the charging technique proceeds. This Example also specifically demonstrates the temperature sensitivity of the gassing or overcharge part of the sweep curve.

EXAMPLE 5

This Example shows the use of the present invention in connection with lead-acid batteries of widely varying types as well as a partially malfunctioning battery.

One set of experiments compared a commercially available Group 34/78 battery with a similar battery that had one cell that was inoperative due to a short. These two batteries, maintained at about 80° F., were charged using the voltage sweep technique of the present invention, and the applied voltage and current were determined as the charging continued. More specifically, these batteries were float-charged. The incremental voltage sweep rate used was 0.2 volts/second, and a sweep was carried out every minute. A k4 slope of 0.25 Amps/volt criterion was used after a minimum slope value was detected.

The results are shown in FIG. 14. As can be seen, the interactive nature of the present invention inherently compensated for the partially shorted battery, lowering the charging voltage. No excessive heat or gas were observed, as would be expected if a fixed voltage-controlled charger had been employed.

The other set of experiments involved charging with the method of this invention, using the parameters described in this Example, a commercially available, sealed marine recombinant lead-acid battery having a rated capacity of about 78 Ampere Hours and a commercially available Group 34/78 lead-acid battery having a rated capacity of about 70 Ampere Hours, the rated capacities being at a 20-hour rate. The results of the charging regime are shown in FIG. 15.

As can be seen by comparing FIGS. 14-15, the use of the present invention inherently alters the charging regime as dictated by the type and condition of the battery.

EXAMPLE 6

This Example demonstrates the inherent compensation for the internal resistance of a battery by using the charging sequence of the present invention.

A commercially available Group 34/78 battery nominally rated at 70 Amp Hours was discharged for about 20 Ampere Hours. Then, the battery was recharged using the technique described herein with a power supply having a 6.4 Amp maximum current output. The incremental sweep rate used was 0.2 volts/second, and k4 was set at zero. During each of 10 minute charging periods, a series of wires with various measured resistances were placed between the charging apparatus and the battery.

As shown in FIG. 16, the resulting charging profiles demonstrate that the voltage of the charger increased proportionally to the resistance of the interconnecting wire to keep the current at a maximum value. This demonstrates that the present invention inherently compensates for resistance.

We claim:

1. A method of charging a lead-acid battery which comprises providing a variable power supply to charge the

battery with an applied voltage, periodically carrying out a voltage sweep through a predetermined range, detecting the applied voltage and current at multiple points as the voltage sweep is being carried out, detecting a slope based upon the applied voltage and current values detected during the voltage sweep that is substantially a maximum slope value, selecting a charging voltage for the battery being charged from the detected values for applied voltage and current wherein the selected voltage corresponds to a voltage greater than the voltage at the maximum slope value, and adjusting the variable power supply to provide the battery being charged with a charging voltage based upon the charging voltage value selected.

2. The method of claim 1 wherein the predetermined range comprises a range of from about the open circuit voltage of the battery being charged up to the charging voltage selected.

3. The method of claim 1 wherein the applied voltage is augmented at a constant rate of from about 0.05 to about 2.0 volts per second for a 12-volt battery.

4. The method of claim 1 wherein the frequency of voltage sweeps varies as the charge progresses.

5. The method of claim 1 wherein charging is terminated when the voltage detected during a series of voltage sweeps remains constant over a predetermined period of time.

6. The method of claim 1, wherein the step of selecting the charging voltage includes the steps of detecting a predetermined slope value, and selecting the charging voltage as the voltage corresponding to the voltage at the predetermined slope value.

7. The method of claim 6, wherein the predetermined slope value is a minimum slope value, and wherein the step of selecting the charging voltage includes the steps of detecting a minimum slope value, and selecting the charging voltage as the voltage corresponding to the voltage at the minimum slope value.

8. An apparatus for charging a lead-acid battery which comprises a variable DC power supply for charging the battery, a DC voltage output controller to control the voltage of the DC power supply, a voltage sweep function generator for applying a voltage sweep through a predetermined range to the battery being charged, detection means to determine the voltage and current at multiple points and times as the voltage sweep is carried out and providing voltage and current signals based upon such detected values, said detection means including means for detecting a maximum slope value based upon the applied voltage and current values detected during the voltage sweep, an analyzer means for receiving the voltage and current signals at the various times detected and selecting a charging voltage greater than the voltage at the maximum slope value, said DC voltage output controller receiving the charging voltage information and adjusting the voltage of said variable DC power supply so that the battery being charged is provided with the selected charging voltage.

9. The apparatus of claim 8, wherein the detection means includes means for detecting a predetermined slope value, and the analyzer includes means for selecting the charging voltage as the voltage corresponding to the voltage at the predetermined slope value.

10. The apparatus of claim 9, wherein the detection means includes means for detecting a minimum slope value as the predetermined slope value, and the analyzer includes means for selecting the charging voltage as the voltage corresponding to the voltage at the minimum slope value.

11. A method of controlling the charging of a lead-acid battery by adjusting the charging voltage in accordance with

periodic voltage sweeps which comprises detecting the voltage of the battery being charged, lowering the voltage being applied to the battery until a minimum acceptable level of current is detected, initiating the voltage sweep over a predetermined range at an augmented voltage rate with time, detecting whether the maximum current for the charger power supply has been reached, setting the charging voltage at that point if the maximum current has been reached and stopping the voltage sweep at or above that point, continuing the voltage sweep when the charger current has not been maximized, determining voltage and current values at intervals during the voltage sweep, detecting whether a maximum slope value has been reached based upon the applied voltage and current values detected during the voltage sweep, selecting the charging voltage based upon the current-voltage values determined wherein the selected charging voltage is greater than the voltage at the maximum slope value, terminating the voltage sweep, delaying for a predetermined period of time and thereafter initiating a further voltage sweep.

12. The method according to claim 11 wherein the initial sweep voltage of the battery is reduced by a discharge current pulse or by a predetermined time.

13. The method of claim 11 wherein the charging voltage is selected by determining the minimum slope based upon the applied voltage and current values detected during the voltage sweep.

14. The method of claim 13 wherein the minimum slope is determined by selecting a predetermined minimum slope value, and periodically resetting said predetermined minimum slope value with slope values determined from detected current and voltage values as the voltage sweep proceeds until a slope value is determined that is larger than the prior determined slope value.

15. The method of claim 14 wherein, after a minimum slope is determined, the charging proceeds until a certain slope value or change in slope value is encountered.

16. The method of claim 14 wherein the voltage is swept beyond the voltage at the minimum slope until a high slope or change in slope value occurs, thereafter offsetting the charging voltage at a voltage between the maximum and the high slope values.

17. The method of claim 11 wherein the end-of-charge state of the battery being charged is determined by selecting a predetermined number of voltage sweep cycles and determining the end-of-charge state when the relative or specific change of the average charging voltage or current is less than a predetermined value.

18. The method of claim 11 wherein the voltage is augmented at a constant rate.

19. The method of claim 11, wherein the step of selecting the charging voltage includes the steps of detecting a predetermined slope value, and selecting the charging voltage as the voltage corresponding to the voltage at the predetermined slope value.

20. The method of claim 19 wherein the step of detecting the predetermined slope includes the step of comparing the predetermined slope value with slope values determined from detected current and voltage values as the voltage sweep proceeds, until a slope value is detected that is larger than the predetermined slope value.

21. The method of claim 19 wherein the step of detecting the predetermined slope includes the step of comparing the predetermined slope value with slope values determined from detected current and voltage values as the voltage sweep proceeds until a slope value is detected that is smaller than the predetermined slope value.

22. A method of charging a lead-acid battery which comprises providing a variable power supply to charge the battery with an applied voltage, periodically carrying out a voltage sweep through a predetermined range, detecting the applied voltage and current at multiple points as the voltage sweep is being carried out, detecting a selected slope value based upon the applied voltage and current values detected during the voltage sweep, selecting a charging voltage value as the voltage corresponding to the voltage at the selected slope value, and adjusting the variable power supply to provide the battery being charged with a charging voltage based upon the charging voltage value selected.

23. The method of claim 22, wherein the step of detecting a selected slope value includes the step of detecting a minimum slope value, and wherein the step of selecting a charging voltage value includes the step of selecting the voltage corresponding to the voltage at the minimum slope value.

24. The method of claim 22, wherein the step of detecting a selected slope value includes the step of detecting a selected slope value having a voltage corresponding thereto that is less than the voltage corresponding to a minimum slope value, thereby selecting a charging voltage value that is less than the voltage at the minimum slope value.

25. The method of claim 22, wherein the step of detecting a selected slope value includes the step of detecting a selected slope value having a voltage corresponding thereto that is greater than the voltage corresponding to a minimum slope value, thereby selecting a charging voltage value that is greater than the voltage at the minimum slope value.

26. The method of claim 22, further comprising the step of selectively discharging the battery prior to the step of periodically carrying out a voltage sweep.

27. A method of charging a lead-acid battery which comprises providing a variable power supply to charge the battery with an applied voltage, periodically carrying out a voltage sweep through a predetermined range, detecting the applied voltage and current at multiple points as the voltage sweep is being carried out, selecting a charging voltage for the battery being charged from the detected values for applied voltage and current, adjusting the variable power supply to provide the battery being charged with a charging voltage based upon the charging voltage value selected, determining whether the battery has reached a desired level of charge from the detected values for applied voltage and current over a plurality of sweeps, and terminating sweep charging when the battery is determined to be substantially charged.

28. The method of claim 27 wherein the step of determining whether the battery has reached a desired state of charge includes the steps of selecting a predetermined number of voltage sweep cycles, and determining whether the desired state of charge has been reached by comparing the relative or specific change of the average charging voltage or current over the number of cycles with a predetermined value.

29. The method of claim 28 further comprising the step of sensing for a low level of current to determine whether the battery has reached a desired level of charge.

30. A method of charging a lead-acid battery which comprises providing a variable power supply to charge the battery with an applied voltage, selectively discharging the battery, periodically carrying out a voltage sweep through a predetermined range, detecting the applied voltage and current at multiple points as the voltage sweep is being carried out, selecting a charging voltage for the battery being charged from the detected values for applied voltage and

21

current, and adjusting the variable power supply to provide the battery being charged with a charging voltage based upon the charging voltage value selected.

31. The method of claim 30 wherein the step of selectively discharging the battery includes the step of connecting a resistive load to the battery to draw current therefrom. 5

32. An apparatus for charging a lead-acid battery which comprises a variable DC power supply for charging the battery, a DC voltage output controller to control the voltage of the DC power supply, discharge means for selectively providing a discharge pulse to the battery, a voltage sweep function generator for applying a voltage sweep through a predetermined range to the battery being charged, detection means to determine the voltage and current at multiple points and times as the voltage sweep is carried out and providing voltage and current signals based upon such 15

22

detected values, an analyzer means receiving the voltage and current signals at the various times detected and selecting a charging voltage, said DC voltage output controller receiving the charging voltage information and adjusting the voltage of said variable DC power supply so that the battery being charged is provided with the selected charging voltage.

33. The apparatus of claim 32 wherein the discharge means includes a switch for selectively connecting a resistive load to the battery to draw current therefrom.

34. The apparatus of claim 32 wherein the output controller is connected to the switch to selectively control the actuation thereof.

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