US006359441B1

(12) **United States Patent**
Bertness

(10) **Patent No.: US 6,359,441 B1**
(45) **Date of Patent: Mar. 19, 2002**

(54) **ELECTRONIC BATTERY TESTER**

(75) Inventor: **Kevin I. Bertness**, Batavia, IL (US)

(73) Assignee: **Midtronics, Inc.**, Willowbrook, IL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/560,920**

(22) Filed: **Apr. 28, 2000**

Related U.S. Application Data

(60) Provisional application No. 60/132,045, filed on Apr. 30, 1999.

(51) **Int. Cl.**^{7} **G01N 27/416**

(52) **U.S. Cl.** **324/426**; 324/433

(58) **Field of Search** 324/426, 430; 320/132, 155, 134; 702/63

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,514,745	A	7/1950	Dalzell	171/95
3,356,936	A	12/1967	Smith	324/29.5
3,562,634	A	2/1971	Latner	31/4
3,593,099	A	7/1971	Scholl	320/13
3,607,673	A	9/1971	Seyl	204/1
3,676,770	A	7/1972	Sharaf et al.	324/29.5
3,729,989	A	5/1973	Little	73/133
3,753,094	A	8/1973	Furuishi et al.	324/29.5
3,808,522	A	4/1974	Sharaf	324/29.5
3,811,089	A	5/1974	Strezelewicz	324/170
3,873,911	A	3/1975	Champlin	324/29.5
3,876,931	A	4/1975	Godshalk	324/29.5
3,886,443	A	5/1975	Miyakawa et al.	324/29.5
3,889,248	A	6/1975	Ritter	340/249
3,906,329	A	9/1975	Bader	320/44
3,909,708	A	9/1975	Champlin	324/29.5
3,936,744	A	2/1976	Perlmutter	324/158
3,946,299	A	3/1976	Christianson et al.	320/43
3,947,757	A	3/1976	Grube et al.	324/28
3,969,667	A	7/1976	McWilliams	324/29.5
3,979,664	A	9/1976	Harris	324/17
3,984,762	A	10/1976	Dowgiallo, Jr.	324/29.5
3,984,768	A	10/1976	Staples	324/62
3,989,544	A	11/1976	Santo	429/65
4,008,619	A	2/1977	Alcaide et al.	73/398
4,053,824	A	10/1977	Dupuis et al.	324/29.5
4,070,624	A	1/1978	Taylor	327/158
4,086,531	A	4/1978	Bernier	324/158

(List continued on next page.)

FOREIGN PATENT DOCUMENTS

DE	29 26 716 B1	1/1981
EP	0 022 450 A1	1/1981
EP	0 637 754 A1	2/1995

(List continued on next page.)

OTHER PUBLICATIONS

"Electromechical Impedance Spectroscopy in Battery Development and Testing", *Batteries International,* Apr. 1997, pp. 59 and 62–63.

"Battery Impedance", by E. Willihnganz et al., *Electrical Engineering,* Sep. 1959, pp. 922–925.

"Determining The End of Battery Life", by S. DeBardelaben, *IEEE,* 1986, pp. 365–368.

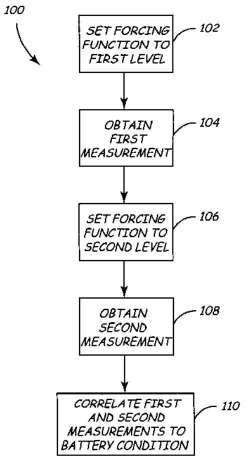
(List continued on next page.)

Primary Examiner—Gregory Toatley
(74) *Attorney, Agent, or Firm*—Westman, Champlin & Kelly, P.A.

(57) **ABSTRACT**

An electronic battery tester for determining a condition of a storage battery includes a forcing function adapted to couple to the battery. Circuitry coupled to the forcing function is adapted to obtain measurements from the battery at multiple levels of the forcing function. In the method according to the present invention, a forcing function is applied to the battery at a first level and a first measurement is obtained. The forcing function is applied at a second level and a second measurement is obtained. The first and second measurements are correlated to condition of the battery.

22 Claims, 3 Drawing Sheets



U.S. PATENT DOCUMENTS

4,112,351	A	9/1978	Back et al.	324/16
4,114,083	A	9/1978	Benham et al.	320/39
4,126,874	A	11/1978	Suzuki et al.	354/60
4,178,546	A	12/1979	Hulls et al.	324/158
4,193,025	A	3/1980	Frailing et al.	324/427
4,207,611	A	6/1980	Gordon	364/580
4,217,645	A	8/1980	Barry et al.	364/483
4,315,204	A	2/1982	Sievers et al.	322/28
4,316,185	A	2/1982	Watrous et al.	340/636
4,322,685	A	3/1982	Frailing et al.	324/429
4,363,407	A	12/1982	Barkler et al.	209/3.3
4,369,407	A	1/1983	Korbell	324/416
4,379,990	A	4/1983	Sievers et al.	322/99
4,390,828	A	6/1983	Converse et al.	320/32
4,392,101	A	7/1983	Saar et al.	320/20
4,396,880	A	8/1983	Windebank	320/21
4,408,157	A	10/1983	Beaubien	324/62
4,412,169	A	10/1983	Dell'Orto	320/64
4,423,378	A	12/1983	Marino et al.	324/427
4,423,379	A	12/1983	Jacobs et al.	324/429
4,424,491	A	1/1984	Bobbett et al.	324/433
4,459,548	A	7/1984	Lentz et al.	324/158
4,514,694	A	4/1985	Finger	324/429
4,520,353	A	5/1985	McAuliffe	340/636
4,633,418	A	12/1986	Bishop	364/554
4,659,977	A	4/1987	Kissel et al.	320/64
4,667,279	A	5/1987	Maier	363/46
4,678,998	A	7/1987	Muramatsu	324/427
4,679,000	A	7/1987	Clark	324/428
4,697,134	A	9/1987	Burkum et al.	320/48
4,707,795	A	11/1987	Alber et al.	364/550
4,709,202	A	11/1987	Koenck et al.	320/43
4,710,861	A	12/1987	Kanner	363/46
4,719,428	A	1/1988	Liebermann	324/436
4,743,855	A	5/1988	Randin et al.	324/430
4,745,349	A	5/1988	Palanisamy et al.	320/22
4,816,768	A	3/1989	Champlin	324/428
4,820,966	A	4/1989	Fridman	320/32
4,825,170	A	4/1989	Champlin et al.	324/436
4,849,700	A	7/1989	Morioka et al.	324/427
4,876,495	A	10/1989	Palanisamy et al.	
4,881,038	A	11/1989	Champlin	324/426
4,912,416	A	3/1990	Champlin	324/430
4,913,116	A	4/1990	Katogi et al.	123/425
4,929,931	A	5/1990	McCuen	340/636
4,931,738	A	6/1990	MacIntyre et al.	324/435
4,937,528	A	6/1990	Palanisamy	324/430
4,947,124	A	8/1990	Hauser	324/430
4,956,597	A	9/1990	Heavvvvey et al.	320/14
4,968,941	A	11/1990	Rogers	324/428
4,968,942	A	11/1990	Palanisamy	
5,004,979	A	4/1991	Marino et al.	324/160
5,032,825	A	7/1991	Xuznicki	340/636
5,047,722	A	9/1991	Wurst et al.	324/430
5,087,881	A	2/1992	Peacock	324/378
5,126,675	A	6/1992	Yang	324/435
5,140,269	A	8/1992	Champlin	324/433
5,144,218	A	9/1992	Bosscha	320/44
5,144,248	A	9/1992	Alexandres et al.	324/428
5,160,881	A	11/1992	Schramm et al.	322/7
5,170,124	A	12/1992	Blair et al.	324/434
5,179,335	A	1/1993	Nor	320/21
5,204,611	A	4/1993	Nor et al.	320/21
5,214,370	A	5/1993	Harm et al.	320/35
5,214,385	A	5/1993	Gabriel et al.	324/434
5,241,275	A	8/1993	Fang	324/430
5,254,952	A	10/1993	Salley et al.	324/429
5,266,880	A	11/1993	Newland	320/14
5,281,919	A	1/1994	Palanisamy	324/427
5,281,920	A	1/1994	Wurst	324/430
5,295,078	A	3/1994	Stich et al.	364/483
5,298,797	A	3/1994	Redl	307/246
5,300,874	A	4/1994	Shimamoto et al.	320/15
5,302,902	A	4/1994	Groehl	324/434
5,315,287	A	5/1994	Sol	340/455
5,321,626	A	6/1994	Palladino	364/483
5,331,268	A	7/1994	Patino et al.	320/20
5,336,993	A	8/1994	Thomas et al.	324/158.1
5,338,515	A	8/1994	Dalla Betta et al.	422/95
5,339,018	A	8/1994	Brokaw	320/35
5,343,380	A	8/1994	Champlin	363/46
5,347,163	A	9/1994	Yoshimura	307/66
5,352,968	A	10/1994	Reni et al.	320/35
5,365,160	A	11/1994	Leppo et al.	320/22
5,365,453	A	11/1994	Startup et al.	364/481
5,381,096	A	1/1995	Hirzel	324/427
5,412,323	A	5/1995	Kato et al.	324/429
5,426,371	A	6/1995	Salley et al.	324/429
5,426,416	A	6/1995	Jefferies et al.	340/664
5,432,426	A	7/1995	Yoshida	320/20
5,434,495	A	7/1995	Toko	320/44
5,442,274	A	8/1995	Tamai	320/23
5,449,996	A	9/1995	Matsumoto et al.	320/20
5,449,997	A	9/1995	Gilmore et al.	320/39
5,451,881	A	9/1995	Finger	324/433
5,457,377	A	10/1995	Jonsson	320/5
5,469,043	A	11/1995	Cherng et al.	320/31
5,485,090	A	1/1996	Stephens	324/433
5,488,300	A	1/1996	Jamieson	324/432
5,519,383	A	5/1996	De La Rosa	340/636
5,528,148	A	6/1996	Rogers	324/426
5,537,967	A	7/1996	Tashiro et al.	123/792.1
5,546,317	A	8/1996	Andrieu	364/481
5,548,273	A	8/1996	Nicol et al.	340/439
5,550,485	A	8/1996	Falk	324/772
5,561,380	A	10/1996	Sway-Tin et al.	324/509
5,562,501	A	10/1996	Kinoshita et al.	439/852
5,572,136	A	11/1996	Champlin	324/426
5,574,355	A	11/1996	McShane et al.	320/39
5,583,416	A	12/1996	Klang	320/22
5,585,728	A	12/1996	Champlin	324/427
5,589,757	A	12/1996	Klang	320/22
5,592,093	A	1/1997	Klingbiel	324/426
5,596,260	A	1/1997	Moravec et al.	320/30
5,598,098	A	1/1997	Champlin	324/430
5,602,462	A	2/1997	Stich et al.	323/258
5,606,242	A	2/1997	Hull et al.	320/48
5,621,298	A	4/1997	Harvey	320/5
5,642,031	A	6/1997	Brotto	320/21
5,650,937	A	7/1997	Bounaga	364/483
5,652,501	A	7/1997	McClure et al.	320/17
5,656,920	A	8/1997	Cherng et al.	320/31
5,675,234	A	10/1997	Greene	320/15
5,677,077	A	10/1997	Faulk	429/90
5,699,050	A	12/1997	Kanazawa	340/636
5,701,089	A	12/1997	Perkins	327/772
5,705,929	A	1/1998	Caravello et al.	324/430
5,710,503	A	1/1998	Sideris et al.	320/6
5,717,336	A	2/1998	Basell et al.	324/430
5,717,937	A	2/1998	Fritz	395/750.01
5,747,909	A	5/1998	Syverson et al.	310/156
5,757,192	A	5/1998	McShane et al.	324/427
5,760,587	A	6/1998	Harvey	324/434
5,773,978	A	6/1998	Becker	324/430
5,789,899	A	8/1998	van Phuoc et al.	320/30
5,793,359	A	8/1998	Ushikubo	345/169
5,808,469	A	9/1998	Kopera	324/43.4
5,821,756	A	10/1998	McShane et al.	324/430
5,825,174	A	10/1998	Parker	324/106
5,831,435	A	11/1998	Troy	324/426
5,862,515	A	1/1999	Kobayashi et al.	702/63

5,872,443	A	2/1999	Williamson	320/21
5,895,440	A	4/1999	Proctor et al.	702/63
5,914,605	A	6/1999	Bertness	324/430
5,929,609	A	7/1999	Joy et al.	322/25
5,939,855	A	8/1999	Proctor et al.	320/104
5,939,861	A	8/1999	Joko et al.	320/122
5,945,829	A	8/1999	Bertness	324/430
5,969,625	A	10/1999	Russo	340/636
6,002,238	A	12/1999	Champlin	320/134
6,008,652	A	12/1999	Theofanopoulos et al.	324/434
6,009,369	A	12/1999	Boisvert et al.	701/99
6,031,354	A	2/2000	Wiley et al.	320/116
6,037,751	A	3/2000	Klang	320/160
6,037,777	A	3/2000	Champlin	324/430
6,051,976	A	4/2000	Bertness	324/426
6,072,299	A	6/2000	Kurie et al.	320/112
6,072,300	A	6/2000	Tsuji	320/116
6,081,098	A	6/2000	Bertness et al.	320/134
6,091,245	A	7/2000	Bertness	324/426
6,094,033	A	7/2000	Ding et al.	320/132
6,104,167	A	8/2000	Bertness et al.	320/132
6,114,834	A	9/2000	Parise	320/109
6,137,269	A	10/2000	Champlin	320/150
6,150,793	A	11/2000	Lesesky et al.	320/104
6,163,156	A	12/2000	Bertness	324/426
6,172,483	B1	1/2001	Champlin	320/134
6,172,505	B1	1/2001	Bertness	324/430

FOREIGN PATENT DOCUMENTS

EP	0 772 056	A1	5/1997
FR	2 749 397		12/1997
GB	2 088 159	A	6/1982
JP	59-17892		1/1984
JP	59-17893		1/1984
JP	59-17894		1/1984
JP	59017894		1/1984
JP	59215674		12/1984
JP	60225078		11/1985
JP	62-180284		8/1987
JP	63027776		2/1988
JP	03274479		12/1991
JP	03282276		12/1991
JP	4-8636		1/1992
JP	04131779		5/1992
JP	04372536		12/1992
JP	5216550		8/1993
JP	7-128414		5/1995
WO	WO 93/22666		11/1993
WO	WO 98/58270		12/1998

OTHER PUBLICATIONS

"A Look at the Impedance of a Cell", by S. Debardelaben, *IEEE,* 1988, pp. 394–397.

"The Impedance of Electrical Storage Cells", by N.A. Hampson et al., *Journal of Applied Electrochemistry,* 1980, pp. 3–11.

"A Package for Impedance/Admittance Data Analysis", by B. Boukamp, *Solid State Ionics,* 1986, pp. 136–140.

"Precision of Impedance Spectroscopy Estimates of Bulk, Reaction Rate, and Diffusion Parameters", by J. Macdonald et al., *J. Electroanal, Chem.,* 1991, pp. 1–11.

Internal Resistance: Harbinger of Capacity Loss in Starved Electrolyte Sealed Lead Acid Batteries, , pp. by Vaccaro, F.J. et al., *AT& T Bell Laboratories,* 1987 IEEE, Ch. 2477 128, 131.

IEEE Recommended Practice for Maintenance, Testings, and Replacement of Large Lead Storage Batteries for Generating Stations and Substations, *The Institute of Electrical and Electronics Engineers, Inc., ANSI/IEEE Std.* 450–1987, Mar. 9, 1987, pp. 7–15.

"Field and Laboratory Studies to Assess the State of Health of Valve–Regulated Lead Acid Batteries: Part 1 Conductance/Capacity Correlation Studies", by D. Feder et al., *IEEE,* Aug. 1992, pp. 218–233.

"JIS Japanese Industrial Standard–Lead Acid Batteries for Automobiles", *Japanese Standards Association UDC,* 621.355.2:629.113.006, Nov. 1995.

"Performance of Dry Cells", by C. Hambuechen, Preprint of *Am. Electrochem. Soc.,* Apr. 18–20, 1912, paper No. 19, pp. 1–5.

"A Bridge for Measuring Storage Battery Resistance", by E. Willihncanz, *The Electrochemical Society,* preprint 79–20, Apr. 1941, pp. 253–258.

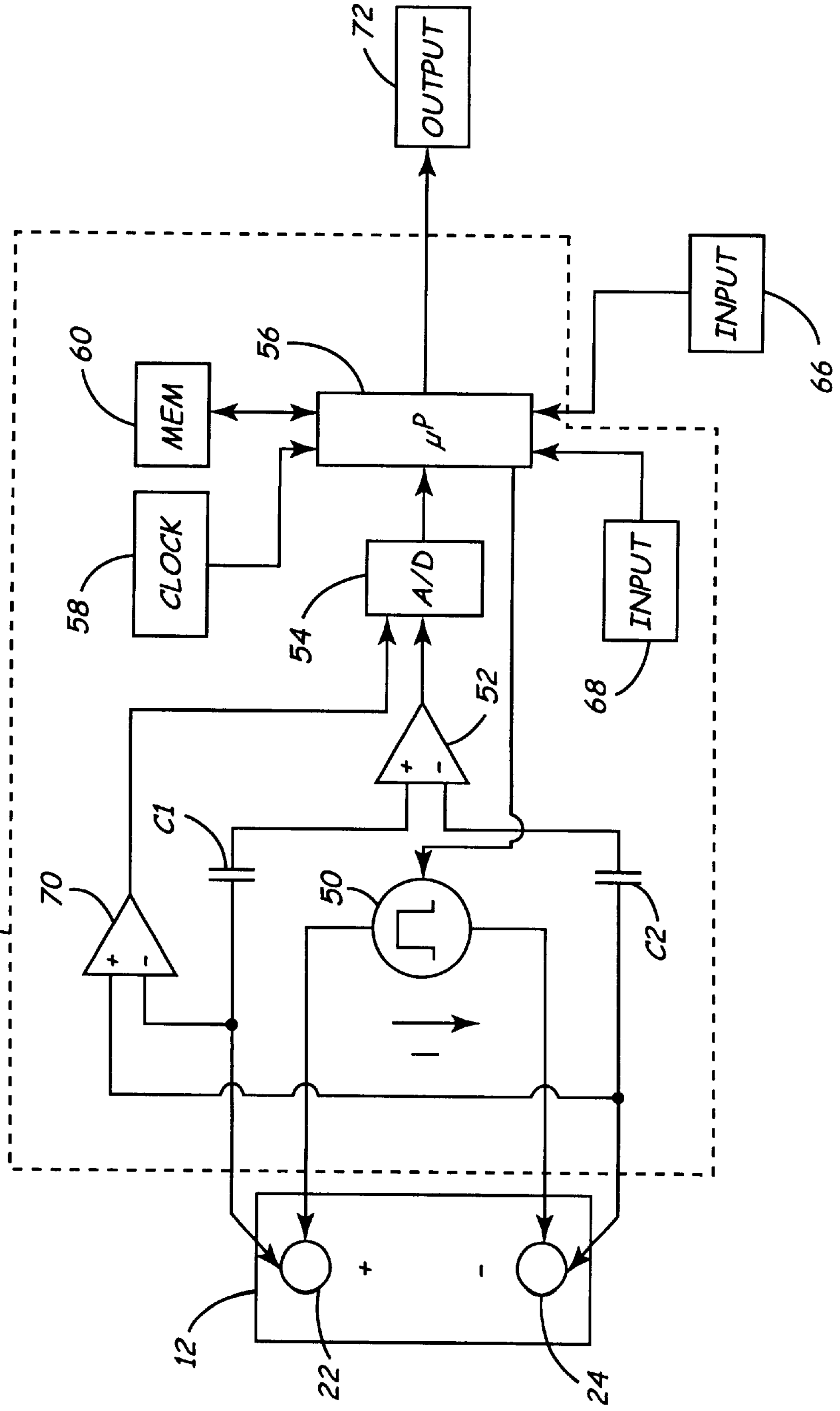

72
OUTPUT
16
60
MEM
56
μP
INPUT
66
58
CLOCK
54
A/D
INPUT
68
52
+
-
70
+
-
C1
50
C2
I
12
+
-
22
24

FIG. 1

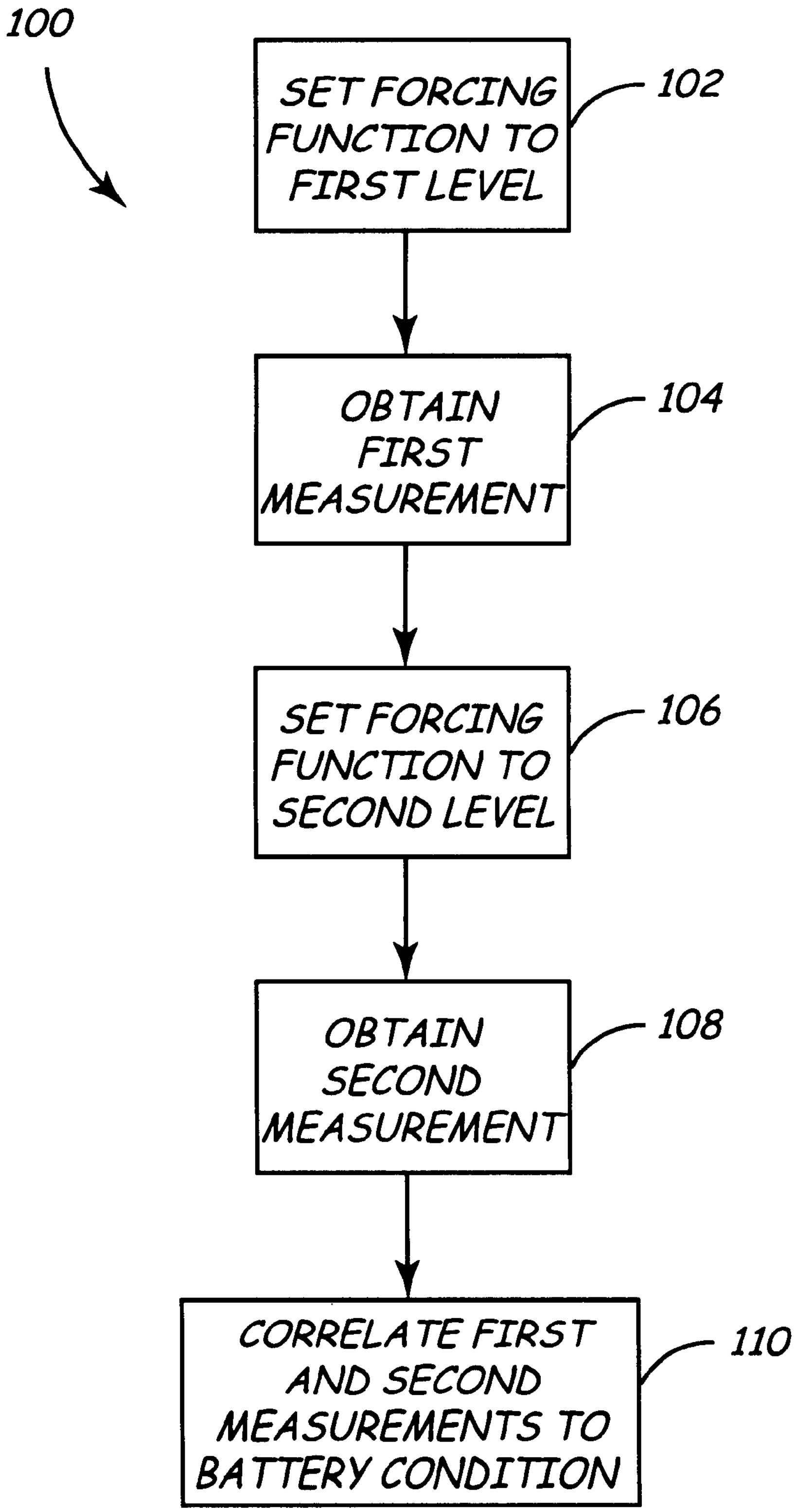
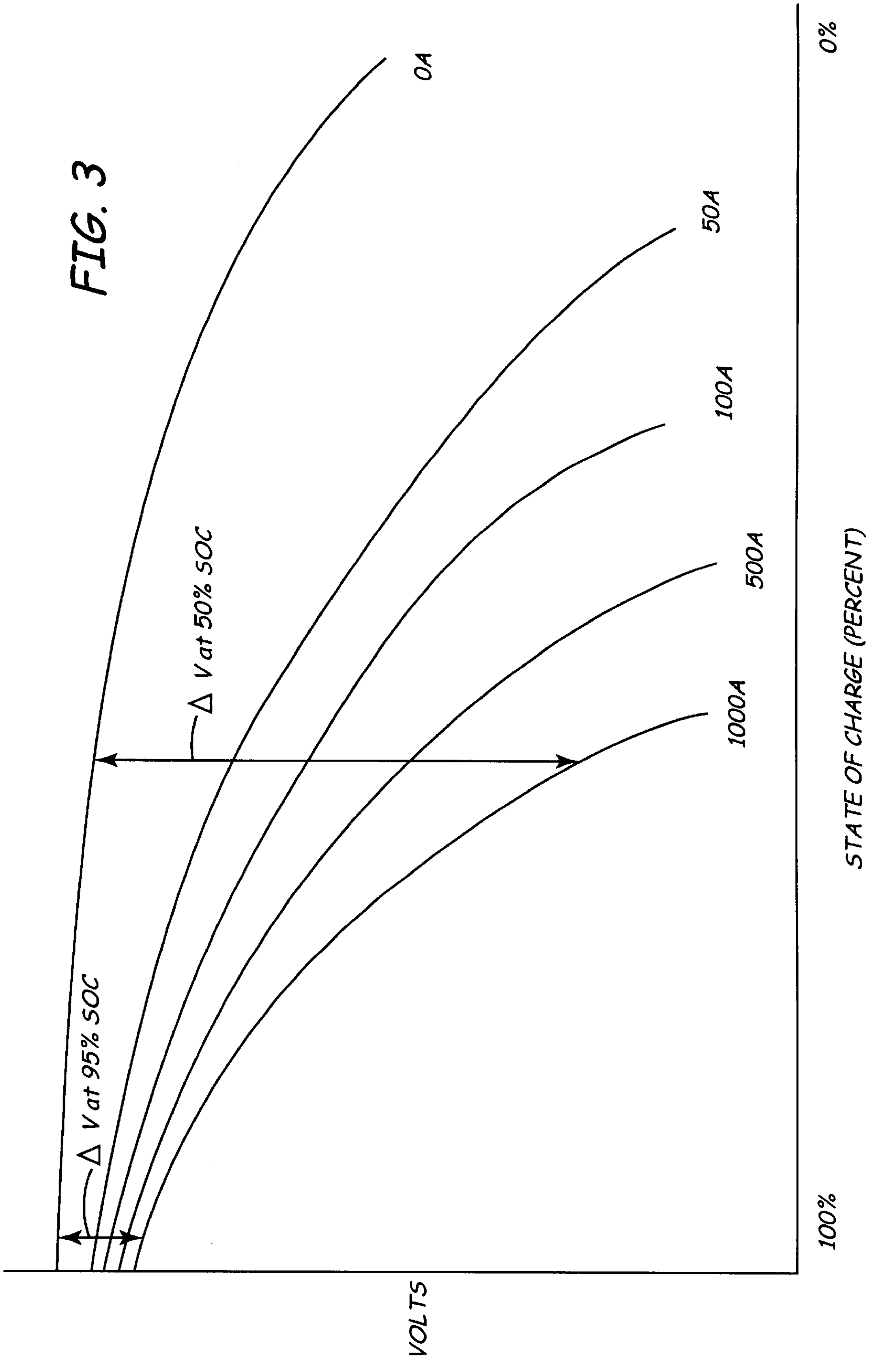

100
SET FORCING FUNCTION TO FIRST LEVEL
102
OBTAIN FIRST MEASUREMENT
104
SET FORCING FUNCTION TO SECOND LEVEL
106
OBTAIN SECOND MEASUREMENT
108
CORRELATE FIRST AND SECOND MEASUREMENTS TO BATTERY CONDITION
110

FIG. 2

FIG. 3


0A
50A
100A
500A
1000A
Δ V at 50% SOC
Δ V at 95% SOC
VOLTS
STATE OF CHARGE (PERCENT)
100%
0%

ELECTRONIC BATTERY TESTER

The present invention claims priority to Provisional Application Ser. No. 60/132,045, filed Apr. 30, 1999, and entitled ELECTRONIC BATTERY TESTER.

BACKGROUND OF THE INVENTION

The present invention relates to testing of storage batteries. More specifically, the present invention relates to testing storage batteries using conductance, impedance, resistance, admittance or their combination.

Storage batteries, such as lead acid storage batteries of the type used in the automotive industry, have existed for many years. However, understanding the nature of such storage batteries, how such storage batteries operate and how to accurately test such batteries has been an ongoing endeavor and has proved quite difficult. Storage batteries consist of a plurality of individual storage cells electrically connected in series. Typically each cell has a voltage potential of about 2.1 volts. By connecting the cells in series, the voltages of the individual cells are added in a cumulative manner. For example, in a typical automotive storage battery, six storage cells are used to provide a total voltage when the battery is fully charged of 12.6 volts.

There has been a long history of attempts to accurately test the condition of storage batteries. A simple test is to measure the voltage of the battery. If the voltage is below a certain threshold, the battery is determined to be bad. However, this test is inconvenient because it requires the battery to be charged prior to performing the test. If the battery is discharged, the voltage will be low and a good battery may be incorrectly tested as bad. Furthermore, such a test does not give any indication of how much energy is stored in the battery. Another technique for testing a battery is referred as a load test. In a load test, the battery is discharged using a known load. As the battery is discharged, the voltage across the battery is monitored and used to determine the condition of the battery. This technique requires that the battery be sufficiently charged in order that it can supply current to the load.

More recently, a technique has been pioneered by Dr. Keith S. Champlin and Midtronics, Inc. for testing storage batteries by measuring the conductance of the batteries. This technique is described in a number of United States patents, for example, U.S. Pat. No. 3,873,911, issued Mar. 25, 1975, to Champlin, entitled ELECTRONIC BATTERY TESTING DEVICE; U.S. Pat. No. 3,909,708, issued Sep. 30, 1975, to Champlin, entitled ELECTRONIC BATTERY TESTING DEVICE; U.S. Pat. No. 4,816,768, issued Mar. 28, 1989, to Champlin, entitled ELECTRONIC BATTERY TESTING DEVICE; U.S. Pat. No. 4,825,170, issued Apr. 25, 1989, to Champlin, entitled ELECTRONIC BATTERY TESTING DEVICE WITH AUTOMATIC VOLTAGE SCALING; U.S. Pat. No. 4,881,038, issued Nov. 14, 1989, to Champlin, entitled ELECTRONIC BATTERY TESTING DEVICE WITH AUTOMATIC VOLTAGE SCALING TO DETERMINE DYNAMIC CONDUCTANCE; U.S. Pat. No. 4,912,416, issued Mar. 27, 1990, to Champlin, entitled ELECTRONIC BATTERY TESTING DEVICE WITH STATE-OF-CHARGE COMPENSATION; U.S. Pat. No. 5,140,269, issued Aug. 18, 1992, to Champlin, entitled ELECTRONIC TESTER FOR ASSESSING BATTERY/CELL CAPACITY; U.S. Pat. No. 5,343,380, issued Aug. 30, 1994, entitled METHOD AND APPARATUS FOR SUPPRESSING TIME VARYING SIGNALS IN BATTERIES UNDERGOING CHARGING OR DISCHARGING; U.S. Pat. No. 5,572,136, issued Nov. 5, 1996, entitled ELECTRONIC BATTERY TESTER WITH AUTOMATIC COMPENSATION FOR LOW STATE-OF-CHARGE; U.S. Pat. No. 5,574,355, issued Nov. 12, 1996, entitled METHOD AND APPARATUS FOR DETECTION AND CONTROL OF THERMAL RUNAWAY IN A BATTERY UNDER CHARGE; U.S. Pat. No. 5,585,728, issued Dec. 17, 1996, entitled ELECTRONIC BATTERY TESTER WITH AUTOMATIC COMPENSATION FOR LOW STATE-OF-CHARGE; U.S. Pat. No. 5,592,093, issued Jan. 7, 1997, entitled ELECTRONIC BATTERY TESTING DEVICE LOOSE TERMINAL CONNECTION DETECTION VIA A COMPARISON CIRCUIT; U.S. Pat. No. 5,598,098, issued Jan. 28, 1997, entitled ELECTRONIC BATTERY TESTER WITH VERY HIGH NOISE IMMUNITY; U.S. Pat. No. 5,757,192, issued May 26, 1998, entitled METHOD AND APPARATUS FOR DETECTING A BAD CELL IN A STORAGE BATTERY; U.S. Pat. No. 5,821,756, issued Oct. 13, 1998, entitled ELECTRONIC BATTERY TESTER WITH TAILORED COMPENSATION FOR LOW STATE-OF-CHARGE; and U.S. Pat. No. 5,831,435, issued Nov. 3, 1998, entitled BATTERY TESTER FOR JIS STANDARD.

However, there is an ongoing need to improve battery testing techniques and derive additional information about the battery using non-invasive electrical means.

SUMMARY OF THE INVENTION

An electronic battery tester for determining a condition of a storage battery includes a forcing function adapted to couple to the battery. Circuitry coupled to the forcing function is adapted to obtain measurements from the battery at multiple levels of the forcing function. In the method according to the present invention, a forcing function is applied to the battery at a first level and a first measurement is obtained. The forcing function is applied at a second level and a second measurement is obtained. The first and second measurements are correlated to condition of the battery.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a simplified block diagram of a battery tester in accordance with the present invention.

FIG. **2** is a simplified flow chart showing steps in accordance with one embodiment of the present invention.

FIG. **3** is a graph of change in voltage versus state of charge (percent) for various values of differential current.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1** is a simplified block diagram of battery monitoring circuitry **16** in accordance with the present invention. Apparatus **16** is shown coupled to battery **12** which includes a positive battery terminal **22** and a negative battery terminal **24**.

In a preferred embodiment, circuitry **16** operates, with the exceptions and additions as discussed below, in accordance with battery testing methods described in one or more of the United States patents obtained by Dr. Champlin and Midtronics, Inc. and listed above. Circuitry **16** operates in accordance with one embodiment of the present invention and determines the conductance (G_{BAT}) of battery **12** and the voltage potential (V_{BAT}) between terminals **22** and **24** of battery **12**. Circuitry **16** includes current source **50**, differential amplifier **52**, analog-to-digital converter **54** and microprocessor **56**. Current source **50** provides one example of an adjustable forcing function for use with the invention.

Amplifier **52** is capacitively coupled to battery **12** through capacitors C_1, and C_2. Amplifier **52** has an output connected to an input of analog-to-digital converter **54**. Microprocessor **56** is connected to system clock **58**, memory **60**, and analog-to-digital converter **54**. Microprocessor **56** is also capable of receiving an input from input devices **66** and **68**. Microprocessor **56** also connects to output device **72**.

In operation, current source **50** is controlled by microprocessor **56** and provides a current I in the direction shown by the arrow in FIG. **1**. Microprocessor **56** also controls the level (i.e., peak to peak, RMS, etc.) of the time varying component of the forcing function. In one embodiment, this is a sine wave, square wave or a pulse. Differential amplifier **52** is connected to terminals **22** and **24** of battery **12** through capacitors C_1 and C_2, respectively, and provides an output related to the voltage potential difference between terminals **22** and **24**. In a preferred embodiment, amplifier **52** has a high input impedance. Circuitry **16** includes differential amplifier **70** having inverting and noninverting inputs connected to terminals **24** and **22**, respectively. Amplifier **70** is connected to measure the open circuit potential voltage (V_{BAT}) of battery **12** between terminals **22** and **24** and is one example of a dynamic response sensor used to sense the time varying response of the battery **18** to the applied time varying forcing function. The output of amplifier **70** is provided to analog-to-digital converter **54** such that the voltage across terminals **22** and **24** can be measured by microprocessor **56**.

Circuitry **16** is connected to battery **12** through a four-point connection technique known as a Kelvin connection. This Kelvin connection allows current I to be injected into battery **12** through a first pair of terminals while the voltage V across the terminals **22** and **24** is measured by a second pair of connections. Because very little current flows through amplifier **52**, the voltage drop across the inputs to amplifier **52** is substantially identical to the voltage drop across terminals **22** and **24** of battery **12**. The output of differential amplifier **52** is converted to a digital format and is provided to microprocessor **56**. Microprocessor **56** operates at a frequency determined by system clock **58** and in accordance with programming instructions stored in memory **60**.

Microprocessor **56** determines the conductance of battery **12** by applying a current pulse I using current source **50**. This measurement provides a dynamic parameter related to the battery. Of course, any such dynamic parameter can be measured including resistance, admittance, impedance or their combination along with conductance. Further, any type of time varying signal can be used to obtain the dynamic parameter. The signal can be generated using an active forcing function or using a forcing function which provides a switchable load, for example, coupled to the battery **12**. The microprocessor determines the change in battery voltage due to the current pulse I using amplifier **52** and analog-to-digital converter **54**. The value of current I generated by current source **50** is known and is stored in memory **60**. In one embodiment, current I is obtained by applying a load to battery **12**. Microprocessor **56** calculates the conductance of battery **12** using the following equation:

$$Conductance = G_{BAT} = \frac{\Delta I}{\Delta V} \qquad \text{Equation 1}$$

where ΔI is the change in current flowing through battery **12** due to current source **50** and ΔV is the change in battery voltage due to applied current ΔI. Based upon the battery conductance G_{BAT} and the battery voltage, the battery tester **16** determines the condition of battery **12**. Battery tester **16** is programmed with information which can be used with the determined battery conductance and voltage as taught in the above listed patents to Dr. Champlin and Midtronics, Inc.

The tester can compare the measured CCA (Cold Cranking Amp) with the rated CCA for that particular battery. Microprocessor **56** can also use information input from input device **66** provided by, for example, an operator. This information may consist of the particular type of battery, location, time, the name of the operator. Additional information relating to the conditions of the battery test can be received by microprocessor **56** from input device **68**. Input device **68** may comprise one or more sensors, for example, or other elements which provide information such as ambient or battery temperature, time, date, humidity, barometric pressure, noise amplitude or characteristics of noise in the battery or in the test result, or any other information or data which may be sensed or otherwise recovered which relates to the conditions of the test how the battery test was performed, or intermediate results obtained in conducting the test. Additional test condition information is provided by microprocessor **56**. Such additional test condition information may include the values of G_{BAT} and battery voltage, the various inputs provided to battery tester **16** by the operator which may include, for example, type of battery, estimated ambient or battery temperature, type of vehicle (i.e., such as provided through the Vehicle Identification Number (VIN) code for the vehicle) or the particular sequence of steps taken by the operator in conducting the test.

Typically, in prior art battery testers, current source **50** applied a fixed current through application of a small fixed load. However, one aspect of the present invention includes the recognition that the conductance, impedance, resistance or admittance measurements obtained using the aforementioned techniques can, in some instances, change depending upon the size of current I used in obtaining the measurement. This change can be correlated, either experimentally or through modeling techniques, to characteristics related to the condition of battery **12**. Thus, microprocessor **56** obtains a number of data points and uses those data points to determine condition information of battery **12**.

Although the embodiment illustrated in FIG. **1** shows a current source **50**, element number **50** can be viewed as a forcing function and can be either an applied current, an applied load or an implied voltage. Typically, in prior art (non-load testers) the current I has been about 0.25 amp or the applied resistance has been about 50 ohms.

In accordance with the present invention, a first forcing function is applied and the resulting change in current or voltage from battery **12** is measured by microprocessor **56** to determine a first data point (conductance, impedance, resistance, admittance, or their combination). Additional data points are then obtained, for example, by varying the forcing function a small amount, such as less than 10%. Other data points can be obtained by varying the forcing function from between about 10% to about 50%. Yet further information can be obtained by changing the forcing function by between 50% to about 100%, or greater than 100% such as orders of magnitude greater than the original forcing function. Note that these ranges are simply examples and other ranges can be used in accordance with the present invention. Further, any number of data points can be collected within a particular range, or spanning different ranges if desired and as determined based upon experimentation. The particular percentages chosen are simply examples and the invention is not limited to these values. In the broad sense, this aspect of the invention relates to comparing data measurements obtained at different forcing function levels and the particular forcing function levels and their relationship to each other is not significant. However, in a more narrow aspect of the invention, the particular relationship between the various forcing functions is significant and can be used in determining the condition of the battery.

In another aspect of the present invention, the forcing function is not varied, instead, a relatively high current level of between about 1 amp and about 100 amps is applied using a resistance of between 10 ohms and about 0.1 ohms. Similarly, a relatively low current level between about 0.1 amps and about 1 amp is applied using a resistance of between 100 ohms and about 10 ohms. (Note that typical prior art load testers draw a fixed current of about 100 to 200 amps using a fixed resistance of about 0.12 ohms and 0.06 ohms).

The microprocessor uses the collected data to determine the condition of the battery. This information is correlated to various physical attributes of the battery which can be determined experimentally. For example, the data can correlate to temperature, state of charge, grid corrosion, loss of active material, sulfation, specific gravity, metallic degradation, polarization or stratification of battery **12**. These or other determinations can be made based upon the measurements made at the different forcing function levels or through the use of a single measurement obtained at a high or low forcing function level.

In yet another aspect of the present invention, measurement information using one measurement technique (conductance, impedance, resistance, admittance, or their combination) is used and correlated with measurement information obtained using a second measurement technique (conductance, impedance, resistance, admittance or their combination). This can be done at a single forcing function level or using the above described multiple level technique. The data from the different techniques can correlate to the condition of the battery. Further, more than two techniques can be used in such a task.

FIG. **2** is a simplified flow chart **100** showing steps in accordance with one aspect of the present invention. At **102**, the forcing function is set to a first level. At **104**, a first measurement is obtained. At **106**, the forcing function is set to a second level and a second measurement is obtained at **108**. At **110**, microprocessor **56** correlates the first and second measurements to a condition of the battery and, for example, provides an output on output **72** to an operator. As described above, more than two different forcing function levels can be used in the present invention.

FIG. **3** is an example of a graph of differential voltage versus state of charge for various differential currents applied to battery **12**, where the differential current levels have values of 0 Amps, 50 Amps, 100 Amps, 500 Amps and 1000 Amps. As illustrated in FIG. **3**, the resultant differential voltage ΔV is different for differing states of charge. FIG. **3** also illustrates that the ratio of $\Delta I/\Delta V$ changes as a function of ΔI. This change in $\Delta I/\Delta V$, for various values of ΔI, can be correlated to other parameters which relate to battery **12**.

The terms "inject" or "apply" is used herein to describe the supply of voltage or current either with active circuitry or by applying load to the battery. Further, the applied signals can be time varying signals such as step functions, pulse signals, periodic signals, etc.

The present invention may be implemented using any appropriate technique. For simplicity, a single technique has been illustrate herein. However, other techniques may be used including implementation in all analog circuitry.

Additionally, by using appropriate techniques, the battery resistance and a reference resistance (the reciprocal of conductance) may be employed in the invention.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention. The present invention can be used with conductance, resistance, impedance, admittance or their combination in performing the battery test.

What is claimed is:

1. An electronic battery tester for determining condition of the storage battery, comprising:

a four point Kelvin connection adapted to electrically couple to the terminals of the battery;

an adjustable forcing function having a forcing function output with a time varying component having an adjustable level in response to an adjustment input, the forcing function output coupled to a first pair of connections of the Kelvin connection;

a dynamic response sensor coupled to a second pair of connections of the Kelvin connection configured to provide a sensed output related to a time varying response of the battery to the forcing function;

digital circuitry coupled to the forcing function and the dynamic response sensor configured to provide the adjustment input to the forcing function whereby the forcing function output level is changed between a plurality of different levels, the digital circuitry configured to measure a dynamic parameter of the battery as a function of the sensed output at a plurality of different forcing function levels.

2. The apparatus of claim **1** wherein the digital circuitry is configured to correlate the dynamic parameters to a condition of the battery.

3. The apparatus of claim **2** wherein the condition comprises state of charge of the battery.

4. The apparatus of claim **1** wherein the adjustable forcing function comprises a load.

5. The apparatus of claim **1** wherein the adjustable forcing function comprises a current sink.

6. The apparatus of claim **1** wherein the dynamic response sensor is configured to sense a voltage having a time varying component.

7. The apparatus of claim **6** wherein the dynamic response sensor includes a differential amplifier.

8. The apparatus of claim **1** including an analog to digital converter configured to provide a digital representation of the sensed output to the digital circuitry.

9. The apparatus of claim **1** wherein the digital circuitry comprises a microprocessor.

10. The apparatus of claim **1** wherein the forcing function output comprises a square wave.

11. The apparatus of claim **1** wherein the dynamic parameter of the battery comprises conductance.

12. The apparatus of claim **1** wherein the dynamic parameter of the battery is selected from the group consisting of resistance, admittance and impedance.

13. A method of testing a battery, comprising:

applying a forcing function having a time varying component at a first level to the battery through a first pair of connections of a Kelvin connection;

obtaining a first dynamic response measurement through a second pair of connections of the Kelvin connection related to a response of the battery to the applied forcing function;

applying the forcing function having a time varying component at a second level to the battery through the first pair of connections of a Kelvin connection;

obtaining a second dynamic response measurement through the second pair of connections of the Kelvin connection related to a response of the battery to the applied forcing function; and

correlating the first and second dynamic response measurements to a condition of the battery.

14. The method of claim **13** wherein applying the forcing function comprises applying a load to the battery.

15. The method of claim **13** wherein obtaining the first and second dynamic response measurements comprises measuring dynamic voltages of the battery.

16. The method of claim **13** wherein correlating the first and second dynamic response measurements include determining a dynamic parameter of the battery as a function of the applied forcing functions and dynamic response measurements.

17. The method of claim **16** wherein the dynamic parameter comprises conductance.

18. The method of claim **16** wherein the dynamic parameter is selected from the group consisting of resistance, impedance and admittance.

19. The method of claim **13** wherein the condition of the battery comprises state of charge of the battery.

20. The method of claim **13** wherein the forcing function comprises a square wave.

21. The apparatus of claim **1** wherein the adjustable level comprises at least two current levels.

22. The method of claim **13** wherein the first and second levels of the forcing function comprise first and second current levels.

* * * * *