DESIGN AND CONSTRUCTION OF A RESISTIVITY METER FOR SHALLOW INVESTIGATION

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Abstract

The cost of brand new resistivity meters (Scintrex, Bison, ABEM) has gone up astronomically. Consequently many institutions that need this equipment for teaching and research purposes cannot afford the price. This predicament compelled the authors to look for electronic components that are available in local markets and shops to fabricate this meter. This simple resistivity meter was then designed and constructed using components purchased locally. It measures current and voltage separately. The resistance is then computed from these readings. A comparison test was conducted with this meter using the ABEM Terrameter SAS 300 as the standard meter. The field testing exercise was conducted on an open field with a flat terrain. The results / data from the two instruments are very comparable; almost the same for a spread of $^{AB}/_{2}$ = 100m. Beyond this spread, the difference in readings is much. Hence, the use of this system is limited to shallow investigations where the target depth is not more than fifty metres (50m). Efforts are being made to improve on its performance.

Keywords: *Design and construction, resistivity meter and field testing.*

Introduction

Most of the popular resistivity meters in the (Scintrex, Bison, Syscal R, ABEM etc) are so expensive that many universities (in Nigeria) and research centers cannot afford the cost because of lack of funds. Students and researchers usually hire from private companies or some international agencies like UNICEF, Coal Corporation, Mining Corporation, etc. Getting this instrument on hire could be frustrating because of protocol. Therefore these authors considered this issue as a challenge and decided to attempt using electronic materials found in local shops and markets to construct a resistivity. The objectives are;

i. to produce a resistivity meter using local materials;
ii. the cost of the metre should be within the reach of academic institutions and other agencies;
iii. invariably the repairs/maintenance should be done locally instead of the usual practice of sending the equipment abroad (US, Europe, etc).

The authors then carried out a market survey. Based on the electric components available, this design was made and the meter was constructed, Fig. 1.

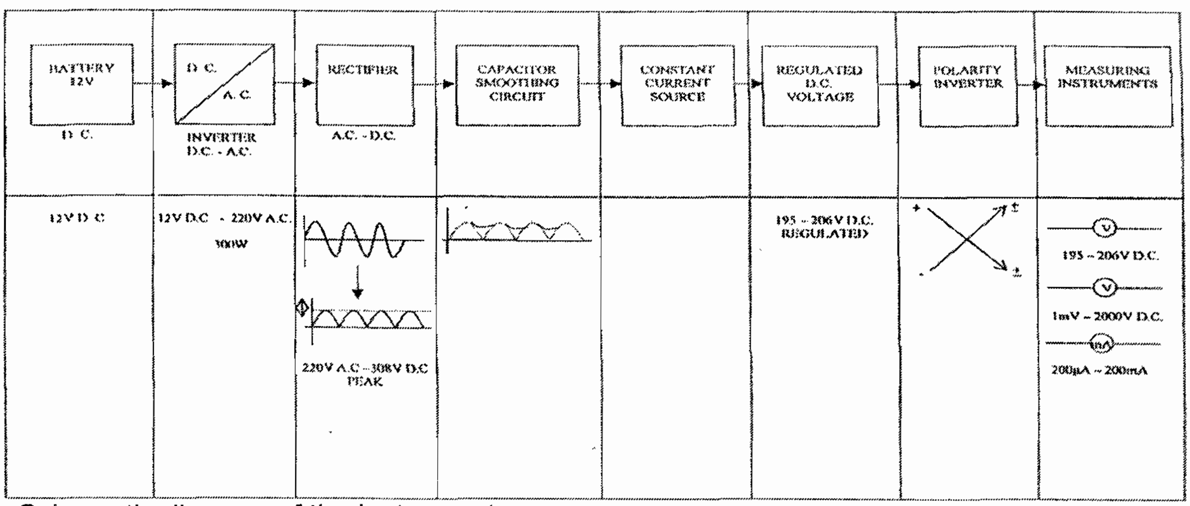

Fig.1: Schematic diagram of the instrument

Components of the Instrument;

Some of the components used in the construction of this instrument are briefly described below;

Power Source: A 12V motor car battery is used for this design. It could be kept in a car with the engine running in order to keep it charged throughout the field exercise.

Inverter: This device converts direct voltage to alternating voltage and at the same time stepping it up (Bedford and Hoft, 1964). The inversion process can be achieved with the help of transistors, SCRs and tunnel diodes, etc. For low and medium outputs, transistorized inverters are suitable but for high power outputs, SCR inverters are essentials (Theraja, 2002). The inverter used for this instrument is a 300W inverter. It is commercial inverter purchased from the market. It converts the 12V direct current of the battery to alternating current and steps it up to about 220V.

Rectification: The output of the inverter which is 220V A.C. is converted to D.C. using a full wave bridge rectification as described by Schuler, 1979.

Capacitor - Smoothing of the direct current: To smoothen the output of the direct current, capacitors having large capacitances were used. The filter circuit depends (for its operation) on the property of a capacitor to charge up (i.e store energy) during conducting half cycle and to discharge (i.e deliver energy) during the non-conducting half-cycle (Theraja, 2002). In simple words, a capacitor opposes any change in voltage. When connected across a pulsating voltage, it tends to smoothen out or filter out the voltage pulsations (or ripples).

Transistors and Resistors: There are two general types of transistors used in computer circuit: Bipolar and Field-effect transistors (F.E.Ts). Other details about transistors and resistors have been discussed by Bartgee, 1986 and A de Sa, 1990. In this design, transistors and resistors are used for regulation of voltage and current. Figure 3 shows the circuit diagram for the voltage regulation. The emitter voltage of transistor T_3, $V_{E(T3)}$ is the final regulated output voltage. For the purpose of this design, $V_{C(T1)}$ was chosen to be between 195 and 206 volts with a variable resistor R_2.

Design Calculation

Transistor T_3

The transistor T_3 is an NPN power transistor

T_C = 300A (Design Value

Direct Current gain (β) = 8

In choosing a transistor, the transistor voltage should be much greater than the highest envisaged in the design.

Therefore for the power transistor:

V_{CE} = 1500V where V_{CE} is the collector emitter voltage (V_{CE} >> 306.6)

V_{CB} = 1500V where V_{CB} is the collector Base voltage (V_{CB} >> 306.6).

Maximum expected base current for transistor T_3 was calculated to be about 37.5mA

Transitor T_2

Likewise for Transistor T_2, the maximum expected base current was calculated to be 0.625mA

Transistor T_1

This is a PNP transistor with a current gain (β) of 86. The maximum base current of this transistor was calculated to be 0.22mA

Metters

Sensitive digital commercial meters were used to measure the output of both current and voltage. Their ranges are from 3000mV to 1000V for voltage and 200μA to 10A for current. Other specifications of these meters are stated below:

DC Voltage

Range	Resolution	Accuracy
200mV	100μV	±0.25%
2000m	1mV	±0.5%
20V	10mV	±0.5%
200V	100mV	±0.5%
1000V	1V	±0.5%

Overload protection: 220Vrms AC for 200mV range and 1000V DC or 750Vrms AC for other ranges.

Range	Resolution	Accuracy
200V	100mV	±1.2%
750V	1V	±1.2%

Overload protection: 1000V DC or 750 Vrms for all ranges.

Response: Average response calibrated in rms of sine wave.

Frequency Range: 45Hz - 450Hz

DC Current

Range	Resolution	Accuracy
200μA	100μV	± 1%
2000μA	1μA	± 1%
20mA	10μA	± 1%
200mA	100μA	± 2%
10A	10mA	± 2%

Overload Protection: 200mA 250V fuse (10A range unfused)

Instrument Operation

The field connection is the same like any other resistivity meter. Two current electrodes are used to inject current into the ground thus creating an electric field while another two potential electrodes measure the potential difference. These electrodes are connected first before energizing the system. The colour coding indicated on the panel is C_1 red and C_2 black for current electrodes while P_1 red and P_2 black are for potential electrodes.

Immediately a 12volt car battery is connected, the meters are switched on. The input voltage meter should be in the 1000V range while the meter for measuring potential difference should be put on the 20V range. The current meter should be put on the 200mA range. To start taking field readings, the measurement button is pressed and held down for about two seconds. Then the readings on the meters (current, I and voltage V) are recorded as shown on Table 1b.

In order to eliminate the effect of polarization, the instrument is fitted with a relay system and a reversing key, which reverses the polarity of the input current. For every measurement, two readings are recorded; one reading at each polarity. The average of the two readings is then calculated as shown on Table 1B.

Finally, the resistance R is calculated using ohm's law (V = IR)

$$R = \frac{\text{Voltmeter Reading}}{\text{Ammeter Reading}}$$

Table 1(a):
FIELD DATA FOR ABEM TERRAMETER -SITE 1
(Schlumberger VES data sheet)

)CATION: Works Layout, Owerri STATE: Imo
:S NO.: 1 DATE: 8 - 10 - 2002
R: N - S INSTRUMENT: ABEM

S/N	AB(m)/2	MN(m)/2	R(Ω)	ρₐ(Ωm)
1	1	0.25	178.10	1050.79
2	2		30.50	754.67
3	2	0.5	71.30	875.35
4	4		31.30	1549.40
5	6		18.37	2057.40
6	6	1.0	20.80	1144.00
7	8		17.96	1778.00
8	10		13.22	2062.30
9	10	2.0	18.36	1367.80
10	15		8.80	1531.20
11	20		5.76	1791.40
12	20	4.0	11.56	1743.20
13	30		6.22	2159.00
14	40		3.80	2363.60
15	40	8.0	7.21	2174.54
16	50		4.87	2329.30
17	60		3.33	2312.00
18	60	120	5.45	2465.60
19	80		3.23	2645.00
20	100		2.12	2735.06

Table 1(b):
FIELD DATA FOR THE NEW METER -SITE 1
(Schlumberger VES data sheet)

LOCATION: Works Layout, Owerri STATE: Imo
VES NO.: 1 DATE: 8 - 10 - 2002
DIR: - N - S INSTRUMENT: New Meter

S/N	AB(m)/2	MN(m)/2	V_1(v)	I_1 (mA)	V_2(v)	I_2 (mA)	R_1(Ω)	R_2(Ω)	R_{AV} (Ω)	ρ(Ωm)
1	1	0.25	1.10	6.6	1.10	6.6	166.70	166.70	166.70	983.53
2	2		0.20	10.2	0.33	10.2	19.60	32.30	25.95	642.00
3	2	0.5	0.70	10.2	0.72	10.1	68.63	71.29	69.96	824.13
4	4		0.25	8.6	0.24	8.1	29.10	29.60	29.35	1452.83
5	6		0.14	8.3	0.12	8.3	16.87	14.46	15.68	1756.16
6	6	1.0	0.18	8.5	0.17	8.3	21.18	20.48	20.83	1145.65
7	8		0.10	6.5	0.11	6.6	15.38	16.67	16.03	1586.97
8	10		0.14	10.9	0.12	11.1	12.84	10.81	11.83	1845.48
9	10	2.0	0.27	11.2	0.12	10.7	24.11	11.21	17.66	1315.67
10	15		0.21	19.4	0.11	18.7	10.82	5.88	8.35	1452.90
11	20		0.016	9.2	0.083	9.3	1.78	8.92	5.35	1663.85
12	20	4.0	0.098	9.3	0.117	9.2	10.54	12.72	11.63	1753.80
13	30		0.187	29.1	0.172	3.02	6.43	5.70	6.07	2106.90
14	40		0.046	15.4	0.066	14.9	2.99	4.43	3.71	2307.62
15	40	8.0	0.084	14.9	0.128	15.5	5.64	8.27	6.96	2099.14
16	50		0.111	19.6	0.057	16.2	5.66	3.52	4.59	2195.40
17	60		0.034	14.9	0.067	15.4	2.28	4.35	3.32	2305.08
18	60	12.0	0.073	14.6	0.089	15.0	5.00	5.93	5.47	2474.63
19	80		0.103	28.9	0.075	26.6	3.56	2.82	3.19	2612.29
20	100		0.052	29.7	0.090	35.6	1.75	2.53	2.14	2760.80

Table 2(a):
FIELD DATA FOR ABEM TERRAMETER -SITE 1
(Schlumberger VES data sheet)

LOCATION: Uratta - Owerri STATE: Imo
VES NO.: 2 DATE: 11 - 10 - 2002
DIR: NE - SW INSTRUMENT: ABEM

S/N	AB(m)/2	MN(m)/2	R (Ω)	ρₐ(Ωm)
1	1	0.25	482.00	2843.80
2	2		169.10	4183.53
3	2	0.5	308.00	3628.24
4	4		93.70	4638.15
5	6		51.50	5768.00
6	6	1.0	75.20	3987.50
7	8		42.20	4177.80
8	10		- 35.10	5475.60
9	10	2.0	37.00	2756.50
10	15		17.20	2992.80
11	20		11.32	3520.52
12	20	4.0	16.37	2468.60
13	30		9.61	3335.63
14	40		7.59	4726.98
15	40	8.0	11.66	3516.66
16	50		8.56	4094.25
17	60		5.97	4144.97
18	60	12.0	9.26	4189.22
19	80		6.99	5724.11
20	100		5.00	6450.50
21	100	20.0	8.34	6288.36
22	150		3.62	6285.23
23	200		2.01	6251.30
24	200	30.0	3.47	7103.78
25	250		2.00	6450.60
26	300		1.239	5780.06
27	300	40.0	1.709	5931.94
28	350		1.075	5103.03
29	400		0.682	4242.04
30	400	50.0	0.716	3542.77
31	500		0.338	2628.09

Table 2(b):
FIELD DATA FOR THE NEW METER -SITE 1
(Schlumberger VES data sheet)

LOCATION: Uratta – Owerri STATE: Imo
VES NO.: 2 DATE: 11 – 10 - 2002
DIR: NE - SW INSTRUMENT: New Meter

S/N	AB(m)/2	MN(m)/2	K	V_1(v)	I_1 (mA)	V_2(v)	I_2 (mA)	R_1 (Ω)	R_2 (Ω)	R_{AV} (Ω)	ρ(Ωm)
1	1	0.25	5.9	9.00	18.8	9.47	19.5	478.7	485.6	482.1	2844.4
2	2		34.74	3.08	18.8	3.12	17.7	163.8	176.3	170.0	4205.8
3	2	0.5	11.78	5.26	17.3	5.90	19.0	304.0	310.5	307.3	3620.0
4	4		49.50	1.70	17.5	1.57	17.5	97.1	89.7	93.4	4623.3
5	6		112.0	0.92	18.4	0.85	16.4	50.5	46.5	48.2	5398.4
6	6	1.0	55.0	1.31	18.2	1.44	18.9	72.0	76.2	74.1	4075.5
7	8		99.0	0.66	15.9	0.65	16.1	41.5	40.4	41.0	4059.0
8	10		156.0	0.36	11.0	0.39	11.1	32.7	35.1	33.9	5288.4
9	10	2.0	74.5	0.31	10.9	0.49	10.9	28.4	45.0	36.7	2734.2
10	15		174.0	0.29	12.1	0.11	12.2	24.0	9.0	16.5	2871.0
11	20		311.0	0.06	15.1	0.26	15.3	4.0	17.0	10.5	3265.5
12	20	4.0	150.8	0.24	15.1	0.25	15.3	15.9	16.4	16.1	2427.9
13	30		347.1	0.12	14.3	0.13	13.2	8.4	9.8	9.1	3158.6
14	40		622.0	0.09	10.9	0.07	10.7	8.3	6.5	7.4	4602.8
15	40	8.0	301.6	0.12	10.6	0.12	10.9	11.3	11.0	11.2	3378.0
16	50		478.3	0.09	10.7	0.09	10.6	8.4	8.5	8.5	4065.6
17	60		694.3	0.06	10.1	0.06	10.3	5.9	5.8	5.9	4096.4
18	60	12.0	452.4	0.05	10.4	0.14	10.4	4.8	13.5	9.1	4116.8
19	80		618.9	0.90	8.9	0.01	9.0	101.1	-0.1	50.6	41440.9
20	100		1290.1	0.0145	11.8	0.108	11.6	1.2	9.3	5.3	6837.5
21	100	20.0	754.0	0.031	11.6	0.111	12.0	26.7	9.3	18.0	13572.0
22	150		1735.7	0.017	10.9	0.0255	11.0	15.2	23.2	19.0	33310.0
23	200		3110.1	0.242	15.3	0.172	15.9	15.8	10.8	133.3	41364.3
24	200	30.0	2047.2	0.009	15.9	0.101	15.8	0.6	6.4	3.5	7163.9
25	250		3223.3	0.085	19.6	0.0075	20.2	4.3	0.4	2.3	7533.2
26	300		4665.1	0.0312	14.0	0.0648	14.0	2.2	4.6	3.4	15861.3
27	300	40.0	3471.0	0.0687	13.9	0.0246	14.0	4.9	1.8	3.3	11553.5
28	350		4747.0	0.322	17.5	0.0665	17.5	1.8	3.8	2.8	13291.6
29	400		6220.0	0.0659	16.8	0.0453	17.2	3.9	2.6	3.3	20320.0
30	400	50.0	4948.0	0.198	16.6	0.165	17.4	11.9	9.5	10.7	52900.0
31	500		7775.4	0.130	14.0	0.117	14.4	9.3	8.1	8.7	67656.0

Field Testing

This instrument was tested in the field with an ABEM SAS 300 terrameter as a standard meter. The first survey had a maximum spread of $^{AB}/_2$ = 100m. The readings were taken concurrently with the two instruments. The objectives of this first field exercise were:

i. to test the workability of the new system.

ii. to compare the reliability of its data with that of a standard equipment (the ABEM Terrameter).

The two sets of data are shown on Tables 2 and 3. The data were later processed using a computer software written by Hemker (1982). The curves for the two instruments are shown Fig. 4 (a and b). The authors became satisfied that the new system functioned and the readings were comparable with those of ABEM Terrameter. Further testing was carried out to determine its depth of penetration. For this second testing, a maximum spread of $^{AB}/_2$ = 500m was experimented. The data for the two equipment are presented in Table 2(a and b) while the corresponding computer curves are displayed on Fig.5` (a and b).

Comments and Observation

The results from the field testing exercises have shown that this instrument works properly and the readings are quite comparable with that of standard meter (the ABEM Terrameter) up to a spread of $^{AB}/_2$ = 100m. Table 5 shows the difference in readings from the two instruments at site 1. Apart from stations 1, 2 and 5 where the differences are 11.4, 4.55 and 2.69 ohm meters respectively, the range of other differences is between 1.93 and 0.01 ohm metres.

Considering Table 6 which is for site 2, the difference in readings is minimum between stations 1 to 20 excluding that of 19 which is exceptionally high. Beyond station 20 i.e from $^{AB}/_2$ = 100m to $^{AB}/_2$ = 500m, the difference are very significant.

Conclusion

Since it has been shown that the readings of this new resistivity meter are only reliable up to a spread of $^{AB}/_2$ = 100m, its uses would be limited to shallow investigations where the depth of interest is not more than 50 meters e.g geotechnical studies, groundwater exploration in basement environments. Efforts are being made to improve on the performance of this system.

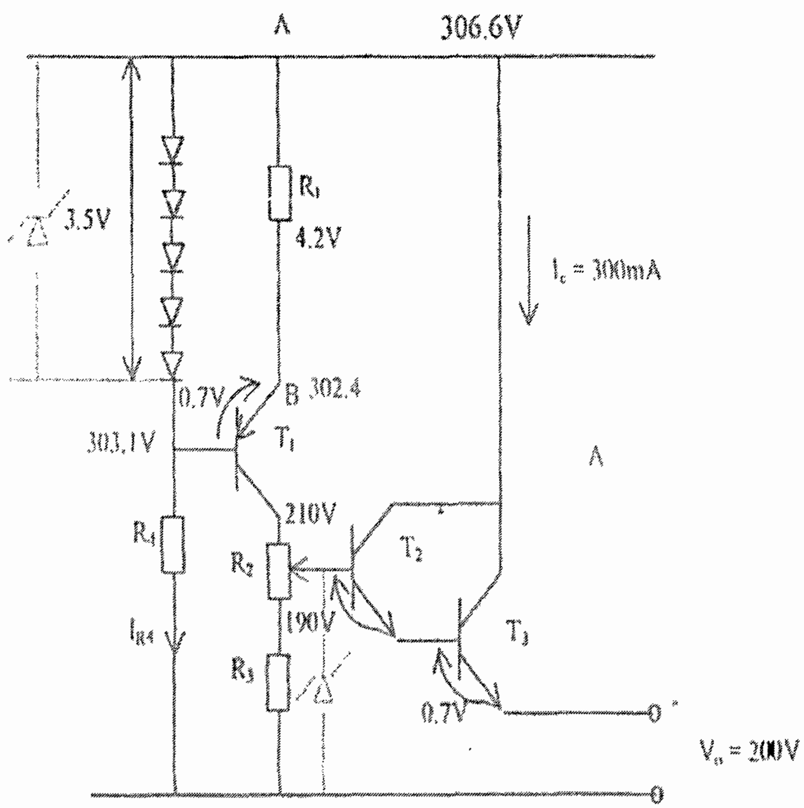

Fig. 2: Transistor and resistor arrangement for regulated voltage and current

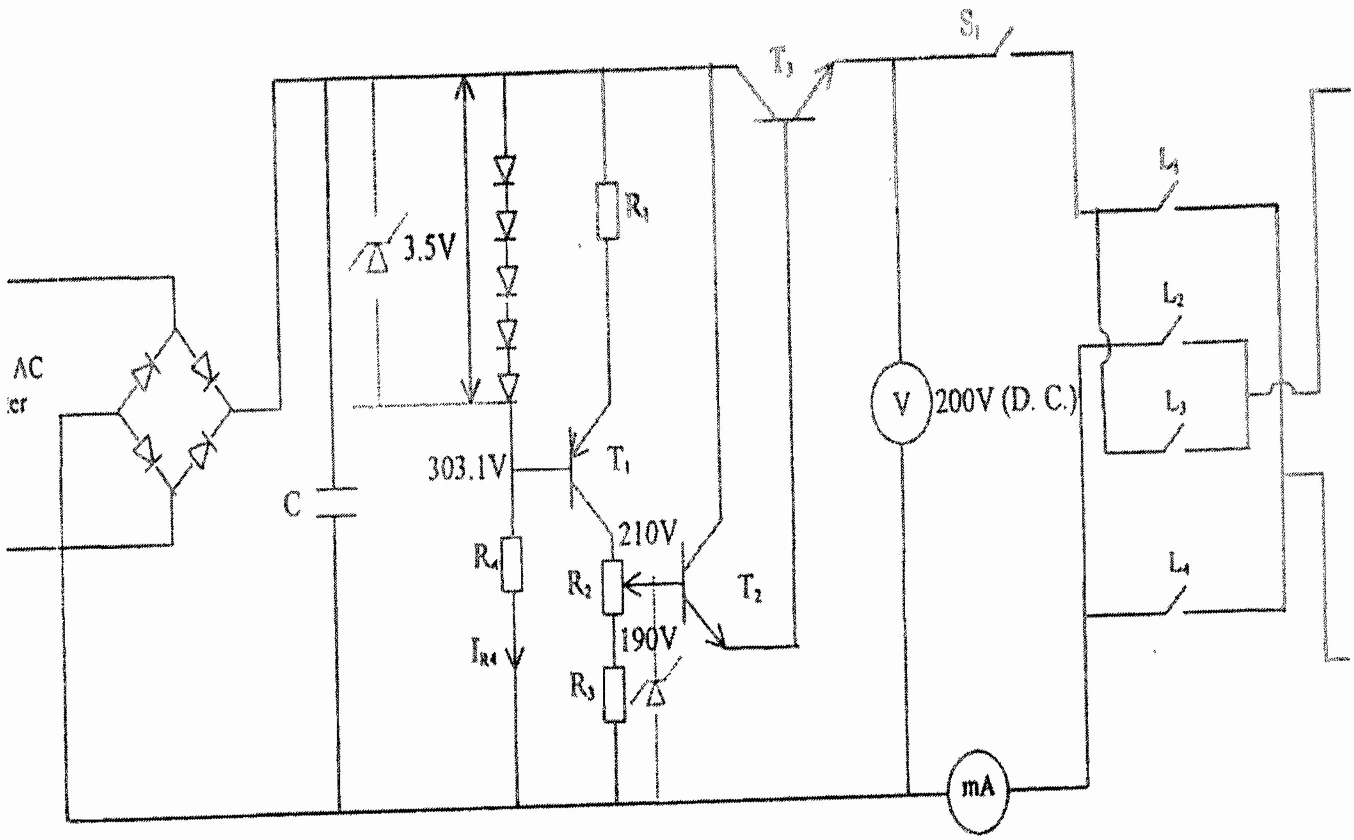

Fig. 3(a): Circuit diagram of the instrument

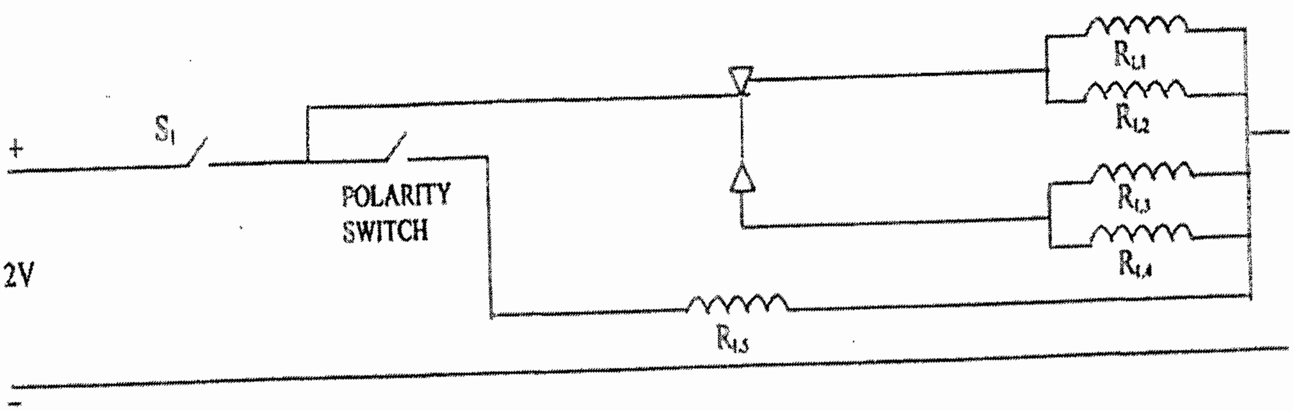

Fig. 3(b): Circuit diagram showing the relay system

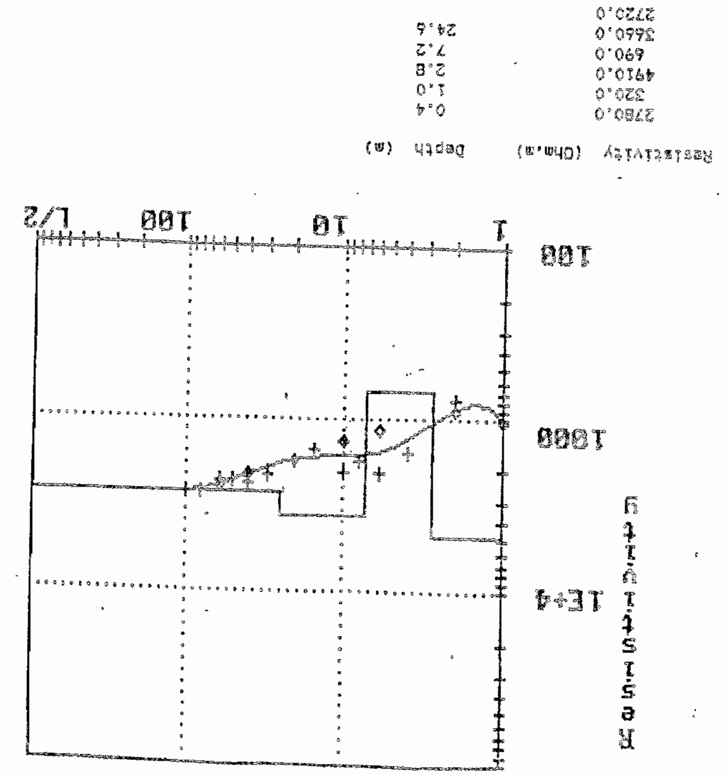

Fig. (4a): Computer curve for ABEM Instrument (Site 1)

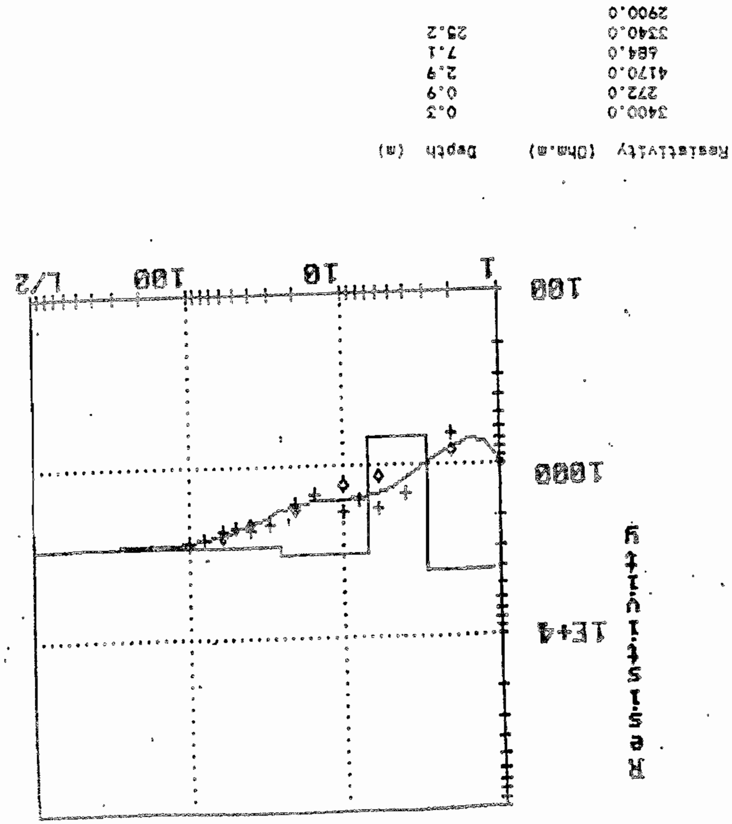

Fig. (4b): Computer curve for the New Instrument (Site 1)

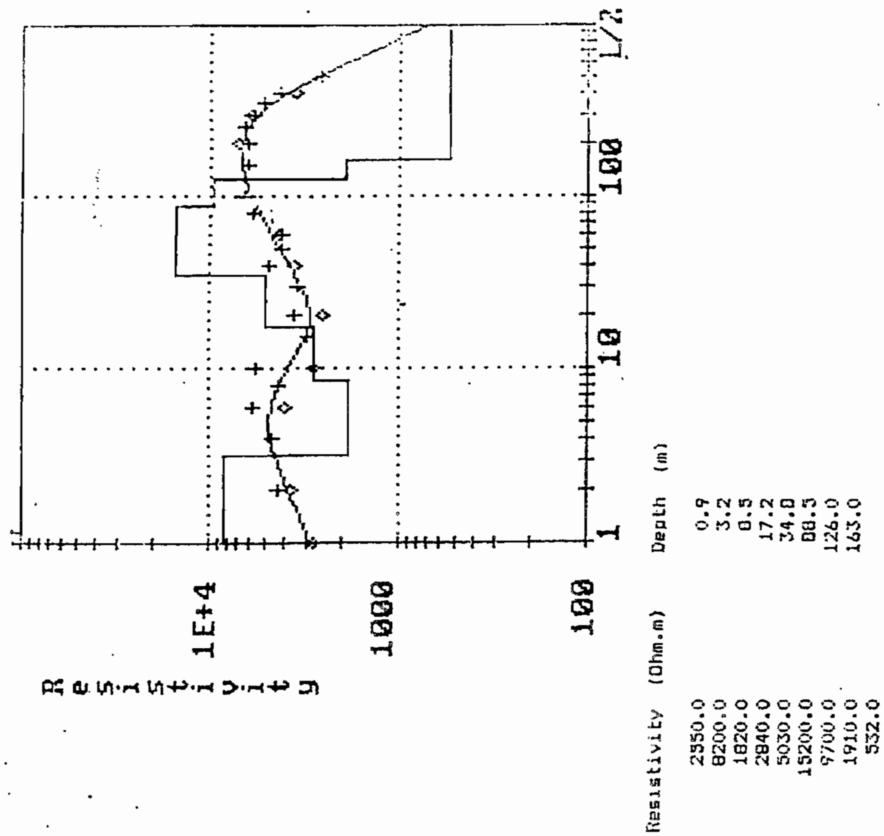

Fig. 5(a): Computer curve for ABEM Instrument (Site 2)

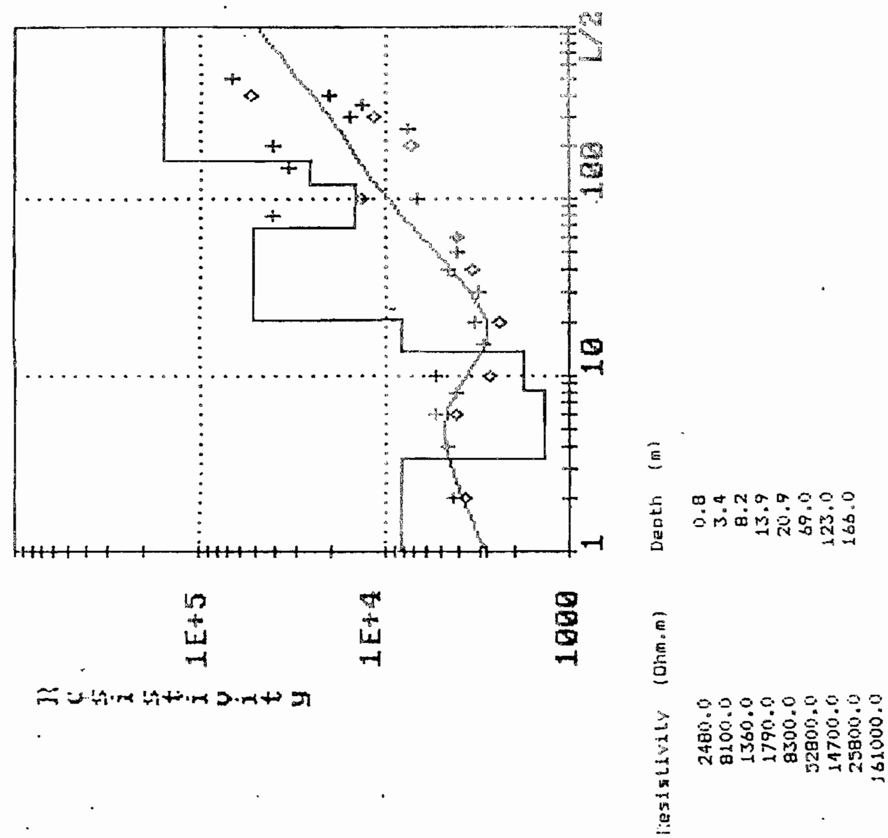

Fig. (5b): Computer curve for ABEM Instrument (Site 2)

Table 3:

COMPARING THE READINGS OF THE TWO METERS AT SITE 1

S/N	AB(m) / 2	MN(m) / 2	ABEM TERRAMETER		NEW METER	
			R(Ω)	ρ(Ωm)	R_{AV}(Ω)	ρ(Ωm)
1	1		178.10	1050.79	166.70	983.53
2	2	0.25	30.50	754.67	25.95	642.00
3	2		71.30	875.35	69.96	824.13
4	4	0.5	31.30	1549.40	29.35	1452.83
5	6		18.37	2057.40	15.68	1756.16
6	6		20.80	1144.00	20.83	1145.65
7	8	1.0	17.96	1778.00	16.03	1586.97
8	10		13.22	2062.30	11.83	1845.48
9	10		18.36	1367.80	17.66	1315.67
10	15	2.0	8.80	1531.20	8.35	1452.90
11	20		5.76	1791.40	5.35	1663.85
12	20		11.56	1743.20	11.63	1753.80
13	30	4.0	6.22	2159.00	6.07	2106.90
14	40		3.80	2363.60	3.71	2307.62
15	40		7.21	2174.54	6.96	2099.14
16	50	8.0	4.87	2329.30	4.59	2195.40
17	60		3.33	2312.00	3.32	2305.08
18	60		5.45	2465.60	5.47	2474.63
19	80	120	3.23	2645.00	3.19	2612.29
20	100		2.12	2735.00	2.14	2760.80

Table 4:

COMPARING THE READINGS OF THE TWO METERS AT SITE 2

S/N	AB(m) / 2	MN(m) / 2	ABEM TERRAMETER		NEW METER	
			R (Ω)	ρ (Ωm)	R_{AV}(Ω)	ρ (Ωm)
1	1		482.00	2843.80	482.1	2844.4
2	2	0.25	169.10	4183.53	170.0	4205.8
3	2		308.00	3628.24	307.3	3620.0
4	4	0.5	93.70	4638.15	93.4	4623.3
5	6		51.50	5768.00	48.2	5398.4
6	6		75.20	3987.50	74.1	4075.5
7	8	1.0	42.20	4177.80	41.0	4059.0
8	10		35.10	5475.60	33.9	5288.4
9	10		37.00	2756.50	36.7	2734.2
10	15	2.0	17.20	2992.80	16.5	2871.0
11	20		11.32	3520.52	10.5	3265.5
12	20		16.37	2468.60	16.1	2427.9
13	30	4.0	9.61	3335.63	9.1	3158.6
14	40		7.59	4726.98	7.4	4602.8
15	40		11.66	3516.66	11.2	3378.0
16	50	8.0	8.56	4094.25*	8.5	4065.6
17	60		5.97	4144.97	5.9	4096.4
18	60		9.26	4189.22	9.1	4116.8
19	80	12.0	6.99	5724.11	50.6	41440.9
20	100		5.00	6450.50	5.3	6837.5
21	100		8.34	6288.36	18.0	13572.0
22	150	20.0	3.62	6283.23	19.0	33310.0
23	200		2.01	6251.30	133.3	41364.3
24	200		3.47	7103.78	3.5	7163.9
25	250	30.0	2.00	6450.60	2.3	7533.2
26	300		1.239	5780.06	3.4	15861.3
27	300		1.709	5931.94	3.3	11553.5
28	350	40.0	1.075	5103.03	2.8	13291.6
29	400		0.682	4242.04	3.3	20320.0
30	400		0.716	3542.77	10.7	52900.0
31	500	50.0	0.338	2628.09	8.7	67656.0

Table 5:

DIFFERENCE IN READINGS FOR THE TWO METERS (SITE 1)

S/N	AB(m) / 2	ABEM TERRAMETER	NEW METER	DIFFERENCE
		R(Ω)	R(Ω)	R(Ω)
1	1	178.10	166.70	11.40
2	2	30.50	25.95	4.55
3	2	71.30	69.96	1.34
4	4	31.30	29.35	1.95
5	6	18.37	15.68	2.69
6	6	20.80	20.83	0.03
7	8	17.96	16.03	1.93
8	10	13.22	11.83	1.39
9	10	18.36	17.66	0.70
10	15	8.80	8.35	0.45
11	20	5.76	5.35	0.41
12	20	11.56	11.63	0.07
13	30	6.22	6.07	0.15
14	40	3.80	3.71	0.09
15	40	7.21	6.96	0.25
16	50	4.87	4.59	0.28
17	60	3.33	3.32	0.01
18	60	5.45	5.47	0.02
19	80	3.23	3.19	0.04
20	100	2.12	2.14	0.02

Table 6:

DIFFERENCE IN READINGS FOR THE TWO METERS AT SITE 2

S/N	AB(m) / 2	ABEM TERRAMETER SAS 300 (STANDARD)	NEW RESISTIVITY METER	DIFFERENCE
		R (Ω)	R(Ω)	R(Ω)
1	1	482.00	482.1	- 0.1
2	2	169.10	170.0	- 0.9
3	2	308.00	307.3	0.7
4	4	93.70	93.4	0.3
5	6	51.50	48.2	3.3
6	6	75.20	74.1	1.1
7	8	42.20	41.0	1.2
8	10	35.10	33.9	1.2
9	10	37.00	36.7	0.3
10	15	17.20	16.5	0.7
11	20	11.32	10.5	0.82
12	20	16.37	16.1	0.27
13	30	9.61	9.1	0.51
14	40	7.59	7.4	0.19
15	40	11.66	11.2	0.46
16	50	8.56	8.5	0.06
17	60	5.97	5.9	0.07
18	60	9.26	9.1	0.16
19	80	6.99	50.6	- 43.11
20	100	5.00	5.3	- 0.3
21	100	8.34	18.0	- 9.66
22	150	3.62	19.0	- 15.38
23	200	2.01	133.3	- 11.29
24	200	3.47	3.5	- 0.03
25	250	2.00	2.3	- 0.3
26	300	1.239	3.4	- 2.16
27	300	1.709	3.3	- 1.59
28	350	1.075	2.8	- 1.725
29	400	0.682	3.3	- 2.618
30	400	0.716	10.7	- 9.98
31	500	0.338	8.7	- 8.36

References

A De Sa (1990): Principles of Electronic Instrumentation. Edward Arnold, London. 270 pp

AldaA. (2006): Instruction Manual for Digital Multimeter, Tokyo, Japan.

Bartee, C. T. (1986): Digital Computer Fundamental McGraw Hill Book Company, New York, US, 610 pp

Bedford, B. D. And Hoft, R. G. (1964): Principles of Inverter Circuits John Wily and Sons Inc., London 641 pp

Golding E. W. and Widdis, F. C. (1962): Electrical Measurements Pitman and Sons Ltd, London UK, 941 pp

Hemker, C. J. (1982): Schlumberger Automatic Analysis, Elandsgracht Amsterdam, Holland.

Schuler, A. C. (1979): Electronics, Principles and ApplicationMcGraw Hill Book Company, New York, US, 286 pp

Theraj, B. L. And Theraja, A. K.(2002): A Textbook of Electrical Technology S.Chand and Company Ltd., Ramnager, New Delhi India, 2432 pp