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# A Remedy for Overcharging and Undercharging of Batteries Connected in Series

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**ABSTRACT:** Direct Current (D/C) is derived majorly from batteries used for different electronic circuits such as inverter circuit. A typical risk with recharging batteries connected in series is the overcharging and undercharging of batteries that set in once there is mismatch among the batteries. An equalisation circuit can be used to eliminate this risk but the equalisation circuits are separate from the charger which makes them unknown by users of inverter systems. It is ideal to design a charger that will eliminate this risk. In this work, a charger that will recharge batteries connected in series separately was designed. The designed charger has separate rectification and regulation for the different battery levels. The charger was used to recharge two mismatched batteries that are connected in series and it was observed that the charging process of the two batteries were independent of each other. This charger has the advantage of placing each battery in a float voltage (standby use) when a full charge is detected irrespective of the other battery's status. The designed circuit ensures that each battery was properly recharged and protects against the overcharging and undercharging risks of charging batteries connected in series. The cost of separate rectification, regulation and cables is negligible to the cost of a battery.

**KEYWORDS:** Battery, Overcharging, Undercharging, Charger, Equalization circuit.

## I. INTRODUCTION

Lead acid battery is the main source of electrical energy storage with a wide range of applications such as uninterruptible power supplies, renewable energy and traction [3]. In renewable energy applications, lead acid batteries are used to address the problems of the electric power in terms of stability, quality and dependability [9].

The cost and obtainable lifespan of batteries are the most discouraging factors for intending and experienced users of inverter systems. The expected lifespan of batteries varies from 3 to 5 years. This lifespan depends on charging and discharging cycles, temperature and other parameters. The battery's lifespan strongly influence the running cost of inverter systems [7].

The performance and lifespan of a rechargeable battery is to a large extent governed by the quality of the charger. Undercharged batteries have reduced charge capacity, while overcharging can damage the battery, cause gassing of the electrolyte, and even explode the battery [4][10].

It is heart breaking to know that the lifespan of batteries connected in series are cut short due to mismatch of battery parameters which leads to overcharging and undercharging of batteries.

II. RELATED WORK

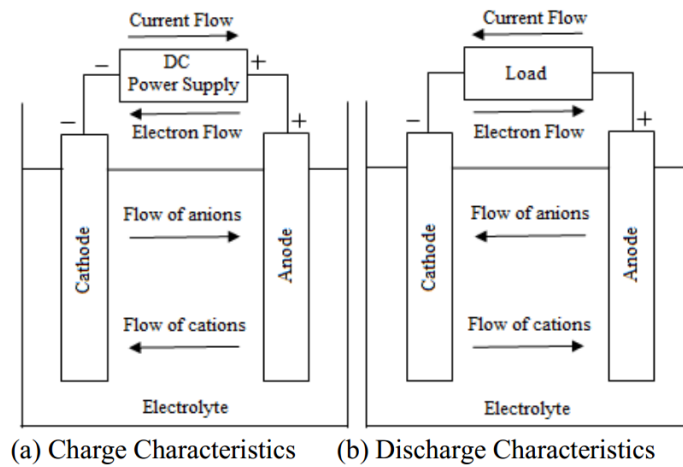


Figure 1: Charge and Discharge Characteristics of a cell [10].

Battery is an electrochemical device that converts chemical energy into electrical energy and electrical energy to chemical energy by oxidation-reduction reactions as in figure 1 [7].

Lead acid batteries are classified either as deep cycle or Starting, Lighting, and Ignition (SLI) type. The difference between the types of lead acid battery is in their internal structure and applications. SLI batteries are used where there is need to deliver high current output for a short period of time, therefore repeated deep discharges will cause degeneration of the battery. These batteries are rated in ampere-hour and cranking amps. Deep cycle batteries are used where there is need to deliver low current output for a long period of time and they are rated in ampere-hour only [8].

In practice, batteries are either connected in series or parallel. The ideal assumption with using batteries in series is that they are identical in every way, that is, they have the same end of charge and end of discharge characteristics.

When a battery reaches full charge, that is, when the charge current through the battery is less than 3% of the rated battery charge capacity, the power supplied to the battery is no longer utilized in recharging the battery, and will be dissipated as heat within the cell. This causes an increase in both cell temperature and internal pressure [10], therefore a fully charged battery should be disconnected from the charge circuit or placed within the recommended float voltage.

Table I. Recommended Charge and Discharge Cut-Off Voltages of Commercial Cells [10].

Battery Chemistry	Nominal Cell Voltage (V)	Charge Cut-Off Voltage (V)	Discharge Voltage (V)
Lead Acid (LA)	2.00	2.40	1.75
Lithium-Ion (Li-Ion)	3.60/3.70	4.20	3.00
Nickel Cadmium (Ni-Cd)	1.20	1.50	1.00
Nickel Metal Hydride (Ni-MH)	1.20	1.50	1.00

Failure mechanisms in the backup battery power system are numerous and are driven by a host of external and internal influences such as Jar Case Cracks, Specific Gravity Changes, Electrolyte Level/Dry-out, Excessive Temperature, High Cycling Rates, Defective Post Seals, Strap Corrosion, Plate Sulfation, Plate Growth (Dendrite Shorts), Plate Deterioration/Separator Problems, and Post/Connection Hardware Problems [6] [1].

Batteries have specific charge voltage and current ranges that are recommended by their manufacturers. Charging a battery outside these parameters will affect the lifespan and charge capacity of the battery. Overcharging leads to dry-out, thermal runaway, or explosion due to excessive production of hydrogen and oxygen gases in the battery [5]. Undercharging leads to loss of battery power due to formation of sulfate crystals on the battery plates. These crystals will eventually harden and reduce the available capacity of the battery over time. Sulfate build-up caused by undercharging is the most common cause of buckling plates, cell short circuit and cracked grids. Sulfate takes up more

room than the original material and strains the plates out of shape. The pressure of expanding active material can break separators and cause short circuits [5].

Batteries are rated at ambient temperature of 77°F (25°C). Operating a battery at higher or lower temperatures affects the performance and lifespan of the battery. A battery’s lifespan is reduced by 50% for every 15°F increase in temperature. Laidig and Wurst, 2006, illustrated a pair of Valve Regulated Lead Acid (VRLA) units studied in a thermal chamber as in figure 2. They varied the temperature from 10 to 100°F (-12 to 38°C) with sufficient time for stabilization and observed that as the temperature approached the lower temperatures, the impedance change was more pronounced while the warmer temperatures provided a slower rate of change of impedance

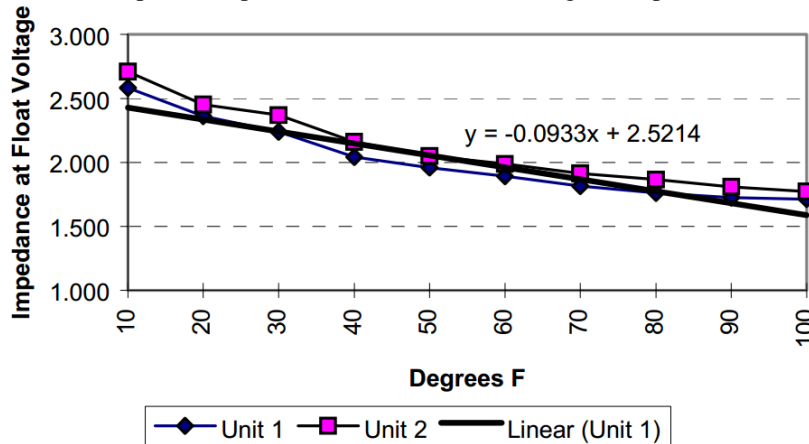


Figure 2: Effect of Temperature on Battery Impedance [6]

Batteries connected in series are charged with a single charger, that is, a single voltage source. This often leads to undercharging and/or overcharging of batteries due to mismatch in battery parameters [5]. For batteries to be properly recharged in series, they should have the same parameters (state of charge/discharge, impedance, temperature, etc). This makes it difficult to properly recharge mismatched batteries that are connected in series. Once a battery has a different parameter from the others connected with it in series, overcharging and undercharging sets in.

It was reported by [2] that the voltage across two batteries recharged in series are E1 = 15.57V and E2 = 13.84V to a supplied charging voltage of 29.41V. The critical observation here is that battery E1 is operating far outside the recommended charging voltage (overcharging) as specified by the manufacturer while battery E2 is not receiving the recommended charge voltage (undercharged).

It was recommended by [1], [2], and [5], to use battery equalization circuitry which will balance the charging voltage among the batteries. The battery equalization circuitry is separate from the charger which makes them optional and unknown by users of inverter systems.

#### IV. METHODOLOGY

If batteries which are connected in series are recharged independently, the issue of overcharging or undercharging will be eliminated irrespective of the batteries state of charge or discharge. The circuit in figure 3 was designed to recharge the batteries connected in series independently. There is flow of current from batteries higher in the series to the lower ones during the bulk charging process but this does not affect the charge characteristics of the lower batteries.

The standbys (STBY) are made 5V to achieve a regulator output of 14.4V for charging and 0V to achieve 13.6V for standby use (float voltage). The circuit can be adopted in all systems that recharge batteries in series.

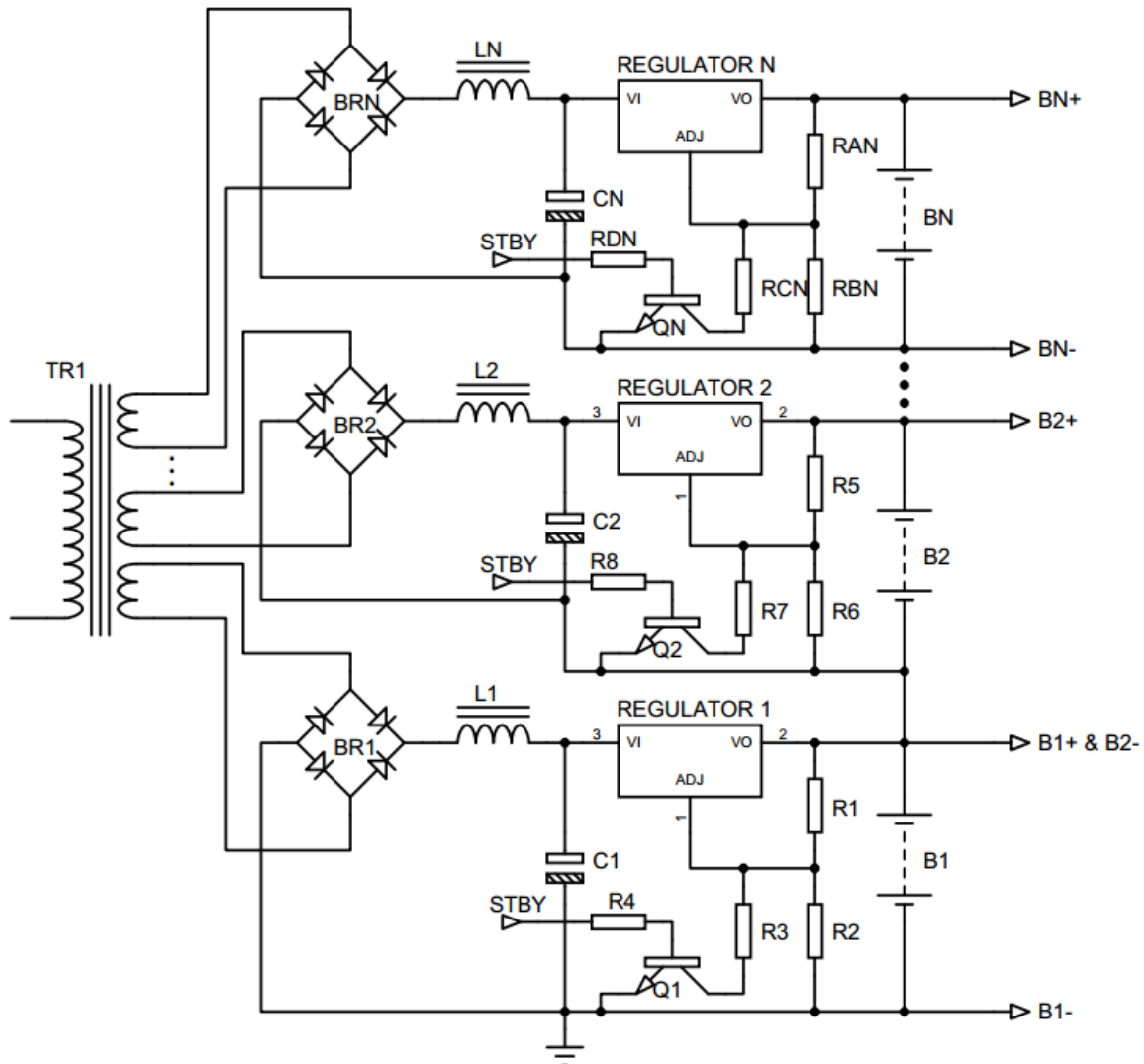


Figure 3: Independent Series Battery Charger.

Two mismatched 12V 18AH battery (B1 and B2, old and new respectively) which were being overcharged and undercharged by a 24V charger as reported by [2], were discharged in parallel to a cut of voltage of 10.5V. They were recharged with the designed circuit of figure 4 with the STBYs made 5V to achieve a regulated output voltage of 14.4V, the voltage and current across each battery was recorded every 10 minutes for 4 hours. When a full charge is detected in any of the batteries, that is, when the charge current is less than 3% of the charge capacity, the STBY is made 0V to place the battery in a standby (float) voltage of 13.6V. A 12V 18AH battery is said to be fully charged when the charge current is less than 0.54A. Then the batteries were discharged in parallel to a cut off voltage of 10.5V. In a second experiment, the batteries were recharged with the designed circuit of figure 4 with the battery positions interchanged (B1 to B2 and B2 to B1). The voltage and current across each battery was recorded every 10 minutes for 4 hours. The readings obtained in experiment 1 and 2 are presented in table 2. The voltage and current across each of the batteries in the two experiments were plotted against time and presented in figure 5 and 6. VB1 is the voltage across battery 1 while VB2 is the voltage across battery 2. IB1 is the current through battery 1 and IB2 is the current through battery 2.

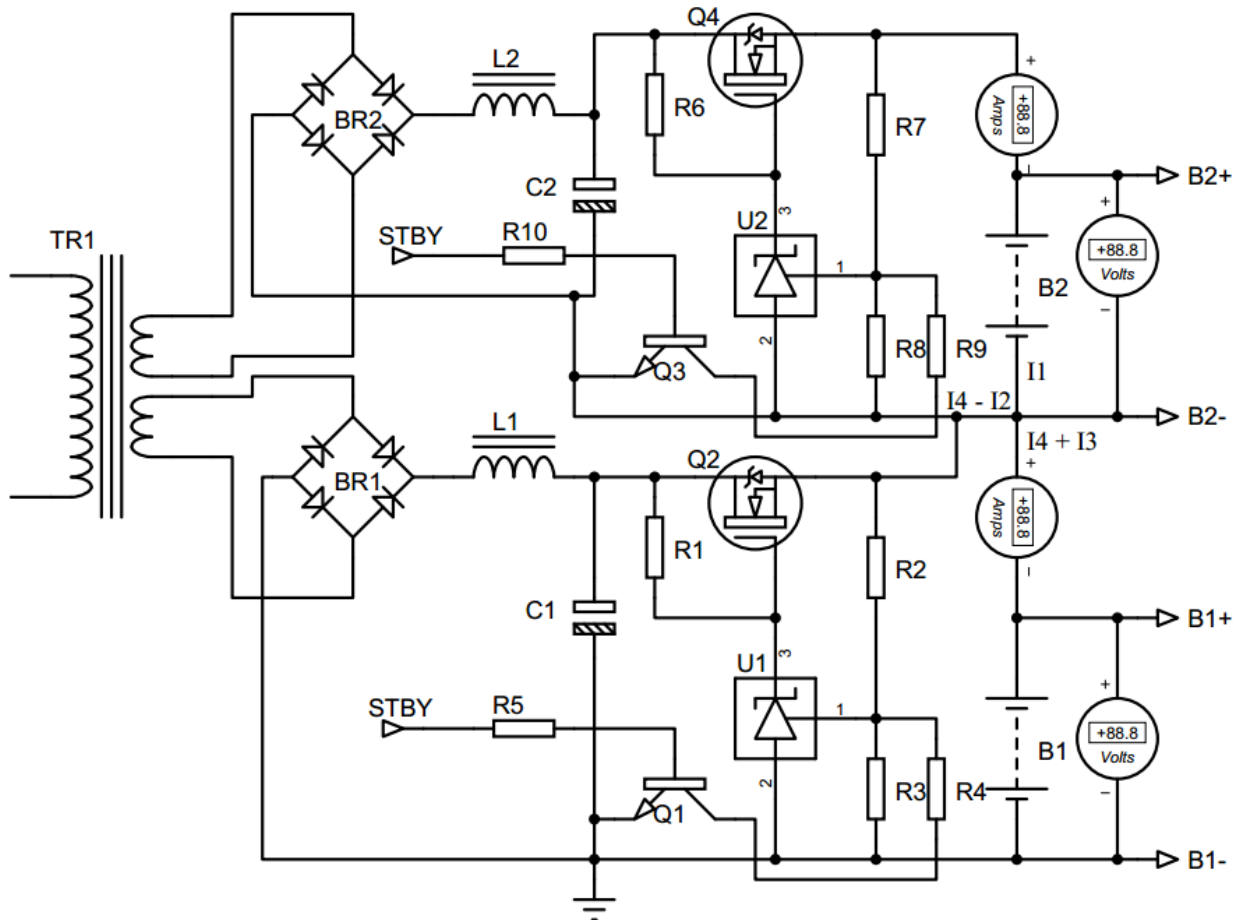


Figure 4: Independent Series Battery Charger Test Circuit.

#### IV. EXPERIMENTAL RESULTS

It was observed that the charging process of the two batteries were independent of each other. A higher current was detected with B1 below or B2 below in the circuit because of the current flowing from B2 above or B1 above (I<sub>1</sub>) to the ground. This current does not have negative effect on the circuit as it appears only during the bulk charge and does not affect the float voltage of the battery below in the circuit.

The charge profile of the two batteries depicts that of a battery that was recharged separately and not in series. The voltage and current through the batteries are independent of each other and are identical in the two experiments.

Table 2: Voltage and Current Readings of the Two Experiments with the Designed circuit of figure 4.

Time (minutes)	Experiment 1				Experiment 2			
	B1 (Below)		B2 (Above)		B2 (Below)		B1 (Above)	
	VB1 (V)	IB1 (I)	VB2 (V)	IB2 (I)	VB2 (V)	IB2 (I)	VB1 (V)	IB1 (I)
0.00	12.42	2.83	12.36	2.53	12.31	2.88	12.35	2.50
10.00	13.24	2.52	13.42	2.29	13.22	2.64	13.26	2.40
20.00	13.30	2.51	13.53	2.18	13.34	2.34	13.31	2.38
30.00	13.39	2.48	13.72	2.06	13.66	2.21	13.37	2.36
40.00	13.48	2.44	13.93	1.81	14.09	2.08	13.44	2.33
50.00	13.51	2.40	14.05	1.68	14.16	1.92	13.50	2.31
60.00	13.61	2.33	14.07	1.56	14.27	1.56	13.62	2.29
70.00	13.70	2.25	14.14	1.45	14.32	1.27	13.71	2.27
80.00	13.79	2.22	14.18	1.28	14.32	1.07	13.83	2.23
90.00	13.95	2.17	14.23	1.17	14.36	0.95	13.92	2.21



100.00	14.04	2.10	14.26	1.09	14.37	0.88	14.01	2.17
110.00	14.18	1.94	14.28	1.00	14.38	0.83	14.12	2.12
120.00	14.22	1.78	14.32	0.94	14.39	0.78	14.20	1.83
130.00	14.26	1.59	14.35	0.87	14.40	0.71	14.26	1.65
140.00	14.28	1.42	14.37	0.80	14.40	0.65	14.29	1.46
150.00	14.29	1.25	14.39	0.74	14.40	0.60	14.31	1.28
160.00	14.30	1.09	14.40	0.65	14.40	0.55	14.33	1.14
170.00	14.32	0.94	14.40	0.59	14.40	0.49	14.35	0.93
180.00	14.35	0.80	14.40	0.51	13.64	0.38	14.37	0.83
190.00	14.37	0.69	13.64	0.45	13.64	0.34	14.39	0.70
200.00	14.40	0.60	13.64	0.36	13.64	0.30	14.40	0.62
210.00	14.40	0.52	13.64	0.27	13.64	0.27	14.40	0.56
220.00	13.64	0.46	13.64	0.25	13.64	0.24	14.40	0.48
230.00	13.64	0.31	13.64	0.22	13.64	0.21	13.64	0.34
240.00	13.64	0.27	13.64	0.20	13.64	0.19	13.64	0.28

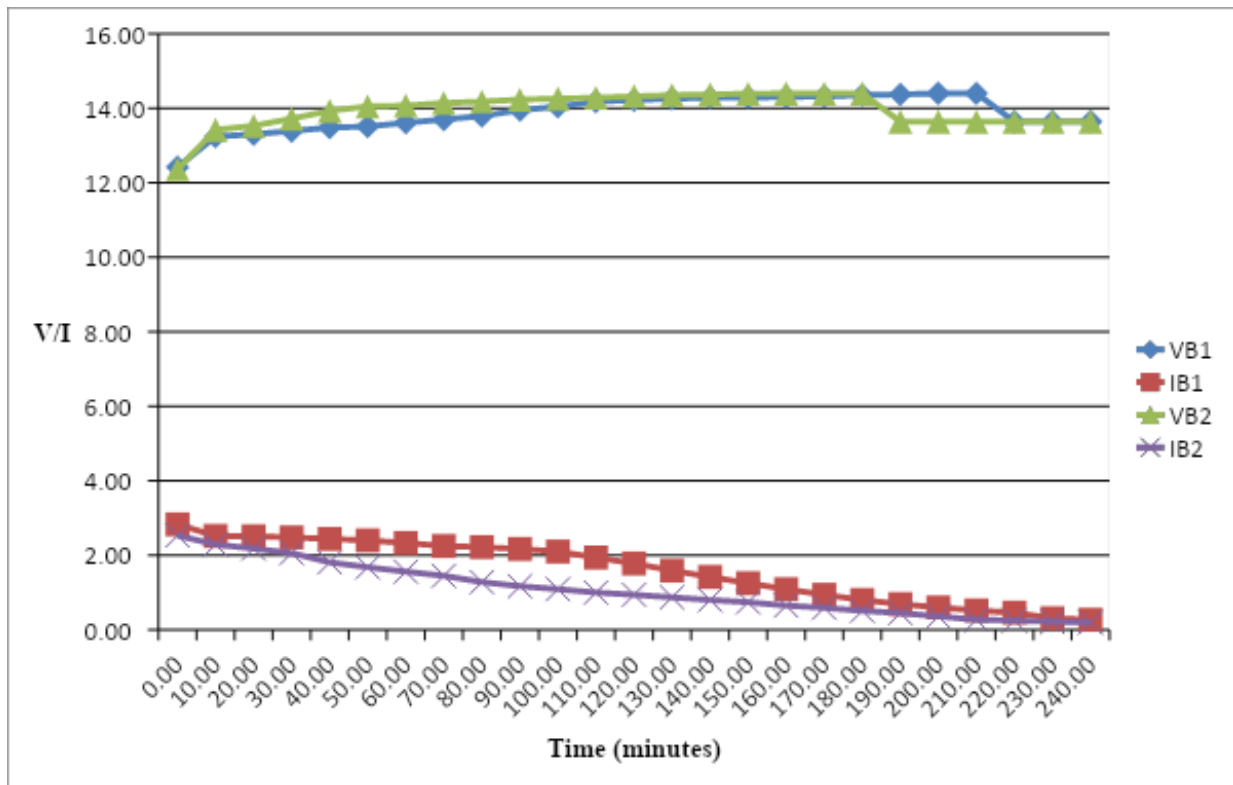


Figure 5: The Charge Profile of the two batteries in Experiment 1.

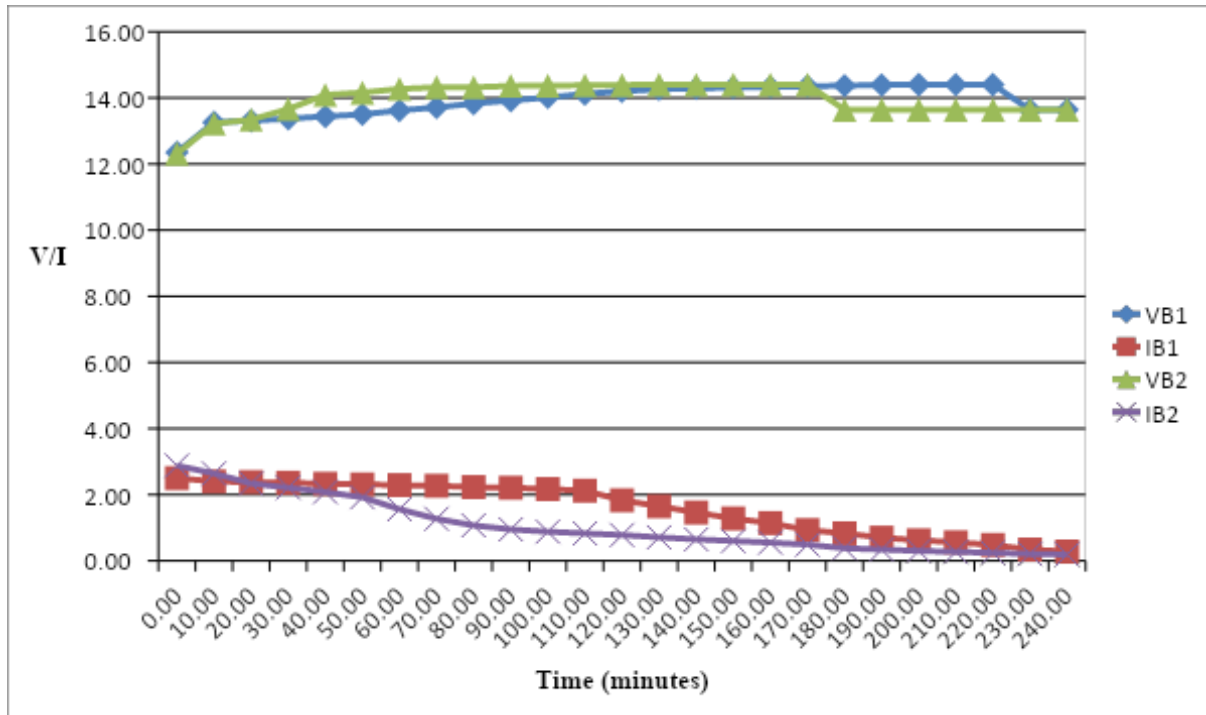


Figure 6: The Charge Profile of the two batteries in Experiment 2.

### V. CONCLUSION

If all that is needed to maintain battery lifespan and charge capacity is separate rectification, regulation, and cables, the additional cost is justified since the cost of separate rectification, regulation, and cables for the individual batteries connected in series is negligible to the cost of a battery. The preservation of battery lifespan via appropriate charging circuit will encourage people to go for inverter systems.

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