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THE PERFORMANCE CHARACTERISTICS OF LEAD ACID DEEP CYCLE BATTERIES THROUGH VOLTAGES AND ROUND-TRIP ENERGY EFFICIENCY FOR SOLAR POWER APPLICATION.

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ABSTRACT

The performance characteristics of lead acid deep cycle batteries through charge/discharge voltages, charge/discharge ratio and round – trip energy efficiency were studied by using two solar panels (model: 80 W, SF 125 x 35V/ 4 Amps), one solar panel (model: 45 W, STP 045 - 12/Rb), 2000 VA inverter, 2 Gaston Sealed Rechargeable Deep cycle batteries (12V / 200 Amp-hr), 2 GA Lead Valve Regulated batteries (12V/100 Amp-hr), a digital multimeter, two light bulbs (100 W) and a digital thermometer. The study shows that the i - v characteristics of the two different batteries were non-ohmic. The Gaston deep cycle battery when discharged has a nominal voltage of 1.69V. The Gaston battery when charged has a nominal voltage of 1.94V and a maximum voltage of 2.04V. The GA lead acid battery when charged has a nominal voltage of 1.94V and a maximum voltage of 2.08V. When discharged, a GA battery has a nominal voltage of 1.80V and a minimum voltage of 1.68V. The ratio of charge/discharge for both Gaston and GA batteries is 1:1. The round-trip energy efficiency for the GA battery is 79.2% while that of Gaston battery is 84.3%. This result shows that a Gaston battery is 5.1% more efficient than the GA battery. The lowered nominal voltage and higher round-trip energy efficiency of Gaston battery favour its comparative usage for solar power generations and other uses.

Key words*:* Nominal Voltage, Battery, Deep cycle, Ambient temperature, Electrochemistry.

INTRODUCTION

A battery is an electrical device that stores energy for future use. A battery is not capable of generating electricity but converts chemical energy into electricity by the use of a galvanic cell. A galvanic or voltaic cell is a simple device consisting of two electrodes, cathode and anode, in an electrolyte solution. Usually, a battery consists of one or more galvanic cells.

Battery cells are mainly characterized into primary and secondary cells. Primary cells produce current by means of an irreversible chemical reaction. They are designed to be used once and discarded when the supply of reactants is exhausted. Secondary cells are electrically recharged after use to their original pre-discharged condition by passing current through the circuit in the opposite direction to the current during discharged.

The historical developments of some batteries were reported by some researchers such as Baghdad battery (Arran, 2003), Linked capacitors (Benjamin, 1749), Trough battery (Bernard, 2002), Volta's pile (Decker, 2005), Zinc - Copper voltaic pile (James, 2000), Daniel cell (Carboni, 1999), Bird's cell (Watt and Philip, 2005), Porous pot cell (Carboni, 1999), Gravity cell (James, 2000) and Groove cell (James, 2000).

A deep cycle battery is a battery designed to be regularly discharged deeply using most of its capacity. In contrast, a shallow or starter battery such as most automotive batteries are designed to deliever short, high current burst for the cranking of the engine, thus frequently discharging only a small part of their capacity.

A deep cycle battery discharges between 45% and 75% of its capacity depending on the construction of the battery (http:www.extension.psu.edu). Although, the battery can be cycled down to 20% charge, the best life span versus cost method is to keep the average cycle at about 45% discharged (http //:www.extension.psu.edu).

There are at least six major rechargeable electrochemistries available today. They are Lead acid (Pb – acid), Nickel Cadmium (NiCd), Nickel-Metal Hydride (NiMH), Lithium ion (Li-ion), Lithium-Polymer (Li-poly) and Zinc-air (Patel, 2006).

Electricity is more versatile in use because it is a highly ordered form of energy that can be converted efficiently into other forms. For example, it can be converted into mechanical form with efficiency near 100% or into heat with 100% efficiency (Patel, 2006).

A disadvantage of electricity is that it cannot be easily stored on a large scale. Almost all electrical energy used today is consumed as it is generated. The photovoltaic and wind energy being intermittent sources of power cannot meet the load demand all of the time, 24 hours a day, 365 days of the year. The energy storage therefore is a desired feature to incorporate with renewable power systems, particularly in stand-alone plants. It can significantly improve the load availability, a key requirement for any power system (Patel, 2006).

Every storage technology will require more energy to charge than discharged. The loss of energy is typically expressed as a percentage (%) known as roundtrip efficiency, which is the ratio of energy discharged from the storage. There will be some energy loss during the process of storing the energy and some losses when converting the stored energy back to electricity. These contribute to round-trip efficiency. Roundtrip efficiency affects the costs of storage. A loss efficient storage system will require more electricity to store the same amount electricity supplied than a more efficient storage system (http://www.irena.org/.../electricity/storage).

The round-trip efficiency is given by

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$$\eta_{energy} = \frac{\text{the energy output over the full discharge}}{\text{the energy input to restore full charge}} \quad x \quad 100\% \qquad (1)$$

Therefore, the design of any energy storage such as battery is influenced by some basic performance characteristics. Patel (2006) reported that NiMH and NiCd electrochemistries have a nominal voltage of 1.2V when charging and 1.45V when discharging under a typical charge/discharge cycle.

In this study, the typical lead-acid (Pb-acid) deep cycle batteries were characterized based on charge/discharge voltages, charge/discharge ratio and round-trip energy efficiency, to determine which is a more efficient energy source.

MATERIALS AND METHODS

The materials employed in this study with their specifications are presented in Table 1.

Table 1: Materials and Specifications

Material	Capacity	Quantity
Power Inverter	2000W/24V	1
Multi-Meter	DT92050A	1
Solar Panel	SF125x35V/4AMPS	2
Solar Panel	STP045-12/Rb	1
Gaston Battery (Sealed Rechargeable Deep Cycle Battery)	12V/200AMPS	2
GA (Lead Valve Regulated)	12V/100AMPS	2
Electrical Cable	2AWG (American Wire Guage)	10m
The Bulb	100W/220V	2
Thermometer	U– MEC Max 1/10 ^{0}C& 5^{0}F	1
Clock	Digital	1

During discharging, the Gaston (12V/200 amp-hour) batteries were connected in series, positive terminal to negative terminal and vice versa, which gave a total of 24V/200 amp-hour. The Gaston batteries were connected to the power inverter (2000AIU) that is, negative terminal of the inverter to the negative terminal of the battery and positive terminal of the inverter to positive terminal of the battery using 2AWG wire. Two bulbs of 100Watts each were powered by the inverter so as to discharge the batteries at periodic time of 15 minutes. The DT 92050 digital multimeter was used to take voltage readings. Digital thermometer measured the ambient temperature at interval of 15 minutes. Similar procedure was repeated for GA (12V/100 amp-hr) battery.

During charging, 3 solar panels were connected together and their common output terminals were connected tightly to the batteries. The voltage and temperature were then measured at the same interval of 15 minutes.

RESULTS

Measurements of voltages and ambient temperature at periodic interval of time were taken. Table 2 shows a typical rate of discharge of Gaston batteries (12V/200 amp-hr). Table 3 shows a typical rate of charge of Gaston batteries for day 1. Table 4 shows a typical rate of discharge for GA (12V/100 amp-hr) battery. Table 5 presents a typical rate of charge for GA (12V/100 amp-hr) battery. Gaston battery took a period twelve hours to discharge completely while the GA battery took six hours to discharge completely.

Table 2: The Rate of the Discharge of Gaston Battery (12V/200amps-hrs)

Time of the Day (Min)	HR	Battery voltage without load (V)	Battery voltage on load (V)	Ambient temperature (^oc)	Cell voltage on load(v)	Current (amps)	Internal resistance (Ω)
8:20	0	24.9	0	35	0	0	0
8:35	0.25	24.8	24.7	35	2.06	800	0.00013
8:50	0.50	24.8	24.7	35	2.06	400	0.00025
9:05	0.75	24.7	24.6	35	2.05	266.7	0.00037
9:20	1.00	24.7	24.6	35	2.05	200	0.00050
9:35	1.25	24.6	24.5	35	2.04	160	0.00063
9:50	1.50	24.6	24.5	35	2.04	133.3	0.00075
10:05	1.75	24.5	24.4	36	2.03	114.3	0.0010
10:20	2.00	24.5	24.4	36	2.03	100	0.0011
10:35	2.25	24.4	24.3	36	2.03	88.9	0.0013
10:50	2.50	24.4	24.3	36	2.03	80.0	0.0014
11:05	2.75	24.3	24.2	36	2.02	72.7	0.0015
11:20	3.00	24.3	24.2	36	2.02	66.7	0.0016
11:35	3.25	24.2	24.1	36	2.01	61.5	0.0017
11:50	3.50	24.2	24.1	36	2.01	57.2	0.0018
12:05	3.75	24.1	24.0	36	2.00	53.3	0.0019
12:20	4.00	24.0	23.9	37	1.99	50.0	0.0020
12:35	4.25	24.0	23.9	37	1.99	47.1	0.0021
12:50	4.50	23.9	23.8	37	1.98	44.4	0.0023
1:05	4.75	23.9	23.8	37	1.98	42.1	0.0024
1:20	5.00	23.8	23.7	37	1.98	40.0	0.0025
1:35	5.25	23.8	23.7	37	1.98	38.1	0.0026
1:50	5.50	23.7	23.6	37	1.97	36.4	0.0027
2:05	5.75	23.7	23.6	37	1.97	34.8	0.0028
2:20	6.00	23.6	23.5	37	1.96	33.3	0.0030
2:35	6.25	23.6	23.5	37	1.96	32.0	0.0031
2:50	6.50	23.5	23.4	37	1.95	30.8	0.0032
3:05	6.75	23.5	23.4	37	1.95	29.6	0.0034
3:20	7.00	23.4	23.3	37	1.94	28.6	0.0035
3:35	7.25	23.4	23.3	37	1.94	27.6	0.0036
3:50	7.50	23.3	23.2	37	1.93	26.7	0.0037
4:05	7.75	23.3	23.2	37	1.93	25.8	0.0039
4:20	8.00	23.2	23.1	36	1.92	25.0	0.0040
4:35	8.25	23.2	23.1	36	1.92	24.2	0.0041
4:50	8.50	23.1	23.0	36	1.92	23.5	0.0043
5:05	8.75	23.0	22.9	36	1.91	22.9	0.0044
5:20	9.00	22.9	22.8	36	1.90	22.2	0.0045
5:35	9.25	22.7	22.6	35	1.89	21.6	0.0046
5:50	9.50	22.6	22.5	35	1.88	21.0	0.0048
6:05	9.75	22.4	22.3	35	1.86	20.5	0.0049
6:20	10.00	22.2	21.9	35	1.83	20.0	0.015
6:35	10.25	22.0	21.7	35	1.81	19.5	0.015
6:50	10.50	21.8	21.5	35	1.79	19.0	0.016
7:05	10.75	21.6	21.2	35	1.77	18.6	0.022
7:20	11.00	21.4	21.0	35	1.75	18.2	0.022
7:35	11.25	21.0	20.9	35	1.74	17.8	0.051
7:50	11.50	21.9	20.7	35	1.73	17.4	0.017
8:05	11.75	20.5	20.3	35	1.69	17.0	0.012
8:20	12.00	20.2	20.0	35	1.67	16.7	0.012

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Table 3: The Rate of Charge for Gaston battery (12V/200amps-hrs) for day 1

Time of the Day(Min)	Hr	Battery Voltage Load(V)	Ambient Temperature (^{O}C)	Cell Voltage Load (V)	Current (amps)
8:05	0	23.3	35	1.94	17.00
8:20	0.25	23.3	35	1.94	17.00
8:35	0.50	23.3	35	1.94	32.0
8:50	0.75	23.3	35	1.94	32.0
9:05	1.00	23.3	35	1.94	62.0
9:20	1.25	23.4	35	1.95	62.0
9:35	1.50	23.4	35	1.95	92.0
9:50	1.75	23.4	35	1.95	92.0
10:05	2.00	23.4	36	1.95	107
10:20	2.25	23.4	36	1.95	107
10:35	2.50	23.5	36	1.96	122
10:50	2.75	23.5	36	1.96	122
11:05	3.00	23.5	36	1.96	137
11:20	3.25	23.5	36	1.96	152
11:35	3.50	23.5	36	1.96	152
11:50	3.75	23.5	36	1.96	167
12:05	4.00	23.6	37	1.97	167
12:20	4.25	23.6	37	1.97	182
12:35	4.50	23.6	37	1.97	182
12:50	4.75	23.6	37	1.97	197
1:05	5.00	23.6	37	1.97	197
1:20	5.25	23.6	37	1.97	212
1:35	5.50	23.7	37	1.98	212
1:50	5.75	23.7	37	1.98	227
2:05	6.00	23.7	37	1.98	227
2:20	6.25	23.7	37	1.98	242
2:35	6.50	23.7	37	1.98	242
2:50	6.75	23.7	36	1.98	257
3:05	7.00	23.7	36	1.98	257
3:20	7.25	23.8	36	1.99	272
3:35	7.50	23.8	36	1.99	272
3:50	7.75	23.8	36	1.99	287
4:05	8.00	23.8	36	1.99	287
4:20	8.25	23.8	35	1.99	302
4:35	8.50	23.8	35	1.99	317
4:50	8.75	23.9	35	1.99	332
5:05	9.00	23.9	35	1.99	332
5:20	9.25	23.9	35	1.99	347
5:35	9.50	23.9	35	1.99	347
5:50	9.75	24.0	35	2.00	362
6:05	10.00	24.0	35	2.00	362

Table 4: The rate of Discharge of GA battery (12V/100amps-hrs)

Time of the Day (Min)	**HR**	**Battery voltage without load (V)**	**Battery voltage on load (V)**	**Ambient temperature (^{o}c)**	**Cell voltage on load (V)**	**Current (amps)**	**Internal Resistant (ω)**
8:05	0	24.9	0	35	0	0	0
8:20	0.25	24.9	24.8	35	2.07	400	0.00050
8:35	0.50	24.8	24.7	35	2.06	200.0	0.00050
8:50	0.75	24.7	24.6	35	2.05	133.3	0.00075
9:05	1.00	24.6	24.5	35	2.04	100.0	0.0010
9:20	1.25	24.6	24.5	35	2.04	80.0	0.0013
9:35	1.50	24.5	24.4	35	2.03	66.7	0.0015
9:50	1.75	24.5	24.4	36	2.03	57.1	0.0018
10:05	2.00	24.4	24.3	36	2.03	50.1	0.0020
10:20	2.25	24.3	24.2	36	2.03	44.4	0.0023
10:35	2.50	24.2	24.1	36	2.01	40.0	0.0025
10:50	2.75	24.1	24.0	36	2.00	36.4	0.0027
11:05	3.00	24.0	23.9	36	1.99	33.3	0.0030
11:20	3.25	23.9	23.8	36	1.98	30.8	0.0032
11:35	3.50	23.8	23.7	36	1.98	28.6	0.0033
11:50	3.75	23.7	23.6	36	1.97	26.6	0.0038
12:05	4.00	23.6	23.5	37	1.96	25.0	0.0040
12:20	4.25	23.5	23.4	37	1.95	23.5	0.0043
12:35	4.50	23.4	23.3	37	1.94	22.2	0.0045
12:50	4.75	23.1	22.9	37	1.90	21.1	0.052
1:05	5.00	23.0	21.0	37	1.83	20.0	0.050
1:20	5.25	22.9	21.7	37	1.80	19.1	0.010
1:35	5.50	22.7	21.5	37	1.79	18.2	0.011
1:50	5.75	21.0	20.6	37	1.72	17.4	0.023
2:05	6.00	20.6	20.2	37	1.68	16.7	0.024

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Table 5: Rate of Charge of GA Battery (12V/100amps-hr) for day 1

Time of the Day (Min)	Hr	Battery Voltage Load (V)	Ambient temperature (^{O}C)	Cell Voltage Load (V)	Current (amps)
8:05	0	23.3	35	1.94	17.00
8:20	0.25	23.3	35	1.94	17.00
8:35	0.50	23.4	35	1.95	32.0
8:50	0.75	23.4	35	1.95	32.0
9:05	1.00	23.5	35	1.96	47
9:20	1.25	23.5	35	1.96	47
9:35	1.50	23.6	35	1.97	62
9:50	1.75	23.6	35	1.97	62
10:05	2.00	23.7	36	1.98	77
10:20	2.25	23.7	36	1.98	77
10:35	2.50	23.8	36	1.99	92
10:50	2.75	23.8	36	1.99	92
11:05	3.00	23.9	36	1.99	107
11:20	3.25	23.9	36	1.99	107
11:35	3.50	24.0	36	2.00	122
11:50	3.75	24.0	36	2.00	122
12:05	4.00	24.1	37	2.01	137
12:20	4.25	24.1	37	2.0I	137
12:35	4.50	24.2	37	2.02	152
12:50	4.75	24.2	37	2.02	152
1:05	5.00	24.3	37	2.03	167
1:20	5.25	24.3	37	2.03	167
1:35	5.50	24.4	37	2.03	182
1:50	5.75	24.4	37	2.03	182
2:05	6.00	24.5	37	2.04	197
2:20	6.25	24.5	37	2.04	197
2:35	6.50	24.6	37	2.05	212
2:50	6.75	24.6	36	2.05	212
3:05	7.00	24.7	36	2.06	227
3:20	7.25	24.7	36	2.06	227
3:35	7.75	24.8	36	2.06	242
3:50	8.00	24.8	36	2.06	242
4:05	8.25	24.8	36	2.07	257
4:20	8.50	24.9	36	2.07	272
4:35	8.75	24.9	36	2.07	272
4:50	9.00	24.9	36	2.07	287
5:05	9.25	24.9	35	2.07	287
5:20	9.50	24.9	35	2.07	302
5:35	9.75	24.9	35	2.07	302
5:50	10.00	24.9	35	2.08	317
6:05	0.25	25.0	35	2.08	332
5:20	9.50	25.0	35	2.08	347
5:35	9.75	25.0	35	2.08	347
5:50	10.00	25.0	35	2.09	362
6:05	10.25	25.0	35	2.09	377

The typical I - V characteristics of Gaston battery during discharging process is shown in Figure 1. The current decreases spontaneously at a constant voltage of 2V over a long period of time. The voltage later dropped to 1.6V when current is nearly 0 Ampere. During the charging process of Gaston battery, i –v characteristics show that current increases as the voltage increases. The trend line (Figure 2) shows direct proportionality between current and voltage although current increases at faster rate than voltage.

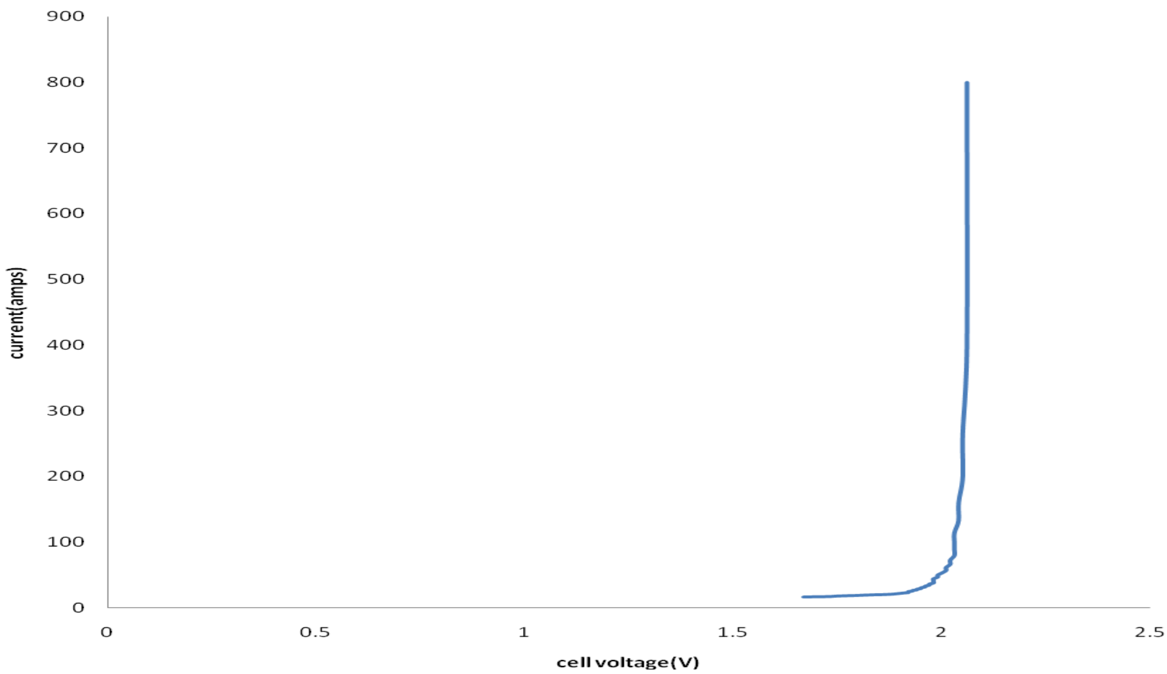

Figure 1: *I-V* Characteristic of Gaston Battery during discharging process.

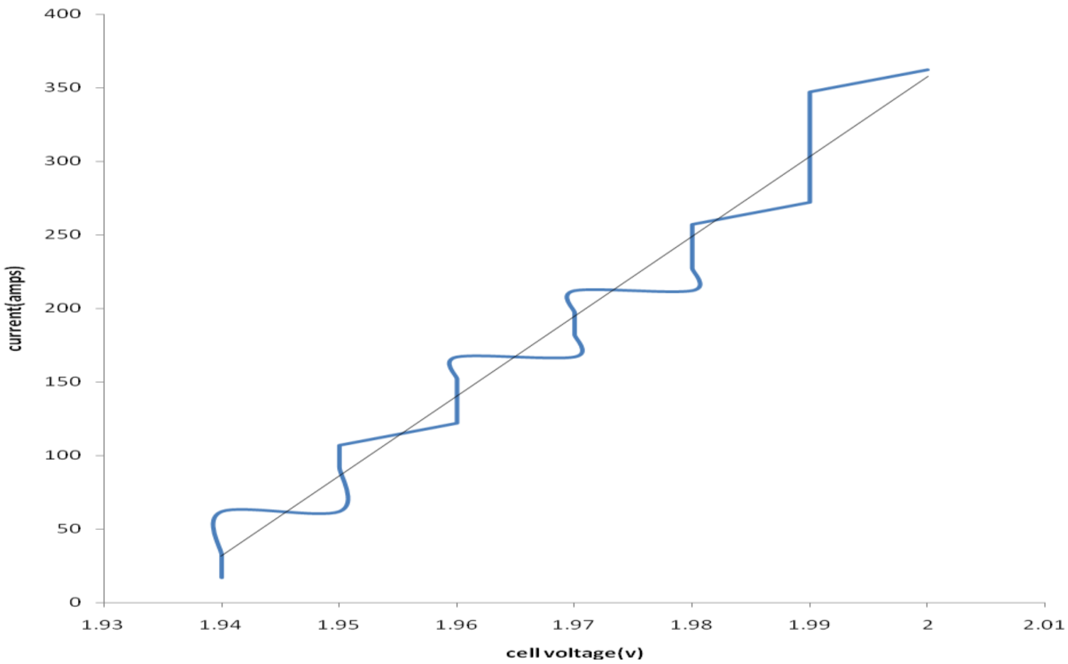

Figure 2: *I-V* Characteristics of Gaston Batteries during charging process.

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The $i - v$ characteristic of GA battery during discharge (Figure 3) and charging (Figure 4) processes show similar trend like Gaston battery. This behaviour could be as a result of the two typical batteries having the same electrochemistry.

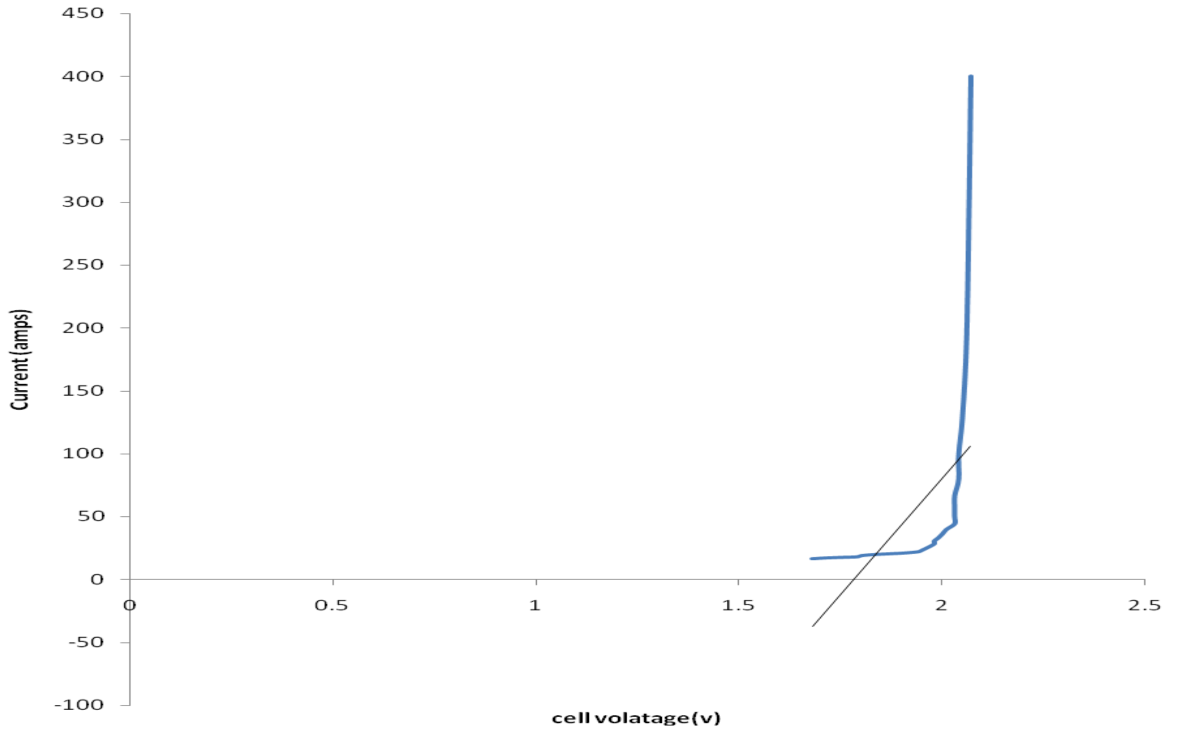

Figure 3: *I-V* Characteristic of GA Battery during discharging process.

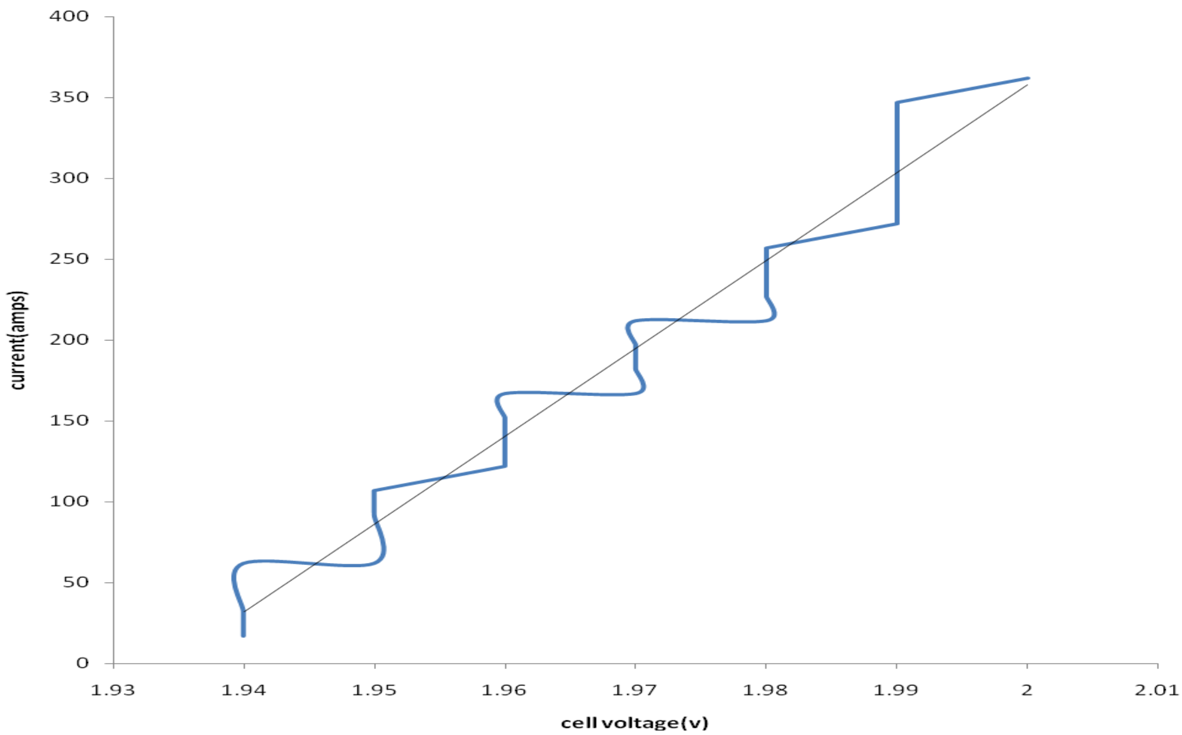

Figure 4: *I - V* Characteristic of GA Battery during charging process.

Figure 5 shows the cell voltage versus cycle time for Gaston battery during discharging process. The cell voltage discharges with time from its maximum value of 2.04V until it gets to a nominal value of 1.69V which is the plateau value. This plateau value was held for about 15 minutes before the inverter was switched off automatically.

Figure 6 shows the cell voltage versus cycle time during charging for Gaston batteries. In this process, the batteries voltage rises from 1.94V to the maximum voltage of 2.04V. It was observed that charging began from 1.94V rather than minimum value of 1.69V during discharging process.

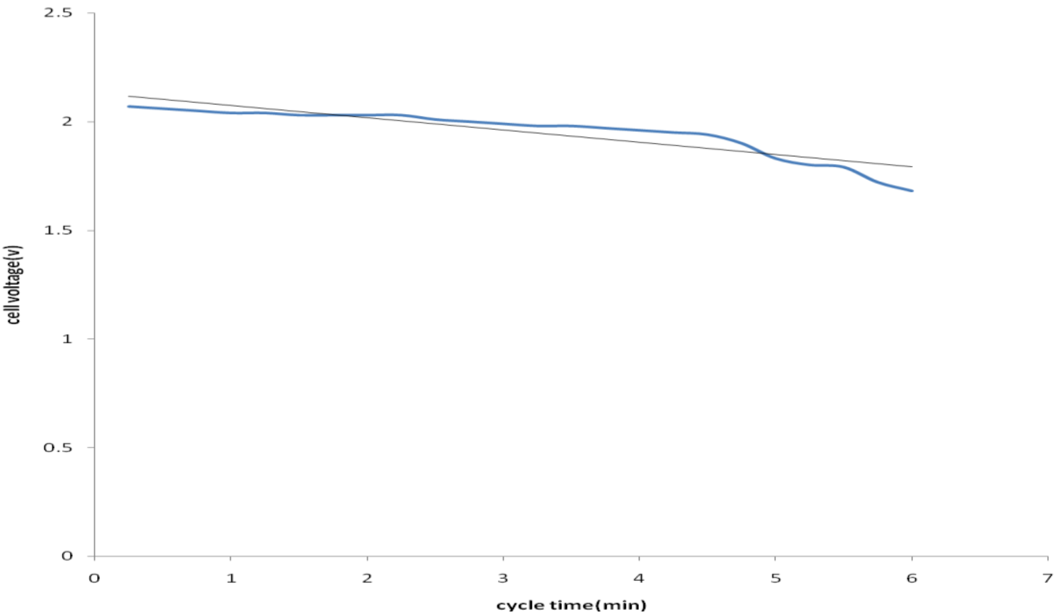

Figure 5: The cell voltage versus cycle time for Gaston battery during discharging process

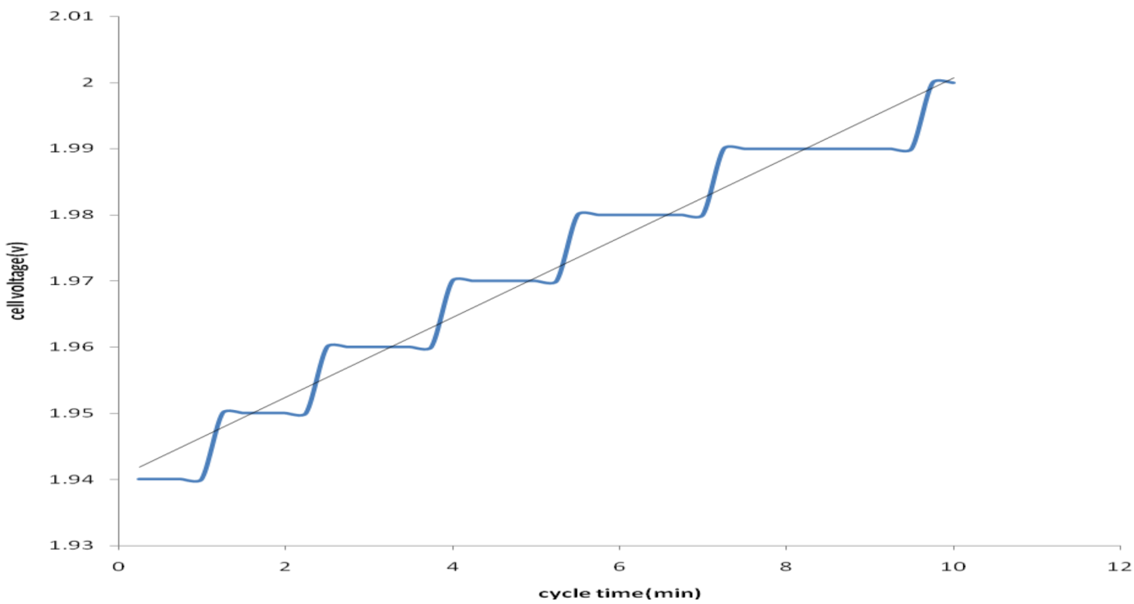

Figure 6: The cell voltage versus cycle time for Gaston battery during charging process

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Figure 7 shows the cell voltage versus cycle time during discharging process for GA battery. The voltage dropped from 2.08V to a plateau value of 1.80V before inverter was switched off automatically. During charging process (Figure 8), the GA battery rose from 1.94V which was plateau value for rate of charge to maximum value of 2.08V.

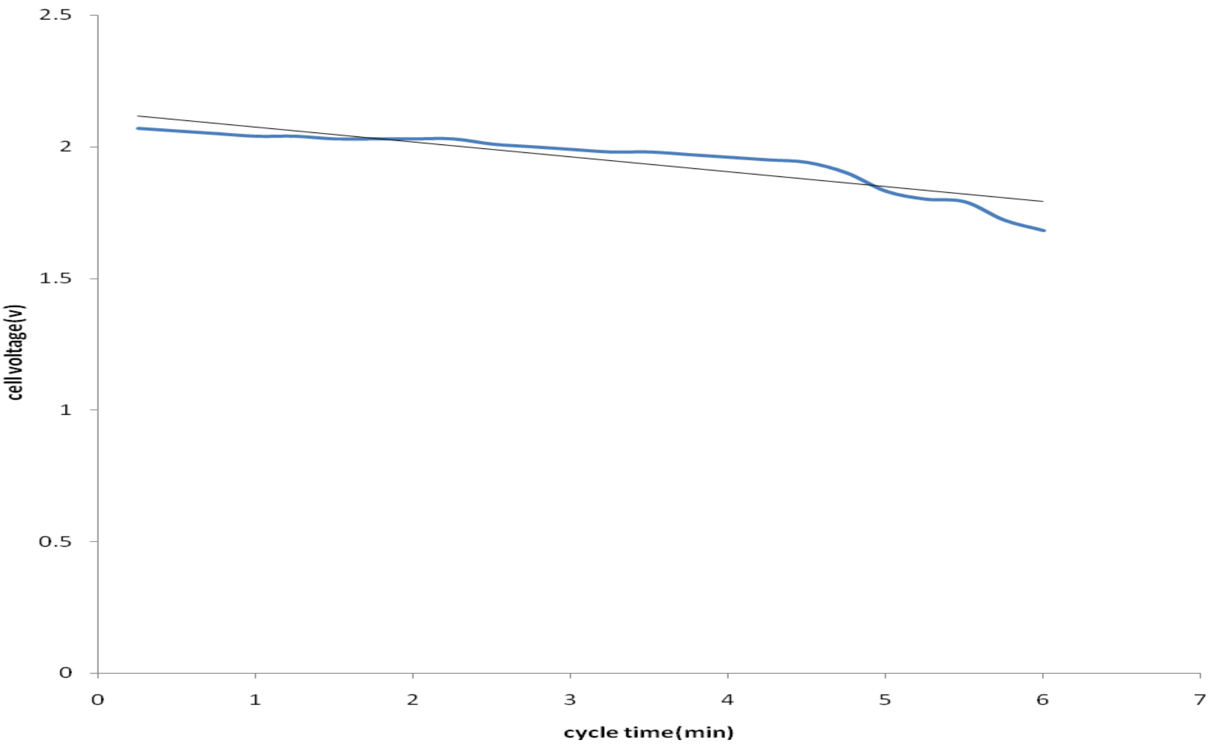

Figure 7: The cell voltage versus cycle time for GA battery during discharging process.

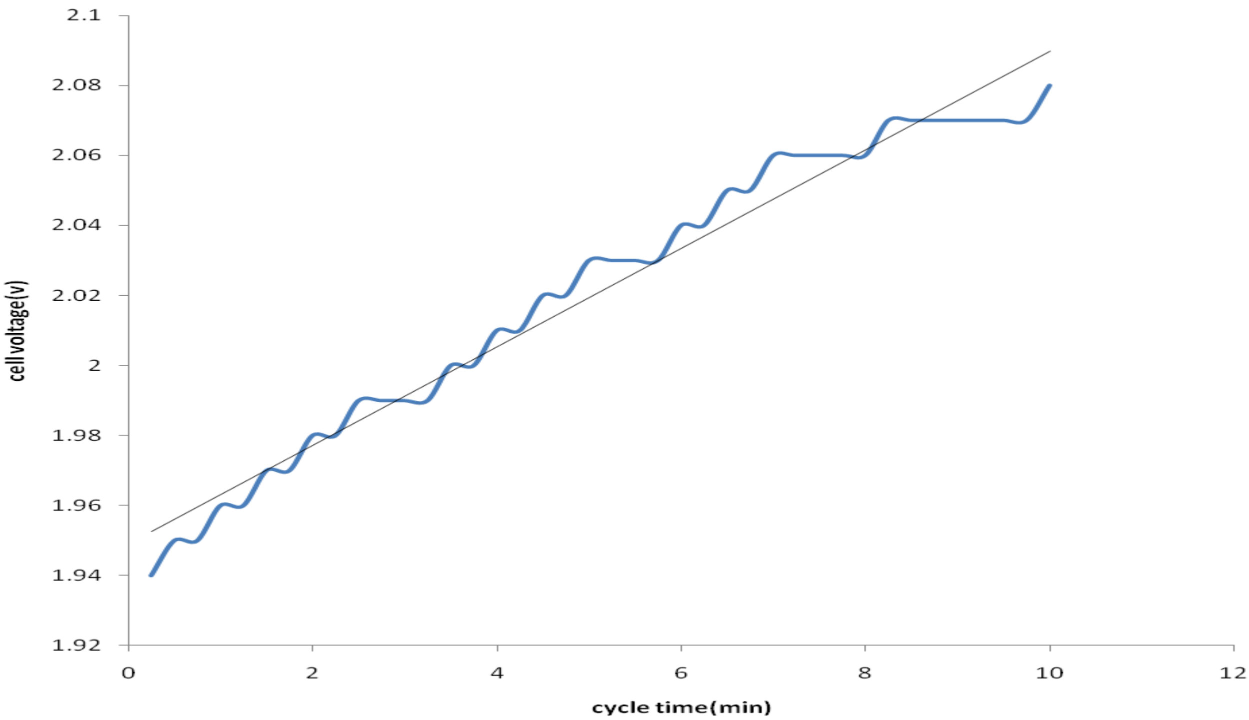

Figure 8: The cell voltage versus cycle time for GA battery during charging process.

DISCUSSION

The I-V characteristics (Figures 1 – 4) of the typical employed two lead acid batteries (Gaston and GA models) show that the relationship was not linear and non-ohmic for the rate of charge and discharge processes.

The cell voltage versus cycle time of GA battery has a plateau value of 1.80V before dropping to a minimum voltage of 1.68V during discharging process. During charging process, the plateau value was 1.94V after which it rose to maximum voltage of 2.08V.

For Gaston battery, the plateau value was 1.69V which was held for about 15 minutes before the inverter was automatically switched off during discharging process. During charging process, the plateau value was 1.94V and later rose to maximum voltage of 2.04V.

Hence, the plateau value for Gaston battery during discharge is lower than that of GA under the same state of discharge. Table 6 briefly summarizes the behaviour of the employed lead acid batteries. Figures 9 and 10 depicted the curves for GA and Gaston batteries during charging and discharging process respectively. The lowered nominal voltage or plateau of Gaston battery can favour its usage compared to GA battery.

Table 6: Comparison of Voltages of the typical employed lead acid batteries.

Battery	Plateau during discharging Process	Minimum Voltage during discharging process	Plateau during charging process	Maximum Voltage during charging process.
GA	1.80V	1.68V	1.94V	2.08V
Gaston	1.69V	1.69V	1.94V	2.04V

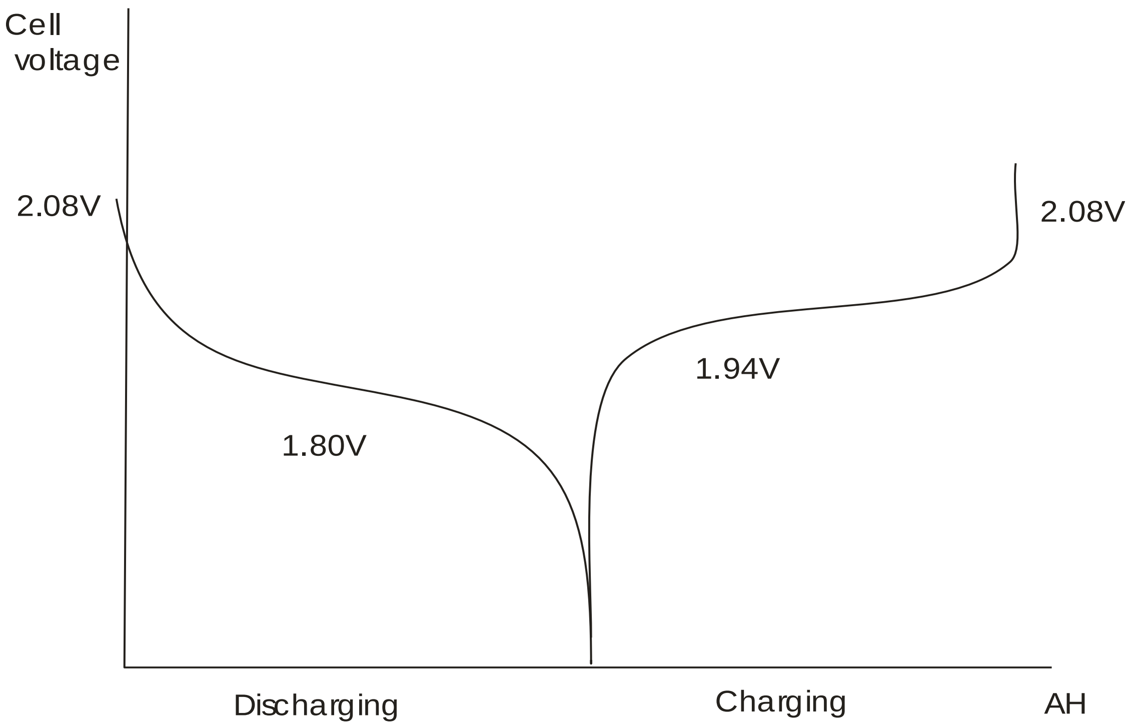

Figure 9: Maximum and nominal voltage for GA battery during charging and discharging process.

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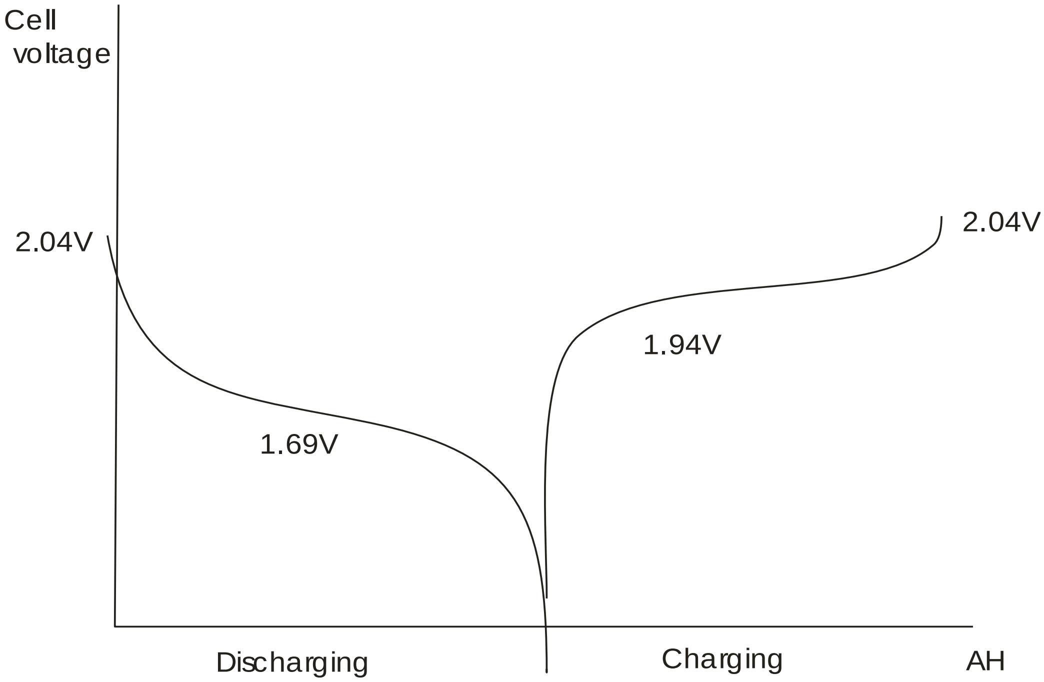

Figure 9: Maximum and nominal voltage for Gaston battery during charging and discharging process.

In comparison, the cell voltage during a typical charge/discharge cycle for NiMH and NiCd electrochemistry with nominal voltage of 1.2 is shown in Figure 10.

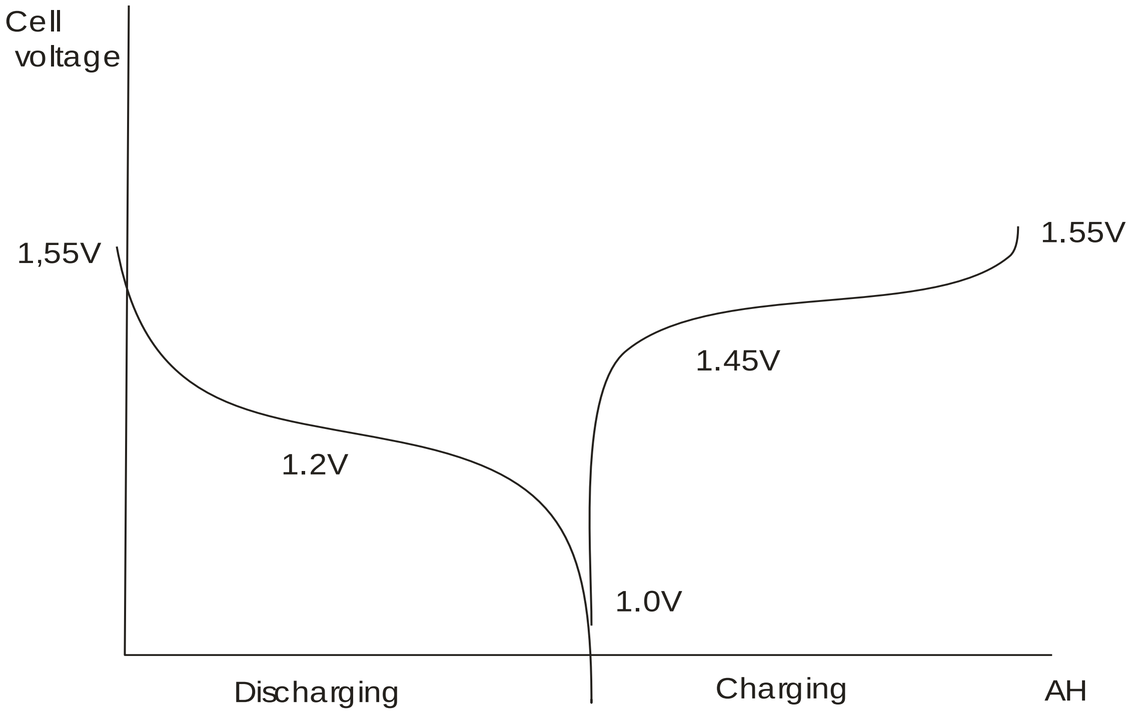

Figure 10: Voltage variation during charge/discharge cycle of Nickel-Cadmium cell with nominal voltage of 1.2V (Patel, 2006).

Though the nominal voltages of NiMH and NiCd batteries are lower than the lead acid batteries, Patel (2006) had revealed that the overall cost of the lead-acid battery is low compared to NiMH, NiCd and Li-ion batteries. Because of its least cost per Watthour delivered over the life, the lead-acid battery has been the workhorse of the industry (Wicks and Hails, 1995).

The ratio of charge/discharge is 1:1 for GA battery. It is also 1:1 for Gaston battery. The charge/discharge ratio of 1:1 of these lead acid batteries is in conformity with 1:1 ratio obtained for typical NiMH and NiCd batteries (Patel, 2006) that has cell voltage of 1.2V.

The round – trip energy efficiency for Gaston battery is calculated as

$$\eta_{energy} = \frac{1.80 \ x \ 200}{1.94 \ x \ 1.1 \ x \ 200} \ x \ 100 = 84.3\%$$

The round – trip energy efficiency for GA is calculated as

$$\eta_{energy} = \frac{1.69 \ x \ 100}{1.94 \ x \ 1.1 \ x \ 100} \ x \ 100 = 79.2\%$$

$$\Delta\eta_{energy} = \eta_{energy}\,(Gaston) - \eta_{energy}(GA) = 84.3\,\% - 79.2\%$$

$$\Delta\eta_{energy} = 5.1\%$$

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