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Ageing in Photovoltaic Lead Acid Batteries and Its Effect on Charge/Discharge Efficiencies, in Relation to the Magnitude of Electric Charging Current Rates

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Abstract

Using circuit diagrams presented in literature, two types of Constant Current (CC) charge controllers were built for experimental purposes and used to charge and discharge batteries at different time intervals, at different current rates and their corresponding efficiency values were computed and compared. In separate experiments, batteries were used to store battery capacity at different charge and discharge rates, from which it was confirmed that with 10Ah capacity stored separately in the old Vanbo and the Vanbo at different current rates, the charging efficiency for the older battery was lower than that of the newer battery. The end voltages after charge varied in a non-proportionate manner with the constant charging current rates tested for old batteries. For the new battery, the efficiencies obtained were higher than those of the old battery. It shows then that charge and discharge cycles at different magnitudes of CC can be used to determine the state of health of lead-acid batteries. It was also found that an increase in their aging process doesn't only lower charge/discharge efficiency, it disrupts end voltage variations after charge, without considerable change in connection with the magnitude of battery capacity tested.

Keywords

Efficiency, Battery Ageing, Current Magnitude, Energy

1. Introduction

The necessity of electrical energy cannot be undermined in all sectors of life.

The human population keeps increasing with projections to reach 9 billion people on the planet by 2050 [1] and all these people will need energy to survive. Many countries have witnessed a great deal of development thanks to the setting up of electrical power systems [2]. As concerns urbanization and industrialization, there exist a positive correlation between industrialization and energy security [3], showing that industrialization is preceded by energy supply. Also, remote areas are in need of electricity as well [4]. It has been projected that 77% of the world may still depend on fossil fuels by 2040 if there is no replacement of fossil fuels with other sources of energy [5]. If the use of fossil fuels keeps rising, oil prices will keep increasing [6] and it will have a negative effect on world's security in the sense that tussles on who should occupy regions of high content of fossil reserves will be on the rise [7]. Renewable sources of energy are therefore very necessary to meet global energy needs so as to fight against climate change. However, these sources are very intermittent, giving rise to the need for energy storage devices which store energy during high peak periods to be used during low peak periods.

Photovoltaic (PV) systems are good examples of such systems that make use of storage devices. PV can be grid-connected, which means that they are linked to the national grid to supply energy to the grid in times of energy shortage from the grid, or to receive energy from the grid when the PV system is found wanting in terms of energy availability [8]. PV systems can also be stand-alone, meaning they are neither linked to the grid nor to other Distributed Generation (DG) renewable sources of energy [9], in which cases storage will be very important. Nevertheless, in most system types, Energy Storage Systems (ESS) are imperative so as to increase their reliability [10] [11]. Again, due to the variability of solar energy, power regulation is enhanced when ESS is deployed [12] [13]. Energy can be stored either in thermal form [14]-[16], mechanical form [17] [18], electrical form or in chemical form [19]. Chemical storage can include but is not limited to the use of Fuel cells [20] and batteries [21]. Lead acid batteries work by taking advantage of electrochemical reactions between electrolytes and electrodes. The way in which these batteries are used has an effect on how efficient they will function during their lifetime.

The present paper mainly sets out to demonstrate how to use magnitude of constant charge/discharge current rates to investigate the effect that a battery state of health conditioned by ageing, can have on the charge/discharge efficiency of lead acid batteries. From results obtained by a recently published paper, which will be shown below, old and new batteries were charged and discharged and their efficiencies compared to each other for conclusions to be made. However, before getting to the details of the techniques used in the topic, there will be a need to use literature to explain the rational of the research work. Nevertheless, the paper organization follows below.

This paper is organized as follows: in section one, under the introduction, the general notions about energy have been presented with emphasis laid on how energy can be harnessed in PV systems to solve the energy problems of mankind, then streamlining the discussion down to the need for energy storage. The literature review on State of Health of batteries is also outlined in this section, followed by explanation of charging and discharging techniques existing today. The next section is section two which is the materials and methods section in which the different materials and equipment used to run the experiments are outlined with the experimental protocols deployed in this work are elucidated upon. Then follows the results section, which is section three, where the important findings that were obtained and presented with corresponding discussions. The paper ends with section four, which is a conclusion section in which the findings were summarized into recommendations and presented the perspectives of the work.

1.1. Battery State of Health Estimation

The estimation of the state of health (SOH) of batteries has been crucial since the unset of the battery technology because it predicts the time expected for a battery to function optimally before failing completely [22]. Electrochemical Impedance Spectroscopy (EIS) has been one of the methods widely used to understand the dynamic processes that occur inside the battery which could lead to failure [23]. Even though it comes with the advantage that the physical integrity of the battery is not too tempered with during the test, the method still remains expensive, needing more complicated electronic circuits and equipment to be built. Another method for state of health estimation is that of deep learning approach with direct current internal resistance reported by Zhongxian *et al.* in [24] and using Deep Neural Networks combined with internal resistance to determine the State of health of lithium ion battery but the method requires high technical knowhow with computer computations and simulations which can only easily be supported by lithium ion batteries. This differs from the case here since the objective is to get a simpler and easier-to-apply approach to getting the SOH of a lead acid battery instead of a lithium-ion battery. Jinhua *et al.* also used a neural network [25] where the interpretability of the results were enhanced, but the very problem of the cumbersomeness of method remains.

Predictions of battery SOH models are usually carried out by simulations before being applied practically in physical circuits. For example, in [26], Zhang Fan *et al.*, presented a SOH estimation scheme based on BP neural network optimized by a Genetic Algorithm - Back Propagation (GA-BP) and fixed characteristic voltage interval to deal with the randomness of data. This ended up with some accuracy validation using the Monten Carlo method. However, just like every neural network-related strategy, this method is still at research stage and complex in conception and implementation.

1.2. Charging and Discharging Methods for Batteries

There are many charge and discharge techniques that are currently being applied in charge controllers for batteries, whose charge and discharge profiles could be used to decipher to a certain degree the state of health of batteries in order to predict their periods of failure. By so doing, the battery will be used to determine its degradation. This can revolutionaries SOH monitoring using simpler circuits which serve both for charge/discharge activities and SOH monitoring.

The charging and discharging techniques used to charge these batteries keep surfacing on daily basis. Some of the methods to charge batteries are: the trickle charge method which hardly really serves as a complete charging method on its own but as a step during the charging process [27]. It consists of charging highly discharged battery so as to limit the initial charging current in order to prevent battery destruction. It is only suitable to serve as a phase of the charging process and not as the method for complete charging. Another method is the Five-step charging pattern [27] which uses five different constant current magnitudes in decreasing order to charge the battery to full. It has the limitation that if the battery is seriously discharged, high current values at the beginning of the charge can destroy the battery. The Pulse charging method on its own part charges the battery very safely by applying small current pulses permitting to charge the battery but the efficiency of charge will hardly be able to be calculated because of the numerous electric current pulses throughout the charging process [28] [29]. The boost charging method on its own side really facilitates charging and even with means of measuring charge efficiency but are more adapted for use in lithium-ion batteries than lead acid batteries [30]. There are also other methods reported in literature like the constant current [31] constant voltage [32] and two step methods [33].

Charging protocols can have an influence on the health of the batteries and at the same time using constant charge to charge the battery may give particular signature which can be used to decipher the state of health of the battery. This is very possible if the charge-discharge protocols were carried out under constant current. In [34], the Suh *et al.* used constant charging methods to show that the higher the current rate, the greater the efficiency of the charge/discharge process. More so, in [35], the Suh *et al.* showed that it is possible to use open circuit voltages to decipher the state of health of lead acid batteries but just that the method could not be used on highly degraded batteries and ageing could not be evaluated without disconnecting the battery. It also involves the very intense solicitation of the battery such that at the end of the test, the capacity of the battery may have largely diminished. Pierre *et al.* in [36], continued to demonstrate that higher charge current rates will increase the efficiency of the charge/discharge process of lead-acid batteries but brought in the temperature factor, showing that temperatures of the electrolytes did not exceed 500C even at current rates as high as 8A, for batteries with relatively good states. However, they latter failed to provide juxtaposing evidence that monitoring lead acid batteries charge and discharge at a constant rate can give an indication of the state of charge of the battery.

That is where this present work comes in.

2. Materials and Methods

The most important materials used in this research work are three lead acid batteries: a new Vanbo battery [37], an old Vanbo battery [37], a New Win Bright battery [38], a 5A Constant Current Circuit (5A CCC), and an 8A Constant Current Circuit (8A CCC). The two CCCs were built in the electronic laboratory and used to carry out the experiments. The charging and discharge protocols were performed using electronic circuits and protocols described in [34], [35] and [36].

For the first and second set of experiments, the new Vanbo battery and the old Vanbo battery were used respectively and charging and discharge processes were carried out through the 5A CCC and the 8A CCC, respectively, taking place at 5 different rates: 1A, 2A, 3A, 4A and 5A. The charge efficiencies for the different current rates were calculated in the same way as were done in [34]. The selection of the current values for the two CCCs was performed by adjusting the nubs of the rheostats, permitting to obtain the quasi-constant current values that are used to charge and discharge the batteries. Varying the resistive paths of the charge and discharge sections, gives rise to a corresponding variation in the constant charge and discharge electric current rates.

The 8A CCC was again used on the Win Bright battery, where the charging and discharging took place through the circuit and efficiencies per current rates were computed. For all three batteries, plots of the current versus time for all the current rates tested per battery were made and analyzed. The voltage variations for all the batteries for all the 5 current rates tested were also plotted per battery and the conclusions made. In addition to that, the end voltages after charge and efficiencies with respect to all the five current values were plotted for the three batteries investigated. Figure 1 shows a block diagram of the experimental test bench that was put in place for the 5A CCC, and Figure 2 shows the circuit diagram for the charge and discharge process.

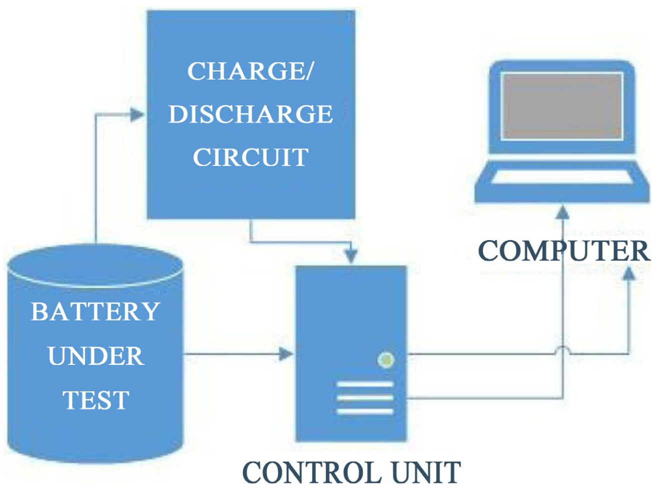

Figure 1. Experimental test bench for the 5A CCC [1].

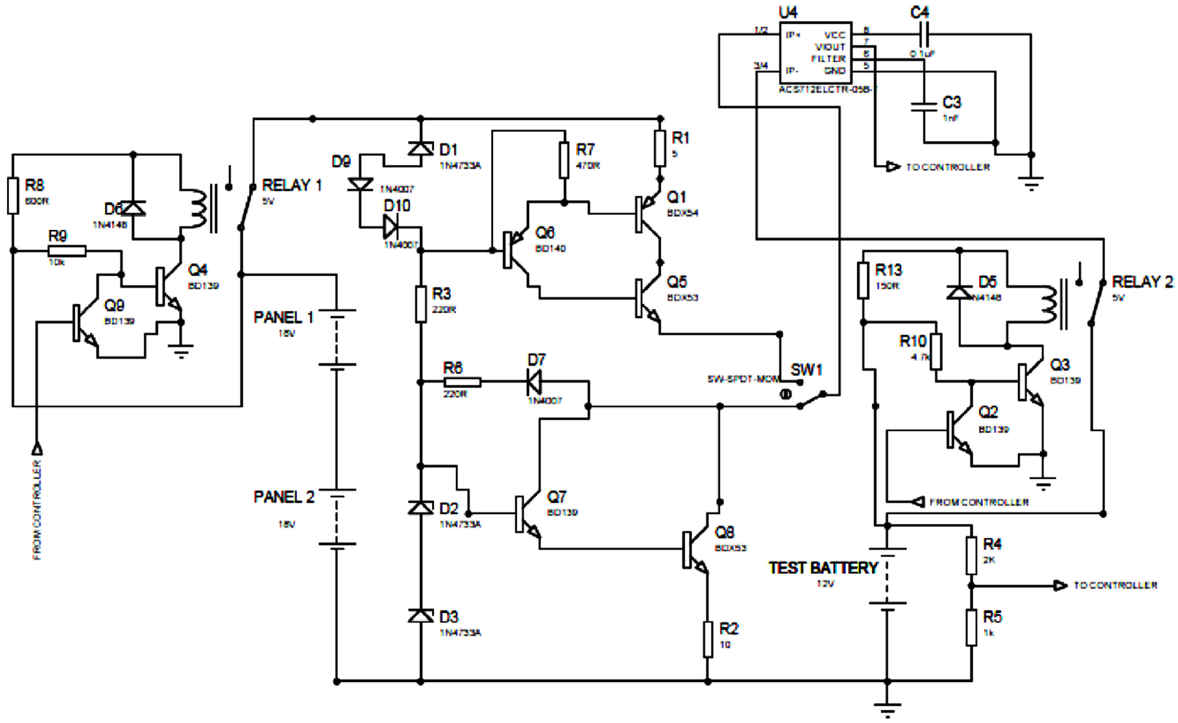

Figure 2. The 5A constant Current Circuit [2].

The circuit is made up of two sections which include charge and discharge. The switch SW1 helps to change from charge to discharge and vice versa. The current sensor U4 permits the measuring of the current for either the charge or discharge and value sent to the microcontroller. The voltage of the battery was also measured through a voltage divider configuration which was sent to the microcontroller for measurement. The microcontroller was interfaced to the computer, where all the values of the current and the voltage were displayed and recorded in real time for later analysis.

As the experiments progressed, whether for the charge or for the discharge phases, the current values were being measured in real time and written on the computer monitoring system for analysis. As far as voltage is concerned, an output from the circuit was from a voltage divider through which the actual voltage for the battery was measured and printed on the computer monitoring system. The time for the experiments was measured from the start of charge to the end of discharge and was done by a programmed microcontroller. It should be noted that the current and the voltage values too were logged on to the computer monitoring system after being sensed and measured by the microcontroller. Note should also be taken that for the experiments conducted, both batteries were identical in terms of the rated capacities, which were all 100Ah capacity batteries. However, the energy input and energy output varied for the new and the old batteries. The experiments conducted on the new Vanbo battery were done in such a way that 5Ah capacity was stored per current rate tested, and discharge took place at 2A for different charge currents ranging from 1A to 5A. On the other hand, the experiments performed on another old Vanbo battery and one new

Win bright battery, but charging that took place was done in such a way that the capacity stored was 10Ah per current rate with different charge current rates ranging from 1A to 8A. This limitation was set because the circuit was constructed to support only current values below 8A and this was also appropriate so as to avoid overheating the batteries. This was so conceived in order to track whether or not the efficiency of the battery could depend on the magnitude of battery capacity stored. **Figure 3** below shows the physical electronic circuit for the 5A CCC followed by **Figure 4**, which details its electronic circuit.

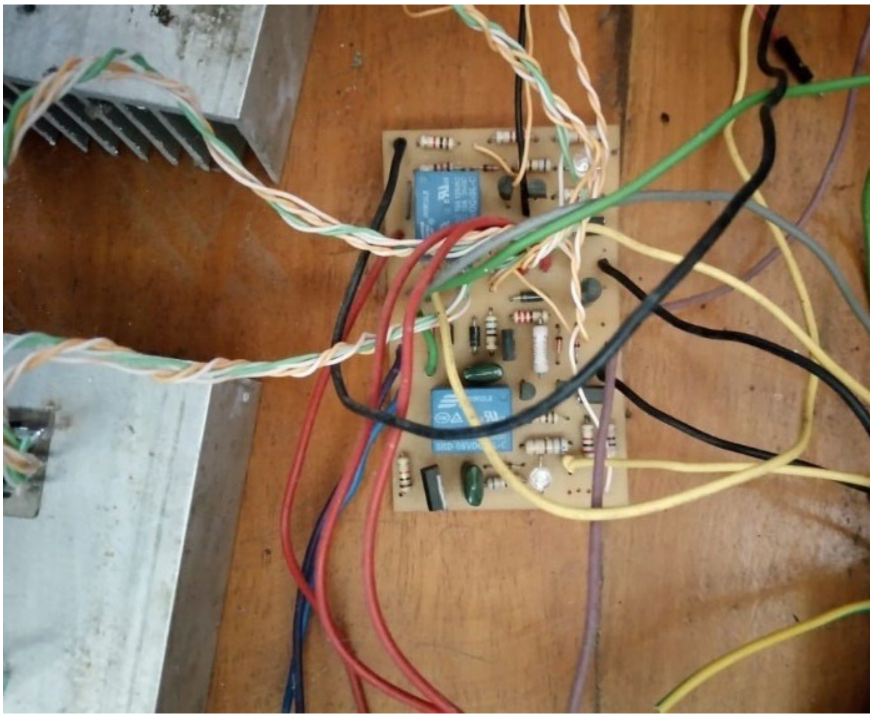

Figure 3. The 5A Constant Current Circuit.

The circuit is capable of producing a maximum constant current of 5A. The relays are used to stop the charging and the discharging sections as needed during the experiments. **Figure 4** shows the experimental test bench for the 8A CCC. This is followed by **Figure 5**, which shows the electronic circuit of the 8A CCC.

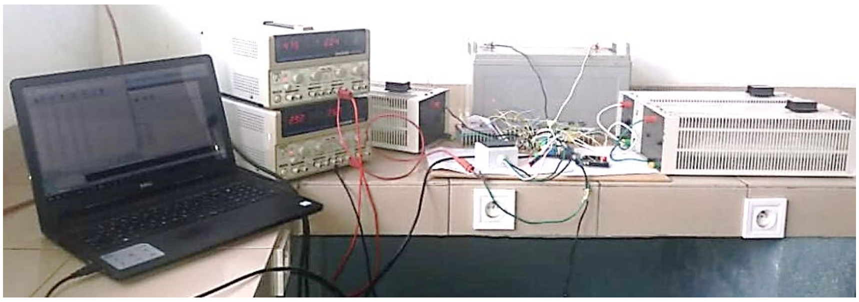

Figure 4. The experimental test bench for the 8A CCC.

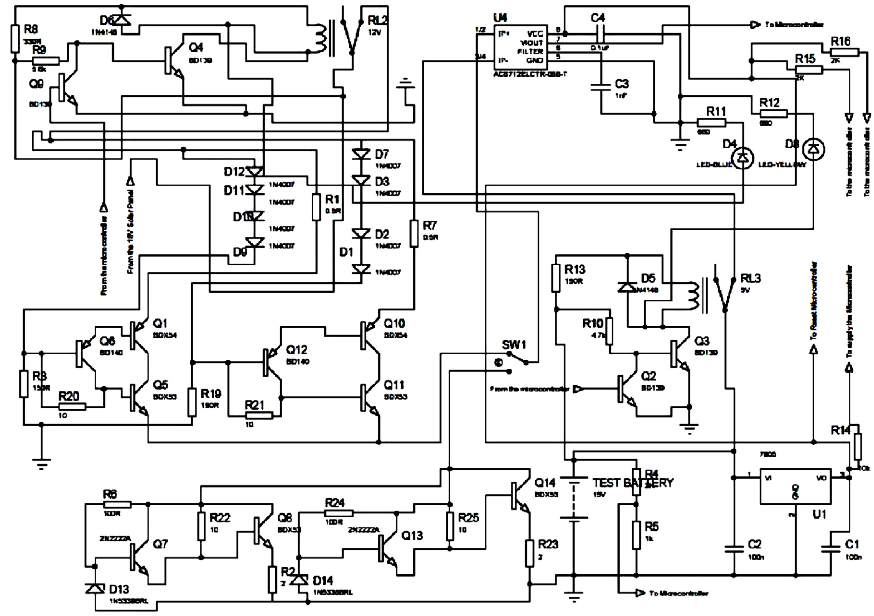

Figure 5. The electronic circuit of the 8A Constant Current Circuit [36].

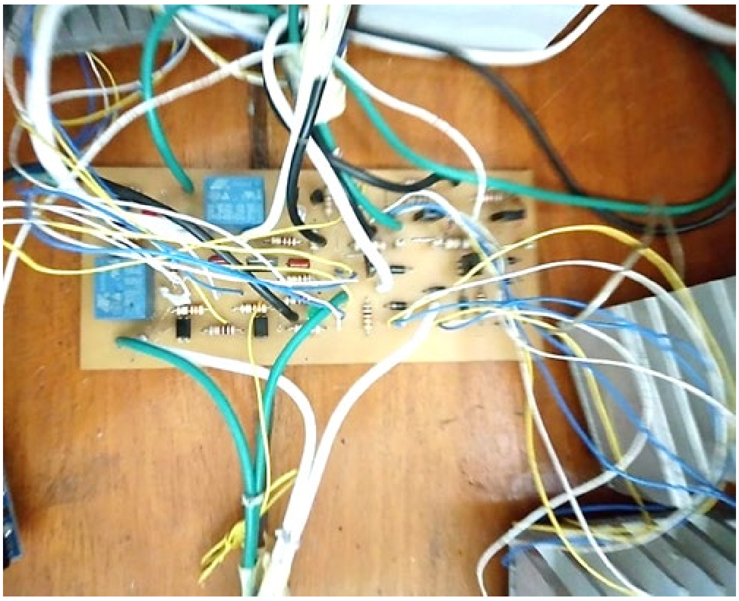

Figure 6. The 8A Constant Current Circuit.

The main difference observed between the 5A CCC test bench and the 8A CCC test bench is at the level of the rheostats. Two rheostats are used in the 5A CCC test bench while three are used for the 8A CCC test bench. The computer monitoring system plays the same role of recording the time, voltages and current values during the experiment.

It should be noted that the electronic circuits used to run these experiments are divided into two sections, one for charging and the other for discharging. With the help of a single pole double throw switch, after the expected theoretical battery capacity had been stored in the battery, the switch is used to change from charge to discharge in such a way that an action on it immediately disconnects the charging section and connects to the discharge section and the discharge relay stops the discharge when the voltage of the battery has dropped to the reference lower voltage of 11.3 V. This process takes place in the same way for all the different current rates tested and for all the three batteries, controlled with the helped of a microcontroller.

3. Results

The results presented are for three sets of experiment conducted on a new Vanbo battery [37], an old Vanbo battery, and a New Win Bright battery [38]. It is worth noting that after the experiments with the new Vanbo battery, it was used in the laboratory for close to nine months. This time allowed the battery to gain some aging effect. For this reason, during the second phase of the experiment, the battery was tested and referred to as the old Vanbo battery. From the results presented, it will be glaringly outstanding that for all the charging rates used to store battery capacity in the new Vanbo battery, only 5Ah of capacity was stored while for the old Vanbo battery and the New Win Bright battery, up to 10Ahr battery capacity was stored. However, the efficiencies can still be compared since they are in percentages for all three batteries tested. It was incumbent to test at least one of the batteries with a different magnitude of capacity stored so as to ascertain if the magnitude of stored capacity could have an influence on the efficiency or not.

3.1. Electric Current

3.1.1. Plot of 1A Current Rates

Figure 7 below shows the plot of the variation of the 1A current for all the three batteries tested.

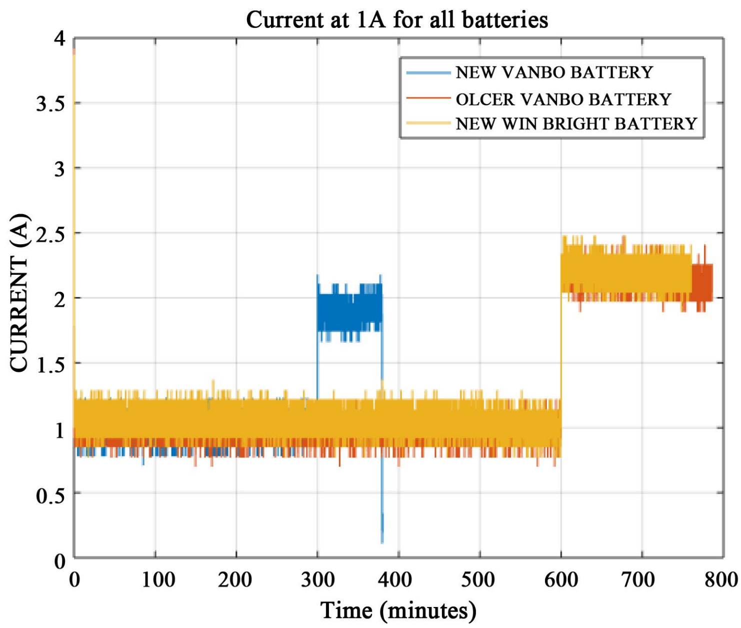

Figure 7. Current variation for the three batteries at an electric charging rate of 1A and a discharge rate of 2A.

It is noticed that the storage of 5Ah of capacity with the new Vanbo battery records an efficiency of 38.2%, for the old Vanbo battery, it stores 10Ah of capacity registering an efficiency of 60% and for the New Win Bright battery, an efficiency of 53.3% was obtained after storing 10Ah of battery capacity. The older battery seems to have been more efficient than the newer ones. This is explained by the fact that at these low charging current rates, the charging is inefficient and so the battery turns to take the time of charge to restore its recovery energy. So, the seemingly high efficiency is due to the recovery energy of the battery gotten from the former processes with the battery. This then suggests that energy recovery levels are different for different state of charge levels.

3.1.2. Plot of the Results for the 2A Current

Figure 8 below shows the plot of the variation of the 2A current for all three batteries tested.

The new Vanbo battery registers a 77% efficiency, the old Vanbo battery registers a 62% and the New Win Bright battery registers a 52%. The older battery shows a smaller efficiency compared to the new one. This is expected, given that age should have an effect on the efficiency.

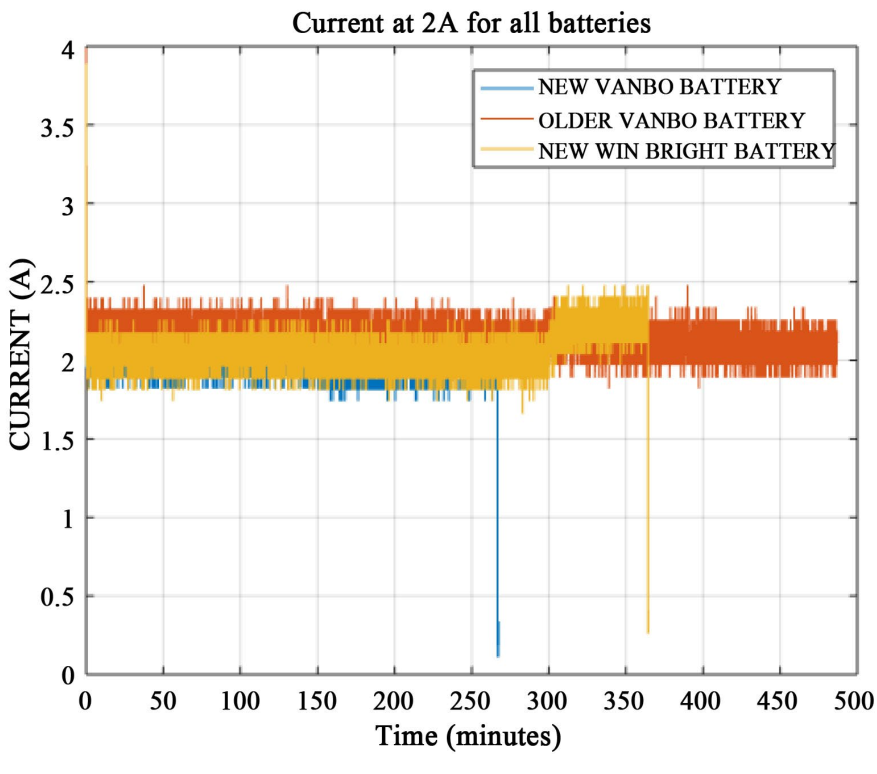

Figure 8. Variation of the 2A current charge and 2A current discharge for all the three batteries tested.

3.1.3. Plot of the Current for the 3A Current Rate

Figure 9 below shows the plot of the variation of the 3A current followed by a discharge of 2A for all the three batteries tested.

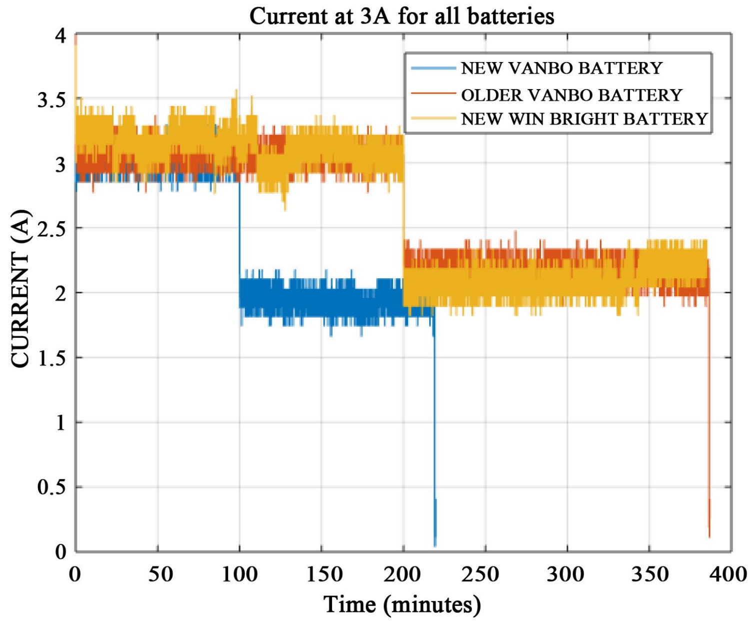

Figure 9. Variation of the 3A current charge and 2A current discharge for all the three batteries tested.

The new Vanbo battery had an efficiency of 80.6%, the old Vanbo battery 62.2% and the New Win Bright battery of 65%. The older Vanbo battery registers a smaller efficiency than all the other two batteries tested.

3.1.4. Plot of the Current for the 4A Current Rate

Figure 10 shows the variation of current at 4A charging rates and 2A discharging rate for all the three batteries tested.

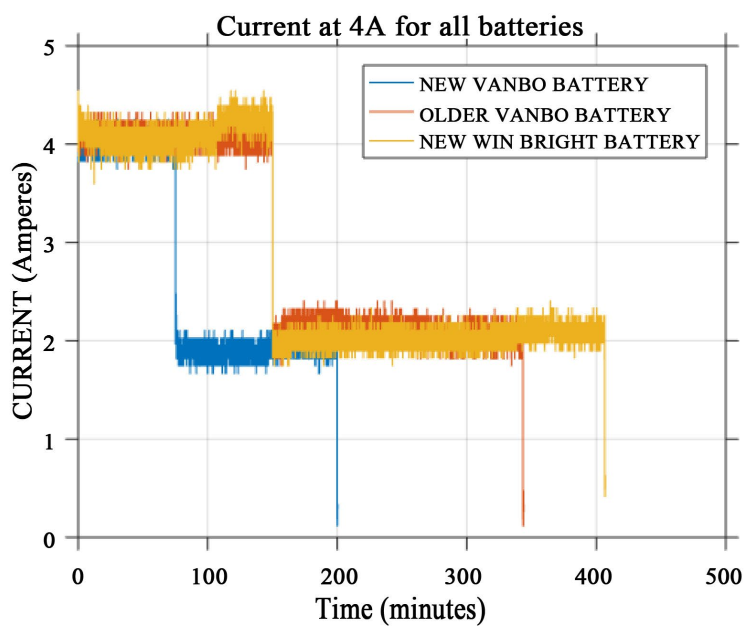

Figure 10. Variation of the 4A current charge and 2A current discharge for all the three batteries tested.

The new Vanbo battery registers an efficiency of 83%, the old Vanbo registers an efficiency of 64% while the New Win Bright battery registers an efficiency of 85%. The older Vanbo battery registers a lower efficiency than all of the other batteries.

3.1.5. Plot of the Current for the 5A Current Rate

Figure 11 below shows the plot of the variation of the 5A current followed by a discharge of 2A for all the three batteries tested.

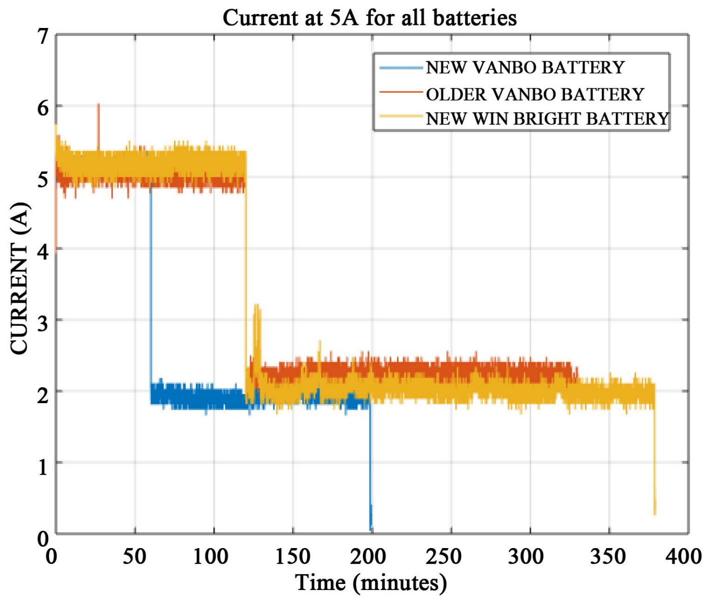

Figure 11. Variation of the 5A current charge and 2A current discharge for all the three batteries tested.

The new Vanbo battery registers an efficiency of 93.3%, the old Vanbo battery registers an efficiency of 70% while the New Win Bright battery registers and efficiency of 86%. The older battery registers a lower efficiency compared to the others

3.2. Plots for the Voltage Variations Per Charging Current Rate

3.2.1. Variation of Voltage for a Charge Rate of 1A Followed by a Discharge Rate of 2A

Figure 12 shows the variation of the voltage of the three batteries when being charged at a current rate of 1A then discharged at a rate of 2A.

The new Vanbo battery charges up to a voltage of 12.27V storing just 5Ah of capacity before discharging. For the older Vanbo battery, it stores 10Ah capacity raising the voltage to 12.47V and for the same capacity storage of 10Ah with the New Win Bright battery, the voltage increases to just 12.0V. This behavior of the old Vanbo battery is so uncalled for and it is blamed on the increased unpredictable dynamic nature of the battery due to ageing, which leads to lower efficiencies.

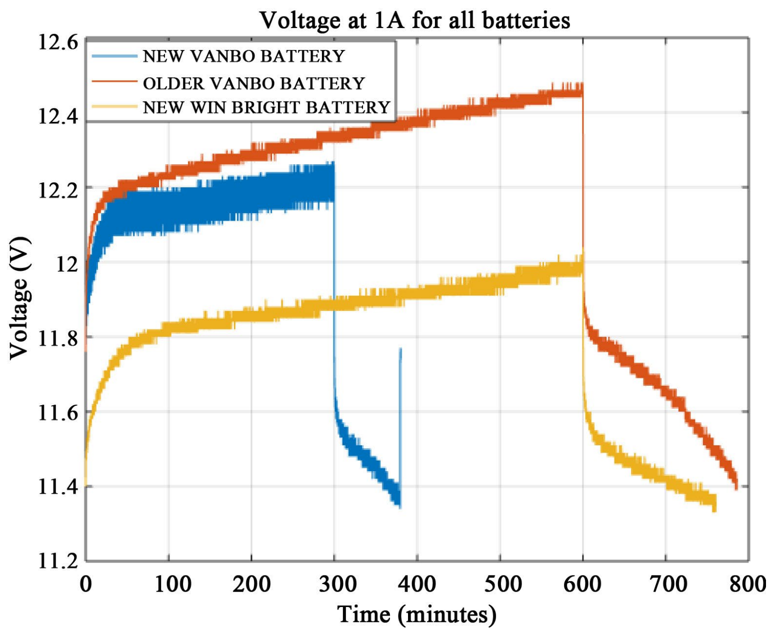

Figure 12. Voltage variation for the charge at 1A followed by a discharge of 2A.

3.2.2. Variation of Voltage for a Charge Rate of 2A Followed by a Discharge Rate of 2A

Figure 13 shows the variation of the voltage when the charge took place at 2A and discharge at 2A.

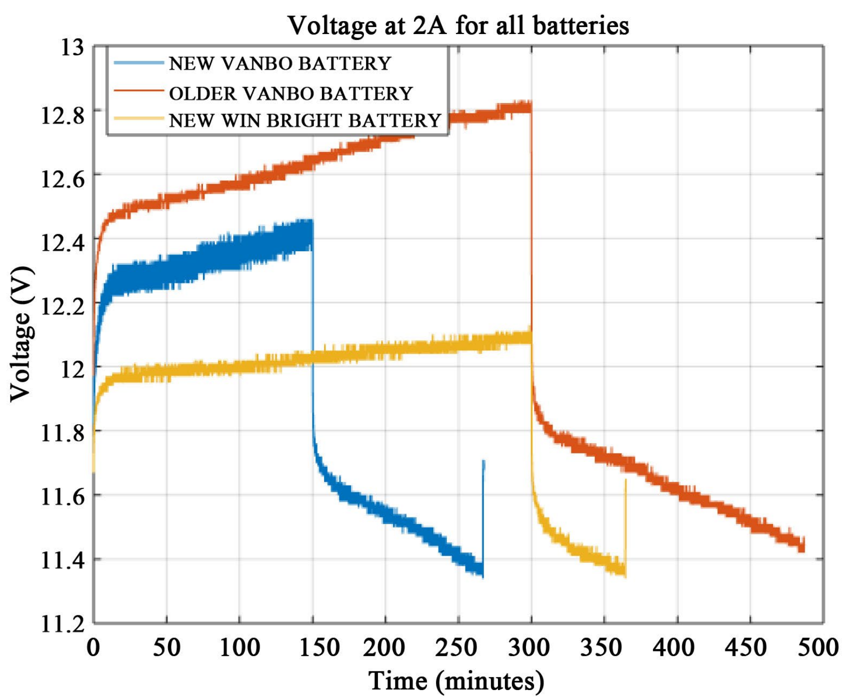

Figure 13. Variation of voltage for a charge rate of 2A followed by a discharge rate of 2A.

The old Vanbo battery continues to show a higher end voltage even though it stored the same 10Ah of energy as the New Win Bright battery. This continues to suggest that the age of the battery distorts the linear expectations of the battery. The unifying factor for these parameters is that they are all batteries of the same technology (Lead acid battery) and they use comparing parameters of energy efficiency. So we have three different batteries of the same technology and different ages being compared according to their different charge/discharge efficiencies.

3.2.3. Variation of Voltage for a Charge Rate of 3A Followed by a Discharge Rate of 2A

Figure 14 shows the variation of the voltage when the charge took place at 3A and discharge at 2A.

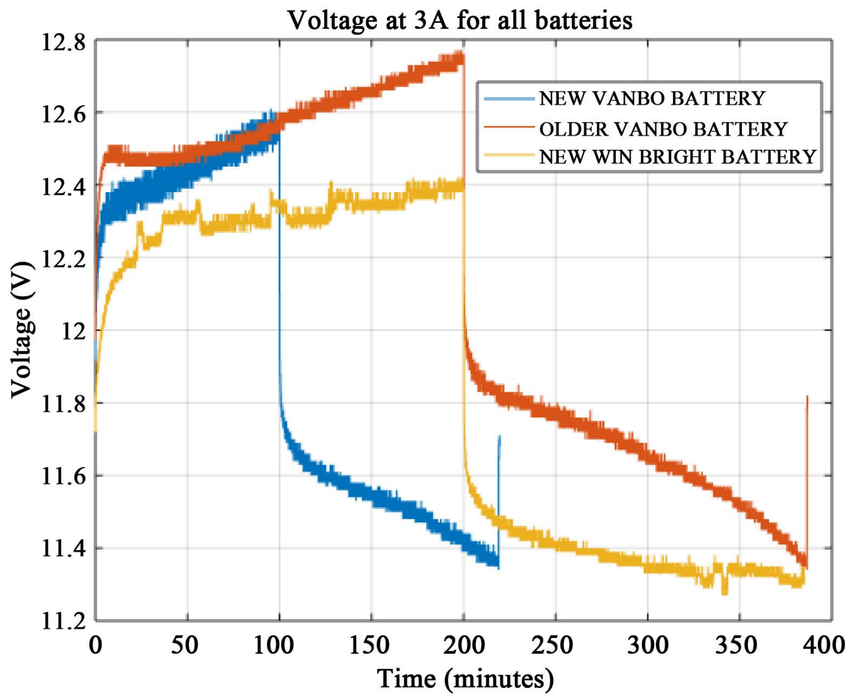

Figure 14. The variation of the voltage when the charge took place at 3A and discharge at 2A.

The older Vanbo battery records a higher end voltage, showing a discrepancy from the expected results. This is due to its lower efficiency. The voltage could just be a virtual one showing up due to inconsistencies coming in because of the age of the battery.

3.2.4. Variation of Voltage for a Charge Rate of 4A Followed by a Discharge Rate of 2A

Figure 15 shows the variation of the voltage when the charge took place at 4A and discharge at 2A.

The New Win Bright battery here discharges for a longer period compared to the old Vanbo battery and for the end voltages, the older Vanbo battery still registers a higher end voltage compared to the New Win Bright battery but registers a very slightly lower end voltage compared to the new Vanbo battery.

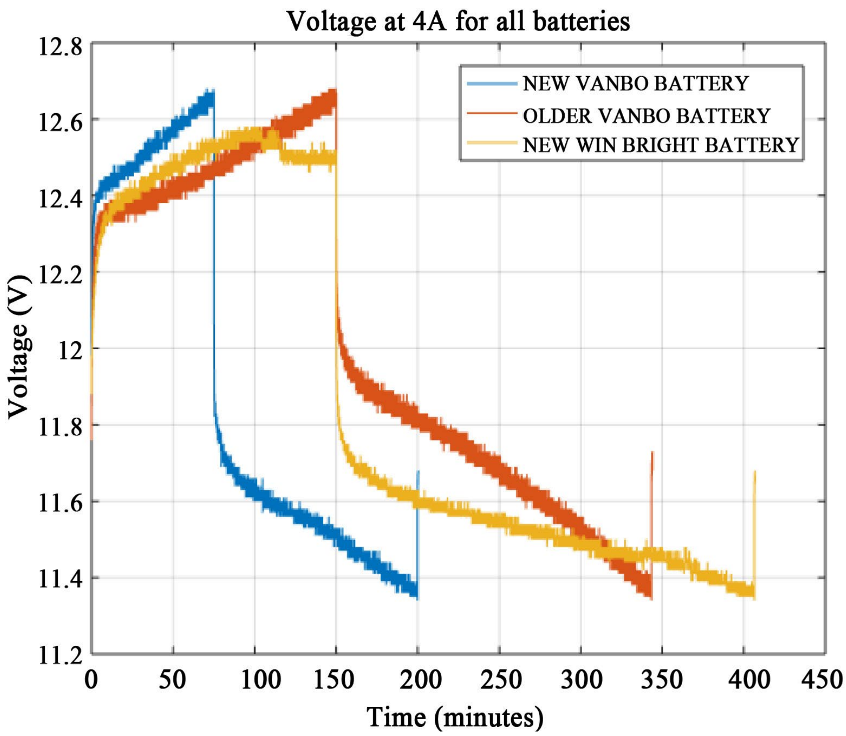

Figure 15. Variation of voltage for a charge rate of 4A followed by a discharge rate of 2A.

3.2.5. Variation of Voltage for a Charge Rate of 5A Followed by a Discharge Rate of 2A

Figure 16 shows the variation of the voltage when the charge took place at 5A and discharge at 2A.

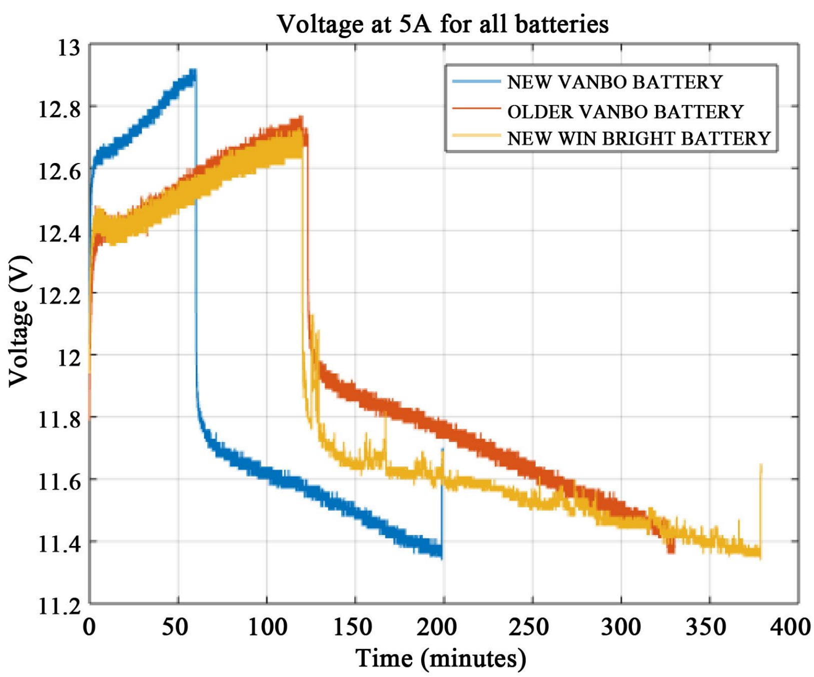

Figure 16. The variation of the voltage was observed when the charge took place at 5A and discharged at 2A.

The higher the current value, the closer the end voltage of the Win Bright battery to that to the old Vanbo battery. The older Vanbo battery registers almost the same end voltage with its New Win Bright battery counterpart but still shows a slight increase in end voltage compared to the New Win Bright battery.

The old Vanbo battery demonstrates inconsistency in the sense that it registers higher end voltages but the discharge level is not as good as expected. It appears to have stored some good quantity of energy when the voltage is considered but the discharge at the same rate causes it to quickly reach the lower cut off voltage and by so doing reducing the efficiency.

3.3. The end Voltages Recorded by All the Three Batteries as Per Current Rates Used

Figure 17 below shows the end voltage variations for all the three batteries tested.

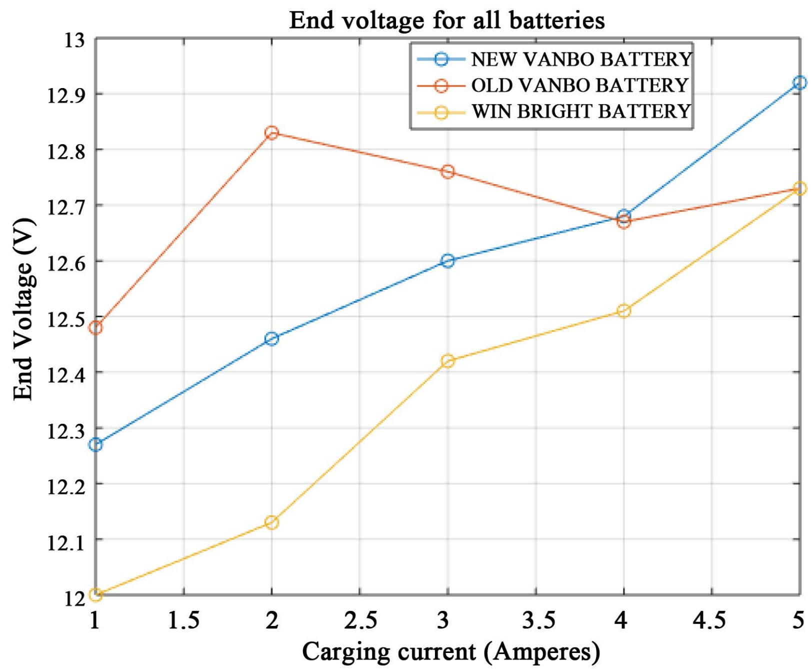

Figure 17. The variation of the voltage when the charge took place at 5A and discharge at 2A.

The higher the current value, the closer the end voltage of the Win Bright battery is to that of the old Vanbo battery. The older Vanbo battery registers almost the same end voltage with its New Win Bright battery counterpart but still shows a slight increase in end voltage compared to the New Win Bright battery.

The old Vanbo battery demonstrates inconsistency in the sense that it registers higher end voltages but the discharge level is not as good as expected. It appears to have stored some good quantity of energy when the voltage is considered but the discharge at the same rate causes it to quickly reach the lower cut off voltage and by so doing reducing the efficiency.

3.4. The End Voltages Recorded by All the Three Batteries as Per Current Rates Used

Figure 18 below shows the end voltage variations for all the three batteries tested.

It is conspicuously noticed that the efficiency of the older Vanbo battery was lower than that of the other batteries. The only discrepancy was at the 1A current where it registered a higher efficiency. This confirms more the suggestion that was made earlier that the recovery energy of a lead acid battery affects the battery behavior more at different employed charging currents. That means that for the time period between the first and second usage, the Vanbo battery depreciated by ageing and this diminished the efficiency of the charge and discharge processes.

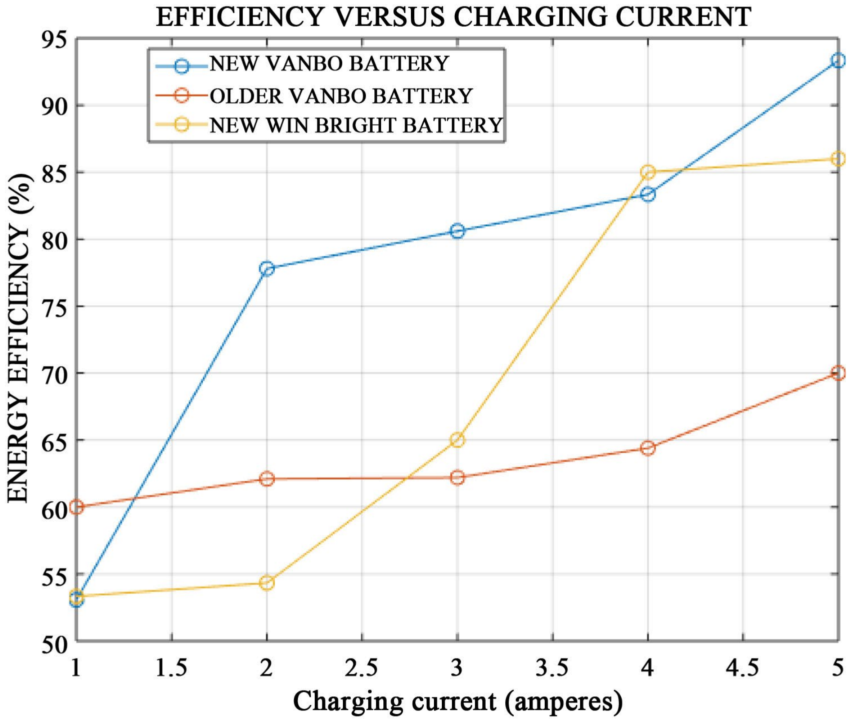

Figure 18. The variation of efficiency with respect to charging current for all the batteries.

4. Conclusion

In this work, it was sort out to investigate the relationship that exists between the ageing of a lead acid battery and the charging efficiency, with respect to charging current. Two new batteries were used, added to one battery which was known to be older than the other two. The age of the battery was estimated by taking into consideration the time the batteries spent in the laboratory. Older batteries would have stayed longer and undergone greater degree of ageing. Experiments were conducted on the lead acid batteries using constant current charging methods. The three batteries were charged in different occasions, storing particular amounts of energy and discharging the very energy in order to calculate the efficiencies at particular current rates. By so doing, energy efficiencies for both the new and old batteries were obtained at different current rates and then compared.

It was noticed that the older battery showed a lower charge/discharge efficiency and also showed unexpected variation of end voltages after charge with current magnitudes, increasing its dynamic behavior. From that it was inferred that choosing particular constant current rates to charge and discharge lead acid batteries will permit to determine the degree of degradation of the batteries. It is also seen that the magnitude of battery capacity stored had no visible effect on the efficiency since the change of capacity stored for the same Vanbo battery but different ages continued to show a lower efficiency for the older battery than the new one. It is inferable here that battery capacity as a parameter cannot be independently used as a method for age detection in lead acid batteries. As a continuation of this work, since only one old battery was deployed for the tests it is envisaged that in the future, a more inclusive study can be carried out by using many older batteries of different marks. Also, other age testing methods can be used to ascertain the ageing degree of the battery rather that assuming ageing only from the time it was purchased to the time of use. Another important perspective of the work is on the investigation of the effect that energy recovery can have on charging efficiency or how the battery portrays energy recovery with respect to its age.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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