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Experimental Evaluation of the True Remaining Capacity of Legacy Lead-Acid Batteries

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Abstract—One of the common challenges in remote microgrid installations is inexpensive, reliable, and less labor-intensive battery tests to measure the capacity of used batteries and link it to their remaining life. These capacity tests are usually misinterpreted, which results in a healthy battery being junked or may arise economic issues due to oversized battery banks in microgrids. In this work, we conducted several discharge experiments on 12V 100Ah lead-acid batteries in a controlled manner using an electronic load. The battery is subsequently discharged to 10.5V at C_{2.5}, C₃, C₅, C₁₀, C₂₀, and C₄₀ rates. When summed up using altered C-rate discharge sequences, the individual capacities resulted in 100.71Ah, 100.23Ah and 78.96Ah, 89.43Ah for the fresh and weak batteries, respectively. Irrespective of the discharge sequence, the cumulative net capacities are found quite close to the battery's actual capacity for fresh but much different for weak batteries. Results show that the remaining battery's true capacity does not disappear at a high rate and may further be utilized at lower discharge rates. The outcome of these experiments provides the basis to identify fresh and weak batteries and to size the battery banks for the low-cost rural microgrids more efficiently and economically.

Keywords—Peukert's law, second-life battery, battery capacity, microgrid, capacity measurement.

I. INTRODUCTION

The lead-acid batteries hold a significant leading position in the microgrid market. Energy storage in batteries had remained an increasingly critical asset in many systems, including the starting/lighting/ignition (SLI) in vehicles [1, 2], renewable systems, electric traction, and the most trending one—*off-grid electrification*, as reported in the Global Energy Storage Database (DOE) report in 2018 [3, 4]. The proven versatility and low cost enabled this technology to use over a hundred years for storing electrical energy [5]. The basic chemistry of the lead-acid batteries is fairly simple [6], but they are complicated, especially when it comes to the capacity response to various loads and different operational situations [7–9]. The degradation mechanisms in batteries are complex, and a detailed analytical description of electrochemical processes involved for the determination of the residual capacity is not explicitly available [10]. Due to the complicated nature of the batteries, most often, the batteries are replaced before their diminished capacities, or on the other hand, the battery bank is incorrectly designed that eventually

result in failure of the target application of which the most affected is the off-grid renewable or hybrid renewable electrification systems [11].

In applications like off-grid electrification systems, apart from the popular flooded lead-acid batteries, another attractive option is valve-regulated lead-acid (VRLA) batteries, which are studied in this work—they require low maintenance and are classified as absorbent glass mat (AGM) batteries and gel electrolyte batteries [12]. In addition, VRLA batteries use much less electrolyte than traditional lead-acid batteries, they are also occasionally referred to as an acid-starved design. VRLA batteries can be mounted in any position. These batteries are designed to be recombinant to eliminate the emission of gases during overcharge, thereby reducing room ventilation requirements. Furthermore, little or no acid fumes are emitted during the normal operation of VRLA batteries. In the event of damage to a VRLA battery, the volume of free electrolyte that could be released is quite small. Finally, there is no need to check electrolyte levels or add water which is lost due to electrolysis. Thus, VRLA batteries are well suited in rural electrification as they are safer, versatile, environment friendly, and require less maintenance [13].

In modern applications, where the remaining battery capacity is crucial, *i.e.*, not only the SLI, but the most critical one—off-grid electrification services; battery users frequently overcharge, inefficiently cycle, and prematurely replace their batteries because accurate and affordable measurement systems for the test and recovery of these batteries do not exist. As a battery gets older, its usable capacity does not fall off in a cliff-like manner, but instead tends to slowly decrease, which is also recoverable. In areas with an increased power cut or no access to electricity, such poor management of batteries and early replacement increases financial stress on the poor and, in parallel, reduces their trust in such stand-alone community microgrids.

Generally, battery state of charge (SOC) is measured by various battery testing equipment, battery management systems (BMS), and software tools to determine the health of a battery [14, 15]. However, testing SOC does not give an accurate measure of a battery's health or remaining capacity [16]. The key measurement of remaining battery life is the percentage of original design capacity or the residual capacity determined by a series of discharge tests at different C-rates. The better way to test capacity is using a constant DC current

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sink such as an electronic load for a certain amount of time. However, the constant current sink method is misunderstood and the obtained results are never realistic to reflect the true residual capacity. More than that, most often, the capacity measurement tests are carried out without considering the recovery and loss of battery capacity due to self-discharge, off-service status, and battery relaxation and thermal equilibrium of electrolyte [17].

Paper contribution

In almost all applications, as stated before—the battery bank stays off-service due to one or other reason and the battery itself is left discharged for a couple of days or an indefinite time. Therefore, our proposed repeated discharge tests at different C-rates and altered sequences enable us to accurately calculate the actual remaining capacity in a supervised manner. Also, it helps to mark/ sort the fresh and weak batteries based on the accumulated individual capacity measurements.

The remaining paper is organized as follows. Section II covers the capacity response and the use of Peukert's equation. In Section III, experimental setup and procedures have been carried out to calculate the battery's actual residual capacity and clarify the confusion created by misinterpretations of Peukert's equation. The measurements and results are discussed with more details in Section IV. Finally, in Section V, conclusions are drawn and some perspectives are given for the possible future experimental outcomes.

II. PEUKERT'S EQUATION AND CAPACITY RESPONSE OF A BATTERY AT HIGH DISCHARGE

The misinterpreted Peukert's law was initially developed for lead-acid batteries over a hundred years ago [18]. This law states that the delivered charge increases when the discharge current decreases or conversely, the battery capacity decreases with an increase in discharge current. In fact, the battery's capacity does not depend on how quickly it is being discharged or charged. The battery datasheet provided by the manufacturers is a piece of useful information. At some point, the datasheets are used incorrectly and mainly misunderstood, especially for the battery capacity.

The concept behind Peukert's equation is widely available in the prior art [19]. It came about over a millennium back in 1897 from a German scientist named—*Wilhelm Peukert*. Peukert realized that the behavior of storage batteries is complicated to understand. There are no good models even today to understand how a battery behaves in all. In fact, there is no general model that is correct for capacity determination. With many complications, even today, the battery models that exist; most of these are the computer models, as they are specifically tailored for one specific application and technology.

Peukert's law expresses the capacity of a battery in terms of the rate at which it is discharged. It is described as the following equation:

$$C_N = I^k * t \quad (k > 1) \quad (1)$$

where, C_N is the nominal capacity of the battery, I is the discharge current, k is the Peukert's constant, which is determined by the internal characteristics of the batteries and its value is greater than one, and t is the discharge time. The

equation indicates that the discharge time and battery capacity decrease exponentially at any given nominal capacity C_N as the discharge current is increased. In addition, the discharge capacity C_D is described in (2) by using the same notation as in (1):

$$C_D = I * t = I^{(1-k)} * C_N \quad (k > 1) \quad (2)$$

Equation (2) indicates that excessive I causes a reduction in the discharge capacity. However, it is shown experimentally that the capacity does not disappear with a high discharge current for fresh but significantly lost for used batteries.

Peukert was able to go through some empirical testing with battery technology and computing tools of that time. He demonstrated that if a battery is charged very quickly, much useful capacity cannot be obtained during discharge. If the same battery is discharged very slowly, far more useful energy out of the battery can be extracted. This complex discharge behavior of batteries is usually misinterpreted for sizing storage batteries in microgrids. This has many practical implications and, in parallel, a lot more confusion. Interestingly, Peukert did a very good job. His data set had remained quite useful, but sometimes not used in its true sense for the capacity response of a battery.

The battery datasheet is misunderstood when the discharge capacity is confused with the battery's true capacity. The datasheet of the battery used in this work [20] claims that the amp-hour (Ah) capacity depends on the discharge rate, but as we demonstrate, this capacity is just the useful capacity. If the battery is continuously discharged at the ten-hour rate (C_{10}) with a constant DC load current of 10A, the battery will drop to a voltage, *i.e.*, 10.5V, which is deemed not useful for further discharge. If the 100Ah battery is discharged very quickly, say at a five-hour rate (C_5) with 20A, it will drop to that minimum acceptable voltage much quicker. However, this does not mean that the capacity went away at C_5 , it means that the remaining capacity is no more useful at C_5 . The remaining capacity can still be used at a lower discharge rate and more out of the Ah can be extracted from the battery.

III. EXPERIMENTAL SETUP AND METHODS

The batteries used in this demonstration are 12V 100Ah Ultracell® UCG 100-12 lead-gel technology. The system setup is as shown in Fig. 1. It consists of a ZS-1812 H&H DC electronic load, lead-acid battery, and a supervisor PC to discharge batteries in a controlled manner. The interface NI-6009 is used between the supervisor PC and electronic load.

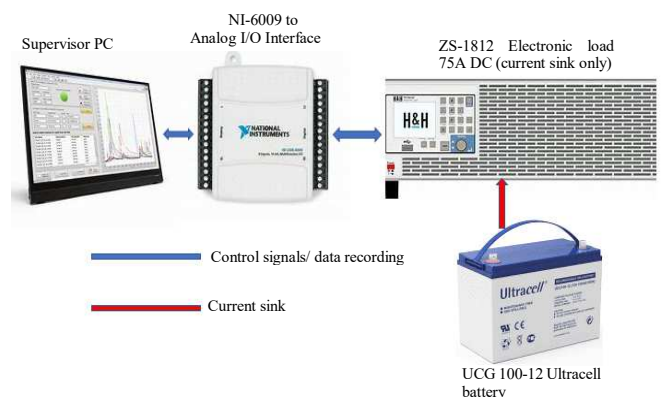


Fig. 1. Schematic representation of the experimental platform for the capacity determination using successive discharges

All the batteries under test are 100Ah each, weigh 67 pounds, and are of AGM gel electrolyte F10 terminal construction [18]. Before starting the discharge tests, batteries are fully charged using H-Tronic HTDC 5000 (5A) smart charger. In the first test, a single 12V battery is randomly selected among the bank of 16 batteries. The lower discharge threshold is set to 10.50V (1.75V/cell).

A. Experimental Procedure

The whole experimental bench is depicted in Fig. 2. In this figure, the electronic load is connected to the supervisor PC via NI6009 to Analog I/O interface to run the experiment in a controlled manner. The cables are of sufficient gauge and minimal length to minimize the voltage drop during high discharge currents. It was observed that these cables survived during the high discharge current test, and they did not heat up abnormally. However, the cable selection could be different for other equipment and may better be adapted to as per application.

The electronic load is initialized and configured to the external mode using LabVIEW® to observe the battery's behavior at different C-rates. This interface is also used to send control signals and measure the battery voltage and current. As shown in the flow diagram of Fig. 3, the discharge process is repeated for other C-rates until C_{40} (2.5A). One-hour relaxation time is used for the open-circuit voltage (OCV) recovery and thermal equilibrium of electrolyte. The total discharge time is recorded each time and multiplied with the discharge current to get the extracted capacity in Ah. After the test is finished for a sequence, the battery is fully recharged to pass through another discharge using a different sequence. Important control parameters and different thresholds for the experiment are detailed in Table I.

TABLE I: ZS1812 CONTROL PARAMETERS AND SETTINGS

Load type	Range/Resolution	Interface	Mode	Accuracy
ZS-1812 current sink	75A DC / R2 settings	NI-6009 to Analog I/O	CC const. current	$\pm 0.2\%$ of measured value
Supervisor	Control mode	Battery type	Cut-off threshold	Relaxation/Recovery time
LabVIEW® 2013	External mode	UCG-100/12 lead-gel	10.50V	60 mins
Charger	Fully charge volt	Temp.	Capacity $C=C_{10}$	Discharge Sequences
H-Tronic HTDC5000	14.30V	Ambient	100Ah	2

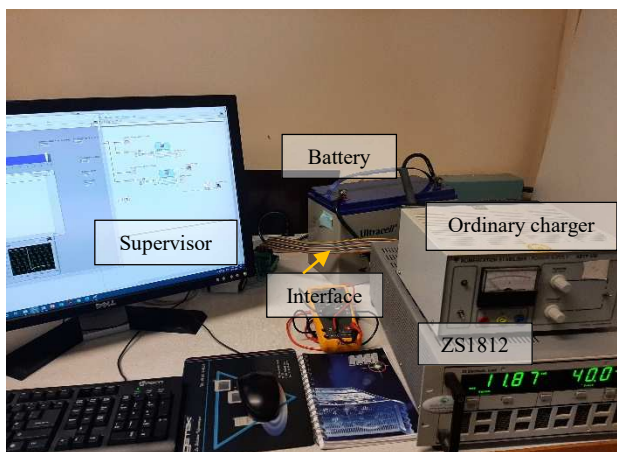


Fig. 2. Experimental bench for the net capacity calculation in a controlled manner

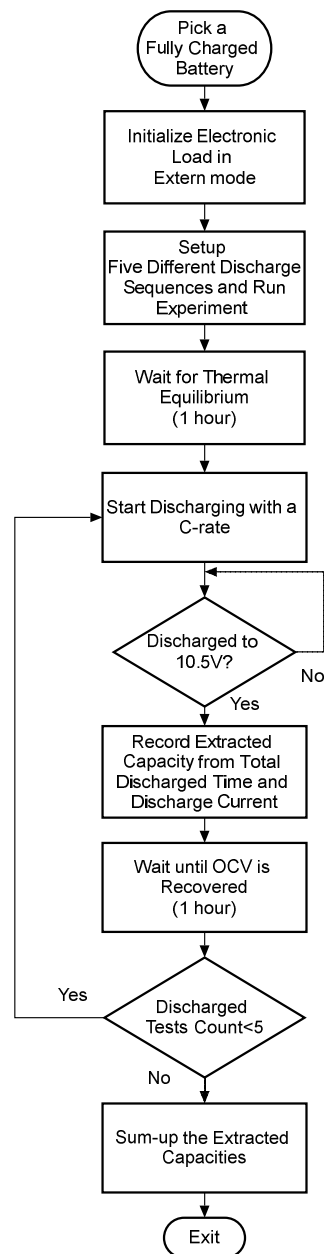


Fig. 3. Flow diagram of the experimental process

B. Discharge Sequences

The following C-rates are used in a shuffled sequence to extract the residual capacity of a fully charged battery:

$$\begin{array}{cccccc} C_{2.5} & C_5 & C_{10} & C_{20} & C_{40} & \text{(fresh battery)} \\ C_3 & C_5 & C_{20} & C_{10} & C_{40} & \text{(weak battery)} \end{array}$$

where C is the rated capacity of the battery under test, which is 100Ah at C_{10} . The discharge currents are configured in LabVIEW® and sent to ZS-1812 electronic load using NI-6009. At the R_2 resolution settings (configured via port 0) with a bit sequence of 00000100, the following voltage ranges are fed to the control of different discharge currents:

$$\begin{array}{cccccc} C_{2.5} & C_3 & C_5 & C_{10} & C_{20} & C_{40} \\ (2V) & (1.67V) & (1V) & (0.5V) & (0.25V) & (0.125V) \end{array}$$

The electronic load is easily disconnected from the battery through a TTL signal at P1.0 (disconnect HIGH). Altering the

discharge sequence enabled the authors to identify fresh and weak batteries based on the net extracted capacity. The fresh battery has no significant capacity loss with a high discharge current. However, the capacity of a weak battery is affected by a high discharge current.

IV. MEASUREMENTS AND DATA RECORDING

In our case, a fully charged 12V lead-acid battery is drained to the cut-off threshold of 10.5V, and still, the remaining capacity turned useful on successive low discharge currents. It is an indication that this capacity calculation method using repeated discharges and different C-rates could help calculate the overall remaining capacity of the battery. The discharge process was carefully controlled to avoid the battery getting sulfated or being damaged from deep discharge using set threshold of 10.5V at the ambient room temperature. As depicted in Table II, we got 100.7Ah and 100.2Ah during the two different discharge sequences for fresh batteries. These results are quite close to the battery's rated capacity. It is observed that altering the discharge sequence did not affect the fresh battery but affected the weak battery.

Out of the 16 batteries on-site, few were identified as weak batteries based on the obtained results (89.4Ah to 78.9Ah) by altering the discharge sequence. The high discharge current roughly dropped 10Ah of the useful capacity for the weak battery. It is a result of internal capacity loss due to high plate resistance and degradation.

TABLE II: IDENTIFICATION OF FRESH AND WEAK BATTERIES

Battery A (fresh)					Battery B (weak)				
Discharge sequence (Test-1) C=C ₁₀ =100Ah									
C ₃	C ₅	C ₁₀	C ₂₀	C ₄₀	C ₃	C ₅	C ₂₀	C ₁₀	C ₄₀
83.2	6.6	5.0	2.9	2.4	66.6	9.3	8.9	0.8	3.7
100.2Ah (Total extracted capacity)					89.4Ah (Total extracted capacity)				
Altered discharge sequence (Test-2) C=C ₁₀ =100Ah									
C _{2.5}	C ₅	C ₁₀	C ₂₀	C ₄₀	C _{2.5}	C _{2.5}	C ₁₀	C ₂₀	C ₄₀
74.6	11.3	6.0	4.1	4.6	64.6	4.6	5.5	2.2	1.8
100.7Ah (Total extracted capacity)					78.9Ah (Total extracted capacity)				
Negligible capacity loss					High capacity loss (due to internal plate resistance)				

The obtained results for the different discharge sequences and different batteries are compared in Table II and graphically represented using Fig. 5. It is interesting to note that the extracted capacities for the weak batteries have a significant deviation due to the altered discharge sequence. It indicates aging and capacity loss due to an increase in the internal plate resistance. We have demonstrated with a real practical battery that the battery does not lose its residual capacity at high C-rates as is being misinterpreted. The response in Fig.6, when summed up, the individual capacities resulted quite nearly to the rated Ah capacity of the fresh battery as the internal loss is quite low and the impact of altered sequence is negligible.

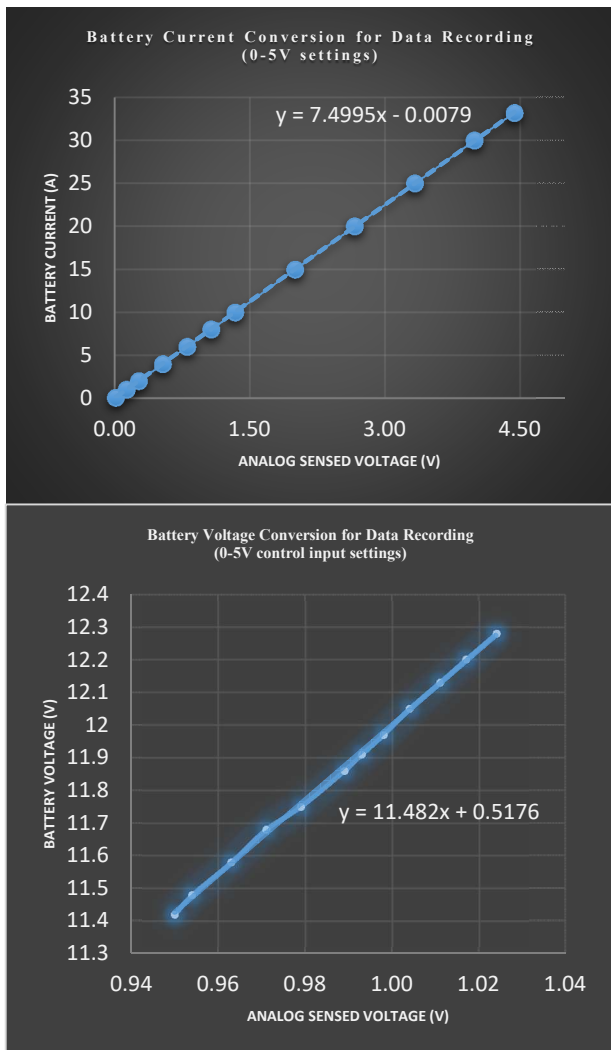


Fig. 4. ZS1812 electronic load settings: Data recording and linear conversion (from ZS1812 to LabVIEW®)

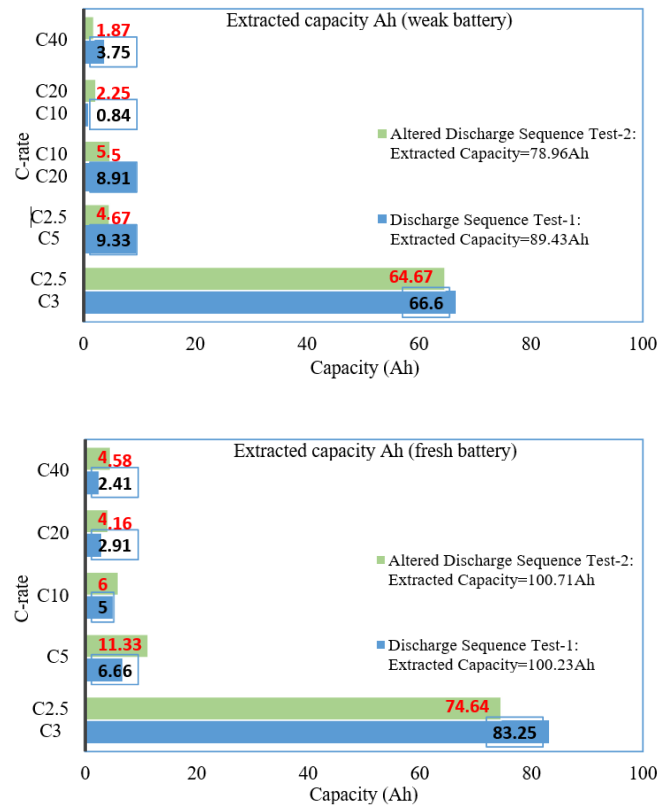


Fig. 5. Extracted capacities from a fully charged 12V battery with different health status (weak/fresh)

The adequate experimental validation in this work shows that a battery does not lose much capacity by discharging it at a high current. It is obvious from the obtained results that the batteries could still be utilized in different groups with different discharge current sequences to take out the maximum of their true capacities and serve longer. These experiments could be of particular interest for the selection of batteries in low-cost stand-alone microgrids.

V. CONCLUSION

The experimental validations on real batteries using successive discharge had reliably determined the remaining true capacity of lead-acid batteries. It was practically demonstrated that a certain battery, e.g., 100Ah AGM in our case, was discharged five times to the threshold of 10.5V with an hour relaxation for voltage recovery and thermal equilibrium of electrolyte. It is observed that irrespective of the C-rates, the net extracted capacities 100.71Ah, 100.23Ah matched exactly the datasheet values for fresh batteries but found a quite large deviation of 78.96Ah, 89.43Ah for weak batteries. The overall analysis also enabled the authors to quickly sort the second-life batteries in fresh and weak groups for use as a battery pack of different health status in reducing the storage cost of off-grid electrification systems for the rural areas. For future work, an extension of these experiments could be used for the parameter extraction of real batteries. This could be helpful in adaptive tuning of the energy management system to evolve with the degraded performance of aged batteries, and also health monitoring of the batteries.

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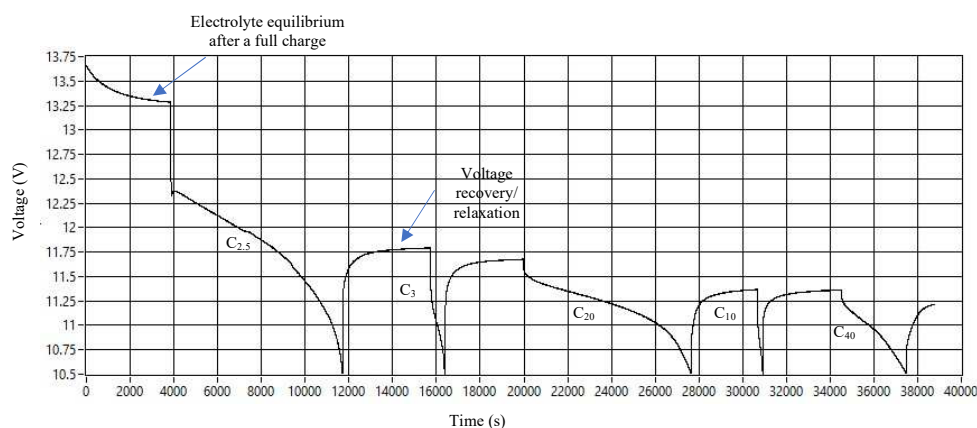


Fig. 6. Net extracted capacity from a fresh battery through five successive discharges