TELKOMNIKA, Vol.17, No.3, June 2019, pp.1577~1583
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v17i3.12241

VRLA battery state of health estimation based on charging time

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Abstract

Battery state of health (SoH) is an important parameter of the battery's ability to store and deliver electrical energy. Various methods have been so far developed to calculate the battery SoH, such as through the calculation of battery impedance or battery capacity using Kalman Filter, Fuzzy theory, Probabilistic Neural Network, adaptive hybrid battery model, and Double Unscented Kalman Filtering (D-UKF) algorithm. This paper proposes an approach to estimate the value of battery SoH based on the charging time measurement. The results of observation and measurements showed that a new and used batteries would indicate different charging times. Unhealthy battery tends to have faster charging and discharging time. The undertaken analysis has been focused on finding out the relationship between the battery SoH and the charging time range. To validate the results of this proposed approach, the use of battery capacity method has been considered as comparison. It can be concluded that there is a strong correlation between the two discussed SoH estimation methods, confirming that the proposed method is feasible as an alternative SoH estimation method to the widely known battery capacity method. The correlation between the charging-disharging times of healthy and unhealthy batteries is very prospective to develop a battery charger in the future with a prime advantage of not requiring any sensor for the data acquisition.

Keywords: *battery capacity, charging time, comparison method, state of health*

1. Introduction

Batteries are used in many daily life activities, such as in portable telecommunication equipments, multimedia devices, hybrid electric vehicles (HEV) [1], electric vehicles (EV) [2, 3], energy harvesting, base-transceiver station (BTS) in the telecommunication system [4], wearable computing devices [5], wireless sensor network (WSN) [6, 7] and energy storage in smartgrid networks [8, 9]. A battery in a system must be used properly in order to reach its lifetime as long as possible. Periodic monitoring is necessary to ensure the remaining battery lifetime and to decide whether it is time to replace with a new battery. A possible damage on a battery may cause the system running unoptimally, or even cause the damage of the system.

The battery damage may occur due to some causes, such as overcharging, discharging, and even the battery life-cycle limits [10]. A diagnostic process is very important to maintain the proper operation of a battery. Battery State-of-Health (SoH) is an important parameter of the battery's ability to store and supply electrical energy. SoH may become an indicator of battery aging,which results in the degradation of battery capacity and power. The battery capacity, internal resistance, and State-of-Charge (SoC) are commonly used as parameters to measure SoH [11-13].

Various methods have been so far explored to calculate the battery SoH, such as through the calculation of battery impedance or battery capacity using Kalman Filter [14], Fuzzy theory [15], Probabilistic Neural Network [16], and the adaptive hybrid battery model-based real-time SoC and SoH estimation method [17]. Qiuting [18] conducted a study on SoH estimation methods of lithium batteries by utilizing the Double Unscented Kalman Filtering (D-UKF) algorithm. The SoH estimation model has been derived based on the battery's internal resistance. The modeling results showed that under different operating conditions, batteries have different internal resistance. Meanwhile, Moura [19] developed a PDE (Partial Differential Equation) observer to estimate SoH and SoC on batteries. The research included the first study to combine SoC/SoH for electrochemical battery models. Adaptive observers make use of the

Received January 9, 2019; Revised January 31, 2019; Accepted February 29, 2019

concept of partial differential equation estimation and adaptive control theory to generate new concepts of battery systems and their control.

In this paper, an approach to estimate the value of SoH based on the battery charging time is proposed. It has been inspired by the fact that in general the new and used batteries require different time duration to take during the battery charging to its full capacity. The proposed approach is compared to the widely known battery capacity method to validate.

2. Valve-Regulated Lead Acid (VRLA) Battery

Lead Acid Battery is one type of battery which uses lead acid as the chemical substance. Commonly, there are two types of lead acid battery, i.e. the Starting Battery type and the Deep-Cycle Battery type. The Starting Battery is a battery type which is used to generate high energy (electric current) in a short time. In other words, it requires a huge amount of current to start a machine, for example in a car application. The Deep-Cycle Battery is designed to produce a stable electrical current for a long time, as normally found for solar cell applications [20]. In addition, the lead acid battery can also be divided into two types, the Flooded Lead Acid Battery and the Valve-Regulated Acid Lead Battery (VRLA). The Flooded Lead Acid Battery is commonly called as Wet Cell, because the cells in the battery are immersed in the electrolyte fluid and need the fluid addition if its ammount decreases.

Each cell on the Flooded Lead Acid Battery is equipped with a valve to fill in with the electrolyte liquid [21]. The VRLA battery is designed to keep the electrolyte fluid inside not reduced due to evaporating or leaking. This type of battery is physically packed and sealed by the factory, so that the external appearance is only in a form of positive and negative terminals pair. It is also equipped with a vent valve to release the resultant gas from a chemical reaction in case of extreme pressure. As there is no valve to charge the electrolyte liquid, this type of battery is known as a Maintenance-Free Battery [22].

Charging the VRLA battery can be done using various methods such as Single-Rate Constant Current Charging, Multi-Rate Constant Current Charging, Taper Current Charging, Constant Voltage Charging, and Modified Constant Voltage-Limited Current Charging. Among those various methods, the most recommended method is the Modified Constant Voltage-Limited Current [22]. This method is essentially the use of the usual limited current source, as shown in Figure 1. Current portion of the ventilator is part of the ability to charge this battery. Part of the error that comes from improvement battery charge state. At present it reaches the asymptotic limit where small internal parasite processes maintain very low current flows [23].

3. State of Health

One purpose of the battery diagnostic process is to know the health condition of battery, commonly called as the battery State of Health (SoH). It is a qualitative measure of the battery's ability to store and provide electrical energy [24]. SoH of the battery can be defined as the quantity of free charges under certain condition, temperature, and voltage limit after being fully charged. Generally, SoH is often called as the ratio between the measurable capacity and initial capacity (nominal capacity):

$$SoH = \left(\frac{C}{\text{Cnominal}}\right) \times 100\% \qquad (1)$$

The SoH value varies from 1 (or 100%) to 0 (or 0%). In practice, a battery is considered to be in a good condition if its SoH value is between 1 and 0.8 (or between 100% and 80%). A battery is considered to reach its end of useful life when its SoH value is less than 80% of the battery initial (nominal) capacity [25].

4. Research Method

4.1. Test-Bench Design

The test-bench design of the proposed method should ensure the execution of the battery charging and discharging, as well as enable the acquisition of the required data, which are current, voltage, temperature, and time. As shown in Figure 2, the test-kit design includes charger/discharger, current, voltage, and temperature sensors, timer, microcontroller, and a personal computer. The research object includes five batteries with various conditions. One battery is in a brand-new condition, while the others have been used previously. The charging time of the five batteries are compared, and their SoH values are calculated based on the capacity ratio and the ratio of the charging time.

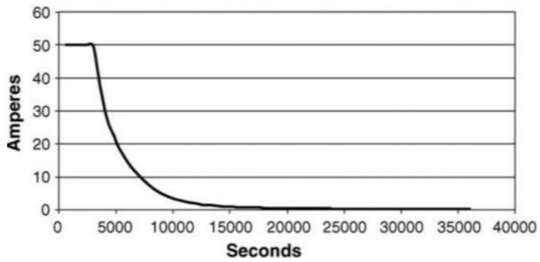

Figure 1. Method of modified constant voltage-limited current charging [22]

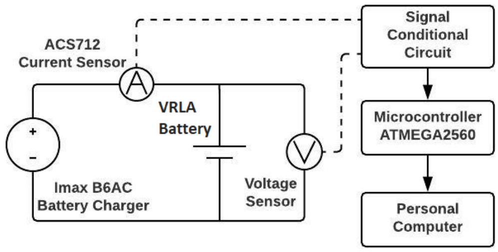

Figure 2. VRLA battery test-bench block diagram

The correlation between the charging-disharging times of healthy and unhealthy batteries is potential to become the fundamental principle in designing a sensorless SoH battery estimator. It is carried out by tabulating the charging time of some different brands of battery with the same capacity and type and some different capacities of battery with the same brand and type. It is the VRLA battery considered in this research, each tabulation occupies different address in the storage memory to facilitate the creation of choice option. The battery under observation is fully discharged before being re-charged. The recorded charging time is compared to the previously stored data in the memory, so that the SoH estimation can be performed.

4.2. Experiments

The measurements have been done on the current (I), voltage (V) and charging time (t) of the battery using the suitable sensors. As described in Figure 2, the test-bench design consists of Imax B6AC Battery Charger, ACS712-20A Current Sensor and Voltage sensor. Voltage measurement is used to determine the maximum charging/battery voltage limits and the current measurement is used to determine the incoming charging capacity. All the sensors are connected to an ATMEGA2560 microcontroller as the data processor. All measurement data of current, voltage, and charging time are sent to PC for further processing. The SoH estimation method discussed in this paper are that being based on the capacity of the battery and that being based on the charging time of the battery. The SoH obtained using the capacity method is used as reference.

Figure 3 indicates a flowchart of the proposed measurement and validation methods of SoH. Being begun with the battery installed in the test-bench, the experiment is done by firstly discharging the battery completely up to 0% (VOC about 10.8V). Furthermore, the charger is turned on and the sensor is turned on by the microcontroller to start measuring current and voltage. At the same time the timer starts up. Measurement data of current, voltage and timer are then sent to the computer to be recorded. The sampling time of the data measurement taken is 1 second to guarantee the obtaining of valid data. The process is done repeatedly until the battery is fully charged and the timer stops.

The SoH is then calculated by measuring the battery capacity by using (1). The charging time is also calculated. The process is repeated with other batteries and other conditions. The calculation results are presented in a form of tables to facilitate analysis. By comparing the SoH calculation result and the measurement results, the correlation between the SoH and the related battery charging time can be obtained.

5. Results and Analysis

The results of the experiment on the battery voltage during the charging process of five batteries under consideration are given in Table 1, whereas in a form of graphic it is given in

Figure 4. As can be seen, at the beginning the batteries are fully discharged to approximately 0% SoC (about 10.8V). It can also be observed that the stable voltage (fully charged) above 14 V is achieved by the Used Battery 1, Used Battery 2, Used Battery 3 and Used Battery 4 in 100, 80, 60 and 20 minutes respectively, whereas it is achieved in about 180 minutes by the New Battery. Figure 4 shows that the time required to fully charged condition of the batteries are in the order of Battery 4-3-2-1, with the Used Battery 1 achieved it the most slowly.

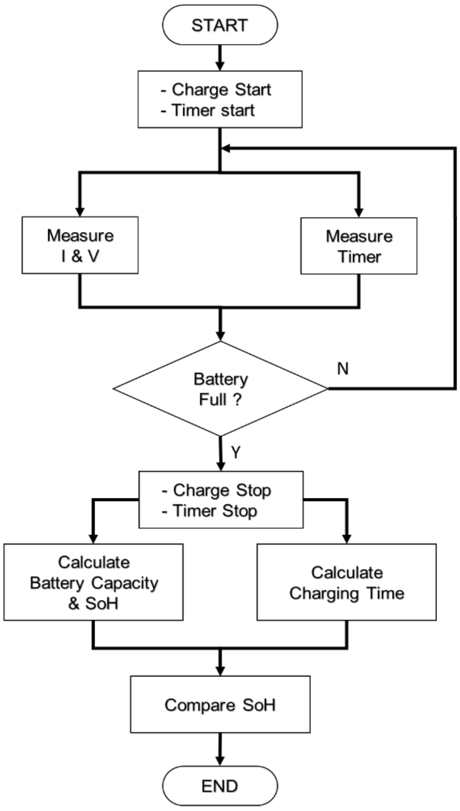

Figure 3. The flowchart of the SoH measurement and validation

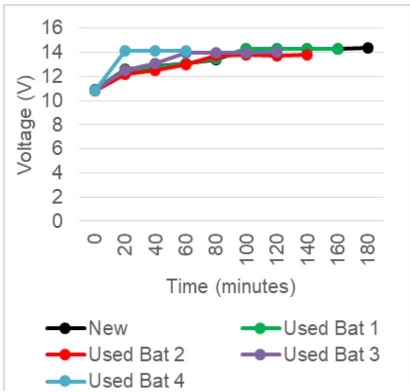

Figure 4. The battery voltage as a function of the charging time for various batteries under consideration

Table 1. The Experiment Results of the Battery Voltage during the Charging Process

Time (Minute)	Average Battery Voltage (V) New	Batt 1	Batt 2	Batt 3	Batt 4
0	10.8	10.8	10.82	10.86	10.82
20	12.5	12.4	12.18	12.47	14.09
40	12.7	12.7	12.53	13.04	14.14
60	13.1	13.0	13.01	13.92	14.15
80	13.4	13.4	13.72	13.97	-
100	14.2	14.2	13.79	13.98	-
120	14.3	14.2	13.71	14.01	-
140	14.2	14.2	13.80	-	-
160	14.3	14.30	-	-	-
180	14.3	-	-	-	-

The results of the experiment on the battery current during the charging process of the five batteries are given in Table 2, whereas in a form of graphic it is given in Figure 5. The results of current sensor measurements is adjusted by the Signal Conditioning Circuit and then processed in microcontroller. The measurement data value are then sent to the Computer via a USB-serial interface.

Table 2. The Experiment Results of the Battery Current during the Charging Process

Time (Minute)	Average Battery Current (A)				
	New	Batt 1	Batt 2	Batt 3	Batt 4
0	0.002	0	0.006	0.004	0.002
20	1.51	1.444	1.466	1.444	1.09
40	1.524	1.464	1.458	1.436	0.274
60	1.454	1.446	1.456	1.284	0.12
80	1.474	1.432	0.998	0.456	-
100	1.48	1.298	0.416	0.19	-
120	0.716	0.56	0.174	0.132	-
140	0.392	0.268	0.122	-	-
160	0.23	0.142	-	-	-
180	0.14	-	-	-	-

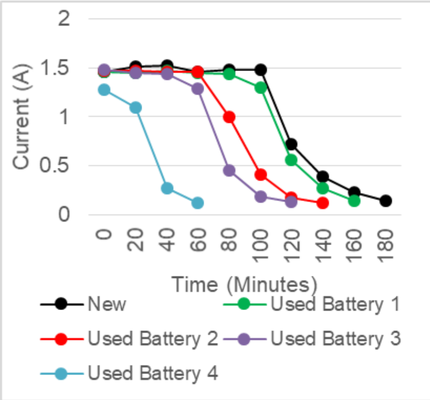

Figure 5. The battery current as a function of the charging time for various batteries under consideration

As can be known from the current test results during the charging process, the Used Battery 4 did not reach the maximum current level of 1.5A as provided by the charging device. In the 20th minute, it has reached the final stage of charging process. During the following minutes, the flowing current is more and more smaller, only 0.274A at the 40th minute, not like the Used Batteries 1,2 and 3 where the flowing currents are still high. Based on Figure 5 it can be confirmed that the Used Battery 4 could not receive the maximum charging current. It can also be observed that longer the battery in the maximum current level is, longer is the time required to reach the fully charged condition. The results of the experiment on the battery capacity during the charging process of the five batteries are given in Table 3, whereas in a form of graphic it is given in Figure 6. The battery capacity is expressed in ampere-hours.

Table 3. The Experiment Results of the Battery Capacity during the Charging Process

Minute	Average Battery Capacity in Charging Process (Ah)				
	New	Batt 1	Batt 2	Batt 3	Batt 4
0	0.00	0.00	0.00	0.00	0.00
20	0.45	0.45	0.45	0.45	0.43
40	0.90	0.90	0.90	0.90	0.60
60	1.35	1.34	1.34	1.28	0.64
80	1.81	1.79	1.76	1.59	-
100	2.26	2.24	1.96	1.69	-
120	2.59	2.51	2.04	1.72	-
140	2.76	2.63	2.06	-	-
160	2.85	2.69	-	-	-
180	2.90	-	-	-	-

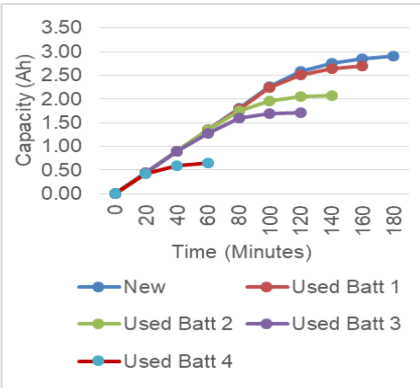

Figure 6. The battery capacity as a function of the charging time for various batteries under consideration

The related measurement results are presented in Table 4, whereas the correlation between the charging time and the SoH is shown in Figure 7. The measurement of SoH based on the battery charging time has been carried out using the following formula:

$$SoH = \left(\frac{t_{charging(tes\_bat)}}{t_{charging(new\_bat)}}\right) \times 100\% \qquad (2)$$

Table 4. SoH Measurement Results based on the Charging Time Method

Battery	Charging Time (s)	State of Health (%)
New	10755.6	96.80
Batt 1	9494.2	89.70
Batt 2	7712.4	68.83
Batt 3	6631.6	57.33
Batt 4	3230.2	21.46

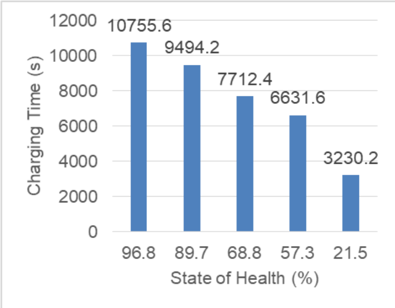

Figure 7. The battery SoH versus charging time for various batteries

In the battery capacity-SoH based estimation method, it is the nominal capacity condition as given by the battery data which is used as reference, whereas in the charging time-SoH based estimation method it is the charging time of a brand-new battery which is used as reference (10755.6 s). The comparison of the SoH value calculation results using both the capacity method and the charging time method are shown in Table 5 and Figure 8. It can be seen that based on the capacity method the Used Battery 1 has an SoH value of 89.7%, the Used Battery 2 has an SoH value of 68.8%, the Used Battery 3 has an SoH value of 57.3%, and the Used Battery 4 has an SoH of 21.5%. The results based on the charging time method has a difference of 1.4%, 2.9%, 4.3%, and 8.6% respectively for the Used Battery 1, 2, 3, and 4.

Voltage and current measurement results in Figures 4 and 5 have proven that the designed system has worked well to detect the increase in battery voltage and current, the quantities of which are actually two parameters usually used to determine the battery level. The comparison of SoH measurement results using the charging time method to the SoH capacity measurement shows that the results difference is still in the tolerance level. The difference in measurement results can be improved by redesigning electronic circuits and the use of more precise time measurement methods.

Table 5. SoH Measurement Results Comparison between the Use of Capacity Method and Charging Time Method

Battery	SoH (%) Based on Capacity	Based on Charging Time	Difference (%)
Used Batt 1	89.7	88.3	1.4
Used Batt 2	68.8	71.7	2.9
Used Batt 3	57.3	61.7	4.3
Used Batt 4	21.5	30.1	8.6

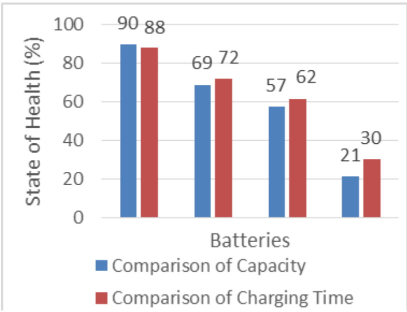

Figure 8. Comparison of battery SoH values using capacity method and charging time method

6. Conclusions

An alternative approach to measure the SoH of a VRLA battery has been proposed. It is based on the charging time of the battery. Its performance is comparabe to the commonly known method based on the battery capacity, which has been used to validate the proposed method. It can be concluded that the strong correlation between the two discussed SoH estimation methods confirms that the proposed method is feasible as an alternative method to capacity-based SoH estimation method. The correlation between the charging-disharging times of healthy and unhealthy batteries is very prospective to develop a battery charger in the future with a prime advantage of not requiring any sensor for the data acquisition.

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