Experimental Verification of Lead Acid Battery Parameters Estimation

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Abstract: The need of sustainable energy without any interference such as harmonics for mobility equipment became the major challenge in selecting suitable energy storage device. The rechargeable batteries become alternatives due to its ability to store and restore the energy that will maintain the continuity of the power supply. However, without proper monitoring of the battery performance, the condition of both equipment and battery itself can be worsening. This paper proposes a new time-frequency distribution (TFD) techniques which are spectrogram based on experimentation of lead acid (LA) battery. Estimation of parameters such as instantaneous of root means square voltage (V_{RMS}), instantaneous direct current voltage (V_{DC}) and instantaneous alternating current voltage (V_{AC}) are extracted from a time-frequency representation (TFR) through the charging and discharging characteristics of the batteries. Experiment is conducted based on three different LA battery with fixed nominal voltage of 12V and storage capacities of 2.3Ah, 4.5Ah and 7.2Ah. The simulation results of equivalent circuit model simulated in MATLAB Simulink are presented and compared to the experimental result. The similarities of both experimental and simulation results are obtained through the parameters estimation at the frequency components. Through these parameters, battery life can be predicted based on the equation proposed.

Key words: Lead acid · Spectrogram · Parameter Estimation · Performance Evaluation

INTRODUCTION

Portable energy storage device becomes a demand due to increased use of mobility equipment. The rechargeable battery is one of the best solutions to overcome this problem. However, non-healthy battery caused by overcharged and over discharge not only damaged the battery itself but also affect the load performance. Parameters of the battery need to be estimated to prevent the battery from damage by following the regulation and safe handling through battery life prediction [1, 2]. According to Feng, Zhao and Lu [3], measurement of the storage and power capacity of battery gives the accurate estimation of the state of charge (SOC) which is important to estimate battery health condition.

To estimate the parameters of the battery, several methods had been proposed namely constant current methods and pulse charge method. Hua and Syue [4] proposed pulse charge method in determining the charging and discharging characteristics of the battery.

Through the results obtained based on LA battery and LiFePO4 battery, the polarization can be reduced and the temperature of the battery can be maintained and gives the accurate value in battery parameters. But the complexity of this method which causes higher computational time compared to the constant current method [5].

From the open circuit test as mentioned in [5], the SOC of the battery can be estimated through the constant current of charging and discharging signal. The SOC estimation is based on the injected current to the battery for a certain period of time [6]. Through the process, the battery is considered as fully discharged when the voltage reaches its cut-off value. However, to determine the SOC based on the open circuit test through the constant current method cannot be done in experiment without taking two constant current measurements.

To overcome the limitation of open circuit test, analysis of the signal using periodogram is proposed [7]. A constant charging and discharging current is applied where the SOC is determined from the DC component

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value. But still periodogram cannot analyse non-stationary signal whose spectral characteristics only present the signal in the frequency domain. This paper proposed a new time-frequency analysis of LA battery using spectrogram for parameter estimation. The charging and discharging signal of the battery is represented in TFR by using spectrogram. The parameters such as instantaneous of root means square voltage (V_{RMS}), instantaneous direct current voltage (V_{DC}) and instantaneous alternating current voltage (V_{AC}) are extracted from TFR for battery performance estimation. The performance of the battery is verified from the comparison results between experimental with the model simulated by MATLAB, Simulink.

Lead Acid: Charging and discharging process of LA battery is through the chemical reaction at the positive and negative electrode using sulphuric acid (H_2SO_4). During the charging process, chemical substances of (PbO_2) is occurred at positive electrode while (Pb) is attached at the negative electrode. However, during the discharging process, sulphate substance (SO_4) is collected at both positive and negative electrodes [8]. Hence, charging and discharging pattern of LA battery is affected by the different nature of the chemical materials. Studies made by [9] develop a model based on equivalent circuit model approaches for LA battery using MATLAB Simulink. The advantage of this model gives the accurate prediction on state of charge and state of discharge of the battery. But still modification based on the battery ageing phenomenon and temperature should be made. The charging and discharging signal is represented using equation (1) and (2) [9]. The polarisation resistance is known to be infinite when *it* is fully charged. However, experimental results in [10] shows the contribution of the polarisation resistance during charging process is known to be shifted by 0.1 of the battery capacity.

Charging:

$$V_t = E_0 - K\frac{Q}{Q-it}it - K\frac{Q}{it-0.1.Q}i - R.i + \exp(t)$$
(1)

Discharging:

$$V_t = E_0 - K\frac{Q}{Q-it}it - K\frac{Q}{Q-it}i - R.i + \exp(t)$$
(2)

Where

$$\exp(t) = \frac{3}{Q_{exp}}it(-\exp(t) + (V_{full} - V_{exp})u(t))$$
(3)

V_t – battery terminal voltage (V)
E_o – battery constant voltage (V)
K – polarization resistance (Ù)
Q – battery capacity (Ah)
it – actual battery charge (Ah)
R – Battery internal resistance (Ù)
i – Actual battery current (A)
$exp(t)$– Exponential zone voltage (V)
$u(t)$ – Charge or discharge mode

Spectrogram: The spectrogram is one of the TFR techniques that provide a distribution of the signal energy in time-frequency marginal [11]. This technique is used to overcome the limitation of periodogram that only represent the signal in frequency marginal and lack in temporal characteristics information [12]. Spectrogram can characterize the battery parameters such as V_{RMS}, V_{DC} and V_{AC} by the frequency division based on DC and AC components. The spectrogram time-frequency representation is calculated as follows [11]:

$$S_x(t,f) = \left| \int_{-\infty}^{\infty} x(\tau)w(\tau - t)e^{-j2\pi f\tau}d\tau \right|^2$$
(4)

Where

$S_x(t,f)$ – Spectrogram
t – Time
f – Frequency
$x(\tau)$ – Input analysis signal
$w(\tau)$ – Observation window

Parameters Estimation
Instantaneous Voltage Means Square: The instantaneous of root means square voltage is a parameter that calculates the signal from 0Hz of frequency to maximum frequency measured using spectrogram. The V_{RMS} includes the overall parameters that occur at DC and AC components. The V_{RMS} can be calculated as [13]:

$$V_{RMS}(t) = \sqrt{\int_0^{f_{max}} S_x(t,f)df}$$
(5)

Where

f_{max} – Maximum frequency

Instantaneous Voltage Direct Current: The parameter of V_{DC} can be estimated through the fundamental frequency bandwidth of the battery. Since battery is a DC source,

amplitude of DC component gives the highest value. The V_{DC} can be defined as [11]:

$$V_{DC}(t) = \sqrt{\int\int_{f_1-\frac{\Delta f}{2}}^{f_1+\frac{\Delta f}{2}} S_x(t,f)df} \qquad (6)$$

Where

f_x – Fundamental frequency that corresponds to System frequency

Δf – Fundamental frequency bandwidth

Instantaneous Voltage Direct Current: The instantaneous of alternating current voltage can be calculated as [14]:

$$V_{AC}(t) = \sqrt{V_{RMS}^2 - V_{DC}^2} \qquad (7)$$

RESULTS AND DISCUSSION

The performance of the battery can be estimated based on charging and discharging signal of LA battery. The LA battery is being charged and discharged with constant current where experimental setup based on adjustable DC power supply model GPC-3030 and programmable DC electronic load model 63804 are used. To avoid cut-off voltage that can cause inaccurate in battery parameters measurement, constant current of 1A were used during 15 minutes of charging and discharging process. Selection of 12V LA batteries with 2.3Ah, 4.5Ah and 7.2Ah of storage capacities were used in this experiment. At the beginning, the battery is being charged for 15 minutes until it reaches a certain level of SOC. Then, the discharging process takes place for the same amount

Table 1: Battery parameters

Parameters	12V 2.3Ah	12V 4.5Ah	12V 7.2Ah
$E_o(V)$	12.2575	12.2575	12.2568
$R(\Omega)$	0.052174	0.026667	0.016667
$K(\Omega)$	0.13971	0.071405	0.044489
$V_{full}(V)$	13.22	13.22	13.23
$V_{exp}(V)$	12.2171	12.2171	12.2171
$Q_{exp}(Ah)$	0.0077	0.015	0.024

of time. The process is repeated for a certain number of battery cycles. In addition, this section displayed the charging and discharging voltage for 8 battery cycles and parameter of the battery is taken between 0.5h to 3.5h. To verify the battery performance, simulation based on equation (1) and (2) is conducted by using MATLAB Simulink. Simulation done is based on time which is 15 minutes of charging and discharging process is conducted where the similarities of the both simulation and experimental results are expected. Table 1 depicts the parameters of the battery model for the charging and discharging characteristics of the battery. Hence, it is assumed that the battery operates under constant room temperature during experimental process and the parameters of the battery is assumed to be operate with constant nominal capacity, constant internal resistance, no memory effect, no temperature effect and unlimited cycle life for simulation process.

Charging and Discharging Signal of Battery: The experimental charging and discharging signals for battery capacity of 2.3Ah, 4.5Ah and 7.2Ah are shown in Fig. 1. During the charging process, the 2.3Ah battery voltage raised higher compared to other two batteries. The 2.3Ah battery voltage gives the value of 12.58V at maximum after 15 minutes of charging
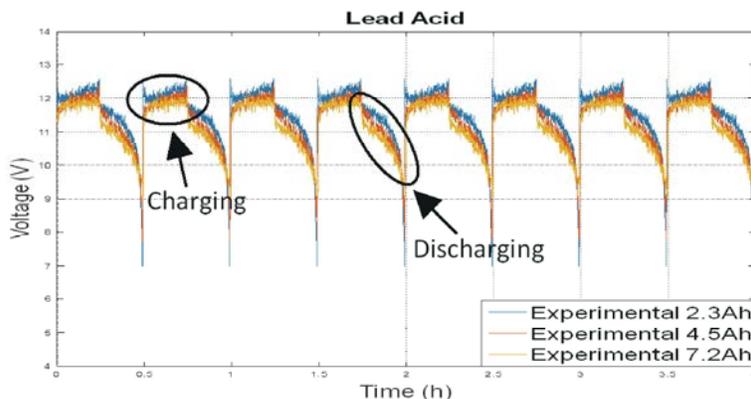

Fig. 1: Experimental of 8 cycles of voltage charging and discharging signal for 12V with 2.3Ah, 4.5Ah and 7.2Ah batteries
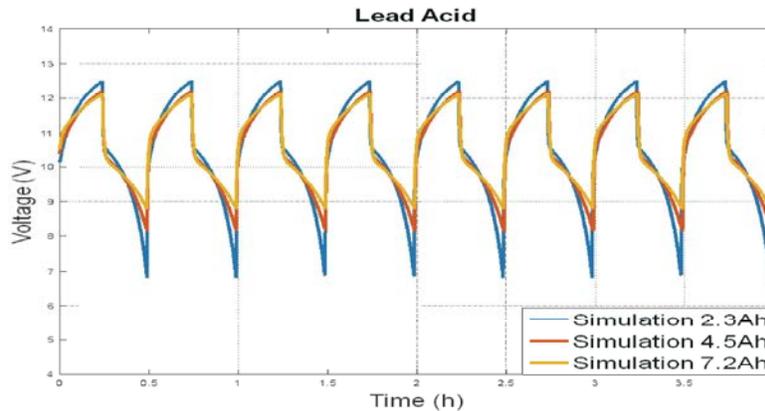
Fig. 2: Simulation of 8 cycles of voltage charging and discharging signal for 12V with 2.3Ah, 4.5Ah and 7.2Ah batteries

process followed by 12.36V for a 4.5 Ah battery and 12.06V for a 7.2 Ah battery. When the batteries are being discharged, the 7.2Ah battery voltage is being drained for about 3.053V. From the signal pattern shows that the voltage for low battery capacity rose faster during the charging process and also drained rapidly when the discharging process is conducted.

Figure 2 depicts the charging and the discharging signals for simulation based on battery model (Equation 1 and 2). Simulation result shows there is a sudden rise of batteries signals for the first 10 second from 0V to 10.13V and increase steadily during charging process for three different batteries capacity. The 7.2Ah battery voltage indicates 12.13V at maximum during charging process which is the lowest among other two batteries. The 4.5Ah battery voltage is 12.22V which is 0.28V different compared to 2.3Ah battery. When the battery is being discharged, the signals are marginally decreased whereas 2.3Ah battery voltage is 6.795V which is 2.017V lower than 7.2Ah battery. Simulation signals show the same pattern as experimental signals (Fig. 1) due to the characteristics of lead acid battery. However, simulation signals are seen to overestimate the battery voltage due to the assumption that the temperature effect is neglected in the battery model. But, this cause is not being investigated.

By using spectrogram technique based on equation (4), three dimensional plot of time-frequency representation are disclosed in Fig. 3. The amplitude of the charging and the discharging signal of the battery can be determined by the color of the graph. The dark red indicated highest signal amplitude and dark blue color represents the lowest amplitude. The TFR graph is seen to appear constant over the time from 0 to 4h due to the

observation window based on time interval as stated in equation (4). A fundamental frequency component which called DC component of the battery can be determined at the lowest frequency component. Usually, the DC component of the battery is nearer to 0Hz. Thus, the AC value can be measured at the higher frequency component.

Instantaneous Voltage Means Square: Fig. 4 illustrates the results of instantaneous of root means square voltage for experimental signal. By using equation (5), V_{RMS} versus time for experimental signals is determined. The experimental value for a 7.2 Ah battery indicates the lowest value which is at 11.2521V. The value of V_{RMS} for 2.3Ah battery is seen to be surpass both 4.5Ah and 7.2Ah batteries with the differences of 0.2324V and 0.3795 respectively. The charging and discharging signal of the battery will affect the value of V_{RMS} with respect to the capacity of the battery. As can be seen from Fig. 1, the higher the peak voltage of charging and discharging signal the higher the V_{RMS} value.

Graph in Fig. 5 shows the comparison of V_{RMS} between experiment and simulation signals for a 7.2 Ah battery using spectrogram technique. The V_{RMS} for simulation signal recorded is 10.7347V while the experimental signal measured is 11.2521V. The difference between simulation and experimental is acceptable since the temperature effect is neglected in this study. But the value is still acceptable and located between the ranges of 10.5000V to 11.5000V.

Instantaneous Voltage Direct Current: The instantaneous direct current voltage for experimental signal is illustrated in Fig. 6 based on equation (6). The V_{DC} for a 4.5 Ah battery indicates 11.3906V.
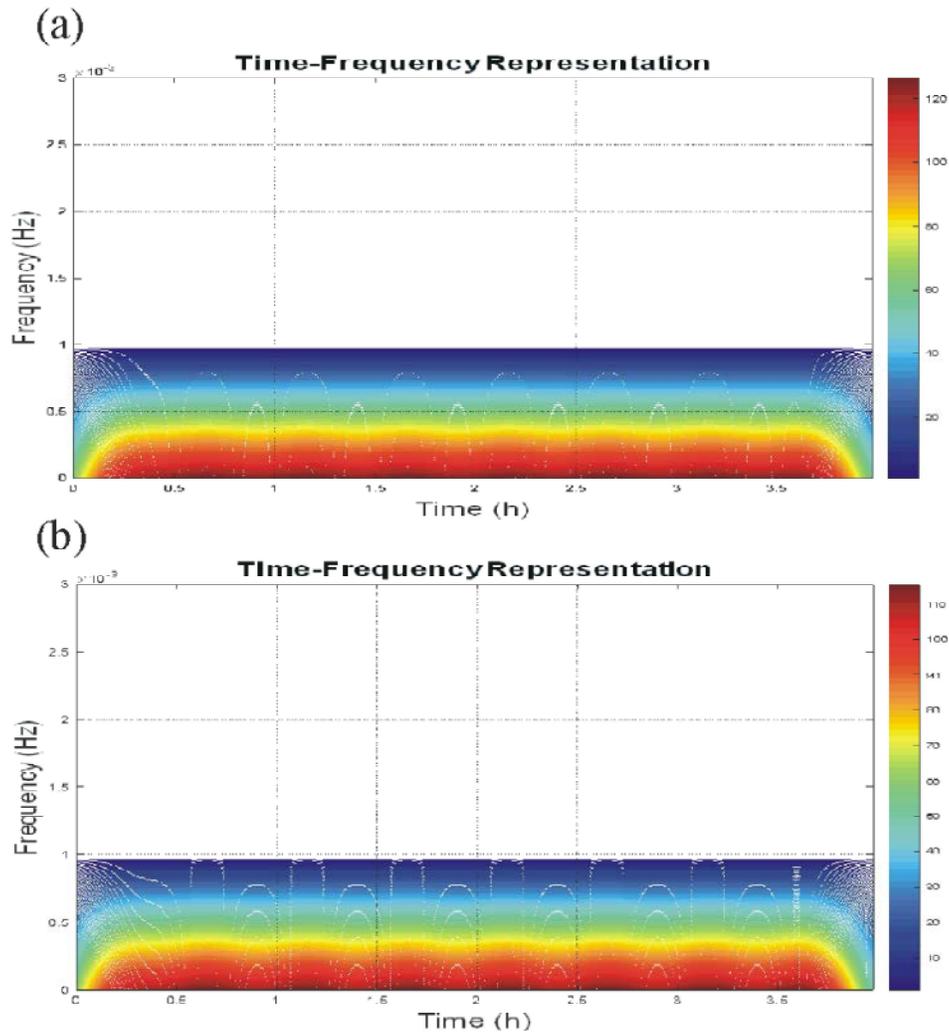
Fig. 3: Time-Frequency Representation with 7.2Ah for (a) Experimental (b) Simulation
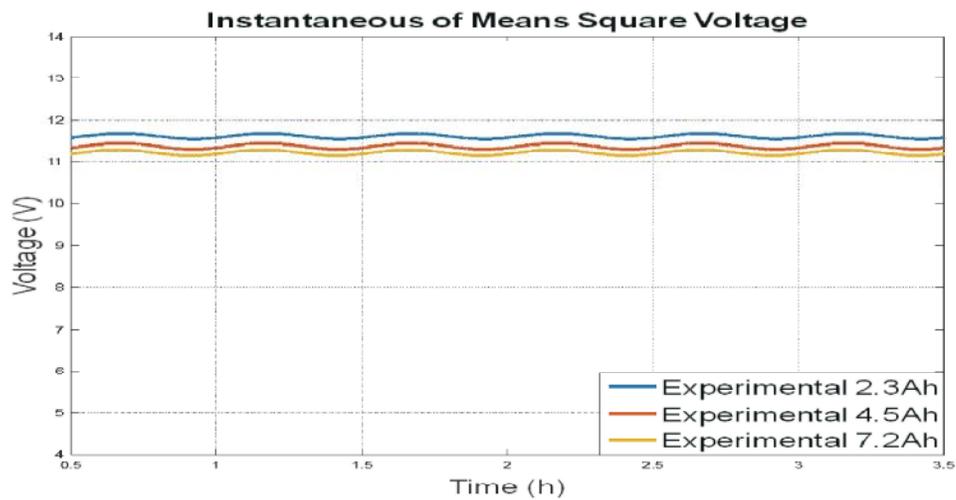

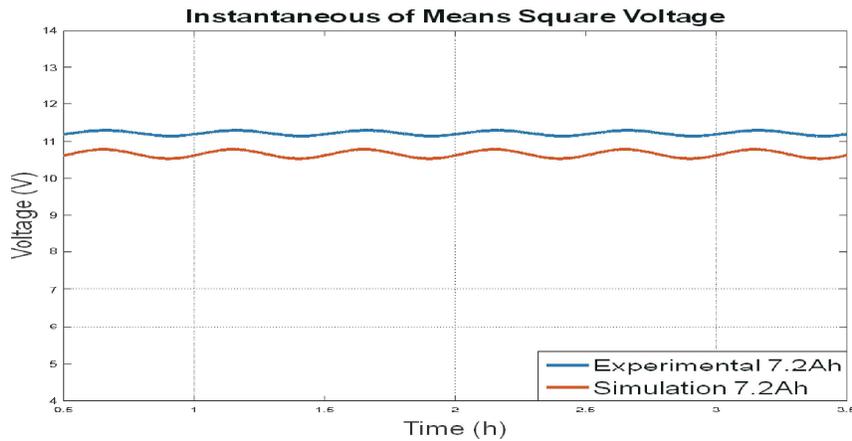Fig. 4: Instantaneous voltage means square for experimental signal

Fig. 5: Comparison of instantaneous voltage means square between experimental and simulation signal
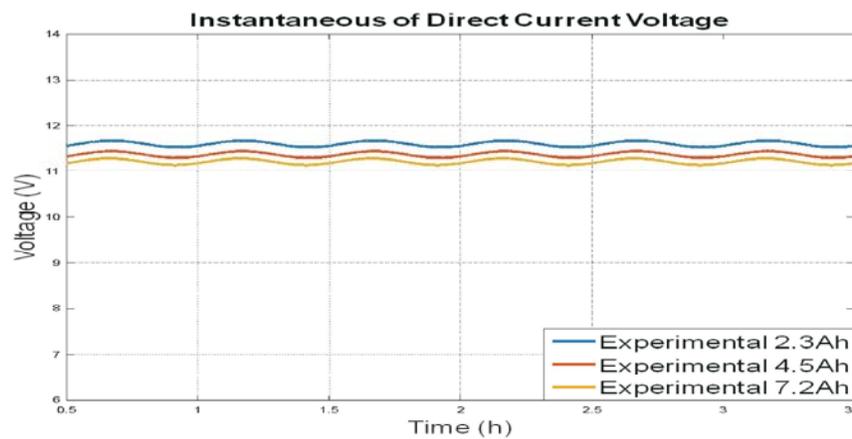

Fig. 6: Instantaneous voltage direct current for experimental signal
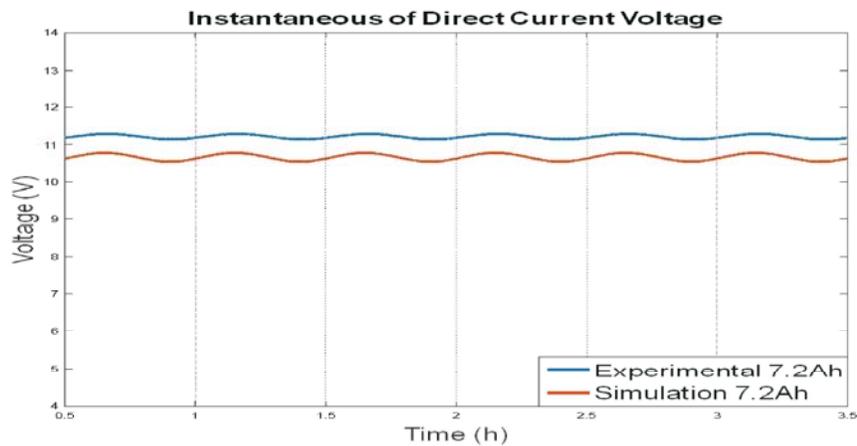

Fig. 7: Comparison of instantaneous voltage direct current between experimentation and simulation signal

The 2.3Ah battery shows slight differences of 0.2254V of V_{DC} compared to 4.5Ah battery. The value of V_{DC} is lower compared to V_{RMS} value. This is because V_{DC} is measured at DC component while the value of V_{RMS} is obtained at both DC and AC components.

In Fig. 7, the values of V_{DC} are obtained based on experimental and simulation signal. From the graph it can be seen that the value of V_{DC} for experimental signal is lower than simulation signal. The results clearly show that V_{DC} for simulation signal is 10.7277V for a 7.2 Ah battery
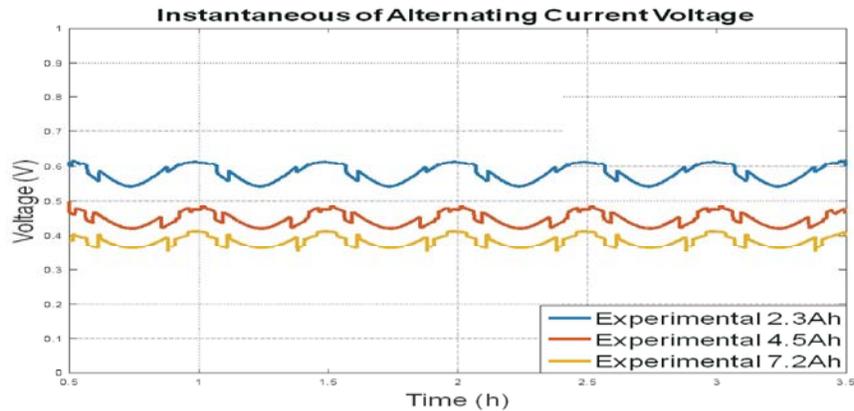
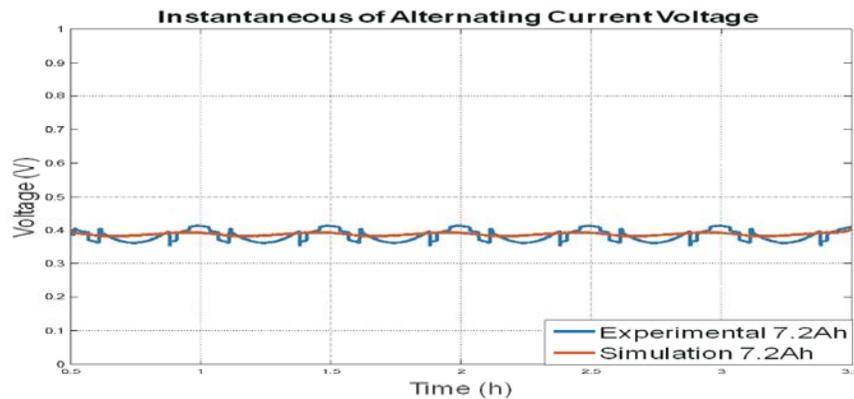Fig. 8: Instantaneous voltage alternating current for experimental signal

Fig. 9: Comparison of instantaneous voltage alternating current between experimentation and simulation signal
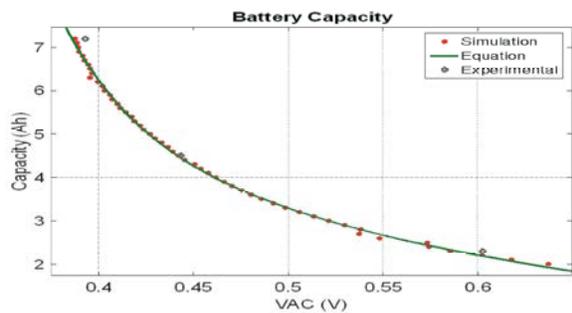

Fig. 10: Battery storage capacity of experimental and simulation result

and expected to give the higher value if the battery capacity is reduced.

Instantaneous Voltage Alternating Current: The graph for voltage versus time for V_{AC} is illustrated in Fig. 8. From the graph, the value of V_{AC} is obtained from 0.5h to 3.5h is the time taken for an eight cycle of charging and discharging signal of the battery (based on Fig. 1). The V_{AC} for 7.2Ah battery is 0.3928 and seem to give the lowest value compared to other battery voltage. Both 4.5Ah

and 7.2Ah batteries give a small difference of 0.0506V in V_{AC}.

The comparison of V_{AC} between experiment and simulation signal is depicted in Fig. 9. The value for experimental and simulation signals is nearer to each other with the different of 0.0054V. The waveform shows the constant trend where these parameters remain constant during charging and discharging process. The V_{AC} is much lower compared to V_{RMS} and V_{DC} (Fig. 5 and Fig. 7). This is because the battery is known to be a DC source, but the AC value can still be identified by using TFR.

Performance Evaluation: Parameter estimation using spectrogram leads to battery lifetimes estimation. The capacity of the battery depends upon the V_{AC} value can be numerically identified that gives an advantage to estimate the state of charge and state of discharge of the battery. Fig. 10 shows the graph of storage capacity versus V_{AC} for the experimental signal and simulation signal results. From the curve in Fig. 10, the similarities between experimental and simulation are obtained. By using curve fitting tools, equation (8) based on a simulation curve in Fig. 10 is produced. Thus, the battery capacity can be calculated as:

Table 2: Data of battery storage capacity

Instantaneous Voltage Alternating Current (V)

Experiment	Simulation	Capacity (Ah)
0.3928	0.3874	7.2
0.4434	0.4421	4.5
0.6025	0.5855	2.3

$$Q(V_{AC}) = 35290\exp^{-24.81V_{AC}} + 19.03\exp^{-3.599V_{AC}} \qquad (8)$$

Table 2 shows the comparison of V_{AC} for experimental and simulation signal based on 2.3Ah, 4.5Ah and 7.2Ah of battery capacity. Simulation results show that the values is not sailed wide from experimental values. Thus, the performance of the battery can be identified through the V_{AC} measured by using spectrogram.

CONCLUSION

The performance of the battery need to be estimated to ensure the power delivered can fulfil the requirement of the load demand. This paper presents the experimentation of LA battery using time-frequency representation namely spectrogram for battery parameters estimation. From the charging and discharging signal of the battery, parameters such as V_{RMS}, V_{DC} and V_{AC} are taken from TFR by using spectrogram technique. The results show V_{AC} parameter can be used to estimate the capacity of the battery from the new equation that has been produced. For the improvement, other TFD techniques such as Gabor transform and S-transform should be implementing in battery performance estimation for better results.

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