Experimental Verification of Nickel-Metal Hydride Battery Parameters Estimation

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***Abstract*— The impact of renewable energy in modern power systems entails the uses of energy storage system. The problem associated with the increase load demand that requires the continuity of power without any interference. One of the best solution is the uses of rechargeable battery. However, incorrect use of the battery not only can harm the equipment but also to the internal structure of the batteries itself. This paper focuses on the experimentation of nickel-metal hydride (Ni-MH) battery by using time-frequency distribution (TFD) which is spectrogram. The charging and discharging signal of the batteries is represented in time-frequency representation (TFR) and then, from the TFR, parameters of the battery such as instantaneous of means square voltage (V_{RMS}), instantaneous of direct current voltage (V_{DC}) and instantaneous of alternating current voltage (V_{AC}) are estimated. The experiments are conducted with three different Ni-MH battery with fixed nominal voltage of 12V and storage capacities of 1.3Ah, 1.8Ah and 2.7Ah respectively. The results are compared with the battery model implemented in MATLAB Simulink. The results show that there are similarities between the battery model and experimental data. Thus, the technique can be implemented through battery model.**

***Index Terms*— Battery parameters; Nickel-metal hydride; Spectrogram; Time-frequency representation.**

I. Introduction

The increased utilization of renewable energy leads batteries to be more pervasively used as the energy storage tank. The renewable energy phenomena put a notable emphasis on the parameters of the batteries, whereas the efficiency and the lifetime becomes the major concern for the performance of the battery [1]. Keep in mind that lack of battery performance not only gives an effect on the power system, but also on the battery itself [2]. Therefore, the parameters such as voltage, current and capacity are required to estimate the performance of the batteries in managing the energy requirement of the powered system. There are different type of batteries namely lead-acid (LA), lithium-ion (Li-Ion), nickel-cadmium (Ni-Cd) and nickel-metal-hydride (Ni-MH) with different characteristics.

Batteries can be classified in different type of models such as electrochemical model and equivalent circuit model (ECM). Selecting suitable and reasonable type of battery model is important to ensure the batteries are designed in an efficient way. According to [3], parameters estimation of batteries using electrochemical model gives accurate estimation of the state of charge (SOC) and state of discharge (SOD). Studies made by [4] show that parameters estimation using full order electrochemical model have the smallest voltage error compared to the equivalent circuit model. However, these two studies concluded that electrochemical model causes longest computational time which is not applicable for real-time monitoring system and proposed on the reduced set of partial differential-algebraic equation (PDAE).

In the ECM approach, the internal part of the battery is represented by the combination of electrical component such as resistors, capacitors and inductor [5]. Through this model, studies made by [6] estimate that the parameter of the open circuit voltage and polarization voltage can be characterized. Moreover, the results clearly show that the equivalent circuit model is low in complexity and more flexible in real-time monitoring system. To overcome the weakness of the equivalent circuit model in low of accuracy, [1] proposed the z-transformed battery model to reduce the error, however the maximum error was found to be similar.

This paper presents the new real-time analysis of Ni-MH battery using time-frequency distribution. The 12V of nominal voltage with 1.3Ah, 1.8Ah and 2.7Ah of the battery capacities are used in this experiment. The output signal at the battery terminal that represent in the time domain will be converted in the form of time-frequency representation through a spectrogram technique [7]. Then, parameters such as instantaneous of means square voltage, instantaneous of direct current voltage and instantaneous of alternating current voltage are extracted from the TFR. To verify the performance of the battery, the results are compared with the model simulated by MATLAB, Simulink.

II. Nickel-Metal-Hydride

Ni-MH battery is developed as an improvement to the weakness of LA and Ni-Cd batteries in creating disposal and maintenance problem due to highly toxic metals, lead and cadmium [8]. As mentioned in [9], the improvement to the performance of Ni-MH is through the constant concentration of aqueous potassium hydroxide from changing and discharging signal of this battery. Hence, Ni-MH battery leads other type of batteries in withstanding over-charge and over-discharge condition in real application. Different types of batteries give different charging and discharging pattern due to the electrochemical reactions of different battery materials. The generated charging and discharging signal for Ni-MH battery model for MATLAB Simulink is represented using Equation (1) and (2) [10]. From the charging model based on

Equation (1), the polarisation resistance is considered to be shifted by 0.1 of the battery capacity from the experimental results in [11] when an actual battery charge (it) is at full.

Charging:

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

Discharging:

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

where:

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

V_t = battery terminal voltage (V)
E_0 = battery constant voltage (V)
K = polarization resistance (Ω)
Q = battery capacity (Ah)
it = actual battery charge (Ah)
R = battery internal resistance (Ω)
i = actual battery current (A)
$\exp(t)$ = exponential zone voltage (V)
$u(t)$ = charge or discharge mode

III. SPECTROGRAM

Analysis of non-stationary signal using time-frequency analysis is presented in the three-dimensional plot in terms of signal energy or magnitude with respect to time and frequency [12]. Parameters such as V_{RMS}, V_{DC} and V_{AC} for Ni-MH battery can be estimated from TFR using spectrogram. Windowed frame of battery signal from frequency spectrum is a result of the spectrogram. The spectrogram is the problem solver to the limitation of fast Fourier transform (FFT) that can only represent signal in the frequency domain. The spectrogram time-frequency representation can be defined as [13]:

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

where:

$S_x(t,f)$ = Spectrogram
t = time
f = frequency
$x(\tau)$ = input analysis signal
$w(\tau)$ = observation window

IV. PARAMETERS ESTIMATION

A. Instantaneous of Means Square Voltage

The instantaneous of means square voltage (V_{RMS}) can be calculated as [13]:

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

where $f_{\max}$ = maximum frequency

B. Instantaneous of Direct Current Voltage

From the spectrogram, the DC parameter can be estimated through the area obtained from the fundamental frequency bandwidth of the battery. The fundamental frequency of the battery is occurred at the highest magnitude of the spectrogram. Hence, the instantaneous of direct current voltage (V_{DC}) can be calculated as [13]:

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

where

f_1 = fundamental frequency that corresponds to system frequency
Δf = fundamental frequency bandwidth

C. Instantaneous of Alternating Current Voltage

The instantaneous of alternating current voltage (V_{AC}) is the voltage that appears at the frequency components. The V_{AC} can be defined as [7]:

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

V. RESULTS AND DISCUSSION

To evaluate the performance of the battery, experiments based on the charging and the discharging signals of the Ni-MH battery are conducted. Adjustable DC power supply model GPC-3030 and programmable DC electronic load model 63804 are used with constant charging and discharging current of 1A as shown in Figure 1. The reason why discharging current is maintained to 1A is to avoid the battery reach the cut-off voltage that causes inaccuracy in measurement. This experiment is conducted for 12V Ni-MH batteries with 1.3Ah, 1.8Ah and 2.7Ah of storage capacities.

Initially, the battery is being fully discharged. The charging process is performed for 15 minutes until the battery reaches certain amount of SOC followed by discharging process for the same amount of time. The process is repeated for a certain number of battery cycle. In this section, the charging and discharging voltage are presented for 8 cycles and the battery parameters are measured between 0.5h to 3.5h. The experimental results based on charging and discharging signals are verified based on the Equation (1) and (2) simulated in MATLAB Simulink. For this experiment, the batteries are considered to operate under room temperature for both charging and discharging conditions.

The charging and discharging characteristics of the battery based on Equation (1) and (2) are represented by a parameters as illustrated in Table 1. Through this model, the battery is assumed to be operate with constant nominal capacity, constant internal resistance, no memory effect, no temperature effect and unlimited cycle life.

Figure 1: Experimental setup for Ni-MH battery

Table 1
Battery parameters

Parameters	12V 1.3Ah	12V 1.8Ah	12V 2.7Ah
$E_0(V)$	12.627	12.6784	12.7773
$R(\Omega)$	0.092308	0.066667	0.044444
$K(\Omega)$	0.042787	0.033536	0.025732
$V_{full}(V)$	15.10	15.17	15.18
$V_{exp}(V)$	12.70	12.75	12.84
$Q_{exp}(Ah)$	0.26	0.36	0.54

A. Charging and Discharging Signal of Battery

Figure 2 shows the results of charging and discharging signals measured during experimental for three different battery capacity of 1.3Ah, 1.8Ah and 2.7Ah respectively. The charging and discharging signals for the three different battery capacities give the same pattern. Initially, all three Ni-MH batteries voltages experienced a sudden increment of 1.7200V when the charging process is conducted. The voltage for all three cases increase steadily for a certain period of time until the charging process is completed. When the battery is being discharged, the voltage signal for 1.3Ah battery fall drastically compared to both 1.8Ah and 2.7Ah batteries. Furthermore, it is clearly be seen that the higher the battery capacity, the faster the battery voltage is raised and the lower the battery capacity the faster the battery voltage is drained.

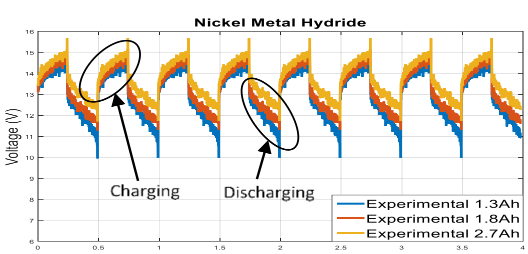


Figure 2: Experimental of voltage charging and discharging signal for 12V with 1.3 Ah, 1.8Ah and 2.Ah batteries

The comparison of battery voltage between experimentation and simulation is represented in Figure 3. For the first 10 second, the experimental signal rise abruptly from 10.9000V to 13.4300V and increases steadily until charging process is completed. Simulation signal shows similar behaviour where the battery voltage increases dramatically at the first 10 seconds. However the simulation voltage is over estimating the experimental voltage until it reaches the maximum value of 14.9200V after 15 minutes of charging process. During the discharging process, the signals for both experimental and simulation are marginally decreased. The battery voltage for experimental is seen to overestimate the simulation. This is probably due to the assumption that the temperature effect is neglected in the battery model ((1) and (2)). However, this cause is not being investigated. Nevertheless, the signal pattern is still same for charging and discharging process.

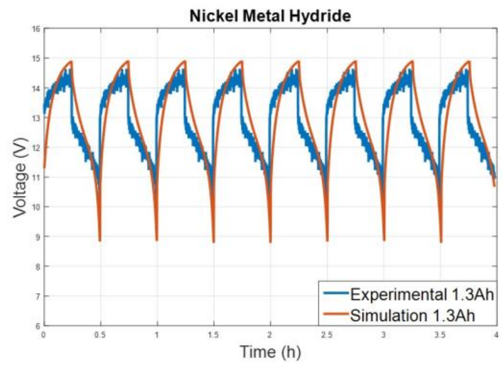
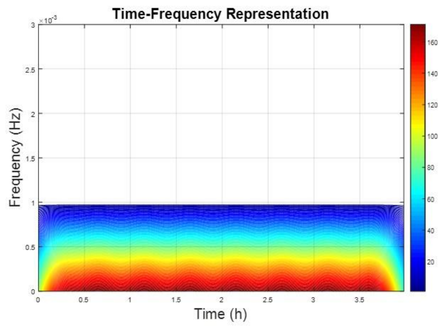


Figure 3: Comparison between experimental and simulation of voltage charging and discharging signal for 12V with 1.3Ah

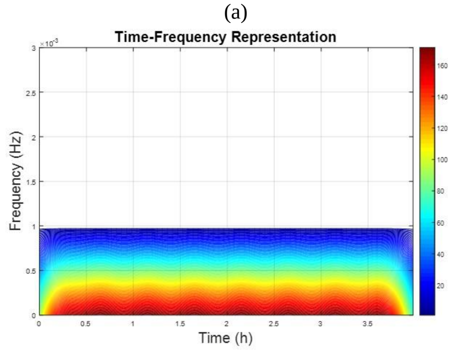
Figure 4 (a) and (b) depict the three dimensional plot of time-frequency representation using the spectrogram technique based on Equation (4). The *y*-axis indicates the frequency of the battery while the *x*-axis represents the time measured in hour. The amplitude of the signal can be determined by the color of the graph. The dark blue line represents the lowest amplitude and dark red indicates highest signal amplitude. TFR graph is represented by the signal captured using observation window based on Equation (4). In this case, the Hanning window with the length of 1024 is used. This observation window will cause TFR graph to appear constant over time duration from 0h to 4h. From the TFR graph, the frequency of the battery can be estimated and the results clearly show that the frequency for experimental signal is between 0Hz to 0.0009Hz. Mostly, the DC component of the battery is measured at 0Hz. Thus, the AC value can be identified at the higher order of frequency.

B. Instantaneous of Means Square Voltage

The graph in Figure 5 clearly shows the measurement of instantaneous of means square voltage for experimental signal. From the TFR graph, the value of V_{RMS} can be calculated by using Equation (5). The V_{RMS} for 2.7Ah battery is 13.7990V which is slightly higher than 1.8Ah battery value. The 1.3Ah battery indicates the lowest value with the differences of 0.2793V and 0.7278V between 1.8Ah and 2.7Ah batteries respectively.



(a)



(b)

Figure 4: Time-Frequency Representation with 1.3Ah for (a) Experimental (b) Simulation

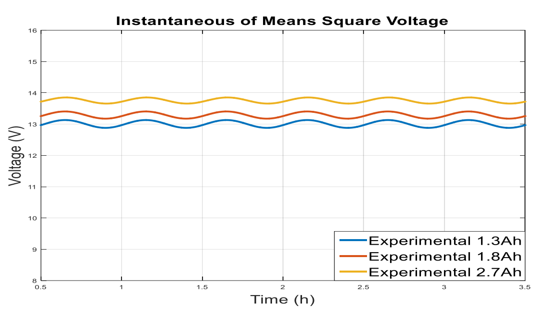


Figure 5: Instantaneous of means square voltage for experimental signal

The instantaneous of means square voltage for experimental and simulation are disclosed in Figure 6. There is slight difference between the values of V_{RMS} obtained from both signals. The V_{RMS} for simulation signal is 13.0889V which is 0.0177V higher than experimental signal. This is due to the different peak voltage of charging and discharging signal between two signals as shown in Figure 3.

C. Instantaneous of Direct Current Voltage

The graph of experimental for V_{DC} is obtained from Equation (6) (see Figure 7). The value of V_{DC} can be determined by repeating the charging and discharging cycle until this parameter is extracted. The value of V_{DC} measured for a 2.7Ah battery indicates 13.7955V followed by 1.8Ah battery with 13.3451V and 1.3Ah battery with 13.0622V. The value of V_{DC} calculated is nearer to the V_{RMS} due to the high amplitude of voltage at DC component.

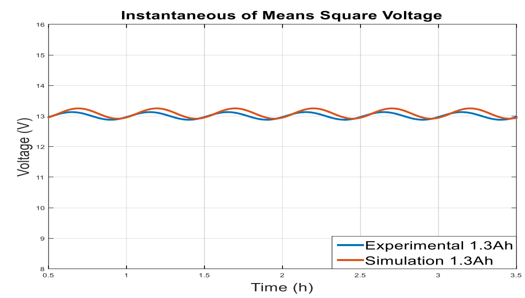


Figure 6: Comparison of instantaneous of means square voltage between experimental and simulation signal

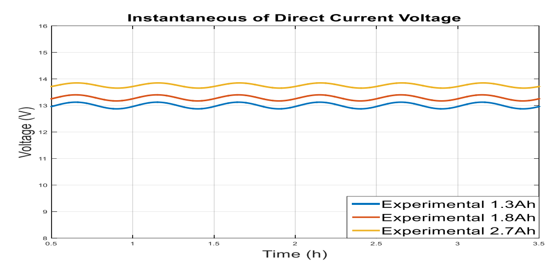


Figure 7: Instantaneous of direct current voltage for experimental signal

Figure 8 shows the comparison of V_{DC} between experimental signal and simulation signals for a 1.3Ah battery. The V_{DC} measured from TFR for experimental signal is lower compared to simulation signal with the value of 13.0622V. The expected results for both signals should be nearer to each other and the simulation value obtained is reasonably acceptable due to the temperature effect that is being neglected.

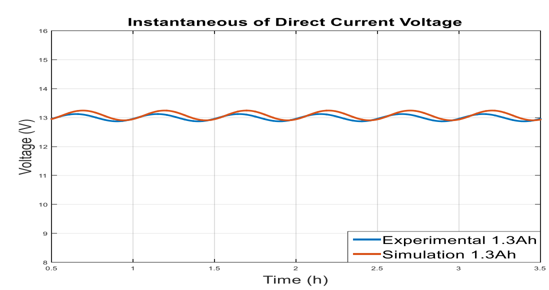


Figure 8: Comparison of instantaneous of direct current voltage between experimentation and simulation signal

D. Instantaneous of Alternating Current Voltage

The instantaneous of alternating current voltage for experimental signal is illustrated in Figure 9. The graph below shows that the values of V_{AC} for all the signals are constant. Experimental result for a 1.8Ah battery indicates 0.3767V which is lower than the 1.3Ah battery value. Meanwhile, the value of V_{AC} for a 2.7Ah battery is only 0.3139V. Although the values of V_{RMS} and V_{DC} for a 2.7Ah battery (see Figure 5 and Figure 7) are the highest compared to the other two batteries, but the value of V_{AC} measured gives the lowest.

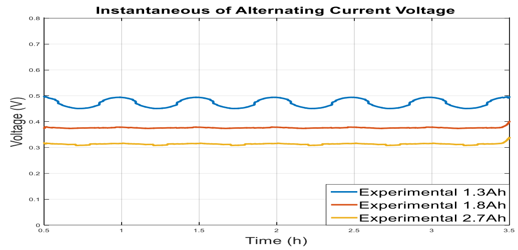


Figure 9: Instantaneous of alternating current voltage for experimental signal

In Figure 10, the values of V_{AC} are obtained from the measurement of ac components. The V_{AC} for experimental signal is practically higher than simulation signal with the differences of 0.0023V. The V_{AC} for simulation signal shows the measurement of 0.4834V. The change in V_{AC} occurred due to the influence of V_{RMS} and V_{DC} based on Equation (7).

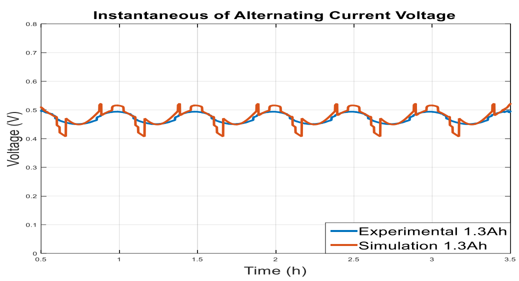


Figure 10: Comparison of instantaneous of alternating current voltage between experimentation and simulation signal

E. *Performance Evaluation*

It is important to estimate the battery capacity in order to determine the state of charge and state of discharge for battery lifetime estimation. Through the spectrogram technique, the graph for battery storage capacity versus V_{AC} for simulation and experimental are represented in Figure 11. The graph shows that the lower the V_{AC} the higher the capacity of battery. The maximum capacity can be estimated from simulation is 3.0Ah from the reading of 0.2950V of V_{AC}. From the simulation curve obtained in Figure 11, Equation (8) is produced based on curve fitting tool simulated using MATLAB. Thus, battery capacity based on V_{AC} obtained by using spectrogram can be estimated. The battery capacity can be calculated as:

$$Q\left(V_{AC}\right)=17600\exp^{-35.07V_{AC}}+6.44\exp^{-3.309V_{AC}} \tag{8}$$

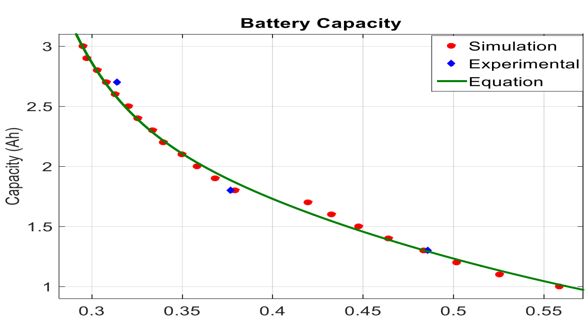


Figure 11: Battery storage capacity of experimental and simulation result

The battery storage capacity from the experimental and simulation is tabulated in Table 2. The measurement of AC is taken from 1.3Ah, 1.8Ah and 2.7Ah of battery capacity. The value of V_{AC} for experimental and simulation are increasing as the capacity of the battery is decreasing. The value of V_{AC} for both results seem to give almost the same value for every different battery capacity.

Table 2
Data of battery storage capacity

Instantaneous Voltage Alternating Current (V)		Capacity (Ah)
Experiment	Simulation	
0.3139	0.3079	2.7
0.3767	0.3791	1.8
0.4857	0.4834	1.3

VI. Conclusion

The performance of the battery needs to be maintained at optimum value to fulfill the requirement of the load system. Experimentation based on Ni-MH battery is conducted by using time-frequency distribution which is a spectrogram to estimate the performance of the battery. To determine the characteristic of the battery, the useful parameters such as V_{RMS}, V_{DC} and V_{AC} are extracted from TFR through charging and discharging signal of the battery. Significantly, battery storage capacity can be identified from the AC components results for battery performance estimation. In order to increase the efficiency of the results, experiments based on different battery capacities should be conducted in future works.

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