

Performance Comparison of VRLA Batteries Under Pulsed and Constant Current Discharge Modes

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Abstract—This work investigates the use of Valve Regulated Lead-Acid (VRLA) batteries under various pulsed current discharge frequencies. Despite their reputation as low maintenance storage devices, commonly used in off-grid systems, VRLA batteries suffer from reduced lifetime compared to alternative energy storage technologies. This work examines how different pulse discharge frequencies affect voltage response, delivered energy, extractable capacity, and internal impedance compared to the constant current discharge method. Results show that pulse frequencies between 10 Hz and 1 kHz can reduce internal impedance, increase extractable capacity by 10% and delivered energy by more than 13% compared to constant current discharge. Frequencies above 1 kHz tend to increase internal impedance and reduce extractable capacity and delivered energy compared to lower frequencies.

Index Terms—VRLA Batteries, Pulsed Current Discharge, Battery Modeling, Energy Efficiency, Pulsed Power.

I. INTRODUCTION

As energy storage efficiency improves, intensive research into battery performance promotes the development of new technologies in areas such as off-grid systems and electric vehicles [1]. Understanding how different battery types perform across various environmental conditions, such as temperature and humidity ranges, is crucial for advancing renewable energy storage [2], [3].

Valve Regulated Lead-Acid (VRLA) batteries continue to be widely used for electrical energy storage due to their low maintenance reputation. However, these batteries exhibit a relatively reduced lifetime compared to alternative energy storage

technologies [4]. Although traditional chemical approaches provide insights into battery behavior, mathematical and electrical models are essential for predicting voltage and current behaviors, state of health (SOH) and state of charge (SOC) [5], [6]. These models characterize battery impedance parameters and electrochemical reactions, enabling the simulation of diffusion impedance during different discharge conditions [7].

The degradation of VRLA batteries primarily results from ion diffusion limitations, where lead sulfate crystals form on the electrode surfaces of the battery (a process known as sulfation) [8], [9]. Similarly, pulse discharge techniques have demonstrated improvements in energy efficiency and SOC enhancements in lithium-ion batteries compared to constant current discharge methods [10]. These techniques reduce the diffusion impedance by disrupting concentration gradients, reducing internal resistance effects and contributing to an extended battery lifespan and improved energy efficiency [11]. The nature of pulse discharge allows for partial relaxation of the electrolyte, enabling a more uniform utilization of active materials [10].

This work investigates how the use of pulsed current discharges impact on the performance of valve-regulated lead-acid batteries. Key performance indicators such as delivered energy, extractable capacity, voltage response and internal impedance were analyzed and compared for various frequencies of pulsed and constant current discharge. The experimental procedure involved subjecting the batteries to controlled pulse discharge profiles using a programmable electronic load, while a universal oven was used to keep the temperature stable during the test. The intended result is to determine whether pulse discharging can improve overall battery performance compared to constant current discharge.

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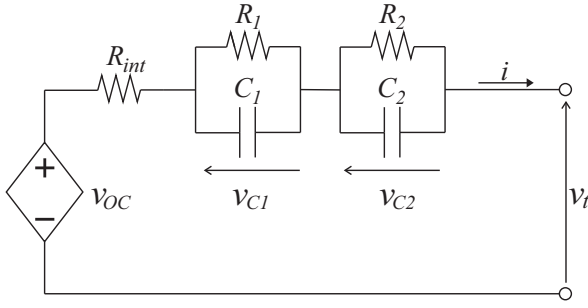


Fig. 1: Equivalent circuit model based on the Thevenin dual polarization approach.

II. METHODOLOGY

A. Battery Model

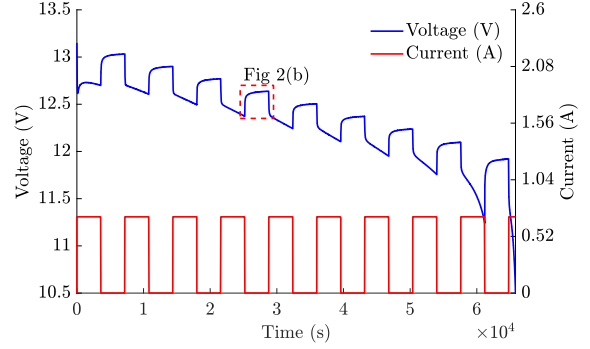
VRLA batteries have a distinct voltage response to current as the electrochemical reactions are accompanied by diffusion processes, which is the movement of particles from a region of higher concentration to a region of lower concentration [9]. During discharge, two primary polarization effects occur: concentration polarization results from the limited diffusion rate of ions between electrodes, creating concentration gradients that hinder charge transfer. The activation polarization arises from the energy barrier that must be overcome to initiate electrode reactions at the electrode-electrolyte interface. These polarization effects contribute to voltage drops during discharge and voltage recovery during rest periods. These processes can be modeled as impedance using the Thevenin dual polarization approach [12]. This model incorporates both concentration and activation polarization components, represented by resistances (R_1 , R_2) and capacitances (C_1 , C_2), as shown in Fig. 1. The internal resistance (R_{int}) accounts for the overall impedance of the battery system.

The dual polarization RC branches can be represented by the state-space equation in (1), where the state variables correspond to the voltages across the branches (v_{C1} and v_{C2}). The output of the system is given by (2) in the time domain, where v_t is the terminal voltage of the battery, the discharge current $i(t)$, and v_{OC} is the open-circuit voltage which is a function of the SOC. The SOC is represented in (3), where C_{bat} is the real capacity of the battery in Ah and $i(t)$ is the discharge current starting from the initial condition t_0 to t .

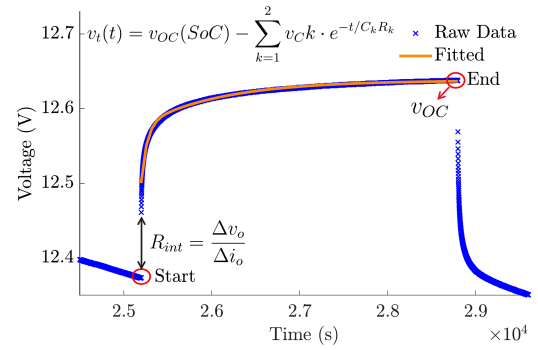
$$\begin{bmatrix} \dot{v}_{C1} \\ \dot{v}_{C2} \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_1 C_1} & 0 \\ 0 & -\frac{1}{R_2 C_2} \end{bmatrix} \begin{bmatrix} v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{1}{C_1} \\ \frac{1}{C_2} \end{bmatrix} i(t) \quad (1)$$

$$v_t(t) = v_{OC}(SoC) - v_{C1}(t) - v_{C2}(t) - i(t)R_{int} \quad (2)$$

$$SOC(t) = SOC(t_0) - \frac{1}{C_{bat}} \int_{t_0}^t i(\tau) d\tau \quad (3)$$



(a) Pulse discharge test



(b) Curve fitting method for parameter estimation

Fig. 2: Low-frequency Impedance Analysis

B. Low Frequency Impedance Behavior

For low frequency ranges, the parameters of the dual polarization model shown in Fig. 1 can be estimated utilizing data from a pulse discharge test with relaxation states, as shown in [13] and [14], and a non-interactive least squares curve fitting method, better described at [15]. This is a well-known method for modeling a battery ECM utilizing time domain data and, for this case in specific, the discharge starts from 100% SoC with current pulses i of 700 mA (C rate of 1/10), period T of 7200s, duty cycle of 50% and controlled temperature of 30 °C. The rest period (zero current) allows the surface voltage v_t to relax towards the open-circuit voltage v_{OC} due to the electrolyte relaxation and diffusion processes, which can be seen in Fig. 2(a).

$$v_t(t) = v_{OC} - v_{C1}(t_0) \cdot e^{-\frac{t}{R_1 \cdot C_1}} - v_{C2}(t_0) \cdot e^{-\frac{t}{R_2 \cdot C_2}} \quad (4)$$

To obtain the parameters of the ECM, the equation (4) is fitted to the terminal voltage response during the relaxation period, as shown in Fig. 2(b). The values of R_{int} are calculated based on the instantaneous voltage response at the start of the relaxation period, the values of R_1 , C_1 , C_2 and R_2 are estimated from the time constants of the exponential behavior

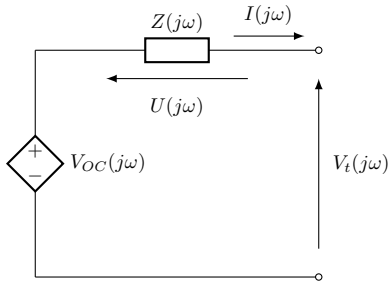


Fig. 3: High frequency ECM for impedance analysis.

of the voltage response and v_{OC} is the last measured voltage before the current pulse starts. This process is repeated for various levels of SoC to obtain a set of parameters that can be used to model the battery behavior at low frequencies.

C. High Frequency Impedance Behavior

For higher frequency discharges, the ECM can be further simplified, as the RC branches in Fig. 1 can be considered as short circuits, and the battery can be modeled as a controlled voltage source with an internal impedance, as shown in Fig. 3. For higher frequencies, analyzing data in the frequency domain is more suitable; observe that the component V_{OC} is a pure DC component and $Z(j\omega)$ is the impedance of the battery in frequency domain.

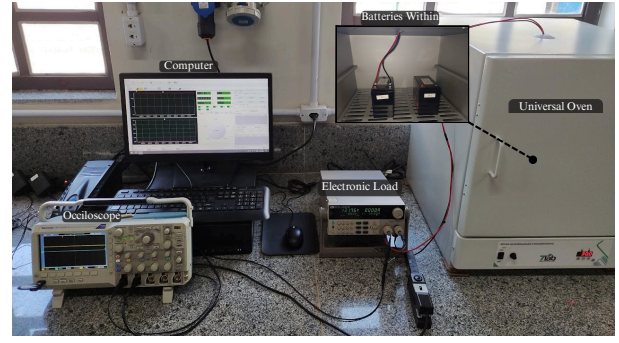
To analyze a battery's impedance at high frequencies, a common approach is to perform Electrochemical Impedance Spectroscopy (EIS), which involves applying a small AC signal to the battery and measuring the resulting voltage response. An alternative approach which provides similar results is to perform a pulsed current discharge test with higher frequency pulses and perform the Fast Fourier Transform (FFT) of the voltage and current response to obtain the impedance spectrum. The impedance voltage drop u , also known as the overpotential, is denoted by (5), and is the difference between the open-circuit voltage v_{OC} and the terminal voltage v_t in frequency domain [16]. With this, the impedance $Z(j\omega)$ can be calculated as shown in (6), where $U(j\omega)$ is the Fourier transform of the overpotential and $I(j\omega)$ is the Fourier transform of the current response. With a controlled pulsed current discharge test and an oscilloscope to capture the terminal voltage and current waveforms, the FFT can be calculated to obtain the impedance spectrum of the battery for a wide range of frequencies [17], [18].

$$u(t) = v_{OC}(t) - v_t(t) \quad (5)$$

$$Z(j\omega) = \frac{\mathcal{F}\{u(t)\}}{\mathcal{F}\{i(t)\}} = \frac{U(j\omega)}{I(j\omega)} \quad (6)$$

III. CASE STUDY

The case study is separated into three parts with the objective to determine the performance of the selected VRLA battery under constant current discharge and pulse discharge methods. The first part consists of the results found in the low



(a) Experimental setup.



(b) Batteries and CC-CV charger.

Fig. 4: Experimental setup and VRLA battery under test.

frequency impedance analysis detailed in Subsection II-B. The second part consists of the results found in the high frequency impedance analysis, detailed in Subsection II-C. The third and final part compares the performance of the battery under constant current discharge and pulse discharge method for the frequencies analyzed in the previous subsections.

The experimental setup, which can be seen in Fig. 4(a), consisted of a programmable DC electronic load (Itech IT8511AG+) to control the discharge current profiles. This device also communicated with a computer via USB to log the voltage and current data during the tests, with a sampling time of 0.5 seconds. It is important to note that the electronic load calculates the average values of current and voltage automatically with a sampling frequency of 20kHz. Also, a Tektronix DPO 2024B oscilloscope was used to monitor the voltage and current waveforms with higher precision during the tests.

A universal oven was utilized to maintain a constant temperature of 30 °C during the tests. The batteries under test were 12V, 7Ah VRLA batteries, labeled as "IN5" and "IN1" for better organization, from the manufacturer "UNIPOWER". The batteries are from the same production batch to ensure consistency in the results. Also, the batteries were fully charged utilizing a Hayama 13.8V CC-CV charger with float stage for at least 48 hours to guarantee 100% SoC state before every test. The batteries and chargers in question can be seen in Fig. 4(b).

IV. RESULTS AND DISCUSSION

A. Low Frequency Results

The Table I shows the estimated parameters for a 7 Ah, 12V VRLA battery, tagged as “IN5”. These parameters were obtained using the curve-fitting method described in Subsection II-B and in Fig. 2(b), with the pulsed discharge test shown in Fig. 2(a).

Following the parameters in Table I, the ECM can be simulated in a numerical environment for pulsed current discharges in low frequency ranges. Taking 90% SoC as an example, the Nyquist Plot of the impedance in response to frequency is shown in Fig. 5. It is possible to see that the magnitude of the impedance decreases as the frequency increases. Also, the Nyquist plot tends to translate itself to the right of the real axis, as the internal resistance R_{int} increases as the SoC diminishes, as can be seen in Fig. 5(b) for various SoC levels. Independent of the SoC level, the characteristics of the Nyquist plot remain the same, with the real impedance being lower at 1Hz and greatest at lower frequencies, specially tending to 0 Hz, which is the case for constant current discharges [19].

B. High Frequency Results

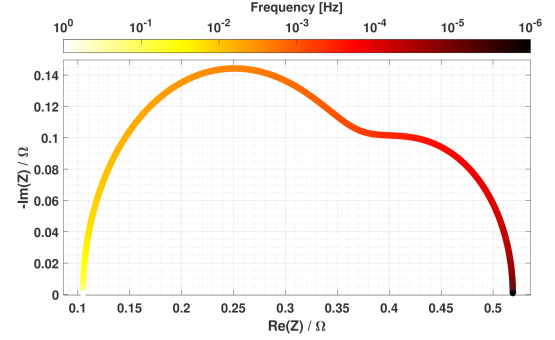
Utilizing the battery “IN5”, also utilized in the low frequency analysis, a pulsed current discharge was conducted with a square wave of 50% duty cycle, DC current pulse with amplitude of 7A. For this test, a higher current amplitude was necessary for a better capture of the voltage signal in the oscilloscope, such as the use of the AC coupling mode for the voltage channel for a better ADC resolution.

The test was performed at the following frequencies: 10Hz, 100Hz, 500Hz, 1kHz, 2kHz and 5kHz. For the purposes of this analysis, the battery was tested only for SoC 90% and 30 °C ambient temperature. Utilizing the oscilloscope, the voltage and current waveforms were saved during the tests, the Fig. 6 shows the voltage and current waveforms for the different frequencies tested.

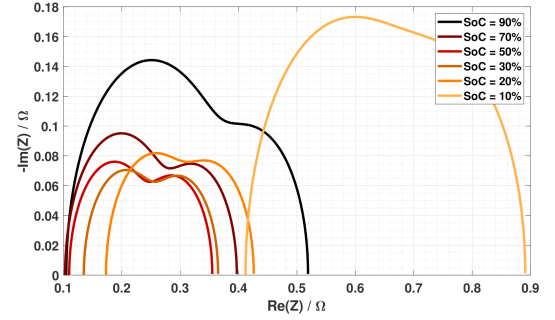
It is possible to see that, compared to the low frequency test in Fig. 2(a), the voltage response to the relaxation period is lower due to the higher frequency. Also, it is possible to see that voltage spikes at the rising and falling edges of the current pulse are more significant at higher frequencies. The FFT for the overpotential and current waveforms were calculated using the CSV data from the oscilloscope. The Fig. 7 shows the

TABLE I: Estimated ECM Parameters and R^2 for Battery IN5

SoC (%)	v_{OC} (V)	R_o (Ω)	R_1 (Ω)	R_2 (Ω)	C_1 (F)	C_2 (F)	R^2
90	13.031	0.105	0.263	0.151	220	4 744	0.995
80	12.900	0.103	0.203	0.129	284	6 458	0.994
70	12.769	0.103	0.172	0.122	345	6 835	0.994
60	12.638	0.105	0.149	0.115	440	7 892	0.995
50	12.505	0.110	0.134	0.111	518	8 165	0.995
40	12.372	0.117	0.122	0.108	638	9 269	0.996
30	12.237	0.135	0.120	0.110	733	9 091	0.996
20	12.097	0.173	0.134	0.119	836	8 374	0.996
10	11.918	0.412	0.271	0.208	461	3 693	0.997

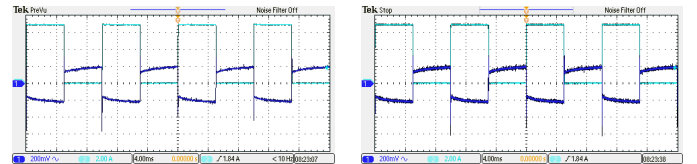


(a) Nyquist plot at 90% SoC.

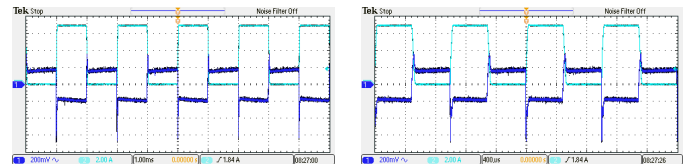


(b) Nyquist plot translation for different SoC.

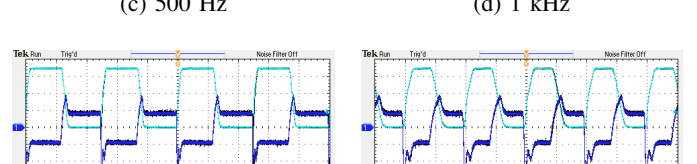
Fig. 5: Nyquist plot of the battery impedance.



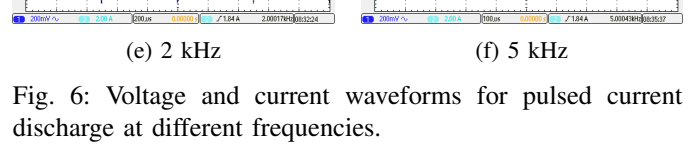
(a) 10 Hz



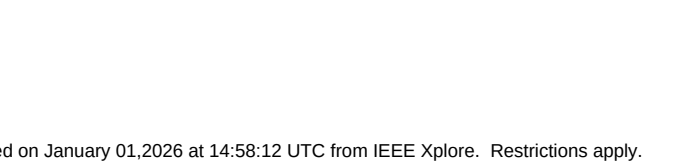
(b) 100 Hz



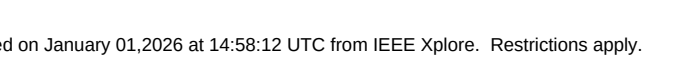
(c) 500 Hz



(d) 1 kHz



(e) 2 kHz



(f) 5 kHz

Fig. 6: Voltage and current waveforms for pulsed current discharge at different frequencies.

TABLE II: Comparison of Extracted Capacity and Delivered Energy for Different Discharge Methods

Test	Capacity Extracted (Ah)	Energy (Wh)
CC	6.26	75.57
10^{-3} Hz	6.54	79.39
10^{-2} Hz	6.89	83.79
10^{-1} Hz	6.99	85.07
10 Hz	7.04	85.82
100 Hz	7.03	85.84
1 kHz	7.00	85.48
5 kHz	6.76	82.46

voltage and current waveforms for some of the frequencies tested.

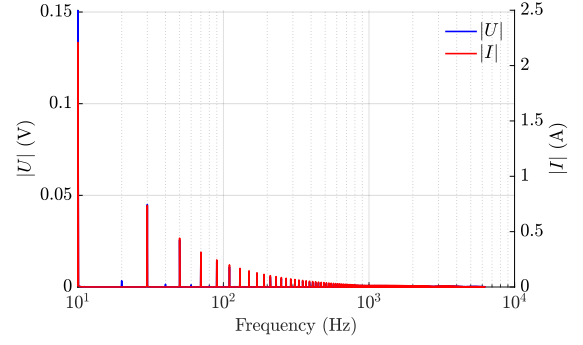
For each fundamental frequency of voltage and current waveforms and their respective harmonics, the impedance was calculated using (6). The Fig. 8 shows the impedance spectrum for the battery “IN5” at 90% SoC and 30 °C.

Analyzing the low frequency analysis, in Fig. 5(a), the real part of the impedance tends to decrease as the frequency increases around 1Hz. It is possible to see a continuity of this behavior in Fig. 8, where the module of the impedance continues to decrease until around 1kHz, even though the values of the impedance are different due to the different methods and currents utilized. After this point, the magnitude of the impedance starts to increase again, which is an expected effect for higher frequencies according to the literature [19].

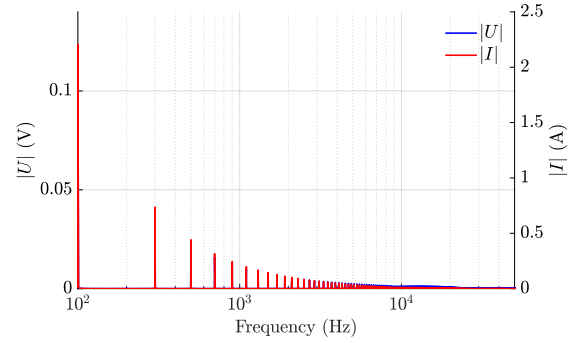
V. PULSED CURRENT AND CONSTANT CURRENT DISCHARGE COMPARISON

To establish a consistent basis for comparison, the battery labeled as “IN1” was discharged using the constant current (CC) method at a current of 1 A until reaching the terminal voltage of 10.5 V, which is the cut-off voltage specified in the device datasheet, corresponding to 0% SoC. Subsequently, a series of pulsed current discharges were performed with current pulses having an RMS value of 1 A, at frequencies of 10^{-3} Hz, 10^{-2} Hz, 10^{-1} Hz, 10 Hz, 100 Hz, 1 kHz, and 5 kHz, all with a duty cycle of 50%. Each test continued until the battery reached the same cut-off voltage of 10.5 V. The use of a square wave with 50% duty cycle and 1 A RMS current (corresponding to pulse amplitudes of 0 to $\sqrt{2}$ A) for the pulsed discharges was a intentional choice for isolating the effects of the impedance varying with the frequency, as the power dissipation for the same internal impedance would be the same with a CC discharge of 1 A and a pulsed current discharge with 1 A RMS in this configuration. The results are summarized in Table II, and the discharge curves are shown in Fig. 9.

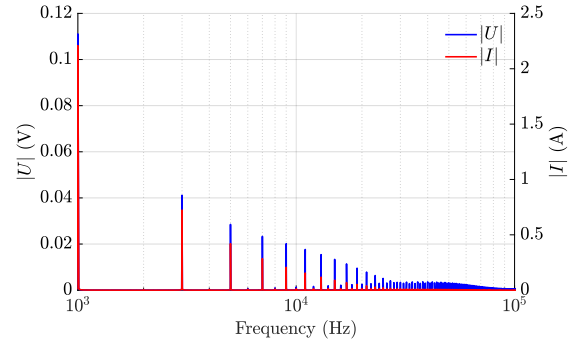
As can be seen in Fig. 9, the constant current discharge method has a lower discharge time due to the fact that the average current was 1 A, while the pulsed current discharge methods had an RMS current of 1 A, resulting in an average current of $\frac{\sqrt{2}}{2}$ A. However, as can be seen in Table II, the pulsed current discharge methods resulted in a higher



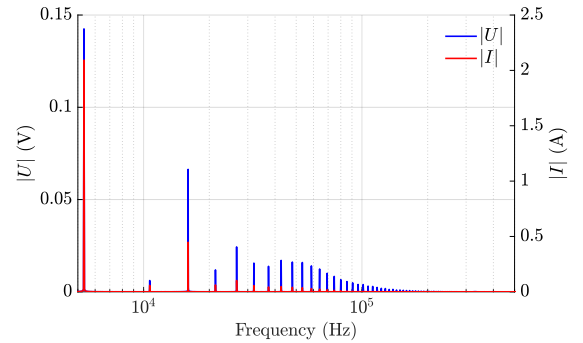
(a) 10 Hz



(b) 100 Hz



(c) 1 kHz



(d) 5 kHz

Fig. 7: Overpotential U and current I FFT for different frequencies.

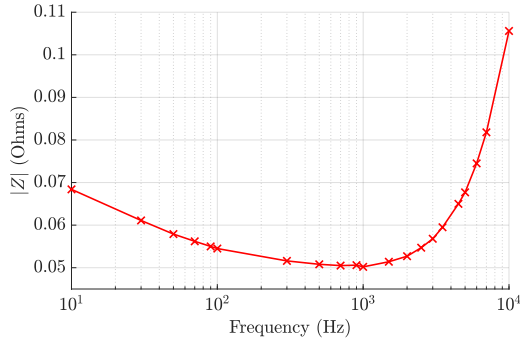


Fig. 8: Impedance spectrum of battery “IN5” at 90% SoC and 30 °C for different frequencies.

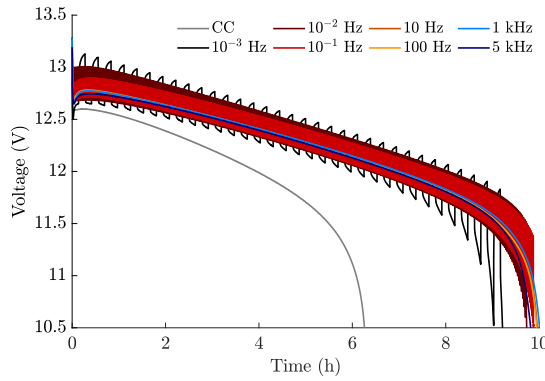


Fig. 9: Discharge voltage curves for different methods.

extractable capacity and delivered energy compared to the constant current method. It is possible to see that 10Hz, 100Hz and 1kHz frequencies surpassed the nominal extractable capacity mark; this is not an error by any means, as the manufacturer specifies the nominal capacity of the battery based only on constant current discharges.

VI. CONCLUSIONS

This work investigated and compared the performance of 12V, 7Ah VRLA batteries under constant current and pulsed current discharge methods. The low frequency impedance analysis revealed that the battery’s internal resistance diminishes with increasing frequency until it reaches a frequency of around 1kHz. Beyond this point an increase in impedance is more pronounced, as could be seen in the high frequency analysis. At last, the comparison between constant current and pulsed current discharge methods demonstrated that pulsed current discharges, particularly at frequencies around 10Hz to 1kHz, improve the extractable capacity and delivered energy. Frequencies above the 1kHz threshold exhibited diminished benefits.

For future works, it is intended to explore a wider range of pulse frequencies and temperatures, as well as different pulse shapes and duty cycles. Additionally, it is intended to

investigate the long-term effects of pulsed current discharges on battery health and lifespan.

REFERENCES

- [1] C. Liu, K. T. Chau, D. Wu, and S. Gao, “Opportunities and challenges of vehicle-to-home, vehicle-to-vehicle, and vehicle-to-grid technologies,” *Proceedings of the IEEE*, vol. 101, no. 11, pp. 2409–2427, 2013.
- [2] F. Calero, C. A. Cañizares, K. Bhattacharya, C. Anierobi, I. Calero, M. F. Z. de Souza, M. Farrokhabadi, N. S. Guzman, W. Mendieta, D. Peralta, B. V. Solanki, N. Padmanabhan, and W. Violante, “A review of modeling and applications of energy storage systems in power grids,” *Proceedings of the IEEE*, vol. 111, no. 7, pp. 806–831, 2023.
- [3] R. C. de Barros, W. C. S. Amorim, W. d. C. Boaventura, A. F. Cupertino, V. F. Mendes, and H. A. Pereira, “Methodology for bess design assisted by choice matrix approach,” *Eletrônica de Potência*, vol. 29, p. e202412, Jun. 2024. [Online]. Available: <https://journal.sobraep.org.br/index.php/rep/article/view/916>
- [4] P. Thapa, G. C. Park, J. Lee, and S. G. Kwon, “A comparative study on vrla and li-ion battery for use in frequency modulation (fm) station,” in *2019 IEEE Green Technologies Conference (GreenTech)*, 2019, pp. 1–4.
- [5] P. J. van Bree, A. Veltman, W. H. A. Hendrix, and P. P. J. van den Bosch, “Prediction of battery behavior subject to high-rate partial state of charge,” *IEEE Transactions on Vehicular Technology*, vol. 58, no. 2, pp. 588–595, 2009.
- [6] P. C. Bolsi, E. O. Prado, R. J. Nazaré, H. C. Sartori, and J. R. Pinheiro, “Simple method to estimate battery lifetime and upkeep of lead-acid and lithium-ion batteries,” *Eletrônica de Potência*, vol. 29, p. e202456, Dec. 2024. [Online]. Available: <https://journal.sobraep.org.br/index.php/rep/article/view/981>
- [7] M. Chen and G. Rincon-Mora, “Accurate electrical battery model capable of predicting runtime and i-v performance,” *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, pp. 504–511, 2006.
- [8] B. Scrosati and J. Garche, *Modern Batteries: An Introduction to Electrochemical Power Sources*, 2nd ed. New York: Springer, 2013.
- [9] D. Durac *et al.*, *Handbook of Batteries*, 3rd ed. New York: McGraw-Hill, 1995.
- [10] F. Savoye, P. Venet, M. Millet, and J. Groot, “Impact of periodic current pulses on li-ion battery performance,” *IEEE Transactions on Industrial Electronics*, vol. 59, no. 9, pp. 3481–3488, 2012.
- [11] C. L. Williams, M. J. Martin, D. A. Wetz, K. Mckinzie, and J. Heinzl, “High rate comparison of lithium-ion, valve regulated lead acid, and nickel metal hydride batteries for use in pulsed power applications,” in *2015 IEEE Pulsed Power Conference (PPC)*, 2015, pp. 1–6.
- [12] S. Piller, R. Vazquez, and D. U. Sauer, *Battery Management Systems, Volume 1: Battery Modeling*. Springer Vieweg, 2022.
- [13] M. Messing, T. Shoa, and S. Habibi, “Electrochemical impedance spectroscopy with practical rest-times for battery management applications,” *IEEE Access*, vol. 9, pp. 66 989–66 998, 2021.
- [14] S. Bampi, G. Waltrich, and A. Vaccari, “Electronic load for parameter characterization in equivalent circuit models of lithium-ion batteries,” *Eletrônica de Potência*, vol. 30, p. e202521, Feb. 2025. [Online]. Available: <https://journal.sobraep.org.br/index.php/rep/article/view/1007>
- [15] M. Bercebar, N. Omar, and J. Van Mierlo, *Battery System Modeling*. Elsevier, 2020.
- [16] J. Lu, Y. Liu, X. Long, K. Yan, L. Liu, R. Zhou, and Y. Wu, “Mathematical modeling and frequency-domain characteristics of a periodic pulse-discharged lithium-ion battery system,” *IEEE Transactions on Industry Applications*, vol. 57, no. 2, pp. 1801–1809, 2021.
- [17] C. Lyu, H. Liu, W. Luo, T. Zhang, and W. Zhao, “A fast time domain measuring technique of electrochemical impedance spectroscopy based on fit,” in *2018 Prognostics and System Health Management Conference (PHM-Chongqing)*. IEEE, 2018, pp. 450–455.
- [18] Z. Xia and J. A. Abu Qahouq, “Method for online battery ac impedance spectrum measurement using dc-dc power converter duty-cycle control,” in *2017 IEEE Applied Power Electronics Conference and Exposition (APEC)*. IEEE, 2017, pp. 1999–2003.
- [19] M. Kwiecien, M. Huck, J. Bädeda, and D. U. Sauer, “Correct processing of impedance spectra for lead-acid batteries to parameterize the charge-transfer process,” *Journal of Applied Electrochemistry*, vol. 48, no. 8, pp. 885–900, 2018.