ELECTRICAL ENGINEERING AND ENERGY

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Analysis of Power Spectral Density as a Diagnostic Tool in PEM Fuel Cells with Pulsed Loads

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Submitted: 4 July 2026
Accepted: 27 August 2026
Online First: 7 September 2026

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DOI:10.64470/elene.2026.40

Abstract: The analysis of fuel cell current power spectral density (PSD) of a Horizon H-100 proton-exchange membrane (PEM) fuel cell stack operating with a pulsed load is presented. Fuel cell current fluctuations can be used as a reliable diagnostic tool for the PEM fuel cell. Analysis of low-frequency flicker noise in a PEM fuel cell can provide a highly sensitive diagnostic tool for detecting degradation and classifying the operating state of the fuel cell. The PSD of the fuel cell current can be used as a statistical descriptor in the frequency domain. The slope α of the PSD of the fuel cell current can be monitored non-invasively to track the operating state and degradation of the fuel cell. The results from experimental tests are presented to illustrate that the value of α can be monitored to detect abnormal operation in the H-100 PEM fuel cell.

Keywords Power spectral density, fuel cells, and pulsed load.

1. Introduction

The proton exchange membrane (PEM) fuel cell has become the most popular type of fuel cell, and has been used in a wide range of applications including automotive power sources, military applications, the more electric aircraft (MEA), portable power, and various hybrid source topologies (Kanouni, et al., 2022; Zenith, et al., 2019; Garcia, et al., 2025). PEM fuel cells are popular due to their high power density, fast startup, light weight, low operating temperature, quiet operation, and negligible environmental effects (Xin & Hu, 2020; Guo, et al., 2024; Denisov, et al., 2017; Martemianov, et al., 2020). Fuel cells can also operate at low pressures, enabling safer operation in a wider range of applications. (Zenith, et al., 2019).

The primary disadvantages of fuel cell systems are related to service life and reliability (Guo, et al., 2025; Cheikh, et al., 2022), particularly when the fuel cell is operated under changing load conditions (Detti, et al., 2017). Durability is the main concern limiting the utilization of fuel cell technology in transportation applications (Guo, et al., 2025). Fuel cells also have high development costs and short life times, which significantly affects the large-scale commercial application of PEM fuel cells (Xin & Hu, 2020; Cheikh, et al., 2022). In recent years, the focus of many researchers has been on increasing fuel cell lifetime and reducing production costs (Zenith, et al., 2019).

Dependable diagnostic tools are needed to improve reliability and operating time of PEM fuel cells without failure (Denisov, et al., 2017). Various diagnostic tools and methods such as polarization curve measurements, impedance spectroscopy, the current interruption technique, optical imaging, and x-ray tomography have been used to improve PEM fuel cell performance and durability (Martemianov, et al., 2021). Online monitoring of the fuel cell state during continuous operation using frequency response analysis (FRA) was used in (Ordonez, et al., 2010). The fast Fourier transform (FFT) and total harmonic distortion (THD) was used to diagnose drying and flooding in PEM fuel cells in (Detti, et al., 2017). The authors in (Detti, et al., 2017) used THD and other variables to detect defects in the fuel cell. An algorithm capable of measuring the degradation state and the remaining useful life (RUL) of a PEM fuel cell using a historical electrochemical impedance spectroscopy (EIS) and a long short-term memory (LSTM) neural network was presented in (Caponetto, et al., 2021). A method to determine the health state of the fuel cell using empirical Fourier decomposition (EFD) and the Hilbert transform was presented in (Cheikh, et al., 2022). Low frequency aging indicators were used to aid in aging indicator extraction and remaining useful life prediction of PEM fuel cells in (Yang, et al., 2025). The development of a digital twin (DT) that is effectively used to generate aging data and study or predict the aging behavior of the PEM fuel cell is presented in (Kumar & Ganguly, 2025). The stack load spectrum and vibration power spectral density was used in (Guo, et al., 2025) to predict and evaluate the performance and reliability of the fuel cell stack.

The operation of PEM fuel cells is determined by a large set of parameters such as the humidity of supplied gases, cell temperature, pressure, electrical operation mode, etc. (Denisov, et al., 2017). The understanding of degradation mechanisms and early detection of the effects caused by these mechanisms is the key to improving fuel cell operation (Denisov, et al., 2017). An effective tool is needed to diagnose the technical state of the fuel cell (Denisov, et al., 2017). However, most of the methods presented in the literature require interruption of system operation and / or perturb the state of the system (Martemianov, et al., 2021). Useful information can only be obtained after fuel cell post mortem in some cases (Martemianov, et al., 2021). The development of reliable diagnostics for PEM fuel cells that avoid operation interruption and / or system perturbations is still an area of interest to researchers (Martemianov, et al., 2021).

A promising way to access the state of the fuel cell is to monitor the fuel cell current fluctuations (Denisov, et al., 2017). Electrical fluctuations can be used to directly characterize the operating state of the fuel cell (Denisov, et al., 2017). One advantage of monitoring the electrical noise fluctuation is the absence of perturbations of the electrochemical system from external signals. It has been shown that electrical fluctuations reflect physical processes within the fuel cell (Denisov, et al., 2017). Therefore, electrical fluctuations such as current fluctuations can be used as a reliable diagnostic tool for the PEM fuel cell.

The power spectral density of fuel cell current can be used as a sensitive diagnostic tool to detect degradation. Monitoring the PSD of a fuel cell can rapidly and accurately detect disturbances in its health, making the method significantly advantageous compared to DC voltage measurements or impedance spectra. The benefit of decomposing fuel cell current fluctuations into frequency dependent power levels is the utilization of PSD to highlight specific physical phenomena such as drying, flooding, and hydrogen starvation, all of which alter the system's noise signature. PSD analysis can isolate key frequency components to extract health indicators that can accurately estimate remaining useful life.

It has been shown that fuel cell electrical fluctuations have a large flicker noise component (Denisov, et al., 2017). Analysis of low-frequency flicker noise (electrochemical noise or 1/f noise) (Fazelinia, et al., 2024) in a PEM fuel cell can provide a highly sensitive diagnostic tool for detecting degradation and classifying the operating state of the fuel cell. The focus of this paper is on monitoring the PSD of the current fluctuations of a PEM fuel cell stack with a pulsed load applied. The PSD of the fuel cell current can be used as a statistical descriptor in the frequency domain.

A pulsed load forces the fuel cell into dynamic operation that acts as a "flicker", revealing through fuel cell current responses how well the fuel cell handles water removal or reactant starvation. The resulting noise due to the pulsed load can also provide valuable information about membrane degradation. When a PEM fuel cell is subjected to a pulsed load, the fuel cell current exhibits specific noise characteristics. The power spectral density (PSD) of the fuel cell current can be monitored for variations related to the operating state

of the fuel cell.
A pulsed load introduces harmonic components to the fuel cell current. The noise intensity is higher when a fuel cell is operating with a pulsed load applied. Pulsed loads cause significant accelerated degradation compared to constant loads. Low-frequency flicker (electrochemical noise) in a PEM fuel cell stack will be studied in this paper by applying a pulsed load to the fuel cell. Applying a pulsed load will provide a method to induce, measure, and analyze the transient current response. The power spectral density of the fuel cell current can be used to classify the operating state of the fuel cell. The PSD can help with detecting fuel cell issues such as water management, membrane degradation, reactant starvation, etc.

2. Power Spectral Density

There are many methods in the literature for making PSD calculations (Martemianov, et al., 2020). Welch's method was used for all PSD analysis presented in this paper. The Welch method divides a given signal into multiple segments, takes modified periodograms of these segments, and averages the modified periodograms (Parhi & Ayinala, 2014). The first step in the algorithm for Welch's method is to divide the signal into segments xi(n) with length L and an overlap Δ. Then, a window function w(n) is applied to each segment:

$$y_i(n) = x_i(n) \cdot w(n) \quad (1)$$

The next step is to calculate the modified periodogram for each segment *i* as:

$$P_i(f) = \frac{1}{LU} \left| \sum_{n=0}^{L-1} y_i(n) e^{-j2\pi f n} \right|^2 \quad (2)$$

Where, $U = \frac{1}{L} |w(n)|^2$ is a normalization factor.

The Welch PSD estimate is the average of these periodograms (Parhi & Ayinala, 2014):

$$S_{Welch}(f) = \frac{1}{K} \sum_{i=1}^{K} P_i(f) \quad (3)$$

The power spectral density *S(f)* of $\frac{1}{f}$ noise is defined by the power law relationship (Denisov, et al., 2017):

$$S(f) = \frac{k}{f^{\alpha}} \quad (4)$$

where *k*=constant, and *a* =slope or spectral exponent. For a signal following a $\frac{1}{f^{\alpha}}$ power law, the PSD is represented as $S(f) \propto \frac{1}{f^{\alpha}}$. The relationship in (4) becomes a linear equation on a log-log plot:

$$log_{10}(S(f)) = log_{10}(k) - \alpha log_{10}(f) \quad (5)$$

On a log-log plot, the slope of the line in (5) directly produces the α value.
Welch's method can be used to subdivide time series into segments. This averages out random fluctuations and provides a smoother PSD, making it easier to fit a straight line to each frequency range to find the corresponding α. The slope α varies depending on the frequency range and the fuel cell's state of health. A change in slope signals a transition between two dominating effects. Instead of calculating a single slope for the entire PSD plot, a "linear" region can be selected on the PSD log-log plot to get a meaningful α for a particular frequency range. Segmenting the PSD analysis or highlighting specific frequency ranges is helpful for accurately identifying the α values (slopes) that correspond to different physical processes.

The presence of multiple slopes indicates that different physical mechanisms or system dynamics dominate the fuel cell's response at different frequency ranges. Degradation such as membrane drying can be identified when the PSD signature shifts to a "three linear slopes" pattern in the low frequency range (below 100 Hz). An increase in the slope α of the PSD normally indicates an increasing degradation degree of the fuel cell.

3. Experimental Setup

The test circuit shown in Figure 1 was built in the laboratory for the purpose of studying the power spectral density of a PEM fuel cell with a pulsed load applied. The fuel cell under test was the Horizon H-100 fuel cell stack. Table 1 lists the parameters of the H-100 fuel cell. The load used during experimental testing was a variable resistive load that allowed for varying current loads to be applied to the fuel cell. The load was pulsed using a Tektronix AFG3151C Single Channel Arbitrary Waveform Generator. The MOSFET used during testing was a Toshiba K7R4A10PL N-channel MOSFET with a rating of 100V and 50A. The gate signal supplied to the MOSFET shown in Figure 1 was set for a 50% duty cycle during all experimental tests. The gate signal supplied to the MOSFET in the test circuit is shown in Figure 2. A Tektronix DPO 7254C Digital Phosphor Oscilloscope and Tektronix TCP0030A Current Probe were used to record and measure the current of the test circuit. Waveforms were sampled from the oscilloscope at a frequency of 20kHz using uniform sampling. The waveforms were then transformed to the frequency domain using MATLAB. Probe attenuation was investigated, and any lost waveform information was corrected accordingly. The test circuit shown in Figure 1 allowed a pulsed load to be applied to the H-100 PEM fuel cell. The test circuit provided a method to induce, measure, and analyze the transient current response.

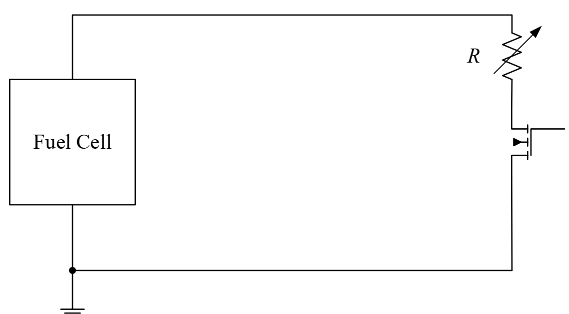

Figure 1 Experimental Test Circuit

Table 1 HORIZON H-100 Parameters

Parameter	Value
Maximum Power	100W
Open-Circuit Voltage	19V
Voltage at Maximum Power	12V
Current at Maximum Power	8.3A
Number of Cells	20

Figure 2 Gate Signal Supplied to MOSFET During Tests

The wave shape of the pulsed load applied to the PEM fuel cell in this paper is shown in Figure 3. The trigonometric Fourier series of the waveform i(t) shown in Figure 3 can be expressed as:

$$i(t) = a_0 + \sum_{n=1}^{\infty}\left(a_n cos\frac{2\pi n}{T}t + b_n sin\frac{2\pi n}{T}t\right) \tag{6}$$

where, a_0, a_n, and b_n are the Fourier coefficients of the waveform *i(t)*. Analysis of the waveform in Figure 3 leads to the following results for the Fourier coefficients:

$$a_0 = AD \tag{7}$$

$$a_n = \frac{A}{n\pi}\sin 2\pi nD \tag{8}$$

$$b_n = \frac{2A}{n\pi}sin^2\pi nD \tag{9}$$

for $0 \leq D \leq 1$. The variable D in (7-9) is the duty cycle, and is defined as:

$$D = \frac{T_{ON}}{T} \tag{10}$$

where T_{ON}=the ON time of the pulse, and T=period of the pulse.
The first four non-zero terms of the Fourier series of the waveform in Figure 3 with D=0.5 can be written as:

$$i(t) = \frac{A}{2} + \frac{2A}{\pi}\sin\omega_0 t + \frac{2A}{3\pi}\sin 3\omega_0 t + \frac{2A}{5\pi}\sin 5\omega_0 t + \cdots \tag{11}$$

4. Results and Discussion

Experimental tests were conducted in the laboratory with a Horizon H-100 fuel cell stack connected directly to a pulsed load as shown in Figure 1. Tests were conducted with 5 Hz and 10 Hz switching frequencies. For each switching frequency, tests were conducted with 4A and 8A pulses applied. Applying a low frequency pulsed load such as 5 Hz and 10 Hz provides a method to induce, measure, and analyze changes in the low frequency spectrum of fuel cell current, which yields invaluable information about membrane degradation. Low frequency current ripple induces stronger membrane degradation, making studies in the low-frequency range critical for assessing membrane health and maximizing fuel cell longevity.

Conducting experiments at 4A and 8A provides an opportunity to observe the fuel cell stack behavior during a transition from one process to another. At 4A, the fuel cell operates closer to the activation loss region. This typically creates more flicker or low-frequency noise, leading to a steeper slope (α) on the PSD plot. At 8A, the fuel cell enters a regime where mass transport losses and convective flow become more dominant. Various research has shown that the slope becomes less steep (smaller α) due to faster reacting transport phenomena. Additionally, water management and gas distribution vary significantly between 4A and 8A loads. The fuel cell will produce more water at 8A. If flooding or higher humidity results, the noise signature changes. This effect leads to higher noise power, but can lower the α value.

Data collected in the laboratory was processed in MATLAB for the purpose of conducting PSD analysis on the fuel cell current waveforms. The pwelch function from MATLAB was used to calculate the power spectral density of all fuel cell current signals analyzed in this study. The pwelch function in MATLAB estimates the PSD of each fuel cell current signal using Welch's method. The following function call was used in the MATLAB m-files to conduct the PSD analyses in this paper:

[pxx, f] = pwelch(I, [ ], [ ], [ ], Fs). Where, pxx=the power spectral density of the current at each frequency step, f=the array of frequency values in Hz that match the power values in pxx (f goes from zero up to the Nyquist frequency (half of Fs)), Fs=the sampling frequency of the original time-domain data, I= the input fuel cell current signal data (which is already a current measurement in the frequency domain), and the empty brackets [ ], [ ], [ ] tell MATLAB to use its default values for window, overlap, and number of FFT points. The MATLAB default is a Hamming window, 50% overlap, and the number of FFT points defaults to the greater of 256 or the next power of two that is equal to or greater than the window length. The inputs for the pwelch function can also be determined by explicit user input. The help and lookfor commands in MATLAB can be used for more details and explanation of all the parameters in the pwelch function.

Figure 4 shows the frequency spectrum of the fuel cell current from a laboratory test with a 5 Hz, 4A pulsed load applied to a Horizon H-100 PEM fuel cell. Figure 5 shows the power spectral density of the fuel cell current with a 5 Hz, 4A pulsed load applied to the fuel cell. The polyfit command in MATLAB was used to find the slope α over a frequency range from 1-100Hz. The slope over this range of frequencies was α=2.5772, as can be seen in the legend in Figure 5. Figure 6 shows the PSD of the fuel cell current with a 5 Hz, 4A pulsed load applied to the fuel cell and broken into two frequency segments. Two frequency regions were selected for analysis during this study. The regions selected were 10-35 Hz, and 35-100 Hz. Analysis of the 10-35 Hz frequency range can help identify membrane electrode assembly (MEA) health, general efficiency degradation, and hydrogen starvation. Analysis of the 35-100 Hz frequency range can help detect water management, mass transport issues, air starvation, and cathode flooding / drying. The value of alpha for the 10-35 Hz segment was found to be α=3.0273, and the value of alpha for the 35-100 Hz segment was found to be α=2.3279, as can be seen in the legend in Figure 6.

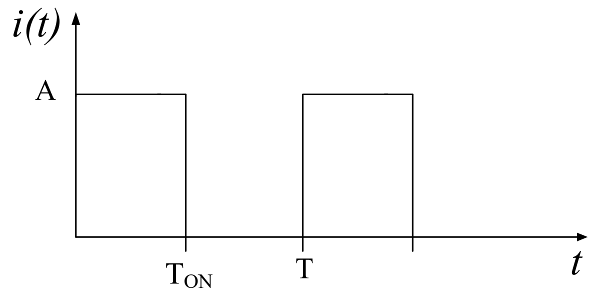

Figure 3 Pulsed load waveform

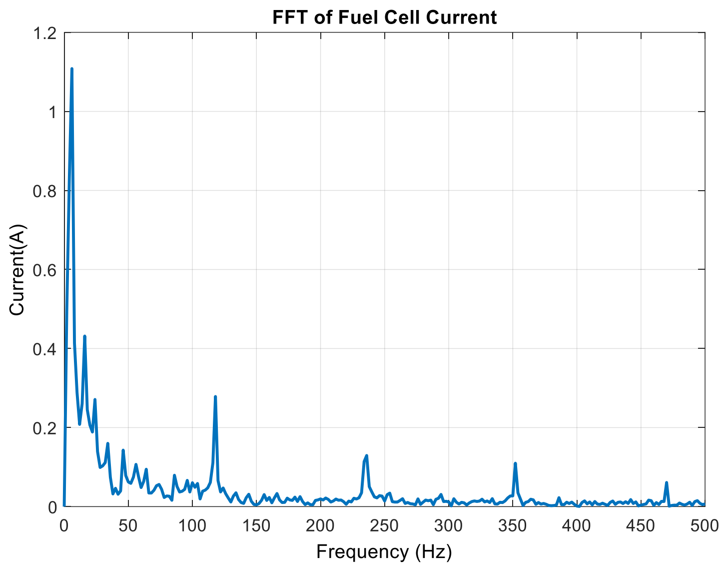

Figure 4 FFT of Fuel cell current with 5Hz, 4A pulsed load

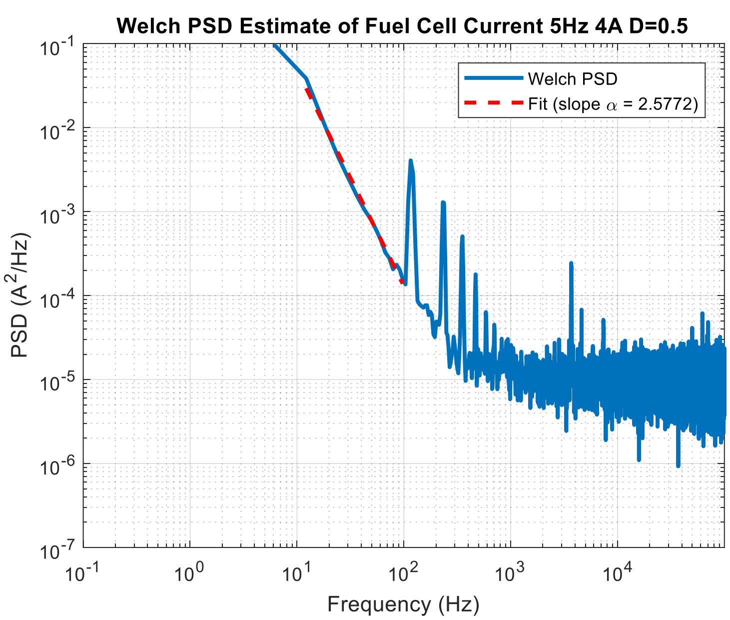

Figure 5 PSD of Fuel cell current with 5Hz, 4A pulsed load

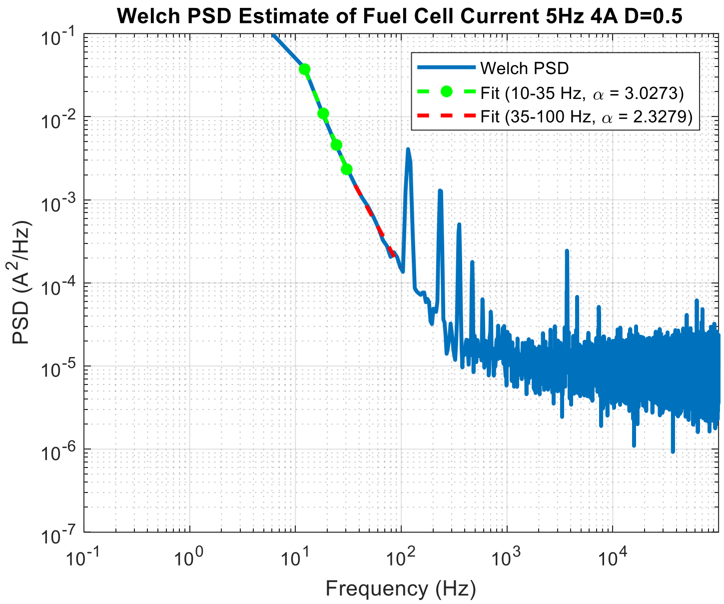

Figure 6 PSD of Fuel cell current with 5Hz, 4A pulsed load with segments

Figure 7 shows the frequency spectrum of the fuel cell current from a laboratory test with a 5 Hz, 8A pulsed load applied to a Horizon H-100 PEM fuel cell. Figure 8 shows the power spectral density of the fuel cell current with a 5 Hz, 8A pulsed load applied to the fuel cell. The slope over the 1-100 Hz range of frequencies was α=2.3959, as can be seen in the legend in Figure 8. Figure 9 shows the PSD of the fuel cell current with a 5 Hz, 8A pulsed load applied to the fuel cell and broken into two frequency segments. The value of alpha for the 10-35 Hz segment was found to be α=3.0032, and the value of alpha for the 35-100 Hz segment was found to be α=2.3294, as can be seen in the legend in Figure 9.

Figure 10 shows the frequency spectrum of the fuel cell current from a laboratory test with a 10 Hz, 4A pulsed load applied to a Horizon H-100 PEM fuel cell. Figure 11 shows the power spectral density of the fuel cell current with a 10 Hz, 4A pulsed load applied to the fuel cell. The slope over the 1-100 Hz range of frequencies was α=2.6525, as can be seen in the legend in Figure 11. Figure 12 shows the PSD of the fuel cell current with a 10 Hz, 4A pulsed load applied to the fuel cell and broken into two frequency segments. The value of alpha for the 10-35 Hz segment was found to be α=3.1724, and the value of alpha for the 35-100 Hz segment was found to be α=2.1855, as can be seen in the legend in Figure 12.

Figure 13 shows the frequency spectrum of the fuel cell current from a laboratory test with a 10 Hz, 8A pulsed load applied to a Horizon H-100 PEM fuel cell. Figure 14 shows the power spectral density of the fuel cell current with a 10 Hz, 8A pulsed load applied to the fuel cell. The slope over the 1-100 Hz range of frequencies was α=2.4856, as can be seen in the legend in Figure 14. Figure 15 shows the PSD of the fuel cell current with a 10 Hz, 8A pulsed load applied to the fuel cell and broken into two frequency segments. The value of alpha for the 10-35 Hz segment was found to be α=2.8198, and the value of alpha for the 35-100 Hz segment was found to be α=2.1669, as can be seen in the legend in Figure 15. A table that summarizes the resulting α values for each PSD plot under the various test conditions is shown in Table 2.

It can be seen in Figure 5, 8, 11, and 14 that the values of α for each PSD plot over the region from 1-100 Hz are all greater than two. A value of $\alpha > 2$ signals abnormal operation of the PEM fuel cell (Martemianov, et al., 2020). During this study, the PSD of the fuel cell current was segmented into the following two frequency ranges: 10-35 Hz and 35-100 Hz. The α values for the frequency range 10-35 Hz were all greater than 3 except one at $\alpha = 2.8198$ for a 10 Hz, 8A pulsed load. However, all of the α values in the frequency range 10-35 Hz are indicative of abnormal fuel cell operation due to multiple issues such as degradation, membrane drying, or gas diffusion layer flooding. The PEM fuel cell under pulsed loading is operating under dynamic stress where large amplitude fluctuations dominate the fuel cell's current as can be seen in Figure 4, 7, 10, and 13. The α values in the 10-35 Hz range can be seen in the legends of Figure 6, 9, 12, and 15. The α values in the frequency range are all greater than 2, and are also indicative of abnormal fuel cell operation. For this frequency range, membrane drying and gas starvation are typical issues with the PEM fuel cell.

It can be observed from the PSD plots that the value of α is higher for a 4A pulsed load vs. an 8A pulsed load. The value of α fluctuates based on water management and gas distribution, which varies greatly between 4A and 8A. At 8A, the fuel cell produces more water. This can change the electrical noise signature and lower α.

Power spectral density is highly sensitive to a fuel cell's water balance. Identification of any deviations from the reference noise signature of a fuel cell operating under normal conditions can allow for early detection and classification of flooding and drying states. PSD analysis is beneficial in highlighting specific frequency ranges associated with distinct α values and physical phenomena. The multiple slopes observed in log-log plots of the fuel cell current PSD are indicative of different phenomena dominating the fuel cell response across different frequency ranges. The α values in the frequency ranges of interest can be monitored for variations or changes in slope to detect degradation.

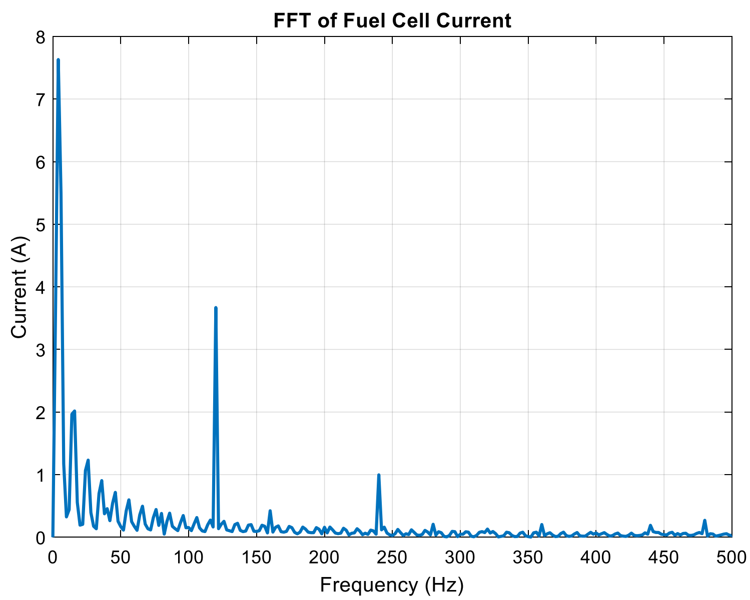

Figure 7 FFT of Fuel cell current with 5Hz, 8A pulsed load

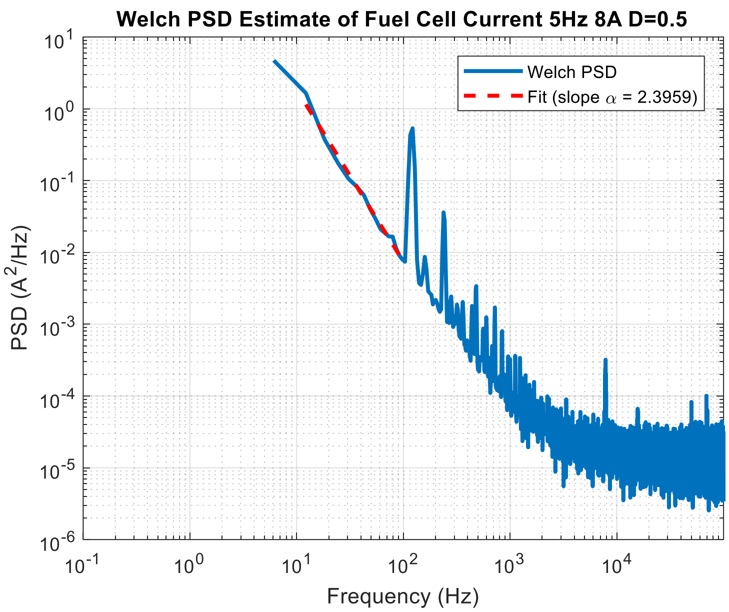

Figure 8 PSD of Fuel cell current with 5Hz, 8A pulsed load

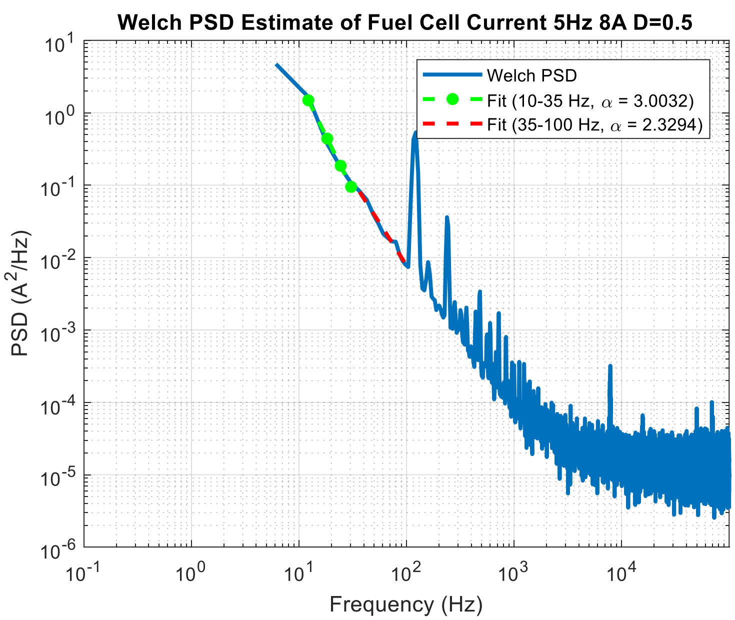

Figure 9 PSD of Fuel cell current with 5Hz, 8A pulsed load with segments

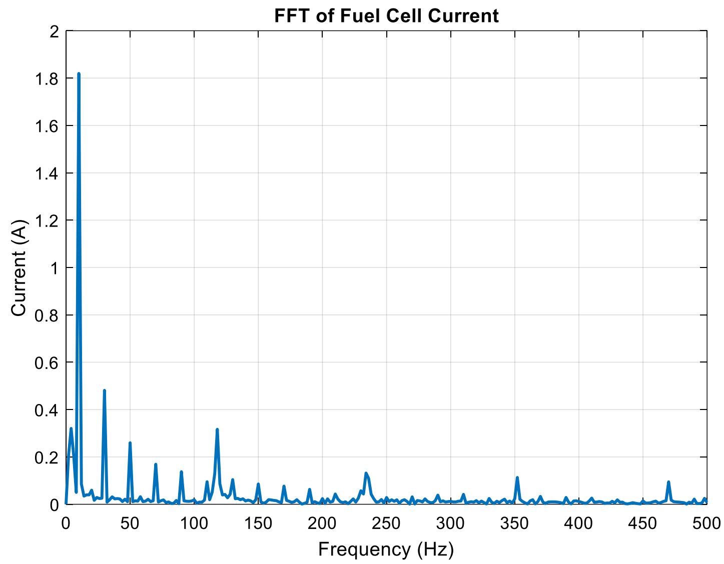

Figure 10 FFT of Fuel cell current with 10Hz, 4A pulsed load

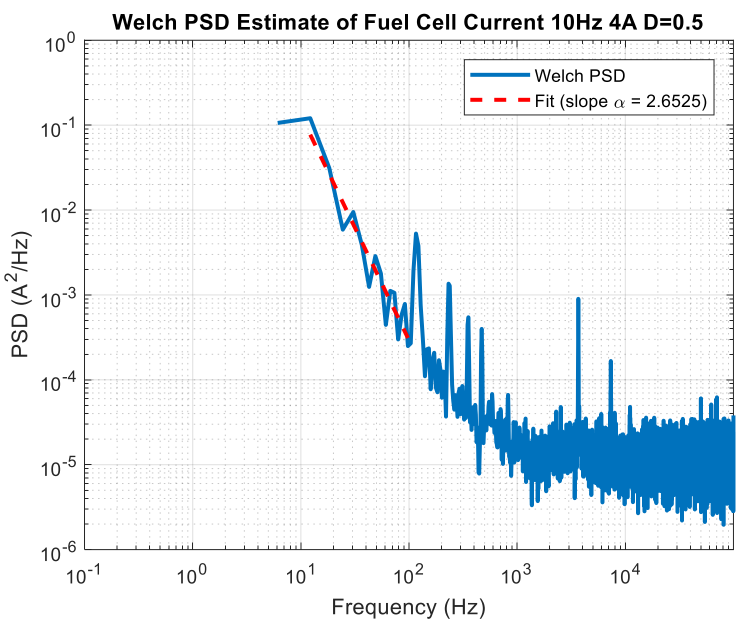

Figure 11 PSD of Fuel cell current with 10Hz, 4A pulsed load

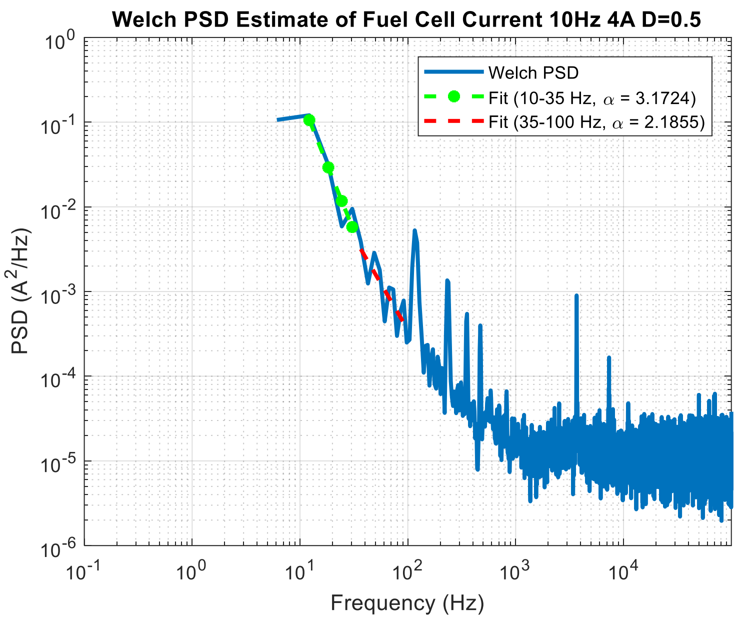

Figure 12 PSD of Fuel cell current with 10Hz, 4A pulsed load with segments

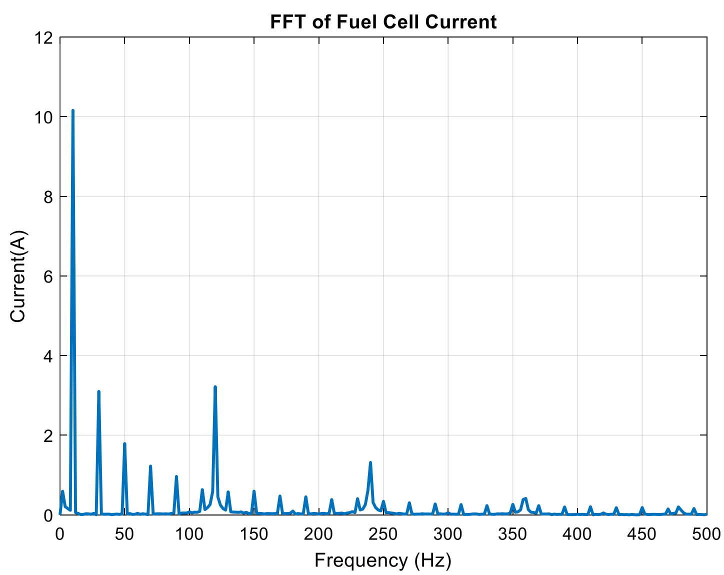

Figure 13 FFT of Fuel cell current with 10Hz, 8A pulsed load

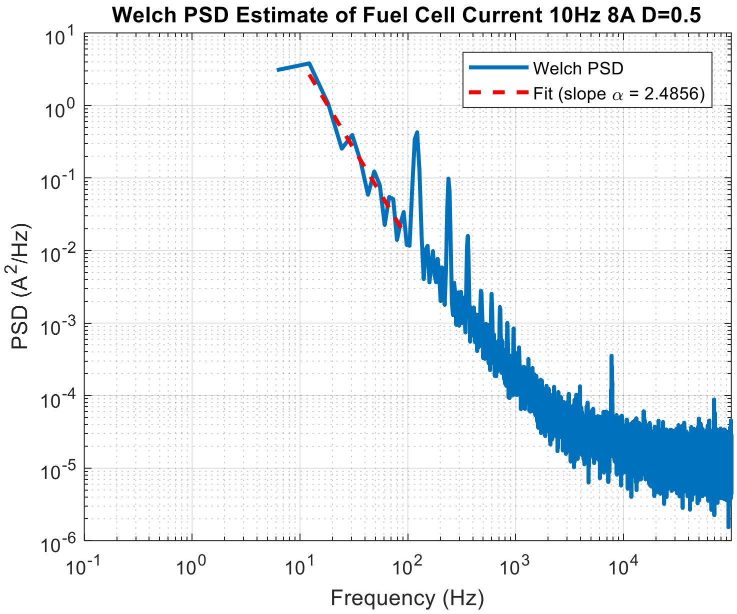

Figure 14 PSD of Fuel cell current with 10Hz, 8A pulsed load

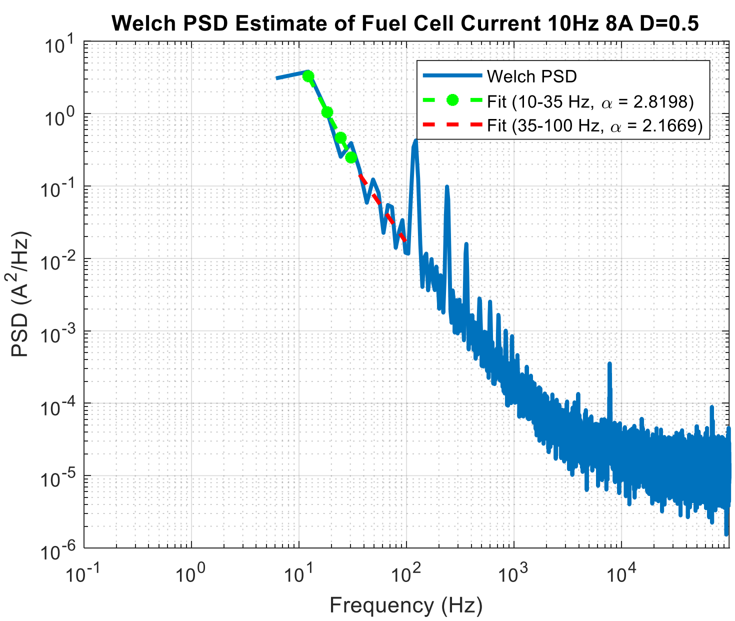

Figure 15 PSD of Fuel cell current with 10Hz, 8A pulsed load with segments

Table 2 Slope (α) of PSD under various test conditions

Frequency Range (Hz)	α	Switch Frequency (Hz)	Pulsed Load (A)
1 - 100	2.5772	5	4
10 - 35	3.0273	5	4
35 – 100	2.3279	5	4
1 - 100	2.3959	5	8
10 - 35	3.0032	5	8
35 – 100	2.3294	5	8
1 - 100	2.6525	10	4
10 - 35	3.1724	10	4
35 - 100	2.1855	10	4
1 - 100	2.4856	10	8
10 - 35	2.8198	10	8
35 - 100	2.1669	10	8

5. Conclusions

In this paper, the analysis of the power spectral density of the fuel cell current of a Horizon H-100 PEM fuel cell stack operating with a pulsed load was presented. Tests were conducted with 5 Hz and 10 Hz switching frequencies (both with 4A and 8A pulses applied). These values of switching frequency were selected in order to study low-frequency flicker in the fuel cell current waveform. The pulsed load provided a method to induce, measure, and analyze the transient current response. Specifically, it allowed the PSD of the fuel cell current to be studied to determine if signs of degradation were present. The experimental tests confirmed that the α values (slopes) of the PSD in the 1-100 Hz frequency range that resulted from testing were indicative of fuel cell degradation. Monitoring the α values of the PSD of the fuel cell current is a non-invasive method that can be used to track degradation in the fuel cell and to monitor the state of fuel cell operation.

Studies like the one presented in this paper can provide foundational data necessary to meet industry targets for fuel cell durability and performance in automotive and UAV applications. Future work could entail looking at the analysis of the PSD of the fuel cell current in order to optimize the pulsing strategy by controlling the frequency and duty cycle of the pulsed load in hopes of minimizing degradation and maintain stability. Other areas of future work may include the development of a digital twin for tracking / predicting degradation in PEM fuel cells.

Declaration of Ethical Standards

The authors of this study declare that it complies with all ethical standards.

Credit Authorship Contribution Statement

A.W. Leedy: Methodology, Software, Validation, Formal analysis, Writing -Original Draft, Visualization.
M.A. Karanja: Methodology, Software, Validation, Visualization, Review & Editing.

Declaration of Competing Interest

The authors declare that no conflict of interest exists.

Funding / Acknowledgements

This work was supported by Kentucky NSF EPSCoR [OIA-1849213].
The authors declare that generative AI was not used for language editing and not for scientific content generation.

Data Availability

Access to data sets will be granted by the authors upon reasonable request.

References

Caponetto, R., Guarnera, N., Matera, F., Privitera, E., and Xibilia, M.G. (2021). Application of Electrochemical Impedance Spectroscopy for Prediction of Fuel Cell Degradation by LSTM Neural Networks. In *2021 29th Mediterranean Conference on Control and Automation (MED)* (pp. 1064-1069). DOI: 10.1109/MED51440.2021.9480253

Cheikh, A., Steiner, N.Y., Pahon, E., Damour, C., Benne, M., and Hissel, D. (2022). Proton Exchange Membrane Fuel Cell Signal-Based Diagnostics Using Empirical Fourier Transform. *In 2022 IEEE Vehicle Power and Propulsion Conference (VPPC)*. DOI: 10.1109/VPPC55846.2022.10003412

Detti, A.H., Jemei, S., Morando, S., and Steiner, N.Y. (2017). Classification Based Method Using Fast Fourier Transform (FFT) and Total Harmonic Distortion (THD) Dedicated to Proton Exchange Membrane Fuel Cell (PEMFC) Diagnosis. In *2017 IEEE Vehicle Power and Propulsion Conference (VPPC)*. DOI: 10.1109/VPPC.2017.8331040

Denisov, E.S., Evdokimov, Y.K., Martemianov, S., Thomas, A., and Adiutantov, N. (2017). Electrochemical Noise as a Diagnostic Tool for PEMFC. *Fuel Cells*, 17 (2), 225 – 237. DOI:10.1002/fuce.201600077

Fazelinia, M., Ebadollahi, S., and Ganjefar, S. (2024). Band-Limited Flicker Noise Modeling Using a Series of Correlated Noises. *IEEE Transactions on Instrumentation and Measurement*, 73, 9518105. DOI: 10.1109/TIM.2024.3472807

Guo, T., Li, S., and Fang, W. (2025). Research on Durability and Reliability Technology of a Fuel Cell Logistics Vehicle. In *2025 IEEE 8th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)* (pp. 1293-1298). DOI: 10.1109/IAEAC65194.2025.11166634

Guo, T., Li, S., and Wang, F. (2025). Development of a Fuel Cell Stack Test Rig Power Spectral Density for Fuel Cell Buses. In *2025 IEEE 2nd International Conference on Energy and Electrical Engineering (EEE)*. DOI: 10.1109/EEE64897.2025.11162873

Guo, T., Sun, L., and Wang, F. (2024). Research on the Method for Formulating Power Spectral Density of Fuel Cell Vehicle Air Compressor Bench Based on Operating Scenarios. In *2024 3rd International Conference on Automation, Robotics and Computer Engineering (ICARCE)*. DOI: 10.1109/ICARCE63054.2024.00112

J.C. Garcia, R.M. Del Toro Matamoros, L.G. Rodriguez, R.B. Guerra, and M.A.R. Gonzalez (2025). Proposed Solution for Improving Efficiency in Fuel Cell Power Systems Based on Short-Circuit Energy Recovering. *IEEE Access*, 13, 173860 - 173868. DOI: 10.1109/ACCESS.2025.3616846

Kanouni, B., Badoud, A.E., and Mekhilef, S. (2022). A SMC – based MPPT controller for proton exchange membrane fuel cell system. In *International Multi-Conference on Systems, Signals & Devices*. DOI: 10.1109/SSD54932.2022.9955704

Kumar, P. and Ganguly, S. (2025). Digital Twin Approach for PEM Fuel Cell Degradation Prognostics Using Equivalent Electrical Circuit Model and Polarization Curves. In *2025 IEEE Kiel PowerTech*. DOI: 10.1109/PowerTech59965.2025.11180714

Martemianov, S., Thomas, A., Adiutantov, N., Denisov, E., Evdokimov, Y., and Hissel, D. (2020). Electrochemical Noise Analysis of a PEM Fuel Cell Stack Under Long-Time Operation: Noise Signature in the Frequency Domain. *Journal of Solid State Electrochemistry*, 24, 3059 – 3071. DOI:10.1007/s10008-020-04759-z

Martemianov, S., Thomas, A., Gervex, A., Lagonotte, P., and Poirot-Crouvezier, J.P. (2021). Electrochemical Noise Diagnostics of PEM Fuel Cell Stack for Micro-Cogeneration Application. *Journal of Solid State Electrochemistry*, 25, 2835 – 2847. DOI:10.1007/s10008-021-05053-2

Ordonez, M., Sonnaillon, M.O., Quaicoe, J.E., and Iqbal, M.T. (2010). An Embedded Frequency Response Analyzer for Fuel Cell Monitoring and Characterization. *IEEE Transactions on Industrial Electronics*, 57 (6), 1925 - 1934. DOI: 10.1109/TIE.2009.2028295

Parhi, K.K. and Ayinala, M. (2014). Low-Complexity Welch Power Spectral Density Computation. *IEEE Transactions on Circuits and Systems-I: Regular Papers*, 61 (1). DOI: 10.1109/TCSI.2013.2264711

Xin,Y. and Hu, Y. (2020). Prediction of Remaining Useful Life of Proton Exchange Membrane Fuel Cell based on Wavelet-LSTM. *In 2020 IEEE 9th Data Driven Control and Learning Systems Conference (DDCLS)*. DOI: 10.1109/DDCLS49620.2020.9275255

Yang, Y., Hu, H., Yang, Y., and Xie, C. (2025). Aging Prediction of PEMFC Based on Low-Frequency Aging Indicators Under Dynamic Operating Conditions. In *2025 4th International Conference on Energy and Electrical Power Systems (ICEEPS)* (pp. 446-449). DOI: 10.1109/ICEEPS66790.2025.11239816

Zenith, F., Halvorsen, I.J., Pivac, I., Bezmalinovic, D., and Barbir, F. (2019). Electrochemical Low-Frequency Impedance Spectroscopy for Diagnostics of Fuel Cells. In *2019 IEEE Vehicle Power and Propulsion Conference (VPPC)*. DOI: 10.1109/VPPC46532.2019.8952402