System noise as a signal source for impedance measurements on batteries connected to operating equipment

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Abstract

Alternating-current impedance measurements provide useful information about the characteristics of electrochemical systems, such as batteries, and are envisioned as the basis for indirect methods of determining battery capacity. Impedance measurements rely on recording the response of the battery to a controlled current or voltage test signal. However, this type of measurement can be difficult with large batteries connected to operating equipment. High background noise levels, caused by time-varying changes in the battery load, interfere with the impedance measurement. Instead of attempting to eliminate background noise, we have used the noise as a test signal, in conjunction with Fourier transform (FT) signal processing. The current and voltage passing through cells in an operating telecommunications lead/acid battery string were determined with a simple, three-terminal connection. Impedance calculations were performed with a commercial FT signal analyzer. The results indicate that completely passive (no externally applied test signal, and not requiring disconnection of the string) impedance measurements of batteries connected to operating equipment are feasible.

Introduction

Alternating-current impedance measurements provide useful information about the characteristics of electrochemical systems, such as batteries [1–3], and are envisioned as a means of determining battery capacity [4–6]. Battery capacity is usually determined by measuring total energy output while discharging the battery into a load. With an uninterruptible power system (UPS), this is impractical because it removes the batteries from service during the test. For a high-capacity UPS, it is also time-consuming and costly, because of the large amount of energy dissipated. Therefore, the ability to measure battery capacity without battery discharge is valuable.

Impedance measurements are usually performed by supplying a sinusoidal, controlled current or voltage test signal of a single frequency, or a combination of signals with different frequencies. The response of the battery to this signal is used to calculate the impedance (voltage divided by current). The test signals may be comprised of a wide spectrum of measurement frequencies, and the Fourier transform (FT) used to convert the time-dependent recording of the battery response to the frequency domain. This gives the battery impedance at many different frequencies, from a single measurement. Impedance measurements on an operating, high-capacity UPS are difficult, however. An example is a telecommunications battery string, connected to operating equipment. Time-varying changes in the battery load (e.g., the number of telephone calls) will cause a high background noise level, which is superimposed on the test signal, complicating the impedance measurement. Here, the battery can be disconnected to circumvent the noise problem, but again, this removes the battery from service.

However, the system noise could also be considered as a kind of test signal. Changes in battery load will cause changes in battery current and voltage. Since the noise is approximately random (determined by the number of calls in progress) it will consist of many different frequencies (true random noise consists of all frequencies). Therefore, by measuring the current through the battery and the voltage across the battery terminals, and using FT methods to transform the data from the time to the frequency domain, one can determine the impedance of the battery in a completely passive manner, that is, not requiring the application of an external test signal, and not requiring battery disconnection. The FT calculations can be performed by a computer or commercial analyzer. The battery impedance characteristics would be measured with the battery on float. This is somewhat different than correlating battery capacity with its impedance after a rest period at open circuit [4–6]. Although there are currently no published studies showing that impedance is useful in predicting the capacity of batteries on float, we are making progress in this area [7].

Figure 1 shows a block diagram of an impedance measurement on a battery cell with a commercially-available impedance analyzer. A test signal is supplied by the analyzer, and cell current and voltage are recorded by the instrument. For a FT-based measurement, the test signal may consist of white noise, which has unit amplitude at all frequencies of the measurement. The quotient of cell current and the voltage response of the cell to the signal are calculated by the analyzer for all frequencies within the analyzer's measurement bandwidth, giving the cell impedance over a wide frequency range. The lowest measurement frequency is determined by the duration of the measurement, so a time recording of current and voltage lasting tens of minutes will give impedance information with a lower frequency limit of several mHz. The highest frequency is determined by the maximum signal measurement rate. Modern FT instrumentation has a measurement bandwidth covering the sub-mHz to tens of kHz range. This frequency range also contains the most meaningful information about battery impedance.

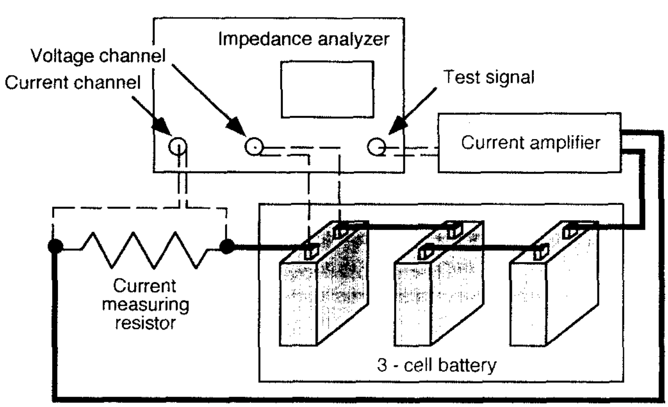

Fig. 1. Block diagram of battery cell impedance measurement apparatus.

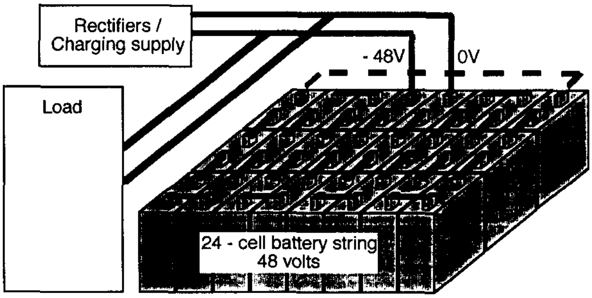

Fig. 2. Diagram of telecommunications backup battery string. Field systems may differ slightly.

Figure 2 shows a simplified diagram of a telecommunications backup battery string. The string is connected to a d.c. power source to maintain a fully charged state. The string is also connected to the telecommunications network or switch. The power source is rectified, unfiltered a.c. with a frequency power spectral distribution weighted at harmonics of the a.c. line frequency, which appear as current spikes in its rectified output. The battery string helps filter the spikes, improving the operation of the switch. The power source supplies the average power demanded by the switch, keeping the batteries fully charged. There is a time-varying current through the battery string, which arises from the time-varying load on the switch (e.g., number of telephone calls in progress) and from the harmonics of the line frequency of the charging supply. This time-varying current interferes with impedance measurements on the battery string, by appearing as background noise. It cannot be completely filtered, because of the random frequency spectral component from the switch. However, the random noise component also mimics the white noise source of the impedance analyzer. While not perfectly random, the spectral content should be rich enough to give information in the needed frequency regions. This possibility is examined experimentally below.

Experimental

First, system noise as a test signal was investigated with a small laboratory lead/acid battery and a simulated background noise source. The setup of Fig. 3 was used. The current and voltage were recorded with a Hewlett-Packard 3562a dynamic signal analyzer, which also calculated and plotted cell impedance. The random noise test signal was supplied through a PAR model 163 potentiostat from the noise source of a second, independent analyzer. The current was measured by recording the voltage drop across a series 0.1 Ω resistor.

Using the connections shown in Fig. 4, the current and voltage of a cell in a higher-capacity sealed lead/acid, operating telecommunications battery string were recorded with the signal analyzer. The metal connection between cells in the string has a small but finite resistance, and effectively acts as a current-measuring resistor. A common connecting lead was used for cell voltage and current. The signal amplitude across each set of leads was several mV. Because of the comparatively large d.c. voltage present, both signals to the analyzer were a.c. coupled, with a low frequency cutoff of 3 Hz (permitting useful signals to ≈ 100 mHz). A better implementation would provide a fixed d.c. offset to the input signal, using additional circuitry, allowing d.c. coupling of the analyzer for better accuracy at low frequencies. The frequency

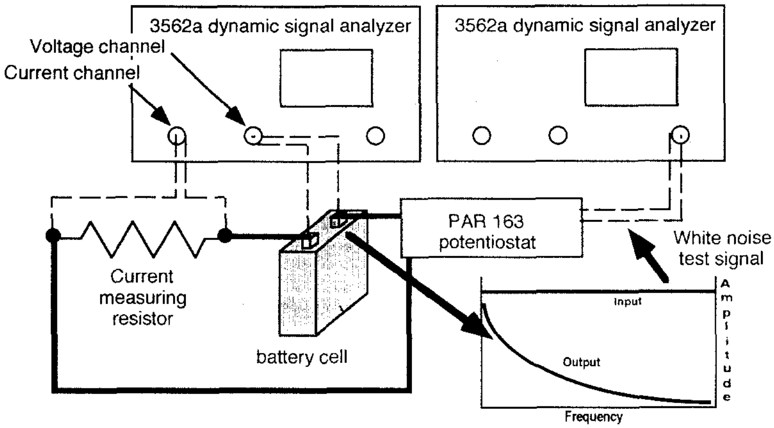

Fig. 3. Apparatus for impedance measurement with independent, simulated system noise. The curves show both the input signal and the battery response.

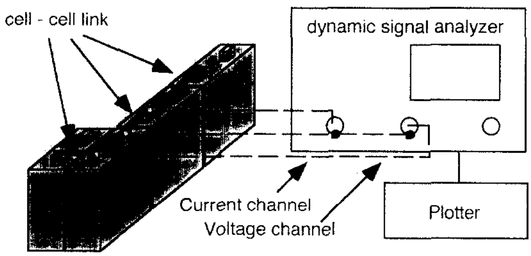

Fig. 4. Connection of apparatus for signal measurement on operating battery string.

range of the measurements was 0.125 to 1000 Hz, and ~400 measurements averaged to obtain the impedance curves. The frequency uncertainty of the analyzer was approximately 0.0625 Hz for a 0.125–50 Hz measurement span, and 1.25 Hz for a 6.25–1000 Hz span.

Results and discussion

A Nyquist (imaginary impedance component plotted against real impedance component) plot of an impedance measurement on a single cell from a laboratory battery, using the connections of Fig. 3, is shown in Fig. 5. The impedance function is a smooth curve, because of the controlled, low-noise measurement conditions, and the nearly ideal characteristics of the test signal. The non-zero x-intercept (estimated by dashed line) of the curve indicates a ≈8 mΩ cell internal resistance.

Magnitude versus frequency plots of the real part of the measured impedance of a single cell in the 24-cell telecommunications battery string, using the connections of Fig. 4, are shown in Figs. 6 and 7. The low frequency measurement of Fig. 6 shows signals grouped in narrow bands at harmonics of 6.75 Hz. The source of signals at these frequencies was unknown, but may be due to the characteristics of the telecommunications switch connected to the battery, the power supply, or both (for instance,

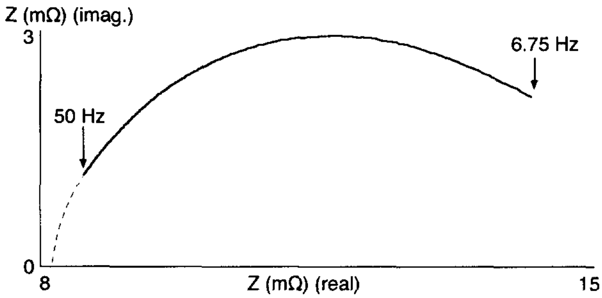

Fig. 5. Nyquist plot of impedance data for laboratory lead/acid cell, measured as shown in Fig. 3. Current measurement resistor = 0.1 Ω, 6.75 to 50 Hz.

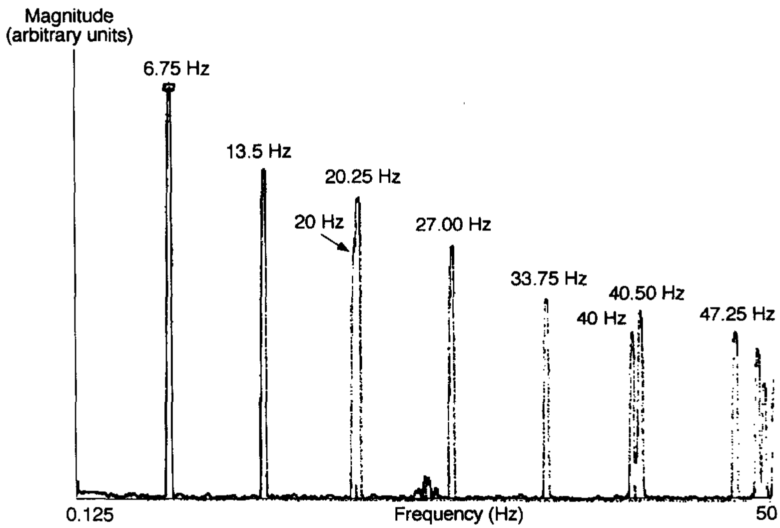

Fig. 6. The real part of the impedance vs. frequency for battery string connected to telecommunications switch, measured as explained in text. Frequency range 125 mHz to 50 Hz, resolution 0.0625 Hz.

a beat frequency resulting from two higher-frequency noise components). As expected, noise was present at 20 Hz (the telephone ringing excitation frequency) and the harmonic, 40 Hz. By comparison, the response, if recorded using the stimulus signal from the measurement of Fig. 5, would show none of the amplitude spikes, because of the broadband nature of the white noise signal source from the analyzer.

Nyquist plots of impedance measurements for two different cells in the battery string are shown in Figs. 8 and 9. The impedance values were calculated based on an estimated cell connector resistance (current measurement resistor) of 50 μΩ. The curve shapes appear noisy, compared with Fig. 5. However, this is not the same noise as the random, uncorrelated noise which appears in a conventional measurement. Such noise can be minimized by signal averaging. Here, the shapes of the curves are not affected by extensive signal averaging, because the noise is the test signal, e.g., correlated with our measurement. In effect, the impedance analyzer cross-correlates the 'input

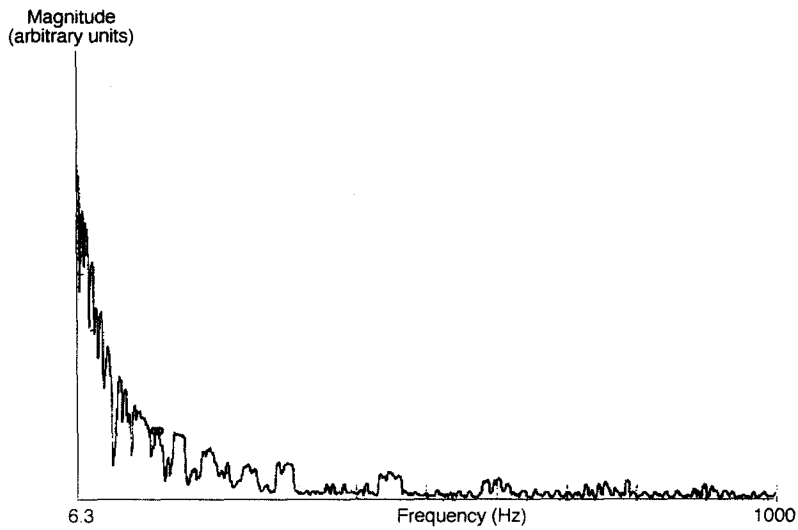

Fig. 7. The real part of the impedance vs. frequency for battery string connected to telecommunications switch. Frequency range 6.3 to 1000 Hz.

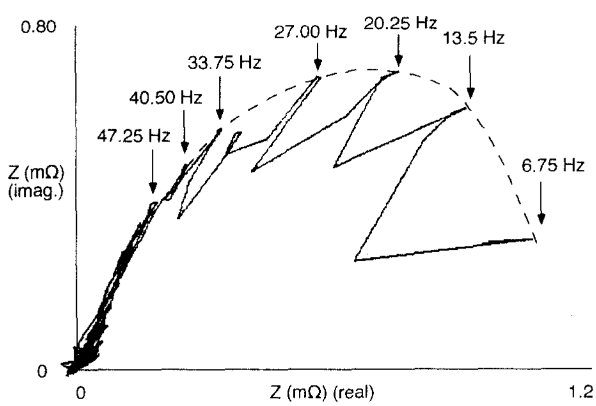

Fig. 8. Nyquist plot of impedance data from operating telecommunications battery string, measured using passive method shown in Fig. 4. Frequency span 1000 Hz, resolution 1.25 Hz.

signal' (noise in the battery current circuit) with the 'output' (the resulting fluctuation in the battery voltage), giving the impedance. The actual impedance curve is described by the function envelope, shown in Figs. 8 and 9 as a dotted curve, connecting the data measured near the noise frequencies of Fig. 6. These are frequencies where, in this case, sufficient signal exists for a reliable measurement. The measurement frequencies are slightly different (by ± 0.5 Hz) than in Fig. 6 because of the reduced analyzer resolution at the broader, 1000 Hz span. However, the measurements still reflect signals at those frequencies because of leakage from adjacent frequency bands [8], and so are labeled accordingly. The function envelopes have the expected shape, e.g., are semicircular, as Fig. 5. Identical results were obtained during successive measurement runs of several hundred averaged measurements on the same cells.

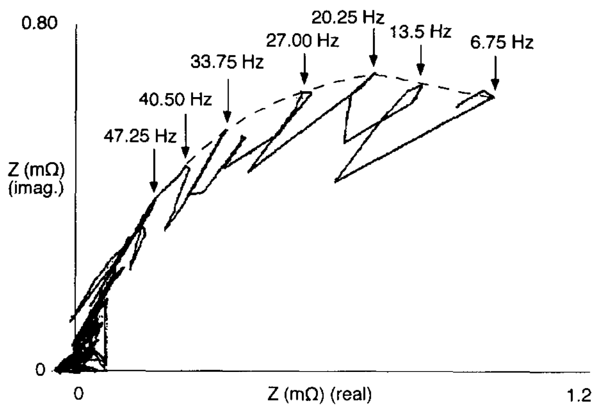

Fig. 9. Nyquist plot of impedance data measured as shown in Fig. 4, different cell in string from Fig. 8.

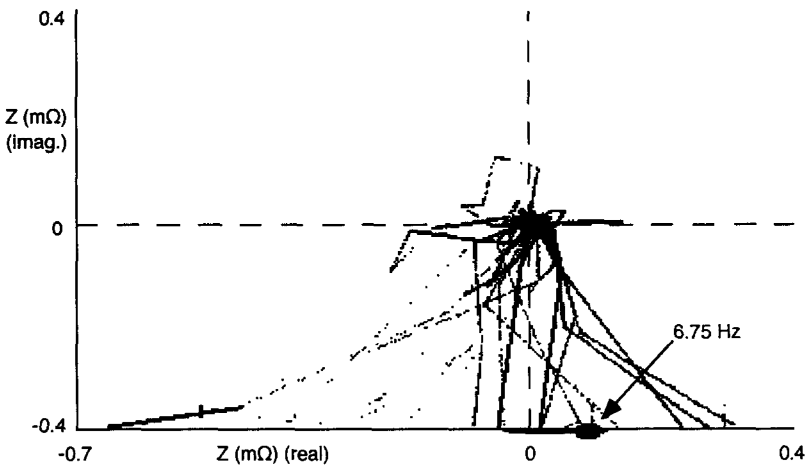

Fig. 10. Nyquist plot of impedance data, a blank taken without current measurement resistor.

While the power supply harmonic signals used may appear to be a poor substitute for a conventional wideband impedance measurement with a proper signal source, there are enough harmonics present to estimate of the shape of the curve. Alternatively, with appropriate signal amplification, the frequencies between the harmonic peaks could be processed and used to generate impedance curves which are continuous over a wider frequency range. In either case, this is an improvement over a single frequency impedance measurement. Furthermore, the method discussed above does not necessarily rely on reproducing a battery's exact impedance curve. It is envisioned as a means of tracking impedance changes that occur during the life of a battery. Therefore, the shape of an individual impedance curve is less important. The changes would be used to indicate the state of a battery's health, by comparing measurements of the same cell over a long time period.

Finally, a blank measurement was performed by eliminating the current measuring resistor, by attaching both current measurement leads to the same battery terminal.

A Nyquist plot of this data is shown in Fig. 10. The data resemble an uncorrelated current–voltage measurement, ruling out the possible influence of spurious signals on the measurement.

Conclusions

Impedance measurements on cells in an operating telecommunications battery string were performed using the intrinsic load and power supply-induced noise of the operating battery string as a signal source. The current and voltage passing through cells in a telecommunications battery string were determined with a simple, three-terminal connection, and impedance calculations performed with a commercial FT signal analyzer. The results indicate that completely passive (no externally applied test signal, and not requiring discharge or disconnection of the string) impedance measurements on telecommunications battery strings are feasible. The passive measurements are envisioned at the basis of an on-line battery capacity monitoring method.

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