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Study of battery resistance online monitoring system using hilbert-huang transform

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ABSTRACT

In battery's internal resistance online monitoring system, voltage collected is influenced by charging ripple, load changes, AC frequency interference, etc. It contains high harmonics and other interference. As Hilbert-Huang spectrum has perfect time-frequency characteristics, it can describe frequency varying with time accurately. Hilbert-Huang transform contains two steps: empirical mode decomposition (EMD) and Hilbert transform. Battery voltage collected is implemented EMD and Hilbert transform respectively, in the obtained time-frequency distribution domain, fundamental component which frequency is the same with fed current is preserved, while others are removed, it is the voltage which has the same frequency as fed current. According to the relationship of average power and resistance, the battery resistance can be computed

KEYWORDS

Battery;
Internal Resistance;
Hilbert-Huang Transform (HHT);
Harmonic.

INTRODUCTION

Battery as a backup power has been widely used in electricity, telecommunications, chemical and oil, etc. Its reliability is related to the security and stability of application system[1]. If battery is lack of capacity or lose efficiency, that will cause a major accident. As deterioration process of battery is long-cycle, cumulative and perishing slowly, how to detect deterioration of battery in running state is not only user's primary concern, but also one of the most difficult problem for backup[2]. For the working principle and failure mode, new standard 1188-2005 of IEEE provides that internal resistance value of battery can be determine whether fail or not, changing of 30%-50% compared with reference value can be regarded as failure mode[3]

Internal resistance of battery contains several factors: physical connection resistance, ion conductivity of electrolyte, electrochemical activity on the surface of plates, connection resistance of batteries. In spare occasion, battery's capacity is usually large, the internal resistance is usually milliohm. It is difficult to measure internal resistance exactly in online monitoring system, especially the battery's terminals are influenced by charging ripple, load changes and AC frequency interference[4].

At present, there are two main methods for battery internal resistance measurement[3]. One is DC method, the other is AC method. DC method is as following: add a load at two ends of battery, measure the step change value of current and voltage, the result of voltage change value divided by current change value is the internal resistance value. This method is suitable for the system which precise and safety is not high, and it is suitable for static or offline measurement. If it is used online, the stability of result is greatly affected by environment. AC method is as following: add an excitation AC current (or AC voltage, in this paper it is AC current) which frequency and amplitude are known at two electrodes of battery, measure every battery's AC voltage drop response, then battery's internal resistance can be computed by Ohm's Law. This method is suitable for online mode. But the responses are interfered by noise, the key of AC method is how to restrain interference effectively, which plays a significant role in system precise and result effectiveness.

BATTERY'S INTERNAL RESISTANCE MODEL AND MEASURING PRINCIPLE

To measure battery's internal resistance, firstly we study its internal resistance model. Figure 1 is the equivalent circuit [4].

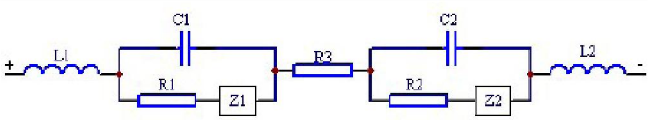

Figure 1: Battery's equivalent impedance circuit

In which, L1, L2 are the positive and negative inductance. R1, R2 are the migration resistance of electrode ions. C1, C2 are the double-layer capacitance of plates. Z1, Z2 are the Warburg impedance, which are decided by ions' diffusion velocity of electrolyte and electrode. R3 is the battery's internal resistance.

As measuring battery's internal resistance, there exists contact resistance of measuring wire. So AC method is used by means of four-wire connection method. Computing resistance need to measure voltage between two terminals of battery. The principle is shown as Figure 2[5], in which, I is the fed AC current, V1 is the terminal voltage of battery, R1is equivalent internal resistance of battery, R2 is equivalent load resistance, as battery's internal resistance and terminal voltage fluctuation are both little, the AC voltage V is little too. In order to measure, V must be amplified, R3 is the equivalent amplifier internal resistance, C1, C2, C3 and C4 are bridge coupling capacitors.

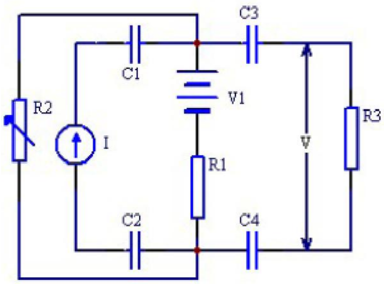

Figure 2 : AC method for battery's internal resistance

Feeding controlled AC current $I = I_{max}\sin(2\pi ft)$ to the terminals of battery, the collected AC voltage drop of R1 is as follows:

$$\mathbf{V} = \mathbf{V}_{max}\sin(2\pi ft + \phi) \quad (1)$$

θ is phase shift of I and V, then the instantaneous power of R1 is:

$$P_i = V_{max} I_{max}\sin(2\pi ft)\sin(2\pi ft + \phi) \quad (2)$$

Energy consumed of R1 in n periods is:

$$W = \int_{nT} V_{max} I_{max}\sin(2\pi ft)\sin(2\pi ft + \phi)dt \quad (3)$$

Then the average power of R1 in n periods is:

$$\overline{P} = \frac{W}{nT} = \frac{1}{nT}\int_{nT} V_{max} I_{max}\sin(2\pi ft)\sin(2\pi ft + \phi)dt \quad (4)$$

So the internal resistance of battery is:

$$\begin{aligned} R = \overline{P}/\left(I_{max}/\sqrt{2}\right)^2 &= \frac{2}{I_{max}^2 nT}\int_{nT} V_{max} I_{max}\sin(2\pi ft)\sin(2\pi ft + \phi)dt \\ &= \frac{2V_{max}}{I_{max} nT}\int_{nT}\sin(2\pi ft)\sin(2\pi ft + \phi)dt \\ &= \frac{2V_{max}}{I_{max} nT}\int_{nT}\frac{1}{2}\left[\cos\phi - \cos(4\pi ft + \phi)\right]dt \\ &= \frac{V_{max}}{I_{max}}\cos\phi \end{aligned} \quad (5)$$

As the accuracy of internal resistance requires high, especially the battery terminals are influenced by charging ripple, load changes and AC frequency interference in online monitoring system. When exciting source is fed to the two terminals of battery, the output signal contains not only stationary response, but also non-stationary transient harmonics and varieties of noise. Hilbert-Huang Transform (HHT) plays an important role for non-stationary and nonlinear signals[6]. Hilbert-Huang Transform contains two parts: empirical mode decomposition (EMD) and Hilbert transform. The key part of HHT is EMD with which any complicated data set can be decomposed into a finite and often small number of intrinsic mode functions (IMFs). The instantaneous frequency defined using the Hilbert transform denotes the

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physical meaning of local phase change better for IMFs than for any other non-IMF time series. The decomposition method is adaptive and therefore highly efficient. As the decomposition is based on the local characteristics of the data, it is applicable to nonlinear and non-stationary processes.

At first, voltage collected is decomposed into several intrinsic mode functions (IMFs), then the IMFs are transformed by Hilbert, and the corresponding time-frequency distribution data can be obtained. In time-frequency distribution domain which frequency is the same as fed current is preserved, while the others are removed. Then the intrinsic mode functions which have no multi-harmonic can be obtained by inverse Hilbert transform, after that the IMFs have been added, it is the voltage data which has the same frequency as the fed current. According to the relationship of average power and resistance, the battery's internal resistance can be gotten online reliably.

RESEARCH OF REMOVING HARMONICS AND VOLTAGE RECONSTRUCTION BASED ON HILBERT-HUANG TRANSFORM

EMD decomposition

The key part of HHT is EMD that any complicated data set can be decomposed into a finite and often small number of IMFs. The IMFs need satisfy the following conditions: (1) In the whole data set, the number of extreme and the number of zero crossings must either equal or differ at most by one. (2) At any data point, the mean value of the envelope defined using the local maxima and the envelope defined using the local minimum is zero.

With the above definition of an IMF in mind, then one can decompose any function through a sifting process, which is as following. The local maxima are connected with a cubic spline to form an envelope, after which the same is done to the local minima. Next, the envelope mean m of local maxima and local minima is calculated, and the first component $h_1(t)$ is obtained by Eq.(6).

$$\mathbf{h_1(t) = x(t) - m} \tag{6}$$

If $h_1(t)$ dissatisfy the conditions of IMFs, regard $h_1(t)$ as original data and repeat Eq.(6) until it satisfy the conditions. After the last subtraction the first IMF s_1 is obtained, that is S1= $h_1(t)$. The first residue is obtained by subtracting the first IMF from the original signal,

$$\mathbf{r = x(t) - s_1} \tag{7}$$

Consequently, another round of sifting process is started using this residue as the original signal, ..., the process is finished until s_n become monotonic or s_n has too small effect. As a result, the original signal can be decomposed as Eq.(8),

$$\mathbf{x(t) = \sum_{i=1}^{n} s_i + r} \tag{8}$$

In which, r is a constant or represents a trend.

Hilbert transform

For any IMF $\mathbf{s_i(t)}$, its Hilbert transform $\hat{s}_i(t)$ is as follows,

$$\hat{s}_i(t) = H[s_i(t)] = s_i(t) * \frac{1}{\pi t} = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{s_i(t)}{t-\tau} d\tau \tag{9}$$

Then we can obtain the analytic function,

$$z_i(t) = s_i(t) + j\hat{s}_i(t) = a(t)e^{j\varphi(t)} \tag{10}$$

Where $j = \sqrt{-1}$. So the corresponding amplitude, instantaneous phase and instantaneous frequency are as follows,

$$a_i(t) = \sqrt{s_i^2(t) + \hat{s}_i^2(t)} \tag{11}$$

$$\varphi_i(t) = \arctan\frac{\hat{s}_i(t)}{s_i(t)} \tag{12}$$

$$f_i = \frac{1}{2\pi}\frac{d\varphi_i(t)}{dt} \tag{13}$$

Using the Hilbert transform to every IMF, the corresponding instantaneous frequencies and instantaneous amplitudes of IMFs can be obtained. In that way, the original signal can be expressed as Eq.(14).

$$x(t) = \mathrm{Re}\sum_{i=1}^{n} a_i(t)e^{j\varphi_i(t)} = \mathrm{Re}\sum_{i=1}^{n} a_i(t)e^{j2\pi\int f_i(t)dt} \tag{14}$$

In which, a_i and f_i are time functions. As instantaneous frequency is defined as the phase differential of an IMF, this technique decomposes non-stationary signals into a set of IMFs adaptively, so it is intuitive, direct, a posterior and adaptive, with the basis of the decomposition derived from the data[10].

The IMFs $s_i(t)$ can be reconstructed from $\hat{s}_i(t)$ by inverse Hilbert transform [10], which is Eq.(15).

$$s_i(t) = -\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{\hat{s}_i(t)}{t-\tau}d\tau \qquad (15)$$

Removing high harmonics and voltage reconstruction

As exciting AC source with certain frequency and amplitude is fed to the electrodes of battery on line, system is inevitably suffered from high order harmonic such as charging ripple, AC frequency interference from the grid, load change, and noise, etc. The voltage collected from electrodes is decomposed using EMD, the result is shown as Figure 3.

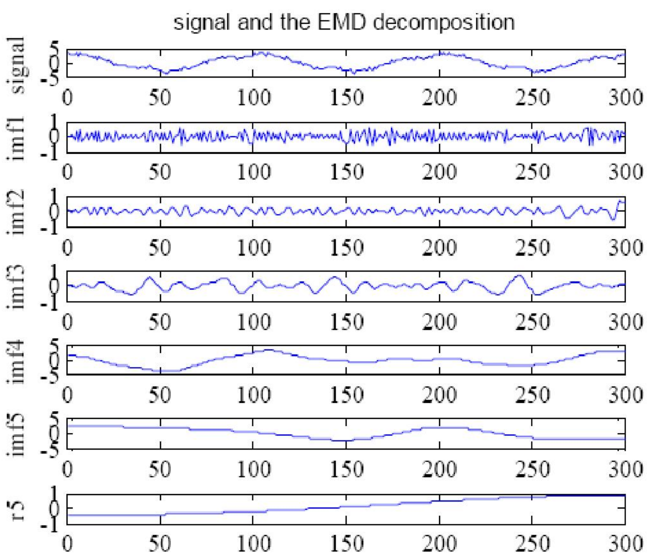
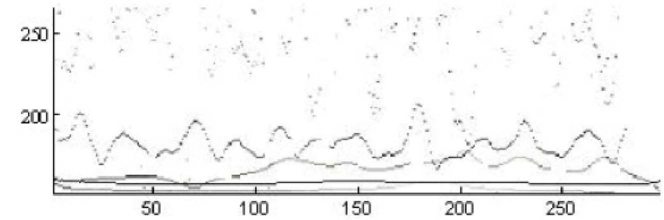


Figure 3 : Voltage collected from electrodes and the EMD decomposition

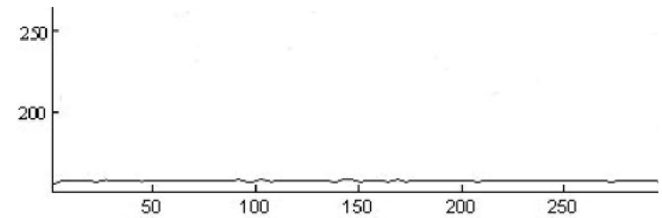
In Figure 3, r5 represents average component mainly, imf2~imf5 are different order harmonics, imf1 is mainly noise and others.

The Hilbert-Huang time-frequency distribution data is shown as Figure 4. From Figure 4(a), there have different order harmonics and noise besides base component obviously. The time-frequency distribution is as shown as Figure 4(b) which frequency is the same as fed current and the others are removed.

The IMFs can be obtained by inverse Hilbert transform, and added to get reconstruction signal. In order to prove validity, the time-frequency data with removing nothing is reconstructed, which is shown as Figure 5(b), compared with Figure 5(a), the reconstruction signal and original signal are similar. Only preserving fundamental component which frequency is the same as fed current, the reconstructed data is shown as Figure 5(c).



(a) time-frequency distribution of voltage collected



(b) time-frequency distribution data preserved

Figure 4 : Time-frequency distribution of signals

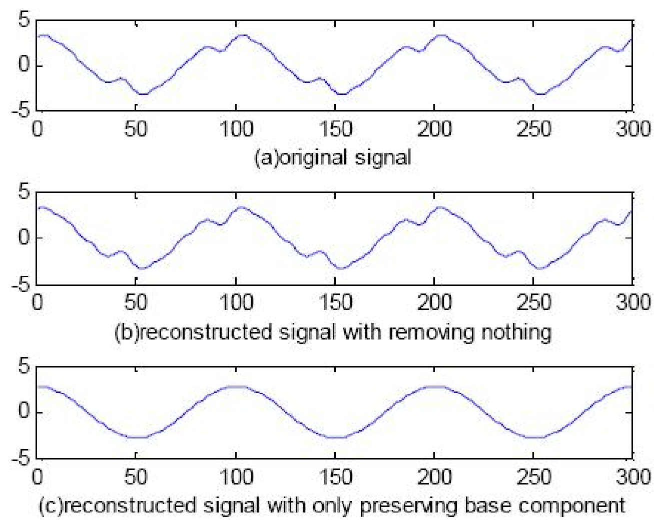


Figure 5 Original signal and reconstruction signal

The process described above can be depicted below.

1) Apply current I with a certain frequency and a certain amplitude to the electrodes of battery;
2) Measure the voltage V of electrodes, decompose V by EMD, every IMF s_i and residue r can be obtained;
3) Transform the IMFs by Hilbert, the corresponding joint time-frequency distribution data can be gotten;
4) Preserve the basis frequency data which frequency

is the same as fed current, the others are cleared away;

5) The new IMFs can be obtained by inverse Hilbert transform, then the reconstructed voltage V can be gotten by adding the IMFs;

6) According the fed current I and reconstructed voltage V, compute instantaneous power P of electrodes, average power $\bar{P}$ can be obtained by integrating in n periods;

According average power $\bar{P}$ and valid value $I_{\max}/\sqrt{2}$ of fed current I, the equivalent resistance of battery can be computed, that is $R = \bar{P}/\left(I_{\max}/\sqrt{2}\right)^2$.

RESULTS AND ANALYSIS

Take two terminal battery for example, their specification are 18Ah/24V and 18Ah/12V respectively, and in state of float charging, they are used about 1 year. When measuring on line, the magnification of amplifier is 50, A/D converter is 12 bits, fed current is AC which peak value is 1A and frequency is 100Hz, sampling interval of electrodes is 4ms, and the total collected points is 300. The data collected and their frequency spectrum, data filtered and corresponding frequency spectrum are shown in Figure 6 and Figure 7 respectively. Figure 6 is the battery of 18Ah/24V, and Figure 7 is the battery of 18Ah/12V.

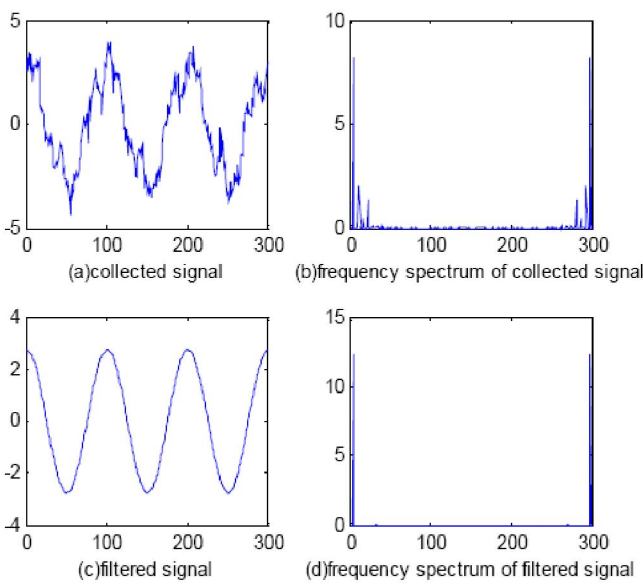


Figure 6 : collected data, filtered data and the corresponding frequency spectrum

According the fed current and reconstructed voltage, the instantaneous power and average power in 3 periods can be computed by Eq.(5), the internal resistance of Figure 6 is 30 milliohm, and the internal resistance of Figure 7 is 25 milliohm, compared with standard specification, the battery of Figure 6 does not lose efficacy, while battery of Figure 7 lose efficacy.

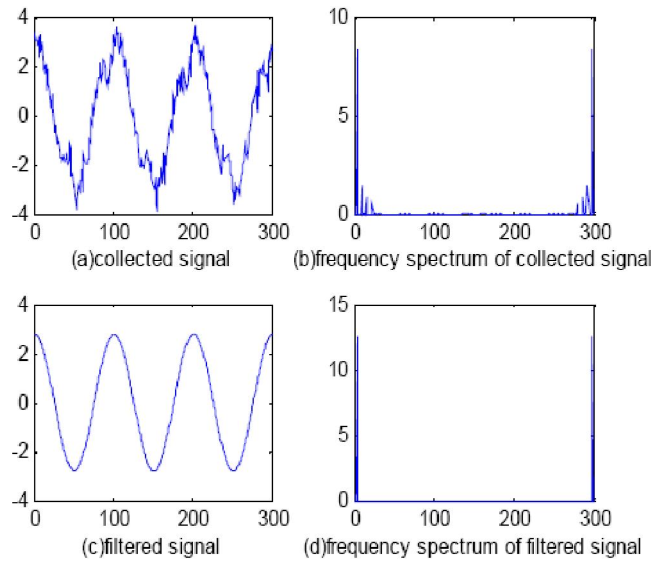


Figure 7 : collected data, filtered data and the corresponding frequency spectrum

CONCLUSIONS

The paper gives a detail analysis of measurement on-line used in the internal resistance of battery, it introduces a AC method that apply a certain frequency and a certain amplitude current to the electrodes of battery, As the voltages collected on-line is influenced by charging ripple and 50Hz power interference, they contain high harmonic interference. Hilbert-Huang spectra has perfect time frequency characteristics, it can describe frequency varying with time accurately. In this paper, Hilbert-Huang transform is used to internal resistance measurement, preserve basis frequency data which frequency is the same as fed current, the others are cleared away, lastly according to the relationship of average power and resistance, the battery resistance can be gotten.

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