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Measuring and analysis of nonlinear characterization of lithium-ion batteries using multisin excitation signal

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Summary

This paper introduces a novel methodology for analysis in the frequency domain. This methodology looks to the battery from a different point of view and covers aspects of the battery that is often neglected in other works and analysis battery precisely. Using periodic signals such as random phase multisine for system identification, allows separating noise and nonlinear distortions from the linear part of the system's response. In addition to a shorter test time in comparison with conventional single sine EIS, by performing extra periods and different phase realizations, transients are eliminated and noise disturbance and also nonlinear distortion is detected.

Keywords: lithium battery model, multisine, nonlinear distortion, linear approximation, noise measurements

1. Background

Availability, certainty and efficiency of rechargeable electro-chemical energy systems, persuade us to consider them as alternative energy source in different applications such as electric and hybrid vehicles, heavy transportation systems, renewable energy systems and smart grids [1]. Therefore due to the wide range of applications, our understanding regarding the behavior of different types of energy storage systems, especially lithium-ion batteries, under different operating conditions has to be extended. For this reason an accurate and comprehensive model is needed to predict the output considering all linear and nonlinear behaviors.
Regarding electrical modeling of batteries and the associated parameter identification, most of the publications rely on hybrid pulse power (HPPC) tests, described in time domain, and are based on a first or second order equivalent circuit, the measured data have been fitted to the model and parameters have been identified [2-3]. In many of them the battery is considered as a linear system with variable parameters, while the nonlinear behavior and noise distortions are neglected.
In contrast to identification in the time domain, identification in the frequency domain, frequency, amplitude and phase of each component of the identifier signal can be controlled. Battery system identification in frequency domain using single-sine with EIS devices have been investigated in many paper [4, 5].
One can design an identifier signal containing arbitrary frequencies with specified amplitude and phase. This flexibility has made frequency domain suitable for identification of a wide range of nonlinear systems. For achieving these goals, random phase multisine has been used as excitation signal. In order to build a random phase multisine, several sine waves with a same amplitude and randomly chosen phase multisine are added

together. The frequency and range of sine waves depend on dynamic of battery and application which model is made for.

2. Theory of new method and analysis

Every nonlinear system can be represented by a linear dynamic system $(j\omega)$ plus stochastic nonlinear distortion (t) and with a disturbing noise source (t) as shown in fig 1.

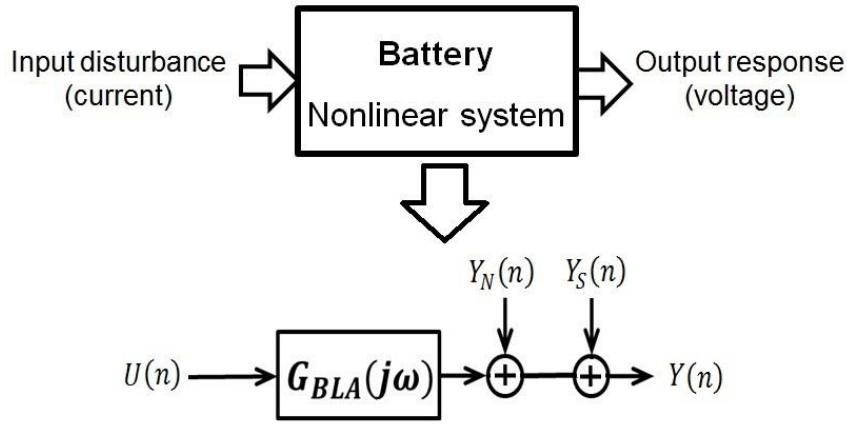

Figure 1: Linear approximation of a nonlinear system

In order to separate and identify these quantities, a special input excitation signal is needed which is consistence against noise, transient can be detected and removed and also is able to show the nonlinear distortion in its spectrum [6-8]. Noise and transient can be detected and eliminated in periodic signals. Therefore if some sine waves (different frequencies) to be added together with same amplitude and different phase according equation 1, noise can be quantified by averaging and transient is identified by voltage response behavior until it gets to steady state.

$$u(t) = \sum_{n=-N}^{N} {}^{A_n}/_{2}\, e^{j(2\pi f_n t+\theta_n)} = \sum_{n=1}^{N} A_n \cos(2\pi f_n t + \theta_n) \tag{1}$$

Thanks to frequency domain analysis, every excited waves and its response can be analyzed and also corresponding impedance be calculated. A nonlinear system can be approximated by a linear dynamic system, which is called the *best liner approximation*. This linear part (linear part of battery impedance) is approximated from the voltage response to multisin excitation current in frequency domain. Besides the noise and transient, the main source of signal distortion in a measurement is nonlinear behavior of battery. This part can be quantified after the linear part has been identified. In this way all aspects of system, whether related to its behavior or external causes (noise), is identified and can be analyzed separately.

2.1. Random Phase Multisine excitation signal

As many papers already have presented single sine sweep (standard impedance spectroscopy), this paper introduces multisine method which has been introduced above. Battery dynamics, such as other electrochemical systems, has transient state and own nonlinear behavior and also it is known that in all measurements noise is unavoidably and has to be considered in identification process. Using periodic signals for identification allows us to reduce noise and also eliminate the transient state from measured data. For this

study, the NMC cell is excited by a multisine signal including summation of odd frequencies from 20Hz to 20mHz. The amplitude of input current is 5 and 60A rms and it is applied at different SoC levels (90%, 70%, 50%, 30%, 10% and 2%). In order to reduce the effects of noise and transient state, the generated multisine is repeated several periods with no pause between. In next step several multisine signals with different phase realizations (same amplitude as previous realizations) will be applied to the battery as well.
Considering the input (current) and output (voltage) measurements in the discrete time domain, we have:

$$u^{[r,p]}(k),\ y^{[r,p]}(k) \quad r=1\ldots M \text{ and } p=1\ldots P \tag{2}$$

Where r and p inside bracket indicate respectively the rth realization and the pth period of the input disturbance or of the output response that is considered. Then the discrete Fourier spectrum can be obtained by applying to both the input and the output a fast Fourier transformation:

$$U^{[r,p]},\ \ Y^{[r,p]} \tag{3}$$

In this case each multisine signals (a realization) has been repeated 15 times and 4 realizations have been considered.

2.2. Best linear approximation (BLA)

As mentioned, a nonlinear system can be approximated by a linear dynamic system. The best linear approximation (BLA) function is calculated through the excited frequencies as:

$$G_{BLA}(j\omega_n) = \arg\min \sum_{r=1}^{M} \left|Y^{[r]}(n) - G(j\omega_n)U^{[r]}(n)\right|^2 \qquad n=1\ldots N \tag{4}$$

Where G is the frequency response function (FRF), calculated directly by output and input signals in excited frequencies in each r realization, N is the number of data samples in one period.

$$\hat{G}^{[r]}(j\omega_n) = \frac{\hat{Y}^{[r]}(n)}{\hat{U}^{[r]}(n)} \tag{5}$$

Where $\hat{U}^{[r]}$ and $\hat{Y}^{[r]}$ are the average of respectively the input and the output over all periods p in r^{th} realization. Based on the average of output and input along the periods and also by averaging the calculated FRF over all M realizations, the best linear approximation is presented as:

$$\hat{G}_{BLA}(j\omega_n) = \frac{1}{M}\sum_{r=1}^{M} \hat{G}^{[r]}(j\omega_n) \tag{6}$$

According to the equation (6), at least two realizations are required. More realizations make BLA function more accurate and reliable. However the measurement time and required memory for saving data will be increased. Another point is that by repeating more periods, the noise can be reduced more effectively by averaging and also the transient state will be eliminated by neglecting beginning periods.

2.3. Noise and Nonlinear distortion

The sources of signal distortion in a measurement are the environmental and equipment noise, transient and nonlinear behavior of system. If we suppose that enough periods are applied to the battery which suppressed the transient state, then disturbing noise and nonlinear distortion have to be detected and also reduced as much as possible.
It should be noticed that it is assumed that all noise is zero-mean and normally distributed. Since the quality of the measurement can be evaluated based on the variance, two different variances of the output voltage are calculated. The first one, σ_N^2, is calculated for the excited lines (FRF) over all the periods after elimination of the transient in each realization:

$$\sigma_N^2(n) = \frac{1}{M*(P-1)} \sum_{r=1}^{M} \sum_{p=1}^{P} \left| G^{[r,p]} - G_p^{[r]} \right|^2 \quad (7)$$

Where

$$G_p^{[r]} = \frac{1}{P} \sum_{p=1}^{P} G^{[r,p]} \quad (8)$$

According to equation (8), the calculated variance is related to the variation of one period to another period. Therefore the calculated disturbance is caused by external factors such as environmental and measurement noise.

On the other hand, It can be concluded that by averaging over periods, the nonlinear distortion is not eliminated as it comes from the nonlinear behavior of system. Therefore if the variance calculation be applied to the M different realizations, then we can detect and also quantify the nonlinear source from the measurement. The second $\sigma_{total}^2$is total variance which is calculated over all realizations:

$$\sigma_{Total}^2(n) = \frac{1}{M*P-1} \sum_{r=1}^{M} \sum_{p=1}^{P} \left| G^{[r,p]} - G_p \right|^2 \quad (9)$$

Where

$$G_p is \ \frac{1}{M*P} \sum_{r=1}^{M} \sum_{p=1}^{P} G^{[r,p]} \quad (10)$$

According to equation 9 the variance is calculated over all periods and realizations and also includes both the nonlinear distortion and environmental noise. However the disturbing noise was already calculated based on equation 7. Now by considering equation 9, the stochastic nonlinear distortion σ_S^2 can be calculated as:

$$\sigma_S^2(n) = M(\sigma_{Total}^2(n) - \sigma_N^2(n)) \quad (11)$$

Now by using this method not only the conventional modeling such as equivalent circuit based models can be performed on the battery cell based on the linear part, but also the nonlinear behavior will be quantified and can be used later for nonlinear characterization and modeling. This method will provide more robust analysis tool for different battery chemistries for different applications such as SoC and SoH estimations and also it increases the quality of results by reducing the noise disturbance from the measurements.

3. Experimental results and discussion

In this part designed multisine current waveforms based on equation (1) are applied to the cell by using test equipment available in VUB battery laboratory. Fig 2.a shows the applied 60A rms current to the 20Ah NMC cell. As it indicated on figure, the input current signal is composed of 4 different multisine realizations (same frequency and amplitude, different phase). Each realization includes 15 periods of designed multisine current signal. The voltage response to the input current at different SoC levels has been shown in fig 2.b. The transient state is seen at the beginning of the voltage response before the time 500 seconds. By neglecting the beginning periods of each realization, transient effect can be eliminated.

In the following sections, all introduced theories from previous part will be applied on the measured data from the cell and it will be shown how linear part can be approximated and also nonlinearity is detected and characterized.

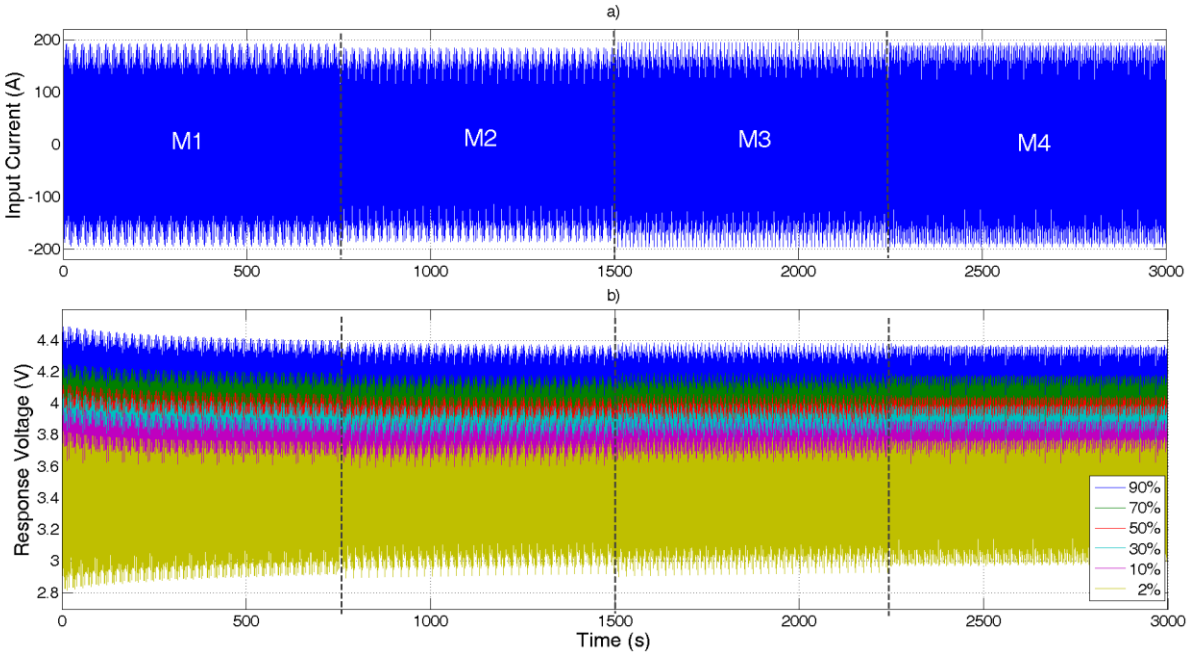

Figure 2: Measured multisine excitation waveformes: a) current signal, 4 realizations and 15 periods for each, b) Voltage response to input current at different SoC levels (%).

3.1. Linear system approximation

As it already mentioned, a nonlinear system can be represented as a linear system working with one or more static nonlinearities. If the linear part be separated, then the nonlinear part also can be calculated with statistical approaches. This section discusses the method approximates the linear part.

According the introduced theory, all measured data have to be converted to the frequency domain. This is a frequency domain approach. As it seen in fig 2, the generated multisine looks like a random signal and if it be converted to frequency domain it shows something different as illustrated in fig 3. This figure shows Fourier transform of input multisine signal at 50% of SoC while amplitude is 5A and 60A rms (fig 3 a and b respectively). The difference in amplitude of excited frequencies between 5A and 60A is obvious but the number and frequency of excited components are same. Fig 3.c and 3.d shows the measured voltage response to the corresponding input multisine current. The excited frequencies and their response are clearly distinguished and it let us to calculate influences of system on excited and non-excited frequencies.

The calculated frequency response function (FRF) based on formula (4), (5) and (6) is shown in fig 4. The FRF for 5A and 60A is calculated considering excited frequencies at 10% of SoC. In this way a nonparametric model for the battery is developed and effect of system on excited lines is evaluated. This function represents linear part of the impedance which later can be used for parametric system identification such as equivalent circuit models.

3.1.1. Nyquist diagram of linear part of system

In order to the approximated linear part be explained in a more obvious way, the Nyquist plot of BLA is illustrated in fig 5. Now the well-known patterns of electrochemical impedance spectroscopy can be seen at different state of the charges. One of the obstacles of EIS measurements is the limitation of input amplitude as it is concerned that high input perturbations may cause battery operates nonlinearly. This method allows us to

increase the input current to its maximum level as the linear part is calculated and extracted from nonlinear part. In this fig (5) imaginary part of the impedance of BLA at excited lines has been plotted versus real part

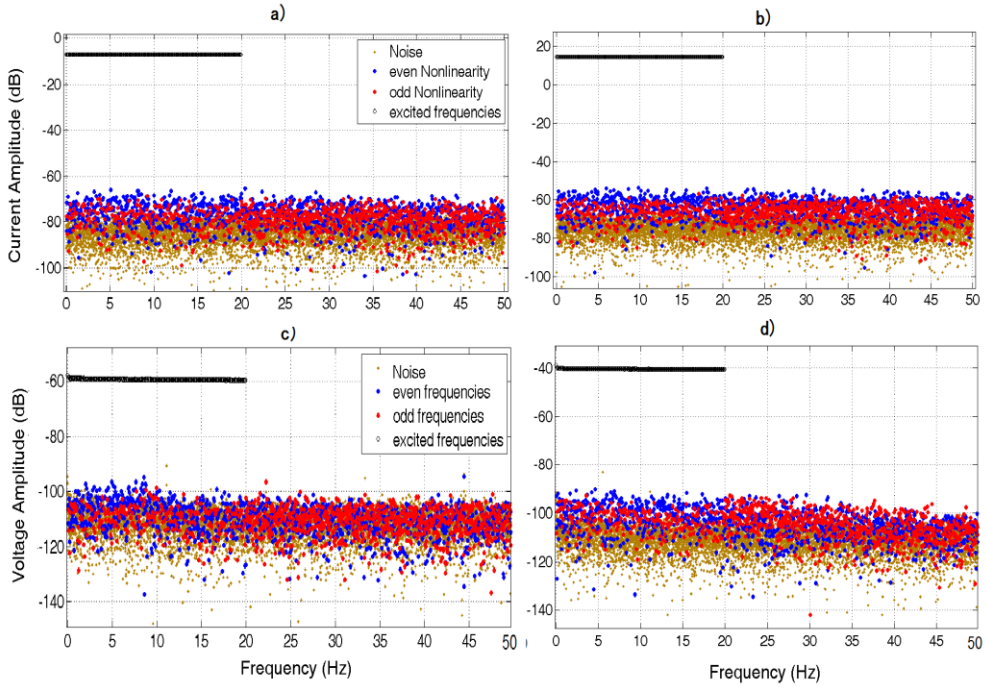

Figure 3: Fourier transform of: a) input 5A rms multisine current, b) input 60A rms multisine current, c) Voltage response to the 5A rms input, d) Voltage response to the 60A rms input

of it. As it is expected, battery impedance curve is getting larger at lower SoC for both current levels due to the difficulty of lithium Ions diffusion into the electrodes.

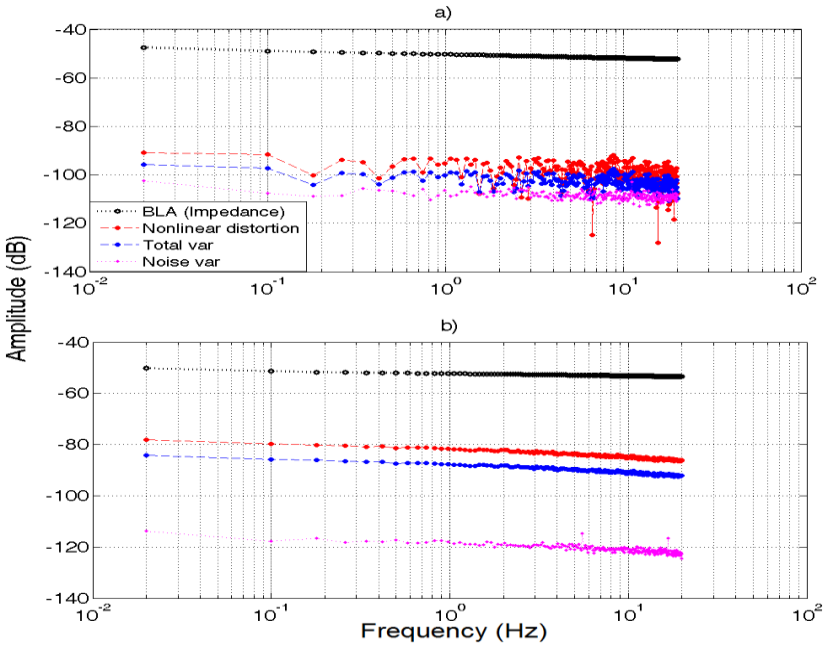

Figure 4: Calculated BLA FRF (amplitude), noise and nonlinear distortion in excited lines at 10% of SoC while rms current is: a) 5A, b) 60A

Another point that can be caught in the figure is that how current amplitude affects the impedance behavior. When amplitude of input current is increasing at fig 5.b, more heat will be generated and subsequently, due to the faster movements of the Ions, the impedance curve is getting smaller and more shrunk.

3.2. Nonlinearities and noise calculations

After approximation of linear part, nonlinear part and environmental noise are calculated. According to the formula (7) to (10) nonlinear distortion is calculated based on the statistical approaches.
The nonlinear distortion has been indicated in fig 4 (a and b) with red lines. The distortion magnitude is very low when input current is 5A in compare with 60A input. According to the fig 4.a the nonlinear distortion is approximately 40db below (100 times smaller) the BLA of system. It means the model error which comes from the nonlinearity is about 1%. While in fig 4.b, when input current is 60A, the distortion magnitude is increased around 20db (10 times bigger). Therefore we have to expect at least 10% error in our model caused by nonlinear behavior of the battery.

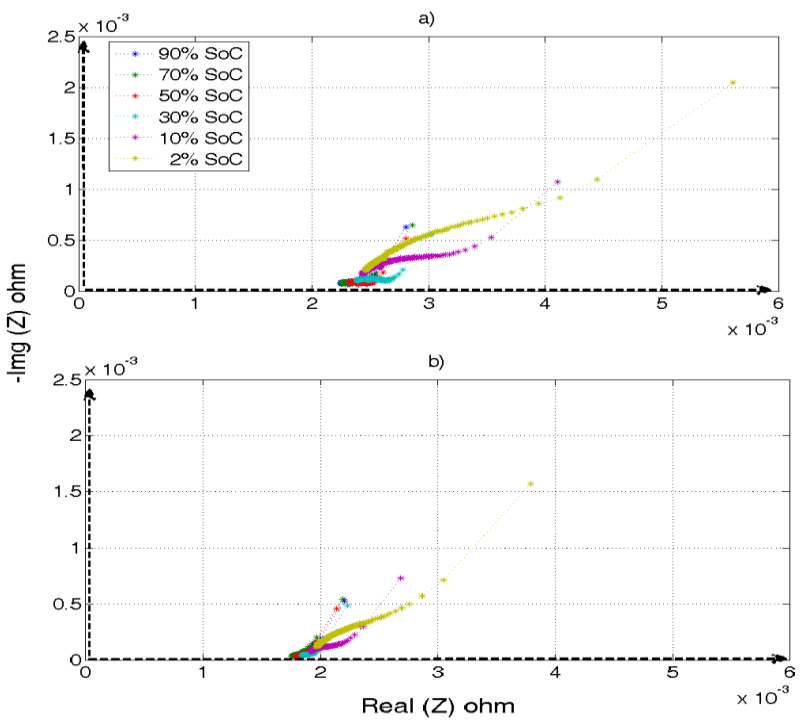

Figure 5: Nyquist plot of BLA of excited lines at various SoC levels while rms current is: a) 5A, b) 25A

Another important issue in signal measurement is the noise distortion which Equation (11) helps us to calculate it. By using multisine method for identification even the quality of measurement devices can be calculated and evaluated. In this case, in fig 4, the noise amplitude is indicated with pink dots. In both input multisines, noise level is very low around -110db to -120db which shows the test equipment is working well and quality of measurement is high enough. The noise level is at least 60db lower (1000 times smaller) that the BLA function. So we should not expect noise have major effects on our modelling process and cause failure in measurements.

4. Conclusion

In this paper a new method for battery characterization and identification has been introduced. The conventional methods such as pulse test and EIS only provide limited and general characteristic of battery. However we know batteries are highly nonlinear and this can varies at different SoC and from chemistry to chemistry. The mentioned conventional tests cannot measure and extract the nonlinear from linear part of the system. Also the noise level of the measured signals is unknown. Therefore the identification process will be more difficult and high order models have to be used in order to the model output being fitted to the measured data. In the other hand, the proposed model is able to extract the approximated linear part from the whole measured data. In addition the nonlinear distortion is calculated which shows how strong is the nonlinearity of the battery and how much will be the output error if linear model will be used. In this way we have a measure that can help to making better decision whether linear or nonlinear model be used for identification. Furthermore multisine is a proper candidate for nonlinear modeling using as we can use excited frequency together with non-excited ones for structured block modeling.

Also as it explained further in the paper, the noise level is calculated based on statistical methods which give us valuable information regarding test equipment whether they qualified for accurate measurement or not.

It can be concluded that by putting more effort for test and analysis of battery according to the new method, not only the modeling will be more accurate, but also more data regarding the battery and test equipment is achieved that can improve our understandings about the different type of battery chemistry and their specific behavior.

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