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Multispectral impedance measurement in embedded systems

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The data basis available for Battery management systems (BMS) is mandatory for a proper operation. For now high dimensional and offline gathered datasets describing the batteries behavior are the basis of algorithms implemented in BMS. In the laboratory, Impedance Spectroscopy (IS) for battery characterization is used for many years. As this method requires a high effort in both, hardware and software, Impedance spectroscopy was limited to laboratory applications. In this paper an approach to provide IS for online battery characterization as support for BMS is presented. Thereby challenges related to hardware and signal processing are considered. The developed approach is capable of doing IS measurements for each of the batteries in a stack of four.

***Keywords**:* battery management, battery diagnosis, digital signal processing, cyber-physical system, impedance spectroscopy

INTRODUCTION

In different applications like electric vehicles and stationary energy storage, high power/energy cells are the most expensive part. For proper and safe usage, extensive knowledge about the batteries and their current state is necessary for both management hardware and system designers. In the laboratory Impedance Spectroscopy (IS) is an adequate method to investigate internal electrochemical processes as charge transfer and diffusion [1]. Thus the complex transfer function is fitted to a model and used to rate the state of the battery [2], [3].

For batteries the measurement is usually done in a frequency range from about 10 mHz to 1 kHz [2]. IS has been prevented to be applied to mobile applications for several reasons: the required measurement time in combination of the wide frequency range needed to be covered with the measurement, the drift of the battery voltages as well as high cost for measurement equipment.

To overcome the mentioned challenges multiple problems needed to be faced: a proper perturbation sequence with minimal hardware requirements as well as a data analysis with low effort in memory consumption and computational power.

Other approaches do not provide measurement of impedance spectra in a wide frequency range from a few mHz to kHz for low ohmic test items. Usually one or more of the following aspects are required: acomplex hardware for pulse forming i.e. using the AD593 [4], [5] or other DAC hardware like presented from TI [6], a measurement time of more than 5 minutes in the case of not using multispectral perturbation, a high memory load for data processing using FFT based determination of spectral components. The presented approach omits all of these issues.

APPROACH

Impedance spectroscopy on batteries

Fundamental for Impedance Spectroscopy on batteries is their interpretation as systems described by a transfer function as the complex frequency dependent impedance. Effects present in batteries like contacts, electrode reactions, diffusion show different reaction rates. They have a different impact on the transfer function depending on the investigated frequency. By applying a frequency varying perturbation signal to the investigated system a differentiated view on the effects of interest [1] is performed. For low ohmic systems like batteries perturbation by modulated current is used. Therefore, the superimposed current acting as the perturbation signal as well as the corresponding voltage, the response signal is measured and transformed into the frequency domain. Division of the voltage and current in the frequency domain yields the complex impedance.

In laboratory applications usually AD/DA hardware in combination with power amplifiers are used to do IS measurements. Sampling rates of several kHz as well as resolutions up to 24bit for commercially available devices like NI4461 fulfill all technical requirements for IS measurements on

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batteries in the target frequency range. Further signal processing i.e. using Matlab as well as model based system identification are state of the art on PC based post processing. The need of partially saving measurement data as well as the complexity of the measurement and pulse forming hardware for the current perturbation has limited this approach to the laboratory. Consequentially a modified approach regarding the used perturbation sequence lowering the effort for HW and SW and an alternative for FFT based methods is required to provide IS measurements in embedded systems.

Signals for system identification

Besides perturbation sequences with one spectral components other signals like noise, mixed sine, or multilevel signals are available for system identification [7] see Fig. **1**. Depending on the requirements of the target device under test and the target application a proper signal needs to be selected for perturbation.

The following main aspects are critical for the selection of a proper perturbation sequence: coverage of the target frequency range, the signal to noise ratio (SNR), the maximum magnitude, fluctuation and the overall time needed for the measurement.

Noise has a continuous spectrum with a flat or frequency proportional dependency of the magnitude in the frequency domain. This provides a high dense observation of the transfer functions characteristics. Other signals like stepped sine or multisine concentrate the energy on selected spectral components. This is positive in terms of the SNR for the measurement. For a proper observation of effects in the battery, a linear distribution of the spectral components in the logarithmic frequency representation is required. This can be achieved by steppedsine and multisine signals easily.

Further optimization for the requirements of system identification is the criterion of linearity having a small magnitude of the perturbation sequence consequently. Tuning the spectral properties of a multisine signal the maximum value can be optimized using the method called “Frequency domain swapping algorithm” [8], [9]. Other empirical approaches also exist to optimize multispectral signals [10]. Time consuming optimization of the parameters describing the perturbation sequence can be done offline on a PC. Either the optimized signal or the set of parameters is stored in the target application later.

Optimizing criteria of the perturbation sequence are the maximum magnitude and fluctuation. Both of them are improved as the crest factor (CF) of multispectral signals is minimized. The better multisine signals are optimized for the CF the more they behave like a multilevel signal in the time domain having adjusted spectral properties matching the required spectral properties (distribution and magnitudes) at the same time. By limiting the available magnitude levels the optimized multisine signal becomes a binary switching signal.

For binary signals high compression in the data representation allows an offline optimization of the signal properties and save the optimized signal in the program code of the target application. By this approach the effort during perturbation for the software can be reduced to a minimum as the sequence is iteratively used to set the superimposed current to be on or off.

The perturbation of the device under test needs to be realized using a hardware as simple as possible. In embedded applications powerful pulse forming hardware i.e. for sine pulse forming is too complex. The most suitable approach according to the binary switching state signal for excitation is a pulsed current. In combination with a simple switch using one MOSFET and a load resistance a multispectral excitation of a battery can be realized at minimum effort in hardware and software.

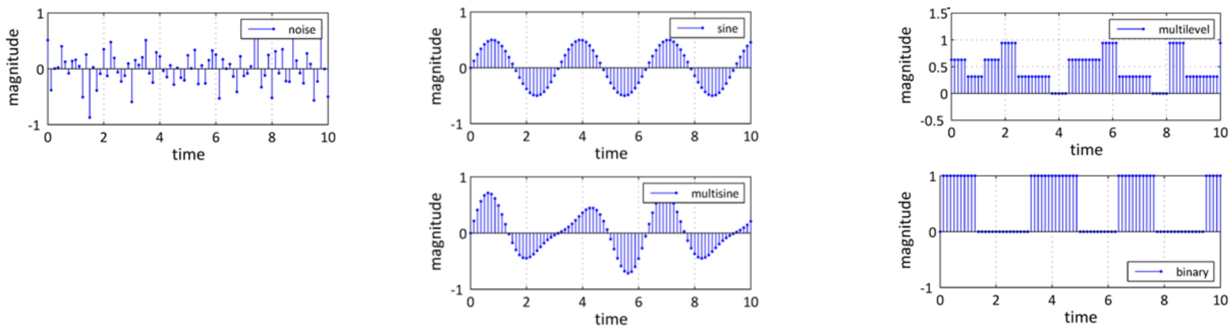

Fig. 1. Commonly used signal types for system identification; noise left, sine based center and amplitude modulated right.

Signal processing

Multispectral signals reduce the overall measurement time by packing the information into parallel information paths, the frequencies. A well-known method to separate the information is the Fourier transformation. For a system of four batteries about 10 MByte of measurement data arise during the measurement. The FFT needs to save and reorder the measured data. Therefore the data analysis using FFT implementation is performed after the measurement only on saved data.

An alternative approach to compute the spectral properties of a signal is the GOERTZEL algorithm[12]. The GOERTZEL algorithm describes an IIR-filter approach to act like a single bin DFT. In the case of a known set of frequencies multiple GOERTZEL filters can be used to detect the frequency components a measured signal.

Further optimization have been found to split the computations needed for the GOERTZEL filter into a recursive part (see Fig. **2**) updated with each new measured value and a feed forward part to correct the phase angle of the calculated spectral property of the tuned frequency. The non-recursive part needs to be calculated only once after the measurement is finished. This approach is called sliding GOERTZEL algorithm [13], [14]. As the frequencies contained in the perturbation sequence are known, domain transformation can be limited to those frequencies.

Tuning the Feedback parameters of the IIR filter the resonant frequency of the filter stage is matched to the frequency of interest. Using filter banks consisting of multiple parallel operating filters tuned to different spectral components a filterbank is constructed. Modern DSP cores with their MAC/SIMD extensions [15] allow fast and efficient transformation of the measurement data from time to frequency domain with low effort in computation time and memory consumption using the filterbank approach.

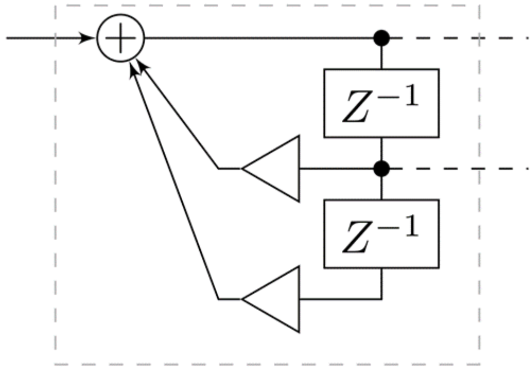

Fig. 2. Recursive part of the GOERTZEL filter acting as single bin dft calculator; the no recursive part is not shown

Comparing both approaches, the FFT and GOERTZEL filter based time to frequency domain transformation the calculated phases as well as the magnitudes show very small relative deviations of less than $5\cdot10^{-5}$. The analyzed multispectral signal has been designed to have equivalent magnitudes of target spectral components with tuned phase angles (see Fig. **3**). The spectral components are shown versus frequency index. The GOERTZEL filter bank approach can be used to perform domain transformation instead of using FFT algorithms consequentially having a reduced effort in memory consumption and a simultaneous calculation of the spectral properties as benefits.

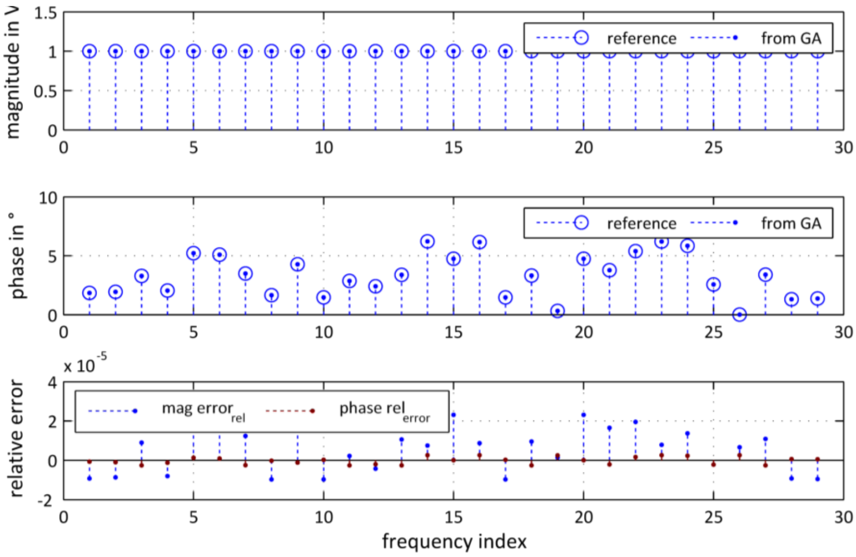

Fig. 3. Comparison of the determined spectral properties of a multisine signal for the FFT(reference) and GOERTZEL(GA) filter bank approach

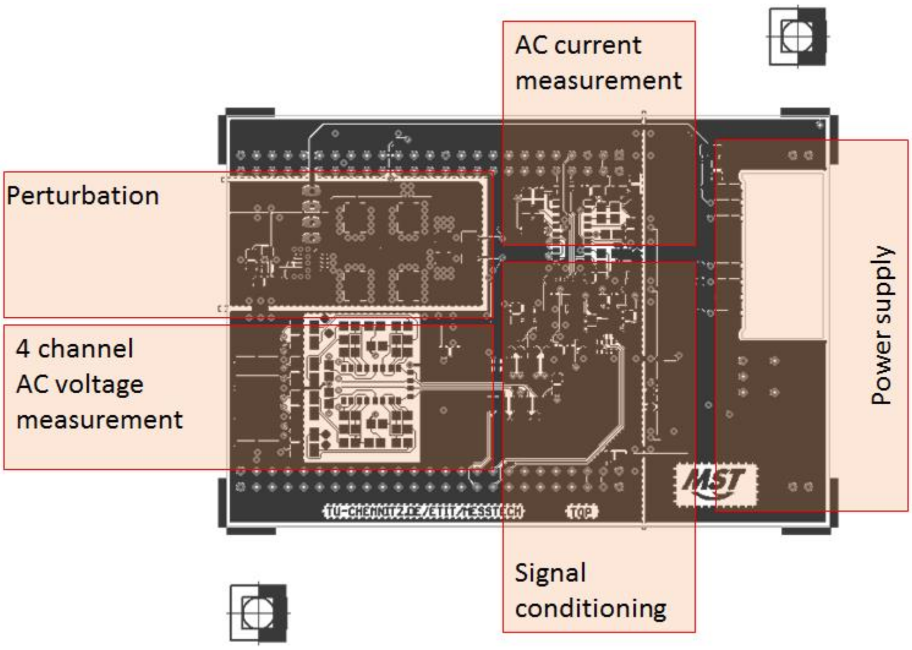

Fig. 4. Developed frontend to perform broadband multispectral impedance measurements using a standard development kit from ST.

Hardware

The developed Hardware (Fig. **4**) covers all required aspects to perform IS measurements for perturbation, measurement, signal conditioning and signal processing. Basis is the STM32f4 discovery board [16].

It provides MAC/SIMD extensions for signal processing, multiple AD-converters as well as integrated timers for controlling the perturbation, channel selection and the measurement. The PCB is designed to be a frontend to the development board performing IS measurement being stacked to it.

Components for perturbation of the batteries connected to this board are placed in the upper left part. A MOSFET is used for discharging the batteries over a current limiting resistor and a shunt for current measurement. The offline optimized binary sequence is used to control the current flow by setting the MOSFET's conduction state. As the batteries are in series, all of them are perturbed simultaneous.

The AC components for both the current and voltages for each cell is decoupled using differential operational amplifiers. Forvoltage measurement an analog multiplexer is used to reduce the number of components for further signal conditioning. This implies programmable amplification and level shift to match the ADC input voltage range of the development board. For current signal conditioning there is no need for a programmable gain as the dynamic range of the current during perturbation is fixed to the cell voltage in contrast to the temperature dependent voltage response of the batteries.

CONCLUSION

The presented approach provides broadband multispectral impedance measurement on a low cost hardware with limited computation power. Key features of the presented approach are: binary sequence for fast and broadband impedance measurement, simple HW for perturbation using a switching MOSFET, no separate current source by using the battery stack as source and DUT at the same time, adapted algorithm for signal processing by using GOERTZEL. Thus i.e. battery management systems can be supported by online measured data describing the dynamic characteristics of batteries.

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REFERENCES

1. C. H. Hamann, W. Vielstich, Elektrochemie. John Wiley & Sons Australia,Limited, 2005, p. 662
2. U. Tröltzsch, O. Kanoun, H.R. Tränkler, *Electrochim. Acta*, **51**, 1664 (2006).
3. P. Büschel, U. Tröltzsch, O. Kanoun, *Electrochim. Acta*, **56**, 8069 (2011).
4. J. Hoja, G. Lentka, *Metrol. Meas. Syst*., **20**, 1 (2013).
5. J. Hoja, G. Lentka, in IMEKO XIX World Congress, (2009), p. 140.
6. http://www.ti.com.cn/cn/lit/wp/spry215/spry215.pdf.
7. R. Pintelon, J. Schoukens, System Identification: A Frequency Domain Approach, 2nd ed. Hoboken, NJ, USA: John Wiley & Sons, Inc., 2012.

8. E. Van der Ouderaa, J. Schoukens, J. Renneboog, *IEEE Trans. Instrum. Meas.*,**37**(2), 207, (1988).
9. M. Schroeder, *IEEE Trans. Inf. Theory* **16**(1), 85 (1970).
10. J. Ojarand, M. Min, P. Annus, *Physiol. Meas.*, **35**(6), 1019 (2014).
11. J. Schoukens, J. Swevers, R. Pintelon, H. Van der Auweraer, *Mech. Syst. Signal Process.*, **18**(4), 727 (2004).
12. G. Goertzel, An algorithm for the evaluation of finite trigonometric series, Am. Math. Mon., 1958.
13. J. F. Chicharo, M. T. Kilani, *Signal Processing*, **52**(3), 283 (1996).
14. Streamlining Digital Signal Processing: A Tricks of the Trade Guidebook. John Wiley & Sons, (2012), p. 480
15. http://www.keil.com/pack/doc/CMSIS/DSP/html/group___f_i_r.html.
16. http://www.st.com/web/catalog/tools/FM116/SC959/SS1532/PF252419.

Мултиспектрални импедансни измервания във вградени системи

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(Резюме)

Базата данни достъпна за системи за управление на батерии (СУБ) е задължителна за установяване на подходящ режим на работа. За сега много-мерни офлайн системи за събиране на бази данни описващи поведението на батериите са основния източник на алгоритмите използвани в СУБ. Импедансната спектроскопия (ИС) за характеризиране на батерии се използва в лабораторията от много години. Тъй като този метод изисква значителни хардуерни и софтуерни усилия, използването на Импедансна спектроскопия беше ограничено до лабораторните приложения. В тази статия е представен подход за предоставяне на онлайн характеризиране с помоща на ИСв подкрепа на СУБ. Разгледани са предизвикателствата свързани с хардуера и обработката на сигнали. Разработеният подход е в състояние да помогне при осъществяването на ИС измервания за всяка от батериите в стак от четири на брой батерии.