
















# Supplementary Materials: Critical Review of Intelligent Battery Systems: Challenges, Implementation, and Potential for Electric Vehicles

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**Table S1.** Overview of investigated publications regarding online EIS, part I of II: Excitation and Signal Acquisition.

Source	Excitation			Signal Acquisition		
	Type	Signal	Actuator	System	AFE	ADC
Alavi et al. [291]	Galvanostatic	Multi-Sine superimposed on an offset	Single quadrant TTI electronic load	NI 6211 Multifunction IO-Device, responsible for data acquisition and controlling the electronic load	CSR as current sensor; undefined voltage sensor; current and voltage are both buffered by a differential amplifier, filtered by a HPF (1 Hz cutoff) and amplified; signals are multiplexed single-ended to a PGA, followed by the ADC inside the data acquisition device	Undefined 1×16 bit consecutively sampling, multiplexed ADC of data acquisition device
Bohlen et al. [269]	Load Current	–	Undefined laboratory battery test bench	Self-developed system based on an undefined MCU, responsible for data acquisition, estimation of Z and evaluation	CSR as current sensor; remainder of channel is undefined	Undefined ADC
Carbonnier et al. [321]	Galvanostatic	Square	Undefined constant current sink/source controlled by a square wave generator	Two separate systems: (1) 2× NI PXIe-4081 for low freq. (2) FPGA based design for high freq.	Undefined voltage and current sensors; signals are amplified, multiplexed and amplified again	(1) 7 1/2-digit DMM at up to 250 S s <sup>−1</sup> (2) 2×16 bit at up to 100 kS s <sup>−1</sup>
Carkhuff et al. [140]	Galvanostatic	Sine	Undefined bidirectional current source	Self-developed system based on an undefined MCU, responsible for excitation and estimation of Z	Current is not measured (excitation is assumed to be accurate); multiplexed voltage measurement of individual cells; HPF followed by a non-inverting amplifier feeding an RMS converter for magnitude estimation and a GPIO of the MCU for phase detection	MCU internal 1×12 bit ADC
Depernet et al. [292]	Galvanostatic	Sine	Bidirectional DC-DC converter with current control (part of the charger)	Self-developed system based on a TI TMS320LF2407A MCU, responsible for excitation, data acquisition and estimation of Z	Undefined voltage and current sensors; digital Attenuator for gain control; DAC and difference amplifier for offset-control; LPF for anti-aliasing	MCU internal 1×10 bit ADC, sampling synchronized with PWM for disturbance rejection; consecutive voltage and current sampling
Din et al. [296]	Galvanostatic	Sine	Bidirectional DC-DC converter with current control (part of a ladder converter for active balancing)	Self-developed system based on a Xilinx Virtex 5 FPGA, responsible for generation and control of PWM, data acquisition and data filtering	CSR as current sensor only measuring balancing/ excitation currents; amplified by two stages and filtered by a 2nd order LPF; digital DC servo-loop circuit to remove DC offset before digitization; 4th order LPF with 100 kHz cutoff	3× (2×12 bit TI ADS7254 SAR-ADC) sampling simultaneously; one chip per cell and one for the cell stack (synchronized by a shared trigger and communication clock)
Ferrero et al. [301]	Galvanostatic	Multi-Sine superimposed on load current	DC-DC boost converter with current control and resistive load (control is implemented in real time unit of SBC)	Self-developed system based on a BeagleBone Black SBC (TI AM3358 Cortex-A8 Processor), responsible for excitation, data acquisition, filtering, estimation of Z and ECM parameter estimation	LEM LA25-P closed-loop Hall current transducer; undefined voltage sensor; undefined LPF & HPF for current and voltage signals; undefined signal conditioning to match ADC specifications	Processor internal 1×12 bit SAR-ADC, sampling voltage and current consecutively
Gong et al. [290]	Galvanostatic	Sine	Hybrid architecture for reduced power dissipation, consisting of an isolated switched mode converter, a linear regulator and an ultracapacitor	ASIC based system (SCS) developed in cooperation with NXP Semiconductors; distributed system for impedance estimation and excitation on a cell level and central measurement of pack current	Sigma-Delta-Modulator as voltage sensor; excitation current is not measured but assumed to be accurate; pack current is measured using a CSR as a current sensor and the AFE of a separate SCS, that is not connected to a cell	1× integrated unspecified Sigma-Delta-Modulator, outputting a bitstream
Hong et al. [303]	Galvanostatic	Sine superimposed on an offset	DC-DC boost converter with current control and resistive load	Self-developed system based on an undefined MCU, responsible for excitation and data acquisition	CSR as current sensor; undefined voltage sensors for simultaneous measurement of series connected batteries	Undefined ADC
Howey et al. [207]	Galvanostatic	White noise & Multi-Sine superimposed on load current	Motor controller in current control mode	NI 6211 Multifunction IO-Device, responsible for excitation and data acquisition	CSR as current sensor; two stage amplification for voltage and current; HPF with 1 Hz cutoff frequency between stages; total gain of frontend is 100	Undefined 1×16 bit consecutively sampling, multiplexed ADC of data acquisition device
Koch et al. [299]	Galvanostatic	Triangle	Bidirectional DC-DC converter with current control (part of the charger)	Self-developed system based on dsPIC33EP DSP and a STEVAL-IHM011V1 evaluation kit, responsible for excitation and data acquisition	Undefined current and voltage sensors; signals are filtered by an active 4th order Butterworth filter with cutoff at 16 kHz	2×16 bit MCP3903 delta-sigma ADC, sampling simultaneously; sampling is synchronized with PWM for improved disturbance rejection
Liebhart et al. [112]	Load current	–	Keysight RP7942A regenerative power system (for emulation of driving current)	NI CompactDAQ data acquisition system, responsible for measuring current, voltage and temperature	LEM LA 55-P/SP1 Hall current transducer with current output, digitized by NI-9203; cell voltage digitized by NI-9239	ADCs of CompactDAQ modules, 4×16 bit for current and 4×24 bit for voltage sensing with at least 25 kS s <sup>−1</sup>
Lohmann et al. [308]	Load current	–	Electronic load in a self-developed cell tester with linear and switched mode excitation	Self-developed single cell tester based on an undefined 32bit MCU (commercially available as EISmeter)	CSR as current sensor; remainder of channel is undefined	Undefined 1×18 bit consecutively sampling ADC for acquisition of current and voltage signals
Moore et al. [302]	Galvanostatic	Multi-sine	Bidirectional DC-DC converter and resistive load	NI USB 6366 data acquisition device, responsible for excitation and data acquisition	Undefined LEM Hall module as current sensor; current and voltage are filtered by a 4th order Butterworth LPF to reduce switching frequency components of actuator	Undefined 2×16 bit ADCs of data acquisition device for current and voltage
Nguyen et al. [300]	Galvanostatic	Sine	Bidirectional DC-DC converter with current control (part of the charger)	Self-developed system based on a TI TMS320F28335 DSP, responsible for excitation, data acquisition and estimation of Z	Undefined current and voltage sensors	DSP internal 1×12 bit pipelined ADC, sampling current and voltage consecutively
Piret et al. [305]	Galvanostatic & load current	PRBS & load current	BioLogic VMP3 potentiostat for generating the PRBS	Oros OR36 data acquisition device, responsible for data acquisition	CSR as current sensor; remainder of channel is undefined	Undefined 2×24 bit simultaneous sampling ADCs of data acquisition system for voltage and current

Source	Type	Signal	Actuator	System	AFE	ADC
Qahouq et al. [304]	Galvanostatic	Approx. exponential pulse superimposed on load current	Closed-loop buck-boost DC-DC converters with voltage control and capacitive load; two in series with inverse phase to cancel out each other's ripple	Self-developed system based on TI TMS320F28335 DSP, responsible for excitation and data acquisition	Undefined current and voltage sensors	DSP internal 1×12 bit pipelined ADC, sampling current and voltage consecutively
Roscher et al. [310]	Load current	–	–	Self-developed distributed system based on a TI MSP430F235, responsible for measuring cell voltage and estimation of Z; synchronization is provided by a radio signal; CECU measures current centrally and broadcasts data to LECUs	Undefined current and voltage sensors; remainder of channel is undefined	MCU internal 1×12 bit SAR-ADC
Sihvo et al. [295]	Galvanostatic	PRBS	Undefined electronic load	NI USB-6363 data acquisition device, responsible for excitation and data acquisition	Testec HV differential probe as voltage sensor; Tektronix clamp-on current probe as current sensor	Undefined 2×16 bit ADCs of data acquisition device for current and voltage
Sockeel et al. [306]	Load current	–	–	Undefined system, responsible for data acquisition	Undefined current and voltage sensors; remainder of channel is undefined	Undefined ADCs, sampling at $20\text{ S s}^{-1}$
Wang et al. [154]	Galvanostatic	Sine	Class A amplifier used as a controllable current source	Self-developed system based on an undefined MCU, responsible for excitation, data acquisition and estimation of Z	CSR as current sensor; undefined voltage sensor and signal conditioning	MCU internal ADCs of undefined resolution for voltage and current
Wei et al. [311]	Galvanostatic	Sine	DC-AC converter with current control based on a full-bridge	Self-developed distributed system consisting of one CECU and many LECUs, connected via CAN; local voltage measurement and estimation of Z; central current measurement (CECU); LECU is based on a TI TMS320F2812 DSP	CSR as current sensor; cell voltage and current are amplified by unspecified differential amplifiers	LECU: 6×18 bit ADI AD7608 bipolar SAR-ADC, sampling all channels simultaneously; CECU: Undefined ADCs
Yokoshima et al. [320]	Galvanostatic	Square superimposed on load current	Power controller of energy storage system	DT9837 data logger, responsible for excitation and data acquisition	Undefined voltage and current sensors; remainder of channel is undefined	Undefined 2×24 bit ADCs of data acquisition device, sampling simultaneously

**Abbreviations:** Z=Impedance; DFT=Discrete Fourier transform; FFT=Fast Fourier transform; PRBS=Pseudorandom binary sequence; CSR=Current sense resistor; MCU=Microcontroller unit; DSP=Digital signal processor; CECU=Central electronic control unit; LECU=Local electronic control unit; SBC=Single board computer; SCS=Single cell supervisor; FPGA=Field programmable gate array; HPF=High-pass filter; LPF=Low-pass filter; BPF=Band-pass filter; CIC=Cascaded integrator-comb; OTP=One time programmable; DLIA=Digital lock-in amplifier; GPIO=General-purpose input/output; PWM=Pulse-width modulation, CAN=Controller Area Network

**Table S2.** Overview of investigated publications regarding online EIS, part II of II: Evaluation and Setup.

Source	Evaluation			Setup		
	Preprocessing	Postprocessing	Computation Device	Cell Type	Frequency Range	Validity Check
Alavi et al. [291]	–	Time domain fitting of a fractional model for direct ECM parameter estimation	Computer	A123 Systems 26650 Li-Ion LFP 2.3 Ah	1 Hz - 2 kHz	Comparison to results of a Bio-Logic VSP
Bohlen et al. [269]	Digital BPFs for frequencies of interest	Correlation-based estimation of Re(Z); estimation of ECM parameters for prediction of cranking capability	MCU	Undefined Lead Acid	–	Check of predicted cranking capability
Carbonnier et al. [321]	–	FFT based estimation of magnitude and phase of harmonics of excitation; estimation of Z from FFT data	Computer	Sony 18650HC Li-Ion	10 mHz - 10 Hz	–
Carkhuff et al. [140]	–	Phase is measured using an MCU internal 16 bit timer; magnitude of Z is calculated from RMS value of response	MCU	Swing 5300 2 × MR18650 Li-Ion 5.3 Ah	1 Hz - 1 kHz	–
Depernet et al. [292]	Gain and offset adjustment, single frequency DFT	PSD based estimation of Z	MCU	VRLA AGM Lead Acid 12 V 100 Ah	0.32 Hz - 1024 Hz	Comparison to results of a Zahner IM6 spectrometer
Din et al. [296]	Variable down sampling to a fixed number of points per perturbation period using a CIC decimation filter, allows to use the same processing to extract Z at all frequencies; FIR filtering & truncation to minimize effect of startup transients	IQ demodulation and low pass filtering to extract magnitude and phase relationship of Z	Computer	Panasonic NCR18650B Li-Ion NCA 3.4 Ah	25 mHz - 7.66 kHz	Comparison to results of a Gamry Reference 3000
Ferrero et al. [301]	Frequency dependent moving average for down sampling, implemented in real time unit of processor; least square fitting in time domain to compensate for the linear drift of cell voltage	Estimation of Z from FFT data; averaging and calculation of standard deviation of Z; standard deviation is used as a measure of uncertainty /quality metric	SBC	12 V 7 Ah Lead Acid	98 mHz - 6.25 Hz	–
Gong et al. [290]	Filtering of bitstream (from Delta-Sigma-Modulator) to extract DC-component and real and imaginary part of the AC-component; demodulator uses the excitation sine as reference for very narrow filter bandwidth, reducing interference from drive currents; offset and gain compensation using factory calibration data from OTP memory; compensation of die temperature	Impedance is estimated by an unspecified method	Computer	6s4p of pouch cells NMC 44 Ah	2 Hz - 2 kHz	Comparison to results obtained with an oscilloscope
Hong et al. [303]	Impedance is estimated by an unspecified FFT based technique	Fitting of an ECM using Zview Test software	Computer	24s5p of LMO 35 Ah	1 Hz - 1 kHz	Comparison to theoretical results
Howey et al. [207]	Undefined windowing of time domain data; DFT of frequencies of interest	PSD based estimation of Z; spectral coherence is used as a quality metric; compensation of passive filter networks in frequency domain	Computer	A123 Systems ANR26650M1A LFP 2.3 Ah	1 Hz - 2 kHz	Comparison to results of a Bio-Logic VSP potentiostat
Koch et al. [299]	–	FFT based estimation of Z	Computer	Samsung ICR18650-30A LCO/NCM 3 Ah	10 mHz - 5 kHz	Comparison to results of a Digatron EISmeter
Liebhart et al. [112]	Compensation of sampling delay between current and voltage; segmentation, windowing using Hamming function and FFT of all segments is computed	PSD based estimation of Z, averaging across segments; spectral coherence is used as a quality metric	Computer	1s4p of Samsung INR18650-25R NMC 2.5 Ah	10 Hz - 12.5 kHz	Comparison to results of Zahner Zennium Pro; Lin-KK test is performed
Lohmann et al. [307]	Windowing & zero-padding for increased frequency resolution	FFT based estimation of Z	Computer	Prismatic LMO/NCM 20 Ah	10 mHz - 1 kHz	Lin-KK & comparison to results of EIS equipment
Moore et al. [302]	–	FFT based estimation of Z	Computer	EIG20Ah C020 Pouch cell NCM 20 Ah	50 mHz - 2 kHz	Comparison to data acquired with an electronic load as excitation source
Nguyen et al. [300]	Phase and magnitude of response are extracted by a DLIA, estimation of Z in the DSP	ECM Parameters are estimated using complex nonlinear least squares method (Levenberg-Marquardt algorithm) applied to Z on the DSP	DSP	Delkor DF80L Lead Acid 12 V 80 Ah	0.1 Hz - 1 kHz	Comparison to results of a Korea Kumho BPS instrument
Piret et al. [305]	Band-stop filtering at 50 Hz and its odd multiples to remove mains interference	PSD based estimation of Z; spectral coherence is used as a quality metric; averaging by exponential average (IIR) is performed; forgetting factor is coupled to coherence	Computer	3s1p Battery pack LiPo 2.2 Ah	20 Hz - 90 Hz	Comparison to results of a BioLogic VMP3
Qahouq et al. [304]	–	Unspecified DFT based estimation of Z	Computer	Tenergy 30005-0 (18650) LCO 2.6 Ah	10 Hz - 9 kHz	Comparison to results of a Keysight E4990A impedance analyzer
Roscher et al. [310]	Voltage data from each cell is collected by CECU; compensation of sampling delay between current and voltage	Estimation of Z by an undefined method on the CECU	MCU of CECU	A123 Systems ANR26650M1-B LFP 2.5 Ah	< 1 Hz - 1 kHz	Comparison to results of a commercial impedance spectrometer

Source	Preprocessing	Postprocessing	Computation Device	Cell Type	Frequency Range	Validity Check
Sihvo et al. [295]	–	Fourier based method for estimation of impedance (not further specified)	Computer	Battery pack NMC 36 V 2.6 Ah	(1) 0.1 Hz - 102.3 Hz for low freq. PRBS (2) 11.7 Hz - 5 kHz for high freq. PRBS	Comparison to a reference EIS-measurement recorded with a network analyzer using a sine-sweep
Sockeel et al. [306]	Windowing using Hamming function; PSD based estimation of Z; squared spectral coherence is used as a quality metric; exponential averaging of Z	Estimates coefficients of transfer function; partial fraction decomposition is performed; parameter estimation for multiple orders (RC) of the ECM; selects order with least RMSE for further investigation	Computer	A123 Systems 7 × 15s2p of AMP201HD-A LFP 19.6 Ah	< 10 Hz	–
Wang et al. [154]	–	Extracts amplitude and phase of voltage and current from their respective min. and max. values for estimation of Z	MCU	Undefined Prismatic LFP 8 Ah	0.1 Hz - 200 Hz	Comparison to results of a Solartron 1287/1255B & a Toyo Seiki PBi250-10
Wei et al. [311]	DLIA to extract magnitude and phase of voltage signal	Relative impedance of cells is calculated to monitor consistency of the cells; estimation of Z on LECUs to reduce load on main BMS and CAN (current data is broadcasted to LECUs)	DSP of LECU	Undefined Prismatic LFP 8 Ah	0.1 Hz - 500 Hz	Comparison to results of an unspecified electrochemical impedance workstation
Yokoshima et al. [320]	Segmentation with overlap	PSD based estimation of Z; calculation of moving average of Z	Computer	11 kWh Energy storage system (240 cells in total)	50 mHz - 2 kHz	Comparison to a reference EIS-measurement

**Abbreviations:** Z=Impedance; DFT=Discrete Fourier transform; FFT=Fast Fourier transform; PRBS=Pseudorandom binary sequence; CSR=Current sense resistor; MCU=Microcontroller unit; DSP=Digital signal processor; CECU=Central electronic control unit; LECU=Local electronic control unit; SBC=Single board computer; SCS=Single cell supervisor; FPGA=Field programmable gate array; HPF=High-pass filter; LPF=Low-pass filter; BPF=Band-pass filter; CIC=Cascaded integrator-comb; OTP=One time programmable; DLIA=Digital lock-in amplifier; GPIO=General-purpose input/output; PWM=Pulse-width modulation; CAN=Controller Area Network

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