Review of Power Converter Topologies for Electrochemical Impedance Spectroscopy of Lithium-Ion Batteries

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Keywords

≪Battery≫, ≪Condition Monitoring≫, ≪Impedance Measurement≫, ≪DC-DC Converters≫, ≪DC-AC Converters≫.

Abstract

Frequency domain impedance of Li-ion batteries contains valuable information about the state of charge (SOC) and state of health (SOH). Normally, electrochemical impedance spectroscopy (EIS) is performed during the relaxation of battery cells. However, performing EIS during the batteries operation has been achieved through switching power converters. This paper reviews the power converter topologies for both online and offline Electrochemical Impedance Spectroscopy (EIS) characterization of batteries. The information that can be extracted from EIS Nyquist plots are discussed. Comparative analysis between converter topologies is presented. Finally, challenges are identified and new converter topologies are proposed for further consideration in online/offline EIS characterization.

I. Introduction

The demand for battery storage systems is increasing in many applications and precise parameter estimation is essential for optimal use of the remaining battery capacity. Even though machine learning

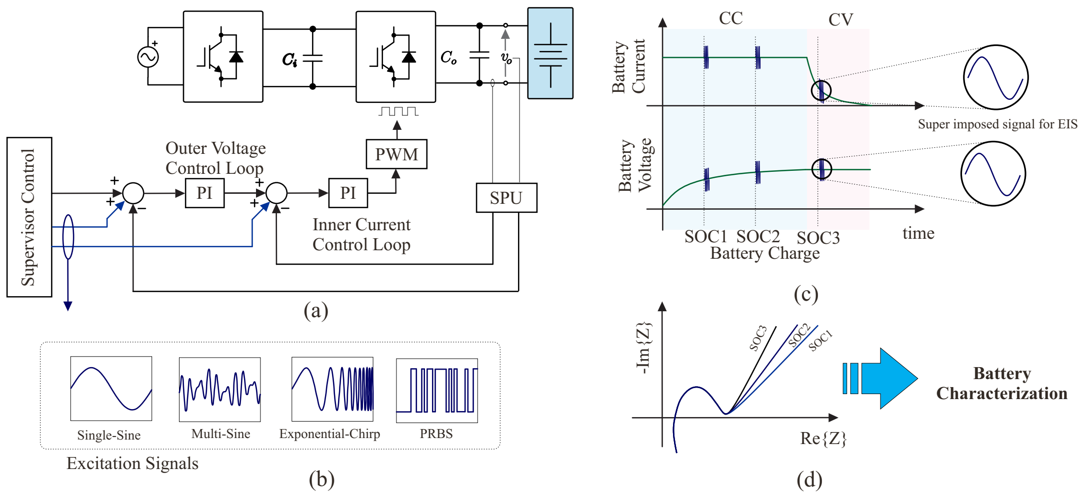


Fig. 1: Concept of EIS through power electronic converters: (a) circuit and control topology, (b) excitation signals, (c) superimposed signals, and (d) extracted EIS results

(ML) techniques significantly improve the parameter estimation of batteries, nevertheless, the capacity fade is quite nonlinear and regular adjustments of the estimator algorithms are required. Electrochemical Impedance Spectroscopy (EIS) is proven to be an effective and comprehensive measurement technique to supply the required data for adjusting the estimator's parameters [1, 2].

Normally, EIS is achieved using linear amplifiers [3] when the battery is relaxed. Therefore, a high-precision EIS can be performed in laboratory environment [4]. Conversely, battery storage systems are interfaced with a load/grid by power electronic converters in the respective applications of electric vehicles (EVs) and stationary storage systems. Power electronic converters have sufficiently flourished in the last decade both in terms of topology and semiconductor technology. On one hand, modular and non-modular converter topologies have emerged in many applications, on the other hand, wide bandgap semiconductor technologies such as SiC and GaN can reach high switching frequencies without sacrificing efficiency. These advancements make power converters a promising tool for performing EIS. However, power converters are not adequately developed for EIS purposes [5]. A comprehensive review is required to unveil the obstacles and draw a road-map for developing EIS as an embedded function in power converters. Although reviews on the state-of-the-art of EIS methodologies are present (see for example [6]), a comprehensive perspective and road-map is still missing.

This paper reviews the current status and addresses the challenges and future developments of power electronic converters for EIS. Frequency-dependent electrochemical behavior of batteries, power converter topologies, control strategies, and signal processing for EIS are compared. Challenges originated from application types are identified at battery cell, module and pack levels. New possibilities to obtain online EIS by power electronic converters are described such as partial power processing, isolated multiport and modular topologies.

II. Principles of EIS and Applications

Conventionally, EIS is done by applying a periodic signal current with known frequency contents and measure its voltage response where the Li-ion battery impedance is defined by $Z(\omega) = \frac{V(\omega)}{I(\omega)}$. Excitation signals are applied to the battery through a linear amplifier [3] while the battery is relaxed (i.e. disconnected from source/load) to achieve EIS. Switching power semiconductors can also be used for EIS as shown in Fig. 1 [5]. Subfigures (a) to (d) show a conventional control strategy, excitation signals, voltage and current profile during charging, and EIS graph, respectively. The signal processing unit (SPU) measures current and voltage, filters and converts signals, and extracts $Z(\omega)$ for battery characterization in the controller.

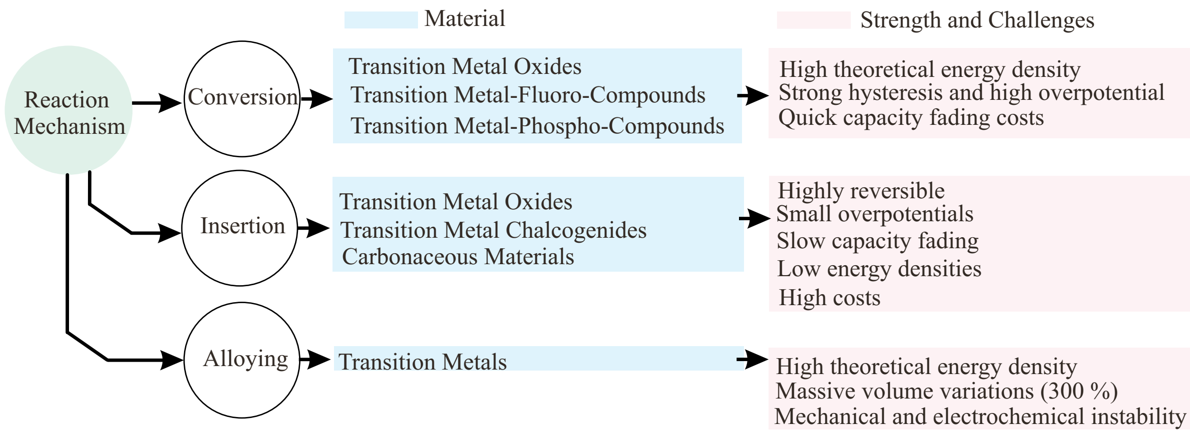


Fig. 2: Different reaction mechanisms, possible battery material and characteristics.

II.1 Electrochemistry

The electro-chemical response of batteries to an excitation depends on their individual chemistry which can be characterized by $Z(\omega)$ obtained from EIS. Li-ion batteries work following the three main reaction mechanisms insertion, conversion and alloying. Insertion reactions allow the accommodation of Li-ions within a host material, whose crystalline structure does not change significantly with the lithium content. In general, insertion reactions are highly reversible, and show very little overpotential and slow capacity fading [7]. Conversion reactions, are displacement reactions where the lithium ions take the place of a species of a binary compound [8]. This kind of reaction mechanism leads to the formation of new phases and it is often characterized by a strong hysteresis in the charge/discharge profile and by a quick capacity fading [9]. Alloying reactions involve a significant change of the original microstructure of the electrode, thus leading to the formation of new phase(s) in dependence of the lithium content (and therefore the potential applied to the electrode) [8]. Metals such as Si, Sn and Sb working through alloying mechanism are typically used as negative electrodes (i.e. anodes) in a Li-ion battery, and upon cycling they go through massive volume variations, higher than 300 % [8, 10]. Fig. 2 summarizes the reaction mechanisms along with their involved materials and advantages/disadvantages.

II.2 EIS Measurement

It is shown in [11] that EIS and other measurement techniques are identical and EIS provides more comprehensive results. Fig. 3 (a) shows the DC pulse test where different components of the resistance inducing from electronic and ionic resistances, charge transfer resistance, and polarization resistance which are shown by R_O, R_{CT}, and R_P respectively. These variables can be also directly obtained from the EIS impedance map as depicted in Fig. 3 (b). Moreover, conventional AC tests which are mainly carried out 1 kHz can be considered as a subset of EIS. Therefore, EIS is the most comprehensive impedance characterization technique for batteries.

A correct measurement of EIS requires special care about battery cell connections as well as the signal to noise ratio (SNR) and the nonlinear behavior of the battery cell. To minimize the error and avoid extra impedance of the connections, the EIS device shall be as close as possible to the battery [18]. Usually, a 4 terminal connection or Kelvin connection results in minimum external impedance [19] at cell level. An optimum current excitation should results in 10 mV voltage amplitude [20]. This selection is a trade off between SNR and non-linearity of the electrochemical reaction as illustrated in Fig. 3 (c). To achieve this voltage amplitude, excitation current should be applied considering the internal impedance of the battery. Fig. 3 (d) shows the required excitation current for NiMnCo (NMC) chemistry versus different battery capacities. It can be observed that the required excitation current amplitude increases linearly proportional to the battery cell capacity.

II.3 EIS Applications

EIS can be used for many purposes in the BMS and as well as battery analysis and modeling [21]. Normally EIS is performed when the cell is relaxed and the Gibbs energy approaches its minimum [22].

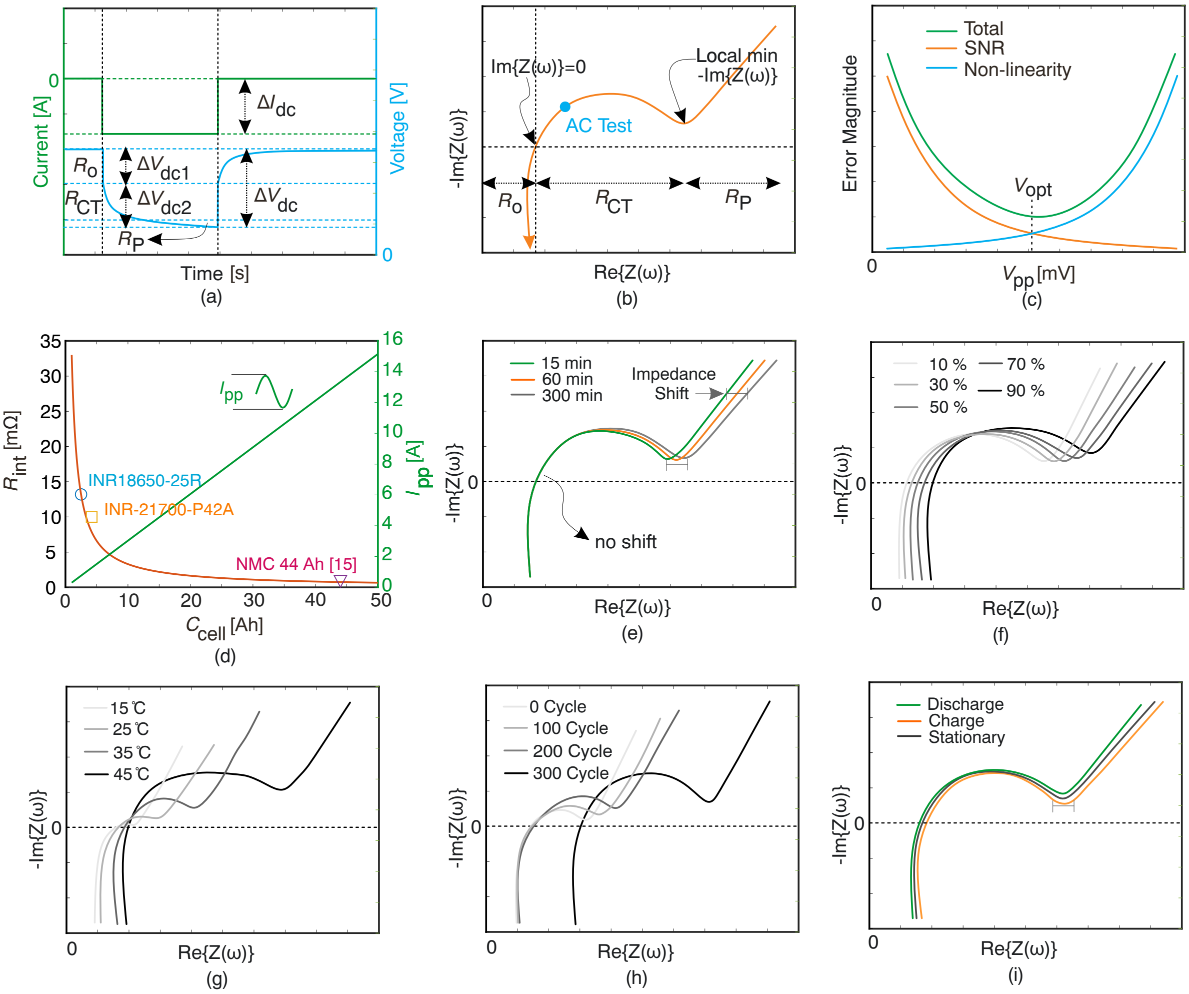


Fig. 3: EIS measurement: (a) DC pulse current for measuring the internal impedance [11], (b) EIS graph in complex coordinate system and an exemplary AC test point [11], (c) optimum voltage magnitude as a compromise between SNR and nonlinearity, (d) required excitation current for Li-ion NMC chemistry, (e) effect of the rest time on the EIS [12, 13], (f) SOC influence on the NMC cell impedance spectra at the same temperature [14], (g) deformation of the EIS Nyquist as a function of the temperature [14], (h) aging of the NMC cells [15, 16], and (i) DC offset during online EIS can displace the EIS Nyquist plot depending on the cell being charged or discharged [17].

Duration of the rest time causes an impedance shift to the right side at lower frequencies around 1 Hz [12, 13]. However, at high frequencies near 1 kHz, the impedance behaves independent to the rest time. The effect of the rest time on the EIS Nyquist plot is shown in Fig. 3 (e).

A preliminary requirement of any BMS is the SOC estimation [23]. Conventionally, EIS data are fitted to an equivalent circuit model (ECM). If EIS is performed online, then the equivalent circuit can be used for online SOC and SOH estimation employing Kalman filter techniques [1, 24–27]. A review of SOC estimation techniques can be found in [23, 28]. Impacts of the SOC on the EIS Nyquist plot are shown in Fig. 3 (f) [14]. There is a shift toward right side and up as the SOC increases. The impedance spectra become more irregular at SOC equal to 0 and 100 %. Battery impedance highly depends on the battery temperature and therefore it should be considered in SOC estimation. EIS Nyquist plots easily reflect this dependency and specially at low temperature the shape of the graph deforms such that the charge transfer region disappears gradually (see Fig. 3 (g)) [2].

Similar to SOC, variation of the EIC spectra during the aging of an NMC cell is shown in Fig. 3 (h) [15, 16]. Aging not only shifts the spectra toward the up right side of the complex plain but also deforms the shape of the Nyquist plot at particularly low frequencies. And finally, online EIS or dynamic EIS spectra differ from the stationary EIS due to the DC offset and as well as zero rest time [17]. Depending

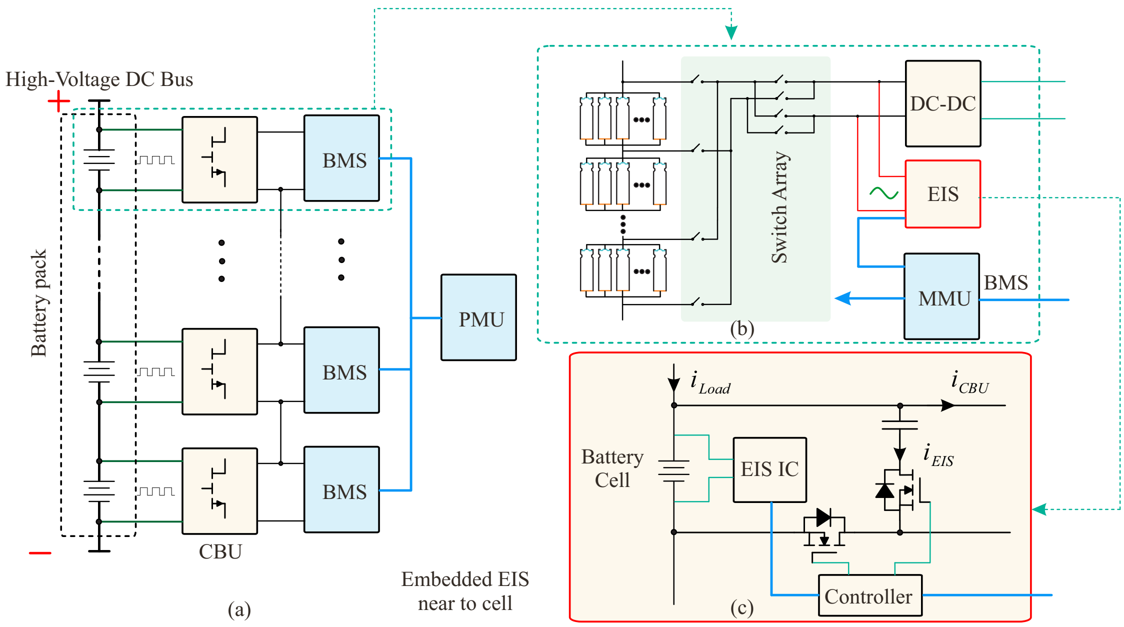


Fig. 4: Online EIS Implementation at cell level [18]: (a) battery pack structure of an EV, (b) battery module and its BMS including EIC subsystem, (c) Circuit topology enabling online EIS

on the state of the cell operation (charging/discharging) the EIS spectra can be slightly higher/lower than that of stationary EIS as demonstrated in Fig. 3 (i). It can be concluded that EIS is a solution for monitoring and state estimation of lithium ion batteries.

III. Power Converter Topologies

EIS can be done by BMS or power converter. The general structure of a battery pack comprising of multiple battery modules each equipped with a BMS is depicted in Fig. 4 (a). Fig. 4 (b) demonstrates how online EIS can be implemented as close as possible to the battery cell [18] to minimize the unwanted additional impedance. An integrated circuit (IC) for online EIS is proposed in [18] and is shown in Fig. 4 (c). Since EIS might be carried out at very short time intervals, the required high current can be provided by a supercapacitor. In [29], an online EIS embedded in the BMS is proposed using minimal hardware where the importance of the correct measurement and signal processing is highlighted. Nonetheless, the proposed method is implemented into the passive cell balancing and its utilization in the active cell balancing still remains questionable.

Normally, a battery pack can be connected to grid or the drive train of EVs using a power electronic converter which might comprise of one or multiple conversion stages. DC-AC and DC-DC converters are frequently used as excitation sources for EIS as well as conversion stages. Also, power electronic converters can be separately used to excite batteries for EIS as shown in Fig. 5 (a). Galvanic isolation is required in many battery storage applications and isolated DC-DC converters can be used for EIS as in Fig. 5 (b) [30]. The AC-DC converter in Fig. 5 (c) achieves EIS by superimposing the excitation signals on the controller reference [31]. Similarly, different non-isolated DC-DC converters perform EIS as shown in Fig. 5 (d) to (g) [5, 32–35]. Most of these researches are focusing on performing EIS on one cell, which limits their usage in a grid or EV battery application. Moreover, the possibility to scale up the proposed EIS to module or pack level is not clarified. Table I provides a brief overview of power electronic converters used for EIS.

In [32], the EIS excitation signal is added to the modulation directly in a feed-forward mode. This strategy might result in instability for high excitation currents comparable to converter rated current. Injecting excitation signal through converters reference signals is the most common way in the literature.

VI. Challenges and Opportunities

This section describes the associated challenges and opportunities with EIS.

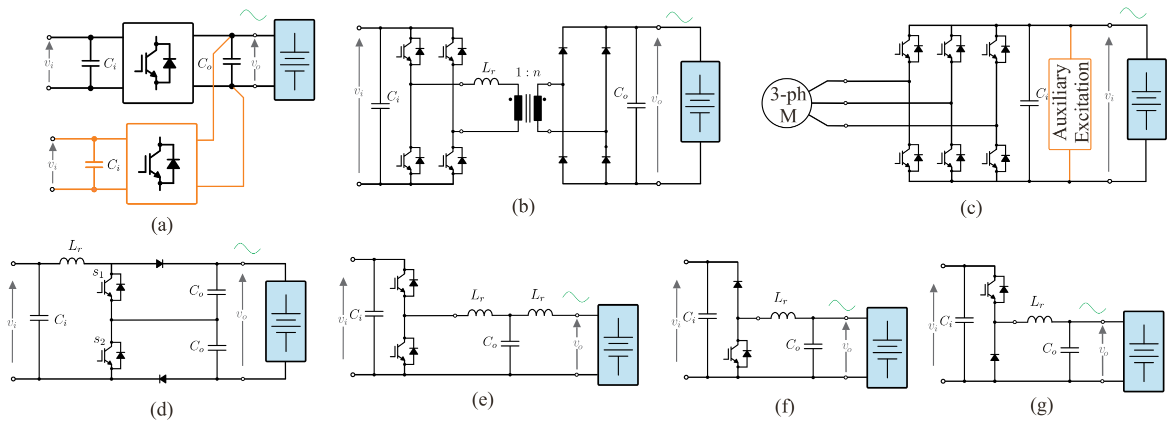


Fig. 5: Converter topologies: (a) separate excitation concept, (b) full-bridge, (c) three-phase drive, (d) three-level DC-DC, (e) synchronous, (f) boost, and (g) buck converters.

VI.1 Challenges in EIS Measurements

EIS has a challenging nature as a consequence of its sensitivity to many parameters as discussed. From measurement point of view, offline EIS is operated after relaxing the battery cell. EIS at low frequency signals in range of mHz is time consuming. Therefore, EIS can only be done in fewer occasions during the battery operational life. Conversely, for online EIS, the accuracy might be impacted and the power converter design and control become complex [36, 37]. Moreover, impedance measurement behind the internal voltage is challenging in comparison to a passive component, because the impedance is very small and needs a large injected current to raise the voltage across the impedance to an acceptable signal-to-noise ratio (SNR) [4].

From the hardware point of view, EIS of battery packs and modules where many cells are connected in series and parallel is challenging. Even if the EIS is isolated from the rest of the cells, the paralleled cells result in smaller sensible voltage rise and consequently a high amount of AC current is required [37]. The extra impedance of terminals, connections and cell balancing system impact on the measured impedance. Therefore, the EIS unit must be as close as possible to cells.

Another main challenge is the sensitivity of the battery cell impedance to operating conditions. The EIS graph changes versus temperature, SOC and SOH and suitable estimation methodologies are required to extract the correct information from the acquired EIS [26].

VI.2 Challenges of EIS Implementation in Power Converters

The mostly used power converters for EIS are non-isolated DC-DC converters owing to their simplicity and minimal requirements. Nevertheless, applying a variable voltage and current to the battery might impact the consumer. Therefore, extra circuits are required for compensating the impact of online EIS [38].

Table I: Comparison of converter topologies for EIS.

Ref.	Converter type	EIS level	Signal Type	Scalability	N. Semiconductors
[5]	DC-DC Synchronous	Cell	Control Ref.	No	2
[18]	DC-DC Cuk	Cell	Control Ref.	Yes	2
[29]	DC-DC Chopper	Cell	Control Ref.	Yes	1
[31]	AC-DC 3-phase	Pack	Multisine/Noise	Yes	6
[32]	DC-DC 3-level Boost	Module	Feed-forward	No	2
[33]	DC-DC Synchronous	Cell	Control Ref.	No	2
[34]	DC-DC Boost	Cell	Control Ref.	No	1
[35]	DC-DC Buck	Cell	Control Ref.	No	1
[36]	Ladder Converter	Module	Control Ref.	Yes	$n+1$ per n cells

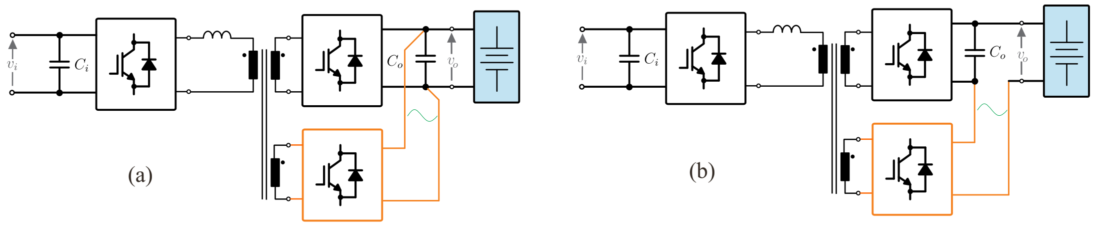


Fig. 6: EIS using isolated multiport DC-DC converters: (a) parallel connection and (b) serial connection.

EIS usage has been limited to laboratory as well as low voltage applications [4]. While in EVs, the pack voltage can be higher than 800V [39] and high voltage converters are required for excitation of EIS. Imposing an AC signal on the base DC current, increases the peak current level in the switches and batteries and therefore the used semiconductors might be overrated.

For a cell connected inside the battery pack, online EIS is influenced by the connected circuits and thereby the measured results need to be compensated [36] or extra circuitry must be utilized to isolate each cell during EIS as in [18]. Since the degradation of the cells could be different, the most promising way is to apply EIS to individual cells or parallel connected cells in modules which results in higher final cost of the product.

Emerging battery technologies, such as solid-state silicon batteries in [40], easily achieve 20 C-rate without significantly losing capacity after 20,000 cycles. Therefore, such a battery storage can be charged and discharged 10 times per hour which leads to maximum 14,400 cycles per year. In such a system, reliability of the power electronic converter becomes a concern rather than the battery itself due the large thermal cycling stress imposed on the semiconductors.

VI.3 Opportunities

Emerging WBG devices allow for high frequency switching without sacrificing the efficiency. Therefore, EIS can be achieved to reasonably high frequencies in the range of hundreds of kHz for a short period of time. Combined with signal processing techniques, up to MHz can be obtained. The AC excitation unit for EIS can be separated from the charging unit. Such a topology can be realized by partial processing converters with maximum efficiency and power density [41, 42].

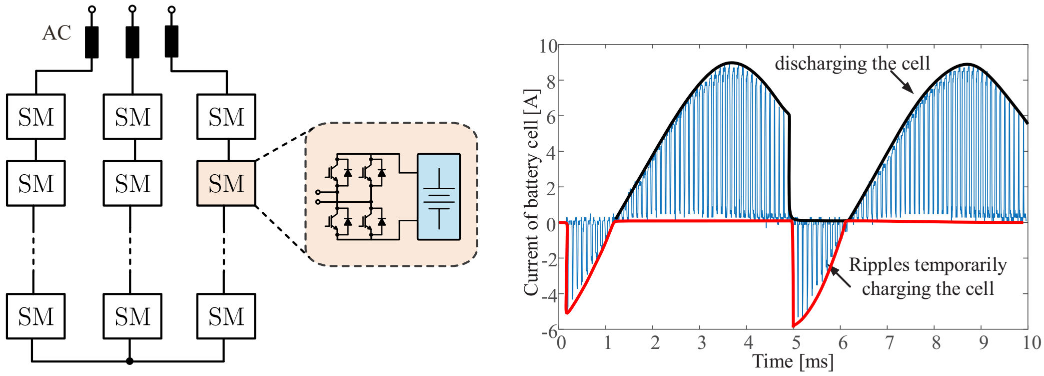
Galvanic isolation is mandatory in many battery storage applications. In isolated topologies, multiport isolated DC-DC converters provide numerous advantages for realizing online/offline EIS with minimum required components and highest possible safety and fault tolerance [43]. Fig. 6 shows possible configuration of multiport isolated converters for conducting EIS.

Lithium batteries are sensitive to temperature variation. In such a case, multiport isolated topologies can be utilized to achieve electrochemical-thermal impedance spectroscopy as the AC component can implement internal heating and therefore an external heater can be omitted [44].

Modular and multilevel converter topologies [45], such as modular multilevel converter (MMC) and cascaded H-bridge (CHB), can contribute to the field by implementing independent EIS function in the sub-modules with minimum interaction with nearby sub-modules. For instance, a CHB converter can be used as an EV drive train which has a charging/discharging current containing both low and high order harmonics as shown in Fig. 7. Since the same current flows through all the cells, EIS can be achieved utilizing suitable voltage measurement and signal processing unit for each cell [46].

V. Conclusion

Electrochemical impedance spectroscopy (EIS) techniques extract the frequency domain features of the device under test. The frequency response of Li-ion batteries contains SOC and SOH information which can be strongly used in condition monitoring and improved state-estimation of batteries. This paper reviews the literature on power electronic converters used for EIS, especially for Li-ion batteries. Moreover, a brief explanation of the EIS Nyquist plots which can be used in battery parameter estimation are presented for NMC chemistry. Comparative studies among different converter topologies are carried



(b) (b)

Fig. 7: CHB converter operation for EV application: (a) topology, (b) current waveform containing hamonics which can online EIS [46].

out. Challenges and opportunities for utilizing power converters as EIS perturbation source are outlined. Multiple issues of the already utilized converters are addressed. New multifunctional converter topologies are introduced which can improve the performance of EIS by implementing internal heating and EIS of Li-ion batteries in the same time.

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