Table 1. Li-ion battery models comparison

Models	Accuracy	Complexity	Physical interpretability	Suited application
Physical	Very high +++	High (> 50 parameters) –	High ++	Battery system design stage
Empirical	Medium -	Low (2–3 parameters) –	Low –	Predictions of life time and efficiency
Abstract	Medium -	Medium to low (from 2 up to 30) +	Limited to acceptable +	Real-time monitoring and diagnosis

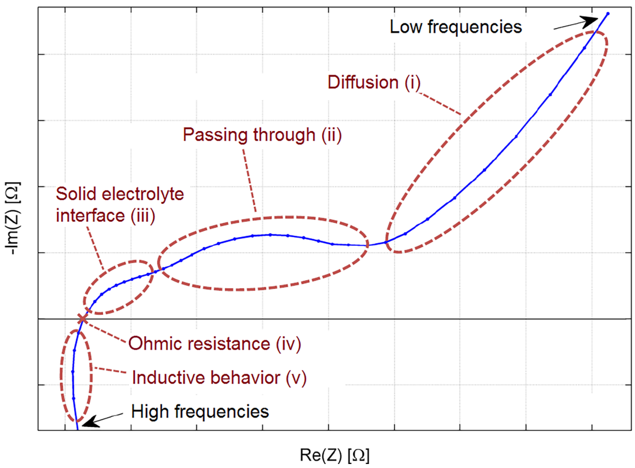

Figure 6. Typical EIS response represented as a Nyquist Plot.

Fig. 6) represents the interlayer effects at the solid electrolyte interface (Keil and Jossen, 2012; Moss et al., 2008).

The intersection with the horizontal axis ($Z'' = 0$, point (iv) in Fig. 6) represents the total ohmic resistance of the system, including the electrolyte resistance, the contact resistance and the electronic contacts. This point generally occurs at a frequency in the KHz range but can vary considerably with the cell design and the used materials (Keil and Jossen, 2012).

The highest frequencies show an inductive behavior with $Z'' > 0$ (tail (v) in Fig. 6) corresponding to the electrode porous structure and to the battery leads.

The equivalent circuit modeling of the impedance response is introduced by Moss et al. (2008) as in Fig. 7, wherein C_{dl} is the electrochemical double layer capacitance, R_{CT} is the faradaic charge transfer resistance, C_{int} is the intercalation capacitance corresponding to the accumulation of the Lithium ions within the electrode matrix, and $Z(\omega)$ is the Warburg solid-state impedance.

Moss et al. (2008) suggest the substitution of the Warburg diffusion impedance with a chain of RC elements. The new

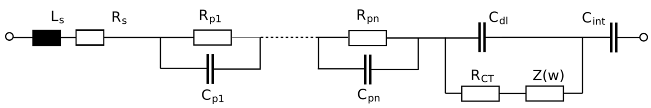

Figure 7. A complex equivalent circuit to model the EIS response.

chain does not mirror the impedance of the Warburg element but represents an approximation with an acceptable accuracy. Taking this approximation technique into consideration, the pertinence of the general assumption widely used in the literature of modeling Li-ion battery cell as a voltage source in series with a resistance R_{s} and a chain of parallel RC elements is verified. This is only possible thanks to Kramers-Kronig relations (Schmidt, 2013), which can be applied on equivalent networks, and which suggest that many different circuits can have the same or similar impedance responses without having the same topology. In other words, the battery can be modeled using an easier topology with circuit elements which do not have any direct physical interpretation. This model is valid, because it has the same frequency response, and would be easier to parametrize.

The choice of the number of RC elements results in a trade-off between fidelity and complexity (Huria et al., 2012; Moss et al., 2008; Keil and Jossen, 2012). The model can be extended with a parasitic branch, which is disregarded for cells with high coulombic efficiencies (Huria et al., 2012), and with a look-up table showing the temperature dependency of the circuit elements' values.

3.4 Models comparison and evaluation for hybrid electric vehicle applications

Table 1 presents a comparative overview of the introduced models according to the comparison criteria previously explained. As a conclusion, a trade-off between accuracy and model complexity should be accepted. Simpler models are less expensive and less susceptible to uncertainties. Complex models need more time to solve algorithms for State of Charge (SoC) and State of Health (SoH) estimations. De-