Dynamic response analysis on a 9-kW vanadium redox flow battery test facility

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RFBs have a strong potential in several grid services, from fast (i.e. power quality) to slow (i.e. energy management) and even advanced uses, such as energy back-up in fast recharge stations have been successful tested [1]. As regards VRFB fast dynamics, an accurate comprehension of the response features of large stacks is needed for the design of efficient Power Management systems (PMSs) and Battery Management Systems (BMSs) [2], [3] capable of interfacing the batteries with the grid, and exploying the capability of VRFBs in providing effective fast grid services. However, extensive experimental campaigns aimed at investigating the fast response of large-scale VRFB systems on the millisecond timescale in different operating conditions are still missing. This work aims at bridging this gap, by presenting the investigations carried out on a 9 kW/27 kWh IS-VRFB test facility that is in operation at the Energy Storage and Conversion Lab of the University of Padua [4], [5]. Investigations were performed at various operating conditions. Two discharge modes were analyzed, namely on a passive load (a variable resistor) and in a galvanostatic operation driven by an electronic load. Timescales of 20 milliseconds and 120 seconds after load insertion were explored in both cases. The faster timescale is relevant for fast grid services, such as primary regulation. In this case, the discharge on a passive load revealed an early period A, shorter than 7 ms, in which stack current and voltage presented large swings, up to 50% of the average trends, Fig.1.

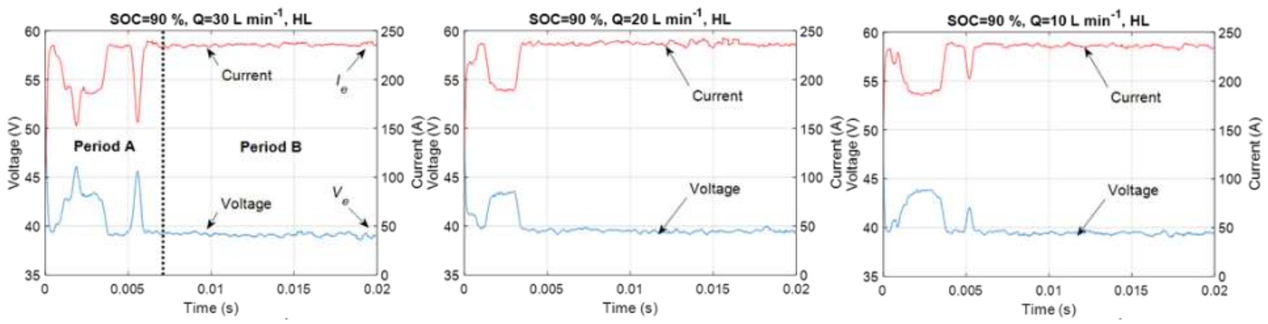

Fig. 1. Measured IS-VRFB current, voltage in the early 20 ms of discharges on a passive load, at *SOC*=90%, different *Q* and load.

Such fast swings disappeared when the battery was discharged in a galvanostatic mode, indicating that such early behavior does not restricts fast services in 50–60 Hz electrical grids, provided the interface power electronics is operated in a current driven mode. The discharge in a galvanostatic mode also revealed a fast response with steady conditions reached in few hundreds of microseconds. If a very fast response is needed (e.g. in 1000-Hz compact internal converters of fast dc-dc services) a fast backup storage system, rated for high power and low energy (e.g. a supercapacitor bank) can be added to make the storage system effective on the short timescales. The analysis on the longer timescale, that is informative of slower grid services such as peak shaving, revealed insertion overcurrents between 100% and 130% and overpowers between 100% and 160%. An equivalent electrical circuit, whose passive parameters were fitted from EIS measurements, has been developed which allows easy numerical simulations, Fig.2. It was used to study the battery discharges at different *SOC*, *Q*, load and in different discharge modes, finding that the experimental measurements and numerical simulations differed significantly in the case of discharges on a passive load, since no swing appeared in the simulations. These evidences suggested that the current and voltage swings which were experimented in the early milliseconds are clue of internal electrochemical events, namely, successive activations of different vanadium species occurring at the solid-electrolyte interfaces in the positive electrode, due to the varying accumulation of different vanadium complexes. From the electrical point of view, these events can be represented as a variable current source. This interpretation is supported by an FFT numerical analysis that properly reconstructed the experimental voltage evolution when the proper impressed current profile was applied.

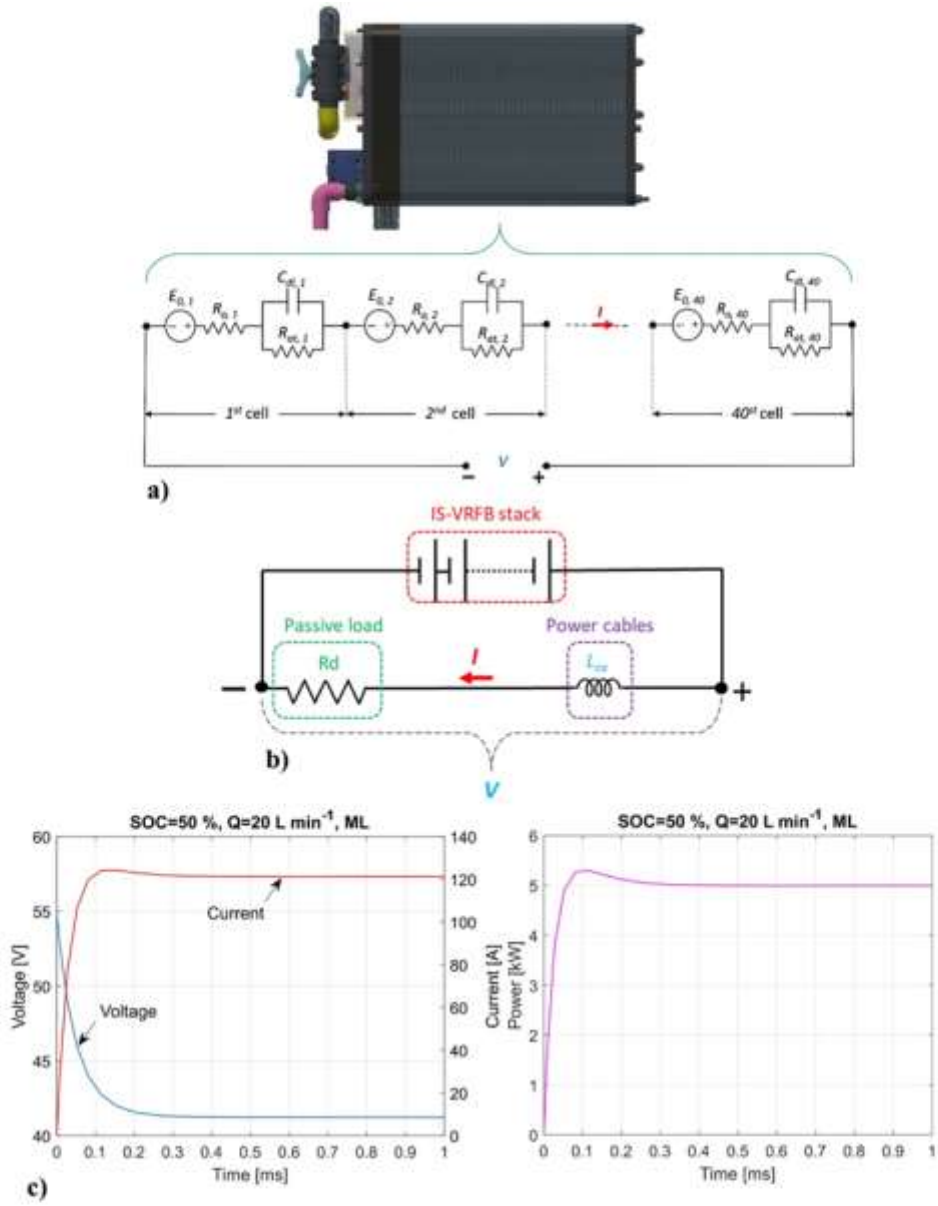

Fig. 2. a) Equivalent circuit of the IS-VRFB stack, with its 40 cells, each represented by a voltage source E_0, an internal resistance R_o and a $R_{at} = R_a + R_t$ and C_{dl} loop [6]. The model topology and parameters values were obtained by means of an optimization algorithm fitting the impedances $Z(\omega)$ EIS measurements. b) Complete equivalent circuit for discharges on passive load; c) simulated current, voltage and power waveforms over 1 ms in the case of initial *SOC* = 50 %, *Q* = 20 L min^{-1} and medium load *ML* load. Similar evolutions were obtained at other *SOC*, *Q* and load.

References

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