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Electrode and electrolyte materials for electrochemical capacitors

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ABSTRACT

Among different electric energy storage technologies electrochemical capacitors are used for energy storage applications when high power delivery or uptake is needed. Their energy and power densities, durability and efficiency are influenced by electrode and electrolyte materials however due to a high cost/performance ratio; their widespread use in energy storage systems has not been attained yet.

Thanks to their properties such as high surface area, controllable pore size, low electrical resistance, good polarizability and inertness; activated carbons derived from polymeric precursors are the most used electrode materials in electrochemical capacitors at present. Other electrode materials such as shaped nano-carbons or metal oxides are also investigated as electrode materials in electrochemical capacitors, but only as useful research tools.

Most commercially used electrochemical capacitors employ organic electrolytes when offering concomitant high energy and high power densities. The use of aqueous based electrolytes in electrochemical capacitor applications is mainly limited to research purposes as a result of their narrow operating voltage. Recent studies on room temperature ionic liquids to be employed as electrolyte for electrochemical capacitor applications are focused on fine tuning their physical and transport properties in order to bring the energy density of the device closer to that of batteries without compromising the power densities.

In this paper a performance analysis, recent progress and the direction of future developments of various types of materials used in the fabrication of electrodes for electrochemical capacitors are presented. The influence of different types of electrolytes on the performance of electrochemical capacitors such as their output voltage and energy/power densities is also discussed.

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Broader Context

In order to meet the low-carbon energy strategy set for 2050 and as the global energy demand increases, renewable energy sources (wind, wave and solar) will need to be deployed effectively on a large scale. With continuous increase in the contribution of electricity generated from renewables to our growing energy demands, energy storage is becoming more important now than any time in the history. On the other hand the wide variations of energy/power requirements of future devices necessitates the design of adaptable energy storage/power supply systems, offering wide ranges of energy and power densities, to overcome the problems associated with poor power quality and inherent intermittency of renewable resources. In the case of no energy generation, technologies capable of storing large amounts of energy and releasing it over a longer period of time are needed. In contrast, in peak demands when energy surge in short discharge periods is required, technologies delivering high power to flatten power outputs fluctuations become imperative. Since no single energy storage technology can address this wide range of energy/power requirements simultaneously, a variety of storage technologies and systems consisted of their combinations have been developed. As a new technology supercapacitors represent energy densities greater than those of conventional capacitors and power densities greater than those of batteries. They are capable of providing additional peak power demands as and when required, and allow engineers to match the specification of various energy storage technologies (such as internal combustion engines, batteries and fuel cells) closer to that of the average power demand. The evolution of the electrochemical supercapacitor to fulfil the ever-increasing power demands of newly emerging devices is largely dependent on the development of optimised electrode materials (in line with the chosen electrolyte) and electrolytes.

Introduction

The future energy landscape foresees significant concerns associated with energy crisis caused by imbalance between the world's energy demand and supply. The global energy demand is going to be doubled in next 50 years [1] and the world is preparing for an era of massively increased energy costs because of escalating shortage of energy resources. Furthermore, there is increased global warming and its affiliated environmental problems due to carbon emission caused by our overdependence on, and increase in the consumption of fossil fuels [2]. In response to these overlapping worldwide concerns the utilization of energy in the form of electricity generated from renewable energy sources such as the wind, tidal and solar power, as cheap and clean (low or zero emission) energy supplies, has become a primary focus of the major world powers and scientific community. However, as the contribution of electricity generated from these intermittent energy resources grows, energy storage and power management become increasingly important. The development of storage technologies to improve efficiencies in supply systems at times of high demand, by storing energy when in excess and releasing it over a variety of timescales, becomes imperative. In this regard batteries, electrochemical capacitors (ECs) and fuel cells recognized as three kinds of the most important electrochemical energy storage/conversion devices will play a vital role to unlock the door of renewable energy to our future energy demands. Yet, the inherent intermittency of supply from generating technologies can only be addressed if there is a step-change in energy storage capability of these devices to ensure security and continuity of energy supply to the consumer from a more distributed and intermittent supply base.

As one of the key electrochemical energy storage devices, electrochemical capacitors also known as supercapacitors have, especially, shown great potential in recent years to meet the short-term power needs and energy demands over the timescale of 0.1–100 s [3]. Their excellent power handling characteristics when combined with various primary energy sources, allow engineers to utilise them as an attractive power solution for an increasing number of applications in order to match the specification of the primary energy sources closer to that of the average power demand in each particular case. However, to fully exploit the potential of ECs in the field of energy storage, further advances in the engineering of materials used for their manufacturing are required. The recent developments in the synthesis of novel electrode materials such as i) carbon nano fibres [4], carbon xerogels [5], carbon spheres [6] and carbon nano-sheets [7] ii) metal oxides including MnO_2 [8] Ni–Co [9] NiO [10] and iii) carbon-metal oxide composites [11–14] has resulted in a significant increase in the capacitance, energy density and power density of the ECs. However with the emergence of new technologies further advances in materials used in ECs are required to address this increasing power/energy demands. In this review the development and recent trends of ECs concerning their energy storage mechanism, power handling characteristics and their applications are reviewed and discussed. In addition, detailed review of different types of carbons as one of the most used electrode materials together with a brief review of different electrolytes and materials used as binder in electrode fabrication for electrochemical capacitors are provided and discussed through extensive analysis of the literature.

Electrochemical capacitors and their energy storage characteristics

First patented by Becker at General Electric Corporation in 1957 [15] and later commercialised by SOHIO in 1978 [16] electrochemical capacitors have developed significantly over the past decades to become an attractive power solution for an increasing number of applications. Unlike the battery in which energy is available as chemical energy through faradaic (oxidation and reduction process) reactions of the electrochemical active materials which facilitates the release of charges between two electrodes with different potentials, an