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Capacitive behavior and stored energy in supercapacitors at power line frequencies

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HIGHLIGHTS

- Supercapacitor operates as smoothing capacitor and energy storage device at 50/60 Hz.
- Capacitances vs. frequency under sine wave & full wave rectified signals are modeled.
- Energy and power of supercapacitors at power line frequencies using Rs-CPE model.
- Possible use of a supercapacitor in compact, low-energy UPS systems.

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ABSTRACT

Supercapacitors are commonly viewed and mainly employed as dc electrical energy storage devices. Their behavior at far-from-dc is usually overlooked and not well explored for potential applications. In this work, we investigate analytically and experimentally the performance of supercapacitor at high frequencies, including the 50 Hz/60 Hz power line frequencies. The variation of effective capacitance, power and energy with frequency are analyzed using a fractional-order model consisting of a series resistance and a constant phase element for both pure sinusoidal and full-wave rectified voltage signals. We show that, although supercapacitors drastically loose their dc-rated capacitance at high frequencies (and therefore their energy storage capability), there still exists sufficient capacitive behavior to be used for power line applications. A 220 V/6 V, 50 Hz step-down transformer, a bridge rectifier circuit and a 3 F dc-rated supercapacitor are used in the experimental setup to drive a dc motor taken as a load. The supercapacitor is proven to be able to function as a filtering capacitor during normal operation with a percentage ripple of 0.83%, and as an energy backup device in the event of ac power interruption.

1. Introduction

Supercapacitors are electrochemical capacitors having typically thousands of times higher capacitance than conventional capacitors [1], and are widely used as energy storage devices for renewable energy systems [2–4], electric vehicles [5–7], power regulators [8], and wireless sensor nodes [9]. The capacitance, and thus the energy stored in these devices, is improved by several orders of magnitude when compared to conventional capacitors through the use of high surface area porous electrode materials soaked in electrolytic solutions [10–14]. This structure results in the capacitance and other electric parameters of supercapacitors exhibiting a strong frequency dependence [13,15,16]. At close to dc frequencies, the capacitance is maximum, whereas as the frequency is increased, the ohmic resistance of the bulk electrolyte dominates, and the capacitance decreases. At the same time the phase angle increases from -90° at low frequency to zero at high frequency [17]. These limitations make supercapacitor devices usually viewed as unsuitable for high-frequency operations [18]. In addition, some supercapacitors show a knee frequency in their impedance Nyquist plot, as depicted in Fig. 1 for an NEC/Tokin supercapacitor (part #FGR0H105ZF, rated 5.5 V, 1 F). The knee frequency, which is due to the nature, morphology, and structure of

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Nomenclature

δ	Loss tangent (dissipation factor)
ω	Angular frequency
ω_n	Normalized angular frequency
$\overline{E_s}$	Average stored energy
τ	Time constant
C	Ideal capacitance
C_α	Pseudocapacitance or CPE parameter
C_{eff}	Effective capacitance
C_{ac}	ac capacitance
$E(t)$	Time-dependent energy
$E_s(t)$	Time-dependent stored energy
$i(t)$	Current signal
I_m	Current magnitude
I_{RMS}	Root mean square current
P_A	Active power
P_n	Normalized active power
Q_n	Normalized reactive power
Q_R	Reactive power
R_s	Series resistance
s	Laplace (complex) frequency variable
S_n	Normalized apparent power
$v(t)$	Voltage signal
V_m	Voltage magnitude
V_{RMS}	Root mean square voltage
Z	Impedance
α	CPE dispersion coefficient
CPE	Constant phase element

electrodes material as well as to the electrochemical reactions at the electrodes/electrolyte interfaces, is located at approximately 28 mHz for this device, and separates clearly the near-ideal capacitive behavior (from 28 mHz to dc) from the Warburg region (from 28 mHz to 824 Hz) [19]. One can immediately recognize that such a supercapacitor will not behave as an ideal capacitor in 50 Hz or 60 Hz power line applications for example, since the operating frequencies lie within the Warburg region where the current-voltage phase angle is approximately −45°. However, not all commercial supercapacitors show this knee frequency behavior as shown in Fig. 1 for a Cooper Bussmann PowerStor supercapacitor (part #HV0820-2R7305-R, rated 2.7 V, 3 F, denoted PS in the figure). Nonetheless, as shall be discussed later in this paper, there still exists a limitation on its high frequency operation.

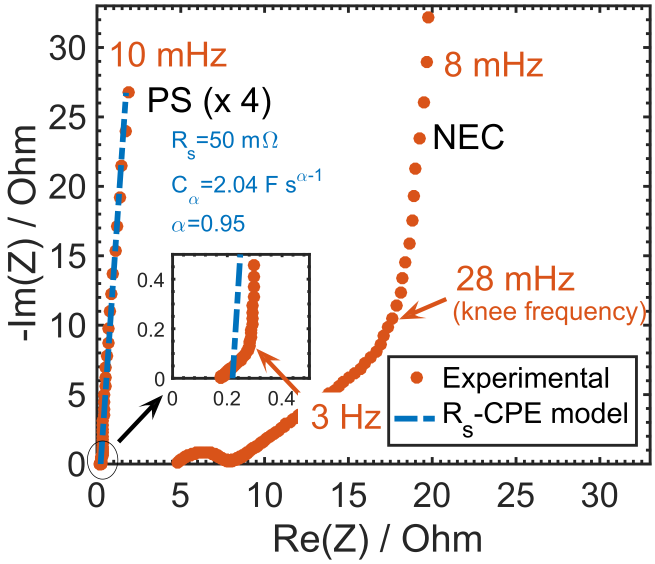

Fig. 1. Nyquist plot of impedance of two commercial supercapacitors from two different vendors (NEC, rated 1 F, and PowerStor (denoted PS), rated 3 F). The NEC device shows a clear "knee frequency" at 28 mHz separating two CPE regions, while the PS device (data are scaled up by a factor 4 for better legibility) shows practically a single CPE behavior. Measurements were done with an applied 20 mV sine signal at open-circuit voltage using a Bio-logic VSP 300 electrochemical station. The R_s-CPE fitting parameters for PS are found to be $R_s = 0.05\ \Omega$, $C_\alpha = 2.04$ F $s^{\alpha-1}$, $\alpha = 0.95$.

In this work, we seek to study whether it is possible to use commercial supercapacitors in 50 Hz/60 Hz standard line-powered applications, which needs first a proper characterization of performance at such frequencies. The electrical behavior of these devices can be represented by a distribution of a number of R_sC relaxation time constants leading to a pseudocapacitance (not be confused with pseudocapacitive energy storage mechanism which is achieved by reversible Faradaic electron charge-transfer with redox reactions, intercalation or electrosorption [1]) rather than an ideal capacitance. However, this electrical behavior can be represented in a much more compact form using non-local-in-time models based on fractional-order derivatives [20–23]. A model consisting of a series combination of a resistance (R_s) with a constant-phase element (CPE, also know as fractional capacitor), is widely used as an equivalent circuit model for electric double-layer capacitors [16,20,21,24], and will be used in this study. In the time-domain, the voltage and current in the CPE can be related by the fractional-order differential equation

$$i_c(t) = C_\alpha \frac{dv_c^\alpha(t)}{dt^\alpha};\ 0 < \alpha \le 1 \tag{1}$$

instead of $i_c(t) = C dv_c(t)/dt$, where C_α is the CPE parameter or pseudocapacitance in units of F $s^{\alpha-1}$ (not pseudocapacitive storage mechanism), and α is the CPE exponent or dispersion coefficient [25]. In the frequency domain, the impedance corresponding to equation (1) is

$$Z_{\text{CPE}} = \frac{1}{C_\alpha s^\alpha} \tag{2}$$

where $s^\alpha = \omega^\alpha \angle\, \alpha\pi/2$, leading to a total impedance of $Z_{sc} = R_s + 1/C_\alpha s^\alpha$ for the R_s-CPE model [20,26–28]. Since supercapacitors are designed mainly for dc energy storage applications, their rated capacitance is given by manufacturers at dc which is not the same at higher frequencies. In Ref. [16], an effective capacitance in Farads that takes into account the CPE parameters and the operating frequency was proposed in the form $C_{\text{eff}} = C_\alpha \omega^{\alpha-1}/\sin(\alpha\pi/2)$ when the device is excited with sinusoidal signals. Other expressions of the effective capacitance for non-sinusoidal excitation (e.g. step input voltage, step input current, linear voltage ramp) can be found in Refs. [19] and [24]. It is therefore concluded that the effective capacitance of supercapacitors depends on the charging/discharging waveforms [22].

In this study we first propose a recommended maximum operating frequency of an R_s-CPE-equivalent supercapacitor using steady-state power analysis under sinusoidal voltage excitation. This is particularly important for supercapacitors that do not show a knee frequency in their spectral impedance response (see Fig. 1). We also propose a performance measure metric, and evaluate the amount of stored energy under sinusoidal excitations. Then, operation of an R_s-CPE-equivalent supercapacitor from unipolar signals and particularly a full-wave rectified voltage is evaluated, which has not been reported yet. In the experimental section, we validate our theoretical analysis with results obtained from a commercial PS supercapacitor, and especially how the effective capacitance of the device declines from the dc-rated value as the frequency is increased using both sinusoidal signals and full-wave rectified signals. Despite the loss of capacitance, a full-wave rectified 50 Hz voltage applied directly across the supercapacitor is