The Rate-Dependence of Supercapacitor Performance: Quantitative Evaluation Using Peukert’s Constant

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Peukert’s law, widely used to model the rate-dependence of battery capacity, is beginning to receive attention in the evaluation of supercapacitors. Here, we demonstrate the use of a simple method of determining Peukert’s constant using impedance spectroscopy in order to analyze the rate-dependence of supercapacitor performance. The relationships between porosity and pseudocapacitance and Peukert’s constant are investigated through the simulation of equivalent circuit models. The utility of Peukert’s constant for the evaluation of the rate-dependence of supercapacitor performance is established through a novel analysis of supercapacitor data available in the literature. The use of a quantitative approach to understanding supercapacitor rate-performance provides additional clarity and insight over the commonly used qualitative approach.

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Supercapacitors (SCs) are a highly promising type of energy storage device, particularly well suited to applications where high power densities are required. They are beginning to reach widespread commercial use. For example, in electrical/hybrid vehicles a combination of Li-ion batteries and supercapacitors improves braking energy recovery and battery life. A key issue in SC development is the dependence of the deliverable energy and power density on the rate of operation: at faster rates, the available energy density reduces to a fraction of that available at slower rates. However, this aspect of supercapacitor performance is inconsistently reported.

Supercapacitors are composed of electrodes separated by an electrolyte. They store energy in electrical double layers formed at the electrode/electrolyte interface when a potential is applied across the cell. Their high power density is a consequence of energy storage without the creation or breaking of chemical bonds. The rate dependence of the capacitance originates primarily from the rate dependence of pseudocapacitance (due to the kinetics of faradaic reactions) and from electrode porosity. Porous electrodes are used to achieve high surface areas, which results in a large capacitance. Due to the complex structure of porous electrodes, the time required for electrolyte ions to reach the electrode surface and form a double layer in response to an applied voltage varies. This leads to dispersion in the accessible surface area, and thus capacitance, at different operation rates, which is often called the effect of pore-accessibility. In order to evaluate and understand supercapacitor performance, it is important to be able to succinctly express the rate-dependent capacitance.

For this purpose, we consider the utility of Peukert’s equation. Peukert’s equation is an empirical relationship between the capacitances and discharge rates of batteries:

\[ C = I^k t \]  

where \( C \) is the capacity, \( I \) is the discharge current, \( t \) is the discharge time, and \( k \) is Peukert’s constant. It is often expressed as either

\[ \frac{C}{C_0} = \left( \frac{t}{t_0} \right)^{1-k} \]  

or

\[ \frac{C}{C_0} = \left( \frac{1}{I_0} \right)^{1-k} \]  

Peukert’s constant \( k \) expresses the rate-dependence of the battery: a value of unity indicates ideal rate independent capacity, while higher values indicate more highly rate-dependent capacity. Different mechanisms of operation lead to different values of \( k \). Other factors also influence \( k \), such as cell geometry and materials. Although Peukert’s constant has been widely used to evaluate batteries, it has recently begun to receive attention for the evaluation of SCs.

In this work we show the utility of Peukert’s equation to evaluate the rate-performance of SCs. First, we demonstrate the determination of Peukert’s constant for a commercial SC using impedance spectroscopy (IS). The use of IS to determine Peukert’s constant is more precise and straightforward than conventional galvanostatic measurement as we have recently reported. More importantly, due to the low currents used in IS measurements, employing this method bypasses inaccuracies that result from device heating during measurement, an issue often reported for galvanostatic measurements. Next, to investigate the effect of key SC parameters porosity and pseudocapacitance on Peukert’s constant, impedance spectra of equivalent circuit models (ECMs) are simulated and analyzed. Finally, literature data extracted from four distinctive sets of SCs were analyzed to determine Peukert’s constant. The chosen studies represented a wide variety of SCs, revealing the influence of porosity and pseudocapacitance on the SC performance. Analysis using Peukert’s constant allowed quantitative examination of the rate-dependence of the capacitance and provided additional clarity and insight compared with typical qualitative analysis.

**Experimental**

**Electrical characterization.** A Maxwell 1 F commercial supercapacitor was characterized with IS and galvanostatic charge/discharge measurements at room temperature. A Novocontrol Apha-A impedance analyzer was used to conduct impedance spectroscopy over the frequency range of \( 10^{-2} \) to \( 10^{7} \) Hz, with 50 mV applied ac bias. Galvanostatic measurements were conducted using an Arbin Instruments MSTAT. Identical charge and discharge currents were used, ranging from 10 mA to 2 A, with no hold time.

**Impedance simulation.** Impedance spectra were simulated and analyzed using MATLAB, from the equivalent circuits shown in Fig. 2. For the impedance spectra shown in Fig. 3, the following

\[ \frac{C}{C_0} = \left( \frac{1}{I_0} \right)^{1-k} \]  

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values were used: Ideal: $R_s = 0.5 \, \Omega$, $R_e = 0.5 \, \Omega$, $C_e = 0.1 \, F$, $C_{edl} = 1 \, F$; Porous: $R_s = 0.5 \, \Omega$, $R_e = 0.5 \, \Omega$, $Z_w = 0.5$, $C_c = 0.1 \, F$, $Q_{pseudo} = 1, n = 0.9$; Combined: $R_s = 0.5 \, \Omega$, $R_e = 0.5 \, \Omega$, $Z_w = 0.5$, $C_c = 0.1 \, F$, $Q_{pseudo} = 1, n = 0.9$. For the heat map shown in Fig. 4, the following values were used: $R_s = 0.5 \, \Omega$, $R_e = 0.5 \, \Omega$, $C_e = 0.1 \, F$, $Z_w = [0:1]$, $C_{edl} = 1 \, F$, $Q_{pseudo} = [0:1]$, $n = 0.9$, $R_{ct} = 2 \, \Omega$.

**Literature data collection.—** Data were extracted from reference papers using the online software WebPlotDigitizer (https://apps.automeris.io/wpd/).

**Results and Discussion**

**Determination of Peukert’s constant using IS.—** We first demonstrate the determination of Peukert’s constant $k$ of a commercial Maxwell 1 F SC using IS, following the approach presented previously.13

The complex capacitance, $C = C_{re} + jC_{im}$, is calculated from the complex impedance $Z = Z_{re} + jZ_{im}$ by

$$C_{re} = \frac{-Z_{im}(f)}{2\pi f |Z(f)|^2}$$

and

$$C_{im} = \frac{Z_{re}(f)}{2\pi f |Z(f)|^2}$$

The real and imaginary components of the complex capacitance are then plotted vs frequency, $f \propto 1/t$, on a logarithmic scale, shown in Fig. 1. Now $k$ can be readily determined from the slope of the real component of the capacitance since

$$\frac{C_{re}}{C_e} = \left(\frac{f}{f_0}\right)^{-k}$$

$C_e$ has linear regions at both low and intermediate frequencies. $k$ has been determined from each $k = 1.07$ and 1.74 for the low and intermediate regions, respectively. We are primarily interested in $k$ in the low frequency region, which directly represents the operating conditions of the SC. At higher frequencies the available capacitance drops to a small fraction of the total capacitance; SC operation in this range is not ideal. Values of $k$ in the intermediate frequency region may be very large or even negative: as the slope $s$ becomes more steeply negative, $k = 1/(1-s)$ passes through an asymptote and becomes negative. Qualitatively, large or negative values of $k$ indicate a sharp drop off in available capacitance as the discharge rate increases.

The relaxation time constant $\tau_0$, another measure of SC rate-performance, can be determined from the complex capacitance. For SCs, a plot of the imaginary capacitance has a peak, with area equal to the total capacitance and broadness representing the dispersion of the capacitance with frequency.14 The maximum occurs at $\tau_0^{-1}$.1 For ideal capacitors, $\tau_0$ represents the discharge time at which the available capacitance is half the total capacitance, and deviations from this are typically small. The relaxation time constant $\tau_0$ marks the point at which the device transitions from primarily energy storage behavior to primarily energy dissipative behavior.15 Given its ease of determination, relevance to device performance, and ease of interpretation, $\tau_0$ is well suited to express the rate-dependence of SC performance. As can be seen from Fig. 1, $\tau_0$ and $k$ correspond to different and complementary aspects of the rate-dependence of the SC’s electrical properties: $\tau_0$ represents the range of good capacitive performance, while $k$ represents how significantly the capacitance decays within that range.

**Analysis of equivalent circuit models (ECMs).—** The relationship between Peukert’s constant and SC impedance was explored through the simulation of impedance spectra from ECMS. In particular, the effects of porosity and pseudocapacitance were investigated. The impedance spectra of four ECMS, shown in Fig. 2, were simulated. The chosen ECMS include an ideal SC, a porous SC, pseudocapacitive SC, and an ECM combining the porous and pseudocapacitive ECMS. The ideal SC ECM is composed of a series resistance ($R_s$), the electrolyte impedance ($R_e$ and $C_e$) and the double layer capacitance ($C_{edl}$). The porous ECM includes a Warburg element.16,17 while the pseudocapacitive circuit adds a branch for the pseudocapacitance, represented by a constant phase element ($Q_{pseudo}$) and an associated charge transfer resistance ($R_{ct}$).18 The constant phase element is used to account for non-ideal capacitive behavior, for example, from variation in rates of charge.

![Figure 1.](https://example.com/image1.png)  
**Figure 1.** The complex capacitance ($C_{re}$ and $C_{im}$) of the Maxwell 1 F SC plotted vs frequency. $k_0$ and $k_p$ were determined from the slope of $C_{re}$ and $\tau_0$ has been determined from the peak of $C_{im}$.

![Figure 2.](https://example.com/image2.png)  
**Figure 2.** The four ECMs simulated and analyzed to examine the effect of porosity and pseudocapacitance on $k$. The Combined ECM combines the elements of the porous and pseudocapacitive ECMS.
transfer reactions. Lastly, the combined circuit comprises both the porous and pseudocapacitive circuits.

The impedance of these ECMs are simulated and plotted in Fig. 3, as Nyquist and normalized complex capacitance plots. For the circuit parameters used in the simulation, values were chosen to give reasonable impedance spectra. As shown previously, \( k \) can be determined from the slope of the low frequency region in the logarithmic plot of \( C_r \) vs \( f \) (\( k_{\text{Ideal}} = 1.00, k_{\text{Porous}} = 1.08, k_{\text{Pseudo}} = 1.10, k_{\text{Combined}} = 1.33 \)).

The contributions of the porous and pseudocapacitive circuit elements to the combined circuit were further investigated by varying the parameters \( Z_w \) and \( Q_{\text{pseudo}} \) representing the influence of porosity and pseudocapacitance, respectively. The values of these parameters were varied between 0 and 1, representing a range between 0% contribution and 100% contribution of these factors, relative to the IS spectra shown in Fig. 3. The resulting \( k \) is plotted in Fig. 4 as a heat map, with percent contribution of porosity and pseudocapacitance along each axis. It can be seen that \( k \) increases with either increased pseudocapacitance or porosity, increasing significantly more rapidly under the influence of both. This is consistent with our expectations, as porosity and pseudocapacitance are known to reduce the rate-performance of SCs. It is interesting to note how much the effect is amplified when both are present.

Peukert’s constant analysis of selected papers.—The rate-dependence capacitance of various SCs in selected papers were analyzed to show the utility of \( k \) for evaluating SCs. The papers were chosen based on their systematic variation of electrode composition or structure. Using the data extracted from the results of the IS and galvanostatic measurements reported, we determined Peukert’s constant, \( k_{\text{ac}} \) and \( k_{\text{dc}} \), respectively. Figure 5 shows a representation of the fit used to determine \( k \) from the IS and galvanostatic measurements. In all cases, the value of \( R \) for the fit used to
determine $k_{ac}$ was between 0.96 and 0.99, showing the good fit of Peukert’s law to the impedance spectra. We also calculated $\tau_0$ from either the real or imaginary capacitance, where possible with the available data.

The determined values of $k_{ac}$, $k_{dc}$, and $\tau_0$ are presented in Table I. Values of $k_{dc}$ are included for comparison, to show the consistency of the IS and galvanostatic measurements. We have previously shown that IS provides more precise values of $k$, so we will use $k_{ac}$ in our discussion and analysis. We note that our intention in presenting this analysis is to show how Peukert’s constant can bring further clarity to evaluating the rate-dependence of the capacity.

In the study reported by Portet et al., the pore size distribution of activated carbon electrodes was modified by the addition of carbon nanotubes (CNTs), leading to greater pore accessibility with increased CNT content. From the results of the ECM simulations, we expect that with greater pore accessibility, $k$ will decrease as the more open pore structure would lead to a less rate-dependent capacitance. A plot of the determined $k_{ac}$ as a function of the CNT content is shown in Fig. 6. Indeed, this plot clearly shows the decrease in $k$ with the CNT content suggesting that the CNT loading results in the weaker rate-dependence of the capacitance, consistent with the ECM simulations. These results qualitatively support the conclusion of the original study that CNT loading contributes to the variation in rate-dependence, as discussed in the paper.

In Zhi et al.’s work, carbon nanofibers with different MnO$_2$ loading were fabricated to take advantage of MnO$_2$’s pseudocapacitive properties in a high surface area electrode. Figure 7 shows the relationship between the determined $k_{ac}$ and the MnO$_2$ loading, for samples treated by iron acetylacetonate (AAI) (top) and untreated (bottom). With the exception of the second AAI treated carbon nanofiber loaded with MnO$_2$ sample, (AAI-CNF@MnO$_2$ 2), $k_{ac}$ increases with increasing MnO$_2$ loading. The high $k_{ac}$ for this particular sample may be due to the relatively larger contribution of pseudocapacitance, as it has the highest MnO$_2$-specific capacitance.

From these plots we can also readily see that the AAI treatment dramatically improves the rate-performance of the electrodes. Figure 8 is a plot of $k_{ac}$ vs electrode resistivity, including data from both AAI and non-AAI treated samples. It shows a clear trend, with increasing electrode resistivity leading to reduced rate performance. This points to electrode resistivity as a main contributor to the variation in rate-performance, rather than simply being the result of pseudocapacitance due to the MnO$_2$ loading. A definitive relationship between the degree of pseudocapacitance and the rate-dependent capacitance similar to that predicted by the ECM simulations was not clearly seen, as the addition of MnO$_2$ modified other electrode properties. Nevertheless, analysis with Peukert’s constant provides quantitative support for the conclusions of the

| Table I. Peukert’s constant of the Maxwell 1 F SC and previously studied SCs. |
|-----------------|-----------------|-----------------|
| **Maxwell 1 F SC** | $k_{ac}(R^2)$ | $k_{dc}(R^2)$ | $\tau_0$ |
| CNT/Activated Carbon$^{17}$ | | | |
| 0% | 1.07 | 1.06 | 3.3 s |
| 5% | 1.15 | 1.046 | 4.7 s |
| 10% | 1.10 | 1.023 | 3.7 s |
| 15% | 1.07 | 1.017 | 3.0 s |
| 30% | 1.08 | 1.026 | 1.8 s |
| 50% | 1.03 | 1.024 | 1.1 s |
| Carbon nanofiber-MnO$_2$ | | | |
| AAI-CNF | 1.06 | 1.06 | 2.1 s |
| AAI-CNF@MnO$_2$ 1 | 1.11 | 1.11 | 2.5 s |
| AAI-CNF@MnO$_2$ 2 | 1.23 | 1.23 | 5.0 s |
| AAI-CNF@MnO$_2$ 3 | 1.13 | 1.13 | 10 s |
| AAI-CNF@MnO$_2$ 4 | 1.19 | 1.19 | 17 s |
| CNF | 1.47 | - | - |
| CNF@MnO$_2$ 1 | 1.73 | 1.73 | 33 s |
| CNF@MnO$_2$ 2 | 4.8 | 4.8 | 50 s |
| CNF@MnO$_2$ 3 | 28 | - | - |
| CNF@MnO$_2$ 4 | 28.2 | - | - |
| Porous carbon enriched in nitrogen (nitrogen Wt%)$^{19}$ | | | |
| 7.2 | 1.05 | 1.09 | 3.1 s |
| 4.2 | 1.03 | 1.07 | 4.9 s |
| 3.1 | 1.01 | 1.07 | 2.6 s |
| 2.6 | 1.00 | 1.02 | 1.0 s |
| 1.9 | 1.02 | 1.07 | 1.9 s |
| NiO Nanoflakes$^{20}$ | | | |
| NiO | 1.62 | 1.57 | - |
| NiO$_2$ | 1.74 | 1.62 | - |
| NiO$_3$ | 1.79 | 1.74 | - |
paper, namely that enhancement of electrode electrical conductivity with AAI led to an improvement in the rate-performance.

In Lota et al.’s work, porous carbon electrodes were enriched with variable amounts of nitrogen with the aim of inducing pseudocapacitance.21 As the nitrogen loading increased, the capacitance increased, with the exception of the 2.6 nitrogen Wt.% sample, due to its significantly higher surface area. The increase in capacitance with nitrogen loading was attributed to either an increased electrode wettability and available surface area or nitrogen induced pseudocapacitance, or both. We determined \( k_{dc} \) and \( k_{ac} \) from IS and galvanostatic data available in Ref. 21, respectively, and \( k_{dc} \) is plotted in Fig. 9 as a function of nitrogen loading (top) and Brunauer–Emmett–Teller surface area (\( S_{BET} \), bottom). While \( k_{ac} \) shows no clear trend with nitrogen loading, it does show a trend with electrode surface area: higher surface areas result in lower rate-dependence. This supports the conclusion that the rate-dependence originates from the differences in available surface area and accessible pore structure, rather than variation in the pseudocapacitance.

Lastly, we examine S. Vijayakumar et al.’s work on pseudocapacitive NiO nanoflakes.22 The electrical properties of three samples named NiO\(_3\), NiO\(_4\), and NiO\(_5\) (corresponding to calcination temperature of 300, 400, and 500 °C) were evaluated through galvanostatic and IS measurements. With decreasing calcination temperature, higher capacitance was observed. This was attributed to improved electrolyte penetration into the pores. \( k_{ac} \) and \( k_{dc} \) were determined from their data, and reported in Table I. \( k_{ac} \) increases with calcination temperature, and is consistent with their explanation of improved electrolyte penetration. Interestingly, all values of \( k \) are significantly larger than 1, ranging between 1.5 and 1.8, corresponding to severe rate-dependent capacitance in the measured frequency range. This is because of the low \( \tau_0 \) of the samples: the time-scale of the measurements are shorter than \( \tau_0 \) so that the capacitance is highly dependent on rate. These samples show the benefit of considering both \( k \) and \( \tau_0 \), as \( k \) allows the comparison of the rate-dependence of the capacitance in the measured range, while \( \tau_0 \) indicates the location of the onset of sharp capacitance drop-off.

We note that the magnitudes of Peukert’s constant from the analysis of literature SCs are consistent with those from the ECM simulations. For the electrodes that lack significant pseudocapacitance, the activated carbon, carbon nanofibers unloaded with MnO\(_2\), and porous carbon electrodes, \( k \) is predominantly between 1.0 and 1.1, consistent with the ECM simulations that do not include pseudocapacitance. On the other hand, electrodes with significant expected pseudocapacitance, the MnO\(_2\) loaded carbon nanofibers and NiO nanoflakes, have higher values of \( k \), in line with ECM simulations that include the effect of both pseudocapacitance and porosity.

**Conclusions**

We have demonstrated the use of Peukert’s constant \( k \) to quantitatively evaluate the rate-performance of SCs. \( k \) was evaluated for a commercial SC, simulated ECMs, and literature data. The results clearly showed that \( k \) well represents the rate-dependence. ECMs were used to investigate the relationship between porosity and pseudocapacitance on \( k \); as expected, both lead to increase in \( k \) corresponding to reduced rate-dependent performance. Through the analysis of literature data we have shown that Peukert’s constant is a useful tool for quantifying the rate-dependence of the capacitance, bringing additional clarity over more qualitative analysis. This work offers a way of easily understanding SC rate-dependent capacitance, and will allow more thorough and penetrating investigation of this important SC behavior.

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References

1. P. Simon and Y. Gogotsi, Acc. Chem. Res., 46, 1094 (2013).
2. J. Yan, Q. Wang, T. Wei, and Z. J. Fan, Adv. Energy Mater., 4, 1300816 (2014).
3. B. E. Conway and W. G. Pell, J. Power Sources, 105, 169 (2002).
4. S. L. Zhang and N. Pan, Adv. Energy Mater., 5, 1401401 (2015).
5. B. E. Conway, V. Birss, and J. Wojtowicz, J. Power Sources, 66, 1 (1997).
6. D. Doerffel and S. A. Sharkh, J. Power Sources, 155, 395 (2006).
7. H. K. Song, Y. H. Jung, K. H. Lee, and L. H. Dao, Electrochim. Acta, 44, 3513 (1999).
8. H. D. Yoo, J. H. Jang, J. H. Ryu, Y. Park, and S. M. Oh, J. Power Sources, 267, 411 (2014).
9. E. Peukert, Elektrotech. Z., 20, 287 (1897).
10. A. Hausmann and C. Depcik, J. Power Sources, 235, 148 (2013).
11. H. Yang, J Energy Storage, 22, 98 (2019).
12. H. Yang, J Energy Storage, 27, 101004 (2020).
13. E. M. Mills and S. Kim, J. Phys. Chem. Lett., 7, 5101 (2016).
14. J. H. Jang and S. M. Oh, J. Electrochem. Soc., 151, A571 (2004).
15. P. L. Taberna, P. Simon, and J. F. Fauvarque, J. Electrochem. Soc., 150, A292 (2003).
16. C. W. Huang, C. H. Hsu, P. L. Kuo, C. T. Hsieh, and H. S. Teng, Carbon, 49, 895 (2011).
17. C. W. Huang and H. S. Teng, J. Electrochem. Soc., 155, A739 (2008).
18. B. E. Conway, Electrochemical Supercapacitors: Scientific Fundamentals and Technological Applications (Springer US, New York) (1997).
19. C. Portet, P. L. Taberna, P. Simon, and E. Flahaut, J. Power Sources, 139, 371 (2005).
20. M. J. Zhi, A. Manivannan, F. K. Meng, and N. Q. Wu, J. Power Sources, 208, 345 (2012).
21. G. Lota, B. Grzyb, H. Machnikowska, J. Machnikowski, and E. Frackowiak, Chem. Phys. Lett., 404, 53 (2005).
22. S. Vijayakumar, S. Nagamuthu, and G. Muradilharan, ACS Applied Materials & Interfaces, 5, 2188 (2013).

Figure 9. Plot of Peukert’s constant vs nitrogen loading (top) and vs BET surface area (bottom).

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