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Frequency dependent piecewise fractional-order modelling of ultracapacitors using hybrid optimization and fuzzy clustering

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HIGHLIGHTS

- Frequency dependent dynamics of ultracapacitors has been investigated.
- Ultracapacitor characteristics are represented by fractional calculus based model.
- Hybrid optimization algorithm is used for parameter estimation.
- Fuzzy clustering is applied to classify the frequency dependent model parameters.
- Proposed approach outperforms existing method under various test conditions.

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ABSTRACT

The usage of ultracapacitors for development of energy storage devices and alternative power sources is increasing at a very rapid rate. However accuracy in selection of ultracapacitor model parameter plays key role in the design of such devices, especially in applications involving wide operating frequency. Ultracapacitors are known to exhibit fractional dynamics and the model parameters vary significantly with frequency. This paper proposes a piecewise modelling and parameter estimation approach for ultracapacitors using a hybrid optimization and fuzzy clustering approach. The proposed modelling technique has been applied over impedance frequency response data acquired from a commercially available ultracapacitor. The model is able to represent the experimental data over different operating points with reduced number of model parameters. Comparative numerical simulations have been carried out to validate the benefits of the proposed approach. The estimated parameters revealed the disparity in the frequency dependent behavior of ultracapacitors and standard electrolytic capacitors.

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1. Introduction

Utilization of renewable energy sources over the traditional fossil fuel based sources are being encouraged due to their unconditional environment friendly availability. However accomplishment of this is highly dependent on the development of efficient electrical energy storage devices. In this context, ultracapacitors (UC), also known as electric double layer capacitor (EDLC), have emerged as efficient and reliable energy storage devices because of their high specific power density and long shelf and cycle life [1], which allow charging and discharging with short intervals of time. The advantages of UC over its traditional counterparts such as batteries and electrolytic capacitors (EC) makes it a popular choice in many practical applications such as hybrid and electrical vehicles, photovoltaic systems, wind turbines etc. [2]. A hybrid energy system consisting of UC coupled with battery helps in lowering the peak energy throughput, thus resulting in less capacitance loss and impedance growth [3], which enhances the life and reliability of the corresponding power application.

The modelling of the electrical behavior of UC is of prime importance for its acceptability as a sole/hybrid energy source. The modelling of UCs is based on their characterization involving comparison of experimental and datasheet results under similar conditions. In recent times, several equivalent circuit models have been proposed in literature that represent the UC characteristics by a set of electrical parameters and their estimation from experimental data. These include models composed of passive

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components (RLC) ladder circuit [4], fractional pole-zero combination [5] and constant phase element (CPE) [6]. Calculus of non-integer order [7] resulting in fractional poles and zeros have been found to be better describe the physical phenomena of systems with UCs [5]. A CPE incorporates fractional impedance as,

$$Z_{CPE}(s)=\frac{1}{C_f s^{\alpha}} \tag{1}$$

where, C_f is the pseudo-capacitance in $F/s^{\alpha-1}$, $\alpha\in\Re$ (a real number) is the order and s ($j\omega$) is the Laplacian operator. CPE better characterizes the inherent fractional dynamics of UC caused by electrochemical diffusion phenomenon and porous material [8]. The fractional exponent α of the CPE has been widely used in literature [9–11] to study the influence of the electrode porosity, surface inhomogeneity, distributed reactivity, roughness and geometry on UC behavior. Energy storage, losses and efficiency in fractional-order circuits and systems have also been correlated with C_f and α [12,13].

The presence of fractional dynamics in UC has been dealt widely in literature [14]. Overall the reported models can be broadly categorized based on their characterization in (a) time domain and (b) frequency domain. However, none of the reported techniques have addressed frequency dependent behavioral modelling. The variation in UC behavior with frequency has been discussed in [15,16]. However, the same has not been incorporated in the existing models with fractional components. The variation in the equivalent circuit parameters of the model with frequency needs to be accounted, for applying UCs in power electronics and energy storage systems [15]. An assumption of constant set of circuit parameters over the entire operating frequency range would lead to incorrect evaluation of the system characteristics. To overcome this, the present work proposes a piecewise approach for modelling the UC behavior by dividing the frequency range into a set of sectors (frequency bands), with each sector represented by a set of circuit and fractional parameters. For each sector, the parameters are estimated from the impedance frequency response data (FRD) using a novel evolutionary optimization technique i.e. hybrid chaotic seeker optimization algorithm (hybrid CSOA). The hybrid CSOA involves coupling of a local search based technique, i.e. Nelder-Mead simplex (NMS) search with a global search technique, i.e. chaotic seeker optimization algorithm (CSOA) [17,18]. Considering the trade-off between better approximation of experimental data and simplicity in the model, which is desirable for on board applications, a fuzzy clustering [19] based approach has been adopted for representing the UC behavior by a smaller number of sectors. The entire modelling procedure has been applied for the UC under test with different input voltage condition. To validate the proposed fuzzy clustered model performance, its comparison has been carried out with the single and equally spaced multiple sectored simulated models data in addition to the experimental data.

Further the paper is organized as follows: Section 2 describes the fractional-order modelling of UC and the parameter estimation in frequency domain using hybrid optimization, Section 3 provides details about the piecewise fuzzy clustering approach to obtain relatively simpler UC model with significant accuracy. Experimental data acquisition and simulation results are discussed in Section 4 and finally Section 5 concludes the paper.

2. Ultracapacitor modelling and parameter estimation in frequency domain

2.1. UC modelling

The proposed modelling approach involves parameter estimation from the impedance frequency response experimental data for frequency steps $\in[\omega_l,\,\omega_u]$, where, ω_l & ω_u represents the lower and upper limit of frequency under consideration (operating frequency). As discussed earlier, fractional dynamics provides better representation of UC behavior. In this regard, the present work assumes the following representation of UC,

$$Z(s)=R_c+\frac{1}{C_f s^{\alpha}} \tag{2}$$

where, R_c is the series resistance.

Using the impedance magnitude and phase data (varying with frequency), the parameter estimation task for model (2) has been formulated as an optimization problem by framing an objective function that seeks to determine a set of model parameters (i.e. R_c, α and C_f) that minimizes the deviation (in both magnitude and phase) between the simulated model and experimental output. The objective function is given as,

$$J\left(R_c,\alpha,C_f\right)=\frac{1}{N}\left[\left\|Z_m-\widehat{Z}_m\right\|_2+\left\|Z_p-\widehat{Z}_p\right\|_2\right] \tag{3}$$

where, $\|-\|_2$ represents the second norm, Z_m and Z_p are experimental impedance magnitude and phase data vectors respectively, whereas, $\widehat{Z}_m$ and $\widehat{Z}_p$ represents corresponding model output taken at N different steps of frequency, ω_i. The magnitude and phase vectors of simulated model output is obtained by,

$$\widehat{Z}_m(\omega_i)=\sqrt{\left[R_c+\frac{\omega_i}{C_f}\cos(\alpha\pi/2)\right]^2+\left[\frac{\omega_i}{C_f}\sin(\alpha\pi/2)\right]^2} \tag{4}$$

$$\widehat{Z}_p(\omega_i)=\tan^{-1}\frac{\frac{\omega_i}{C_f}\sin(\alpha\pi/2)}{R_c+\frac{\omega_i}{C_f}\cos(\alpha\pi/2)} \tag{5}$$

The estimation process for the model parameters is initialized by dividing the frequency range $\omega_l<\omega_i<\omega_u$, into a set of frequency bands, i.e. ω_1, ω_2, … , ω_P as $\omega_1=(\omega_{1,l},\ldots,\omega_{1,u})$ $\omega_2=(\omega_{2,l},\ldots,\omega_{2,u})$, …, $\omega_P=(\omega_{P,l},\ldots,\omega_{P,u})$, such that,

$$\omega_1\cup\omega_2\cup\ldots\omega_p\ldots\cup\omega_p=(\omega_l\ldots,\omega_i,\ldots,\omega_u) \tag{6}$$

where, $\omega_{p,l}$ and $\omega_{p,u}$ represents the lower and upper frequency limit for the frequency band ω_p (p=1,2,… ,P) . The right hand side of (6) represents the set of frequency steps across which the data is recorded.

2.2. Parameter estimation using hybrid CSOA

To investigate the frequency dependent UC modelling, for each frequency band (ω_p), the respective model parameters are estimated by formulating the estimation task as an optimization problem. The above optimization problem has been solved by a hybrid algorithm i.e. hybrid CSOA, which combines a local search technique, i.e. NMS algorithm with a global search approach, i.e. CSOA.

CSOA is an enhanced variant of seeker optimization algorithm (SOA) [20], which simulates the behavior of group of seekers and their means of information exchange to obtain the optimal solution by wider exploration of the search space. SOA and its variants have been widely used by researchers in different engineering applications like filter design [21,22], system modelling [17,23], power systems [24] etc.

The hybrid algorithm starts with CSOA, which includes a chaotic component to help the algorithm to escape from any unconditional

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