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SUPERCAPACITOR LIFETIME MODELING AND RELIABILITY-ORIENTED SYSTEM DESIGN IN ENERGY STORAGE APPLICATION

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ABSTRACT

Supercapacitor (SC) is a novel and potential device in energy storage system (ESS), which owns the characteristics of high power density, fast response time, and long lifetime expectancy. As closely related to the reliability of SCs, lifetime estimation plays an important role in performance evaluation and device sizing. This paper presents a review on SC lifetime models, and depicts the reliability-oriented design procedure of SCs system. At first, physics-of-failure (PoF) mechanism is discussed as the fundamental of lifetime modeling. Afterwards different models from literature are analyzed systematically according to different concern of stressors. At last, a reliability-oriented design procedure is given for SCs system, from the perspective of users. This paper serves to provide a clear picture of the state-of-the-art research in lifetime modeling, and give some application-oriented suggestions and future research directions for SCs.

Keywords: supercapacitor, energy storage system, lifetime model, reliability-oriented design

NOMENCLATURE

Abbreviations

ESS	Energy storage system
SC	Supercapacitor
O&M	Operation and maintenance
LCOS	Levelized cost of storage
PoF	Physics-of-failure
ESR	Equivalent series resistance
EDLC	Electric double-layer capacitor
PC	Pseudo-capacitor
HSC	Hybrid supercapacitor
HESS	Hybrid energy storage system

Symbols

L	Real lifetime
V	Operating voltage
T	Operating temperature
I	Operating current
L_0	Reference lifetime
S_T	Temperature related scaling factor
S_V	Voltage related scaling factor
S_I	Current related scaling factor
E_a	Activation energy (in eV)
k	Boltzmann constant (8.617e-5 eV/K)
c_T	Temperature related parameter
k_T	Temperature related parameter
T_0	Reference temperature
c_V	Voltage related parameter
k_V	Voltage related parameter
V_0	Reference voltage
m	Power of the voltage multiplier
c_I	Current related parameter
k_I	Current related parameter
I_0	Reference current
C_0	Initial capacitance of the SC
I_{RMS}	RMS current

1. INTRODUCTION

ESS plays a crucial role in the enhancement of grid stability, penetration of renewable energy resources, and efficiency improvement of energy systems [1]. With high power density, fast response time, and long lifetime expectancy as its outstanding characteristics, the rising energy storage device SC is widely used in numerous applications such as wind power generation, railway transportation, electric vehicles, power grid, et al [2–5]. Such extensive applications require SCs to face challenges such as cost reduction pressure in the whole

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life cycle, maintenance-free demands, and stringent operation environment (e. g. high applied voltage, high ambient temperature, et al.).

To solve these challenges, the reliability of SCs needs to be studied, in order to understand the performance and real lifetime in practical conditions rather than test conditions given by the datasheet, and help design appropriate products for specific requirements, so as to reduce the cost of O&M and optimize the LCOS. Several lifetime models [6,7,16,8–15] have been employed to predict the operation lifetime, but there is still a lack of systematical analysis especially from viewpoint of failure mechanism. Given these requirements, this paper reviews different lifetime models of SCs in a systematical way, and proposes some suggestions for system design based on reliability. Besides, the PoF mechanism is also discussed as the fundamental of lifetime modeling.

2. POF MECHANISM OF LIFETIME MODELING FOR SCS

Lifetime models are the fundamental of lifetime prediction, online condition monitoring, and O&M for SCs. The chemical reaction on the electrode and the decomposition of solvent are the main failure mechanisms of SCs [17]. They produce solid and gaseous products, which will block porosity of SCs and increase internal pressure, leading to capacitance reduction and ESR increase further (as shown in Fig 1). According to a number of research results [6,7,16,8–15], the operating temperature, voltage, and current are the critical

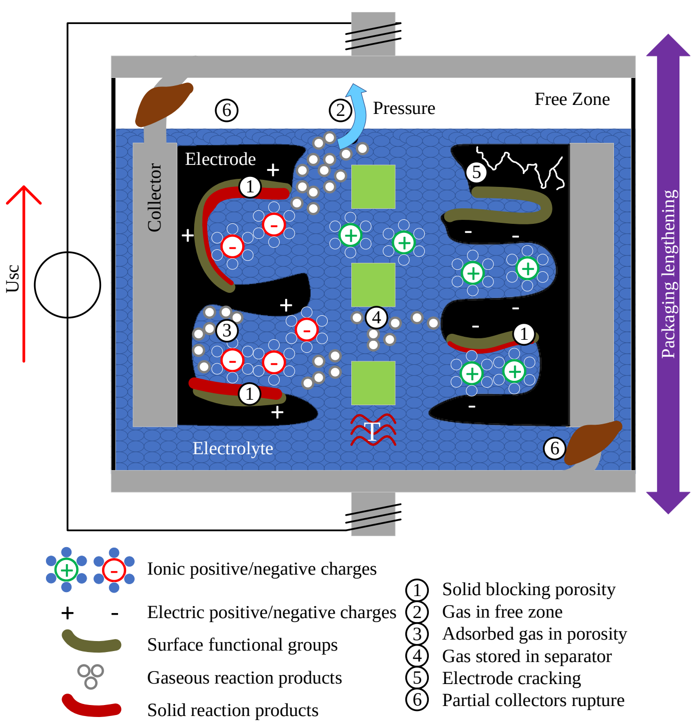

Fig 1 Failure mechanisms of a SC cell [17]

stressors of failure, which will speed up the rate of chemical reaction and solvent decomposition, playing important roles in aging rate and lifetime expectancy. Thus, the lifetime model can be established as a function of these stressors.

3. STRESSOR-BASED LIFETIME MODELS

On the basis of Eyring law [18], the chemical reaction rate can be modeled as a function of stressors, and so is the time to failure (i.e. lifetime). Therefore, a general lifetime model of SCs can be given:

$$L(T,V,I)=L_0\times S_T\times S_V\times S_I \qquad (1)$$

where the three S terms represent the impact of T, V, and I respectively, and can be modeled further with different function form, as depicted below.

3.1 The modeling of T

The impact of T on lifetime can be modeled as a logarithmic form with natural constant as the base, i.e. $e^{\frac{E_a}{k}\left(\frac{1}{T}-\frac{1}{T_0}\right)}$ [6–9,16]. It is based on Arrhenius law [18], with the assumption that lifetime is proportional to the chemical reaction time and the inverse reaction rate.

Other researchers modeled the impact of T to the form of $c_T^{\frac{T_0-T}{k_T}}$, with an ordinary constant as the base instead of e, and the power term also changed [10–14,17]. It can be proved that this model is a special form of the former one, which can be derived when E_a equals to a specific value [9]. Whereas, this model is also popular because of simplicity, and of course the applicability needs to be considered when using.

3.2 The modeling of V

According to several research results, the impact of V on lifetime can be modeled as $c_V^{\frac{V_0-V}{k_V}}$ [10–15,17].

Besides, N. Williard et al. [16] applied a model usually used for electrolytic capacitor to predict the lifetime of SC, i.e. $\left(\frac{V_0}{V}\right)^m$. In addition, considering the degradation occurs relatively slowly with increasing voltage until it reaches a point at which degradation accelerates, another model is proposed, i.e. $-e^{m(V-V_0)}$.

3.3 The modeling of I

I_{RMS}, the effect current in a charge/discharge cycle, is used to represent the effect of cycling on the lifetime of SCs [11,19], which can be modeled as $c_I^{\frac{I_0-I}{k_I}}$ [11,13,15] or $e^{-\frac{k_I I}{C_0}}$ [14].

Different model forms of each stressor can be summarized in Table 1. The marks in the last column denote each model form for short, which will be used in the following analysis.

Table 1 Summary of model forms

Stressor	Model form	Mark
T	$e^{\frac{E_a}{k}\left(\frac{1}{T}-\frac{1}{T_0}\right)}$	T1
	$c_T^{\frac{T_0-T}{k_T}}$	T2
V	$c_V^{\frac{V_0-V}{k_V}}$	V1
	$\left(\frac{V_0}{V}\right)^m$	V2
	$-e^{m(V-V_0)}$	V3
I	$c_I^{\frac{I_0-I}{k_I}}$	I1
	$e^{-\frac{k_I I}{C_0}}$	I2

In practical applications, models for different stressors need to be combined to form an appropriate overall model for the specific requirements. Table 2 analyzes the configuration of different lifetime models in literature. It should be noted that the forms listed in Table 2 are the basic parts of the lifetime model, and there may exist some other components of scaling factor. For example, in [15], the authors added a nonlinear pre-exponential factor into the lifetime model to improve the prediction accuracy.

There are some rules of parameter value in lifetime models. For example, according to several manuals of leading SC manufacturers [20–22] and numerous test results [9,13,19,23], the lifetime is reduced by half when the applied voltage increases by 0.2 V, or the temperature increases by 10 ℃ or 10 K. Therefore, k_T in T2 is usually assigned to be 10 ℃ or 10 K, and k_V in V1 is 0.2 V. c_T and c_V are close to 2, according to regression analysis of test results [12]. The analysis on the current is similar, which deduces k_I in I1 is 30 A, and c_I is close to 2 [11]. These rules can be useful when predicting the lifetime roughly. Whereas, if conditions allow, it is better to conduct specific tests in order to improve the prediction accuracy.

Table 2 Comparison of different lifetime models in literature

Dominant stressor	Inclusive model form of stressor	L_0[h]	Reference
T	T1	6.17e4	[6]
		*1.35e4	[7]
		*1.80e5	[8]
		*2.68e5	[9]
T, V	T2, V1	5.87e4	[11,13]
		8.76e4	[12]
		5.17e4	[14]
		8.64e4	[15]
	T1, V2	8.76e4	[16]
	T1, V3		
T, V, I	T2, V1, I2	5.87e4	[11]
	T2, V1, I1	*2.65e4	[14]

* The value is not given by the reference directly, but calculated based on test results.

4. RELIABILITY-ORIENTED SCS SYSTEM DESIGN

In practical applications, there are different system solutions for SC-based ESS, according to specific requirements. For example, HESS with more than one kind of energy storage device is popular in various applications aiming to optimally exploit the benefits of different ESS elements [24,25]. It should be noted that SCs are usually used as a module (series and parallel connected inside) in applications, as the rated voltage of a cell is typically low (e.g. 2.7 to 5V).

With requirements for better performance of ESS, the design focus is not only from aspects of electrical specifications, but also from those of thermal stress, cost, and reliability. This section presents a reliability-oriented design procedure for SCs system (as shown in Fig 2), suitable for both solutions of all SC-based ESS and HESS. It takes into account key points of system design, and highlights reliability as the guideline for the overall design procedure. Key steps are discussed as follows:

(a) System level analysis. Some system requirements and design constrain need to be considered from a global perspective. ESS configuration and key design limits are defined in this step. Mission profile, the representation of all relevant conditions that the system will be exposed to in all of its intended application throughout its entire lifecycle [26], is highlighted as the reliability-related factor, except those of electrical and thermal. It should be noted that these system level considerations need to be premeditated, but also updated and improved during the following procedure.

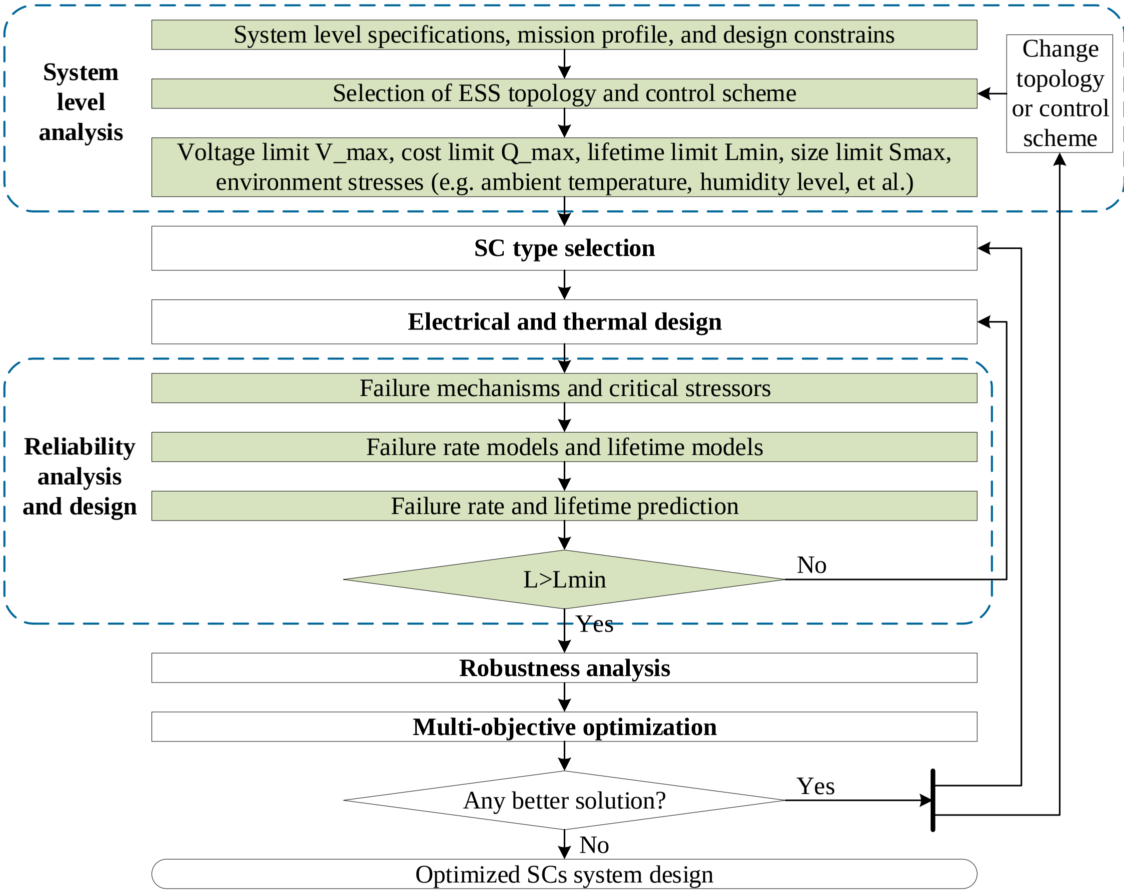

Fig 2 Schematic of reliability-oriented design procedure

(b) SC type selection. Based on system requirements and performance comparison of different SCs, SC type can be selected. Major specifications include power density, energy density, and discharge time, as shown in Fig 3 [27–29].

(c) Electrical and thermal design. This step basically includes selection of voltage and capacitance, number calculation of series-/parallel-connected cells, and cooling design, which can refer to [30,31].

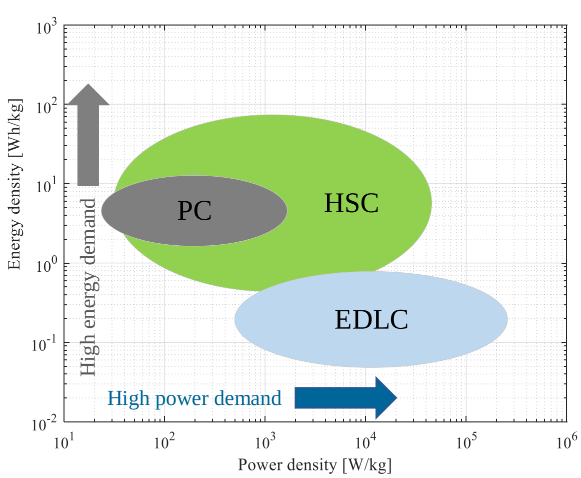

Fig 3 Comparison of SCs in Ragone Plot

(d) Reliability analysis and design. Unlike conventional design step (e.g. electrical or thermal), this step considers not only the initial conditions, but also the operating conditions during the whole life cycle for SCs (i.e. mission profile). Failure mechanisms and critical stressors are analyzed, then failure rate models and lifetime models are established and failure rate and lifetime predicted. During the process, parameters of SCs are set to be realistic, which vary with mission profile, rather than rated in conventional design (e.g. nominal capacity, rated applied voltage, tested ambient temperature). With realistic parameters, the reliability is analyzed and suitable reliability design is selected for the specific system requirements. It could be seen that lifetime model plays a vital role in this step, which is not only the basis of design lifetime, but also the basis of feedback to the former two steps, forming a close loop to improve the overall design.

(e) Robustness analysis and multi-objective optimization. Robustness analysis mainly considers the analysis of design margin [26]. After that, a multi-objective optimization can be conducted, including reliability, robustness, cost, and size, and outputs an optimized SCs system design.

In a word, the idea of reliability is the guideline throughout the whole design procedure, and coupled with conventional ideas of electrical, thermal, cost, size, et al., to obtain a comprehensive optimized solution for a given ESS. Paying more attention to reliability, this design procedure serves to extend the range of multi-objective optimization, and reduce the failure and LCOS during the operating life cycle.

5. CONCLUSION

This paper gives an overview on lifetime models of SC, and analyzes the model structure systematically. Then a reliability-oriented design procedure based on the feedback of lifetime prediction is presented. Some research directions can be addressed:

(a) Establishing a failure mechanism dominant lifetime model, or deriving the dominant failure mechanism from the existing model, in order to reflect the impact of respective failure mechanism on lifetime directly.

(b) System-level thermal modeling. It is not a simple linear combination from device-level (cell) thermal modeling to system-level (stack). An improved system-level thermal modeling is helpful for more realistic lifetime prediction and reliability assessment.

(c) Large amounts of data accumulation and analysis. As mission profile is the vital basis of lifetime prediction and reliability assessment, massive data need to be accumulated from operation and test, as well as properly analyzed.

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