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Degradation and Reliability Evaluation for Passive RC Filters Based on Kirchhoff's Circuit Laws

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Abstract: Passive RC filters are usually required with stable performance and high reliability in order to perform well in their applications of signal processing, noise suppression, and frequency selection. However, current methods cannot construct the physical relationship between the performance degradation and reliability of filters and their components. To address this problem, we take passive low-pass RC filters as the research object and propose a degradation and reliability evaluation method based on Kirchhoff's circuit laws. Firstly, the performance modeling of passive RC filters is conducted based on Kirchhoff's circuit laws. Then, considering the degradation of filter components, including resistors and capacitors, the degradation model of passive RC filters is constructed. Next, combined with the function requirements of passive RC filters, the margin model is constructed, and finally, the reliability model is established. A practical case of passive RC filters is applied to illustrate the practicability and advantages of the proposed method.

Keywords: Passive low-pass RC filter, degradation modeling, reliability evaluation, Kirchhoff's circuit law, performance.

1. Introduction

In electronic systems, passive RC filters, with their advantages of simple structure, low cost, and stable performance, are widely used in the fields of signal processing, noise suppression, and frequency selection. In practical applications, passive RC filters are subject to various environmental stresses and operating conditions, such as temperature, humidity, and voltage, which can cause the degradation of filter components, and further lead to the degradation of filter performance and reliability. Therefore, it is crucial to identify the physical relationships between the performance degradation and reliability of passive RC filters and their components.

In the field of degradation and reliability modeling of electronic devices, current studies can be mainly classified into three types: physics of failure methods, failure logic methods, and data-driven methods.

Physics of failure methods leverage the knowledge and understanding of the processes and mechanisms that induce failure to predict the reliability of products. Jiao et al. (Jiao, De et al.

2019) synthetically used the digital model, CFD, and FEA to analyze the failure points of the circuit board and fit the failure distribution by simulation data for reliability evaluation. Wang et al. (Wang, Kang, and Chen 2021) used Bayesian deep learning to deduce the failure mechanisms and cloud computing to solve the copious samples, then reliability simulation was conducted with the physics of failure theory and failure behavior model to evaluate the mean time between failures. Sun et al. (Sun, Fan, et al. 2016) integrated SPICE simulation, compact thermal modeling, and Monte Carlo simulation to predict the failure rate distribution of electrolytic capacitors in LED drivers. It can be seen from existing studies that physics of failure methods applied to electronic devices primarily focus on the failure issues caused by stress limits, such as thermal failure, vibration failure, and fatigue failure, and rarely consider the reliability issues related to the performance of electronic devices not satisfying functional requirements.

Failure logic methods mainly focus on the failure logic relationship between the product reliability and failure rates of components. Thangavel et al. (Thangavel, Raghavendra Rao, et al. 2024) evaluated the reliability of a three-phase interleaved step-up DC-DC converter in electric vehicles based on the Markov chain, in which the failure rates of components are determined through a military handbook. Vlasov (Vlasov 2024) constructed the reliability model of reversible circuits with 2D second-order cellular automata. Chen et al. (Chen, Yang et al. 2015) presented a reliability evaluation method for electronic systems considering five types of failure logics including trigger, acceleration, inhibition, accumulation, and competition. Such methods utilize failure logic relationship, which diminishes the accuracy and interpretability of physical mechanisms; on the other hand, they mainly focus on the reliability of electronic products, instead of performance. In addition, some studies pointed out that some assumptions in failure logic methods may not be well-suited for most real-world products (Zio 2016, Zhang, Mahadevan and Deng 2017, Elsayed 2020).

Data driven methods use experimental observations, mainly including performance degradation data and time-to-failure data, to evaluate product reliability based on data analysis technologies. One main type of such methods is the statistical method, which first makes statistical assumptions for data based on mathematical theories, such as probability theory, possibility theory, and uncertainty theory, and then derives performance degradation models and reliability models. Sun et al. (Sun, Fu et al. 2020) developed a multivariate dependent accelerated degradation test model based on a random-effect general Wiener process and D-vine copula with application to a tuner. Haghighi and Bae (Haghighi and Bae 2015) proposed a reliability estimation method for light-emitting diodes from linear degradation and failure time data with competing risks under a step-stress accelerated degradation test. In recent years, with the advancement of artificial intelligence techniques, many related algorithms and models have been increasingly applied to reliability evaluations of electronic products. Zhang and Gao (Zhang and Gao 2023) used the LightGBM machine learning model to compute the junction temperature of IGBTs in photovoltaic inverters and then conducted reliability and lifetime assessment based on the Bayerer model. Baharani et al. (Baharani, Biglarbegian, et al. 2019) applied stacked long short-term memory for collective reliability training and inference across collective MOSFET converters based on device resistance changes. Data driven methods are black box models, offering the statistical characteristics rather than physical mechanisms of the performance degradation and reliability of electronic products.

Though current research has contributed a lot to the performance degradation and reliability modeling of electronic products, they have not constructed the physical relationship between the performance degradation and reliability of electronic devices and their components. Motivated by the above problem, we take passive RC filters as the research object and propose a degradation and reliability evaluation method based on Kirchhoff's circuit laws. The following contributions are highlighted:

(i) Performance, degradation, margin, and reliability models of passive RC filters are established based on Kirchhoff's circuit laws, which are highly physically interpretable.

(ii) The constructed models can recognize the impact of component degradation on the degradation and reliability of passive RC filters.

(iii) The constructed models can account for multiple performance parameters of passive RC filters.

The remainder of this paper is organized as follows. Section 2 presents the degradation and reliability evaluation for passive RC filters. Section 5 provides case studies to illustrate the proposed method. Section 6 concludes the paper.

2. Degradation and Reliability Evaluation for Passive RC Filters

2.1. *Performance Modeling Based on Kirchhoff's Circuit Laws*

A passive RC filter is a filter that passes signals with frequencies lower than a selected cutoff frequency and attenuates signals with frequencies higher than the selected cutoff frequency. The structure of a passive RC filter is shown in Fig. 1, where $U(t)$ is the power voltage, E is the DC power voltage, U_0 and f are the amplitude and the frequency of the alternating current (AC) power voltage, respectively, R is the resistance of the resistor, C and ESR are the capacitance and the equivalent series resistance of the capacitor, R_L is the load resistance.

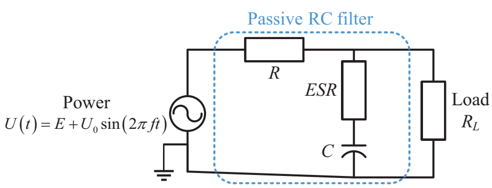

Fig. 1 Structure of a passive RC filter

According to the Kirchhoff's current law, we have

$$i = i_C + i_L \tag{1}$$

where i, i_C, and i_L are the currents passing through the power, the capacitor, and the load resistance, respectively.

According to the Kirchhoff's voltage law, we have

$$\begin{cases} U_R + U_{ESR} + U_C = U(t) \\ U_{ESR} + U_C - U_L = 0 \end{cases} \tag{2}$$

where U_R, U_{ESR}, U_C, and U_L are the voltages on the resistance R, the equivalent series resistance ESR, the capacitance C, and the load resistance R_L, respectively.

Combined with the characteristics of the resistance and the capacitor, we can re-organize Eq. (1) and Eq. (2) as

$$\begin{cases} (i_C + i_L)\cdot R + i_C \cdot ESR + \frac{1}{C}\int i_C \mathrm{d}t = U(t) \\ i_L \cdot R_L - i_C \cdot ESR - \frac{1}{C}\int i_C \mathrm{d}t = 0 \end{cases} \tag{3}$$

Define

$$\mathbf{q} = \begin{bmatrix} \int i_C \mathrm{d}t \\ \int i_L \mathrm{d}t \end{bmatrix}, \dot{\mathbf{q}} = \begin{bmatrix} i_C \\ i_L \end{bmatrix}, \mathbf{Q} = \begin{bmatrix} U(t) \\ 0 \end{bmatrix}$$
$$\mathbf{A} = \begin{bmatrix} \frac{1}{C} & 0 \\ -\frac{1}{C} & 0 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} R+ESR & R \\ -ESR & R_L \end{bmatrix} \tag{4}$$

Then, we can transfer Eq. (3) into its matrix form as

$$\mathbf{A}\mathbf{q} + \mathbf{B}\dot{\mathbf{q}} = \mathbf{Q} \tag{5}$$

Eq. (5) is first-order ordinary differential equations. In order to solve Eq. (5), this section proposes a numerical algorithm based on the Runge-Kutta method, as shown in Algorithm 1.

Algorithm 1 Numerical algorithm for performance parameters of passive RC filters

Initialize:	Define $f(\mathbf{q}, t) = \mathbf{B}^{-1}(\mathbf{Q} - \mathbf{A}\mathbf{q})$ and set step size of physical time $h > 0$ and initial conditions $\mathbf{q}_0$ at initial time t_0.
Step 1	Compute: $\mathbf{q}_{n+1} = \mathbf{q}_n + \frac{h}{6}(\mathbf{k}_{q1} + 2\mathbf{k}_{q2} + 2\mathbf{k}_{q3} + \mathbf{k}_{q4})$, $t_{n+1} = t_n + h$, where $\mathbf{k}_{q1} = f(\mathbf{q}_n, t_n)$, $\mathbf{k}_{q2} = f\left(\mathbf{q}_n + h\frac{\mathbf{k}_{q1}}{2}, t_n + \frac{h}{2}\right)$, $\mathbf{k}_{q3} = f\left(\mathbf{q}_n + h\frac{\mathbf{k}_{q2}}{2}, t_n + \frac{h}{2}\right)$, $\mathbf{k}_{q4} = f(\mathbf{q}_n + h\mathbf{k}_{q3}, t_n + h)$.
Step 3	Compute $\dot{\mathbf{q}}_n = (\mathbf{q}_{n+1} - \mathbf{q}_n)/h$. Then, i_C and i_L are obtained.

Further, the amplitude-frequency characteristics can be computed as

$$H(f)=20\lg\left(\frac{|U_L|}{|U_0(f)|}\right)=20\lg\left(\frac{|i_L\cdot R_L|}{|U_0(f)|}\right) \quad (6)$$

For passive RC filters, the cutoff frequency P_1, DC attenuation P_2, and AC attenuation P_3 are typically three key performance parameters of engineering concern. Based on the above derivations, P_1, P_2, and P_3 can be computed as

$$\begin{aligned} P_1 &= f|_{H=-3} \\ P_2 &= H(f=0) \\ P_2 &= H(f=f_0) \end{aligned} \quad (7)$$

where f_0 is the target frequency.

2.2. *Degradation Modeling Considering Component Degradation*

In practical applications, passive RC filters are subject to various environmental stresses and operating conditions, such as temperature, humidity, and voltage, which can cause the degradation of filter components, and further lead to the degradation of filter performance and reliability. According to existing literature, both the resistors and capacitors in passive RC filters degrade under long-term operation, which is specifically manifested as (Gupta, Yadav et al. 2018, Mallett 2019):

(i) Resistors undergo oxidation in the air, which thins the metal conductive films and further causes an increase in the resistance. High temperatures can accelerate the degradation process of resistors.

(ii) The evaporation of electrolytes is the primary degradation mechanism of capacitors, which thickens the electrolyte and further leads to a decrease in the capacitance and an increase in the equivalent series resistance. High temperatures can accelerate the degradation process of capacitors.

Based on the above degradation mechanism analysis, it is considered that the resistance R of the resistor, and the capacitance C and the equivalent series resistance ESR of the capacitor are subject to degradation. Considering that high temperature can accelerate the degradation of R, C, and ESR, and there always exists fluctuation during the degradation (Li 2022), the degradation processes of $R(\vec{t})$, $C(\vec{t})$, and $ESR(\vec{t})$ are modeled as

$$\begin{aligned} R(\vec{t}) &= R_0+\exp\left(\alpha_{R0}+\alpha_{R1}\varphi(T)\right)\vec{t}^{\,\beta_R}+\sigma_R B(\vec{t}) \\ C(\vec{t}) &= C_0-\exp\left(\alpha_{C0}+\alpha_{C1}\varphi(T)\right)\vec{t}^{\,\beta_C}+\sigma_C B(\vec{t}) \\ ESR(\vec{t}) &= ESR_0+\exp\left(\alpha_{ESR0}+\alpha_{ESR1}\varphi(T)\right)\vec{t}^{\,\beta_{ESR}} \\ &\quad +\sigma_{ESR}B(\vec{t}) \end{aligned} \quad (8)$$

where $\vec{t}$ is the degradation time, indicating the degradation irreversibility; R_0, C_0, and ESR_0 are the initial values; α_{R0}, α_{C0}, α_{ESR0}, α_{R1}, α_{C1}, and α_{ESR1} are constants related to the degradation rates; T is the temperature in K; $\varphi(T)$ is a normalization function of T, shown in Eq. (9); β_R, β_C, and β_{ESR} are the nonlinear coefficients of the degradation processes; σ_R, σ_C, and σ_{ESR} are the diffusion coefficients; $B(\vec{t})$ is the Brownian motion with stationary independent increments following the normal probability distribution N with expected value 0 and variance $\vec{t}$, i.e., $B(\vec{t})\sim N(0,\vec{t})$.

$$\varphi(T)=\frac{\dfrac{1}{T^L}-\dfrac{1}{T}}{\dfrac{1}{T^L}-\dfrac{1}{T^U}} \quad (9)$$

where T^L and T^U are the lowest and highest values of T, respectively.

By substituting the degradation models (8) of resistors and capacitors into the performance models (7) of passive RC filters, the degradation models of passive RC filters are obtained, denoted as $P_1(\vec{t})$, $P_2(\vec{t})$, and $P_3(\vec{t})$. In order to calculate $P_1(\vec{t})$, $P_2(\vec{t})$, and $P_3(\vec{t})$, a Monte Carlo simulation based on Algorithm 1 is presented, as shown in Algorithm 2.

2.3. *Margin Modeling with Function Requirements*

As mentioned above, a passive RC filter is designed to pass signals with frequencies lower than a selected cutoff frequency and attenuate signals with frequencies higher than the selected cutoff frequency. Therefore, the cutoff frequency of passive RC filters should be as close as possible to the selected cutoff frequency to achieve good filtering performance. Generally, it can be considered that a passive RC filter has met its function requirements when its cutoff frequency falls a specified range of frequencies, i.e., $P_1 \in [P_1^L, P_1^U]$. Additionally, a passive RC filter should optimally retain the DC signals and effectively attenuate the AC signals above the selected cutoff frequency. It requires that the DC attenuation is below a specified value and the AC attenuation is above a specified value, i.e., $P_2 > P_2^L$ and $P_3 < P_3^U$. Based on the above analysis, the margin models of passive RC filters can be constructed as

$$\begin{aligned} M_1(\vec{t}) &= \min\left\{P_1(\vec{t}) - P_1^L, P_1^U - P_1(\vec{t})\right\} \\ M_2(\vec{t}) &= P_2(\vec{t}) - P_2^L \\ M_3(\vec{t}) &= P_3^U - P_3(\vec{t}) \end{aligned} \tag{10}$$

Then, the comprehensive margin $M(\vec{t})$ of passive RC filters can be regarded as the minimum of all the margins, i.e.,

$$M(\vec{t}) = \min\left\{M_1(\vec{t}), M_2(\vec{t}), M_3(\vec{t})\right\} \tag{11}$$

In order to calculate $M_1(\vec{t})$, $M_2(\vec{t})$, $M_3(\vec{t})$, and $M(\vec{t})$, a Monte Carlo simulation based on Algorithm 1 is presented, as shown in Algorithm 2.

2.4. *Reliability Modeling*

According to the belief reliability theory, the reliability of passive RC filters can be defined as the probability that the margins of passive RC filters are greater than zero. According to sections 2.1-2.3, for the margins $M_1(\vec{t})$, $M_2(\vec{t})$, and $M_3(\vec{t})$ of each performance, the associated reliability is

$$\begin{aligned} R_1(\vec{t}) &= \Pr\left\{M_1(\vec{t}) > 0\right\} \\ R_2(\vec{t}) &= \Pr\left\{M_2(\vec{t}) > 0\right\} \\ R_3(\vec{t}) &= \Pr\left\{M_3(\vec{t}) > 0\right\} \end{aligned} \tag{12}$$

where Pr is the probability measure.

Then, regarding the comprehensive margin $M(\vec{t})$, the associated reliability is

$$R(\vec{t}) = \Pr\left\{M(\vec{t}) > 0\right\} \tag{13}$$

In order to calculate $R_1(\vec{t})$, $R_2(\vec{t})$, $R_3(\vec{t})$, and $R(\vec{t})$, a Monte Carlo simulation based on Algorithm 1 is presented, as shown in Algorithm 2.

Algorithm 2	Numerical algorithm for degradation, margin, and reliability models of passive RC filters
Initialize:	Set degradation time $\vec{t}_m > 0$, the number of degradation time intervals m, step-size of physical time $h > 0$, initial conditions $\mathbf{q}_0$ at initial time t_0, and the number of simulations N_{sim}.
Step 1	Divide the closed degradation time $[0, \vec{t}_m]$ into $0 = \vec{t}_0 < \vec{t}_1 < \vec{t}_2 < \cdots < \vec{t}_m$, where $\vec{t}_i = \frac{i}{m}\vec{t}_m$.
Step 2	Randomly generate samples $\varepsilon_1^{(l)}(\vec{t}_i)$, $\varepsilon_2^{(l)}(\vec{t}_i)$, and $\varepsilon_3^{(l)}(\vec{t}_i)$ based on the probability distributions $\sigma_R B(\vec{t}_i)$, $\sigma_C B(\vec{t}_i)$, and $\sigma_{ESR} B(\vec{t}_i)$ for $i = 0, 1, 2, \cdots, m$, respectively.
Step 3	Based on Algorithm 1, combined with Eq. (8), utilize $\varepsilon_1^{(l)}(\vec{t}_i)$, $\varepsilon_2^{(l)}(\vec{t}_i)$, and $\varepsilon_3^{(l)}(\vec{t}_i)$ to compute $\mathbf{q}_n^{(l)}$ and $\dot{\mathbf{q}}_n^{(l)}$ at t_n for $n = 0, 1, 2, \cdots$, and at degradation time $\vec{t}_0, \vec{t}_1, \vec{t}_2, \cdots, \vec{t}_m$, respectively.
Step 4	According to Eq. (7), compute performance $P_1^{(l)}(\vec{t}_i)$, $P_2^{(l)}(\vec{t}_i)$, and $P_3^{(l)}(\vec{t}_i)$ for $i = 0, 1, 2, \cdots, m$.
Step 5	According to Eq. (10) and Eq. (11), compute margins $M_1^{(l)}(\vec{t}_i)$, $M_2^{(l)}(\vec{t}_i)$, $M_3^{(l)}(\vec{t}_i)$, $M^{(l)}(\vec{t}_i)$ for $i = 0, 1, 2, \cdots, m$.
Step 6	Repeat step 2 to step 5 for N_{sim} times, and compute the numbers of $M_1^{(l)}(\vec{t}_i) > 0$, $M_2^{(l)}(\vec{t}_i) > 0$, $M_2^{(l)}(\vec{t}_i) > 0$, and $M^{(l)}(\vec{t}_i) > 0$ for $l = 1, 2, \cdots, N_{sim}$ and $i = 0, 1, 2, \cdots, m$, denoted as $N_1(\vec{t}_i)$, $N_2(\vec{t}_i)$, $N_3(\vec{t}_i)$, and $N(\vec{t}_i)$, respectively.
Step 7	Compute $R_1(\vec{t}_i) = N_1(\vec{t}_i)/N_{sim}$, $R_2(\vec{t}_i) = N_2(\vec{t}_i)/N_{sim}$, $R_3(\vec{t}_i) = N_3(\vec{t}_i)/N_{sim}$, $R(\vec{t}_i) = N(\vec{t}_i)/N_{sim}$.

3. Case Study

In this case study, we select the passive RC filters composed of a resistor with model

RN1/2WS160ΩFT/BA1 and a capacitor with model VT1C100M0405, and conduct a reliability experiment. The basic parameters of the resistors and capacitors are obtained based on their handbooks and the reliability experiment, listed in Table 1.

Table 1. Basic parameters of passive RC filters

Parameters	Values	Parameters	Values
R_0	159.89	ESR_0	7.70
α_{R0}	-5.70	α_{ESR0}	-8.43
α_{R1}	1.88	α_{ESR1}	6.95
β_R	0.77	β_{ESR}	1.00
σ_R	0.18	σ_{ESR}	0.40
C_0	9.79×10^{-6}	P_1^L	85
α_{C0}	-22.74	P_1^U	110
α_{C1}	5.11	P_2^L	-0.5
β_C	1.12	P_3^U	-3
σ_C	4.01×10^{-5}	/	/

According to the proposed method, we can first obtain the degradation of resistance, capacitance, and the equivalent series resistance under different temperatures (set to be 20-80°C), shown in Fig. 2. Further, the performance degradation, margin, and reliability of passive RC filters can be computed, shown in Fig. 3, Fig. 4, and Fig. 5, respectively.

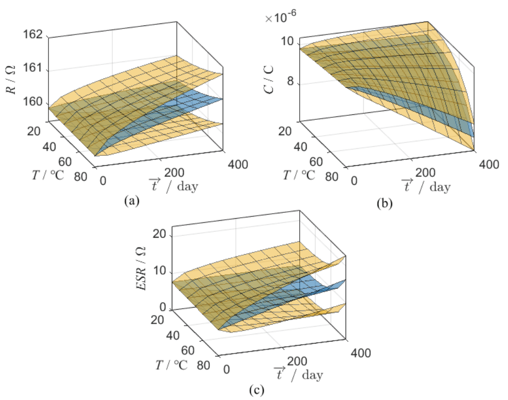

Fig. 2 Degradation of resistance, capacitance, and the equivalent series resistance

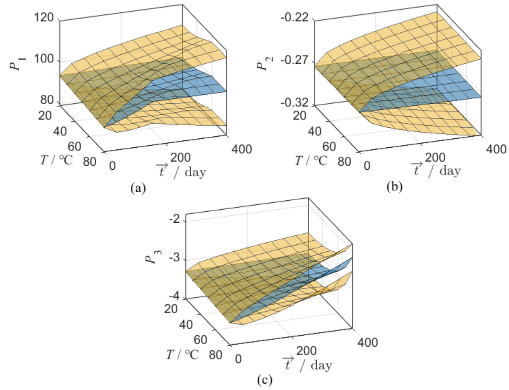

Fig. 3 Performance degradation of passive RC filters

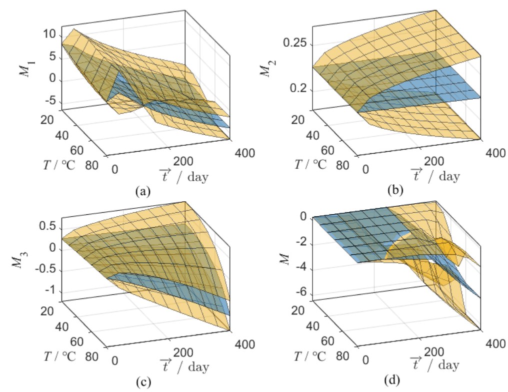

Fig. 4 Margins of passive RC filters

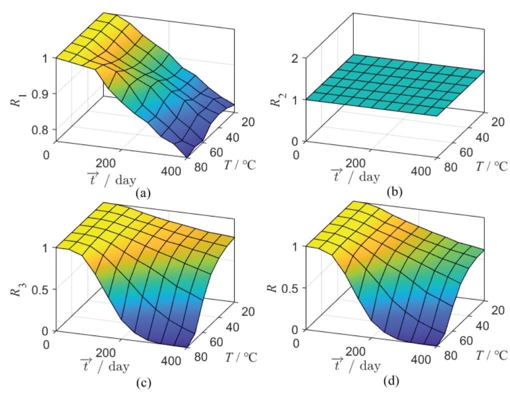

Fig. 5 Reliability of passive RC filters

Based on the above results, it can be observed that the performance, margin, and reliability of passive RC filters degrade over time, and the higher the temperature is, the faster the degradation occurs. Combined with Fig. 4 and Fig. 5, it can be seen that the DC attenuation P_2 consistently maintains a high margin and reliability. Therefore, in engineering practice, more attention can be focused on the cutoff frequency P_1 and AC attenuation P_3, with P_1 being of greater concern at low temperatures and P_3 at high temperatures. Moreover, since this method has established the physical relationship between the performance degradation, margin, and reliability of passive RC filters and the degradation of their components, resistors, and capacitors, it not only allows for an understanding of the degradation laws of the performance, margin, and reliability of passive RC filters, but also identifies the critical components and the use scenarios that require attention. This can provide specific guidance for product design and maintenance.

4. Conclusions

To construct the physical relationship between the performance degradation and reliability of electronic devices and their components, this paper takes passive RC filters as the research object and proposes a degradation and reliability evaluation method based on Kirchhoff's circuit laws. The following conclusions are drawn.

(i) Based on Kirchhoff's circuit laws, considering the component degradation and the function requirements of passive RC filters, the performance, degradation, margin, and reliability models of passive RC filters are constructed.

(ii) A practical case of passive RC filters is applied to illustrate the practicability and advantages of the proposed method. The results show that the proposed method not only allows for an understanding of the degradation laws of the performance, margin, and reliability of passive RC filters, but also identifies the critical components and the use scenarios that require attention. This can provide specific guidance for product design and maintenance.

In addition to the study in this work, the performance oriented reliability modeling for complex electronic devices is indeed worthwhile for future research.

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