Comparative Analysis of the Reliability of Passive Power Decoupling Components for Photovoltaic Microinverters

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Abstract

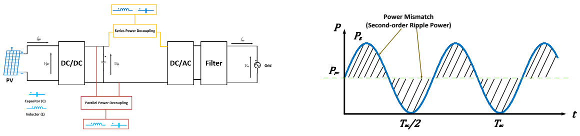
Photovoltaic (PV) microinverters serve as plug-and-play electrical devices integrating a single PV module with a power conditioning circuit, facilitating the conversion of solar energy into alternating current (AC). However, in typical single-phase grid-connected PV systems, a power mismatch or imbalance is often observed in the output waveforms under ideal conditions. To tackle this challenge, passive components such as capacitors and inductors are employed as auxiliary ripple energy storage devices to mitigate this time-varying double-line frequency power, also known as second-order ripple power. Despite the widespread use of aluminum capacitors due to their low cost and high energy density for nullifying excessive ripple power, their shorter lifespan compared to PV panels has prompted the exploration of alternative methods, such as using inductors possessing similar ripple cancellation properties. Therefore, this paper conducts a comprehensive comparative analysis of these two devices as decouplers for grid-connected PV systems, focusing on reliability, energy density, and estimated lifetime. Simulation results obtained using MATLAB demonstrate that, overall, an inductor-based decoupler outperforms a capacitor in terms of performance.

1 Introduction

The reduction in the overall cost of photovoltaic (PV) panels over the past three decades has significantly contributed to their rapid integration with new and emerging technologies[1]. Compared to traditional central-inverter or string-inverter systems, PV microinverters (also known as AC modules), as illustrated in Fig. 1a, are integrated electrical devices combining a single PV module and a single power conditioning system for the direct conversion of abundant solar energy into alternating current (AC) at high efficiency for end users.

In the context of a single-phase grid-connected PV system, a transient power mismatch is usually observed between the constant input power of the PV panel and the AC output at the grid, contributing to inaccuracies in power control algorithms and a reduction in overall system efficiency[2]. According to relevant literature, one of the most widely adopted techniques for suppressing this power imbalance is the utilization of capacitors. In their basic form, these capacitors, which can be placed on either the PV-side, DC-link side, or AC-side, act as buffers to prevent the backflow of unwanted power[2]. Despite its numerous advantages, including cost, the usage of this passive component (especially aluminum) as an auxiliary ripple storage element has been presumed to have a significantly lower expected lifetime compared to the 25-year warranty of a typical PV panel.

An in-depth analysis of the second-order ripple waveform in Fig. 1b shows that the double-line frequency is an offshoot of superimposed AC components on the output waveform. Thus, by applying ripple cancelation techniques, the power mismatch can be significantly reduced[2].



(a) (b)

Fig. 1 Operating principles of a typical PV microinverter (a) block diagram description (b) power decoupling requirements for a single-phase inverter (P_{pv}: DC power from PV module; P_g: Instantaneous AC output power).

Inductive devices, which are coils wound around a magnetic core, have also been proven to exhibit similar power decoupling characteristics as a typical capacitor[2]. Hence, this paper conducts an extensive evaluation of the behavior and features of these two passive power decoupling components for effective ripple cancellation in grid-connected PV systems.

2 Evaluation Criteria

In assessing the performance of the power electronics system depicted in Fig. 1a, several evaluation criteria have been proposed by academics and technicians for specific conditions. These criteria include failure rate estimation[3], mean-time-between-failure (MTBF) estimation[4], and lifetime estimation[5]. They provide clarity on (a) the number of components failing or developing faults under specified conditions and (b) how long an electronic component will survive under specified conditions.

Under normal operating conditions, the behavior and characteristics of any electronic component depend on various application-specific conditions, with the most crucial parameter being its maximum operating temperature. Thus, the unifying constraint for these criteria is the specified maximum temperature at which the passive component is expected to operate without failure. For this analysis, failure is considered any event that places the PV microinverter out of service and into a state of repair, while MTBF quantifies the elapsed time between inherent failures[3,4].

Several mathematical equations in literature have been proposed to predict the remaining useful life and overall expected lifetime of different types of capacitors used in power electronics systems. These equations derive from a general rule of thumb known as the 10-degree Celsius rule, interpreted as *"for every 10℃ rise in operating temperature, the lifetime of a capacitor is halved"*[5]. In their basic form, these equations are derivatives of the Arrhenius equation, mathematically identical to the power law, denoted as[6]

$$y = kx^b, \qquad (1)$$

where y and x are quantities, k is a constant parameter, and b is the exponential parameter determining the rate of change of the two quantities.

Based on these interconnected relationships, a mathematical equation for estimating the lifetime of an inductor can also be derived following the same rule of thumb. After an extensive survey of relevant technical guides and specifications, some key information emerges: (a) the maximum allowable temperature rise

Table 1 Comparison of the performance of the two passive components as power decouplers in PV-connected systems (a) Lifetime estimation (b) Military handbook (c) Internal properties.

(a) Lifetime Estimation[5]				
Component			Time [Hours]	Time [Years]
Inductor			211,800	70
Capacitor	Aluminum	Radial Type	10,940	4
		Surface Mount	79,640	30
	Film		69,780	20

(b) Military Handbook[3,4]		
Component	Failures [$/10^6$ *Hours*]	MTBF [Hours]
Inductor	1.08×10^{-5}	925,900
Capacitor	8.55×10^{-3}	117,000

(c) Internal Property[7,8]		
Component	Energy Density [$10^{-5} J/m^3$]	Decoupler Volume [m^3]
Inductor (Air Core)	91.86	1,171
Capacitor (Dry Paper)	47.70	209.4

can be interpreted as a percentage fraction of the reference temperature, and (b) the relationship between the current flowing through an inductor and its operating temperature is also exponential. Since an inductor comprises, a coil wound around a long-lasting magnetic core, it can be inferred that the lifetime of an inductor quadruples for every 10℃ decrease in its operating temperature. Based on this theoretical explanation and using (1), the mathematical equation for estimating the lifetime of an inductor can be expressed as

$$L_{inductor} \approx m \times 4^{\frac{T_{ref}-T_{op}}{10}}, \qquad (2)$$

where $m \approx \frac{T_{op}}{T_{ref}} \times 100$ is the relative percentage increase in temperature, T_{ref} is the maximum reference temperature specified in a typical manufacturer's datasheet, and T_{op} is the specified operating temperature. Finally, considering that passive components are energy storage elements, this paper also compares each component's energy density and volumetric size using well-defined existing explicit mathematical equations[7,8].

3 Results and Discussions

For this analysis, the two passive components are evaluated based on the specifications of a commercial microinverter technology[9] using MATLAB. A comprehensive summary of the obtained simulation results is outlined in Table 1. Although the widely used radial-type aluminum capacitor is relatively cheaper, its overall estimated lifetime is about one-fifth of a typical PV panel. While direct replacement using a surface-mount aluminum or film capacitor can increase the lifetime to match a typical PV panel under ideal conditions, the estimated lifetime of an inductor-based power decoupler is estimated to be more than three times longer than that of a typical PV panel.

Similarly, evaluation of the passive components based on shows that inductor-based decouplers have a longer MTBF when compared with that of a capacitor at the same operating temperature of 65℃[3,4]. However, in terms of weight using the

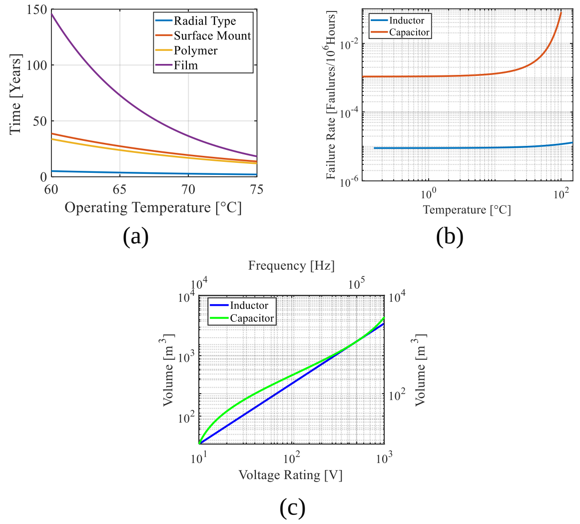


Fig. 2 Simulation results obtained using MATLAB (a) Lifetime estimation[5] (b) Military handbook[3,4] (c) Internal properties[7,8].

most readily available materials[7,8], the volume of an inductor-based power decoupler is about six times larger than that of the capacitor when operating at the same converter switching frequency.

4 Conclusion

This paper conducted a comparative analysis of the capabilities of inductors and capacitors as auxiliary ripple energy storage devices for applications in grid-connected PV systems. The analysis justified why these two decoupling techniques can be used interchangeably, but also highlighted a tradeoff between various constraints, particularly estimated lifetime, MTBF, and the weight of these energy storage devices.

5 Acknowledgments

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1. Introduction

- **Photovoltaic (PV) microinverters** serve as **plug-and-play electrical devices** that integrate a single PV module with a power conditioning circuit, facilitating the **conversion of solar energy into alternating current (AC)**.

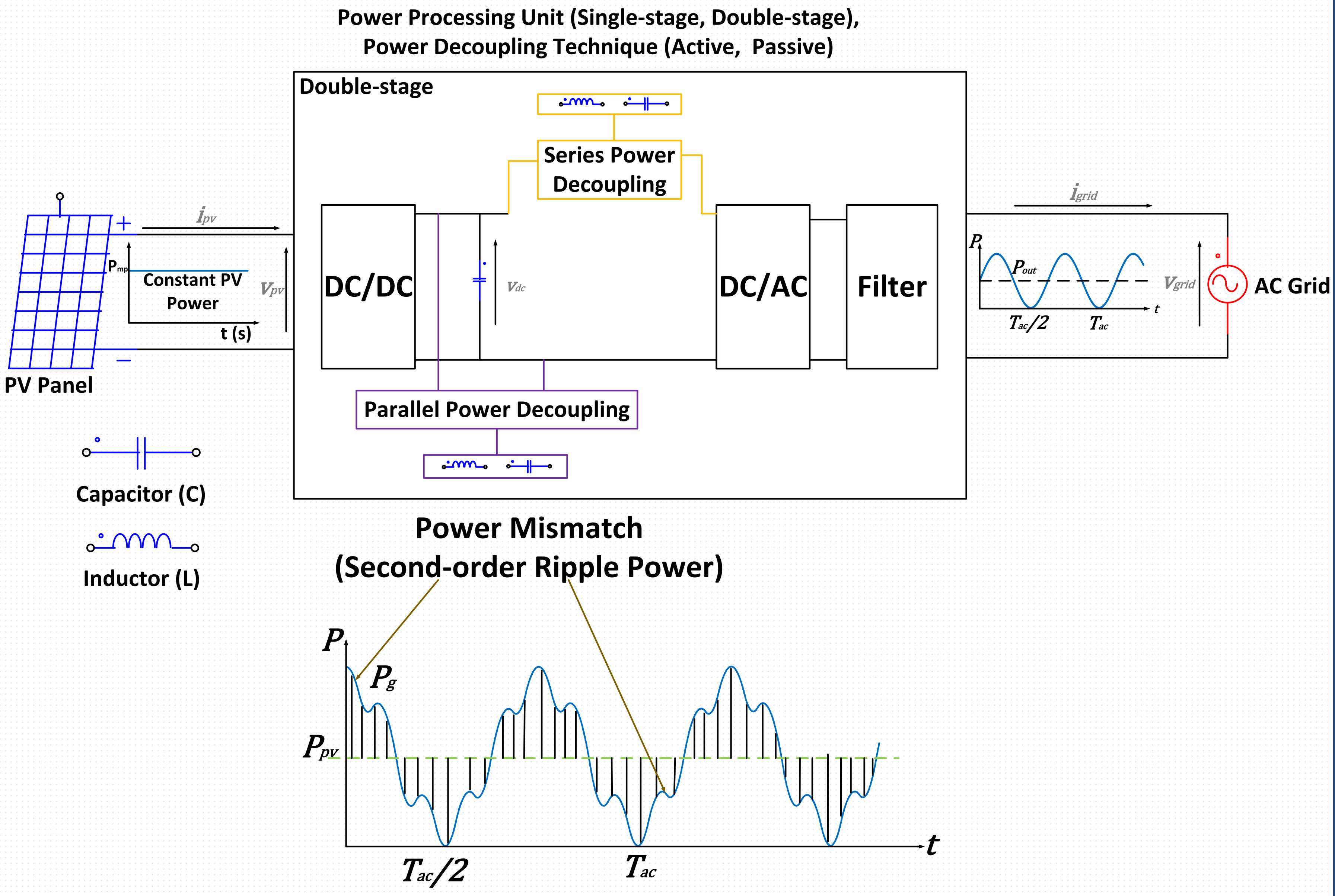
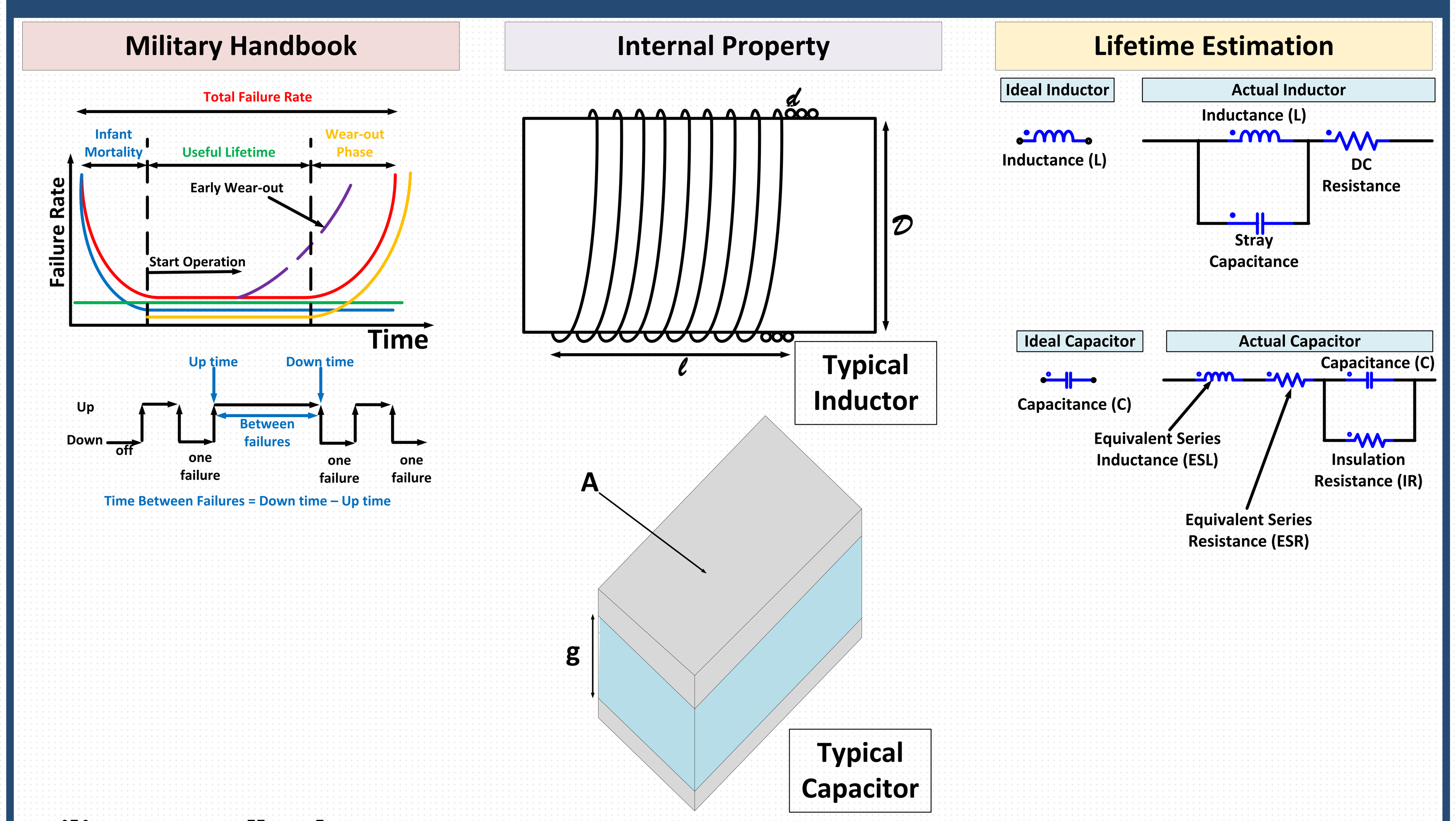


Fig. 1. *Block diagram describing the operating principles and power decoupling requirements for a typical single-phase photovoltaic inverter (P_{pv}: DC power from PV module; P_g: Instantaneous AC output power).*

- To reduce **excessive second-order ripple power**, several **power decoupling (PD) techniques**, such as **capacitor-based or inductor-based methods**, have been proposed in literature for the **suppression of double-line frequency ripple**.
- Due to their **lower cost**, capacitor-based PD techniques have been the most predominant, acting as **auxiliary ripple storage elements**.
- Considering the **ripple power** as a **superimposition of AC on the grid output**, inductor-based PD techniques are now being suggested as alternatives.

2. Evaluation Criteria



Military Handbook

Failure Rate

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{R(t) - R(t + \Delta t)}{R(t)\Delta t} \quad (1)$$

Mean-time-between-failure (MTBF)

$$\text{MTBF} = \frac{1}{\lambda(t)} \quad (2)$$

where Δt is the time interval with $\Delta t > 0$.

Lifetime Estimation

Capacitor

$$L_{capacitor} = L_O \times \left(\frac{V}{V_O}\right)^{-n} \times 2^{\frac{T_{ref} - T_{op}}{10}} \quad (3)$$

where $n \approx 3 - 5$.

Inductor

$$L_{inductor} \approx m \times 4^{\frac{T_{ref} - T_{op}}{10}} \quad (4)$$

where $m \approx \frac{T_{op}}{T_{ref}} \times 100$.

Internal Property – Decoupler Volume Vol_i, Energy Density e_i

Capacitor

$$Vol_{capacitor} = Ag$$

$$e_{capacitor} = \frac{\varepsilon_r \varepsilon_o E^2}{2} \quad (5)$$

Inductor

$$Vol_{inductor} = \frac{\pi D^2 l}{4}$$

$$e_{inductor} = \frac{\pi l \alpha^2 J^2}{(9D + 20l)} = K\alpha^2 J^2 \quad (6)$$

3. Simulation Results

Table. 1. *Comparison of the performance of the two passive components as power decouplers in PV-connected systems (a) Lifetime estimation (b) Military handbook (c) Internal properties.*

(a) Lifetime Estimation

Component			Time [Hours]	Time [Years]
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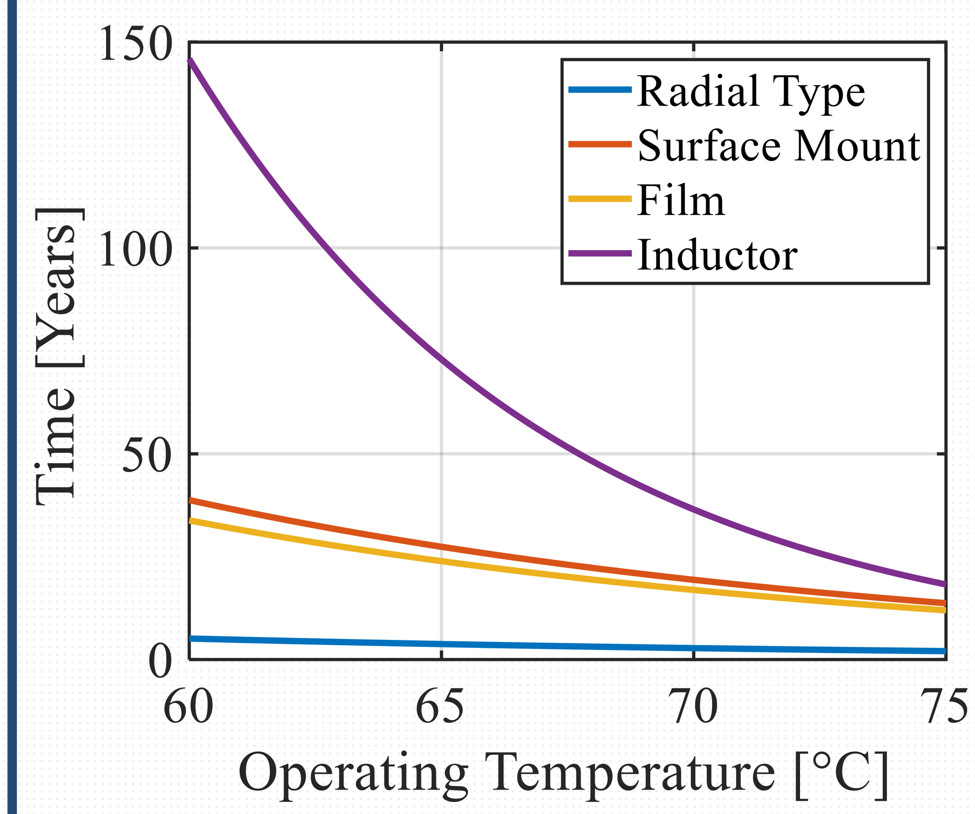


The **lifetime** of an inductor is estimated to be **more than three times longer than that of a typical PV panel**.

Fig. 2. *Lifetime estimation of the passive power decoupling components for PV microinverters.*

At the **same operating temperature – 65 °C**, inductors exhibit a **longer MTBF** when compared to that of a capacitor.

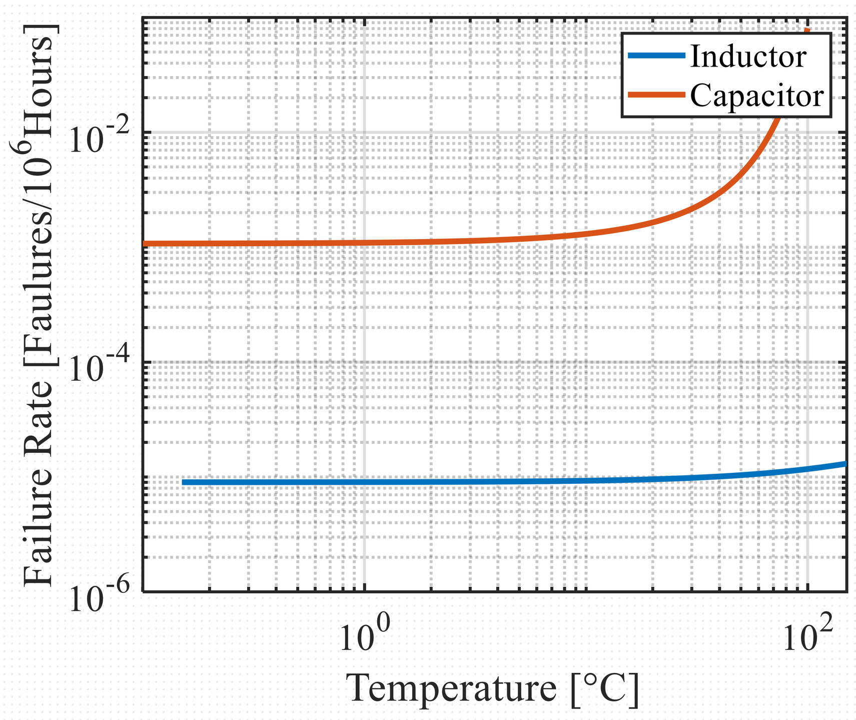
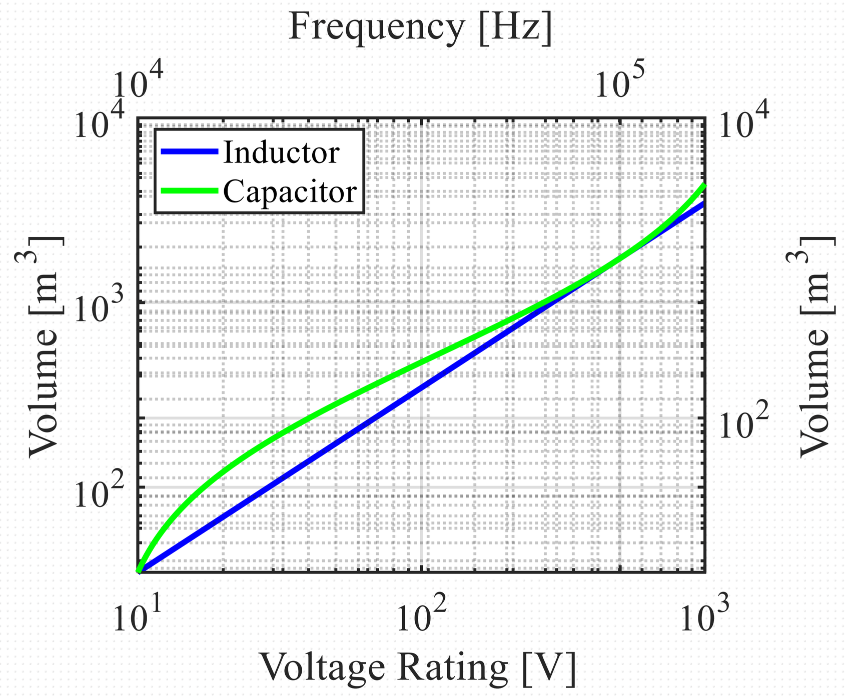


Fig. 3. *Failure and MTBF estimation of the passive power decoupling components for PV microinverters.*



Assuming same **converter switching frequency**, the inductor's **volume** is about **six times larger** than that of a capacitor.

Fig. 4. *Internal properties of the passive power decoupling components for PV microinverters.*

4. Conclusion

- This paper conducted a **comparative component-level analysis** of **passive components** used as **auxiliary ripple storage elements** in PV microinverters.
- The analysis highlighted the **tradeoff** between the **estimated lifetime, MTBF, and weight** of **inductor-based and capacitor-based power decoupling techniques**, justifying their **interchangeable use** while **emphasizing the constraints** involved.
- The established **constrained relationship** will subsequently be applied to the **system-level optimization** of PV microinverters.

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