

# Fundamentos de análise de confiabilidade de inversores fotovoltaicos

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# Apresentação pessoal



- ❑ 2013 - Graduação em Engenharia Elétrica – UFV;
- ❑ 2015 - Mestrado em Engenharia Elétrica – UFMG;
- ❑ 2019 – Doutorado em Engenharia Elétrica – UFMG/AAU;
- ❑ Professor – CEFET MG (desde 2014);
- ❑ Pesquisador do GESEP-UFV, LEACOPI e LCCE-UFMG, .

Áreas de interesse:

- ❑ Energia Solar Fotovoltaica e Eólica;
- ❑ Acionamentos Elétricos;
- ❑ Sistemas de Armazenamento de Energia por Baterias;
- ❑ Confiabilidade de Conversores Eletrônicos.

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📄 [Allan F Cupertino](#)

# GESEP – Gerência de Especialistas em Sistemas Elétricos de Potência



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Gesep



Pesquise por:  
“GESEP UFV”



EStimate - Sistemas  
Fotovoltaicos



Pesquise por:  
“EStimate”

# Tópicos a serem abordados

- Estruturas e tecnologias de inversores fotovoltaicos;
- Por que estudar confiabilidade?
- Mecanismos de falha e modelos de vida útil;
- Projeto com foco em confiabilidade;
- Exemplos de aplicação da metodologia.





# Estrutura e tecnologia de inversores fotovoltaicos



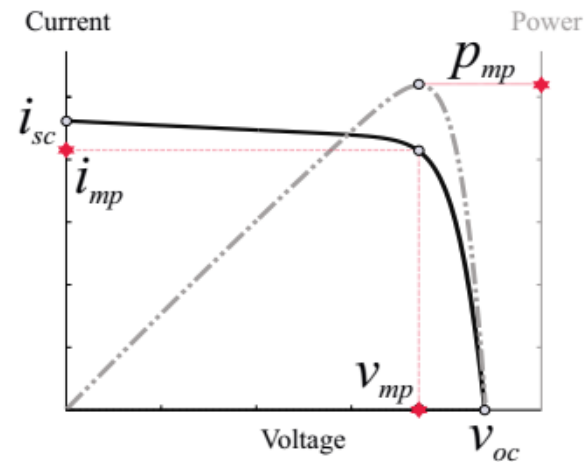
# Sistemas fotovoltaicos conectados à rede elétrica

❑ Módulo fotovoltaico → tensão contínua;

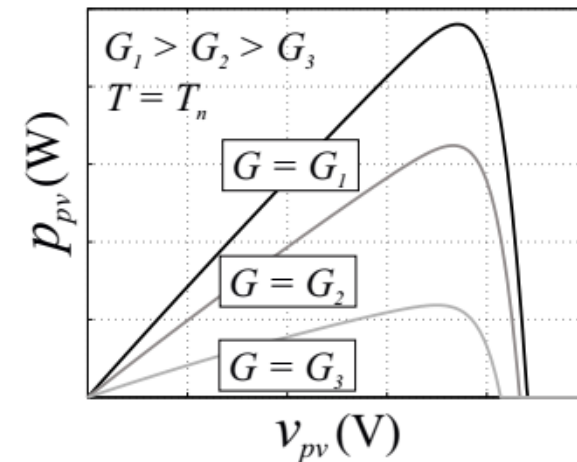
❑ Conversão CC-CA;

❑ Otimização da extração de potência;

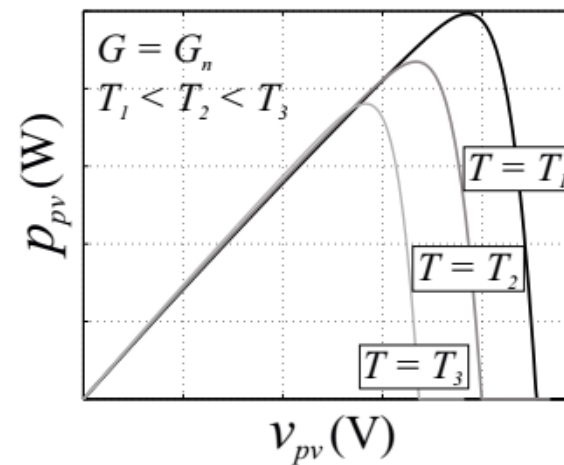
❑ Proteção e monitoramento.



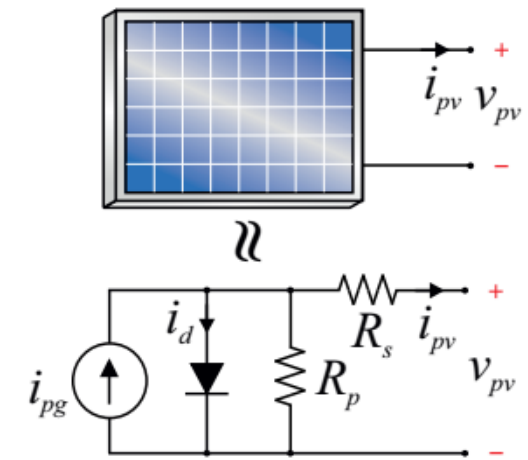
(a)



(b)



(c)

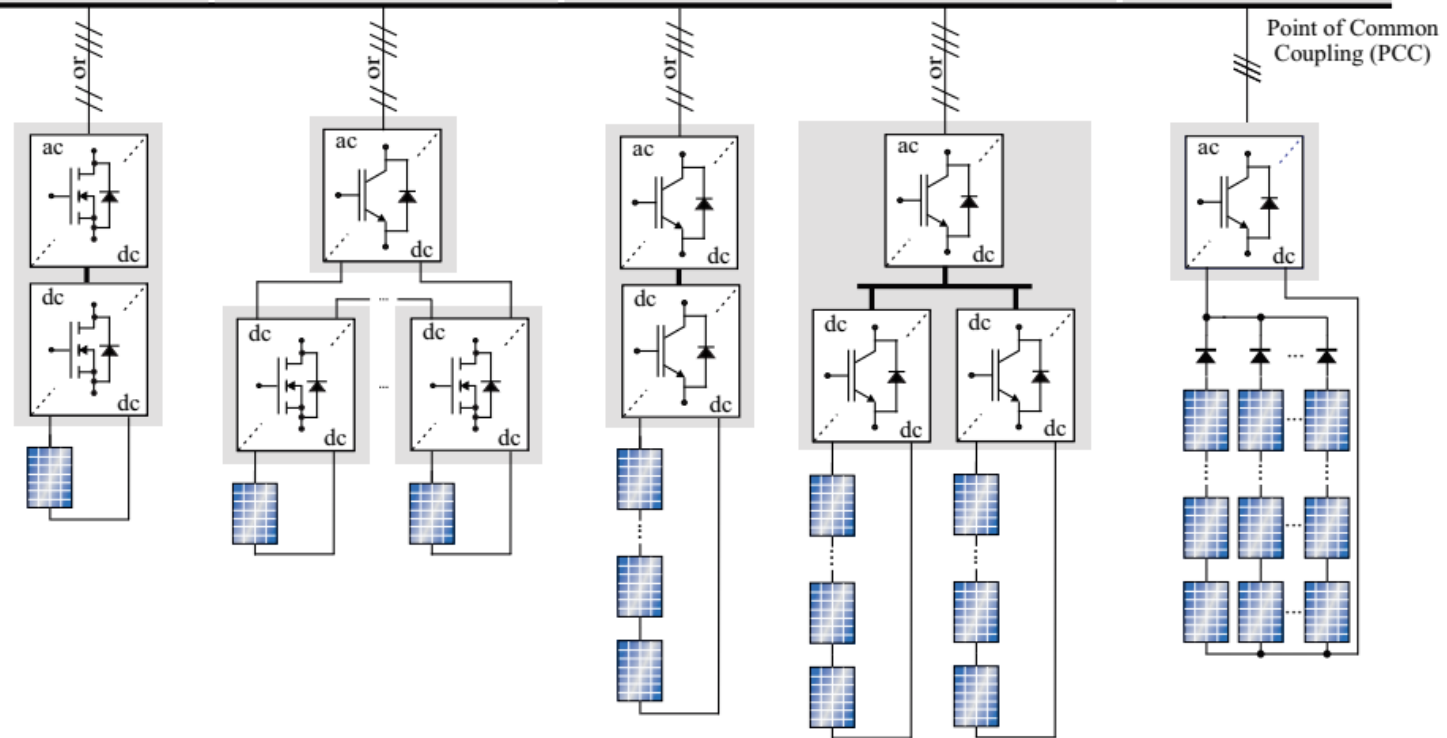


(d)

Fonte: A. F. Cupertino e H. A. Pereira. “Next generation of grid-connected photovoltaic systems: modelling and control”. Book Chapter. Elsevier. *In Press*.

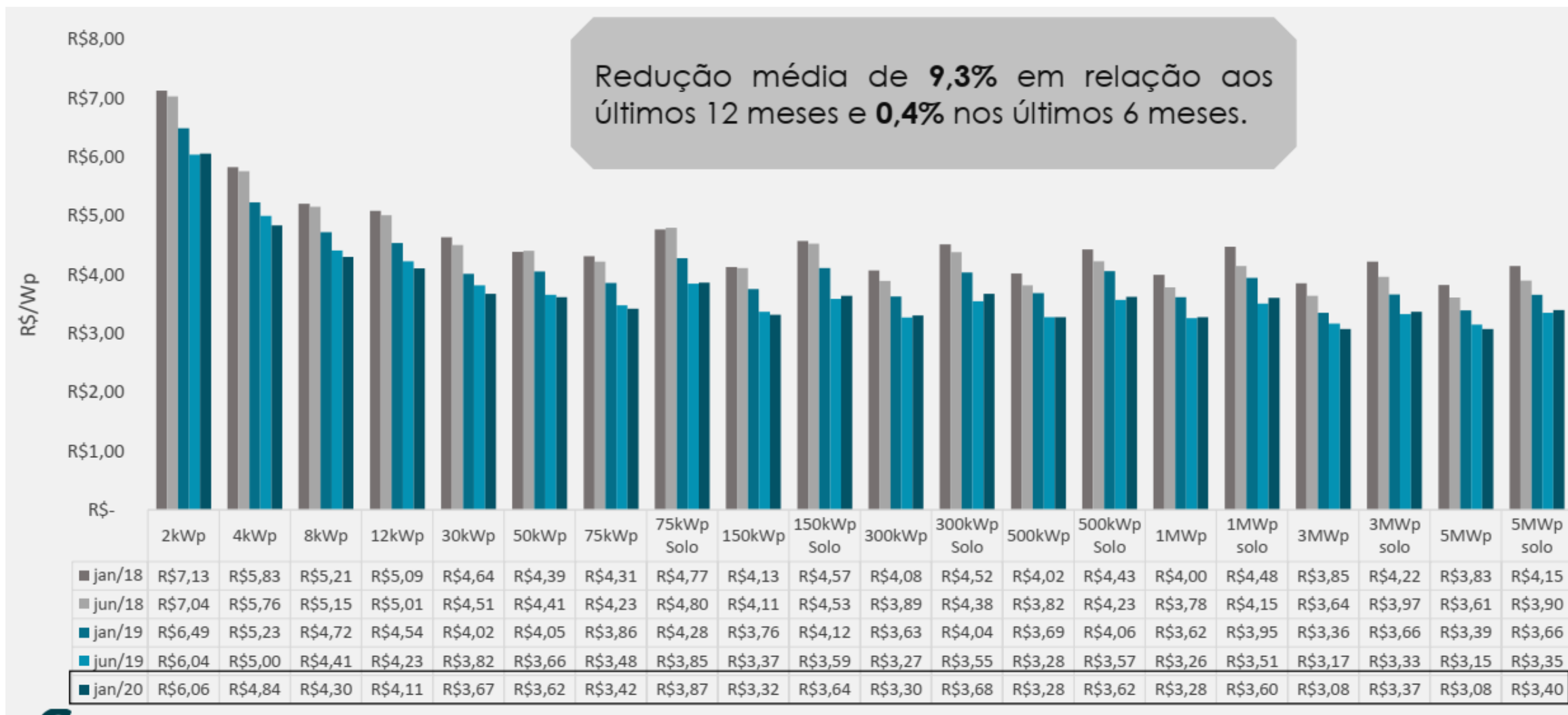
# Arquiteturas de sistemas fotovoltaicos conectados à rede

■ <i>architecture</i>	Microinverter	Power Optimizer + String Inverter	String Inverter	Multi-string Inverter	Central Inverter
■ <i>power range</i>	100 - 500 W	250 - 900 W	1,5 kW - 10 kW	1.5 kW - 30 kW	> 30 kW
■ <i>Applications</i>	small systems Residential systems	small systems Residential Systems	Residential Systems	Residential Systems Commercial Systems	Commercial Systems Solar Power Plants
■ <i>Market Share</i>	≈ 1 %	≈ 3 %	≈ 52 %		≈ 44 %
■ <i>Efficiency</i>	90 - 95 %	upt to 98.8 %	up to 98 %		up to 98.5 %
■ <i>Costs</i>	28 euro cents/Wp	9 euro cents/Wp	6 - 17 euro cents/Wp		5 euro cents/Wp



Fonte: A. F. Cupertino e H. A. Pereira. "Next generation of grid-connected photovoltaic systems: modelling and control". Book Chapter. Elsevier. *In Press*.

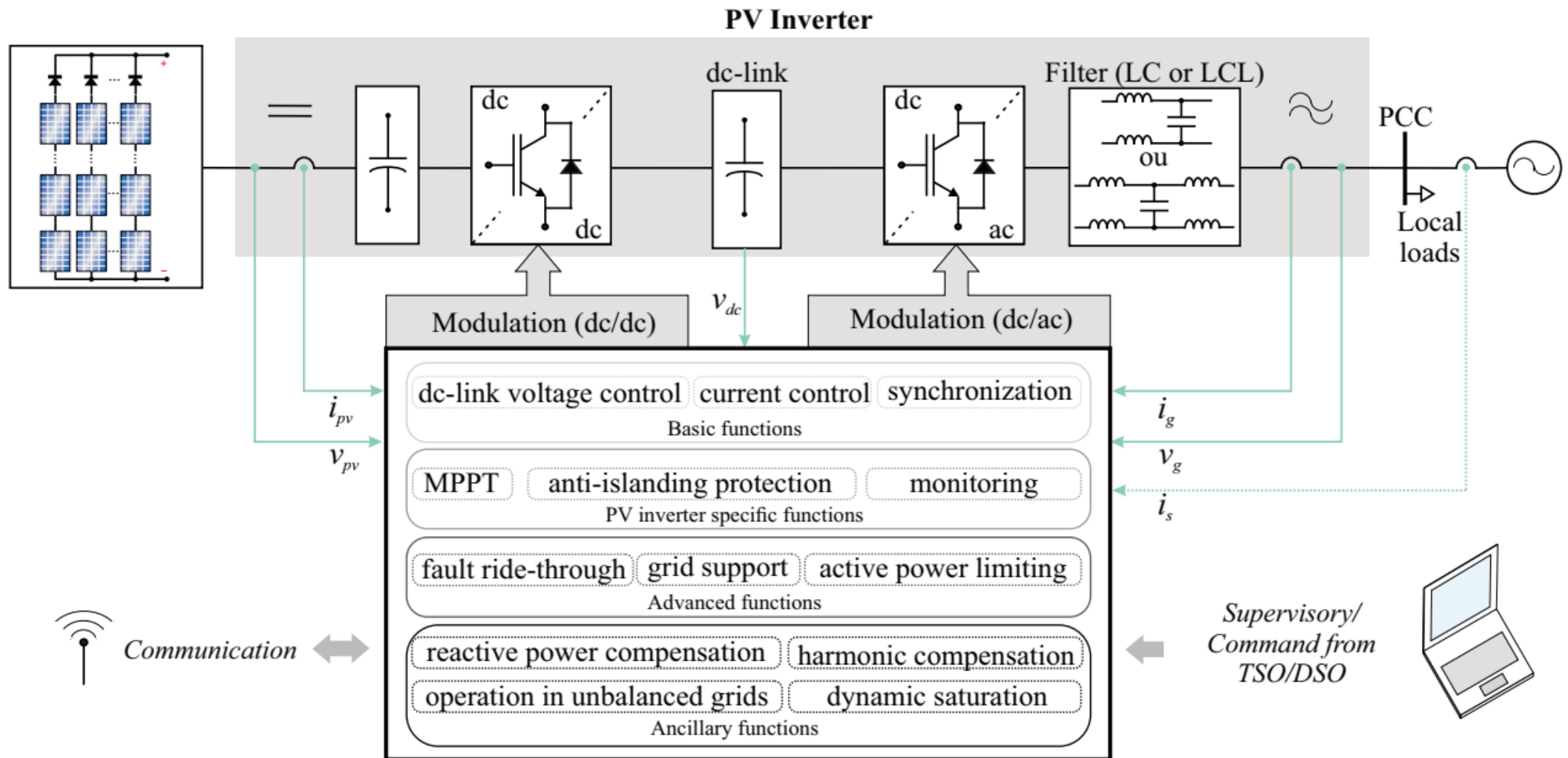
# Evolução do preço de sistemas fotovoltaicos = cliente final



Fonte: Greener. Estudo Estratégico: Mercado Fotovoltaico de Geração Distribuída. 2019.



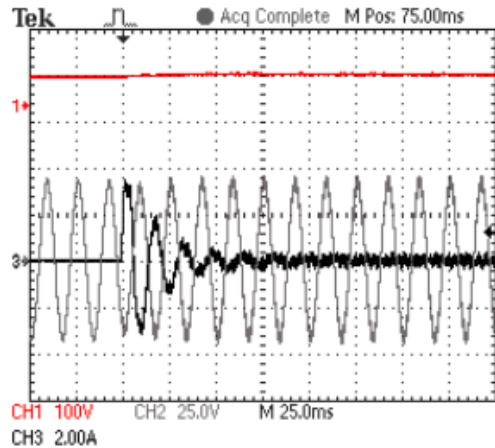
# Funcionalidades de um inversor fotovoltaico



Fonte: A. F. Cupertino e H. A. Pereira. "Next generation of grid-connected photovoltaic systems: modelling and control". Book Chapter. Elsevier. *In Press*.

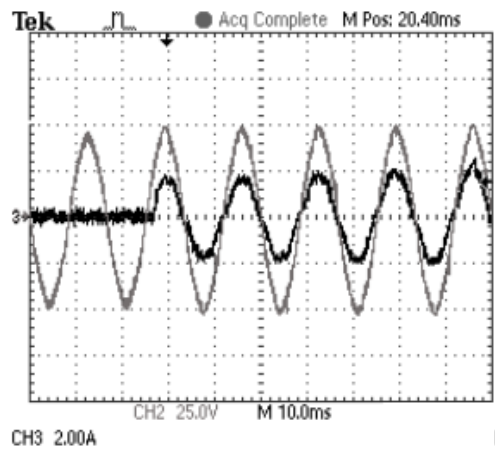
# Inversor fotovoltaico monofásico injetando potência reativa

☐ Conexão;



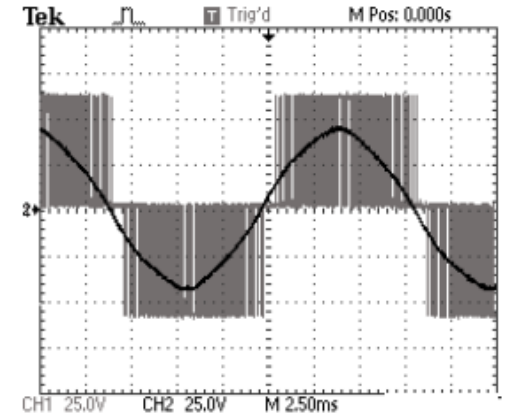
(a)

☐ Operação



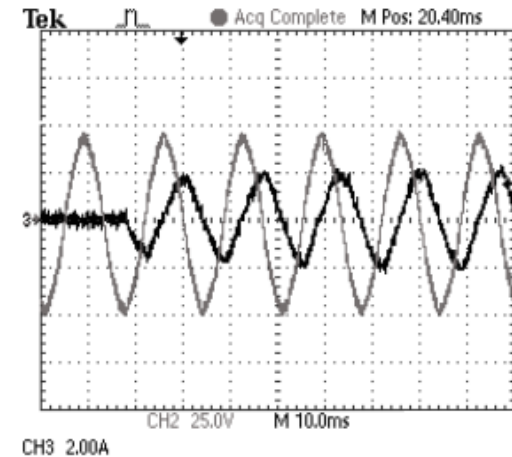
(c)

☐ Tensão modulada



(b)

☐ Injeção de potência reativa.

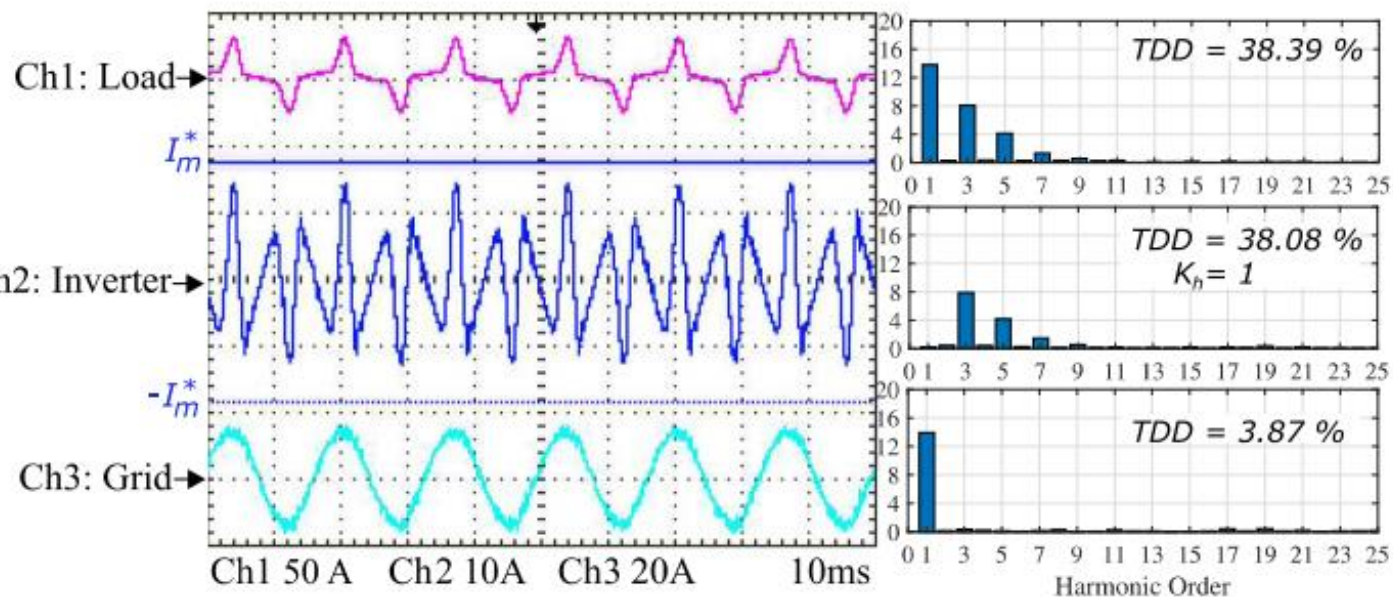


(d)

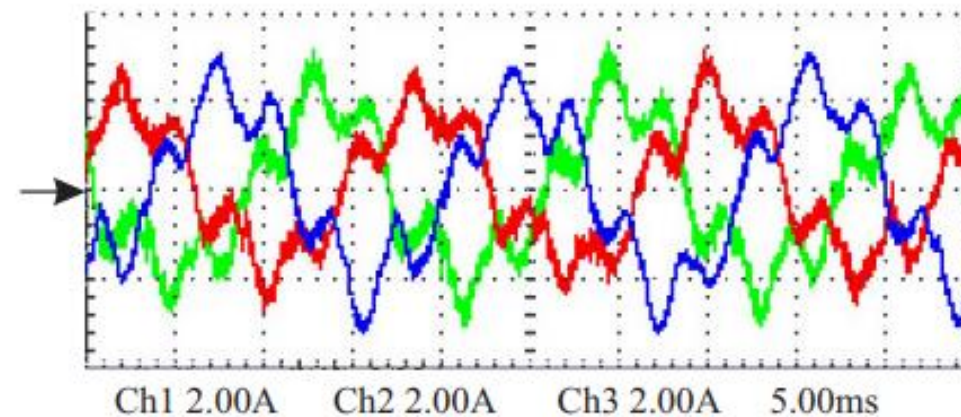
Fonte: A. F. Cupertino e H. A. Pereira. "Next generation of grid-connected photovoltaic systems: modelling and control". Book Chapter. Elsevier. *In Press*.

# Inversor fotovoltaico injetando harmônicos

☐ Inversor monofásico [1].



☐ Inversor trifásico [2].

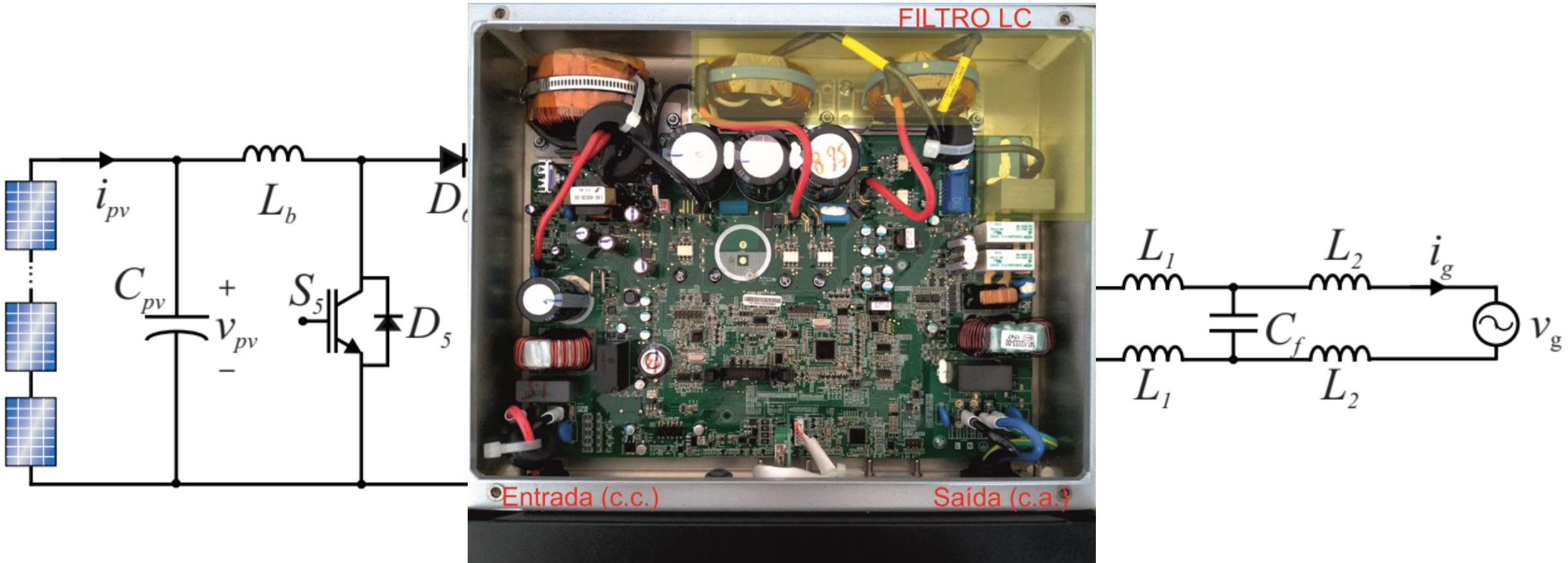


Fontes:

[1] L. S. Xavier et. al. "Partial Harmonic Current Compensation for Multifunctional Photovoltaic Inverters". IEEE Transactions on Power Electronics. 2019.

[2] V. M. Rodrigues et. al. "Operation Limits of Grid-Tied Photovoltaic Inverters with Harmonic Current Compensation Based on Capability Curves". IEEE Transactions on Industry Applications, 2019.

# Aspecto de um inversor comercial

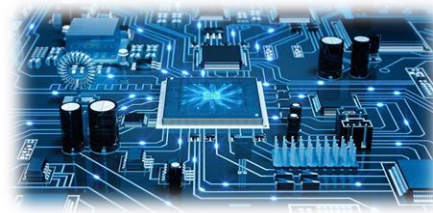


❑ Cada elemento do inversor é um possível ponto de falha!

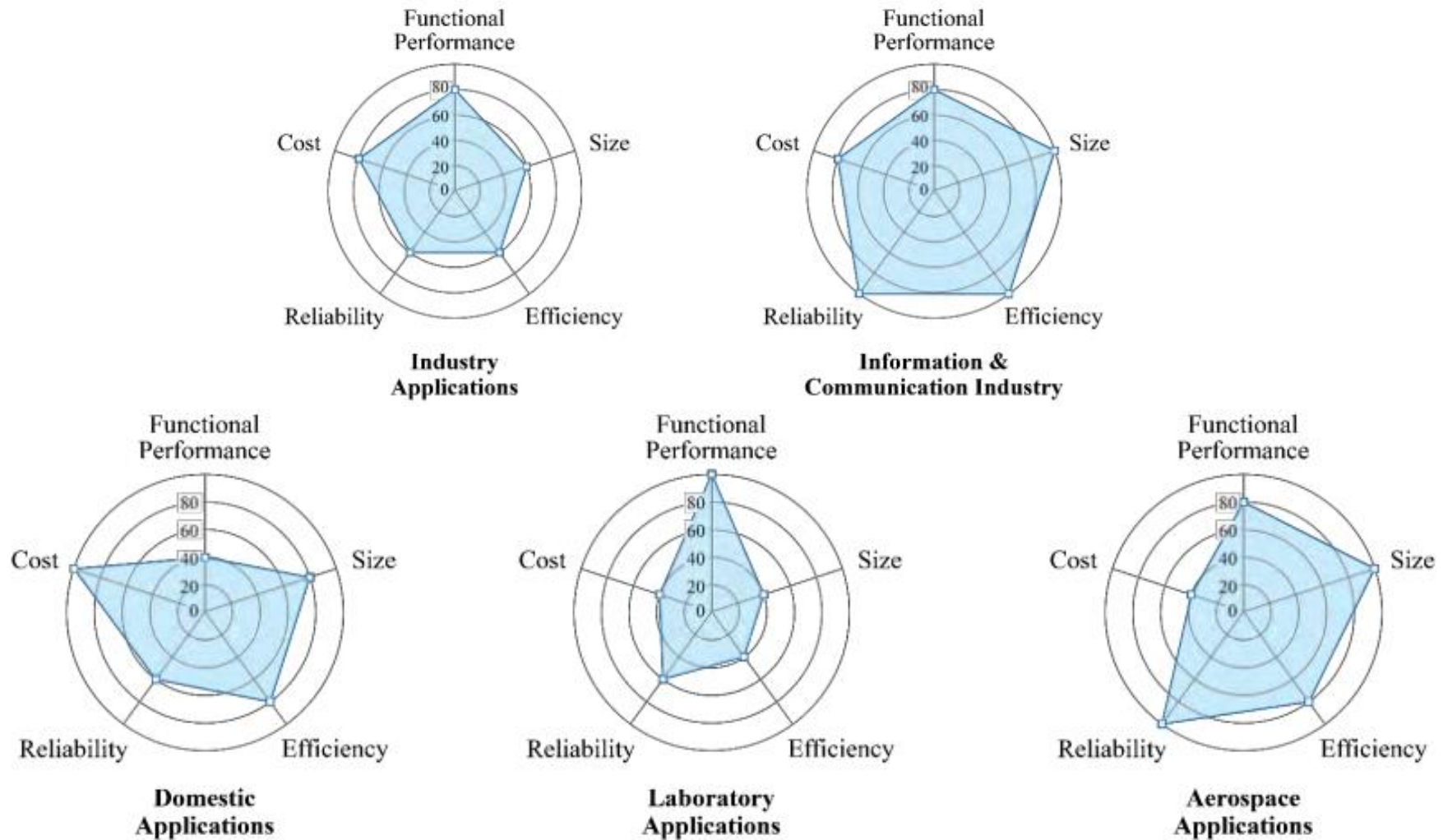




## Por que estudar confiabilidade?

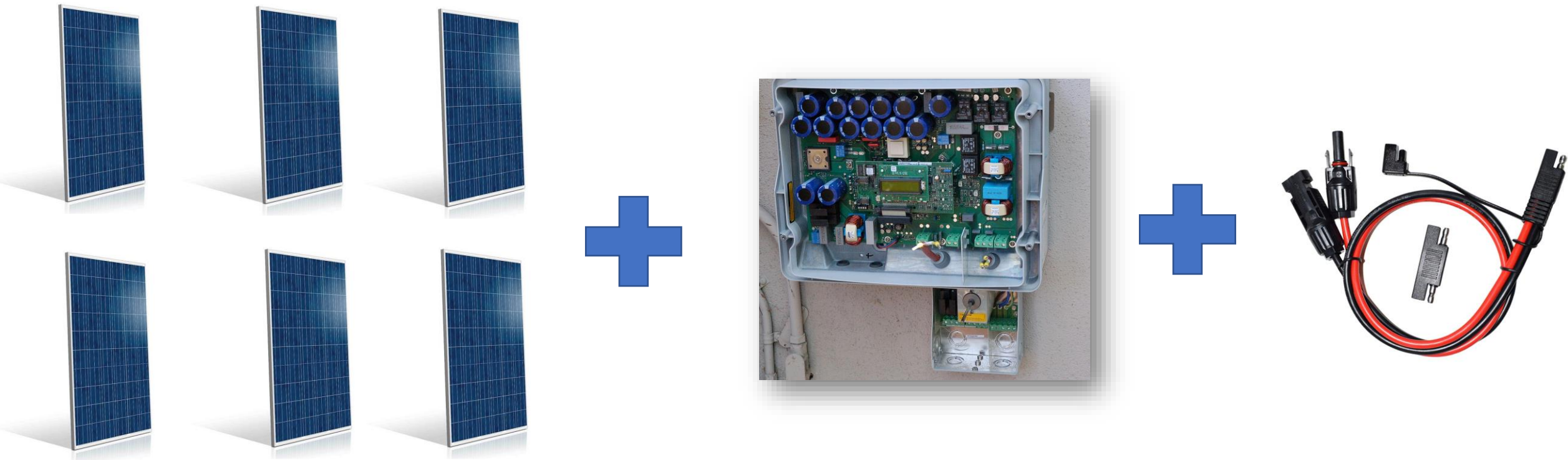


# Desempenho depende da aplicação



Fonte: B. M. Burkart and K. Kolar. “Advanced Modeling and Multi-Objective Optimization / Evaluation of SiC Converter Systems” Tutorial WIPDA. 2015.

# Por que aumentar a confiabilidade do inversor?



Fonte: A. F. Cupertino e H. A. Pereira. "Next generation of grid-connected photovoltaic systems: modelling and control". Book Chapter. Elsevier. *In Press*.

# Por que aumentar a confiabilidade do inversor?

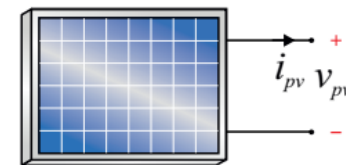
- ❑ Inversores → Garantias típicas de 5 a 10 anos;
- ❑ Módulos fotovoltaicos → Garantias de 20 a 25 anos;
- ❑ LCOE – Levelized cost of energy;
- ❑ Substituição do inversor → Custo;
- ❑ Como compatibilizar a vida útil dos dois elementos?



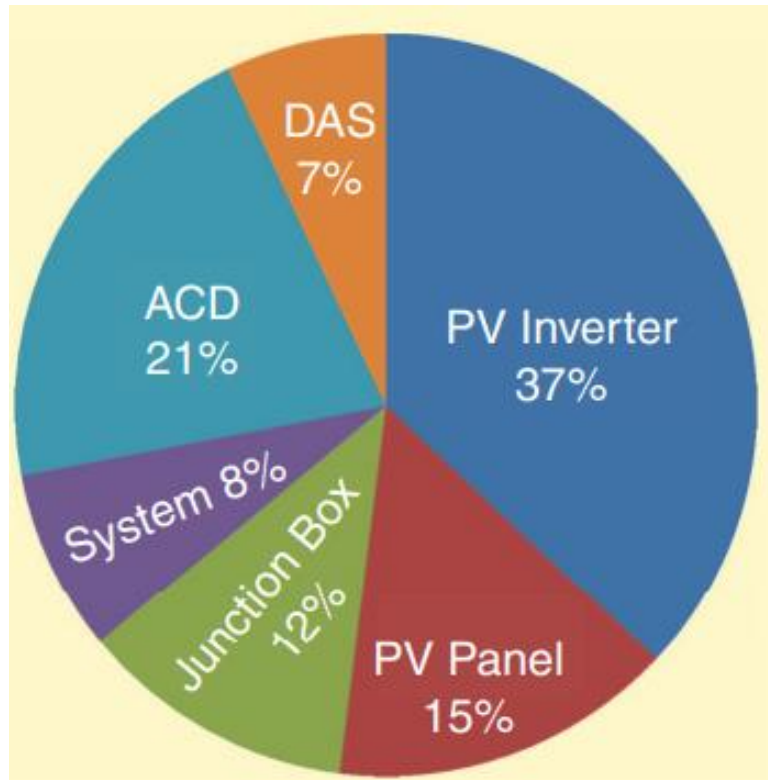
Fonte: A. F. Cupertino e H. A. Pereira. “Next generation of grid-connected photovoltaic systems: modelling and control”. Book Chapter. Elsevier. *In Press*.



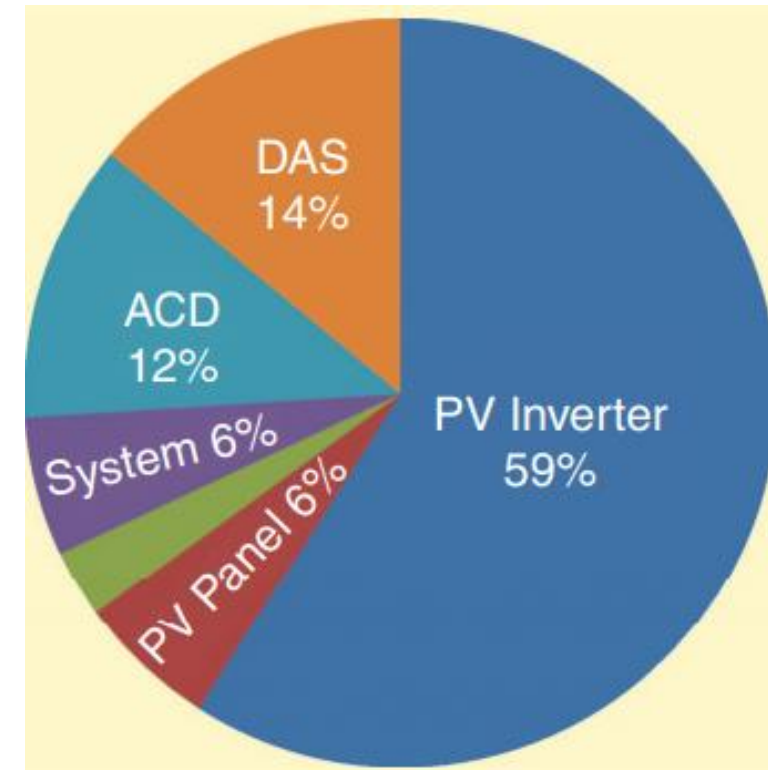
# Estatísticas de falha em sistemas fotovoltaicos – 3,5 MW



☐ Estatística de falhas



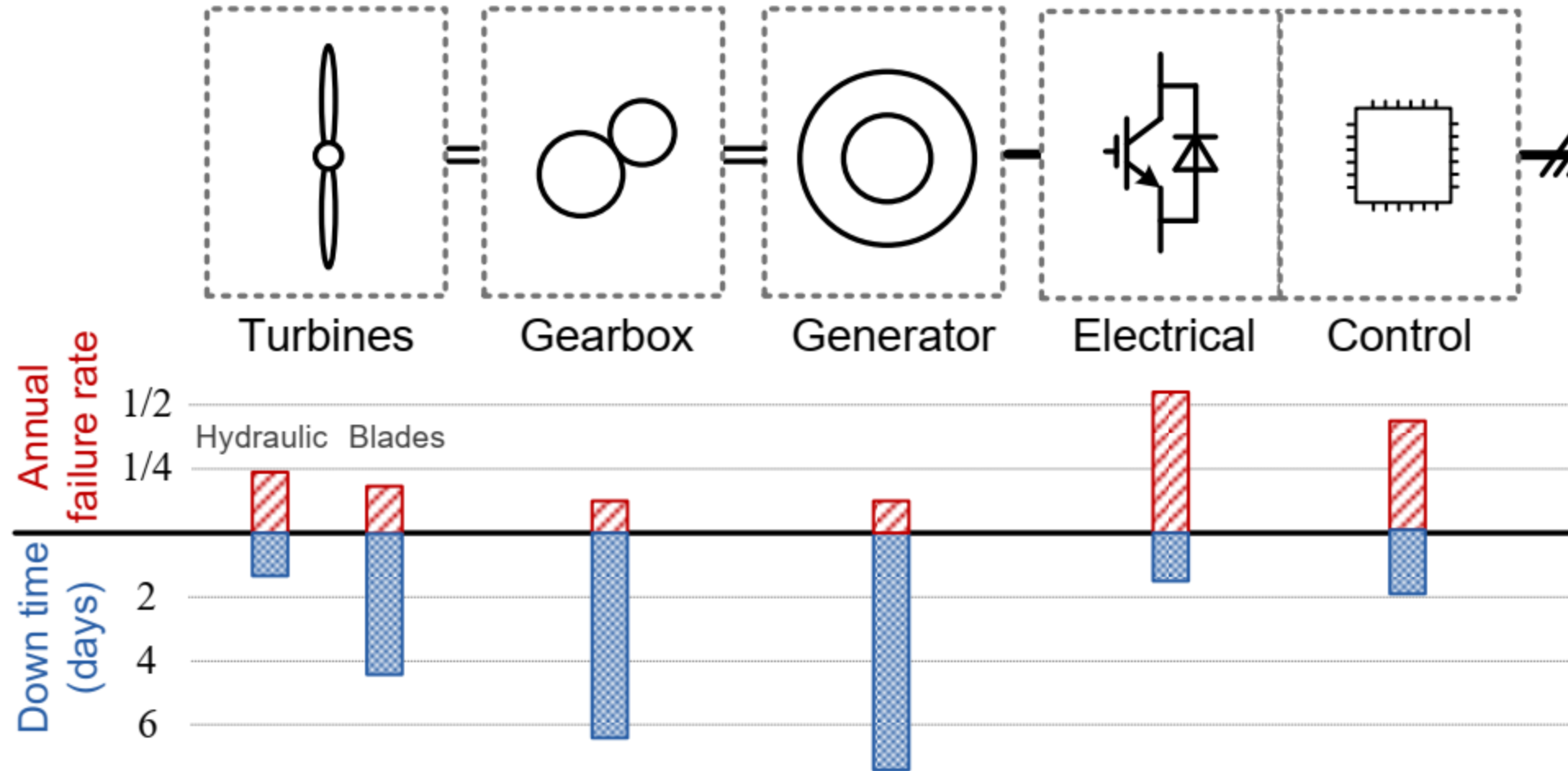
☐ Custo associado a falha.



Nota: DAS = Data Acquisition System

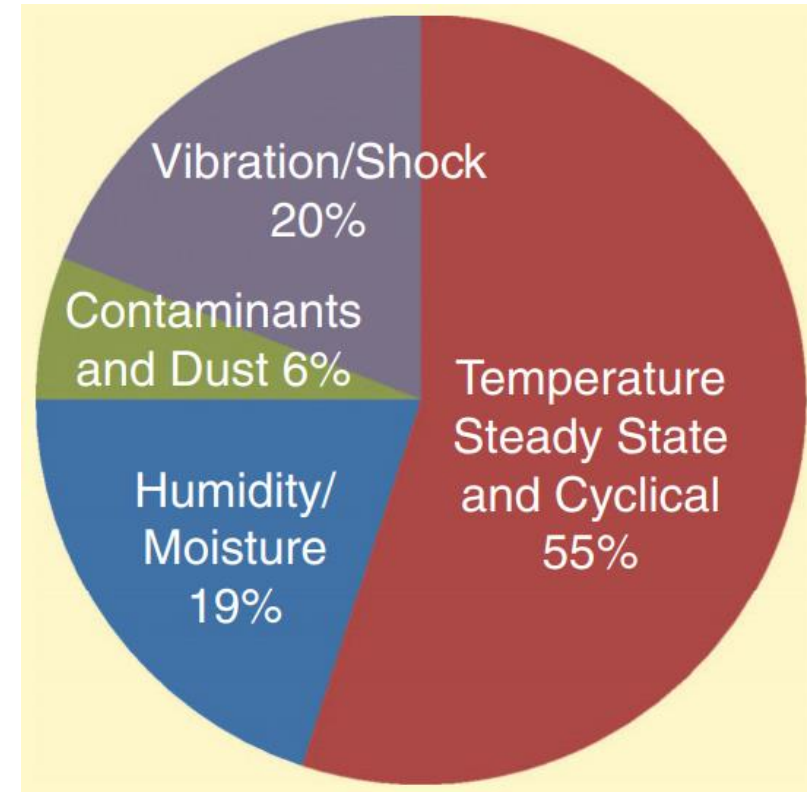
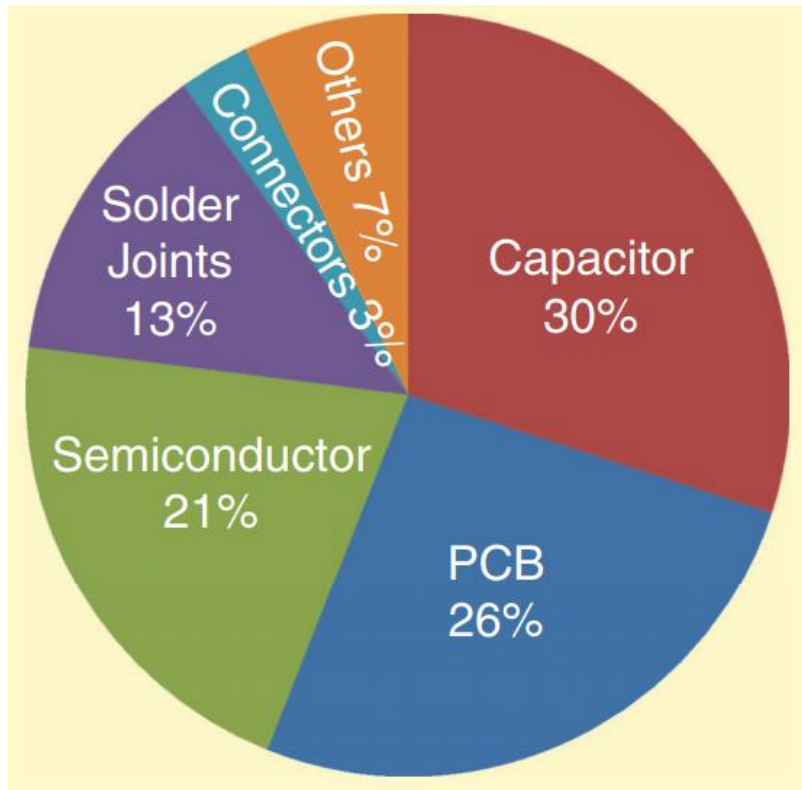
Fonte: H. Wang, M. Liserre e F. Blaabjerg. “Toward Reliable Power Electronics: Challenges, Design and Opportunities”. IEEE Industrial Electronics Magazine. 2013.

# Estatísticas de falha em sistemas de geração eólica



Fonte: Ke Ma. "Power Electronics for the Next Generation Wind Turbine System". Ph.D. Thesis. Aalborg University. 2013.

# Falhas em conversores eletrônicos e fontes de estresse



Fonte: H. Wang, M. Liserre e F. Blaabjerg. "Toward Reliable Power Electronics: Challenges, Design and Opportunities". IEEE Industrial Electronics Magazine. 2013.

# Perspectiva da indústria – Objetivo de vida útil

APPLICATION	RESPONSES
All	83
Wind power	Eight
PV	Nine
Electric vehicles	21
Drive systems	20
Traction	Eight
UPS and power supplies	Seven
Lighting	Two
Air and spacecraft	Five
Energy transmission	Three

UPS: uninterruptible power supply.

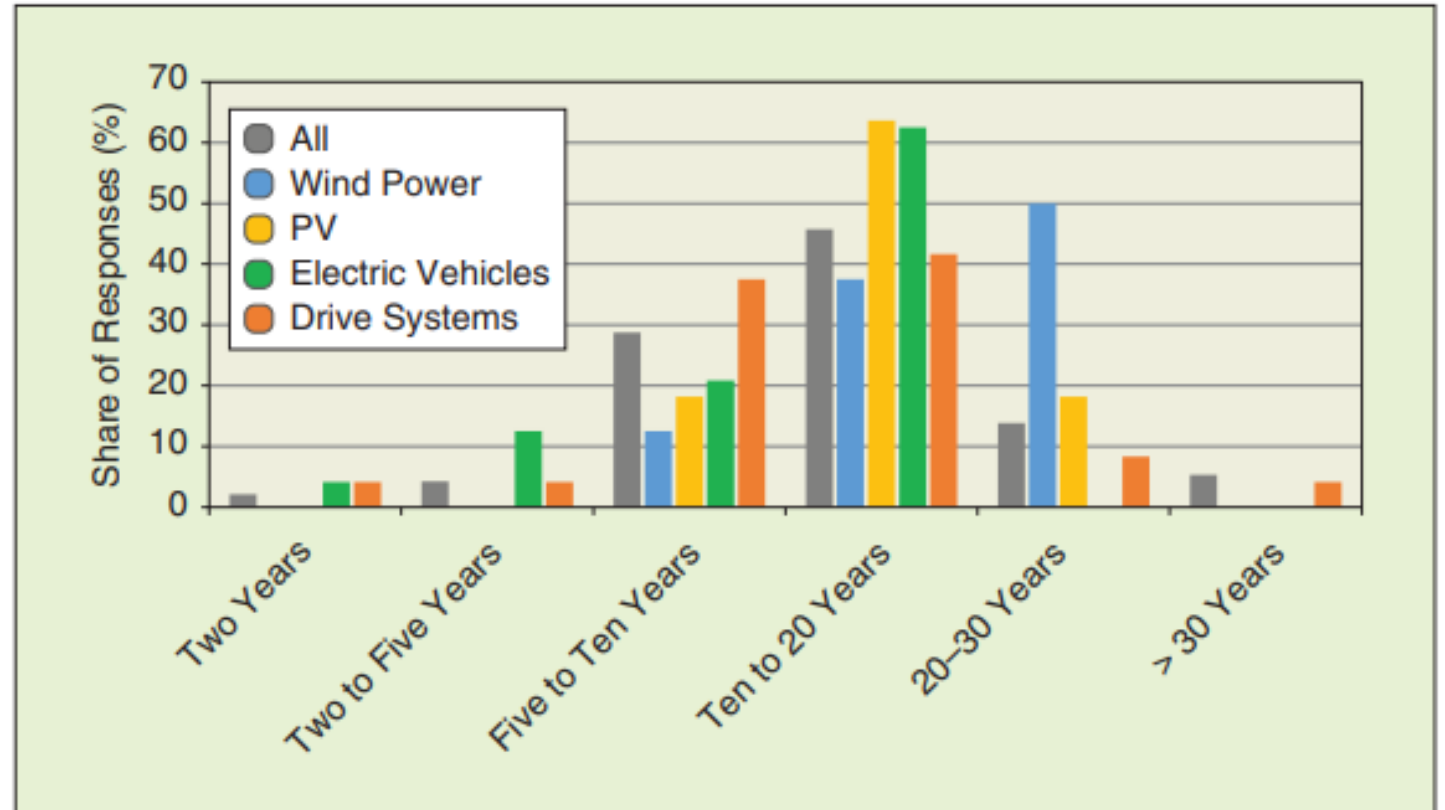
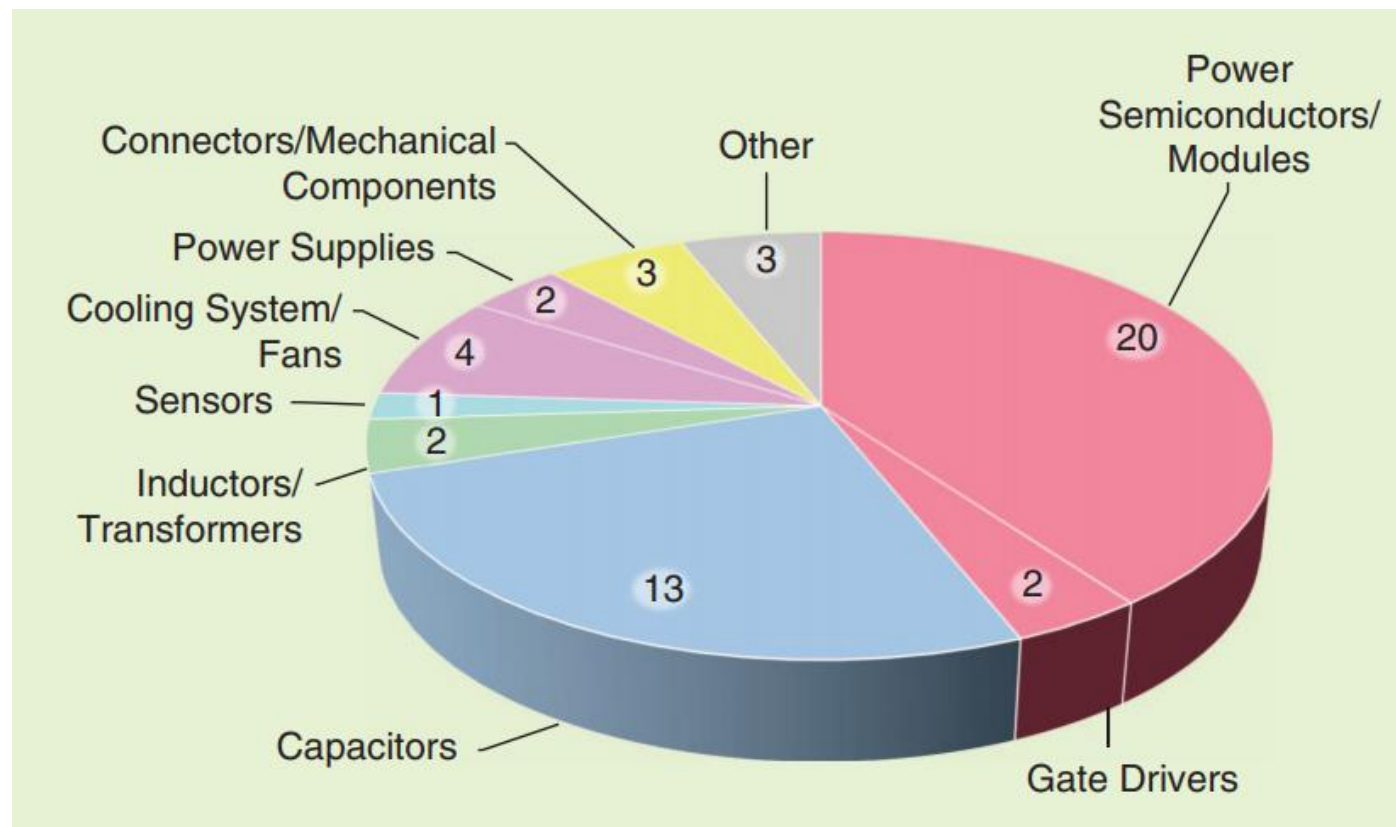


FIGURE 5 – The typical target lifetimes of power electronics systems by application, from industry experts' answers to the question, "What is the typical target lifetime of power electronics systems manufactured by your company in this application field?"

Fonte: J. Falk et. al. "Reliability of Power Electronics: An Industry Perspective". IEEE Industrial Electronics Magazine. 2018.

# Perspectiva da indústria – foco de pesquisa

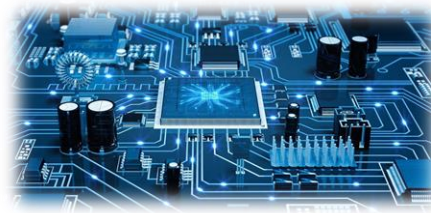
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UPS: uninterruptible power supply.	



Fonte: J. Falk et. al. “Reliability of Power Electronics: An Industry Perspective”. IEEE Industrial Electronics Magazine. 2018.



## Estatística de falhas e mecanismo de falha



## Algumas definições

□ Confiabilidade;

$$R(x) = 1 - F(x) = \frac{N(x)}{N(0)}$$

□ Distribuição de probabilidade de falha;

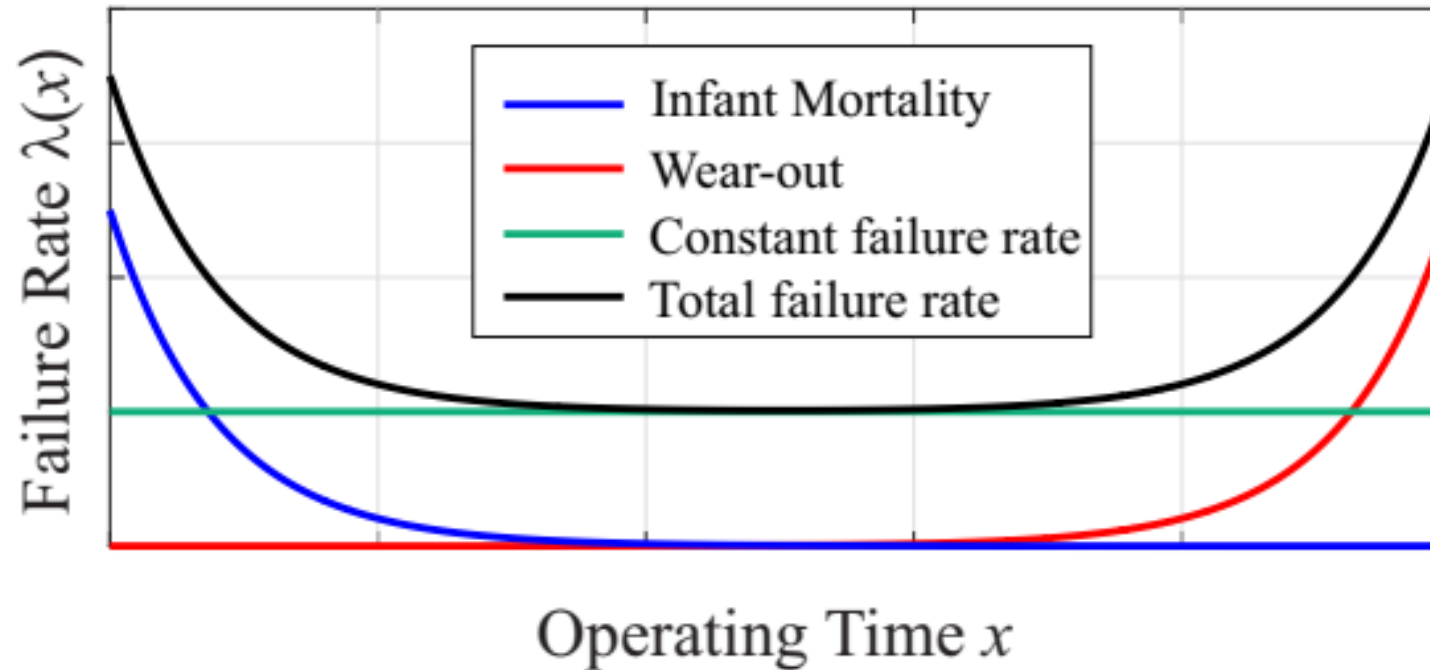
$$f(x) = \frac{dF(x)}{dx} = -\frac{dR(x)}{dx}$$

$$\lambda(x) = \lim_{\Delta t \rightarrow 0} \frac{N(x) - N(x + \Delta x)}{N(0)\Delta x} = \frac{f(x)}{R(x)}$$

□ Taxa de falha.

$$\lambda(x) = -\frac{1}{R(x)} \frac{dR(x)}{dx} \Rightarrow R(x) = \exp\left(\int_0^x \lambda(\tau) d\tau\right)$$

# Curva da banheira



- ❑ Região de falha constante → FIT (Failure in time);
- ❑ 1 FIT significa 1 falha a cada  $10^9$  horas de operação.



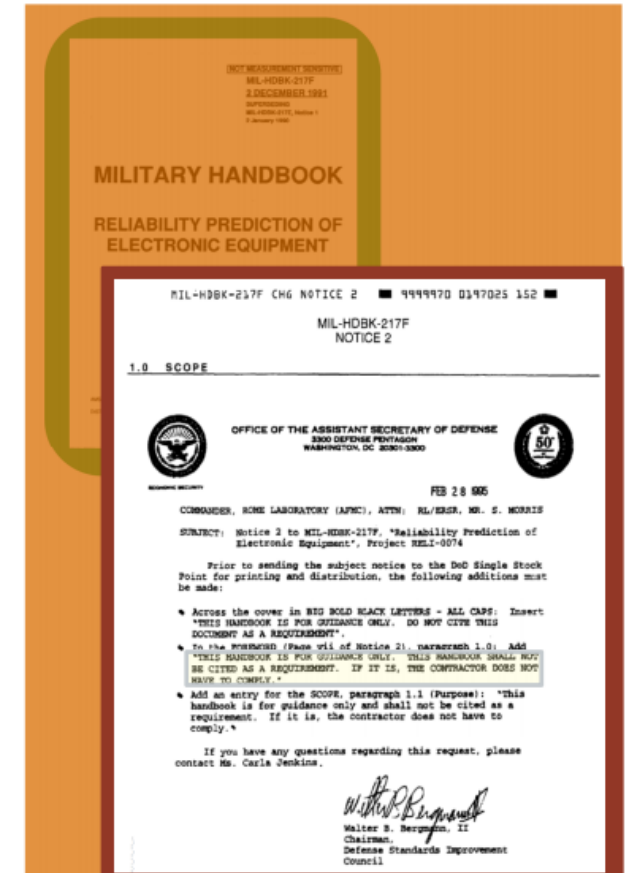
# Utilização de Handbooks – abordagem antiga

❑ 1952 → AGREE (Advisory group on Reliability of Eletronic Equipament);

❑ 1962 → MIL-HDBK-217 → FIT e MTBF;

❑ Fatores de correção de acordo com temperatura;

❑ 1995 → MIL-HDBK-217: Cancelado!

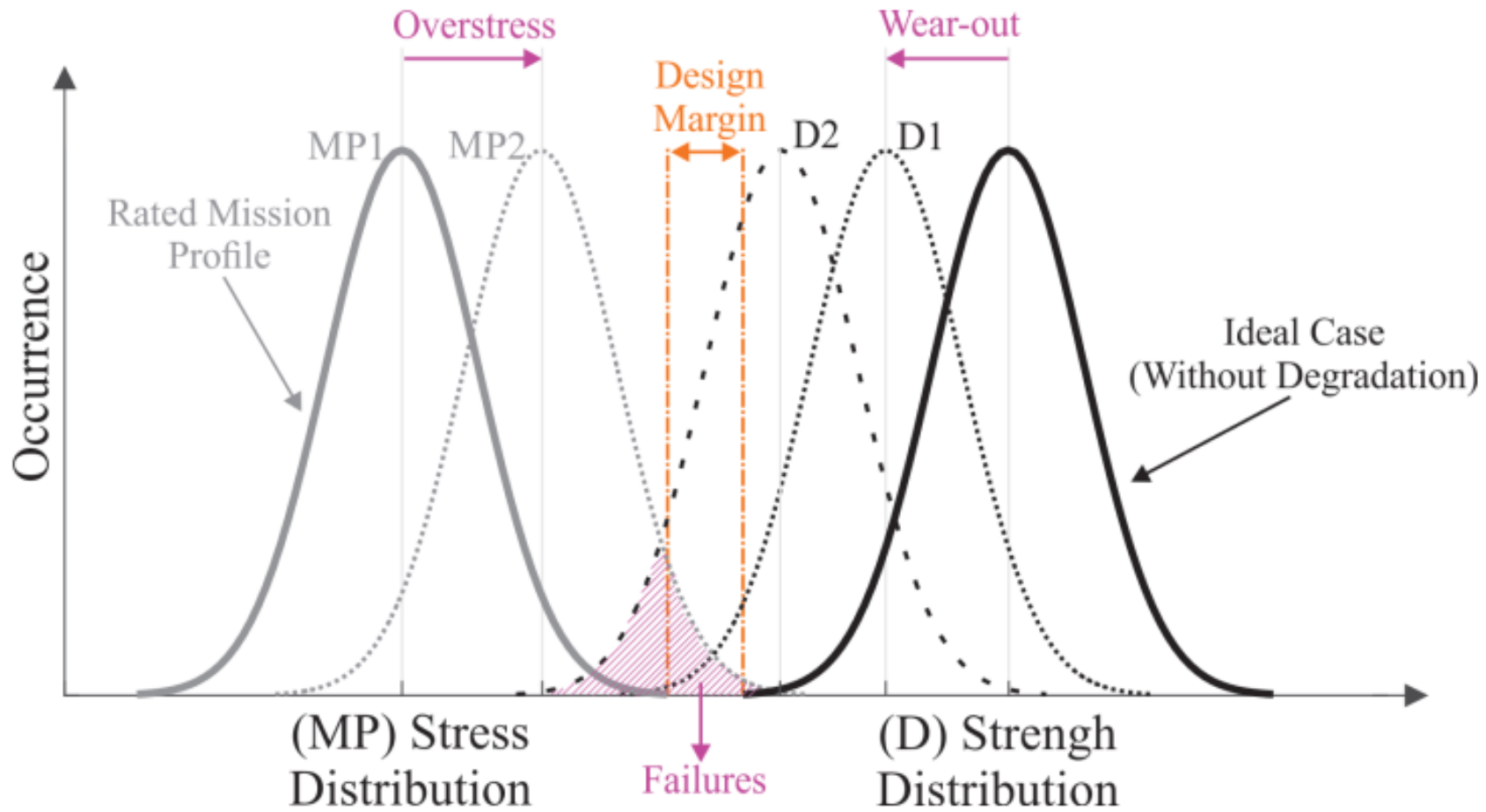


# Abordagem moderna – Modelos baseados na física da falha

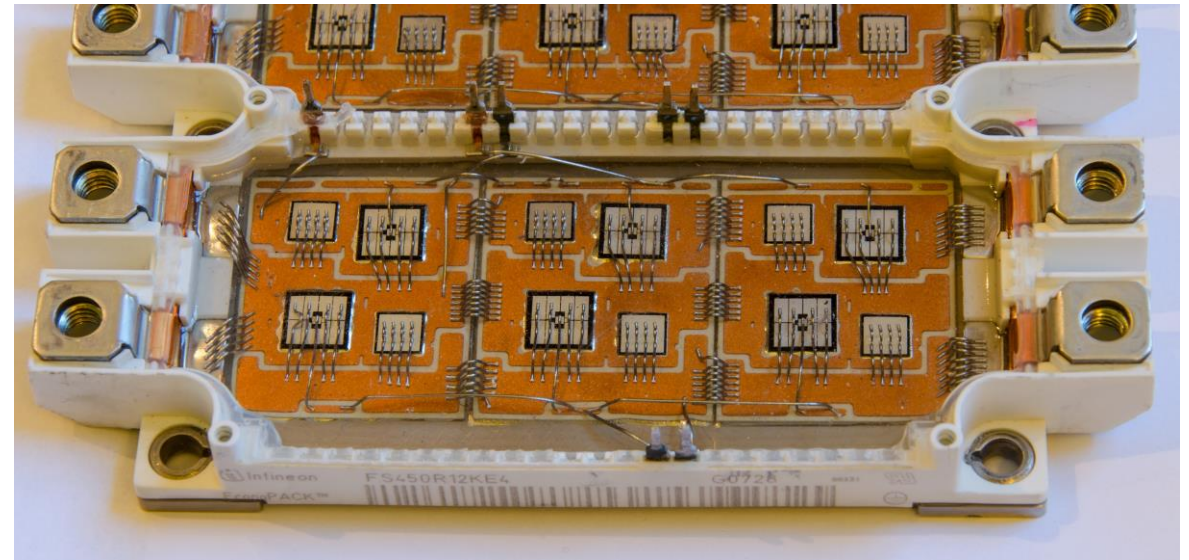
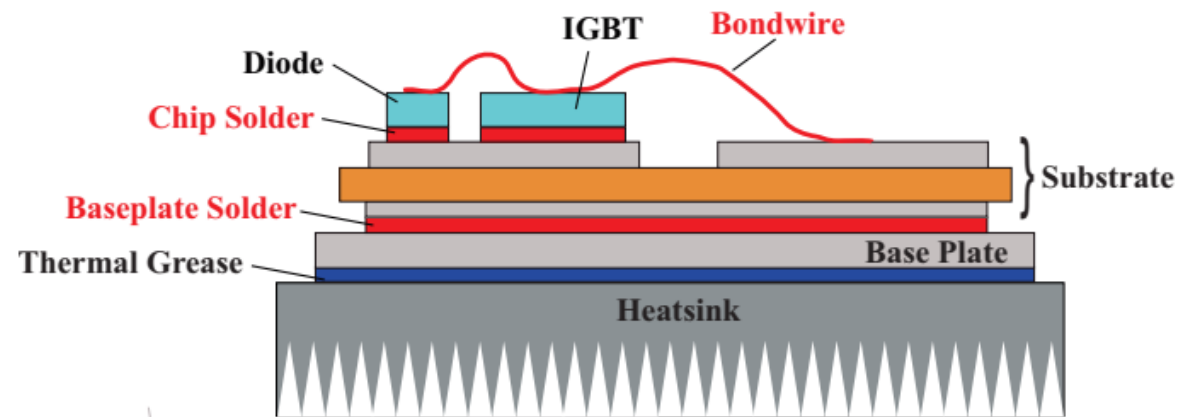
- ❑ O que causa o envelhecimento dos componentes?
- ❑ Quais são os fenômenos de degradação?
- ❑ Como modelar o efeito da degradação em função do estresse?
- ❑ Análise multifísica → Temperatura, humidade, estresse mecânico;
- ❑ Objetivo: Previsão mais precisa de tempo de vida e garantias.



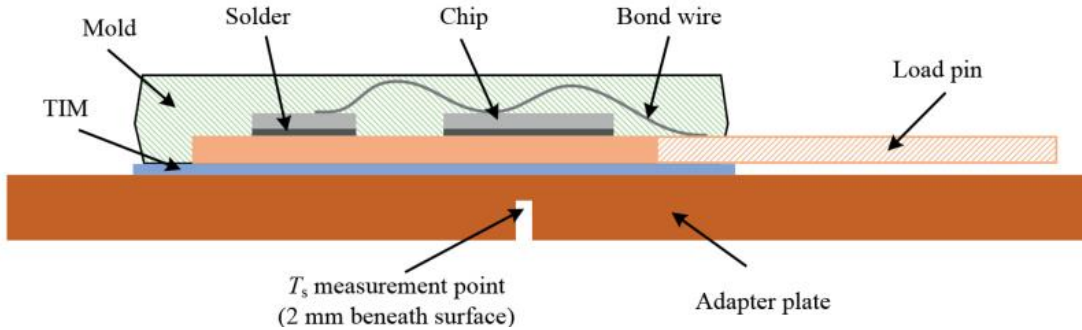
# Efeito do envelhecimento do componente



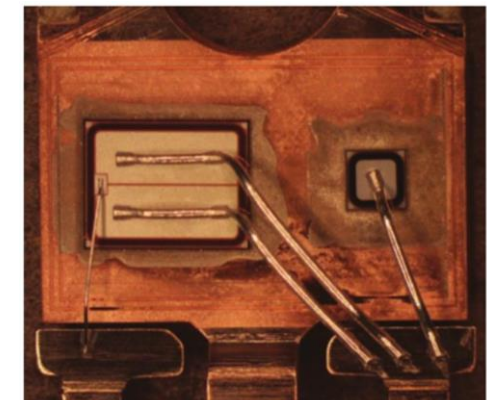
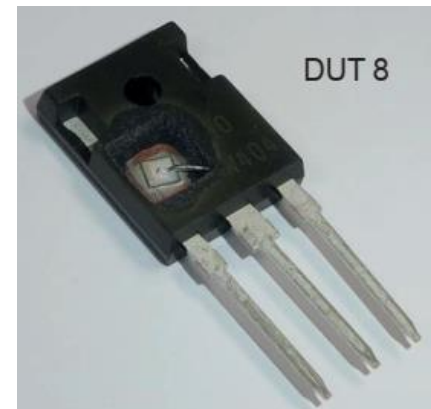
# Estrutura interna de um módulo semicondutor



Fonte: Infineon Technologies.

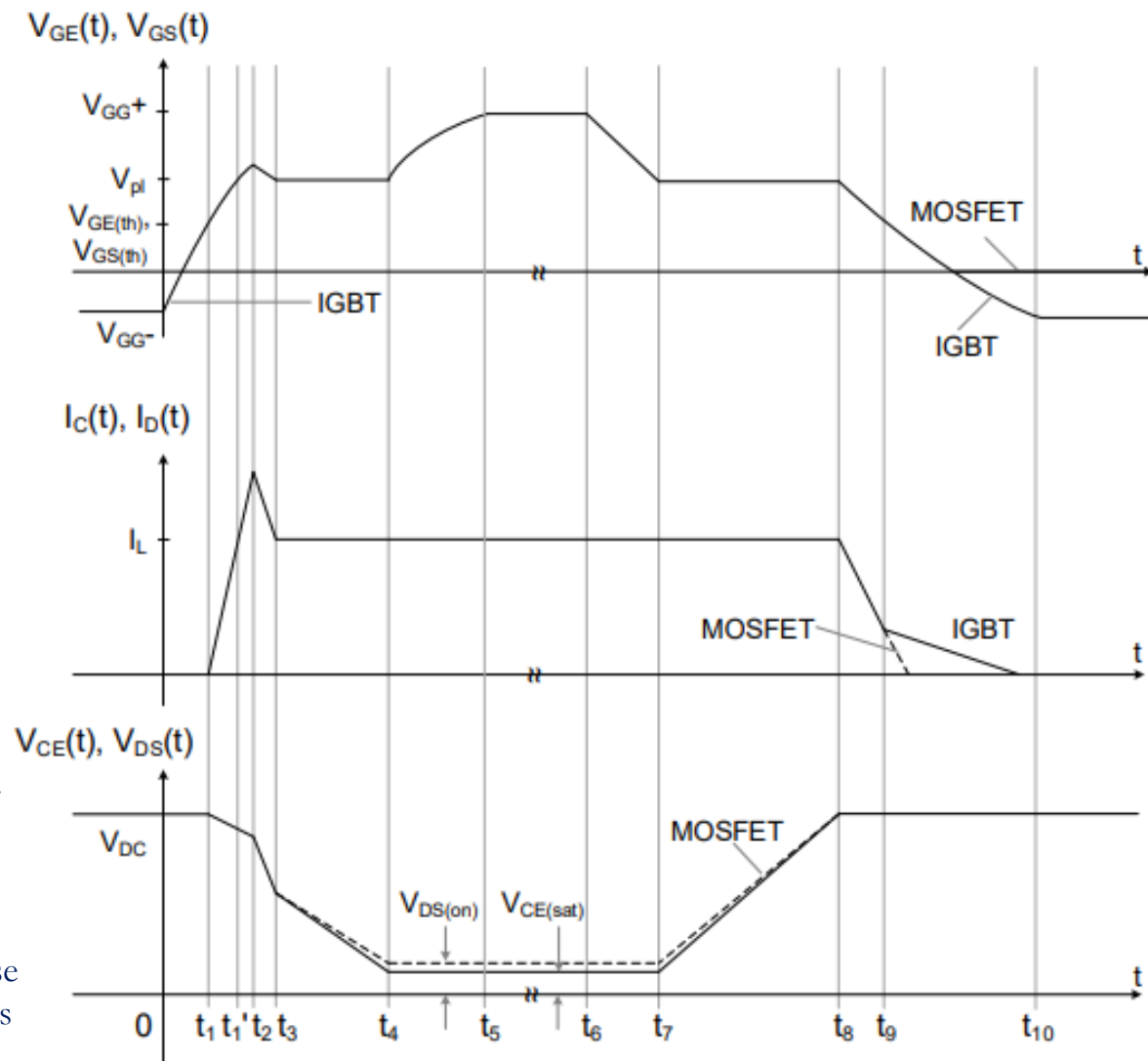
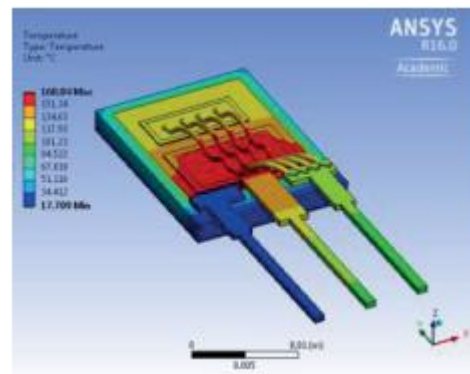
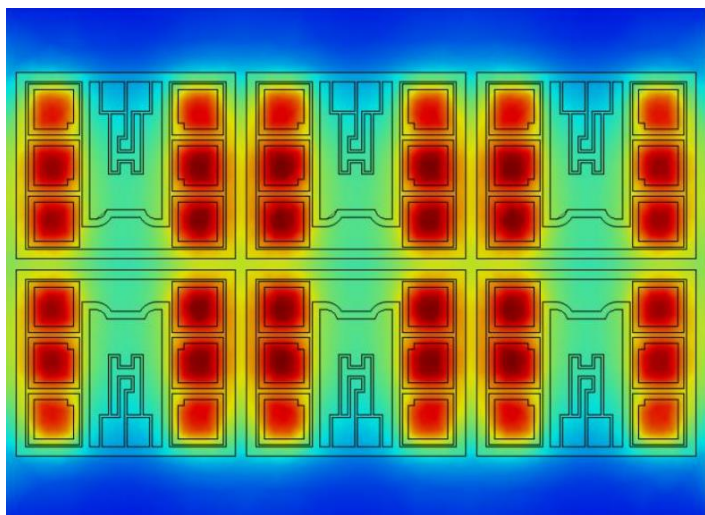


Fonte: G. Zeng et. al. "First results of development of a lifetime model for transfer molded discrete power devices". PCIM Europe 2018



Fonte: On Semiconductors.

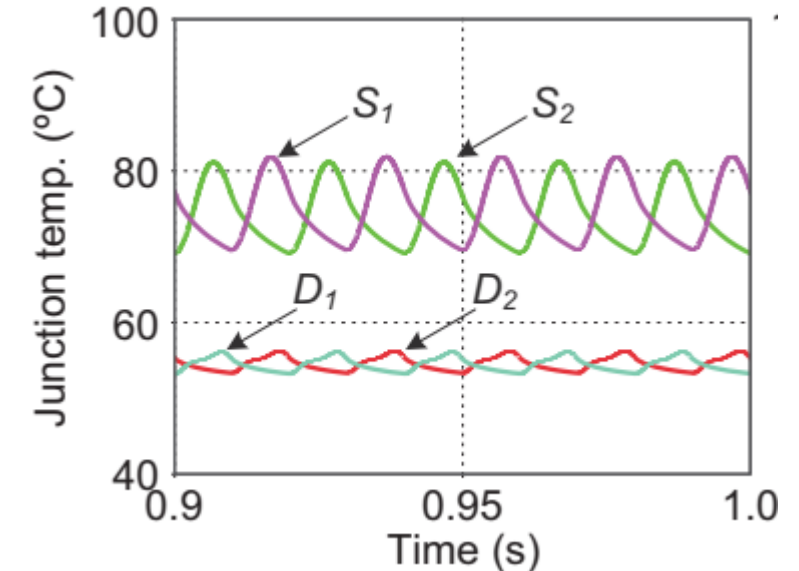
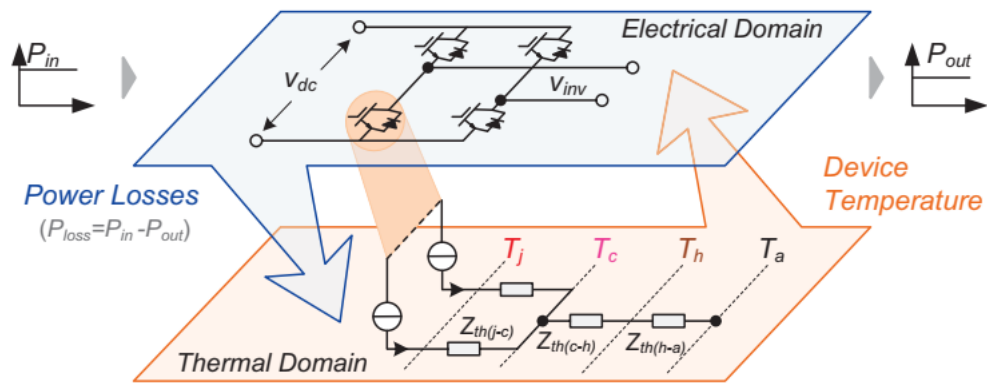
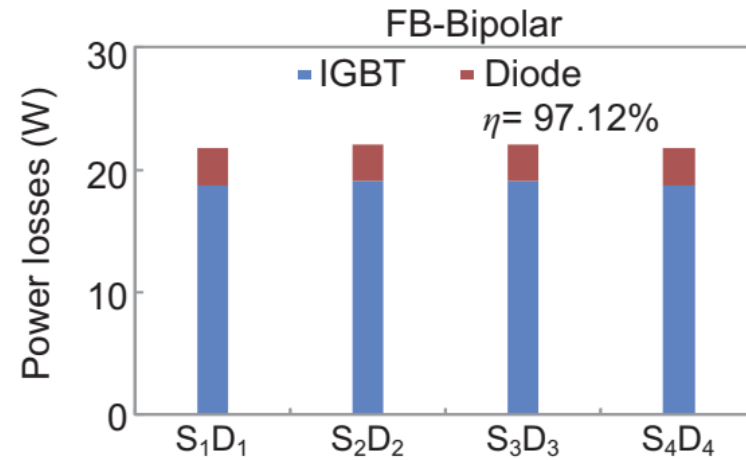
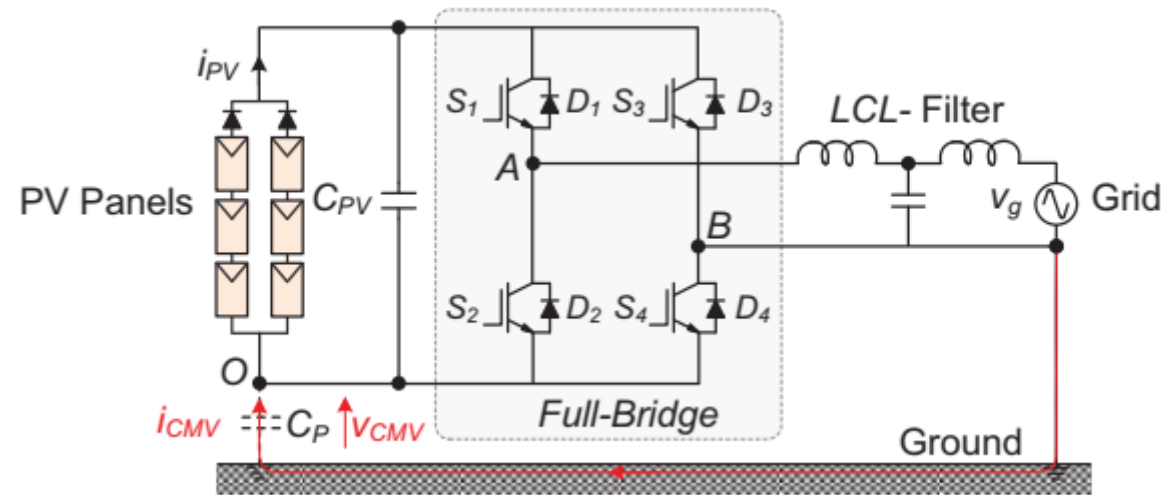
# Perdas e estresse térmico em um IGBT



Fontes:

- [1] S. Hartmann et.al.. “Packaging Technology Platform for Next Generation High Power IGBT Modules”. 2014.
- [2] : G. Zeng et. al. “First results of development of a lifetime model for transfer molded discrete power devices”. PCIM Europe 2018
- [3] A. P. Cota. Semikron. “Desenvolvimento de ferramentas computacionais para a análise de perdas em conversores estáticos: aplicação ao cálculo de rendimento de UPS’s trifásicas de dupla conversão”. Dissertação de mestrado. UFMG. 2016.

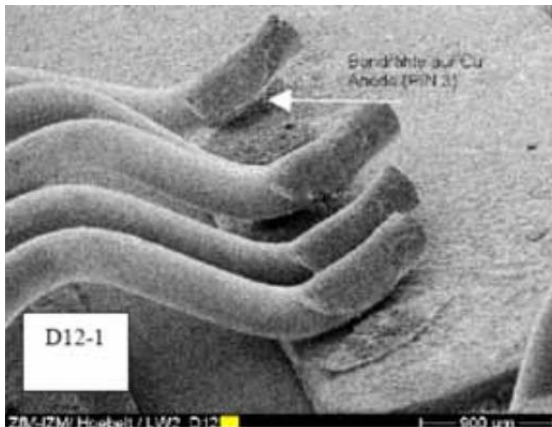
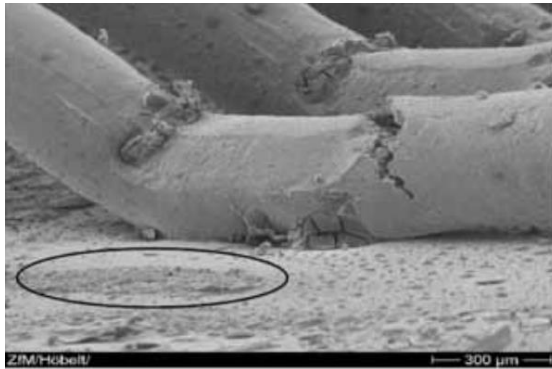
# Perdas e estresse térmico em um IGBT



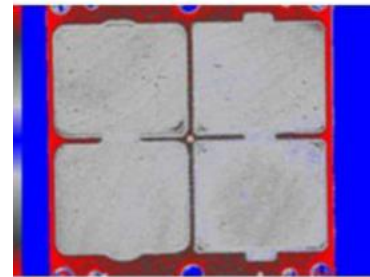
Fonte: Y. Yang. "Advanced Control Strategies to Enable a More Wide-Scale Adoption of Single-Phase Photovoltaic Systems". Ph.D. Thesis. Aalborg University. 2014.

# Alguns mecanismos de falha de IGBTs

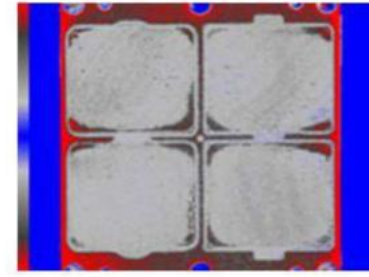
## Bond Wires



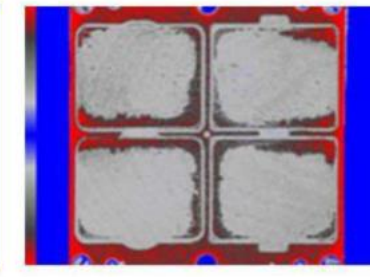
## Chip Solder



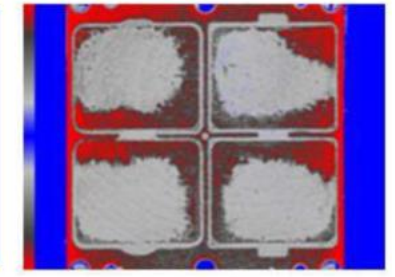
200 Cycles



1000 Cycles

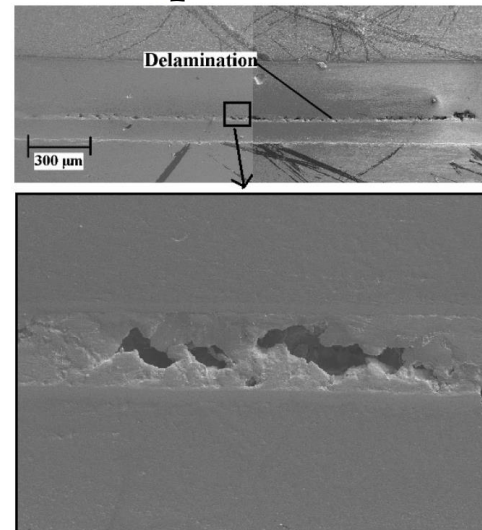


2000 Cycles



4000 Cycles

## Baseplate solder



## Thermal grease



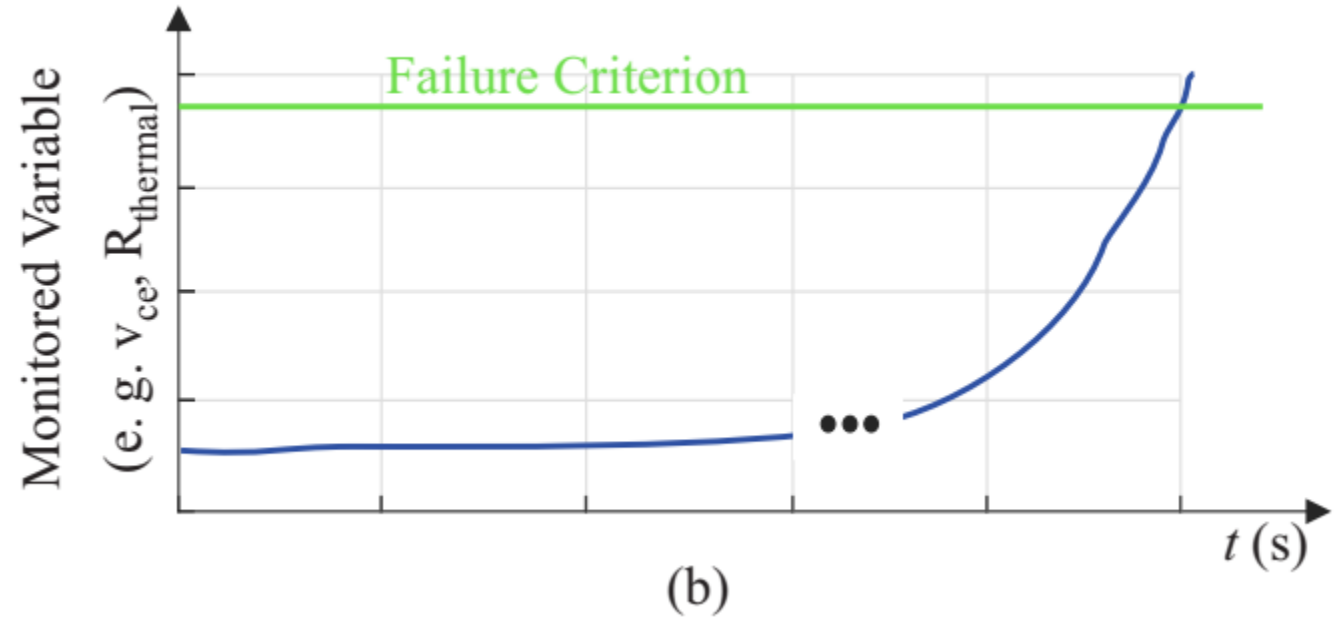
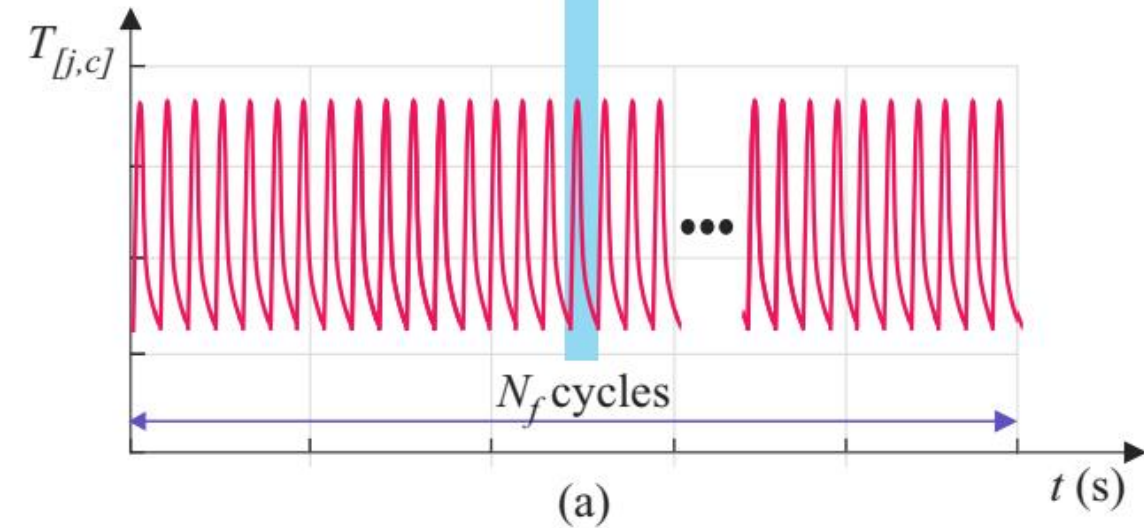
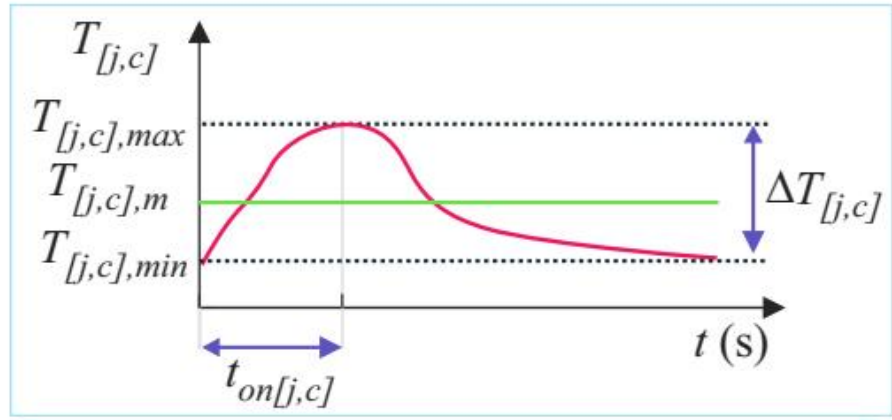
Fontes:

[1] Semikron. "Application Manual of Semiconductors". 2015.

[2] T. Lhommeau et. al. "Base-plate solder reliability study of IGBT modules for aeronautical application". ECCE Europe.2007.

[3] M. Schulz, "Thermal management details and their influence on the aging of power semiconductors," EPE-ECCE Europe. 2014

# Testes de ciclagem térmica



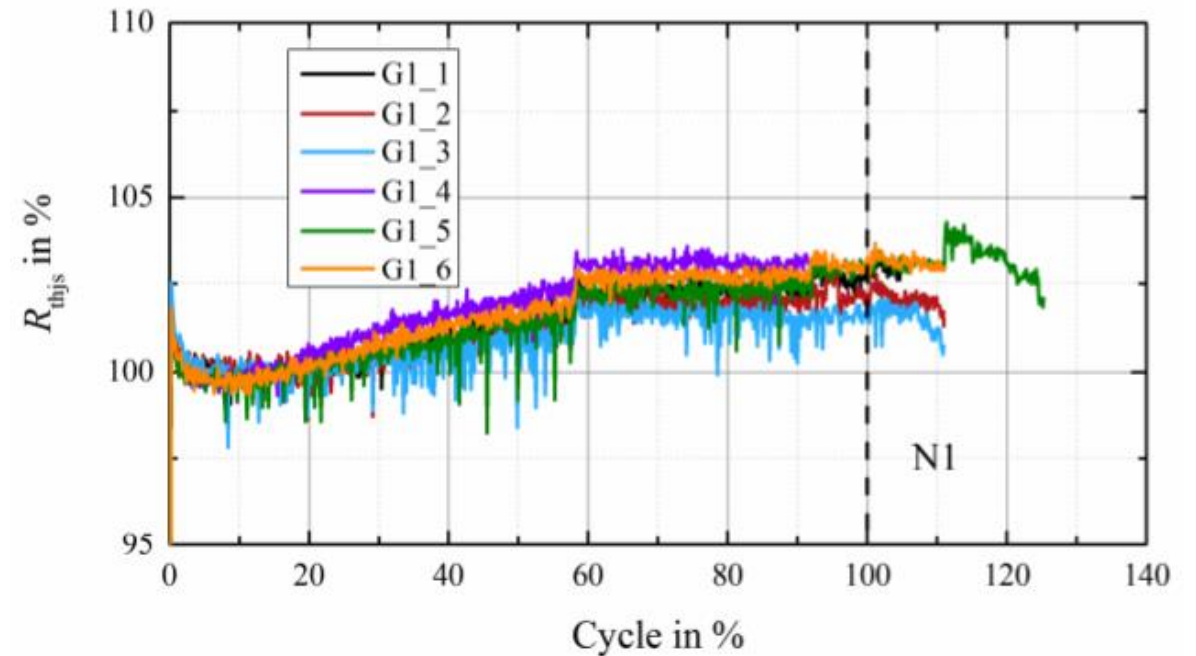
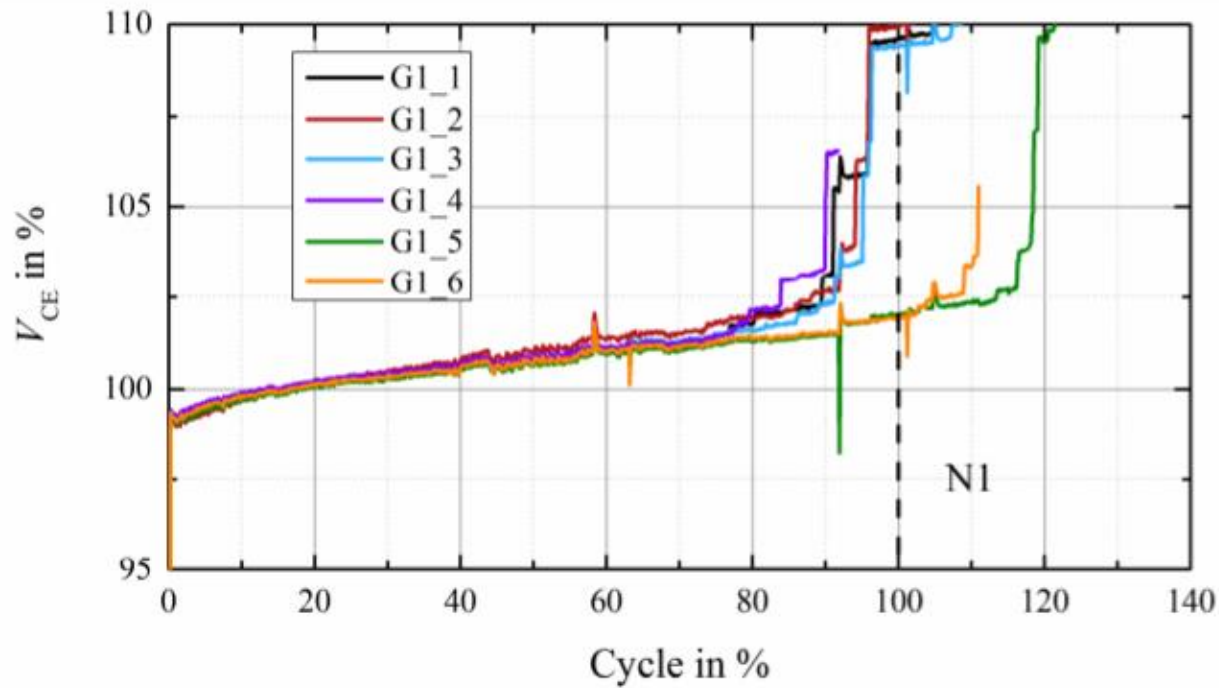


# Alguns desafios para obtenção de modelos de vida útil

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- Como desacoplar as variáveis?
- Quantas amostras são ensaiadas?
- Qual o critério de falha?
- Como separar os diferentes mecanismos de falha?

# Exemplo de resultados de testes reais – módulos de potência



Fonte: G. Zeng. “Experimental Investigation of Linear Cumulative Damage Theory With Power Cycling Test”. IEEE Transactions on Power Electronics. 2019.

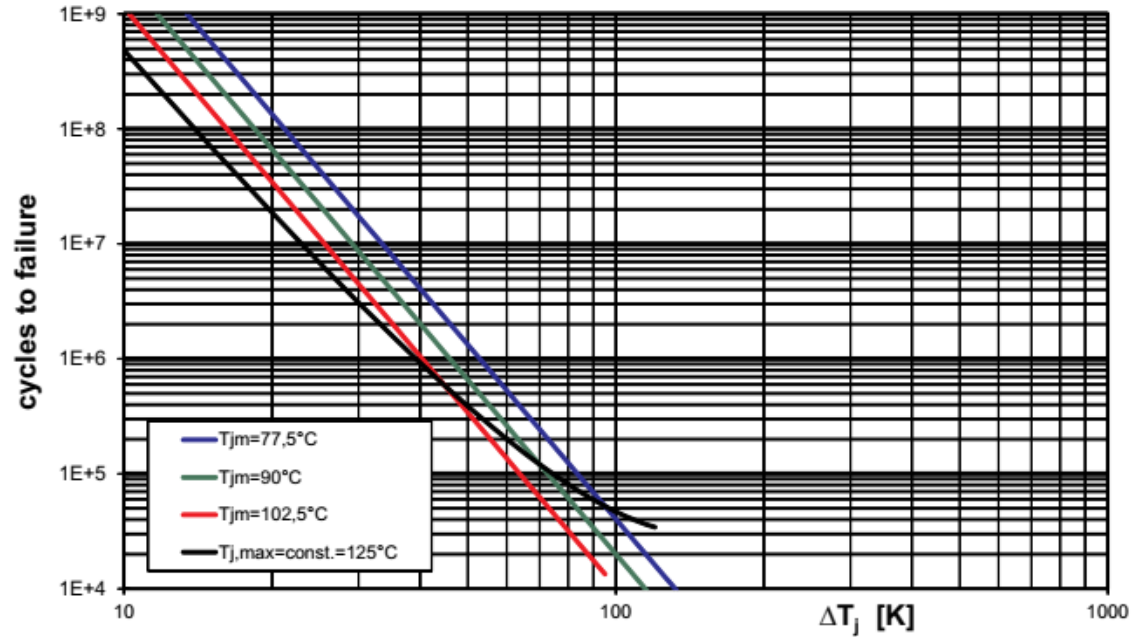
# Modelos de vida útil para semicondutores

	Analytical models	
<b>Coffin-Manson Model</b>	$N_f = A\Delta T_j^{-n}$	
<b>Modified Coffin-Manson Model</b>	$N_f = A\Delta T_j^{-n} \left( \frac{E_a}{k_B T_{jm}} \right)$	
<b>Norris-Landzberg Model</b>	$N_f = A\Delta T_j^{-n} \left( \frac{E_a}{k_B T_{jm}} \right) f^{-n_2}$	
<b>Bayerer's Model (2008)</b>	$N_f = A\Delta T_j^n \left( \frac{\beta_2}{T_{j,\min}} \right) t_{on}^{\beta_3} I^{\beta_4} V^{\beta_5} D^{\beta_6}$	
<b>Semikron model (2013)</b>	$N_f = A\Delta T_j^{-n} (\text{ar})^{\beta_1 \Delta T_j + \beta_0} \left( \frac{C + (t_{on})^y}{C} \right) \left( \frac{E_a}{k_B T_{jm}} \right) f_{diode}$	

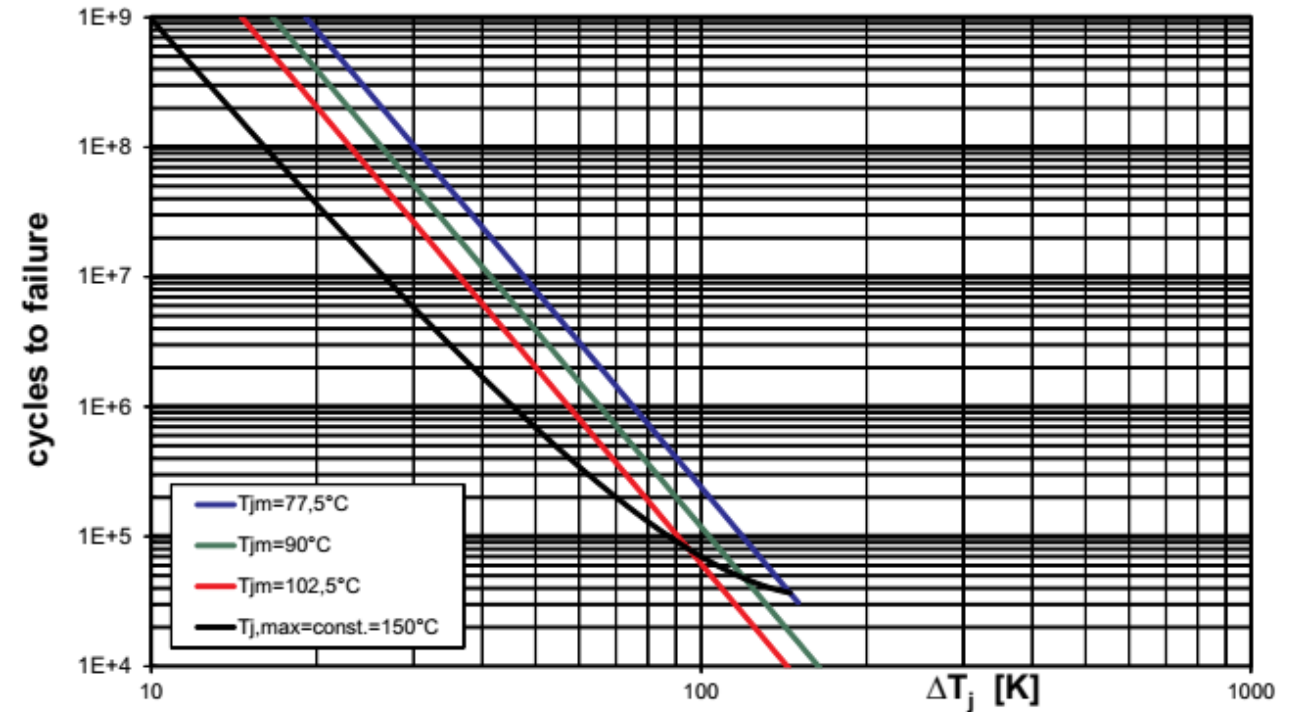
Fonte: F. Ianuzzo. "Reliability of active switching devices". Ph.D. Course. Aalborg University. 2018.

# Modelos de vida útil para semicondutores

**Standard IGBT modules**  
Power cycling lifetime as a function of  $\Delta T_j$  and  $T_{jm}$



**Advanced IGBT modules**  
Power cycling lifetime as a function of  $\Delta T_j$  and  $T_{jm}$



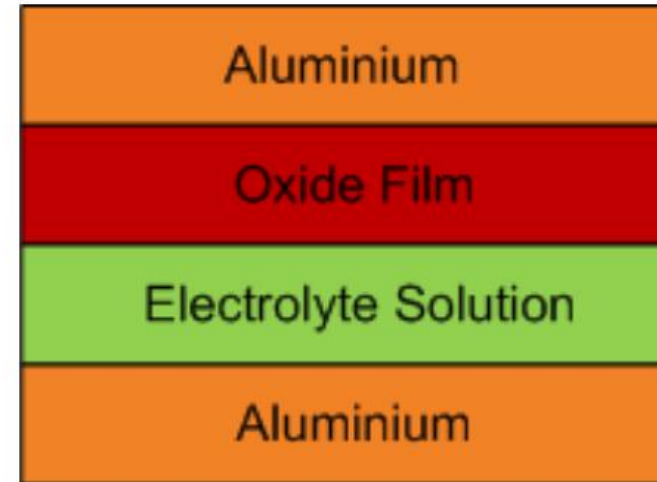
Fonte: Semikron. "Application Manual of Semiconductors". 2015.

# Capacitores



**Sandwich**

(Source: [http://www.jhdeli.com/Templates/Cold\\_Sandwich.html](http://www.jhdeli.com/Templates/Cold_Sandwich.html))



**Aluminum Electrolytic Capacitor**

## Capacitance

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

## Ripple current rating

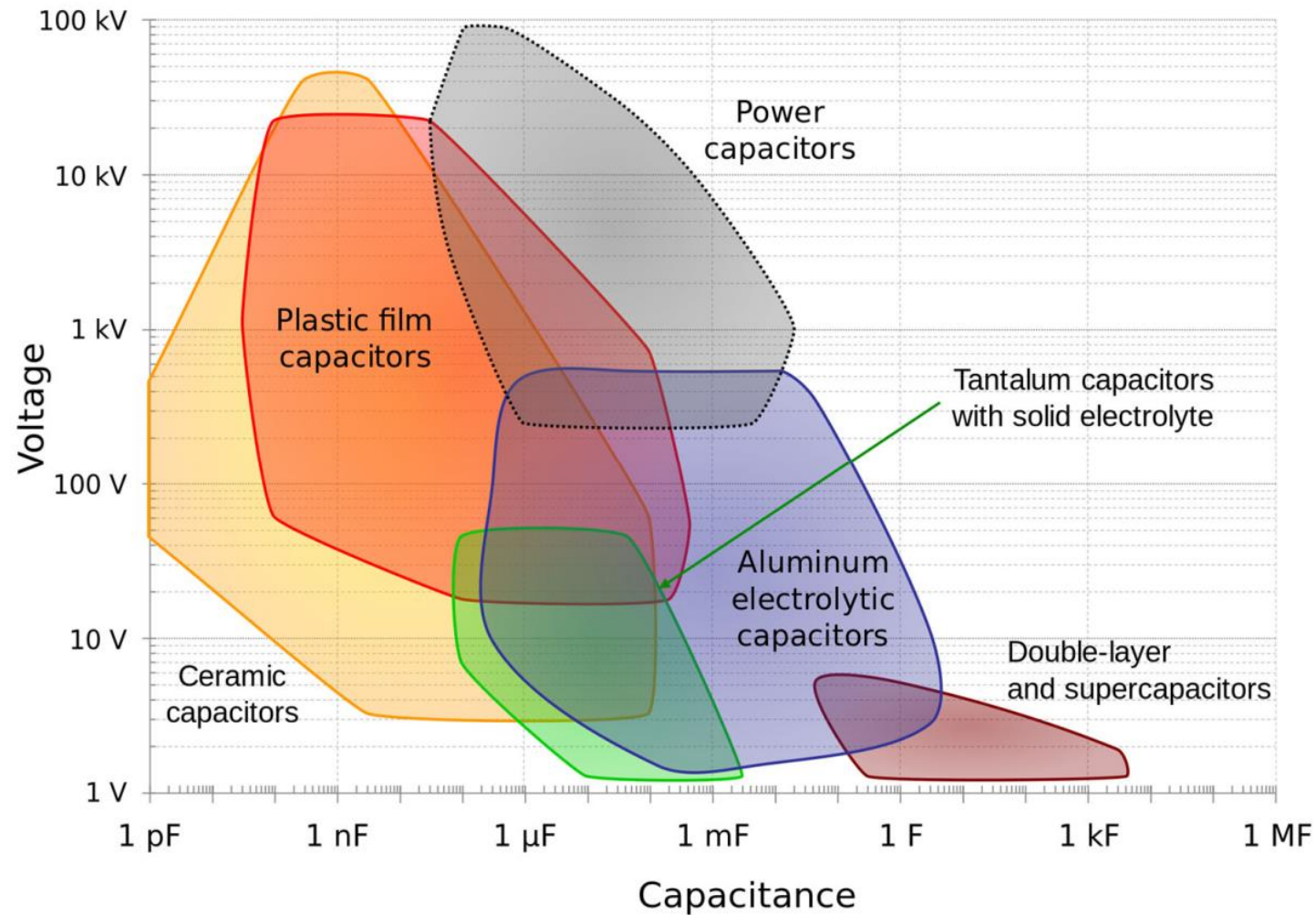
$$I_r = \sqrt{\frac{P_d}{R_s}} = \sqrt{\frac{hA\Delta T}{R_s}}$$

## Volumetric efficiency

$$\eta_v = \frac{CV}{\text{volume}}$$

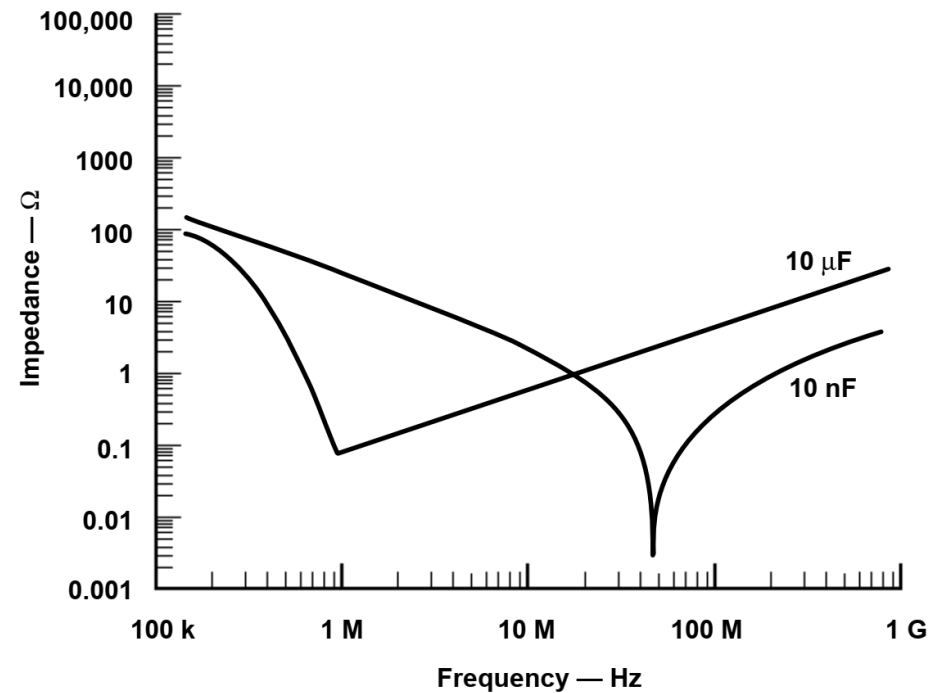
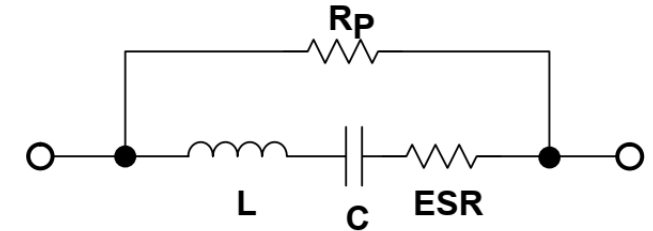
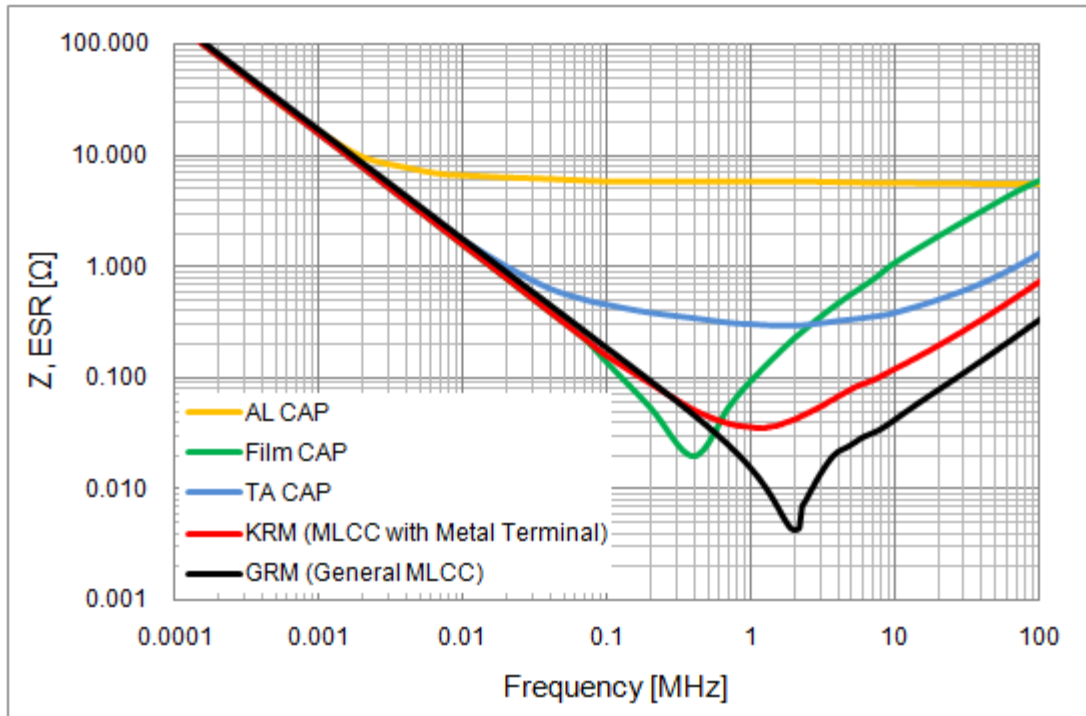
Fonte: H. Wang. "Capacitors in Power Electronics Applications". Ph.D. Course. Aalborg University. 2018.

# Capacitores



Fonte: H. Wang. "Capacitors in Power Electronics Applications". Ph.D. Course. Aalborg University. 2018.

# Efeito da frequência na impedância do capacitor

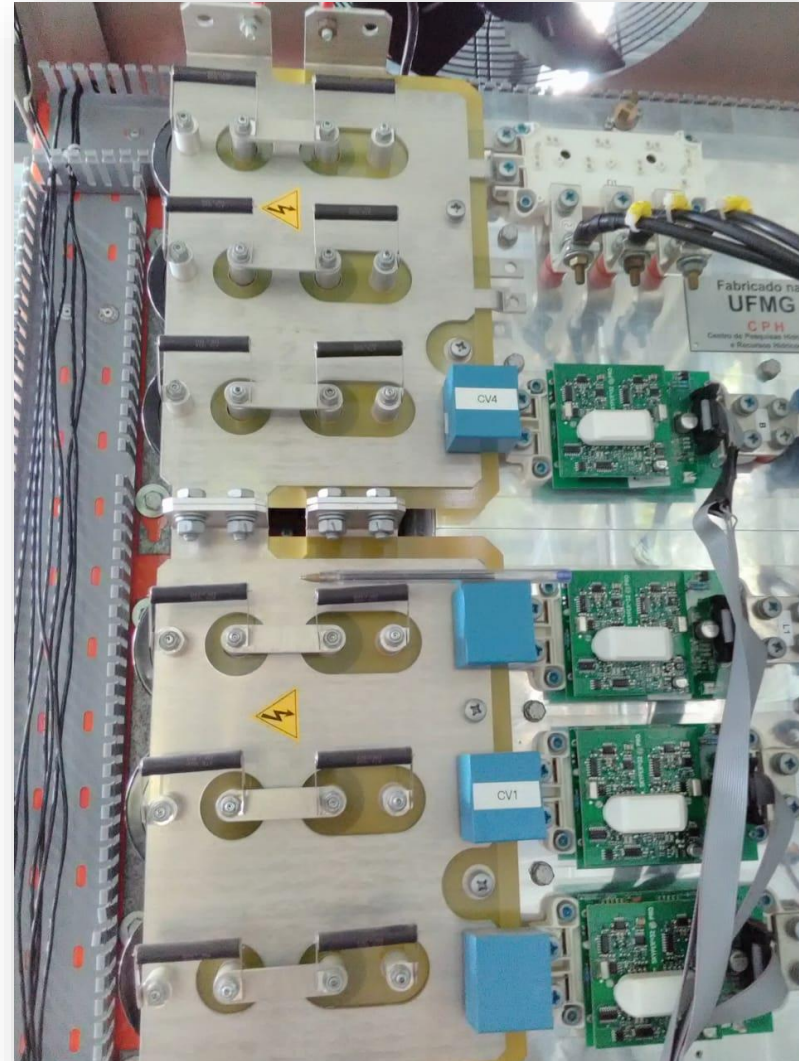
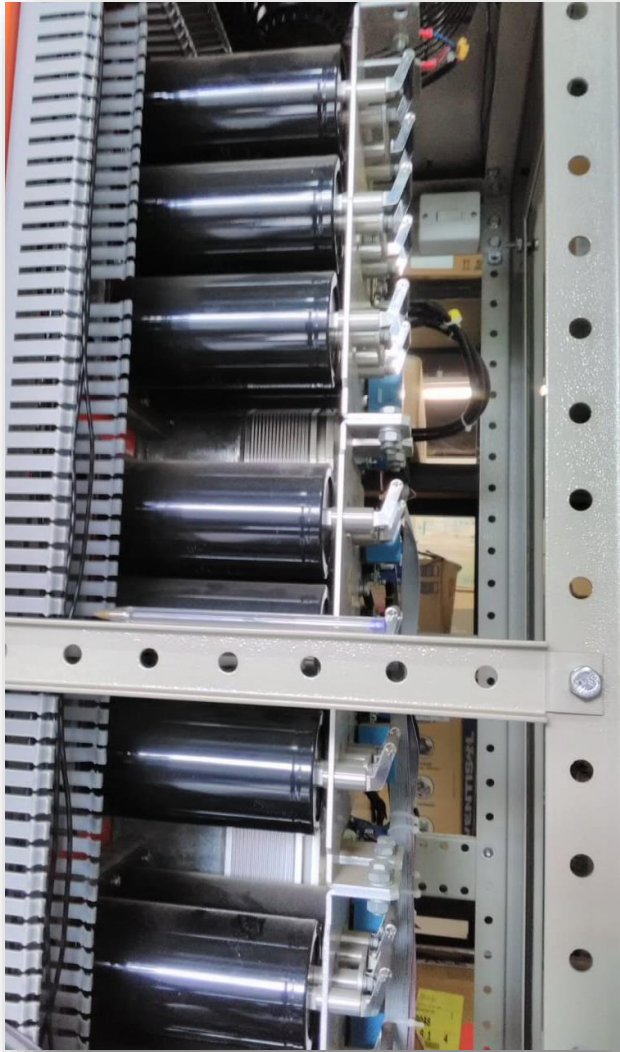


Fontes:

[1] <https://www.murata.com/en-eu/support/faqs/products/capacitor/mlcc/char/0027>

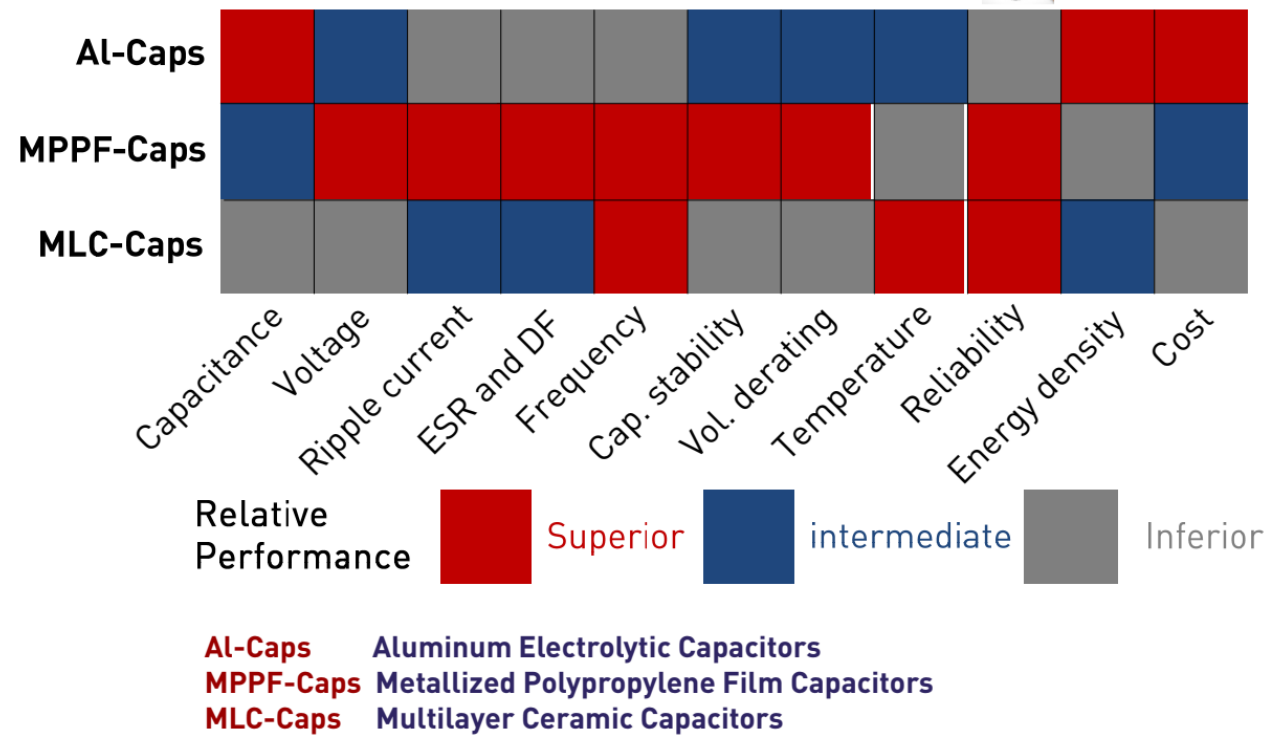
[2] Texas instruments. "Op Amps for Everyone"

# Exemplo: Inversor de 100 kVA





# Comparação das tecnologias mais utilizadas em EP



Fonte: H. Wang. “Capacitors in Power Electronics Applications”. Ph.D. Course. Aalborg University. 2018.

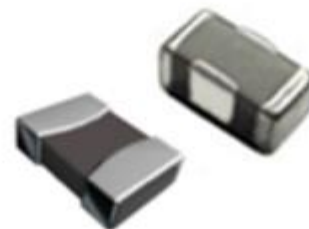
# Mecanismos de falha de capacitores e fatores críticos

	Al-Caps	MPPF-Caps	MLCC-Caps
Dominant failure modes	wear out		
	open circuit	open circuit	short circuit
Most critical stressors	$T_a, V_C, i_C$	$T_a, V_C, \text{humidity}$	$T_a, V_C, \text{vibration/shock}$
Self-healing capability	moderate	good	no

**Al-Caps** Aluminium Electrolytic Capacitors

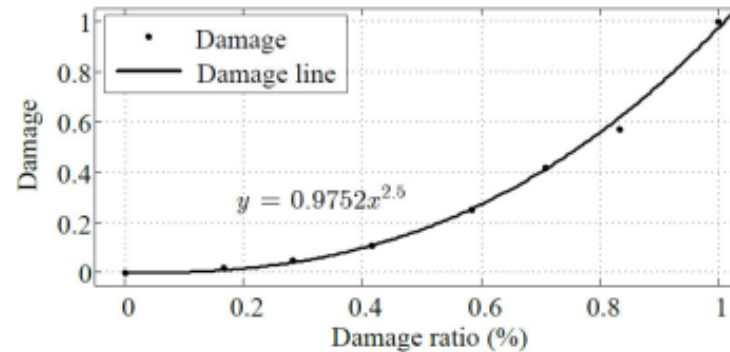
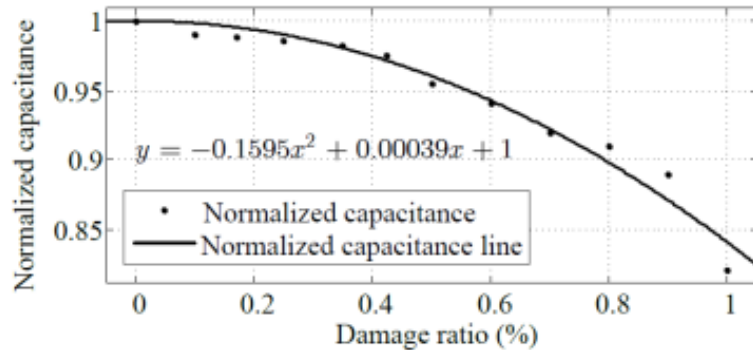
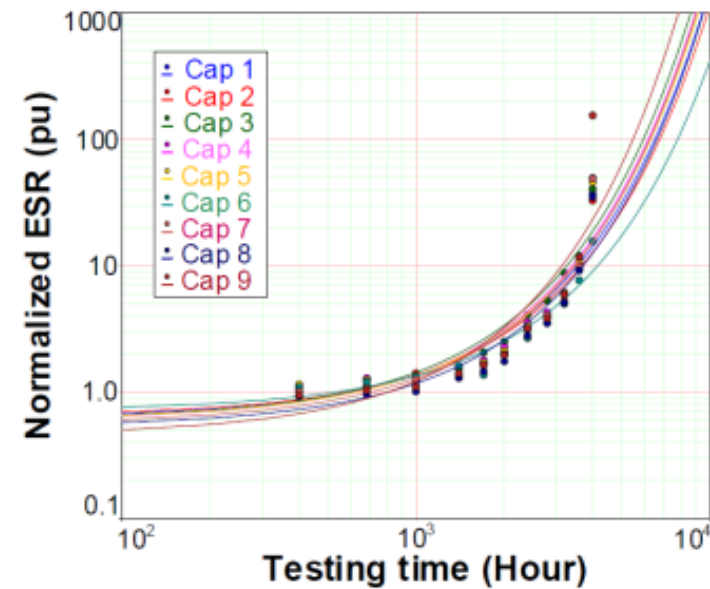
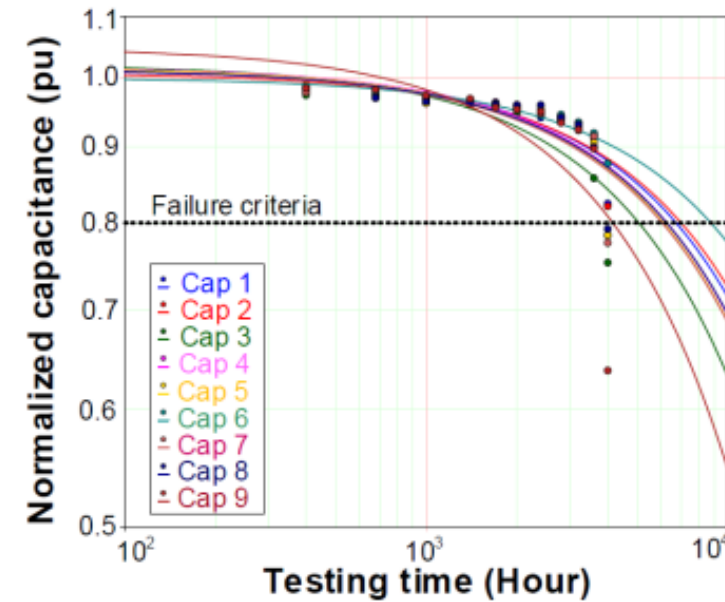
**MPPF-Caps** Metallized Polypropylene Film Capacitors

**MLC-Caps** Multilayer Ceramic Capacitors



Fonte: H. Wang. "Capacitors in Power Electronics Applications". Ph.D. Course. Aalborg University. 2018.

# Exemplo de resultados de testes reais – Capacitores



Fonte: H. Wang. “Capacitors in Power Electronics Applications”. Ph.D. Course. Aalborg University. 2018.

## Exemplo modelos de vida útil de capacitores

$$L = L_0 \times \left(\frac{V}{V_0}\right)^{-n} \times \exp \left[ \left(\frac{E_a}{K_B}\right) \left(\frac{1}{T} - \frac{1}{T_0}\right) \right]$$

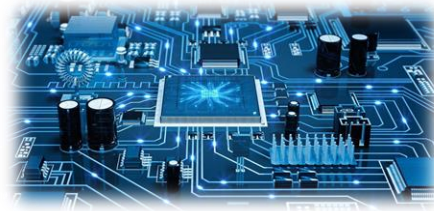
$$L = L_0 \times \left(\frac{V}{V_0}\right)^{-n} \times 2^{\frac{T_0 - T}{10}}$$

$$\frac{L}{L_0} = \begin{cases} \left(\frac{V_0}{V}\right) \times \exp \left[ \left(\frac{E_a}{K_B}\right) \left(\frac{1}{T} - \frac{1}{T_0}\right) \right] & \text{(low } \xi) \\ \left(\frac{V_0}{V}\right)^{-n} \times \exp \left[ \left(\frac{E_a}{K_B}\right) \left(\frac{1}{T} - \frac{1}{T_0}\right) \right] & \text{(medium } \xi) \\ \exp [a_1(V_0 - V)] \times \exp \left[ \frac{E_{a0} - a_0\xi}{K_B T} - \frac{E_{a0} - a_0\xi_0}{K_B T_0} \right] & \text{(high } \xi) \end{cases}$$

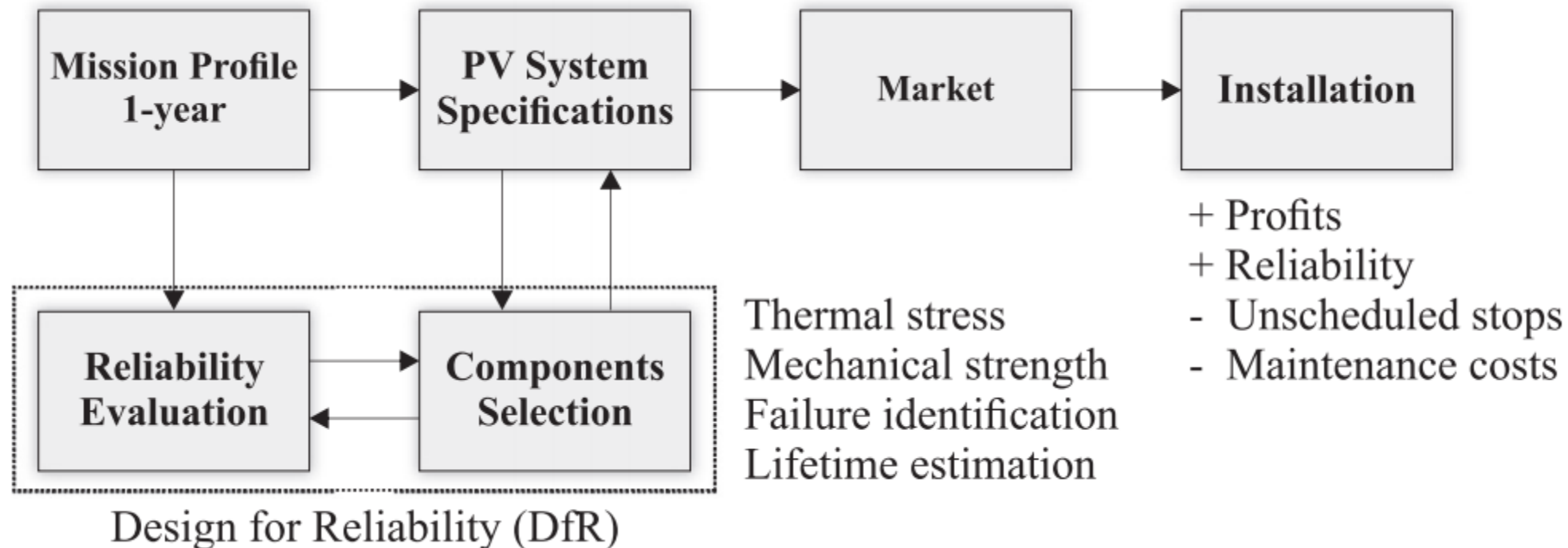
Fonte: H. Wang. "Reliability of Capacitors for dc-link Applications in Power Electronics – An Overview". IEEE Transactions on Industry Applications. 2014



# Projeto com foco em confiabilidade



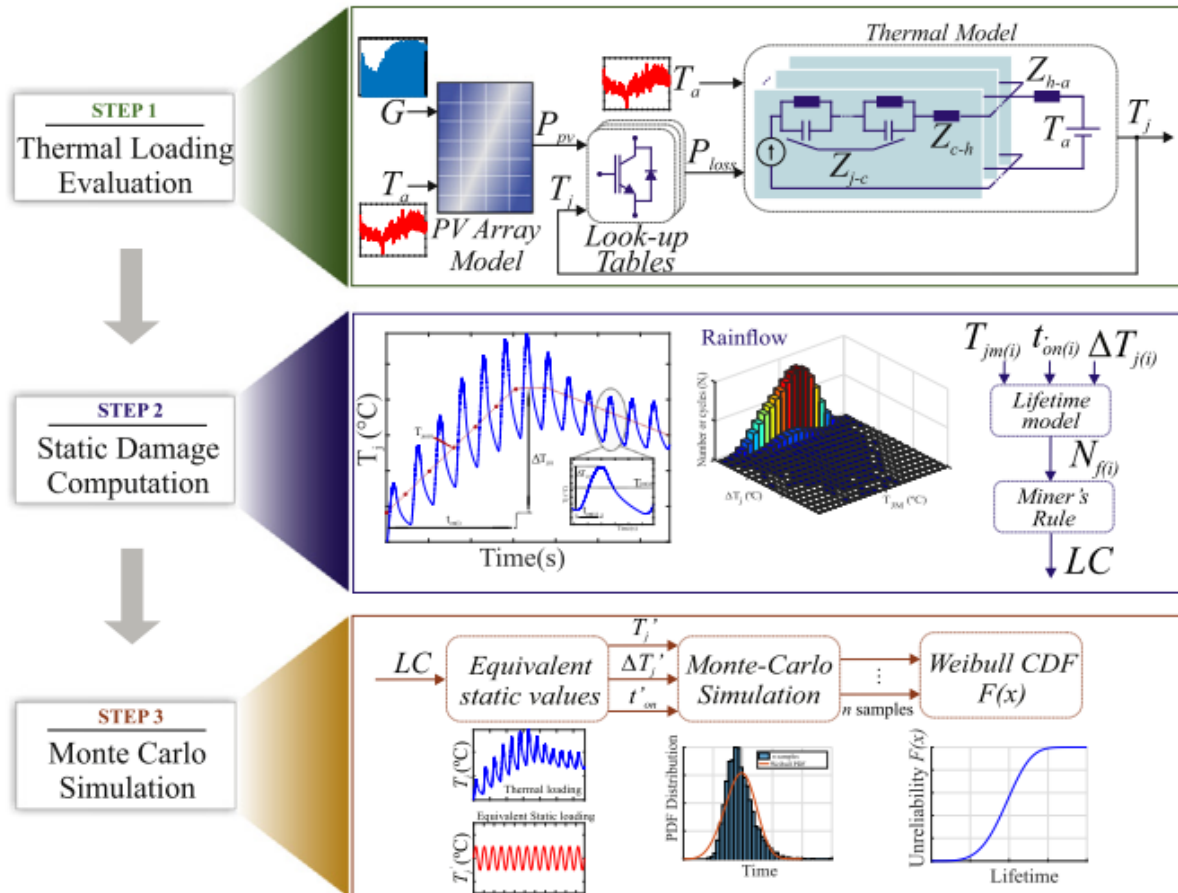
# Projeto com foco em confiabilidade



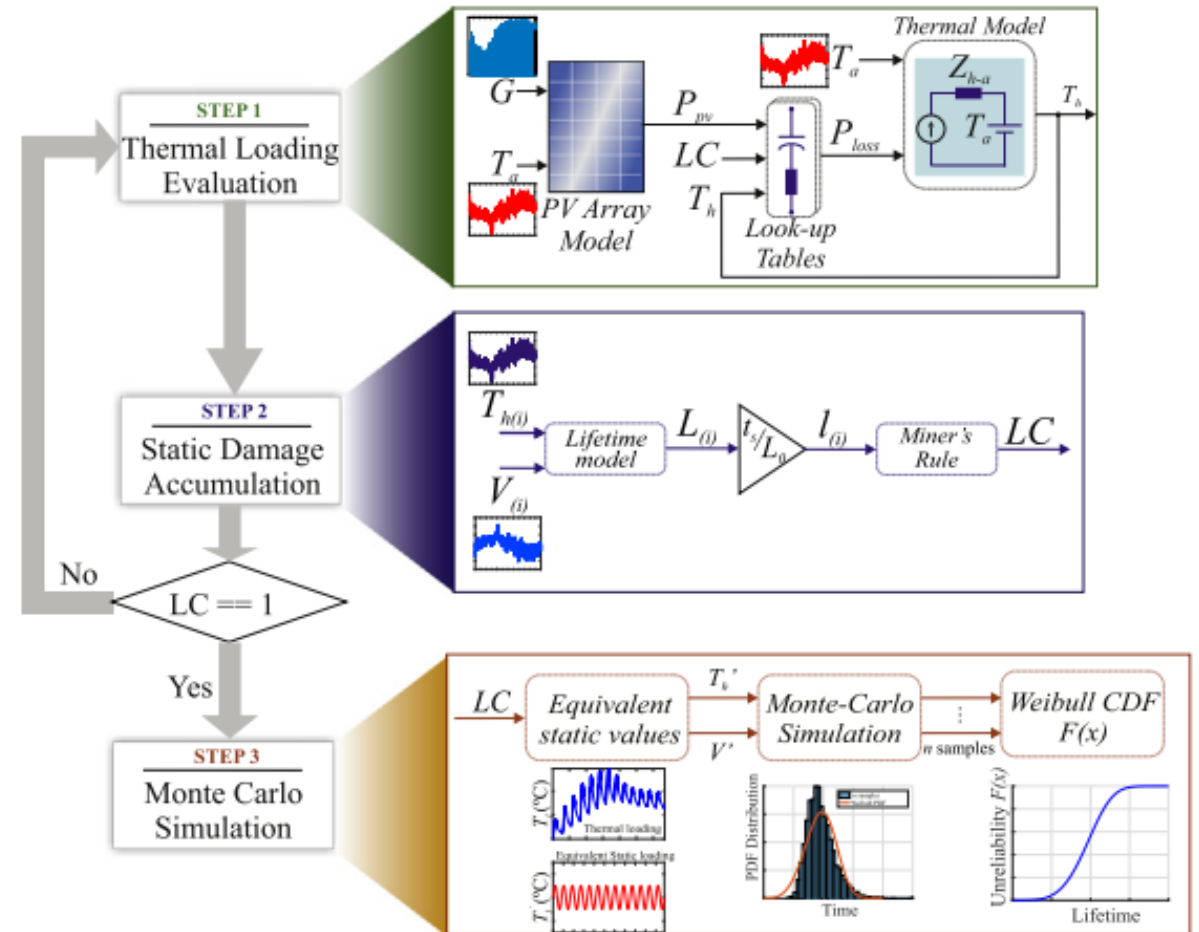
Fonte: E. M. S. Brito et. al. "Impact of meteorological variations on the lifetime of grid-connected PV inverters". Microelectronics Reliability. 2018.

# Fluxograma detalhado – Avaliação do Wear-out

## ❑ Semicondutores.



## ❑ Capacitores.



Fonte: A. F. Cupertino et. al. "Impact of the mission profile length on lifetime prediction of PV inverters.". Microelectronics Reliability. 2019

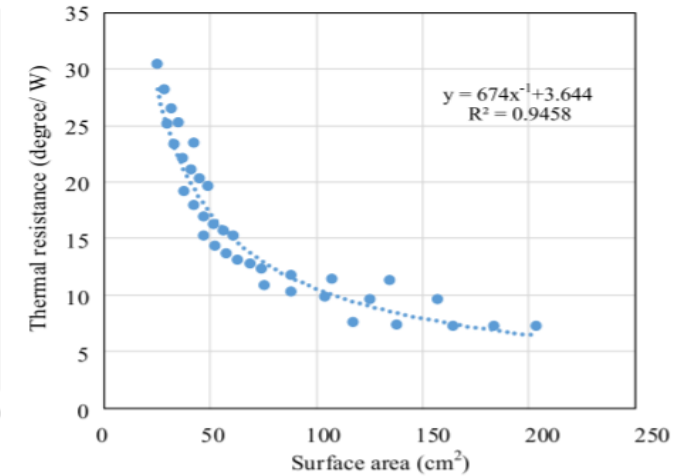
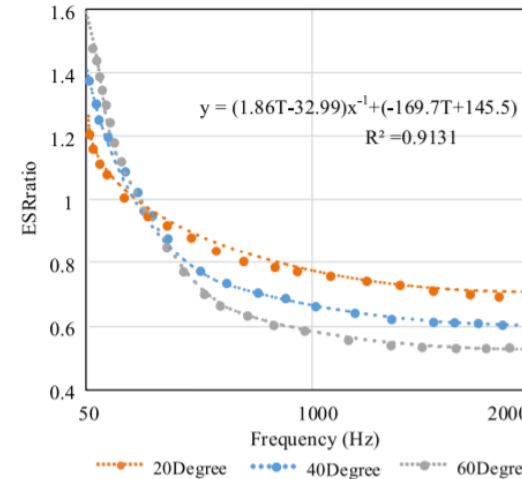
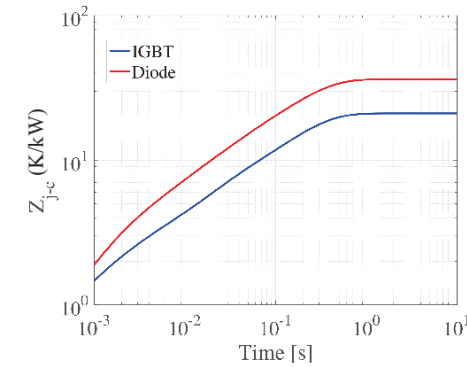
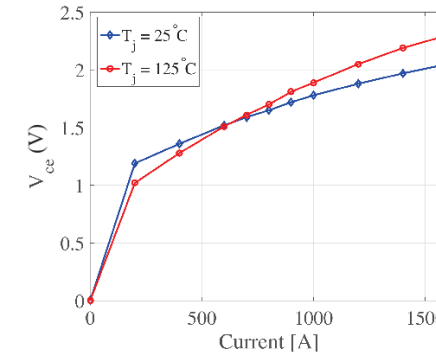
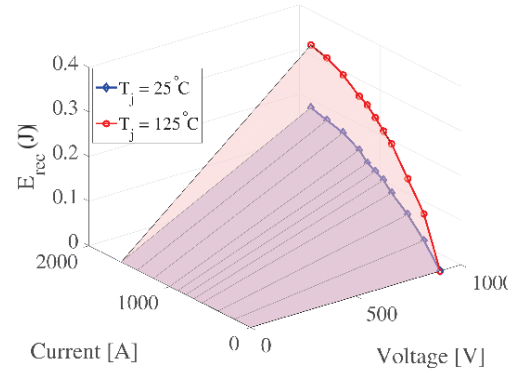
# Estimativa de perdas – Datasheet ou experimentos

❑ Perdas de condução;

❑ Perdas de comutação;

❑ ESR do capacitor;

❑ Impedâncias térmicas.



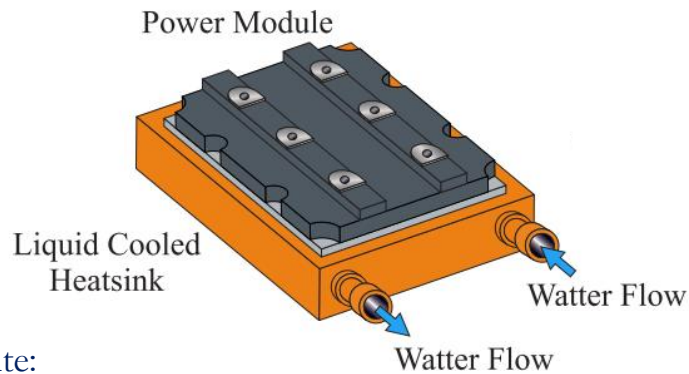
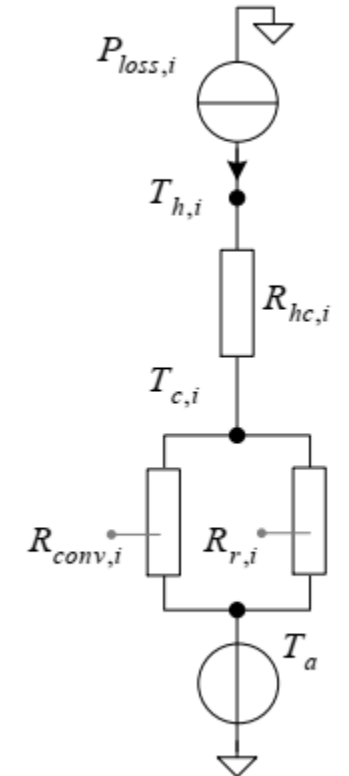
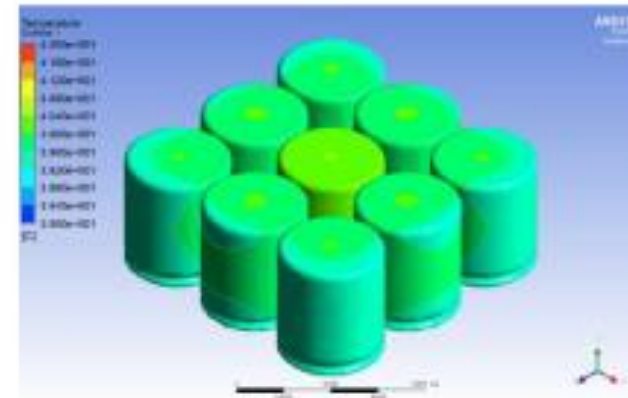
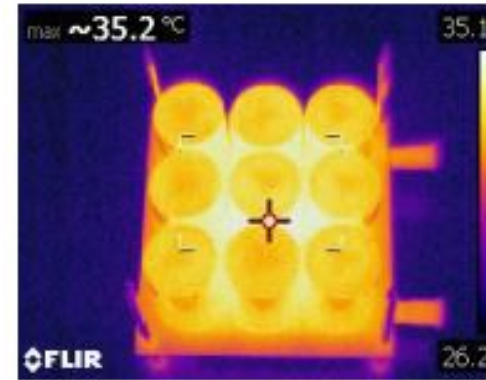
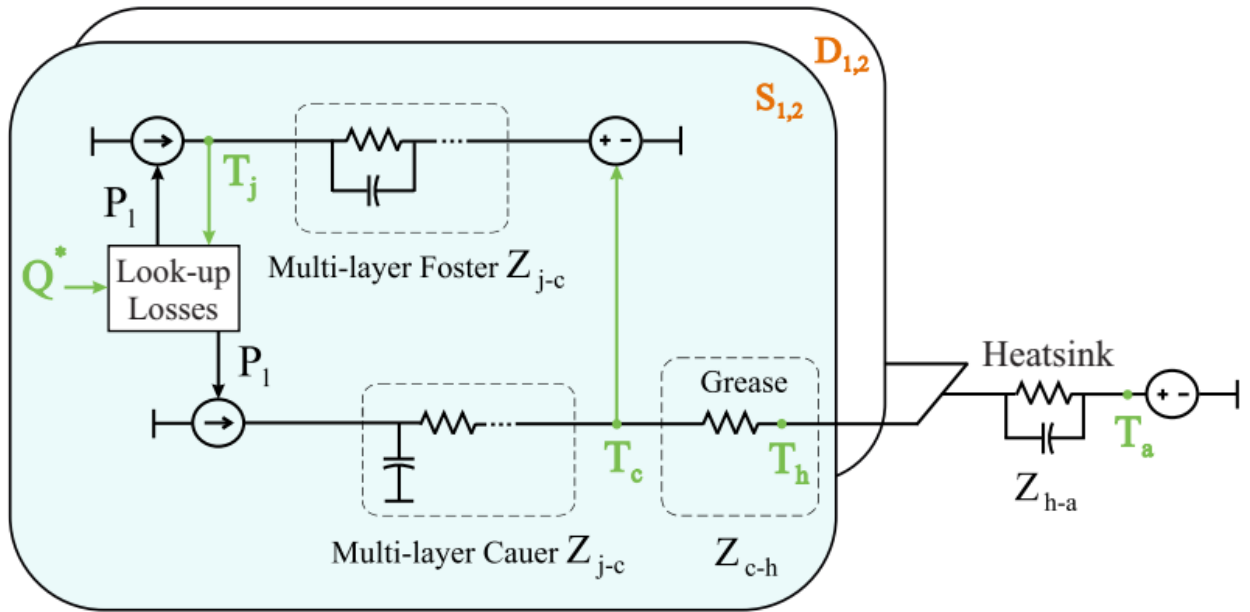
Fonte:

[1] A. F. Cupertino “Modeling, Design and Fault-Tolerant Strategies for Modular Multilevel Cascaded Converter-based STATCOMs. PhD Thesis. UFMG. 2019

[2] H. Wang. “Model-Based Design and Optimization of Hybrid DC-Link Capacitor Banks”. IEEE Transactions on Power Electronics. 2020.



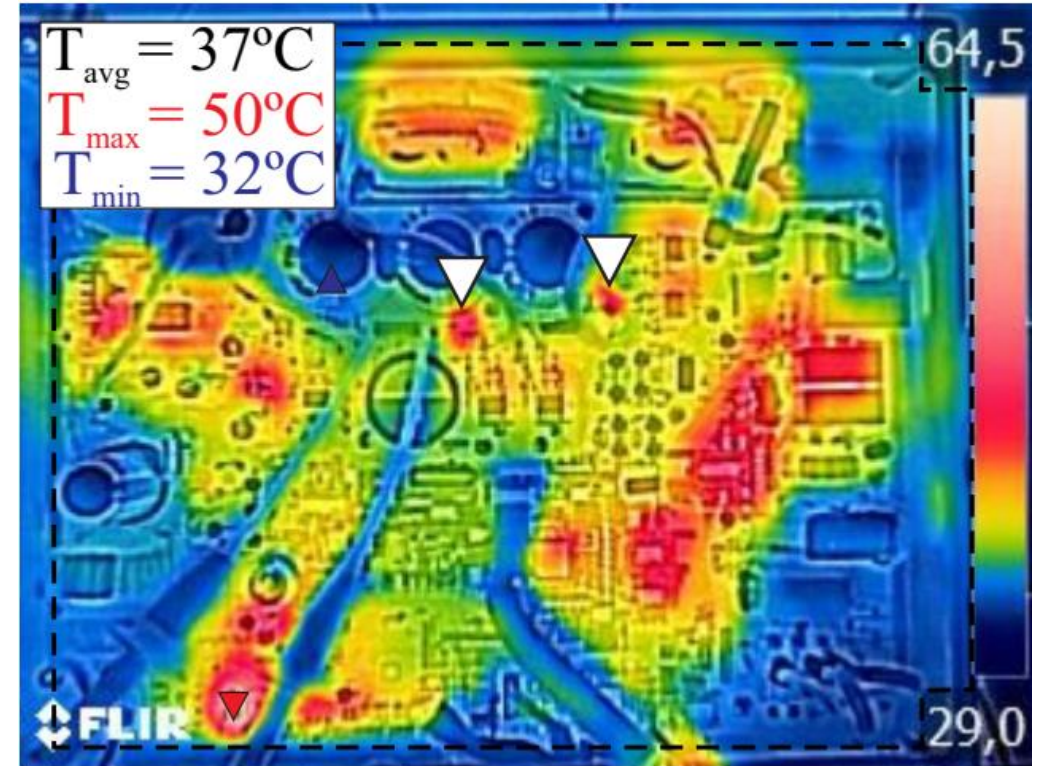
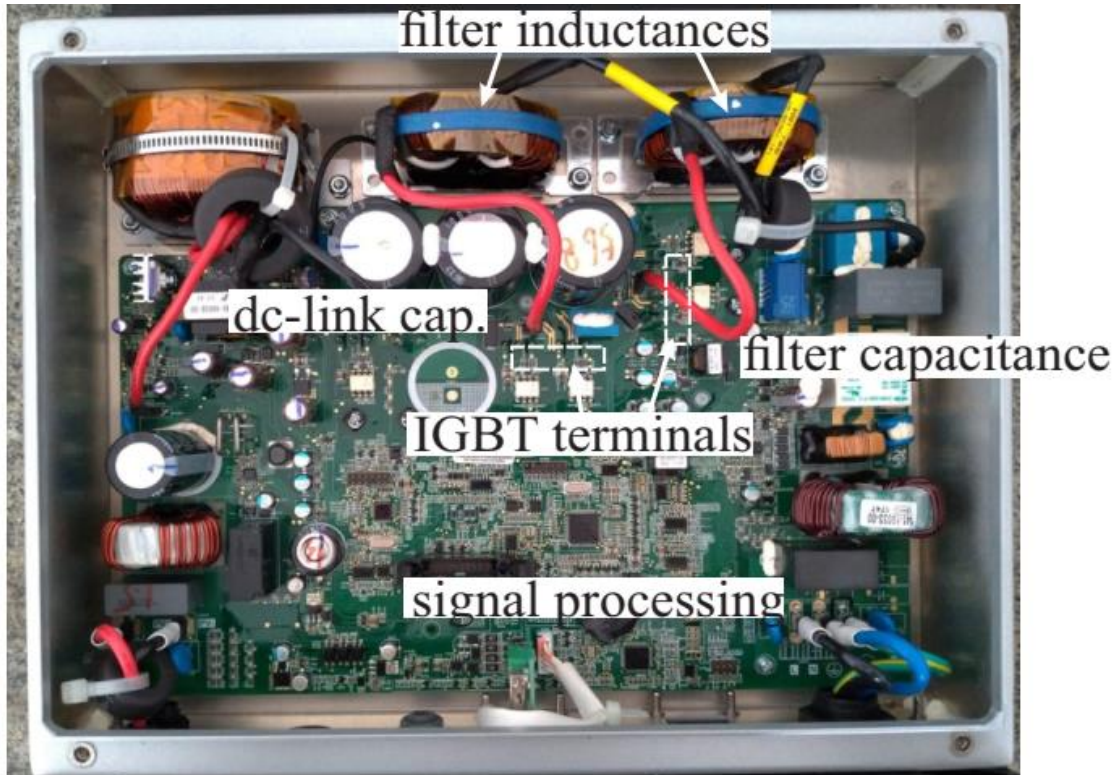
# Modelo térmico – fundamental na estimativa



Fonte:

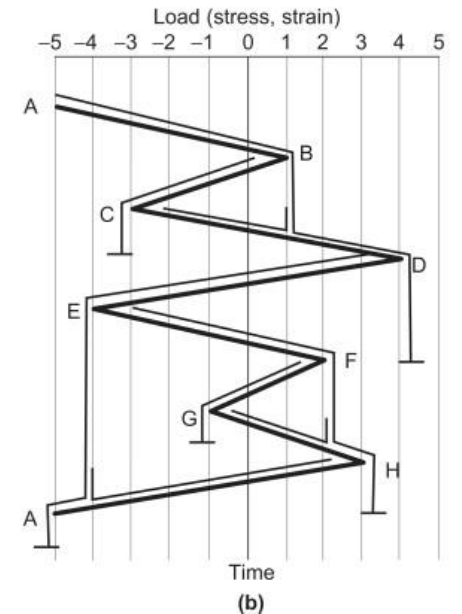
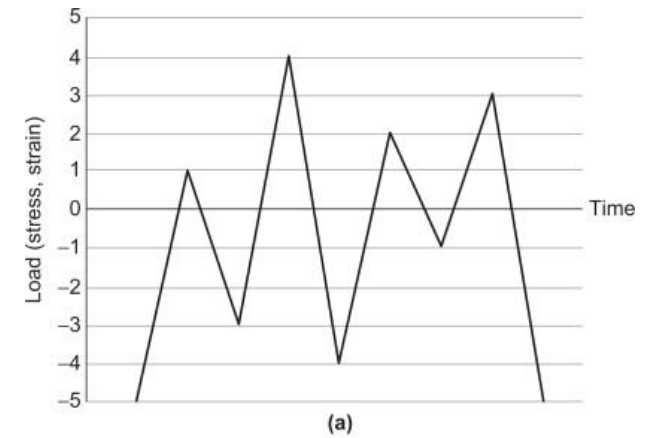
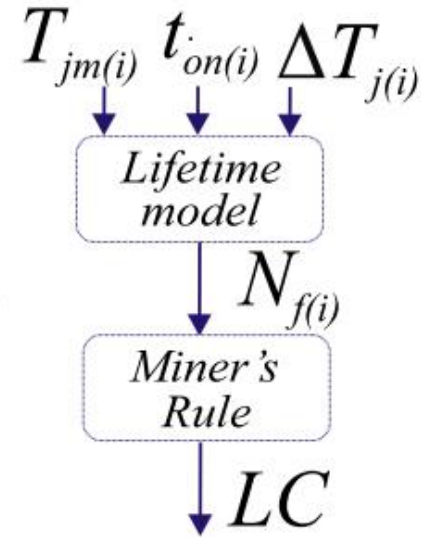
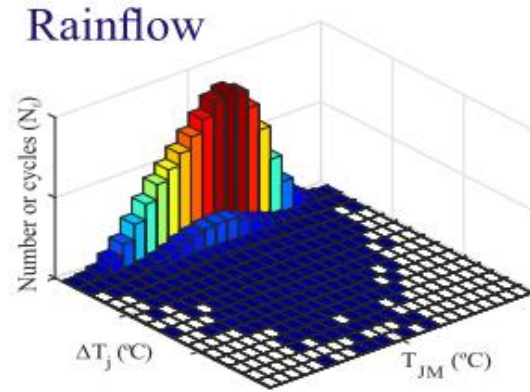
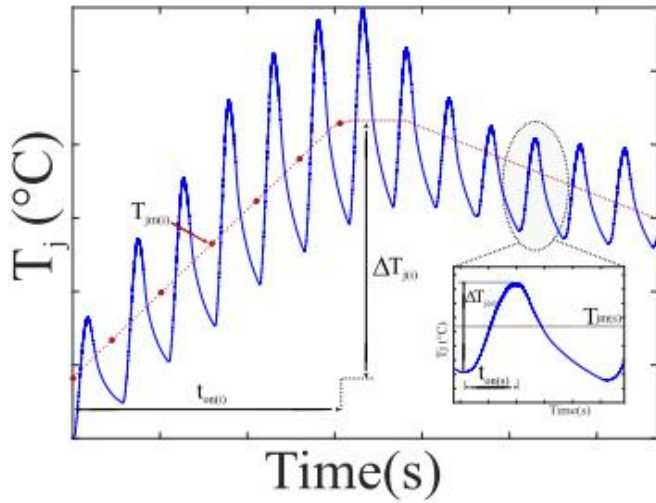
- [1] A. F. Cupertino “Modeling, Design and Fault-Tolerant Strategies for Modular Multilevel Cascaded Converter-based STATCOMs”. PhD Thesis. UFMG. 2019.
- [2] H. Wang. “Capacitors in Power Electronics Applications”. Ph.D. Course. Aalborg University. 2018

# Modelo térmico – acoplamento entre os componentes



❑ Problema complexo!

# Caracterização dos ciclos térmicos e dano acumulado



$$N_f = A (\Delta T_j)^\alpha (ar)^{\beta_1 \Delta T_j + \beta_0} \left[ \frac{C + (t_{on})^\gamma}{C + 1} \right] \exp \left( \frac{E_a}{k_b T_{jm}} \right) f_d$$

$$LC = \sum_i^n \frac{1}{N_{f,i}}$$

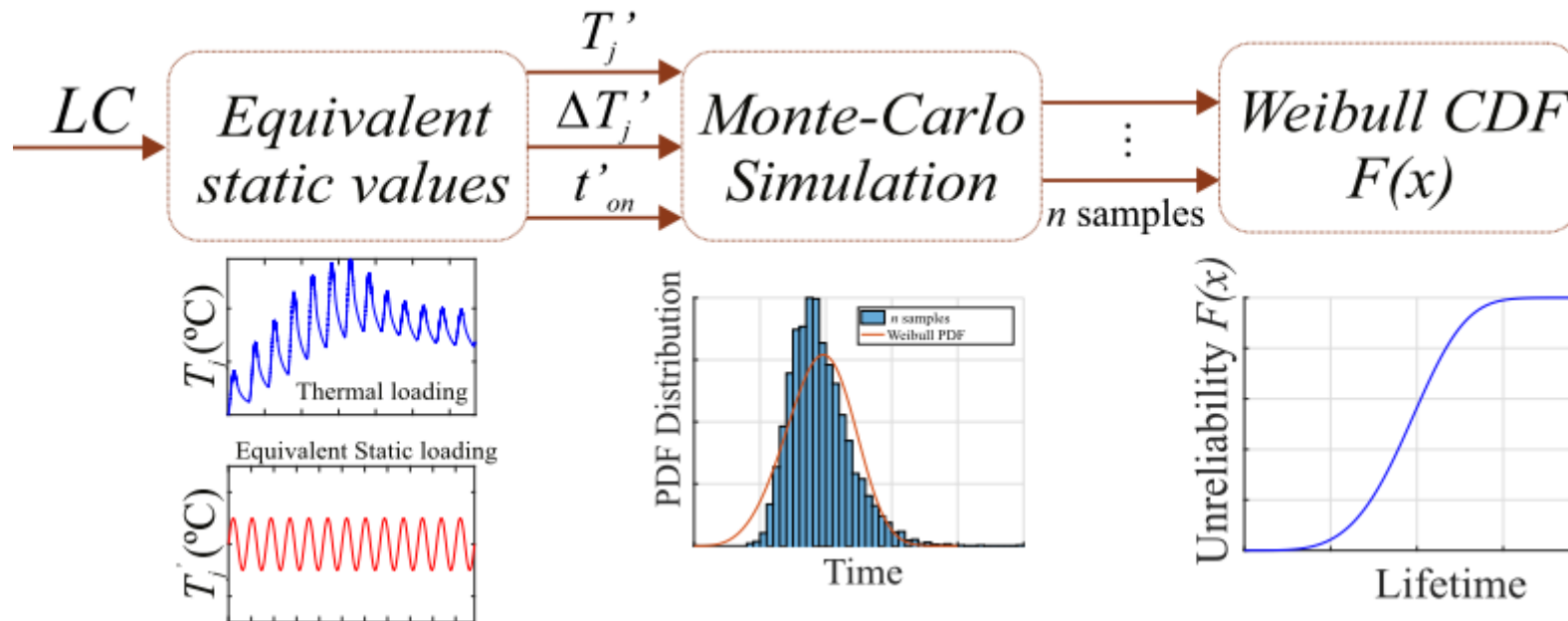
Fonte: A. F. Cupertino et. al. "Impact of the mission profile length on lifetime prediction of PV inverters.". Microelectronics Reliability. 2019

# Necessidade de uma análise estatística

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- ❑ O dano LC é uma estimativa de vida útil se todos os dispositivos falham ao mesmo tempo;
- ❑ Contudo, os conversores são compostos por mais de um componente;
- ❑ Componentes não são perfeitamente idênticos;
- ❑ Solução → Simulação de Monte Carlo;
- ❑ Confiabilidade é uma variável probabilística!

# Simulação de Monte-Carlo



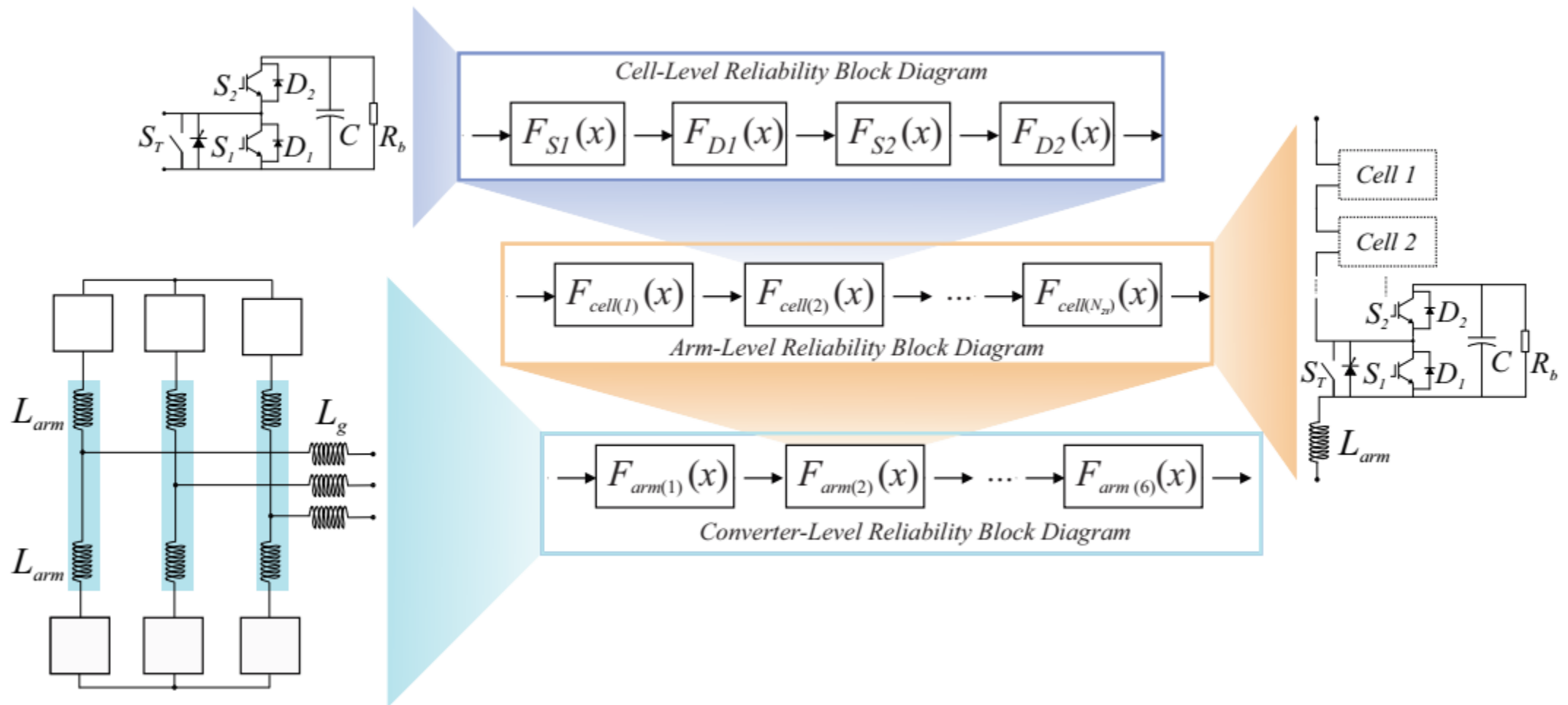
$$f(x) = \frac{\beta}{\eta^\beta} x^{\beta-1} \exp \left[ -\left( \frac{x}{\eta} \right)^\beta \right]$$

$$F(x) = \int_0^x f(x) dx$$

□ Inclusão de variação paramétrica;

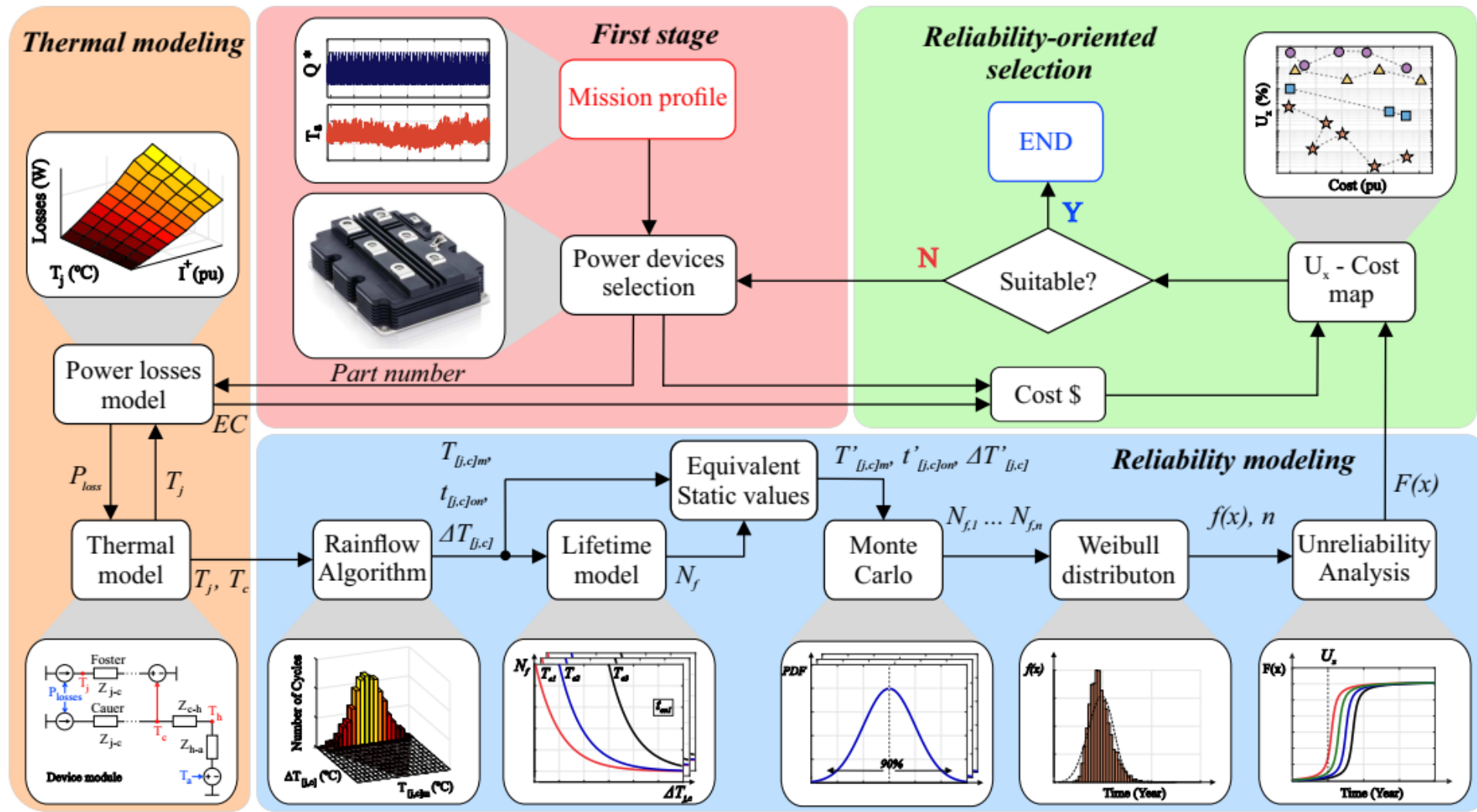
Fonte: A. F. Cupertino et. al. “Impact of the mission profile length on lifetime prediction of PV inverters.”. Microelectronics Reliability. 2019

# Confiabilidade a nível de sistema



Fonte: A. F. Cupertino "Modeling, Design and Fault-Tolerant Strategies for Modular Multilevel Cascaded Converter-based STATCOMs". PhD Thesis. UFMG. 2019.

# Seleção dos projetos – Diversas possibilidades



Fonte: A. F. Cupertino "Modeling, Design and Fault-Tolerant Strategies for Modular Multilevel Cascaded Converter-based STATCOMs". PhD Thesis. UFMG. 2019.

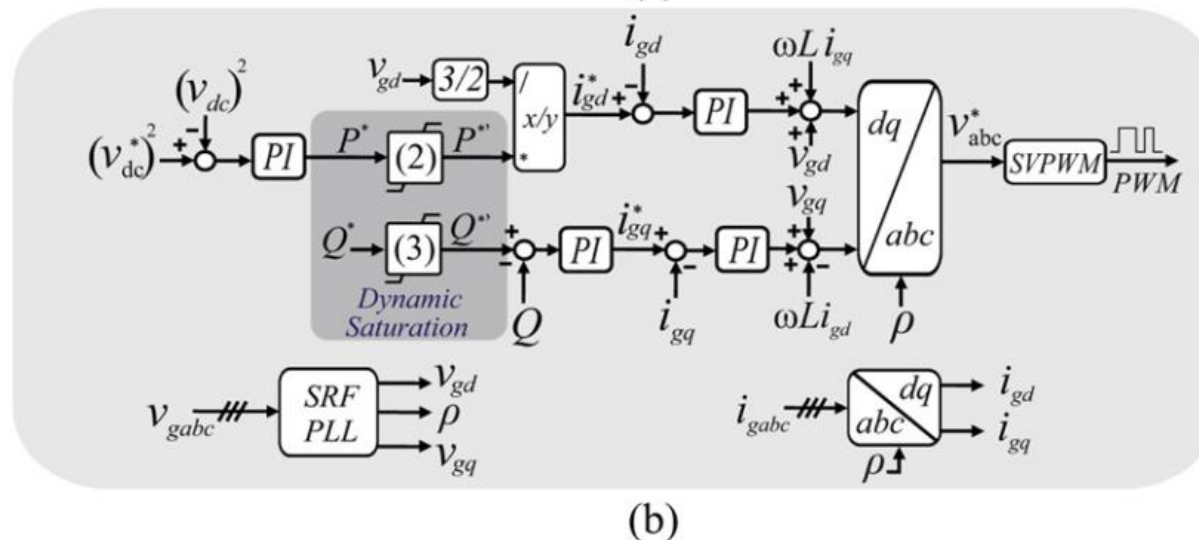
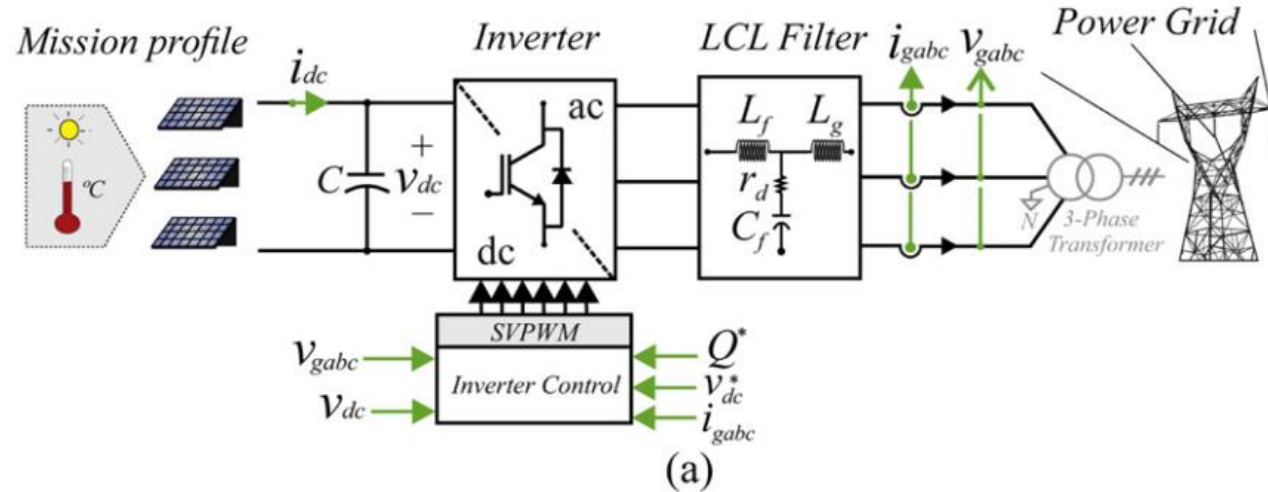


## Aplicação 1 – Inversor multifuncional de 8 kVA



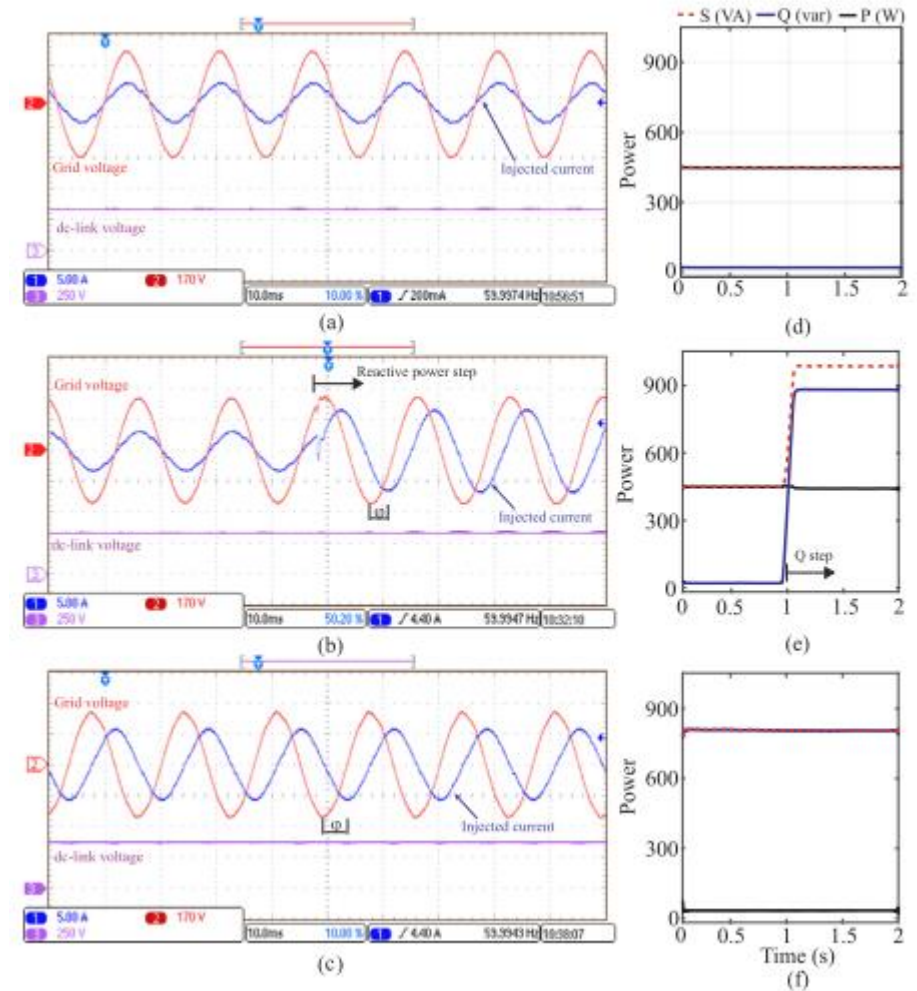
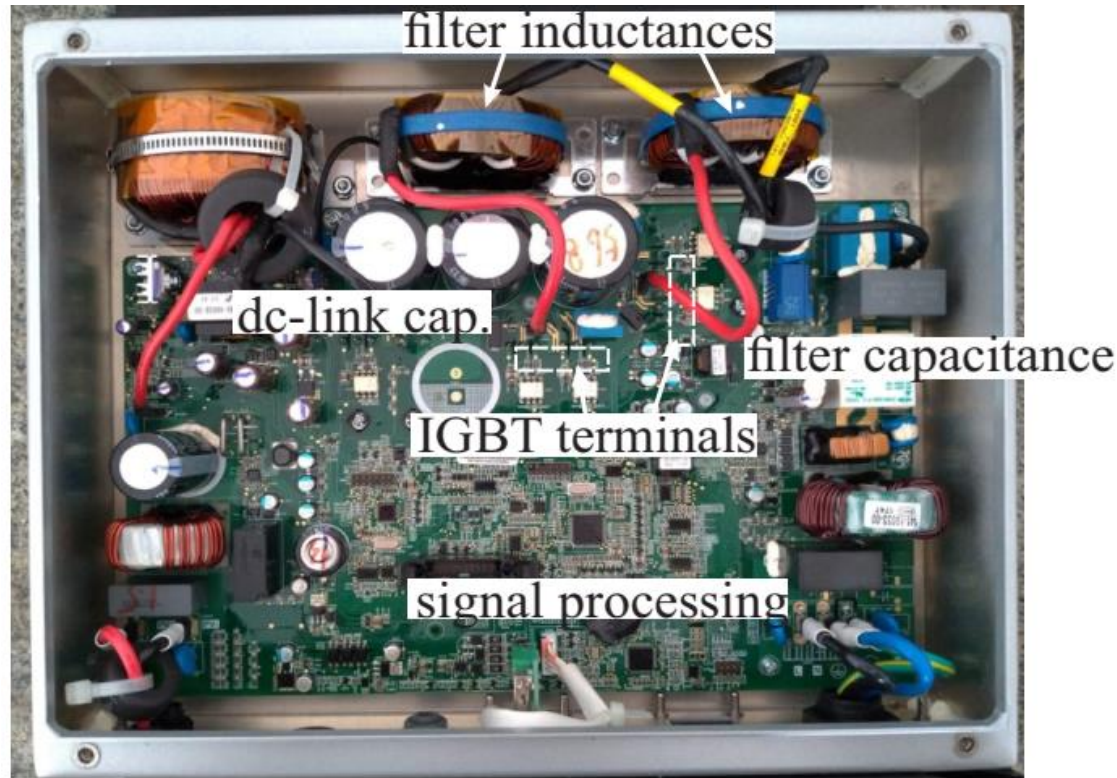


# Exemplo 1 – Inversor multifuncional



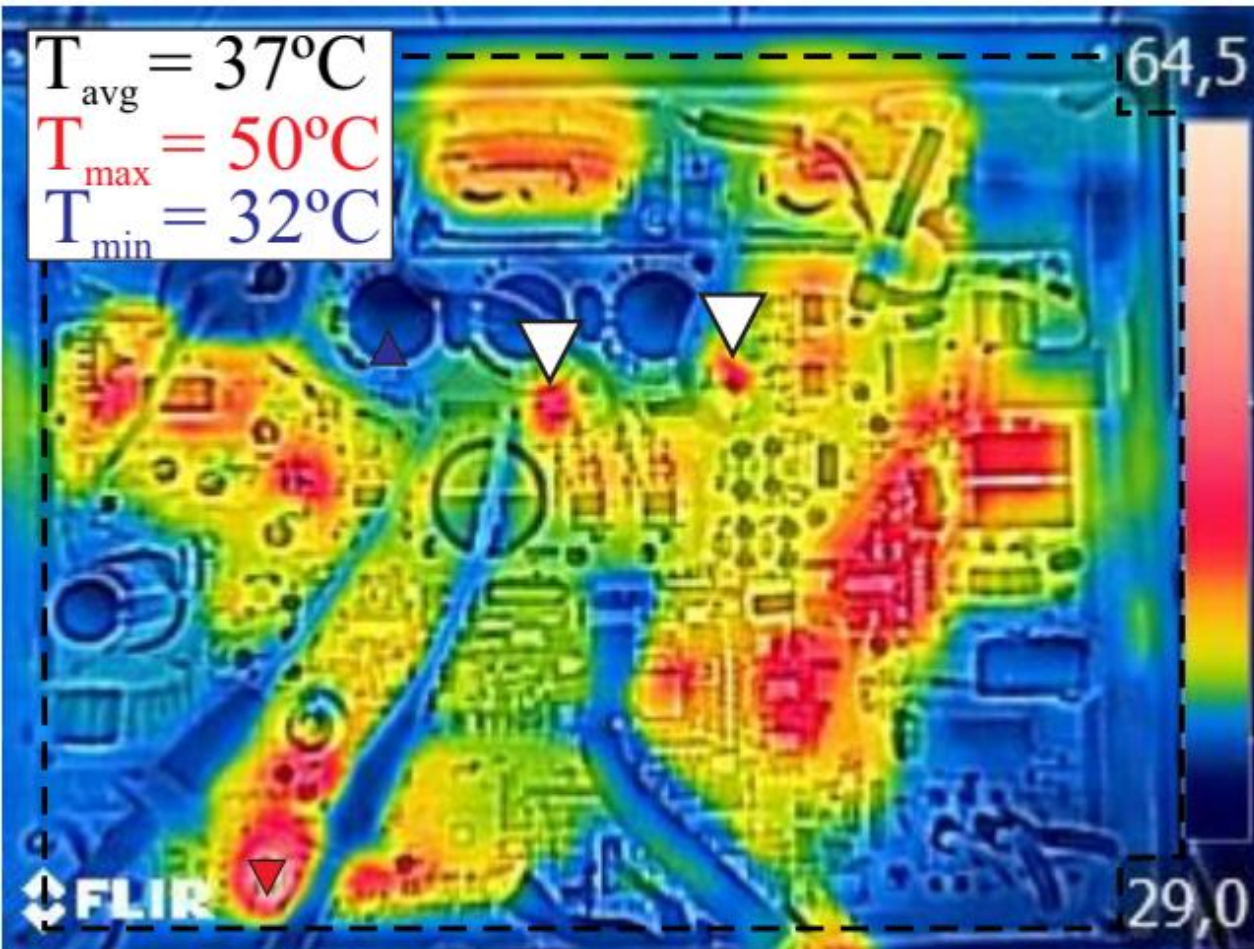
Fonte: J. M. S. Callegari. “Lifetime evaluation of three-phase multifunctional PV inverters with reactive power compensation”. Electric Power Systems Research. 2019.

# Efeito da injeção de potência reativa - experimento

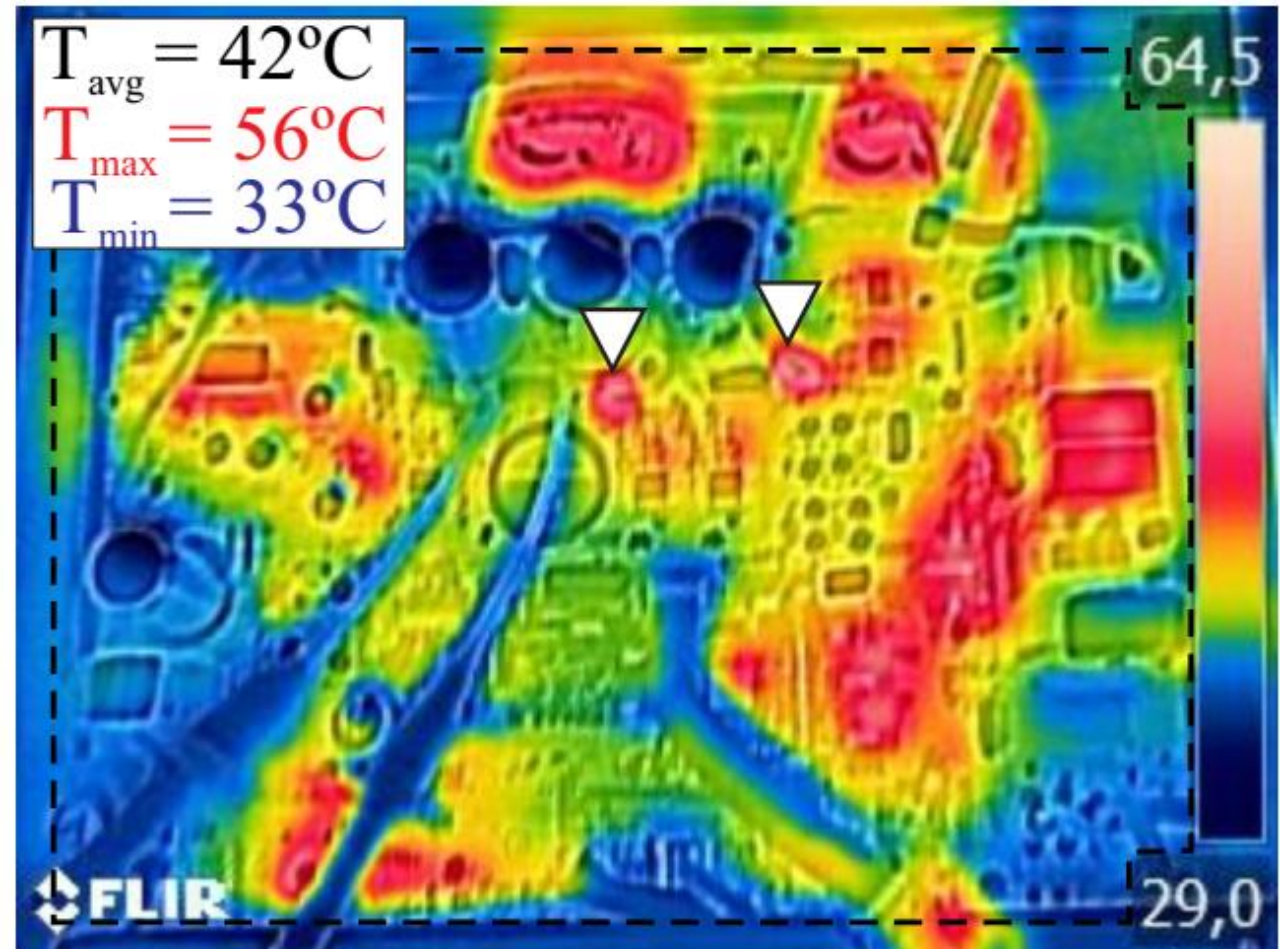


Fonte Lucas S. Gusman. "Design for reliability of multifunctional PV inverters used in industrial power factor regulation". Electrical Power and Energy Systems. 2020.

# Efeito da injeção de potência reativa – temperatura do inversor



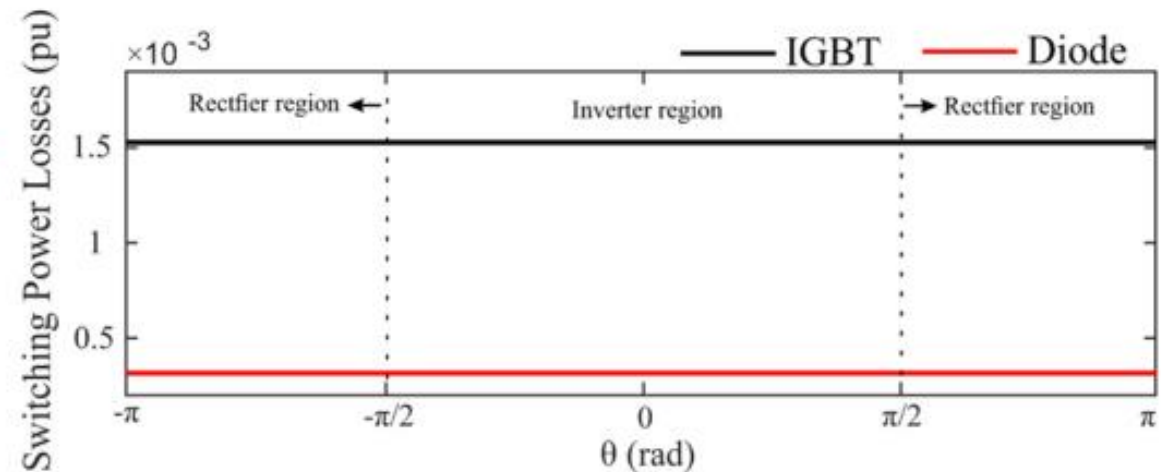
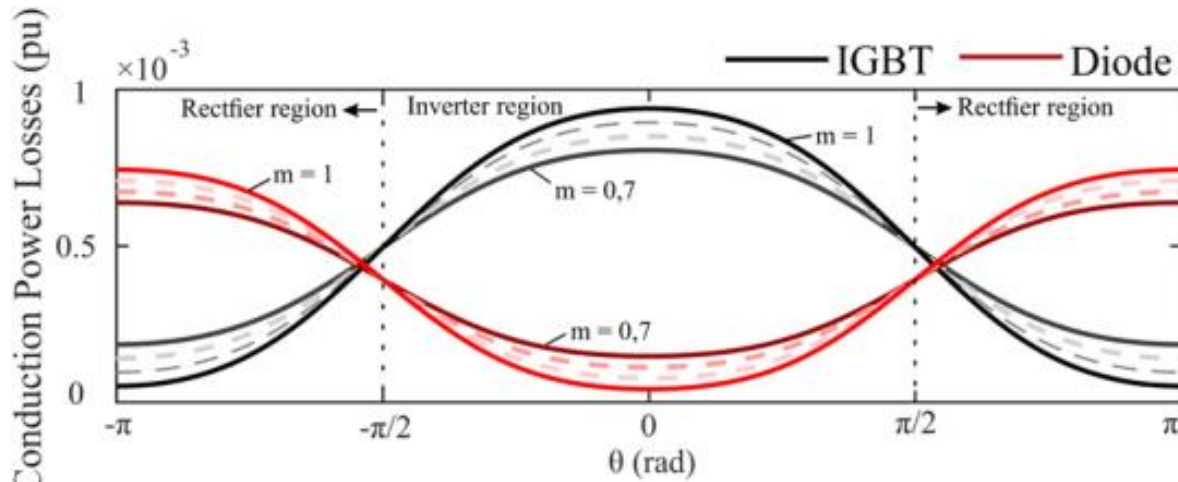
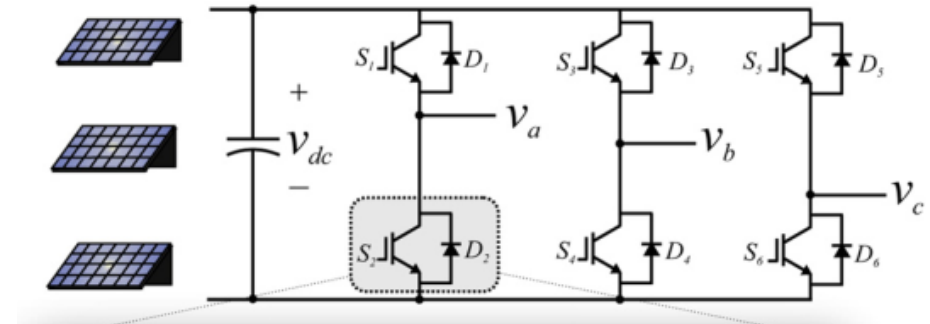
**Sem injeção de reativo**



**Com injeção de reativo**

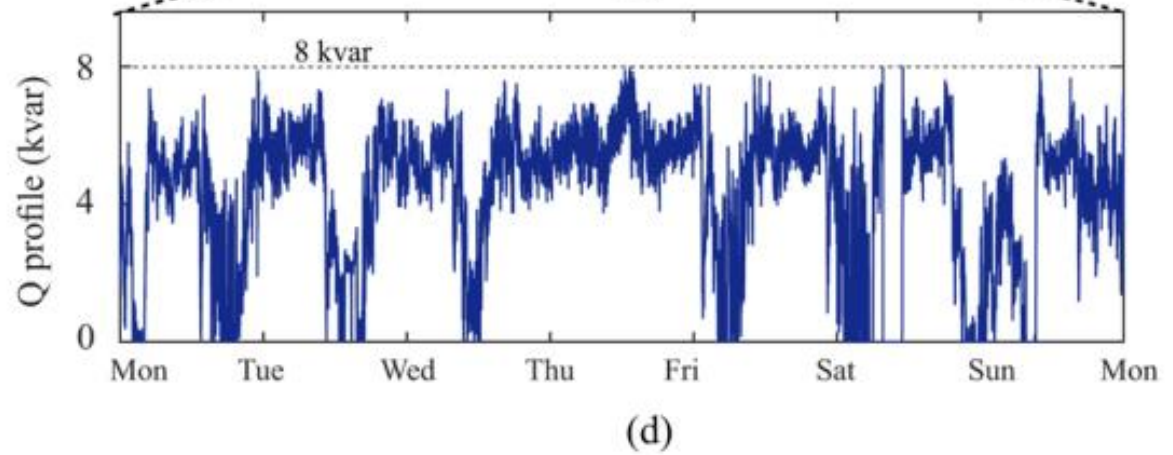
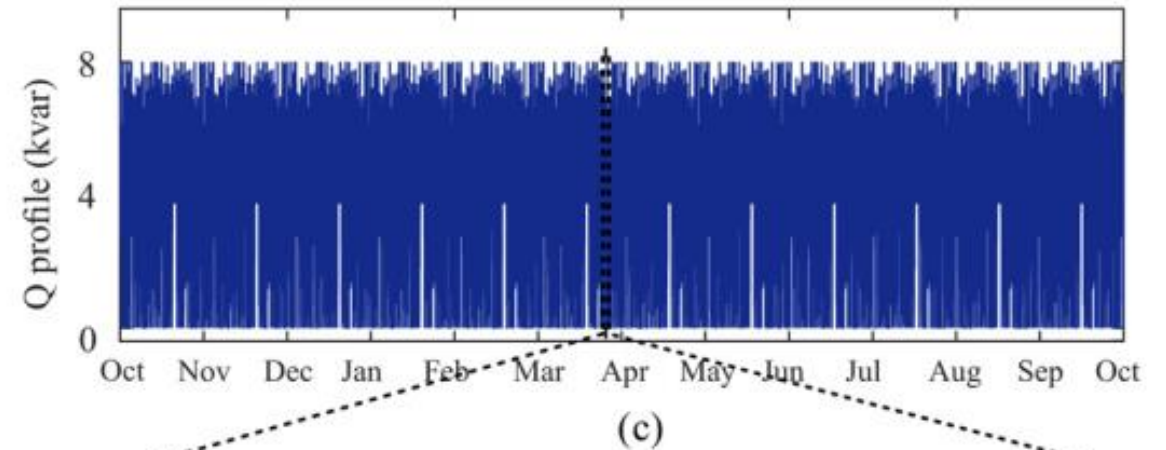
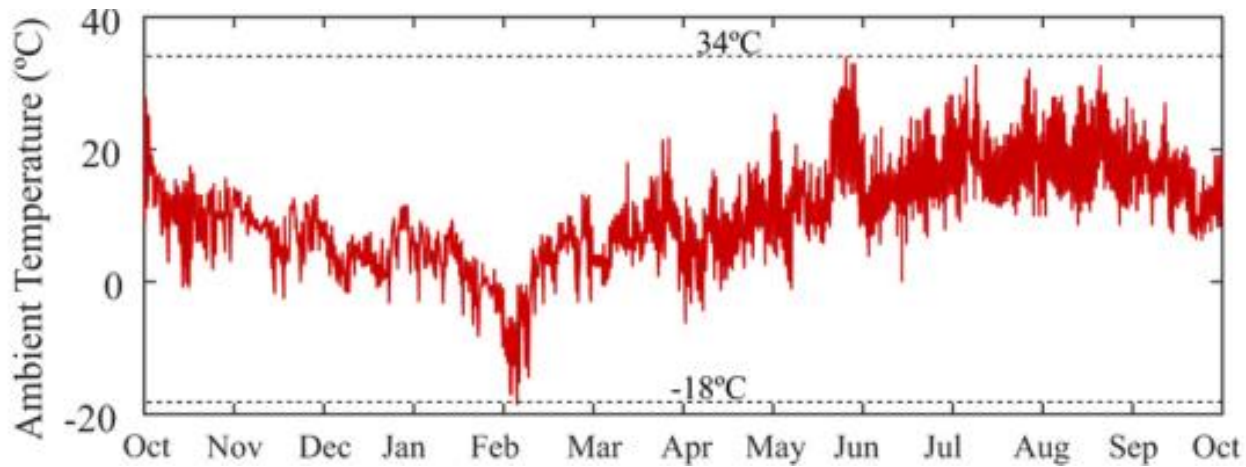
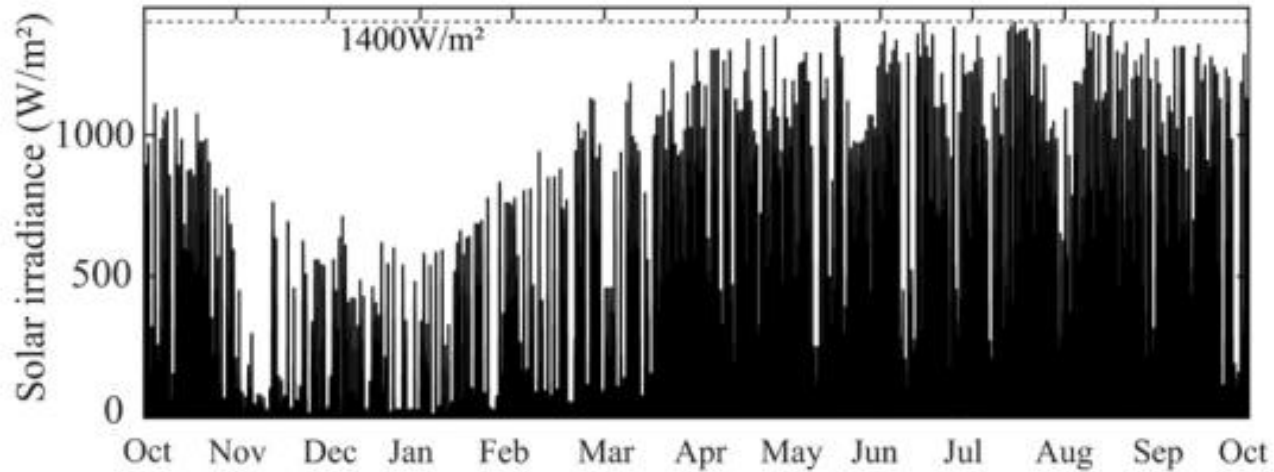
# Efeito da potência reativa nas perdas do inversor

- ❑ Modelo analítico;
- ❑ Considera o estresse de corrente nos componentes;
- ❑ Desconsidera o efeito da ondulação de corrente de saída;
- ❑ Assume que as perdas não variam com a temperatura;
- ❑ Análise de pior caso.



Fonte: J. M. S. Callegari. "Lifetime evaluation of three-phase multifunctional PV inverters with reactive power compensation". Electric Power Systems Research. 2019.

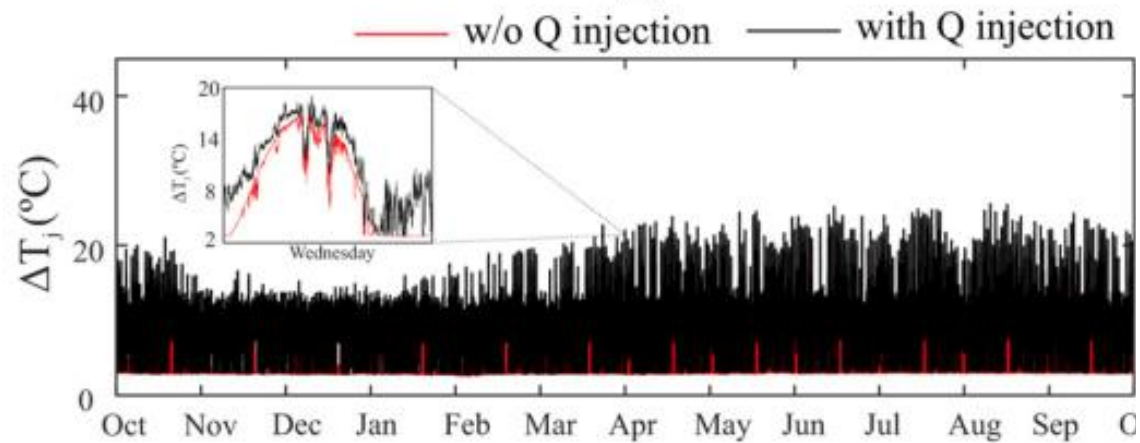
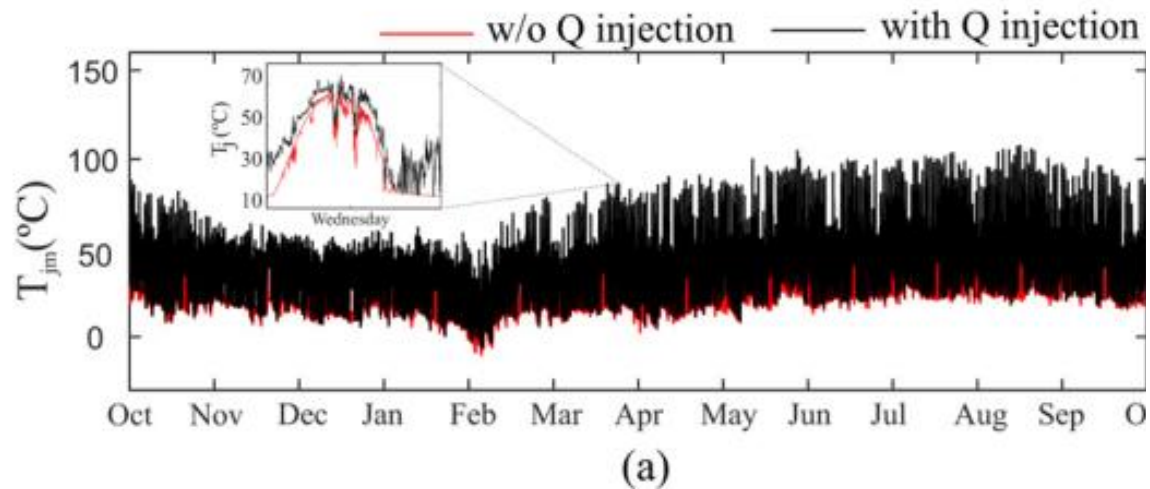
# Perfil de operação



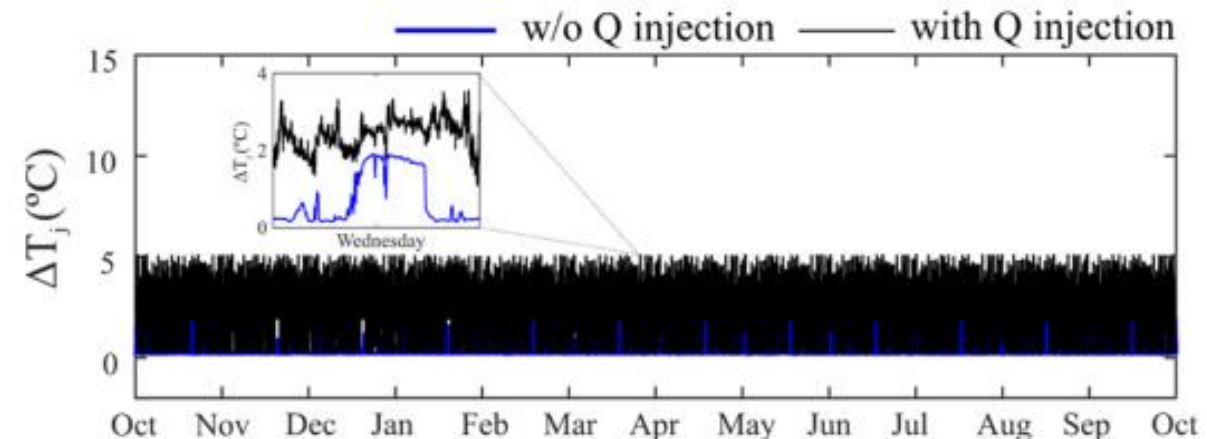
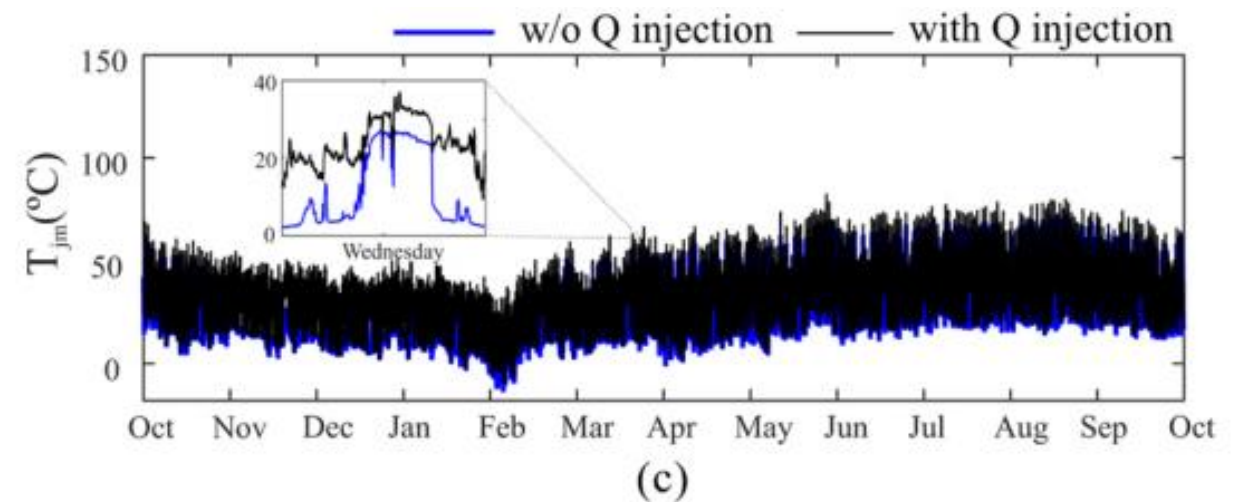
Fonte: J. M. S. Callegari. "Lifetime evaluation of three-phase multifunctional PV inverters with reactive power compensation". Electric Power Systems Research. 2019.

# Efeito da injeção de potência reativa – inversor de 8 kVA

□ IGBT's.



□ Diodos.

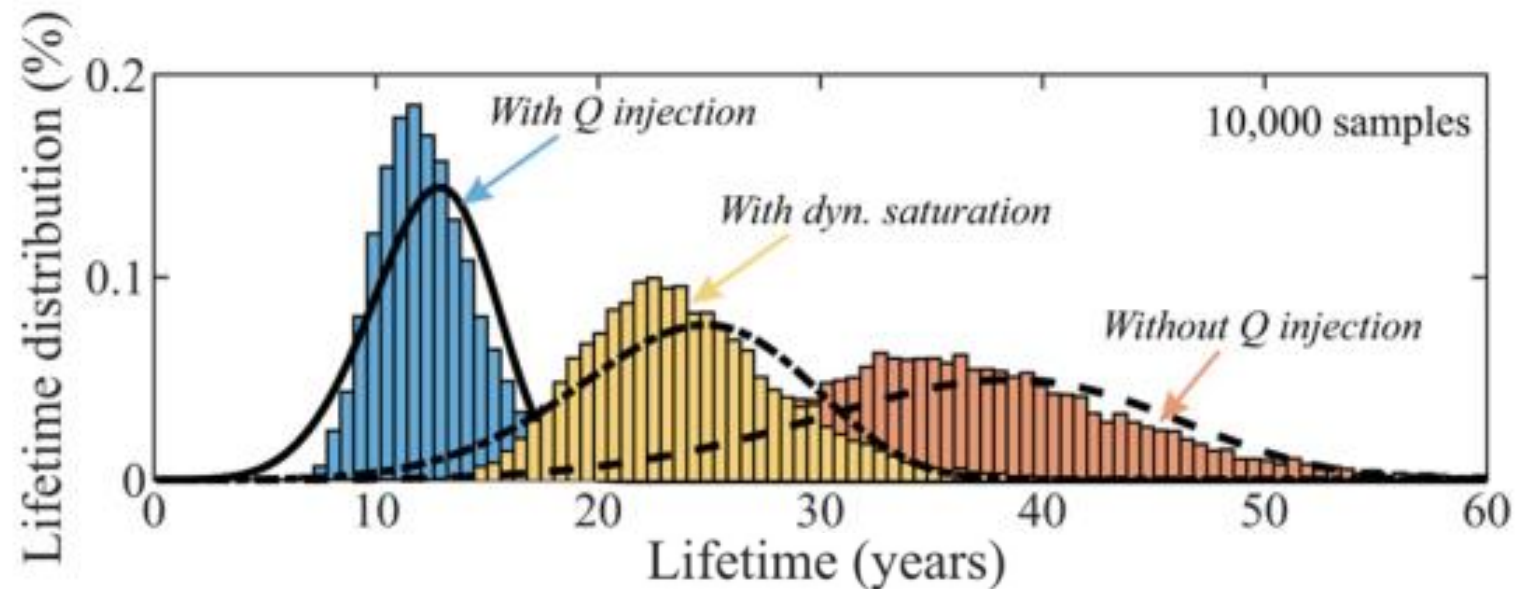


Fonte: J. M. S. Callegari. “Lifetime evaluation of three-phase multifunctional PV inverters with reactive power compensation”. Electric Power Systems Research. 2019.

# Efeito da injeção de potência reativa – inversor de 8 kVA

Lifetime consumption (LC)

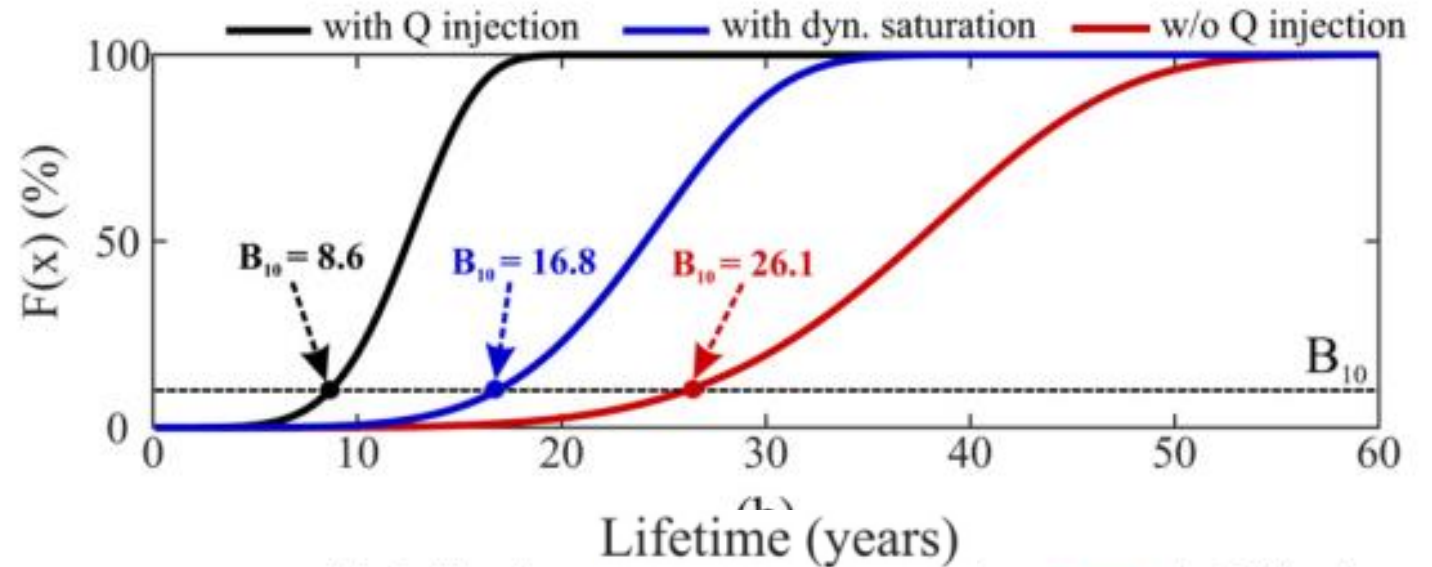
w/o Q inj.	with Q inj.	with dyn. sat.
0.0357	0.1067	0.0551



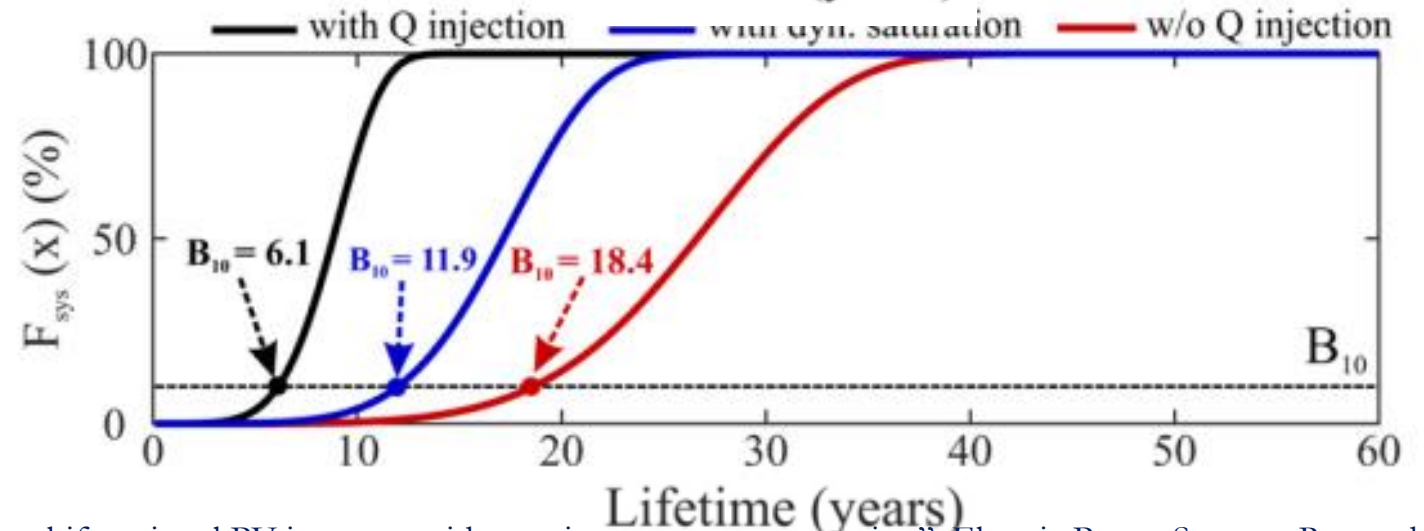
Fonte: J. M. S. Callegari. “Lifetime evaluation of three-phase multifunctional PV inverters with reactive power compensation”. Electric Power Systems Research. 2019.

# Efeito da injeção de potência reativa – inversor de 8 kVA

□  $F(x)$  a nível de componente



□  $F_{sys}(x)$  a nível de sistema



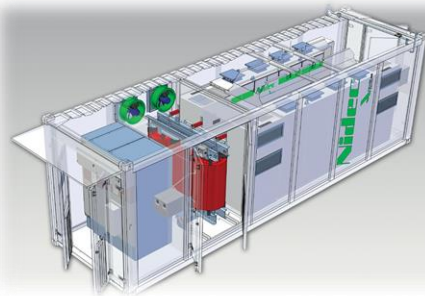
Fonte: J. M. S. Callegari. “Lifetime evaluation of three-phase multifunctional PV inverters with reactive power compensation”. Electric Power Systems Research. 2019.



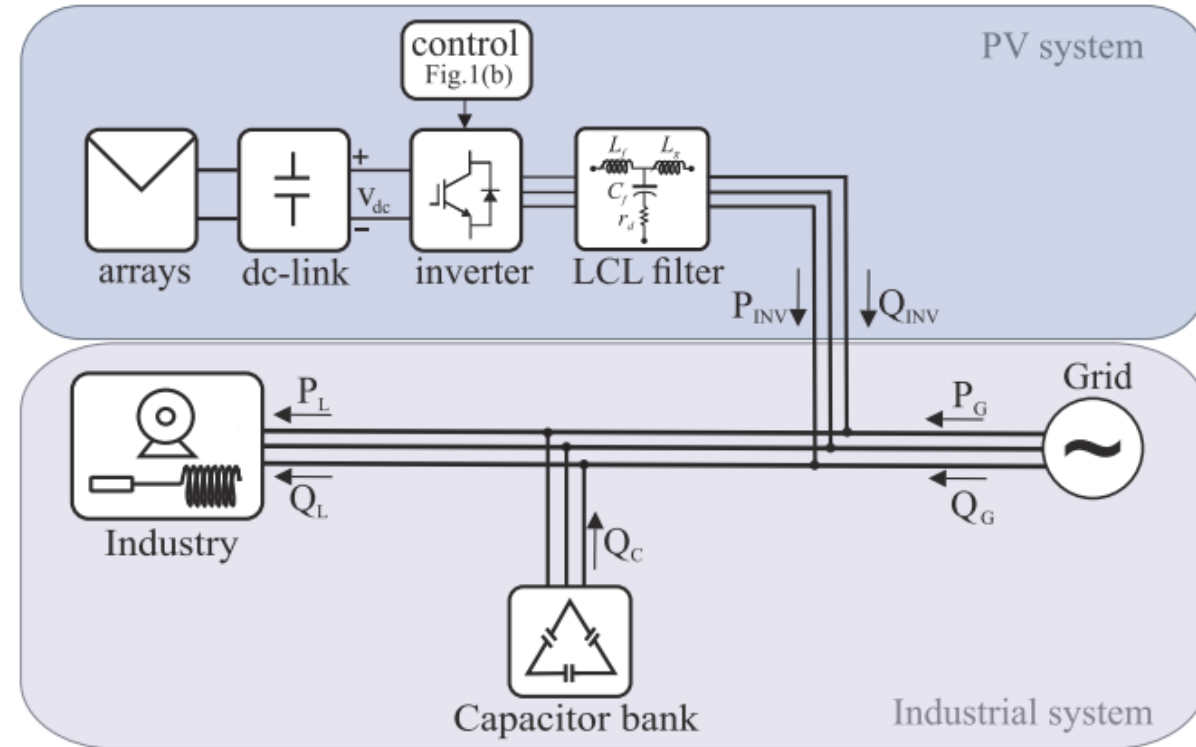
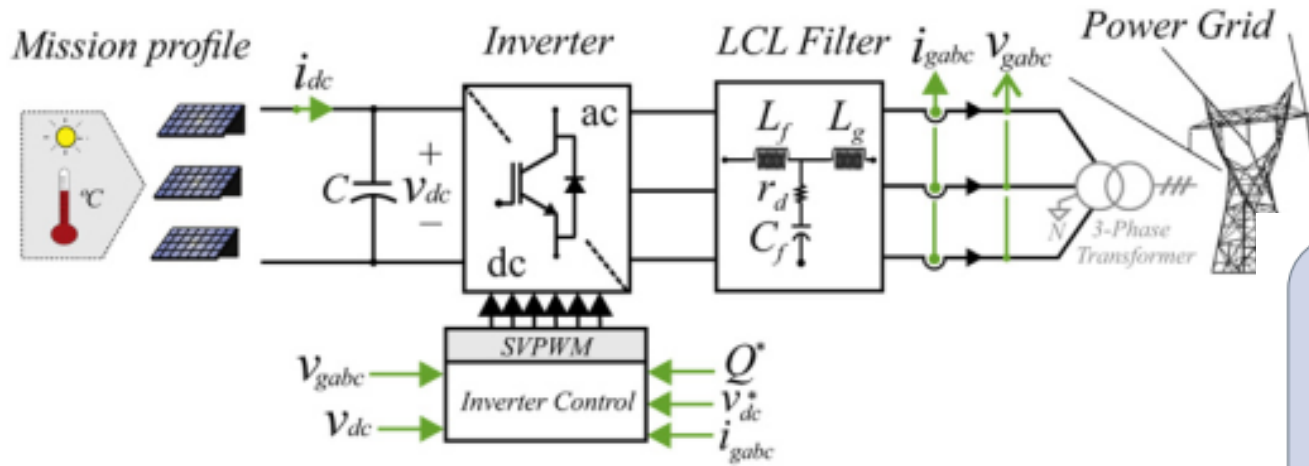


## Exemplo 2 – Inversor multifuncional de 25 kVA

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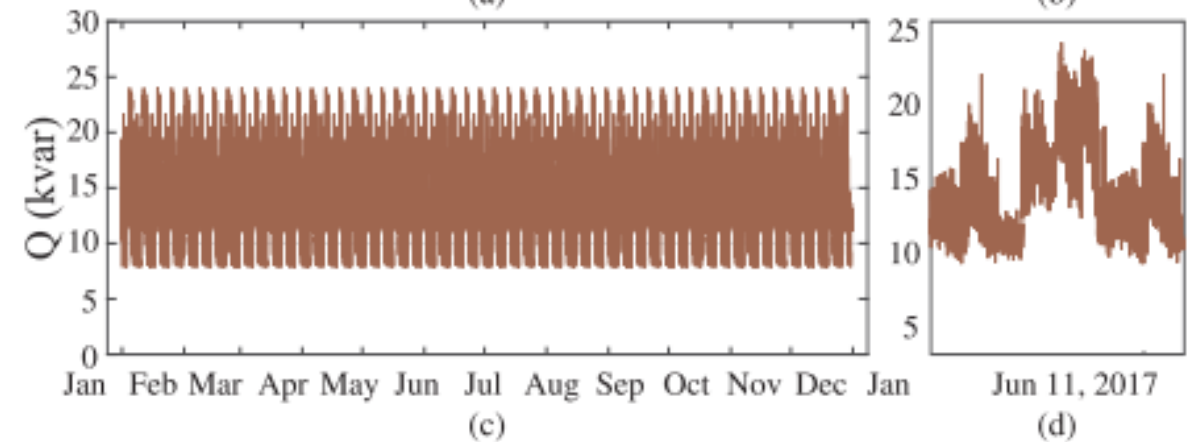
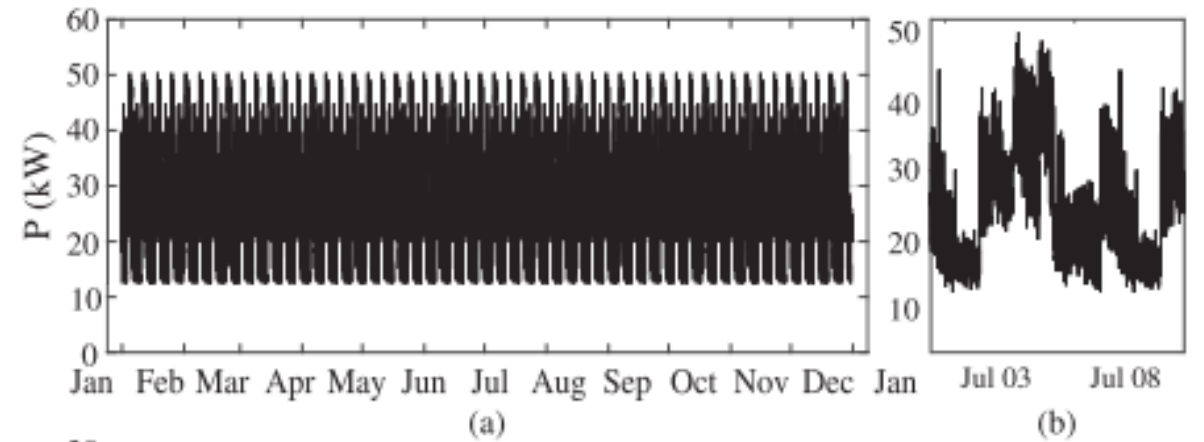
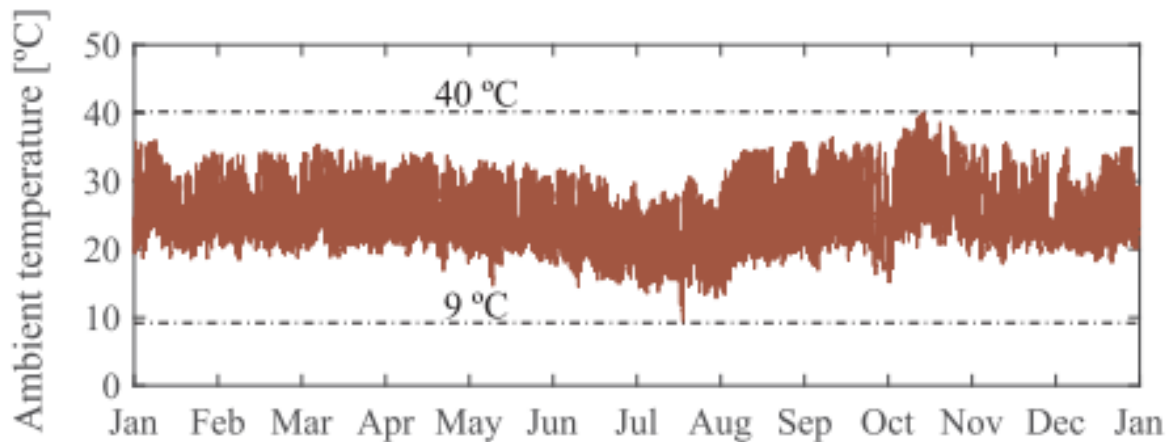
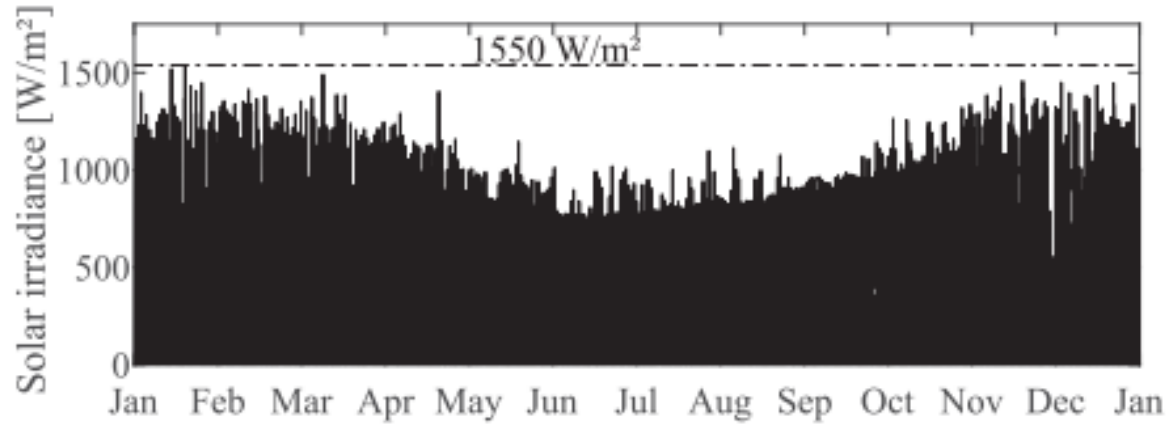


## Exemplo 2 – Inversor multifuncional de 25 kVA



Fonte Lucas S. Gusman. “Design for reliability of multifunctional PV inverters used in industrial power factor regulation”. Electrical Power and Energy Systems. 2020.

# Perfis de operação – Inversor de 25 kVA



Fonte Lucas S. Gusman. “Design for reliability of multifunctional PV inverters used in industrial power factor regulation”. Electrical Power and Energy Systems. 2020.

# Projetos considerados

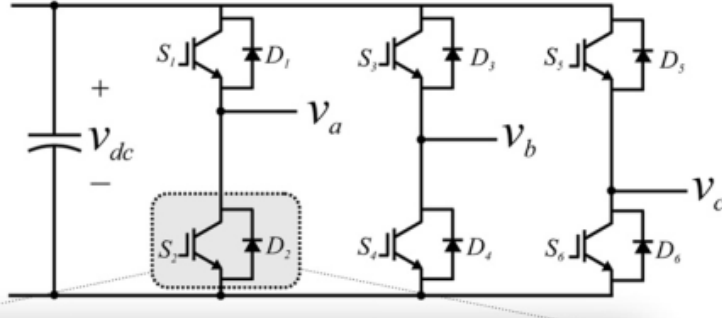
## Projeto 1:



5 x 2 cap. 680  $\mu$ F / 400 V



75 A/1200 V



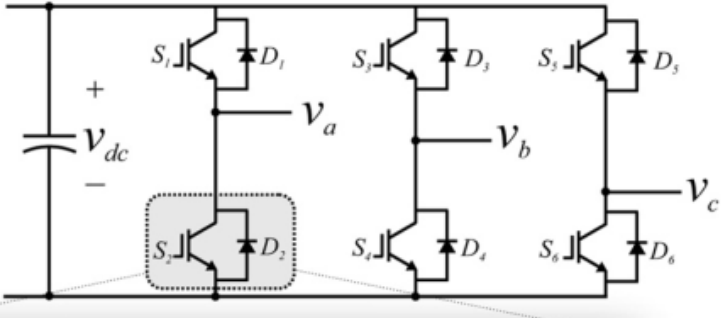
## Projeto 2



6 x 2 cap. 680  $\mu$ F / 400 V



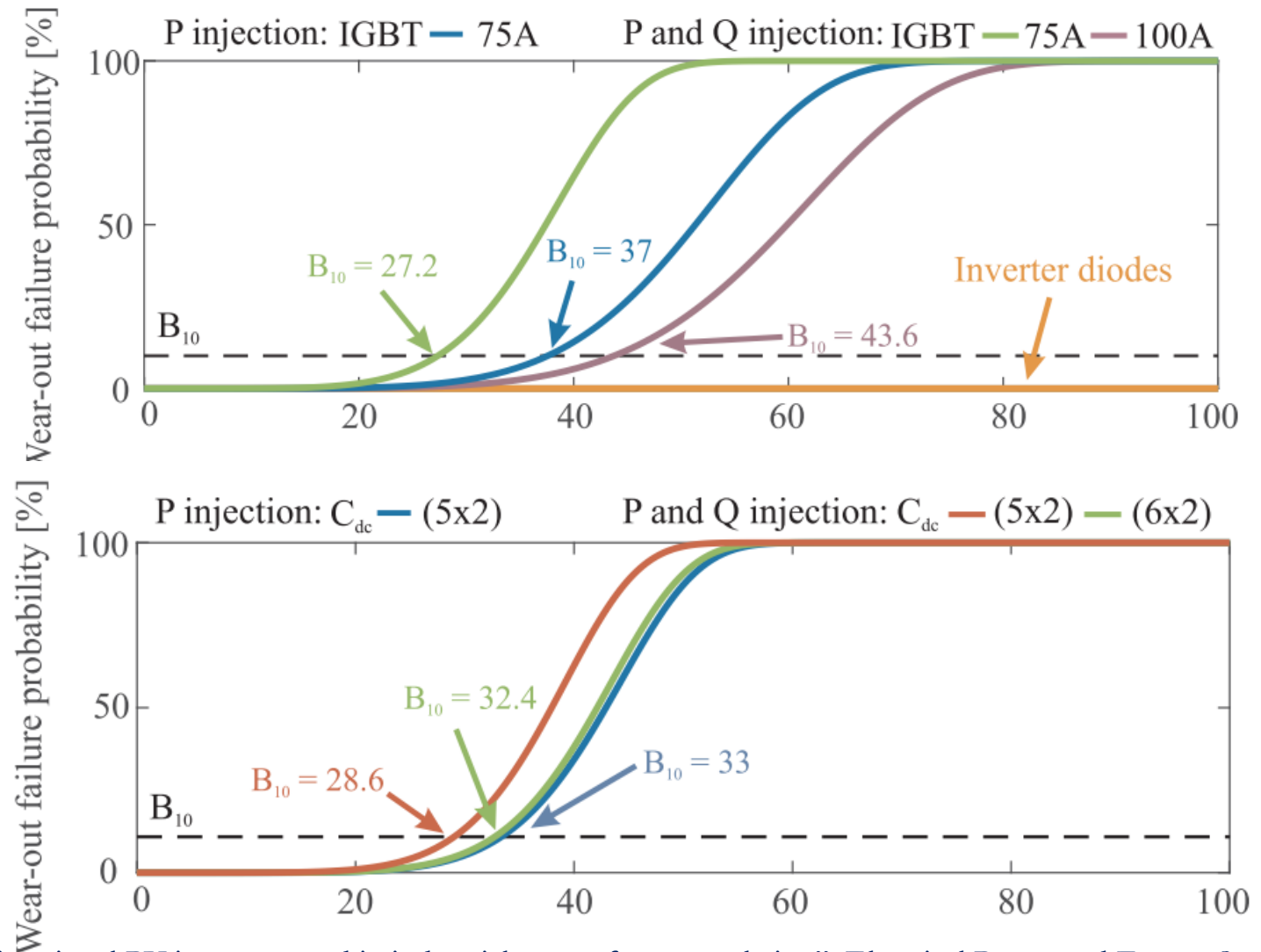
100 A/1200 V



# Confiabilidade a nível de componente

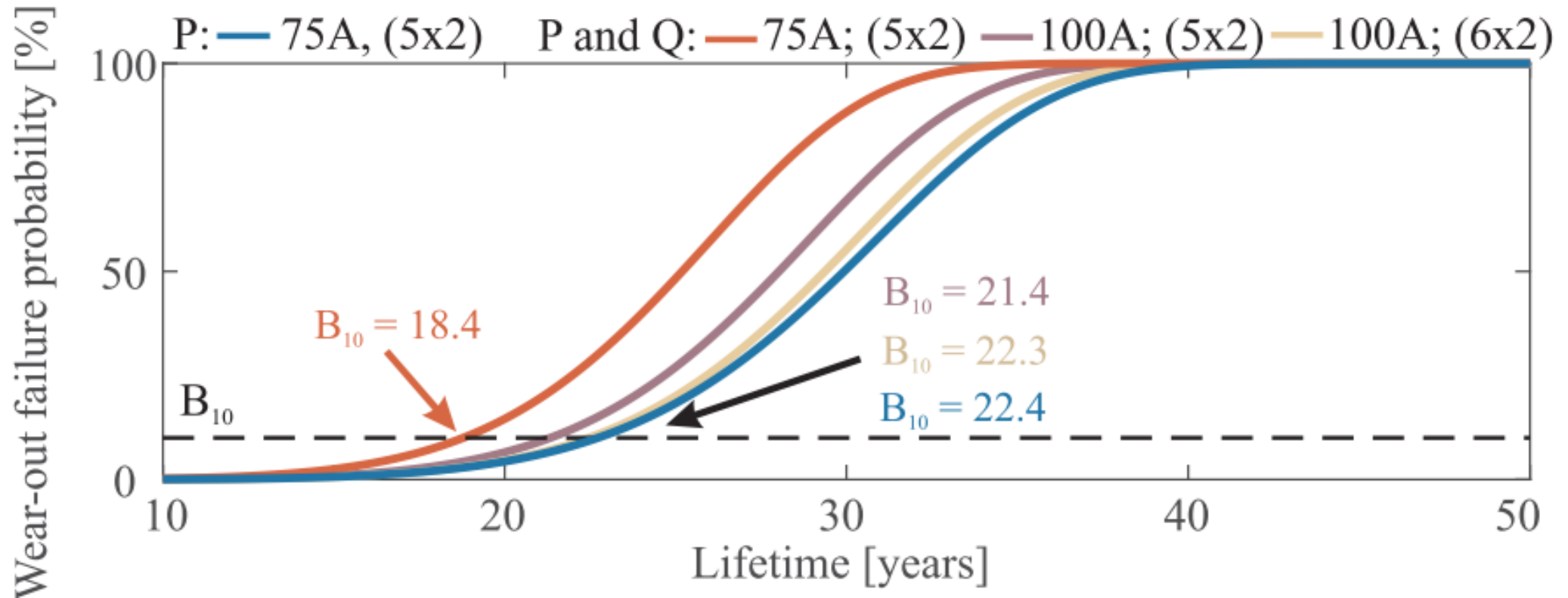
❑ Semicondutores;

❑ Capacitores.



Fonte Lucas S. Gusman. “Design for reliability of multifunctional PV inverters used in industrial power factor regulation”. Electrical Power and Energy Systems. 2020.

# Perfil de irradiância e temperatura

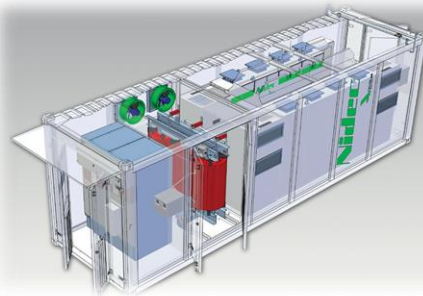


Fonte Lucas S. Gusman. “Design for reliability of multifunctional PV inverters used in industrial power factor regulation”. Electrical Power and Energy Systems. 2020.

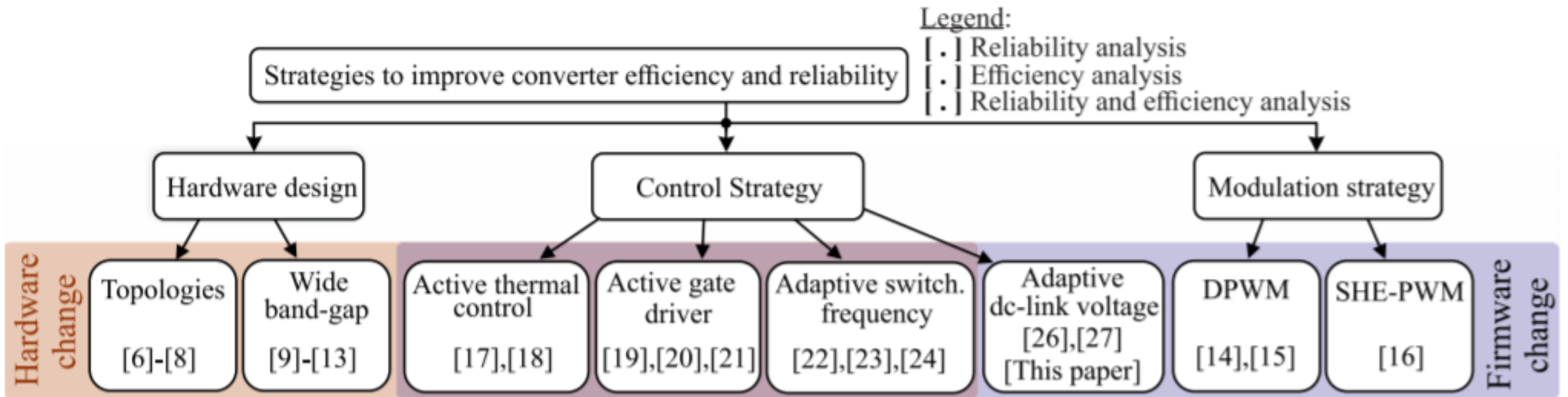


## Exemplo 3 – Proposta para extensão de vida útil

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[afcupertino@ieee.org](mailto:afcupertino@ieee.org)



# Estratégias para entender a vida útil do inversor

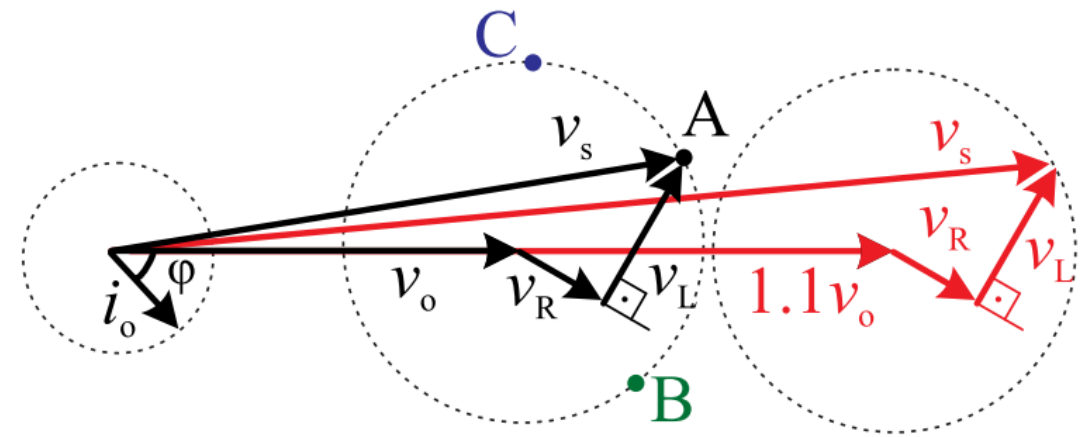
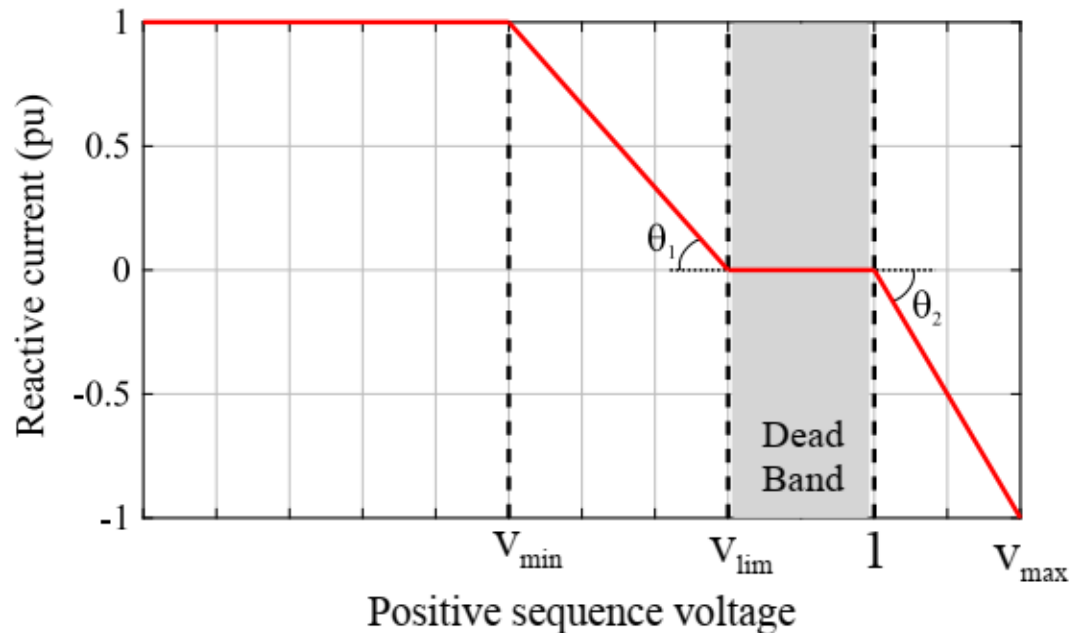


Fonte J. M. Callegari et. al.. “Minimum DC-Link Voltage Control for Efficiency and Reliability Improvement in PV Inverters”. IEEE Transactions on Power Electronics. In Press.



# Característica da tensão de barramento CC

- ❑ Tensão do barramento CC → valor mínimo para que o inversor se conecte a rede;
- ❑ Problema: Requisitos de sobretensão dos códigos de rede;



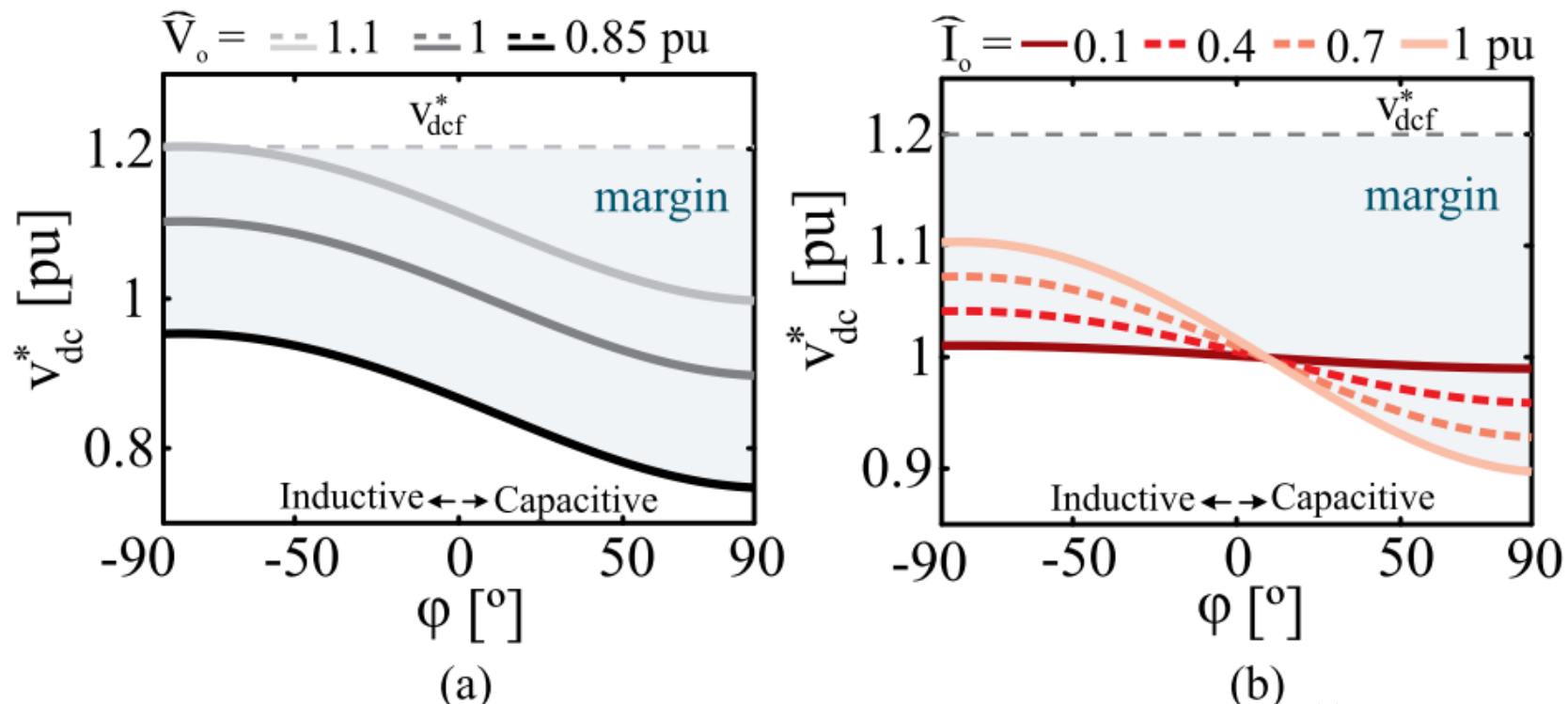
Fonte:

[1] A. F. Cupertino et. al.. “Benchmarking of power control strategies for photovoltaic systems under unbalanced conditions”. Electrical Power and Energy Systems. 2019

[2] J. M. Callegari et. al.. “Minimum DC-Link Voltage Control for Efficiency and Reliability Improvement in PV Inverters”. IEEE Transactions on Power Electronics. In Press.

# Característica da tensão de barramento CC

$$v_{dc}^* = k \sqrt{\left( Ri_d - \omega_n Li_q + \widehat{V}_o \right)^2 + \left( i_q R + \omega_n Li_d \right)^2}$$



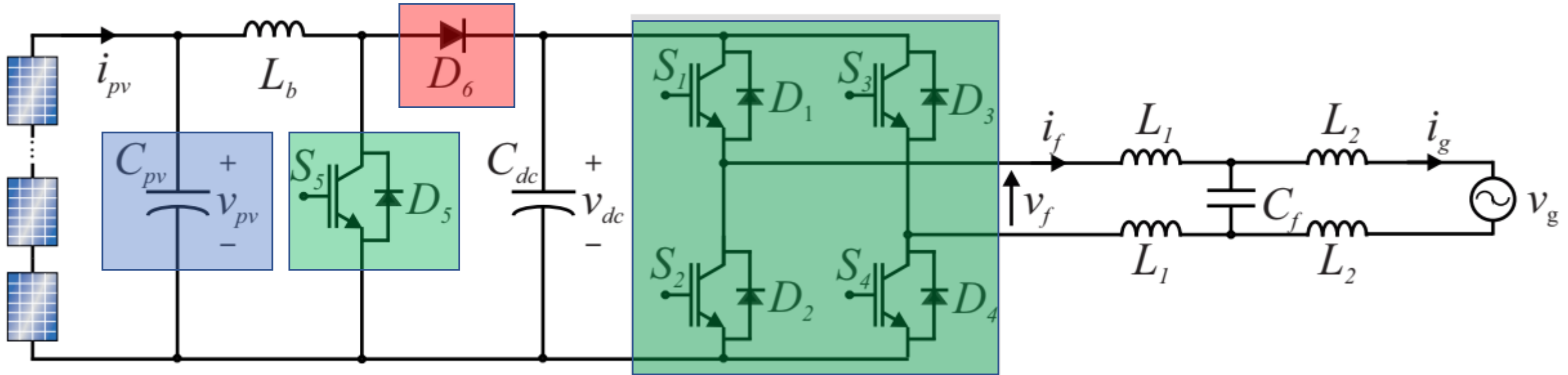
Fonte J. M. Callegari et. al.. "Minimum DC-Link Voltage Control for Efficiency and Reliability Improvement in PV Inverters". IEEE Transactions on Power Electronics. In Press.

# Proposta: Controle de barramento CC mínimo

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- ❑ Tensão do barramento CC → afeta a perda dos semicondutores
- ❑ Afeta o estresse de tensão nos capacitores.
- ❑ Potencial para redução de perdas e extensão de vida útil;
- ❑ Vantagem: modificação simples do firmware do equipamento.

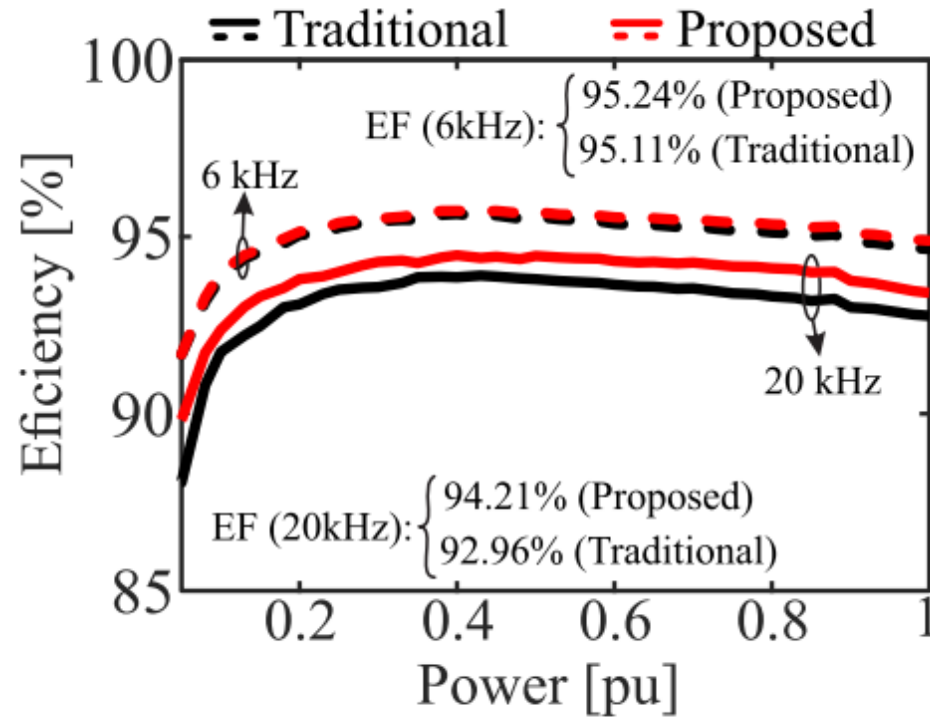
# Proposta: Controle de barramento CC mínimo



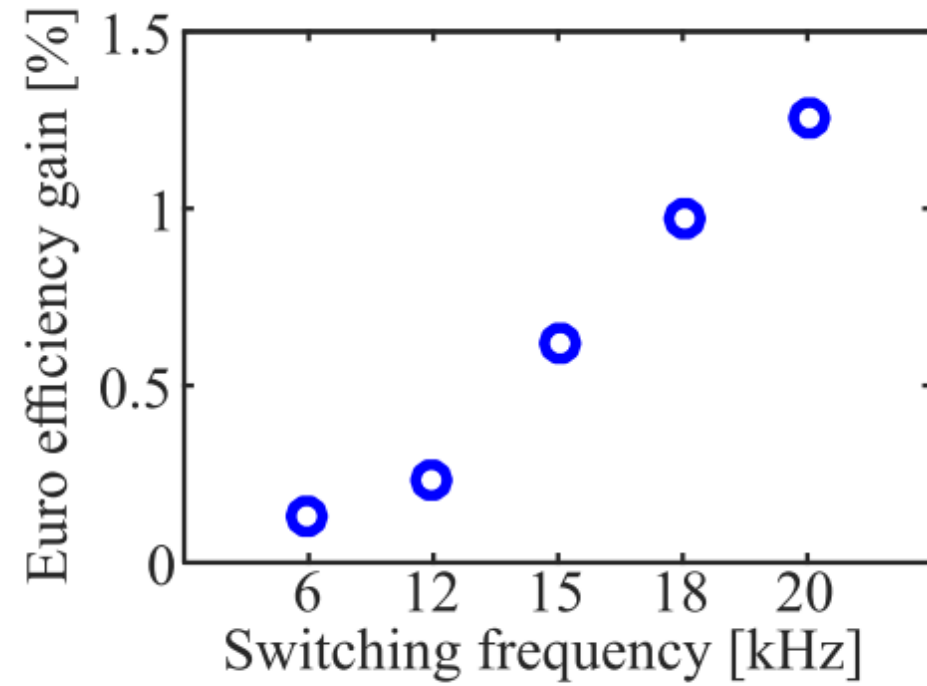
❑ Acoplamento térmico pode ajudar!

Fonte: A. F. Cupertino e H. A. Pereira. "Next generation of grid-connected photovoltaic systems: modelling and control". Book Chapter. Elsevier. *In Press*.

# Controle de barramento CC mínimo – redução de perdas



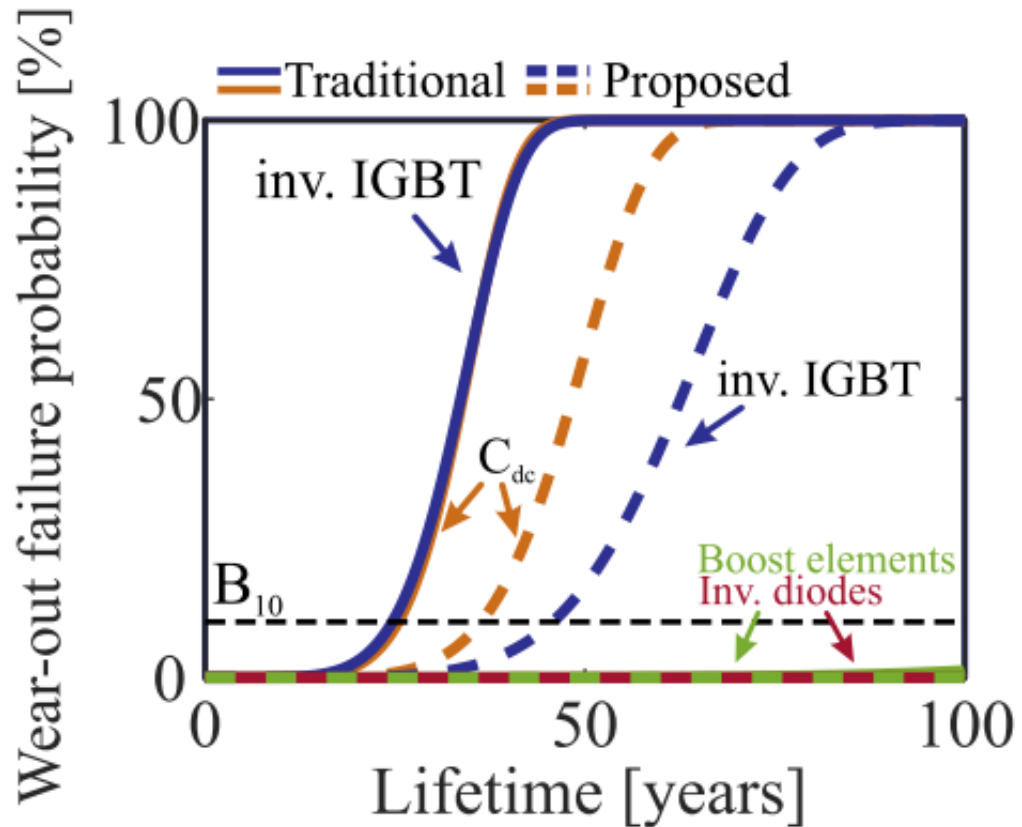
(a)



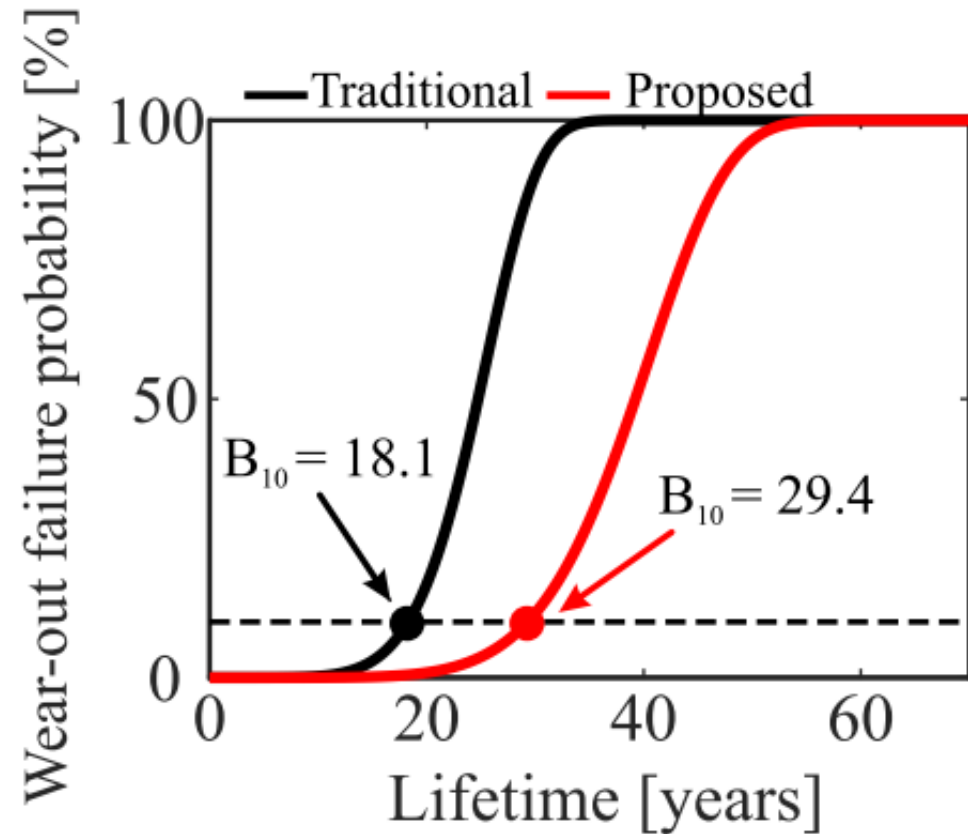
(b)

Fonte J. M. Callegari et. al.. “Minimum DC-Link Voltage Control for Efficiency and Reliability Improvement in PV Inverters”. IEEE Transactions on Power Electronics. In Press.

# Controle de barramento CC mínimo – confiabilidade



(a)



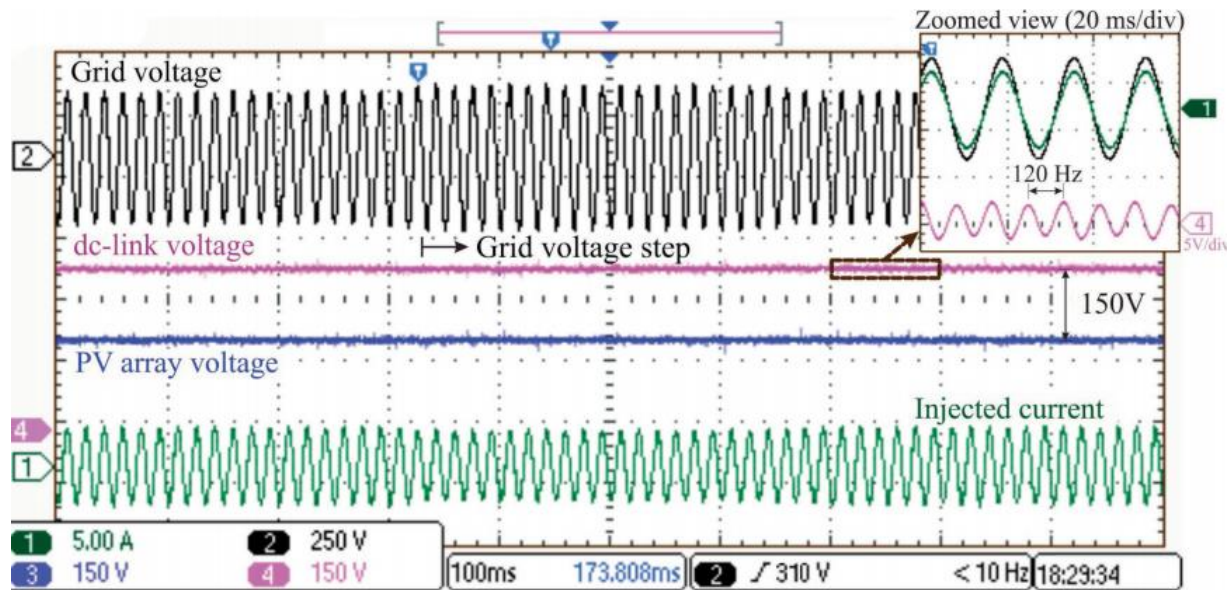
(b)

Fonte J. M. Callegari et. al.. “Minimum DC-Link Voltage Control for Efficiency and Reliability Improvement in PV Inverters”. IEEE Transactions on Power Electronics. In Press.

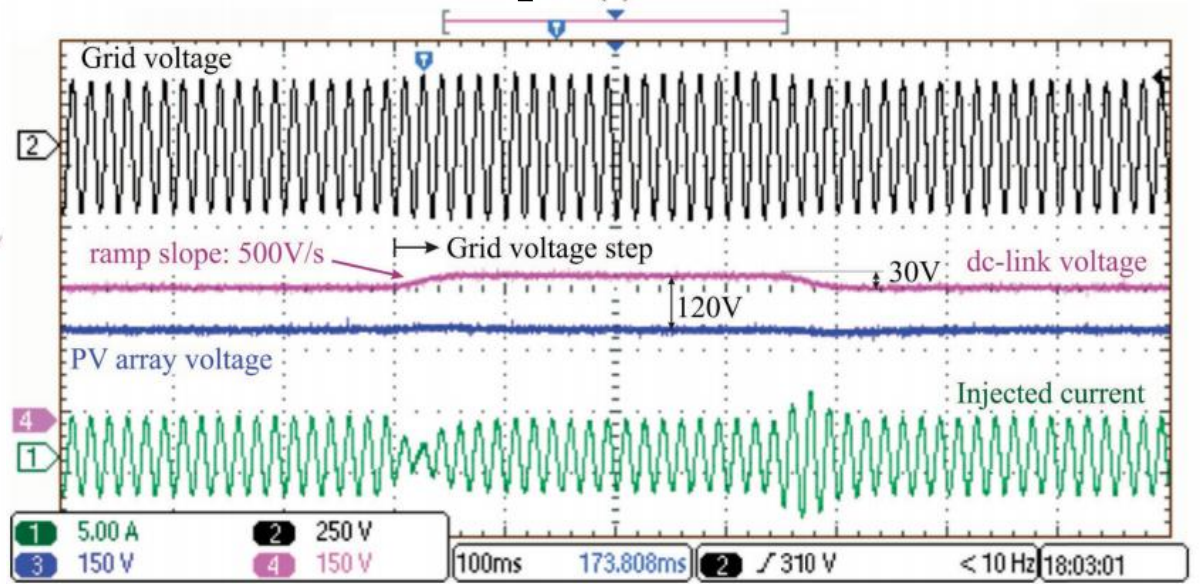
# Controle de barramento CC mínimo – Dinâmica

- Variação de tensão da rede.

## Convencional



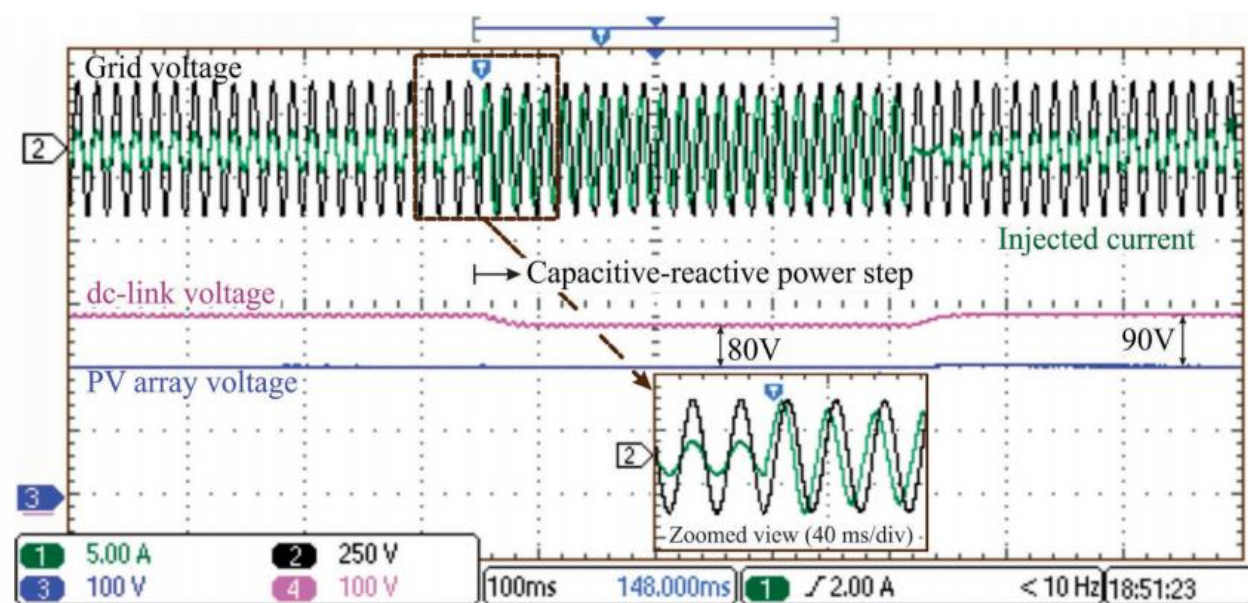
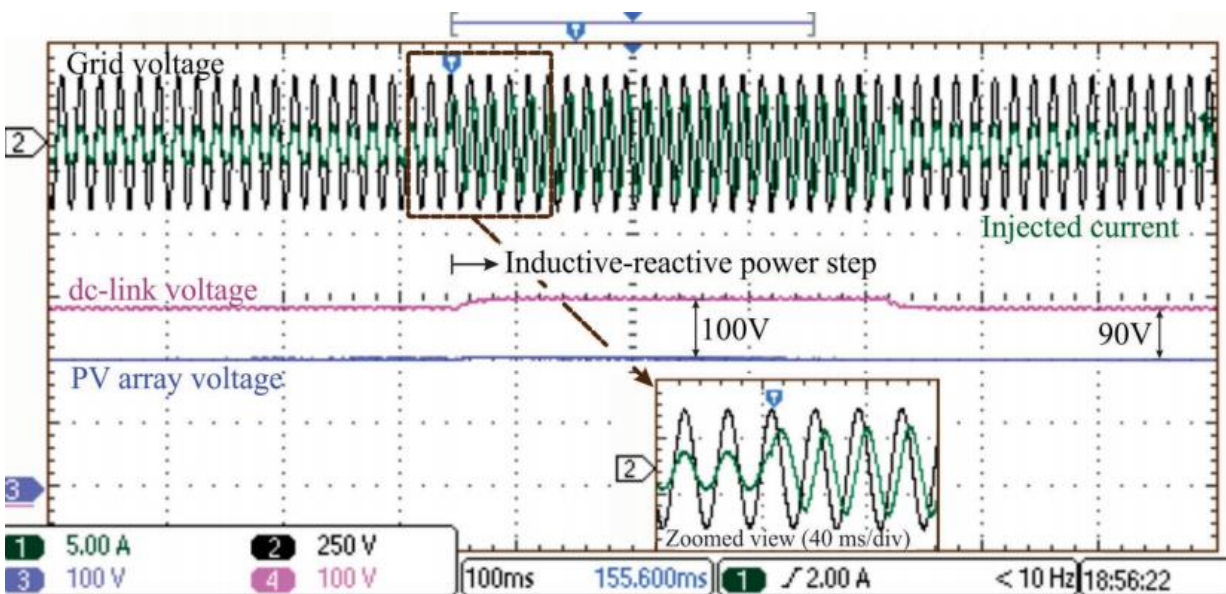
## Proposto



Fonte J. M. Callegari et. al.. “Minimum DC-Link Voltage Control for Efficiency and Reliability Improvement in PV Inverters”. IEEE Transactions on Power Electronics. In Press.

# Controle de barramento CC mínimo – Dinâmica

☐ Injeção de potência reativa.

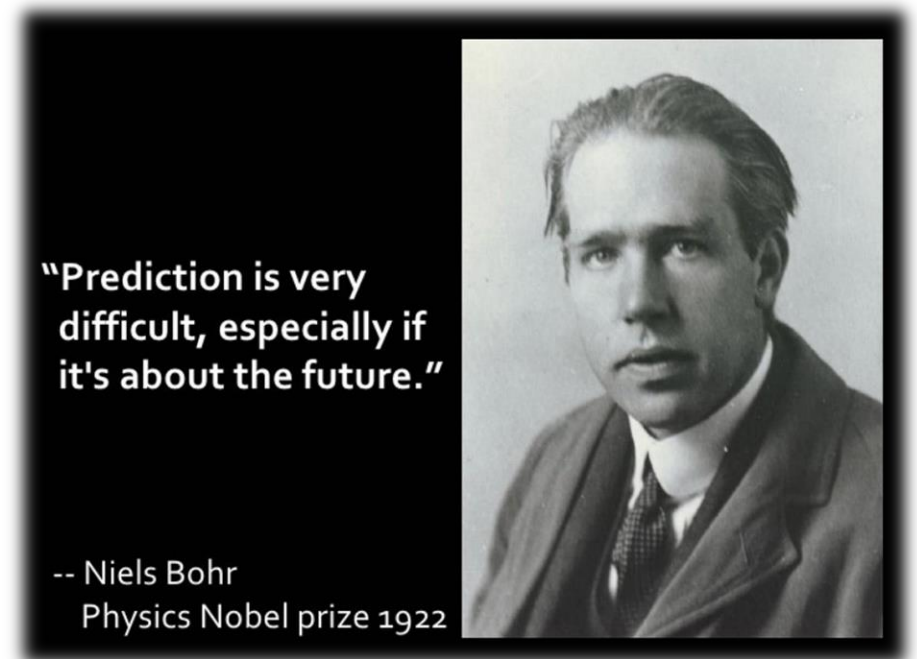


Fonte J. M. Callegari et. al.. “Minimum DC-Link Voltage Control for Efficiency and Reliability Improvement in PV Inverters”. IEEE Transactions on Power Electronics. In Press.



# Sumário dos pontos discutidos

- ❑ Confiabilidade e custo são funções **correlacionadas!**
- ❑ Modelos de vida útil → faixa de validade muitas vezes **não adequada;**
- ❑ Confiabilidade → probabilidade;
- ❑ Resultados devem ser interpretados com cuidado;
- ❑ Figura de mérito para quantificar o stress térmico!



# Obrigado pela Atenção



Bons estudos!



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