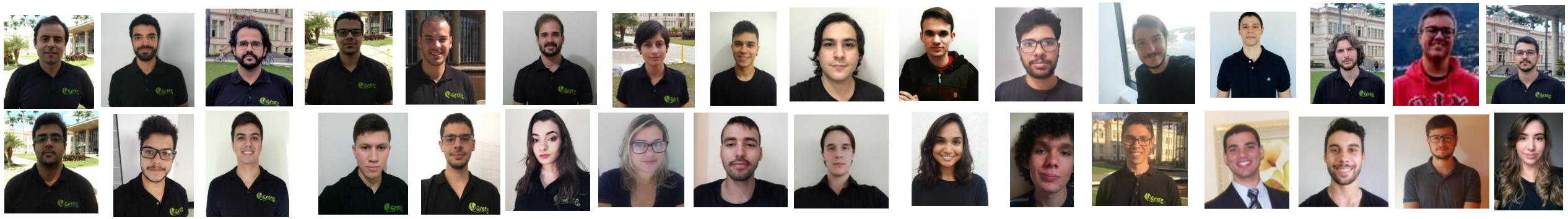
Confiabilidade de inversores fotovoltaicos: fundamentos e desafios

Prof. Allan Fagner Cupertino
afcupertino@ieee.org

GESEP – Gerência de Especialistas em Sistemas Elétricos de Potência



www.gesep.ufv.br

@GESEP

@gesep_vicosa

Gesep

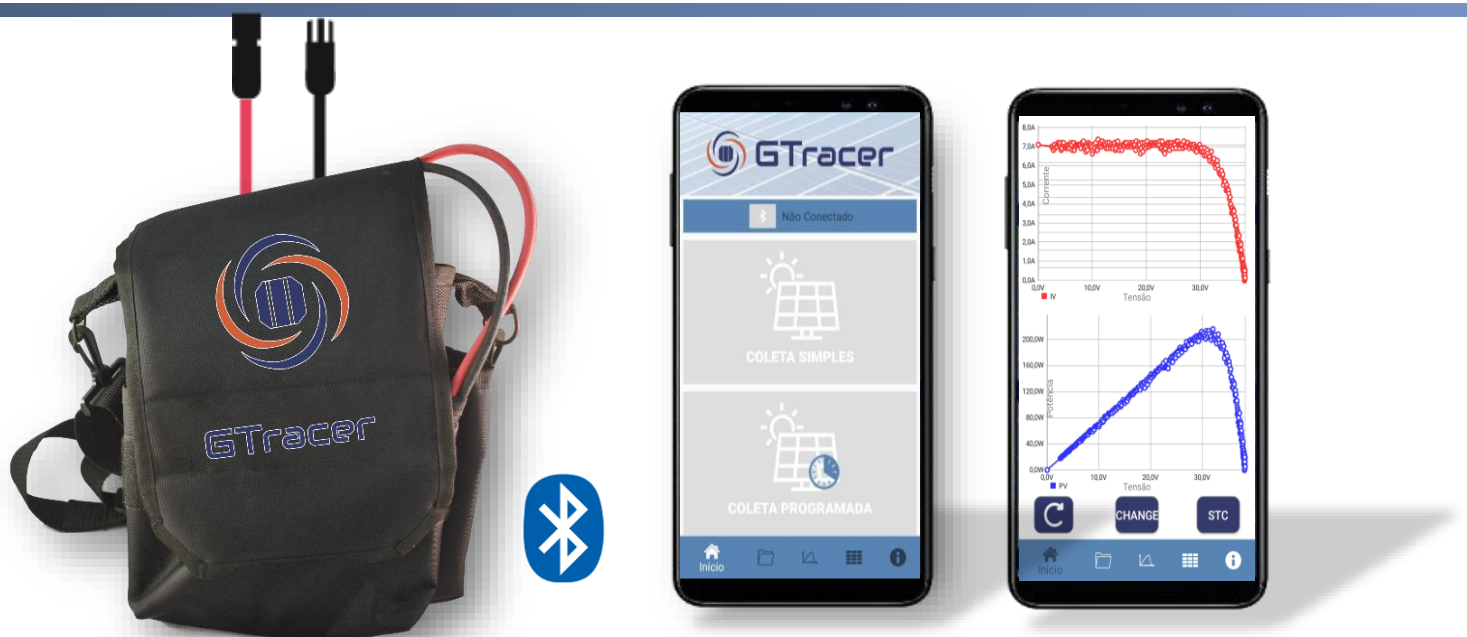
Pesquise por:
"GESEP UFV"

EStimate - Sistemas Fotovoltaicos

Google Play

Pesquise por:
"EStimate"

GESEP – Gerência de Especialistas em Sistemas Elétricos de Potência



EStimate - Sistemas Fotovoltaicos

Google Play

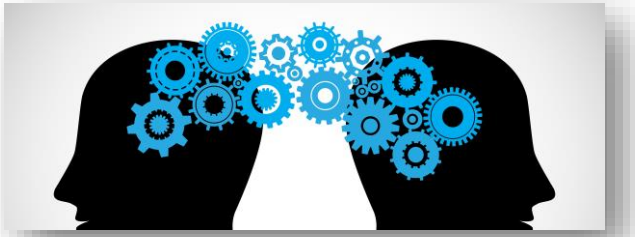
PÓS-GRADUAÇÃO LATO SENSU

SISTEMAS FOTOVOLTAICOS ISOLADOS E CONECTADOS À REDE ELÉTRICA

Busca desenvolver no participante a formação conceitual, científica e tecnológica, com competência, para promover ações no setor de energia solar fotovoltaica, criar sua empresa e prestar serviços na área.

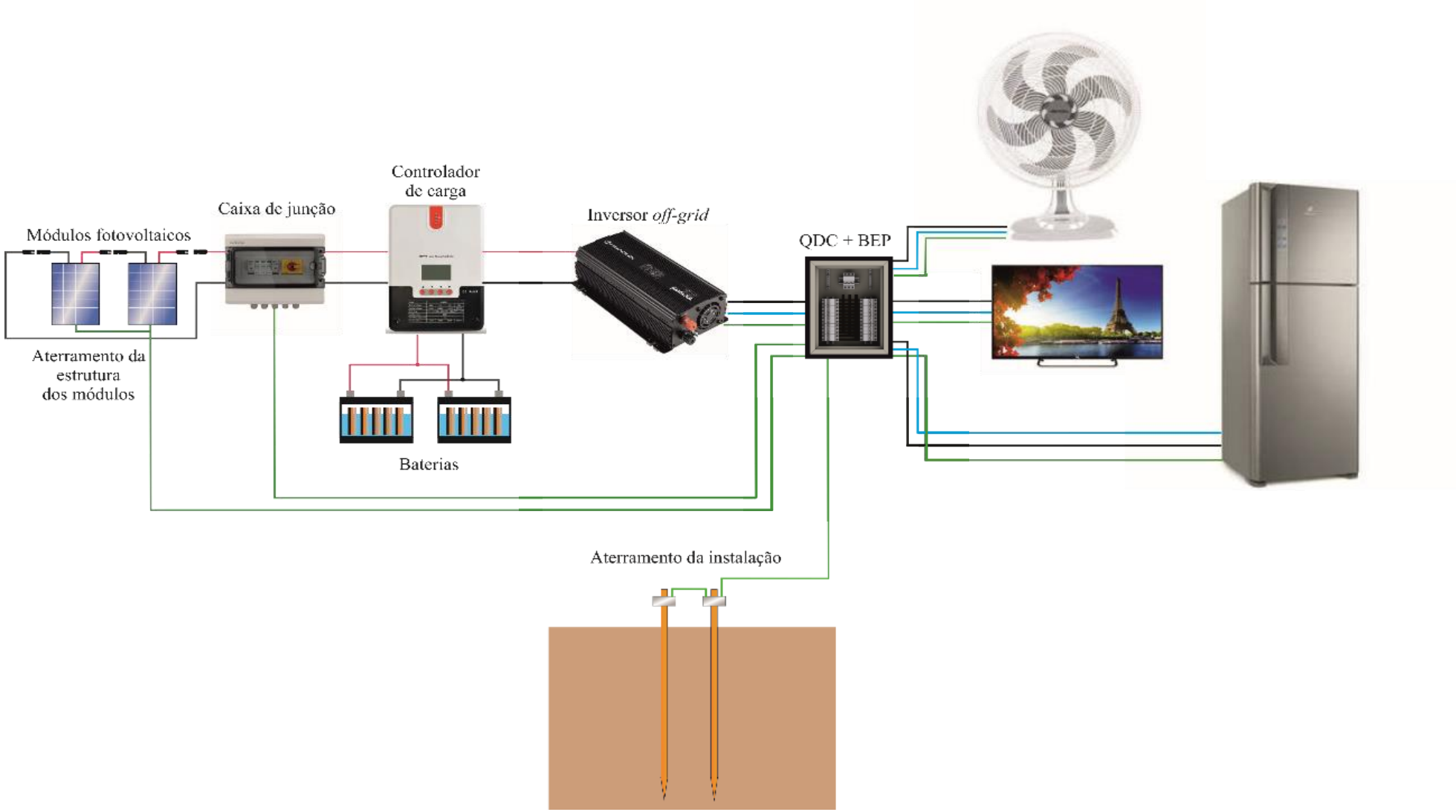
Tópicos a serem abordados

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

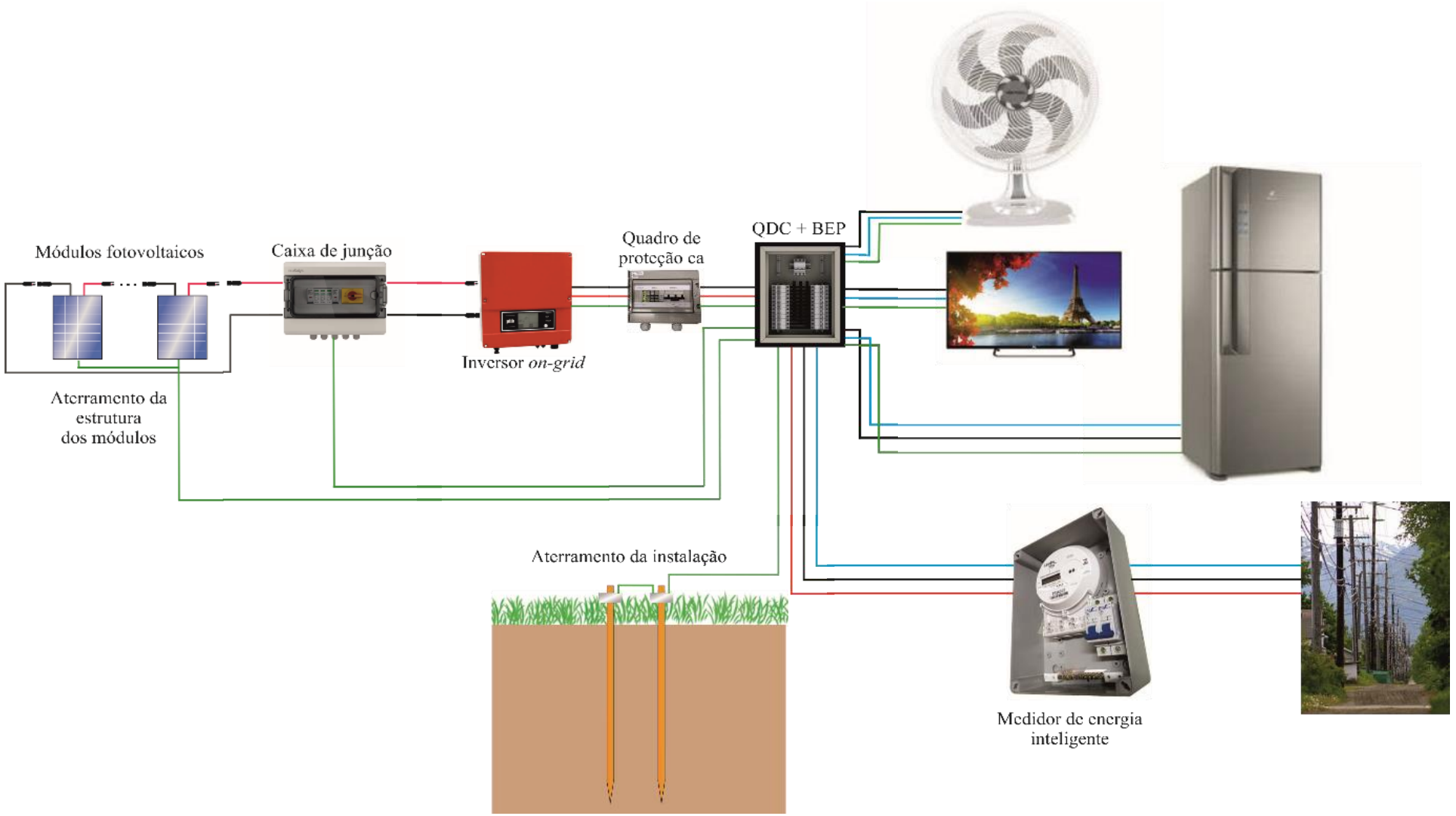


Estrutura e tecnologia de inversores fotovoltaicos

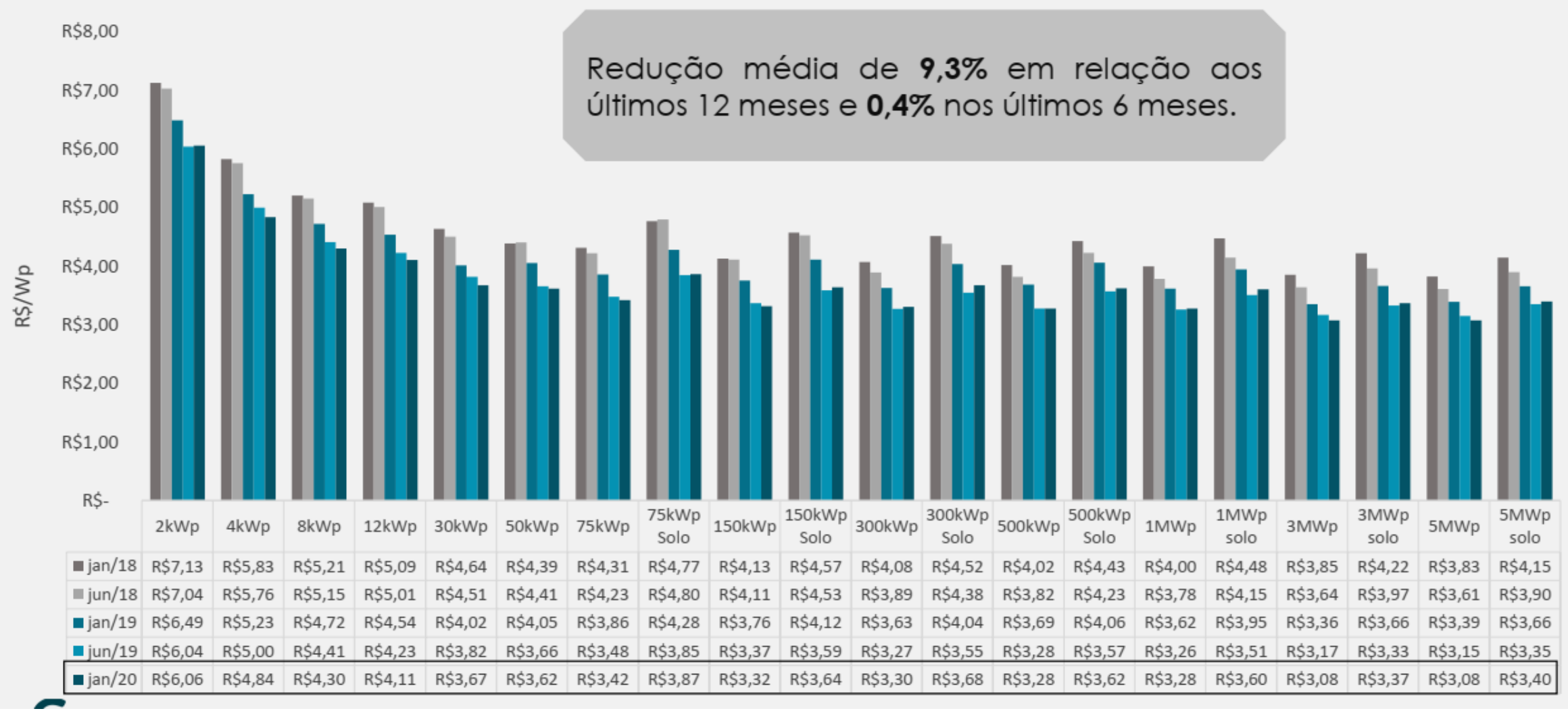
Sistemas fotovoltaicos isolados



Sistemas fotovoltaicos conectados à rede elétrica



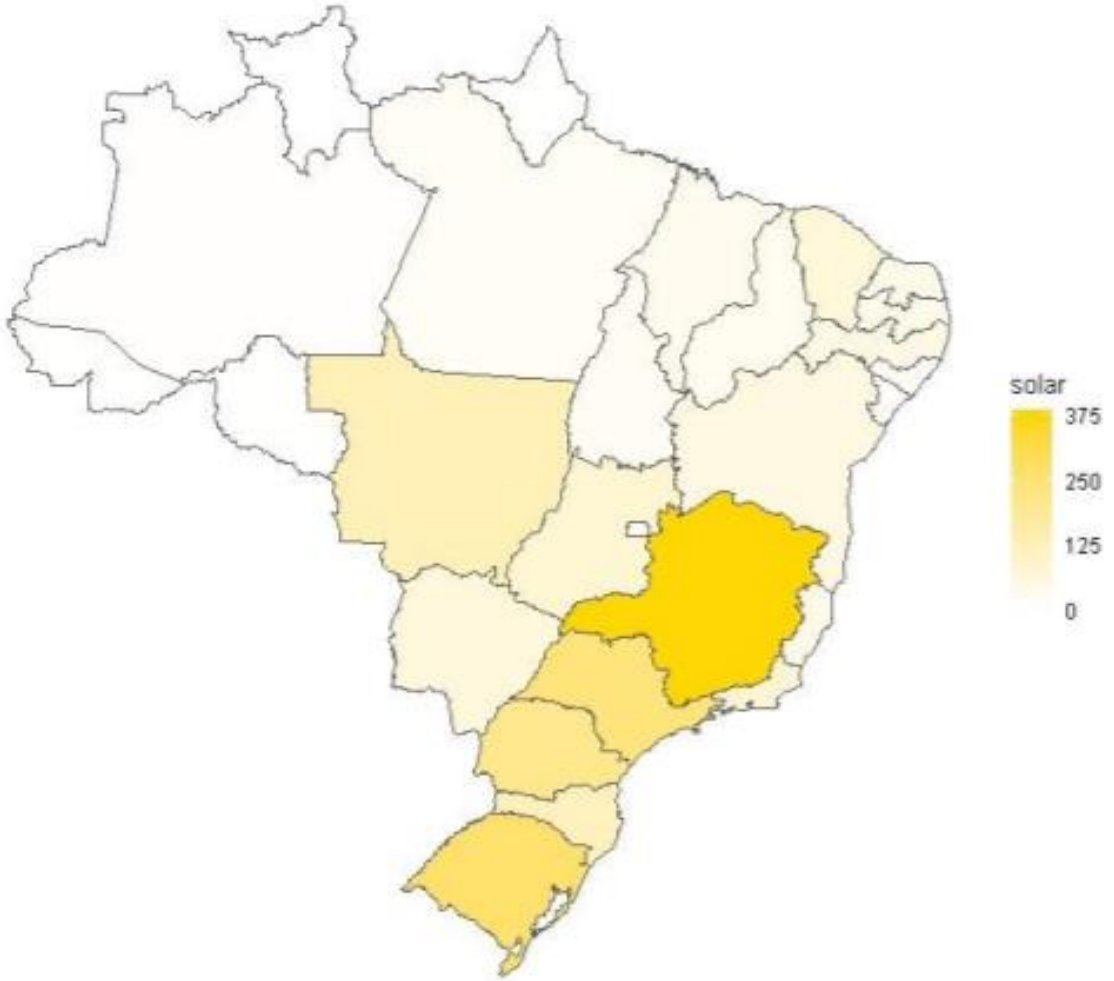
Evolução do preço de sistemas fotovoltaicos → cliente final

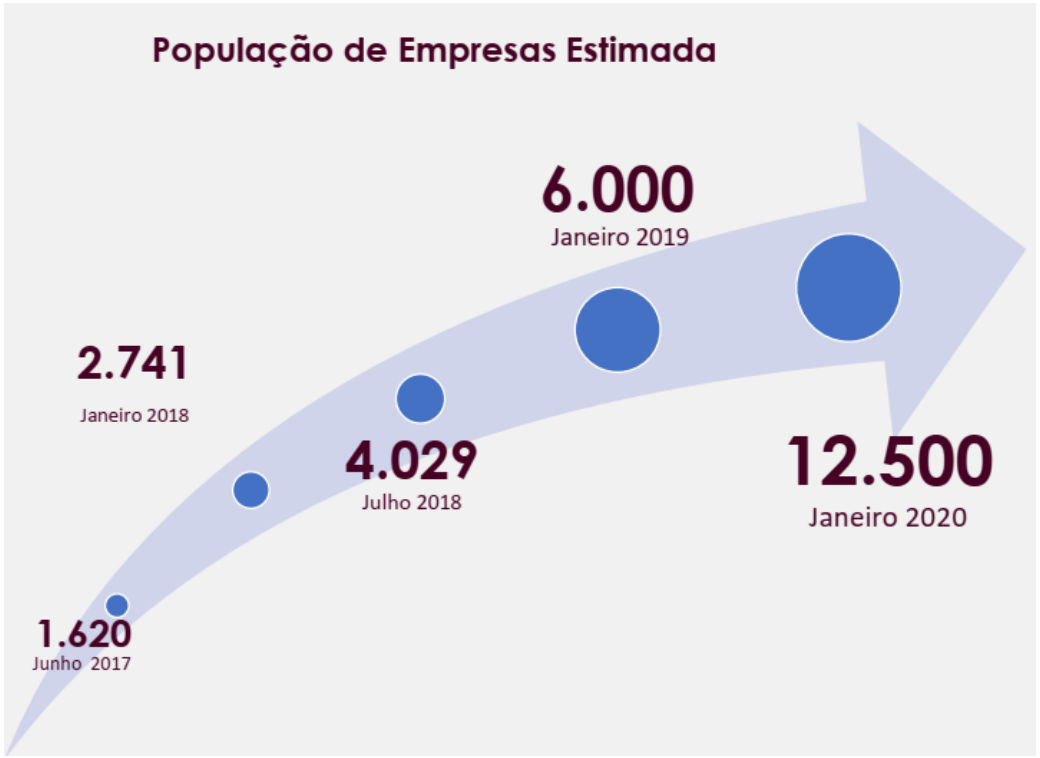


	2kWp	4kWp	8kWp	12kWp	30kWp	50kWp	75kWp	75kWp Solo	150kWp	150kWp Solo	300kWp	300kWp Solo	500kWp	500kWp Solo	1MWp	1MWp solo	3MWp	3MWp solo	5MWp	5MWp solo
jan/18	R$7,13	R$5,83	R$5,21	R$5,09	R$4,64	R$4,39	R$4,31	R$4,77	R$4,13	R$4,57	R$4,08	R$4,52	R$4,02	R$4,43	R$4,00	R$4,48	R$3,85	R$4,22	R$3,83	R$4,15
jun/18	R$7,04	R$5,76	R$5,15	R$5,01	R$4,51	R$4,41	R$4,23	R$4,80	R$4,11	R$4,53	R$3,89	R$4,38	R$3,82	R$4,23	R$3,78	R$4,15	R$3,64	R$3,97	R$3,61	R$3,90
jan/19	R$6,49	R$5,23	R$4,72	R$4,54	R$4,02	R$4,05	R$3,86	R$4,28	R$3,76	R$4,12	R$3,63	R$4,04	R$3,69	R$4,06	R$3,62	R$3,95	R$3,36	R$3,66	R$3,39	R$3,66
jun/19	R$6,04	R$5,00	R$4,41	R$4,23	R$3,82	R$3,66	R$3,48	R$3,85	R$3,37	R$3,59	R$3,27	R$3,55	R$3,28	R$3,57	R$3,26	R$3,51	R$3,17	R$3,33	R$3,15	R$3,35
jan/20	R$6,06	R$4,84	R$4,30	R$4,11	R$3,67	R$3,62	R$3,42	R$3,87	R$3,32	R$3,64	R$3,30	R$3,68	R$3,28	R$3,62	R$3,28	R$3,60	R$3,08	R$3,37	R$3,08	R$3,40

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

Capacidade instalada – Energia solar fotovoltaica



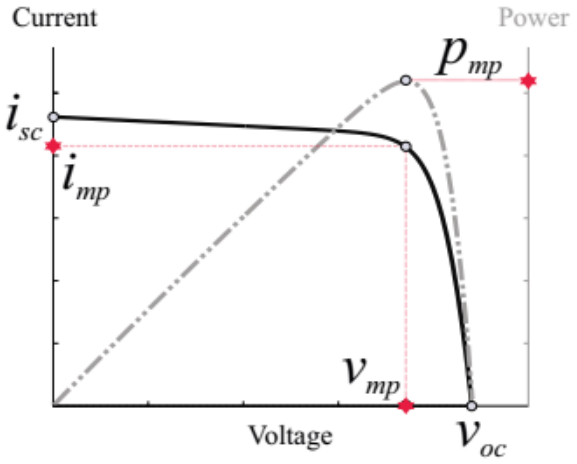


Fonte:

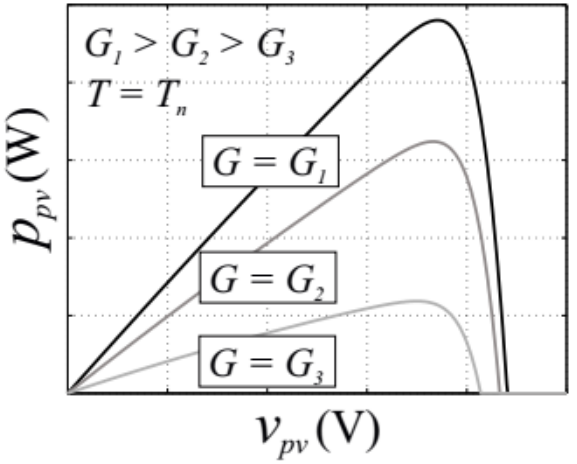
[1] Empresa de Pesquisas Energéticas. Balanço energético nacional – BEN. 2020.
[2] Greener. Estudo Estratégico: Mercado Fotovoltaico de Geração Distribuída. 2019.

Sistemas fotovoltaicos conectados à rede elétrica

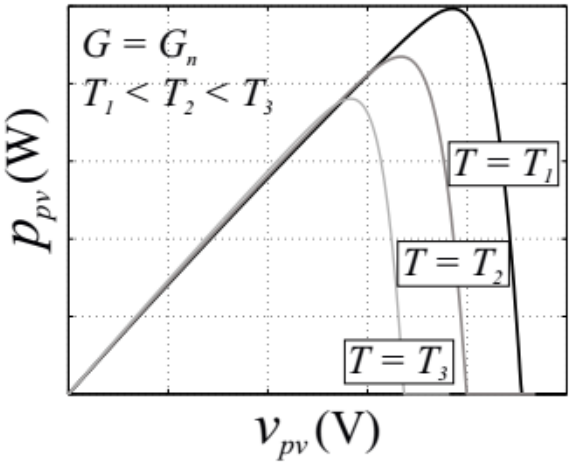
- Módulo fotovoltaico → tensão contínua;
- Conversão CC-CA;
- Otimização da extração de potência;
- Proteção e monitoramento.



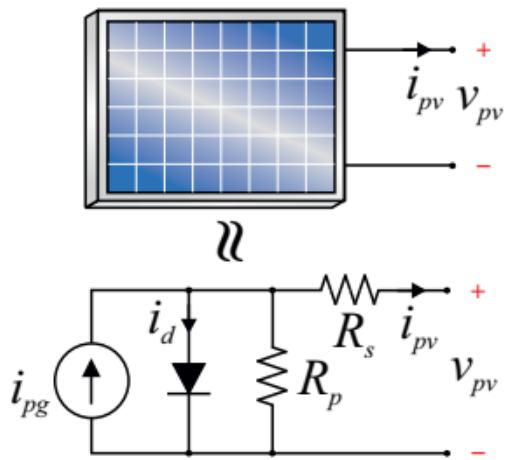
(a)



(b)



(c)

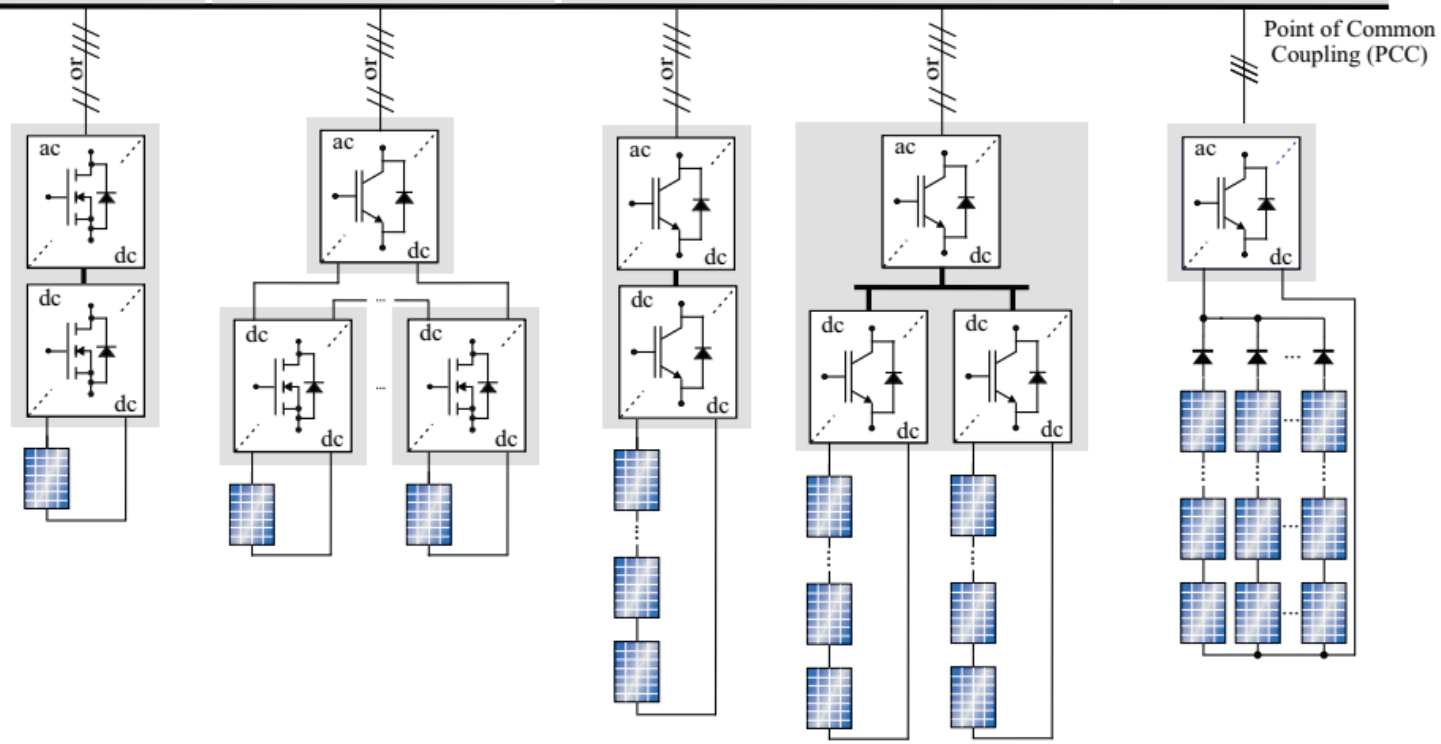


(d)

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

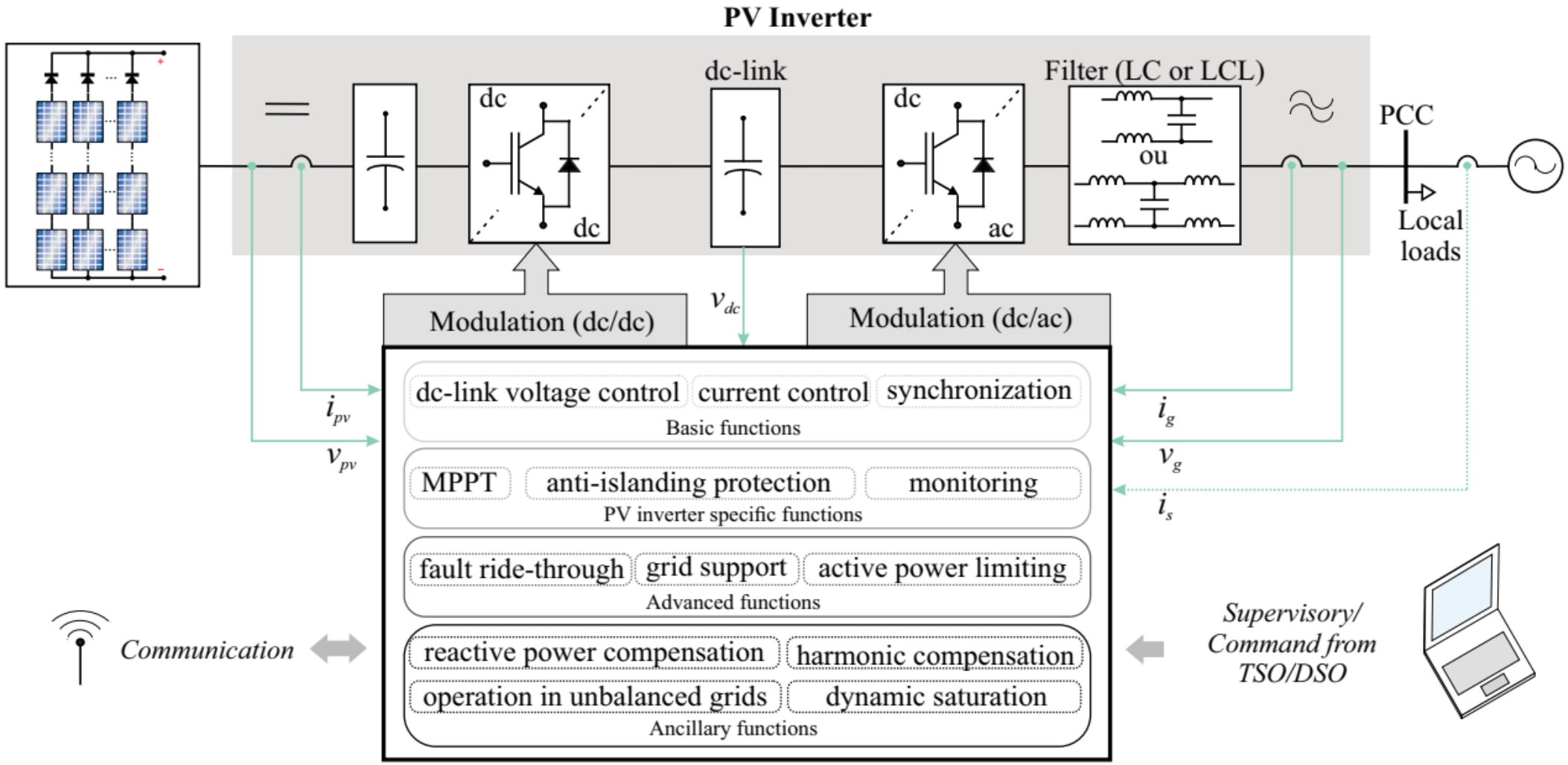
Arquiteturas de sistemas fotovoltaicos conectados à rede

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



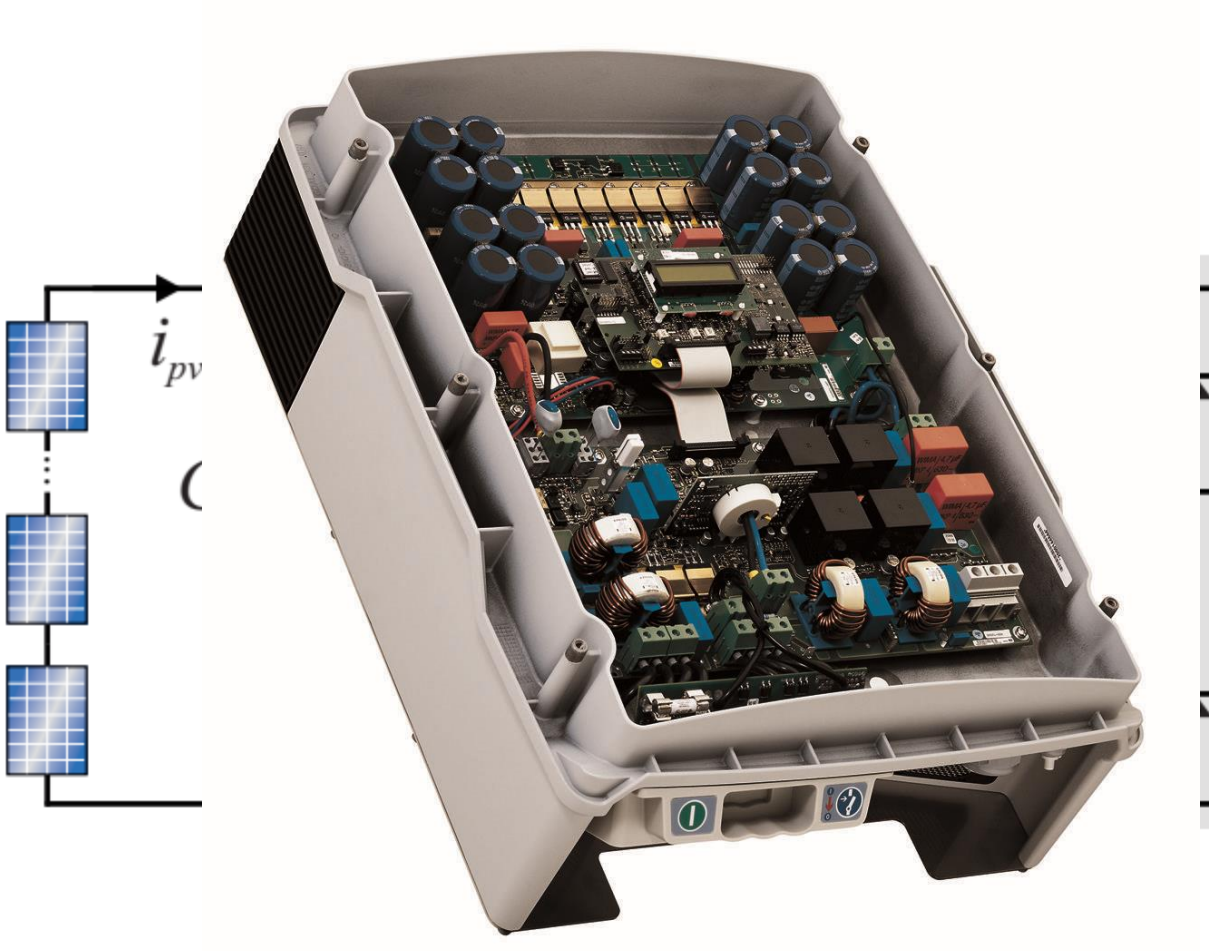
Fonte: A. F. Cupertino e H. A. Pereira. "Next generation of grid-connected photovoltaic systems: modelling and control". Book Chapter. Elsevier. *In Press*.

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*.

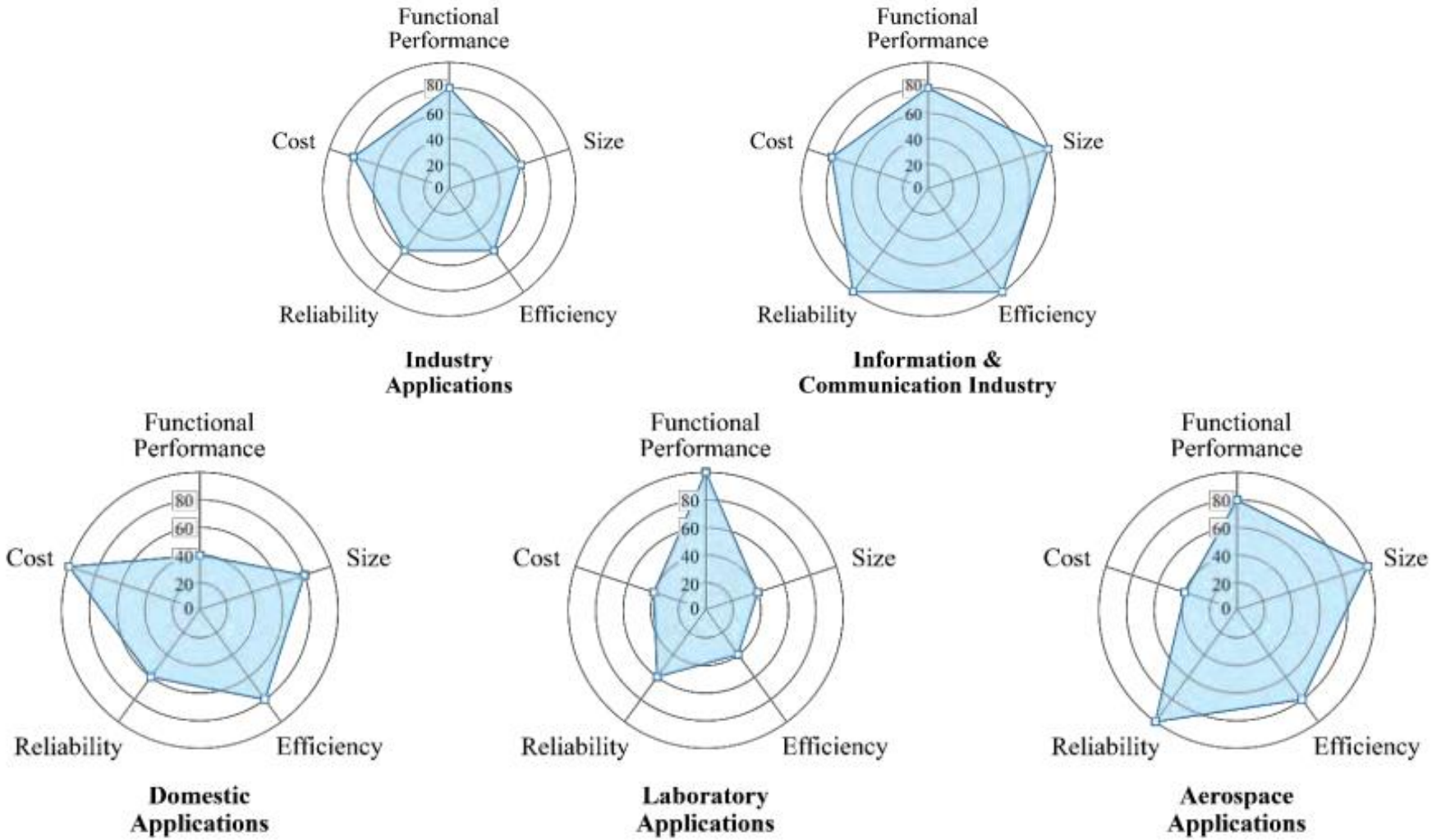
Aspecto de um inversor comercial



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

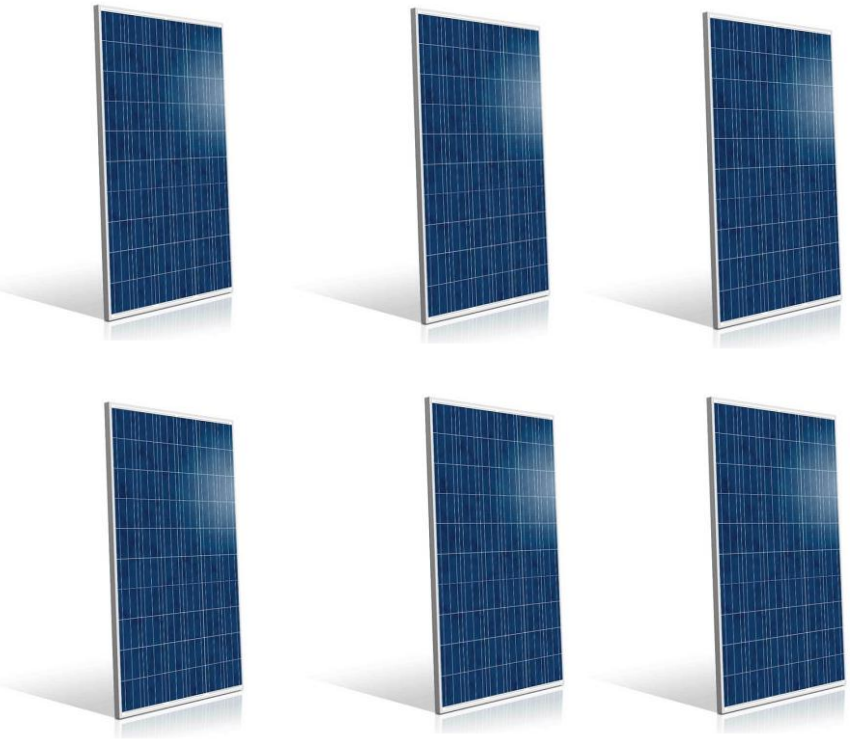
Por que estudar confiabilidade?

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?



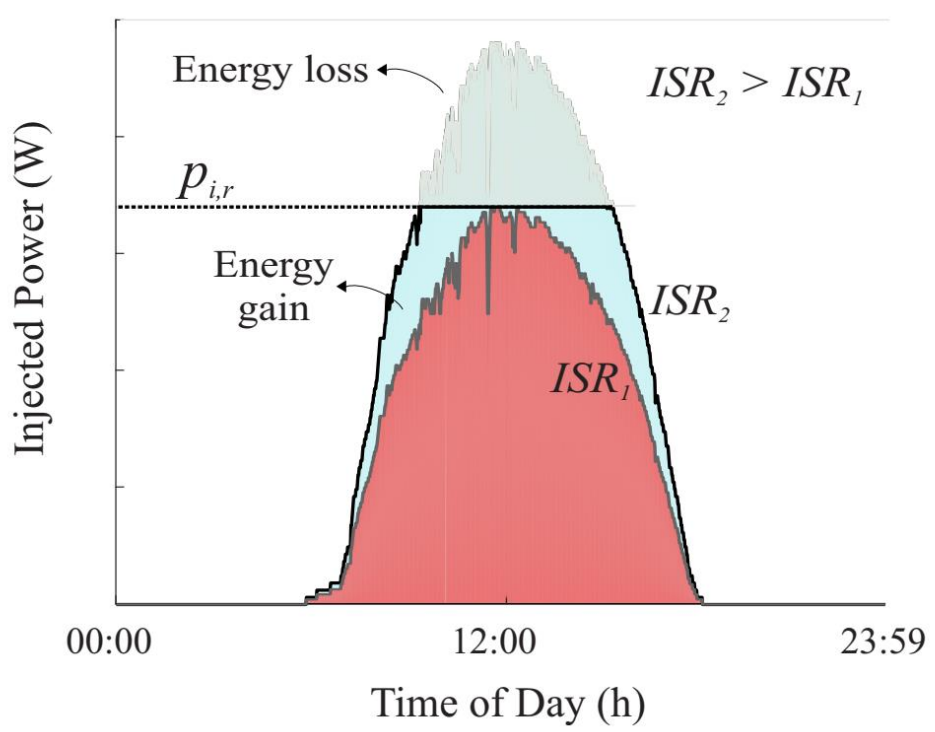
Fonte: A. F. Cupertino e H. A. Pereira. "Next generation of grid-connected photovoltaic systems: modelling and control". Book Chapter. Elsevier. *In Press*.

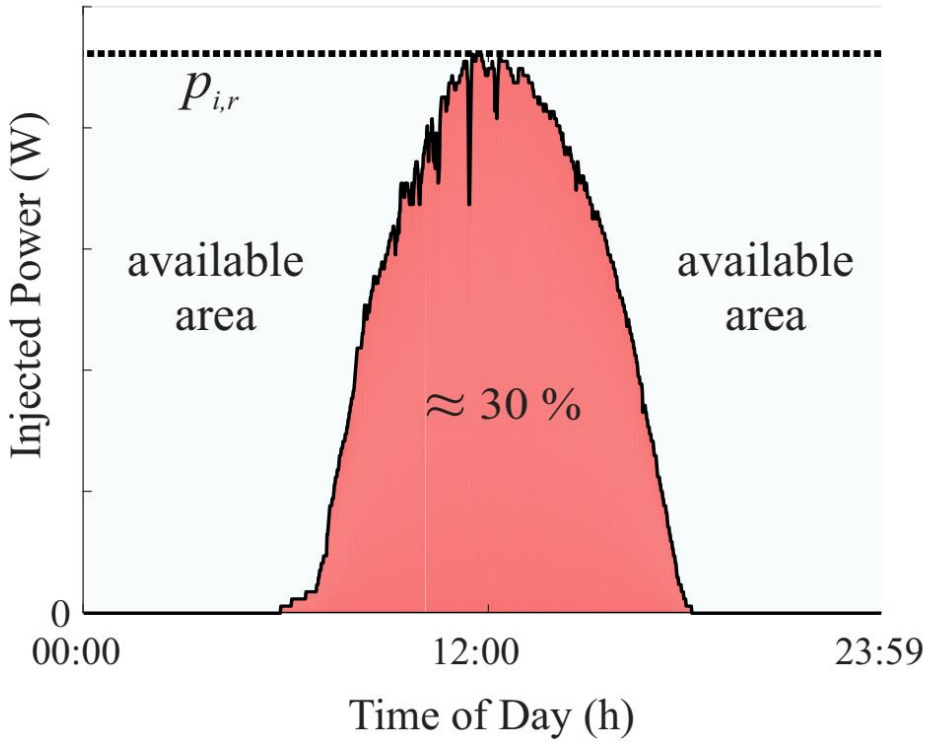
Por que aumentar a confiabilidade do inversor?

- 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*.

Por que aumentar a confiabilidade do inversor?

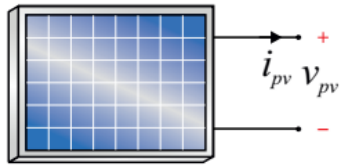




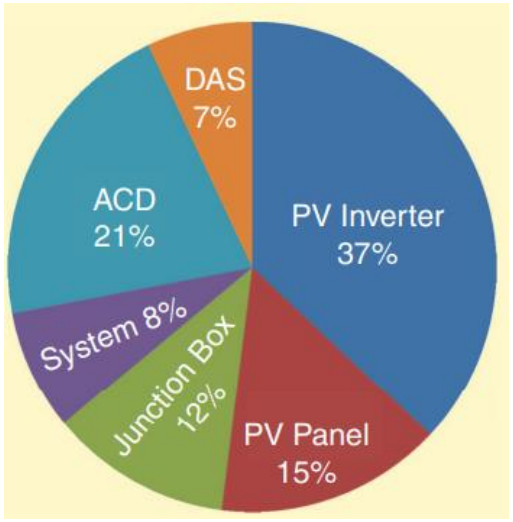
- Potencial para realização de serviços auxiliares;
- Isto pode afetar a vida útil do equipamento!

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

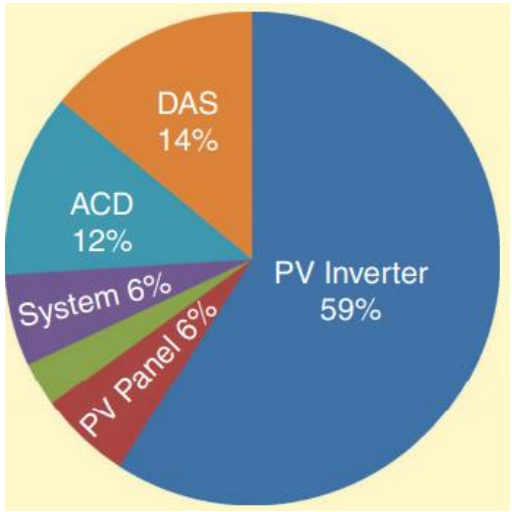
Estatísticas de falha em sistemas fotovoltaicos

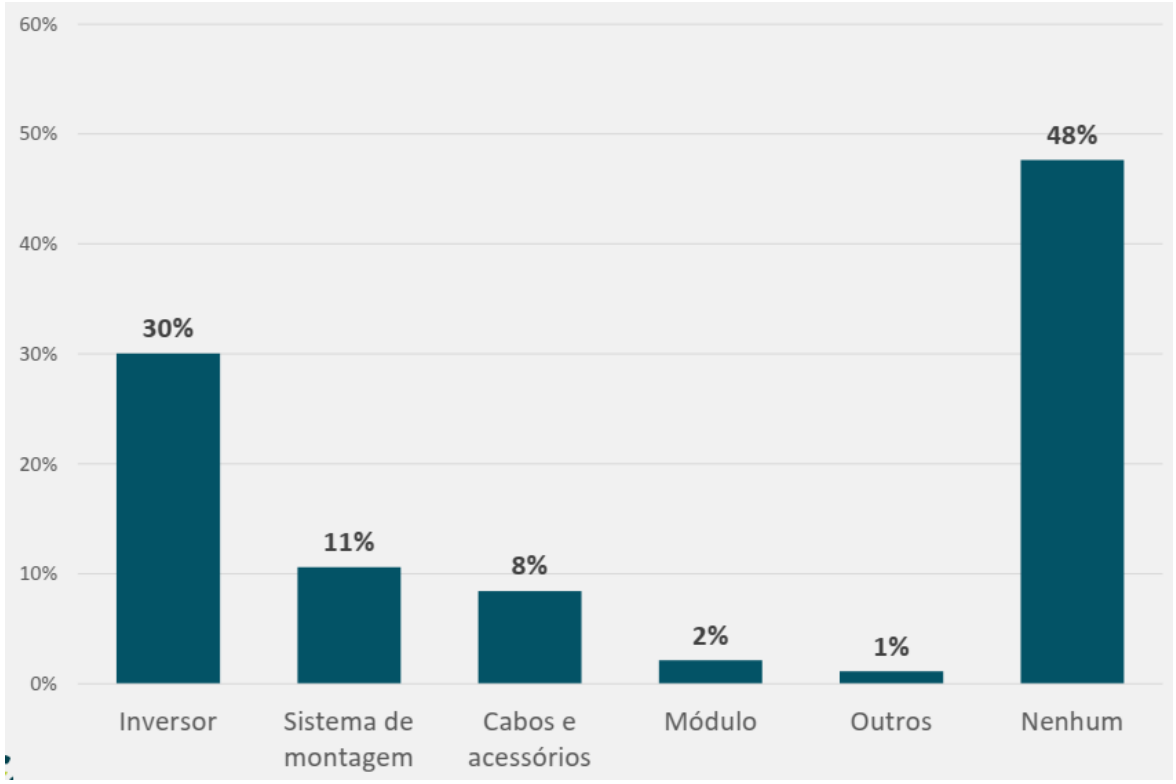


Estatística de falhas



Custo associado a falha

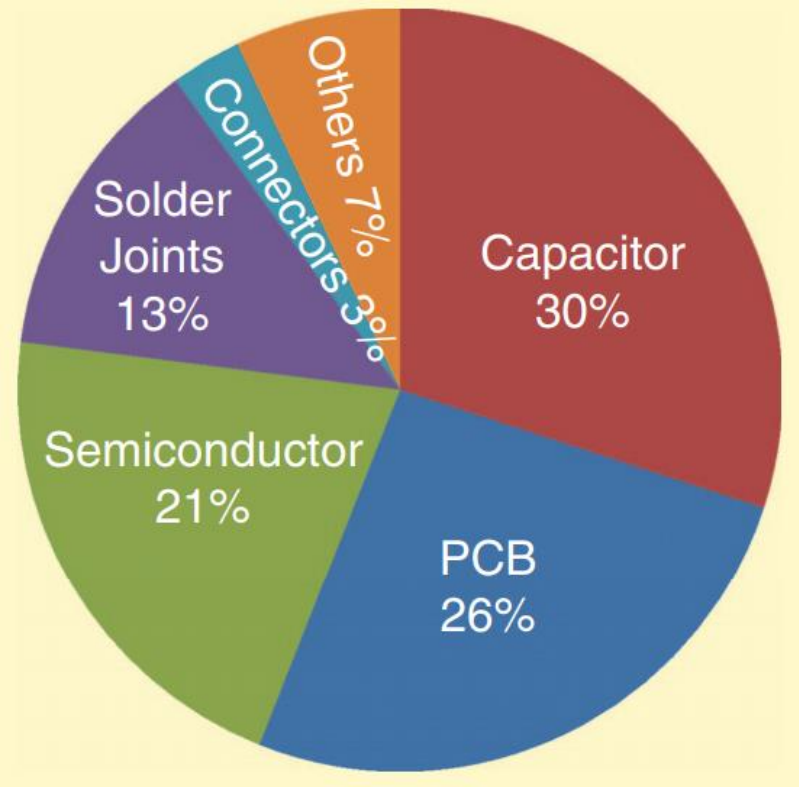


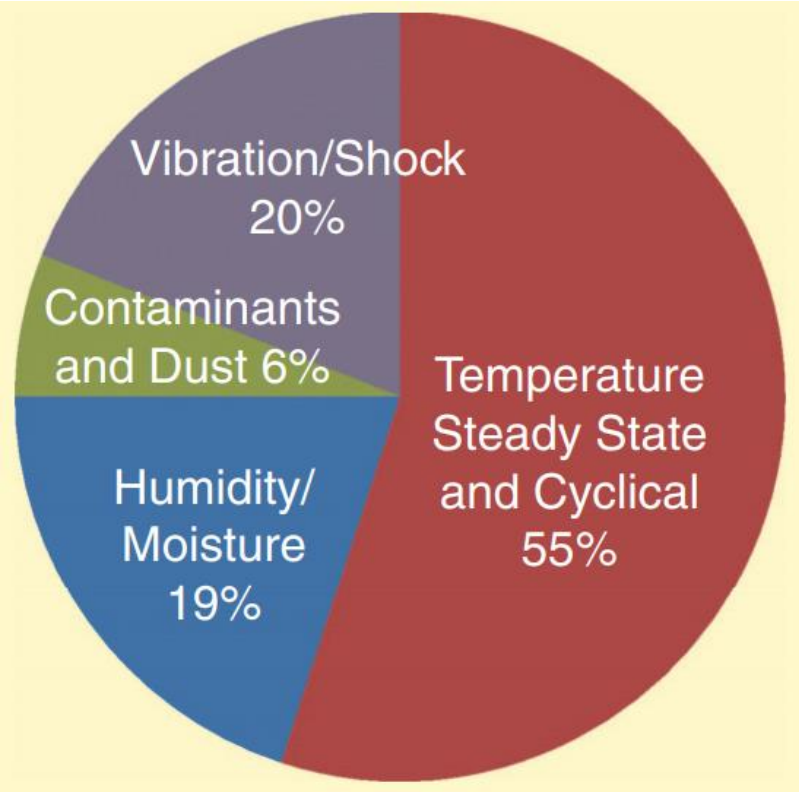


Nota: DAS = Data Acquisition System

Fonte: [1] H. Wang, M. Liserre e F. Blaabjerg. "Toward Reliable Power Electronics: Challenges, Design and Opportunities". IEEE Industrial Electronics Magazine. 2013.
[2] Greener. Estudo Estratégico: Mercado Fotovoltaico de Geração Distribuída. 2019.

Falhas em conversores eletrônicos e fontes de estresse

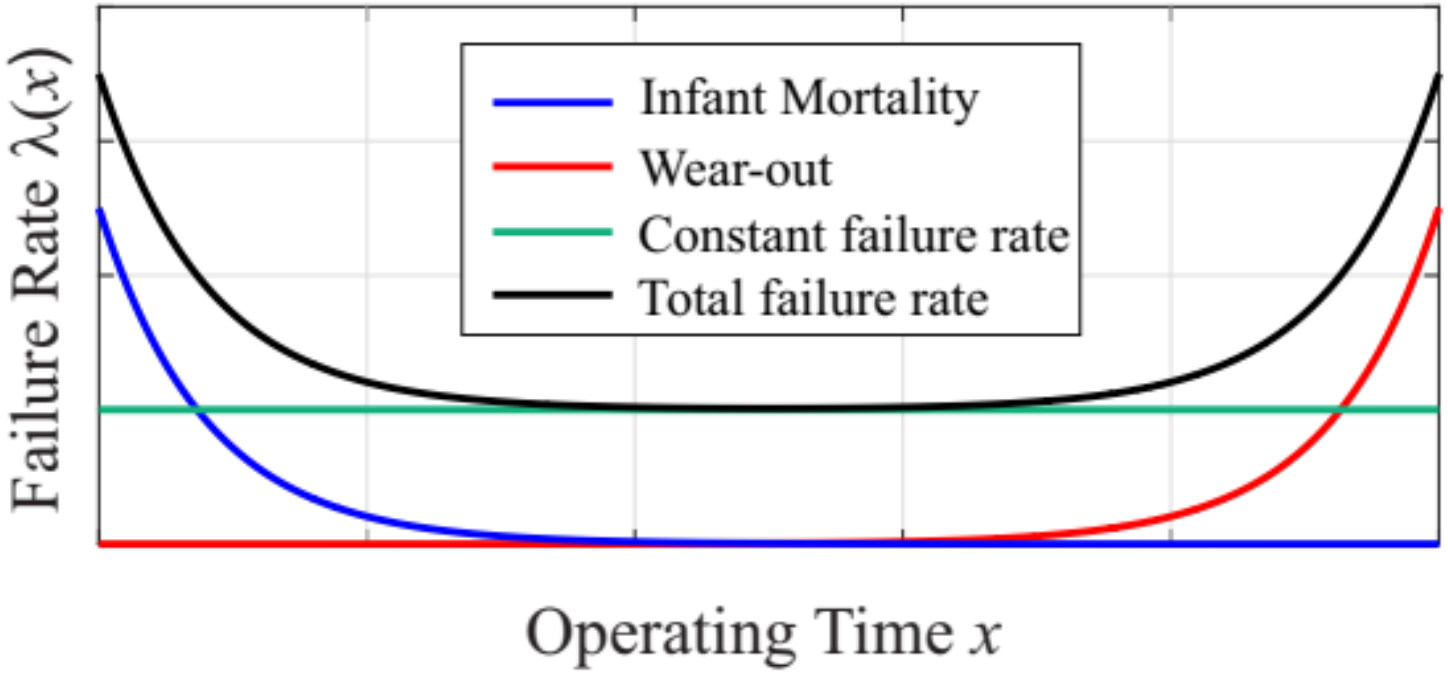




Fonte: H. Wang, M. Liserre e F. Blaabjerg. "Toward Reliable Power Electronics: Challenges, Design and Opportunities". IEEE Industrial Electronics Magazine. 2013.

Estatística de falhas e mecanismo de falha

Curva da banheira



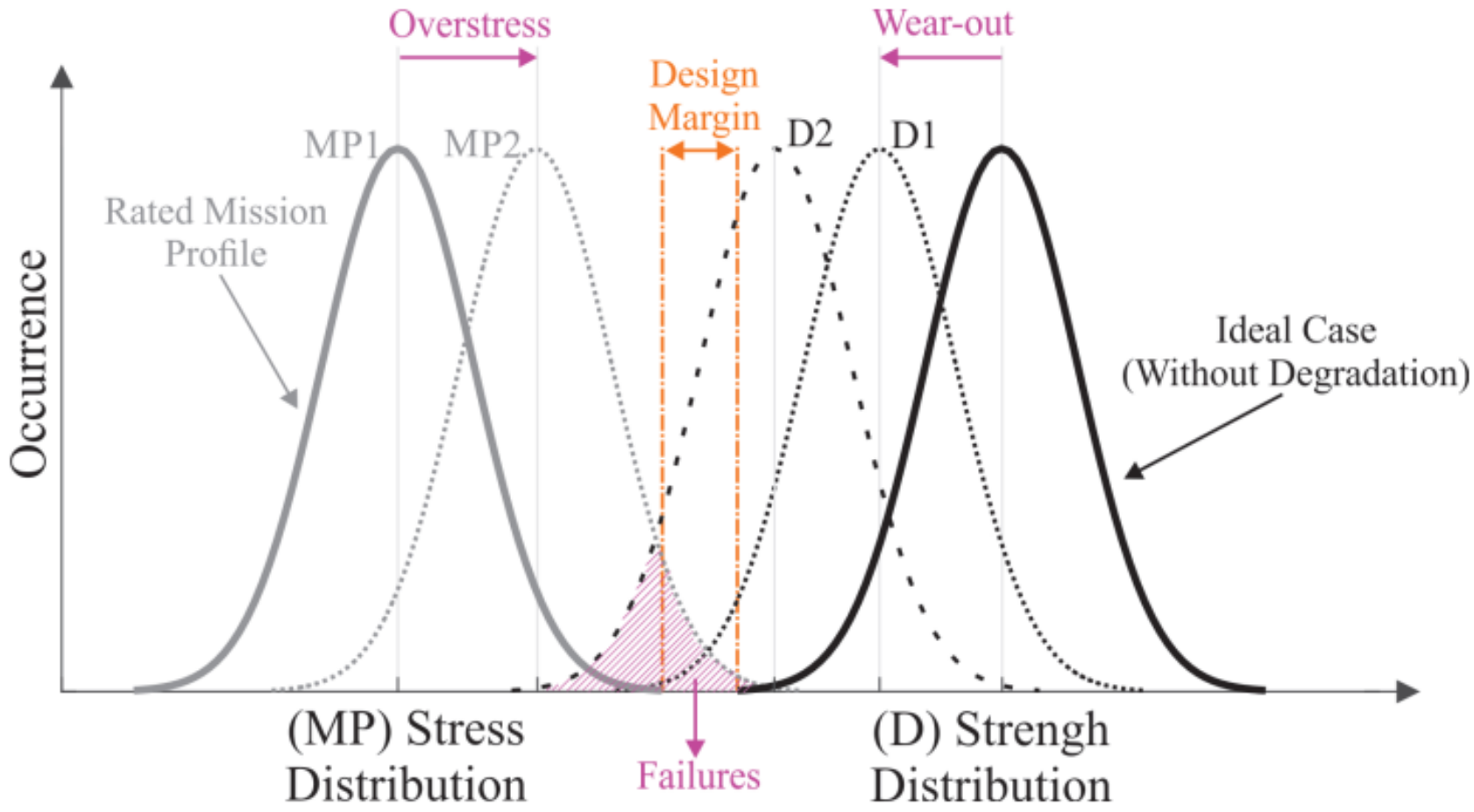
- Região de falha constante → FIT (Failure in time);
- 1 FIT significa 1 falha a cada 10^9 horas de operação.

Abordagem moderna – Modelos baseados na física da falha

- O que causa o envelhecimento dos componentes?

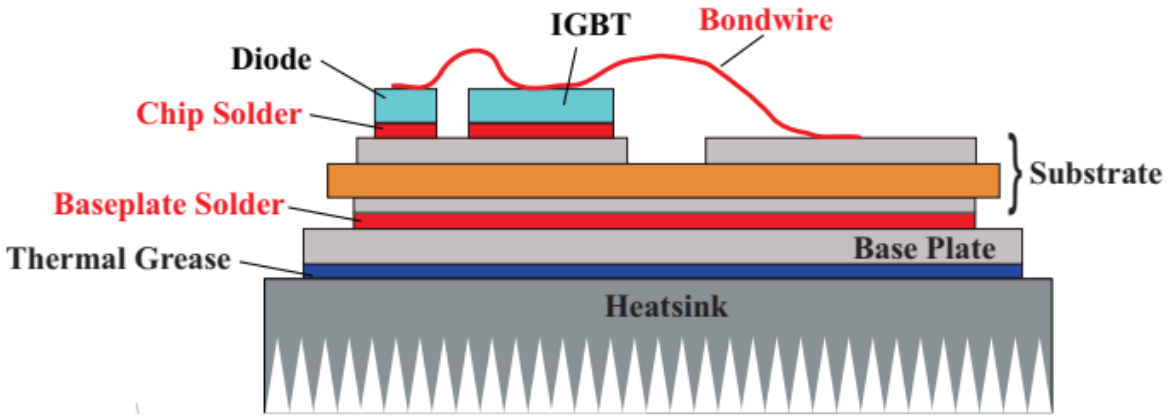
- Quais são os fenômenos de degradação?
- Como modelar o efeito da degradação em função do estresse?
- Análise multifísica → Temperatura, humidade, estresse mecânico;
- Objetivo: Previsão mais precisa de tempo de vida e garantias.

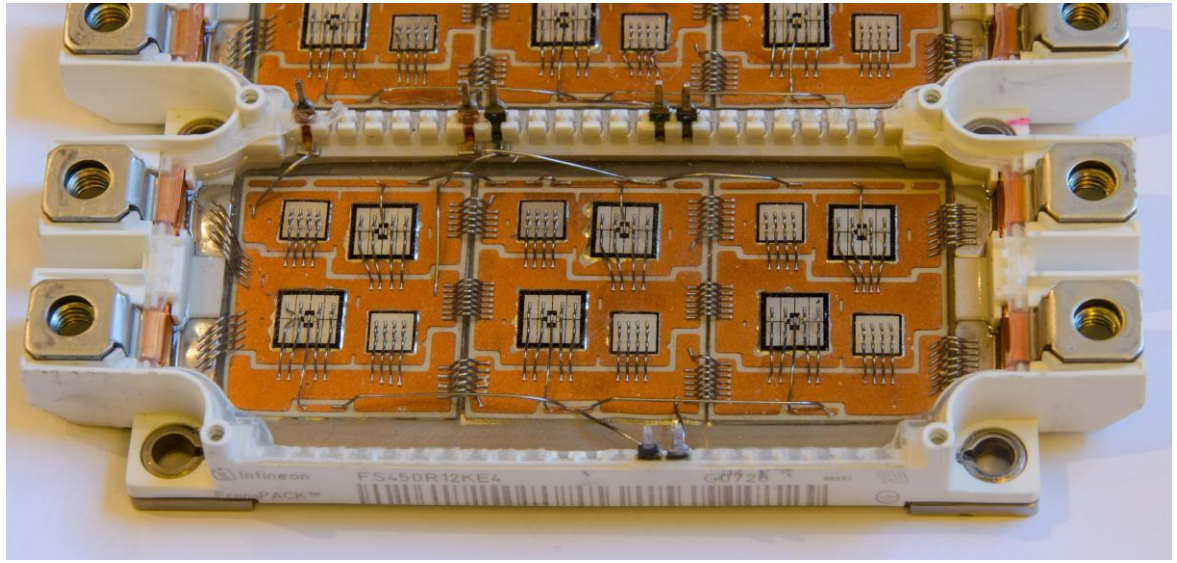
Efeito do envelhecimento do componente



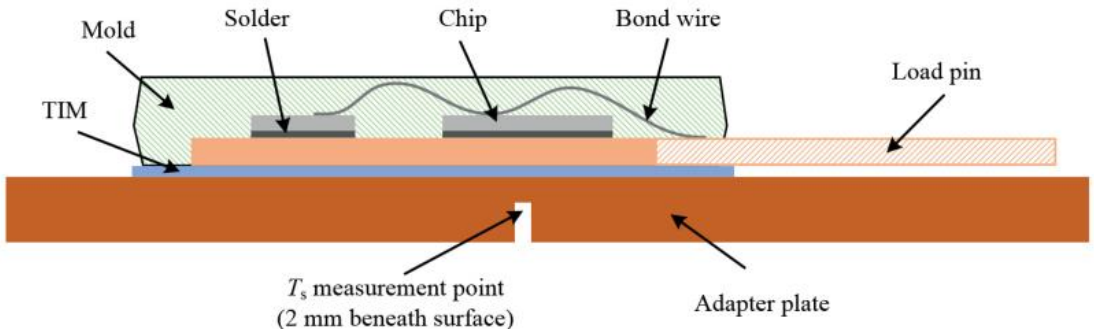
Semicondutores: mecanismos de falha típicos

Estrutura interna de um módulo semicondutor

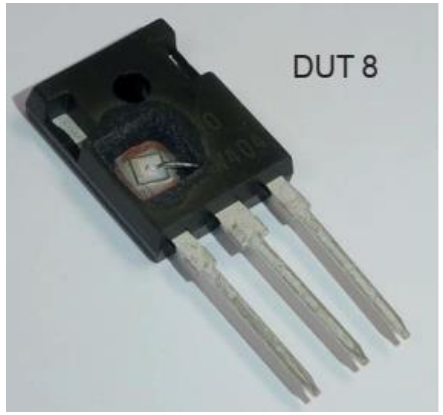


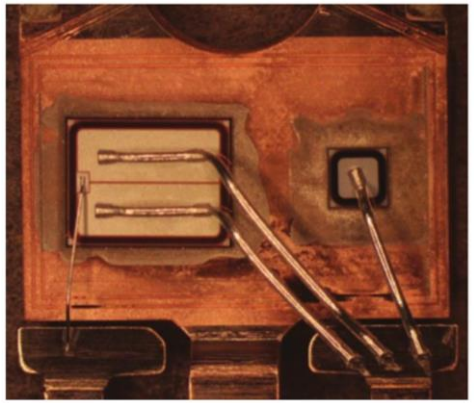


Fonte: Infineon Technologies.



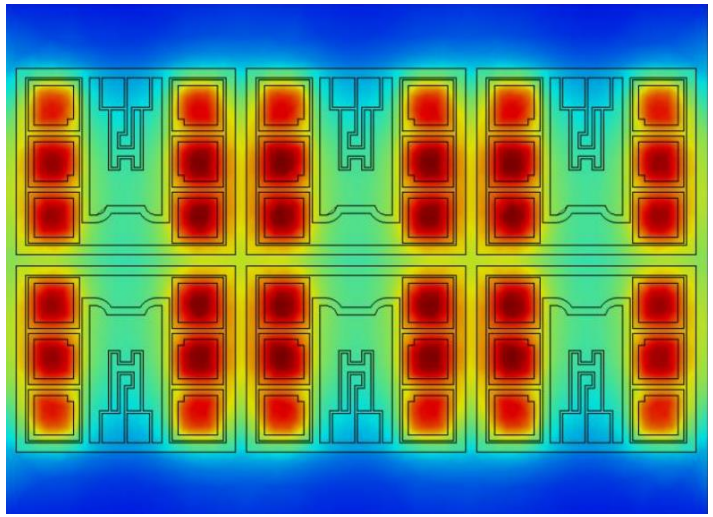
Fonte: G. Zeng et. al. "First results of development of a lifetime model for transfer molded discrete power devices". PCIM Europe 2018

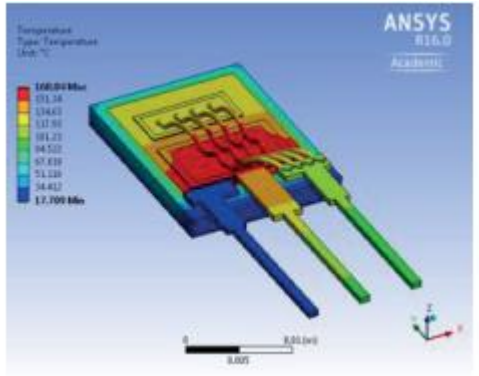


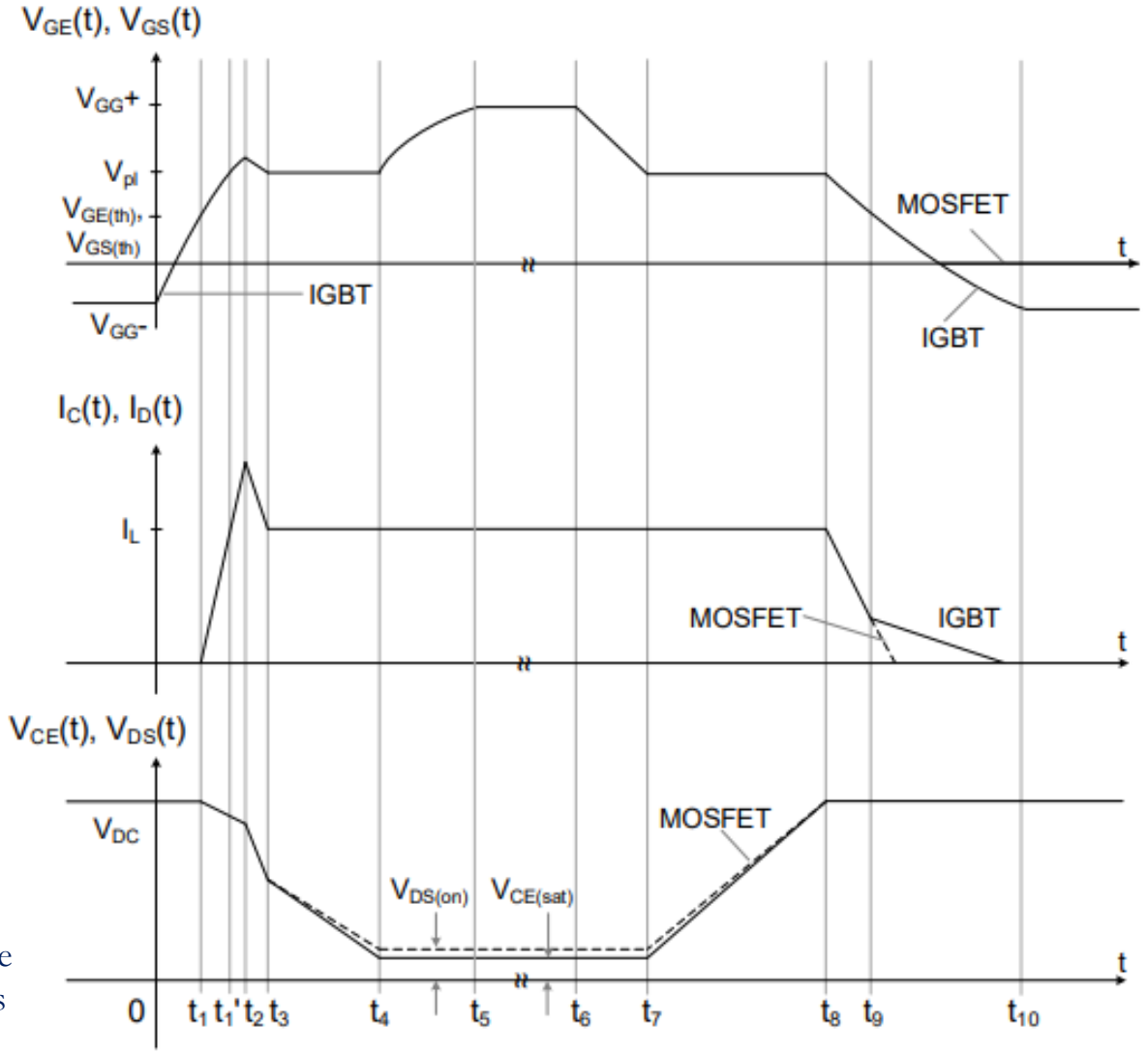


Fonte: On Semiconductors.

Perdas e estresse térmico em um IGBT







Fontes:

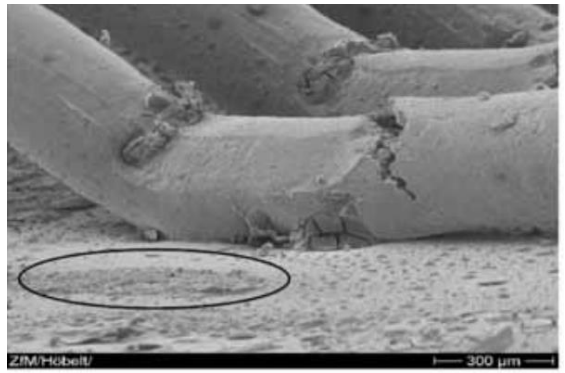
[1] S. Hartmann et.al.. "Packaging Technology Platform for Next Generation High Power IGBT Modules". 2014.

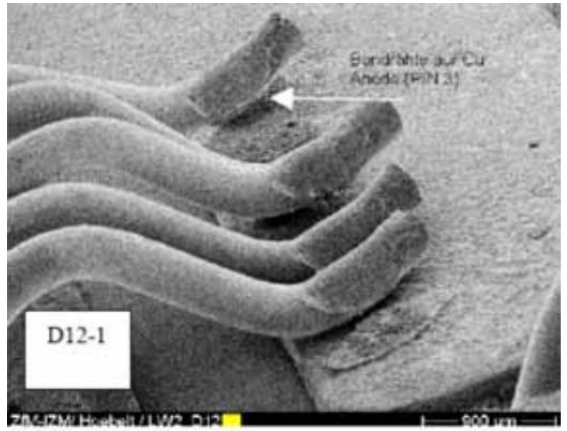
[2] : G. Zeng et. al. "First results of development of a lifetime model for transfer molded discrete power devices". PCIM Europe 2018

[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.

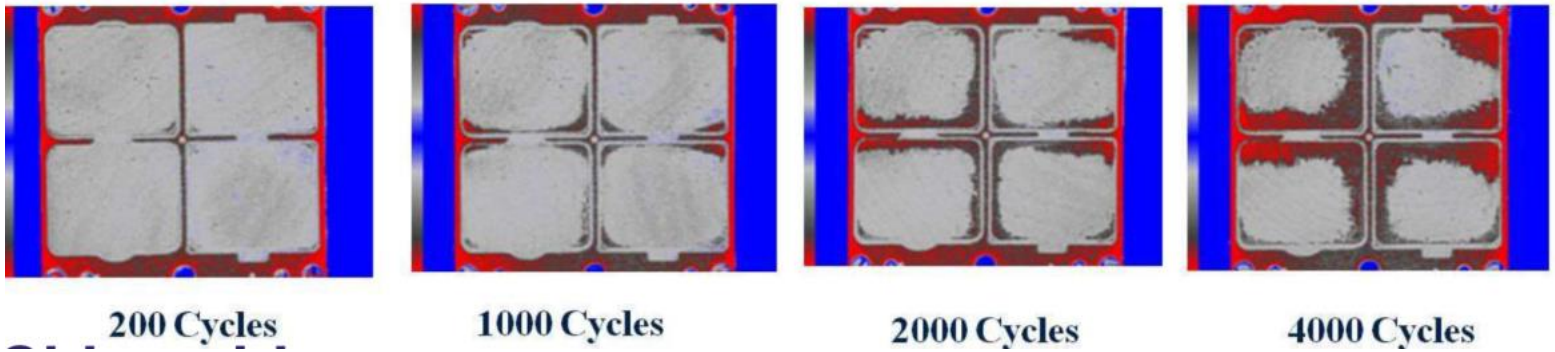
Alguns mecanismos de falha de IGBTs

Bond Wires

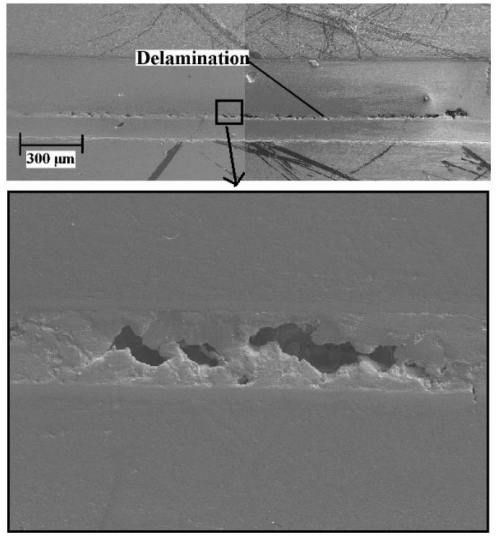




Chip Solder



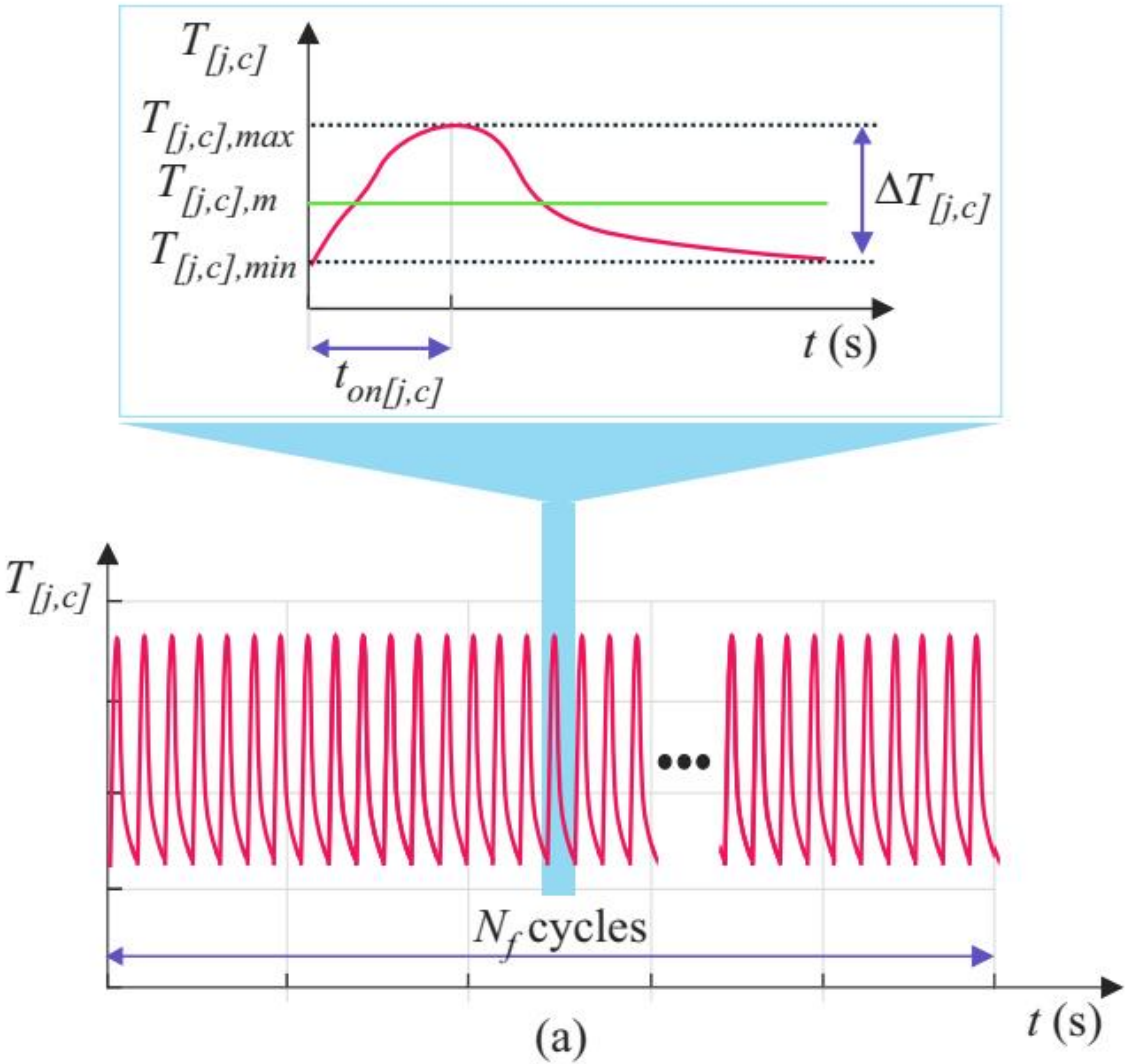
Baseplate solder

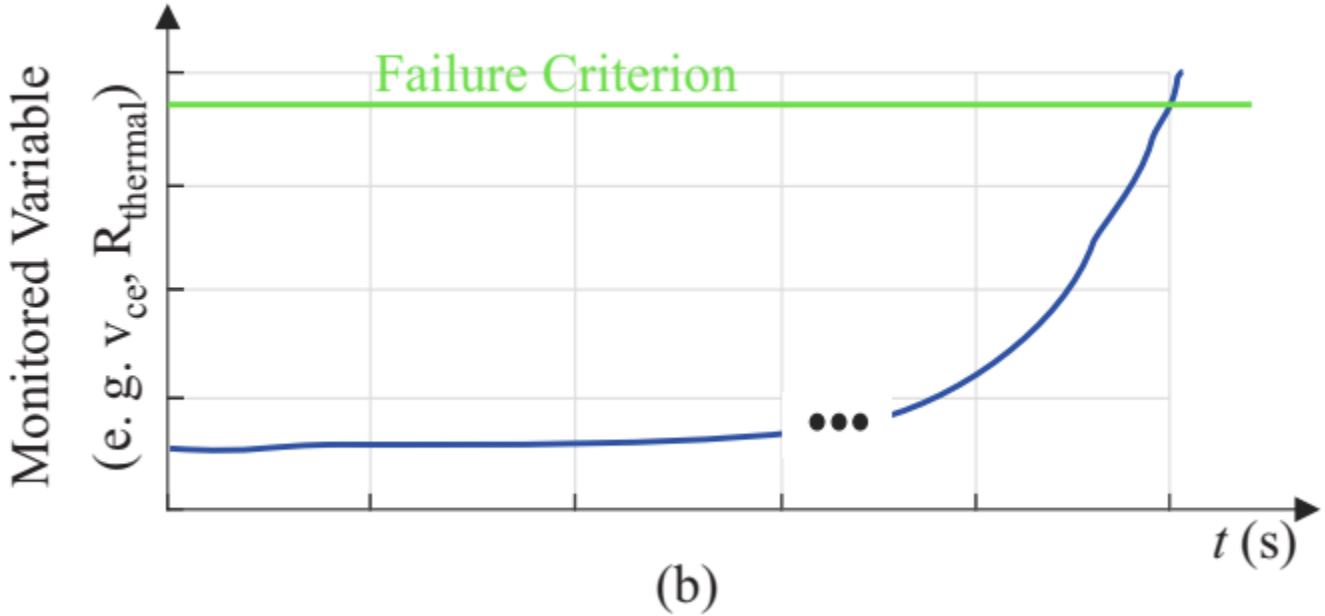


Thermal grease

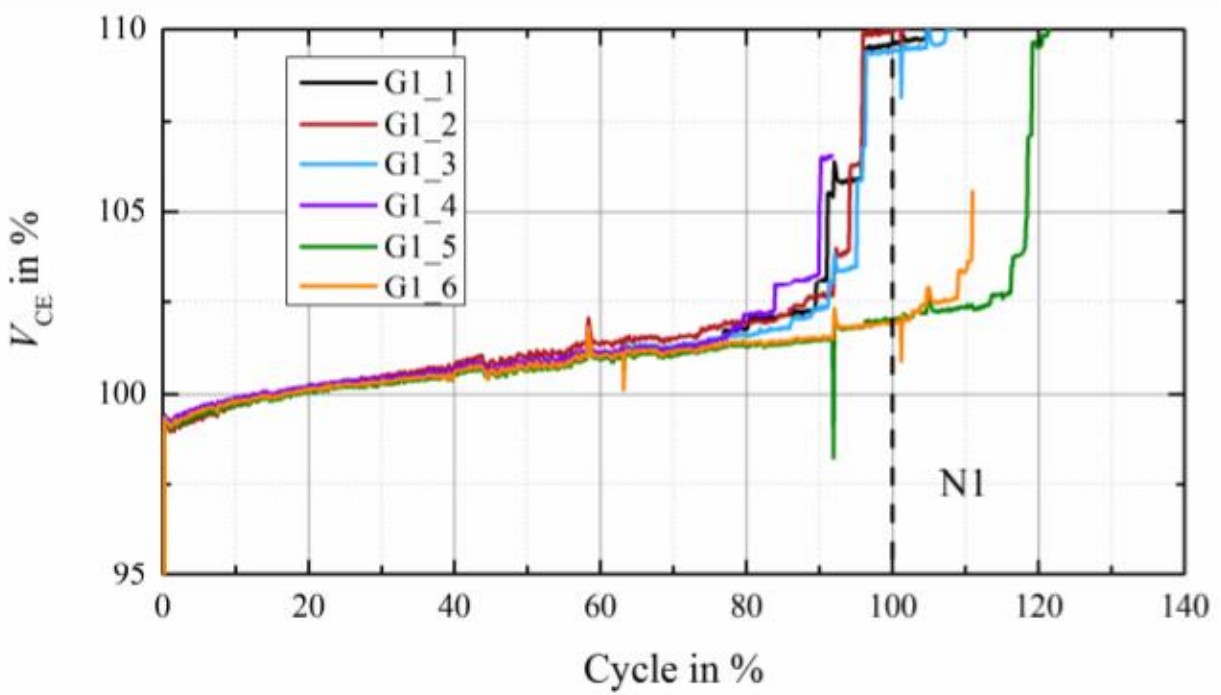
Fontes:
[1] Semikron. “Application Manual of Semiconductors”. 2015.
[2] T. Lhommeau et. al. "Base-plate solder reliability study of IGBT modules for aeronautical application”. ECCE Europe.2007.
[3] M. Schulz, "Thermal management details and their influence on the aging of power semiconductors," EPE-ECCE Europe. 2014

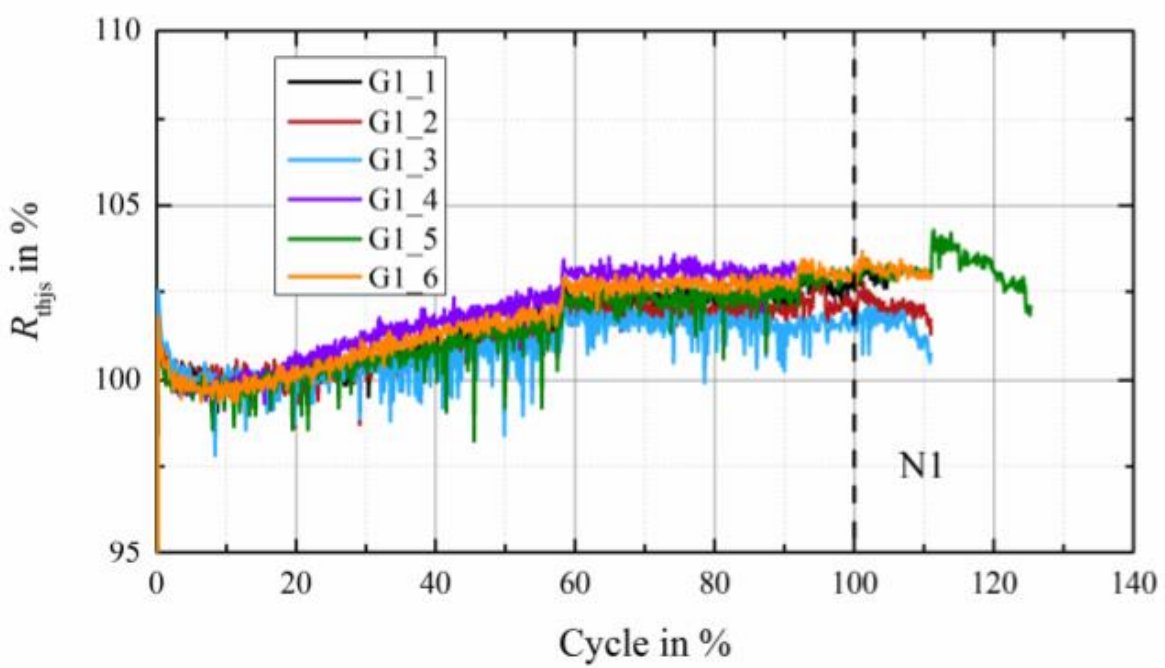
Testes de ciclagem térmica





Exemplo de resultados de testes reais – módulos de potência





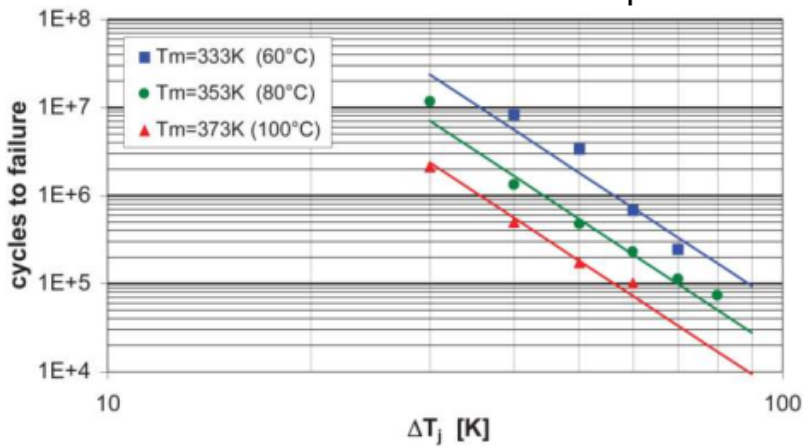
Fonte: G. Zeng. "Experimental Investigation of Linear Cumulative Damage Theory With Power Cycling Test". IEEE Transactions on Power Electronics. 2019.

Alguns desafios para obtenção de modelos de vida útil

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

Modelos de vida útil para semicondutores

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

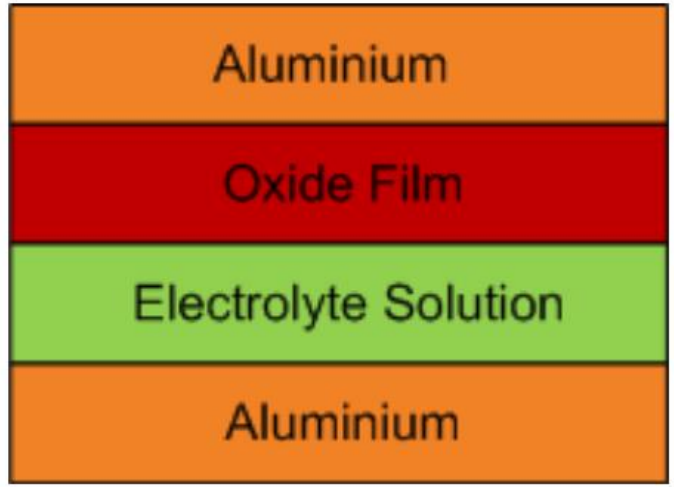


Fonte: F. Ianuzzo. "Reliability of active switching devices". Ph.D. Course. Aalborg University. 2018.

Capacitores: Mecanismos de falha típicos

Capacitores

Sandwich
(Source: http://www.jhdeli.com/Templates/Cold_Sandwich.html)



Aluminum Electrolytic Capacitor

Capacitance

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

Ripple current rating

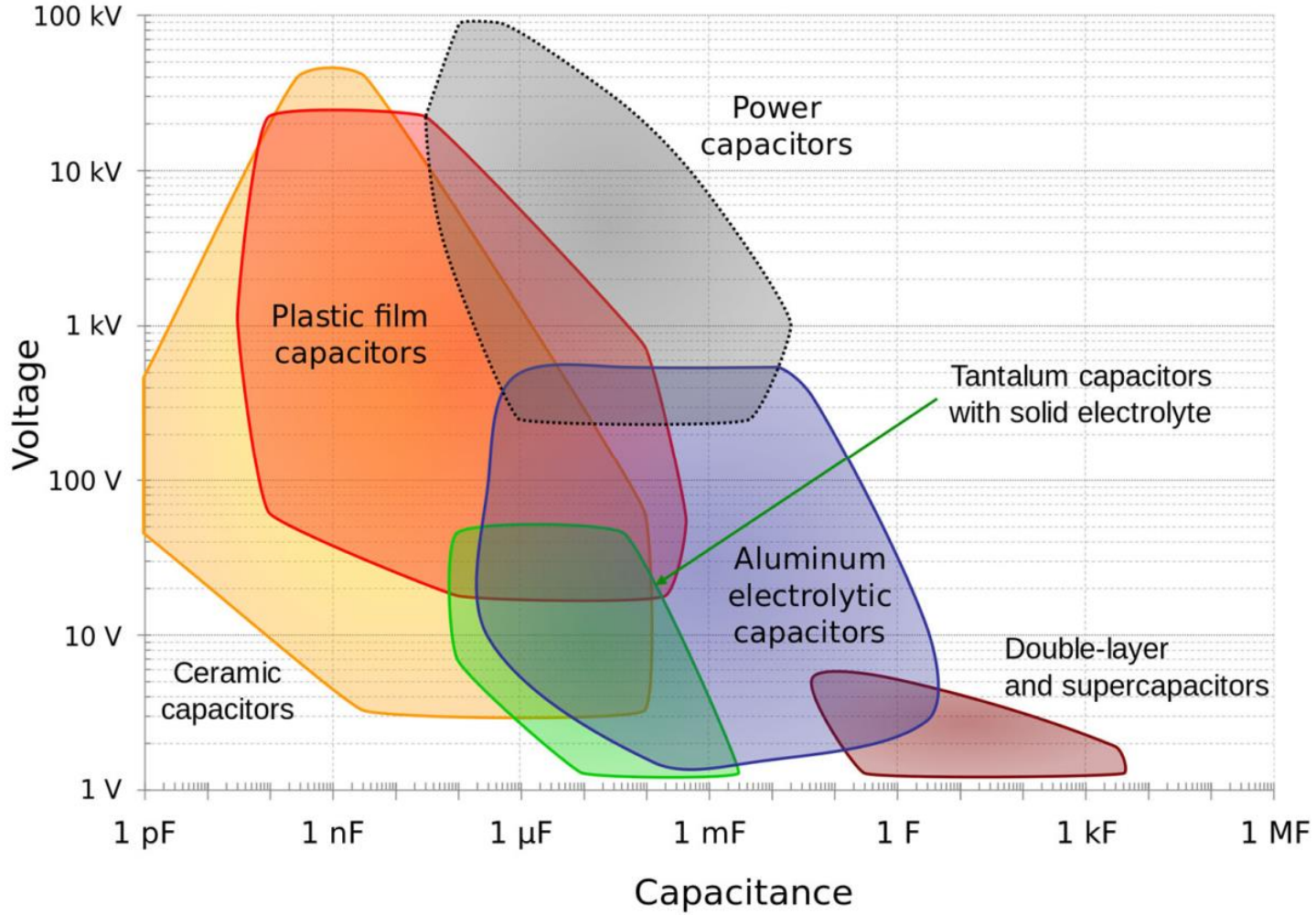
$$I_r = \sqrt{\frac{P_d}{R_s}} = \sqrt{\frac{hA\Delta T}{R_s}}$$

Volumetric efficiency

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

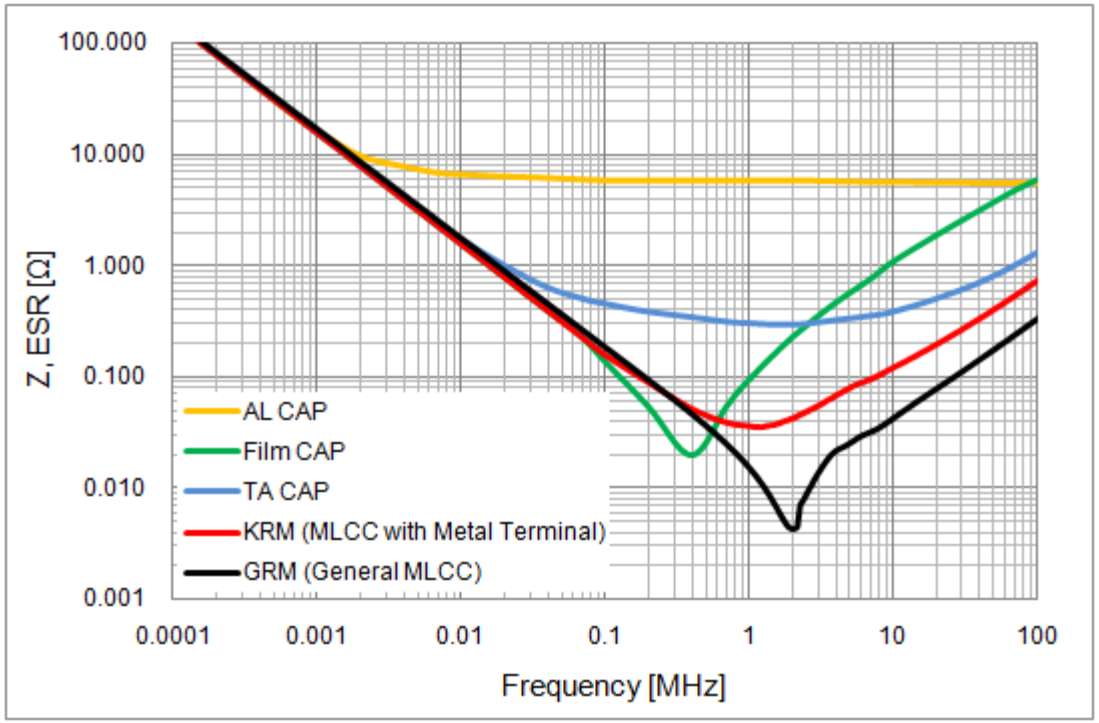
Fonte: H. Wang. "Capacitors in Power Electronics Applications". Ph.D. Course. Aalborg University. 2018.

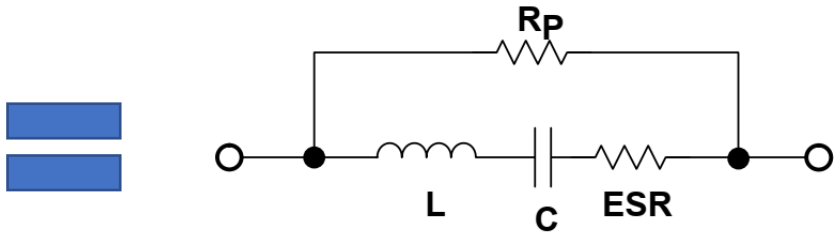
Capacitores

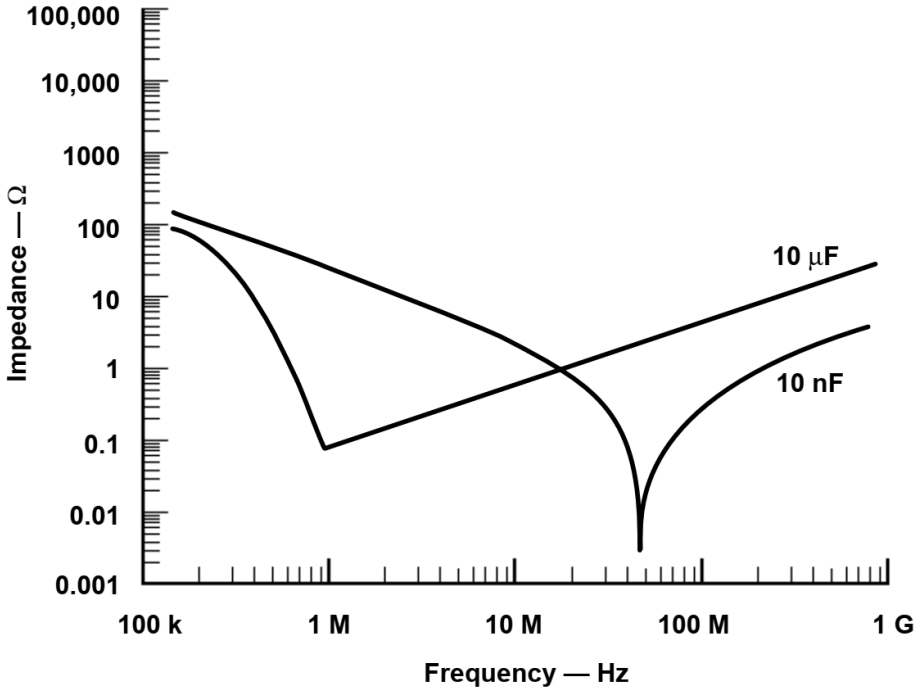


Fonte: H. Wang. "Capacitors in Power Electronics Applications". Ph.D. Course. Aalborg University. 2018.

Efeito da frequência na impedância do capacitor





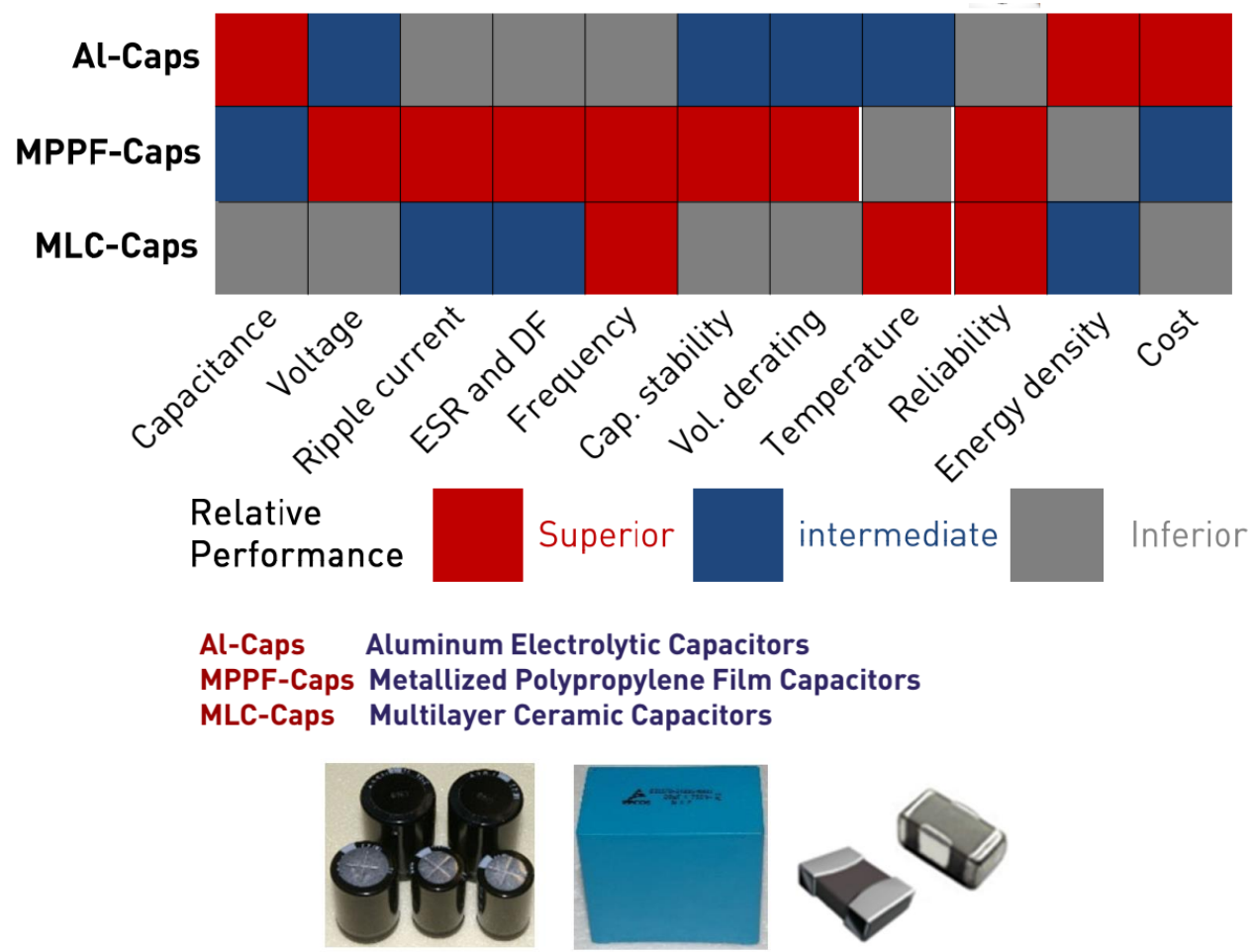


Fontes:

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

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

Comparação das tecnologias mais utilizadas em EP



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

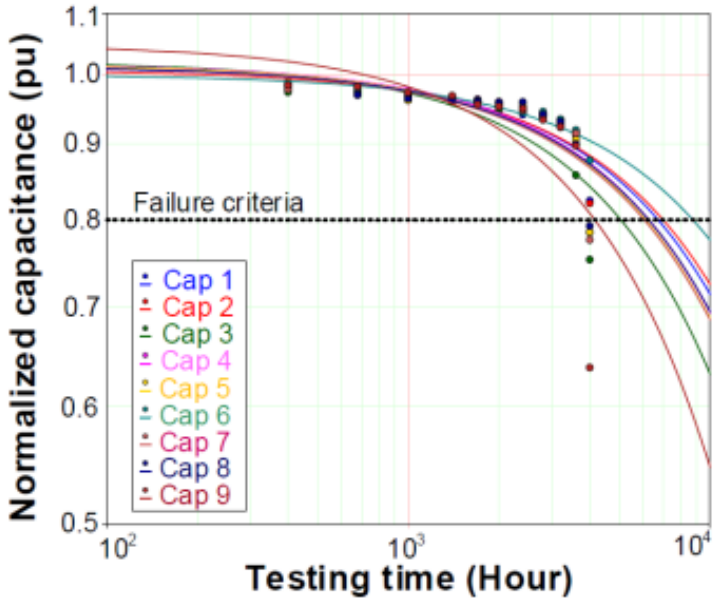
Mecanismos de falha de capacitores e fatores críticos

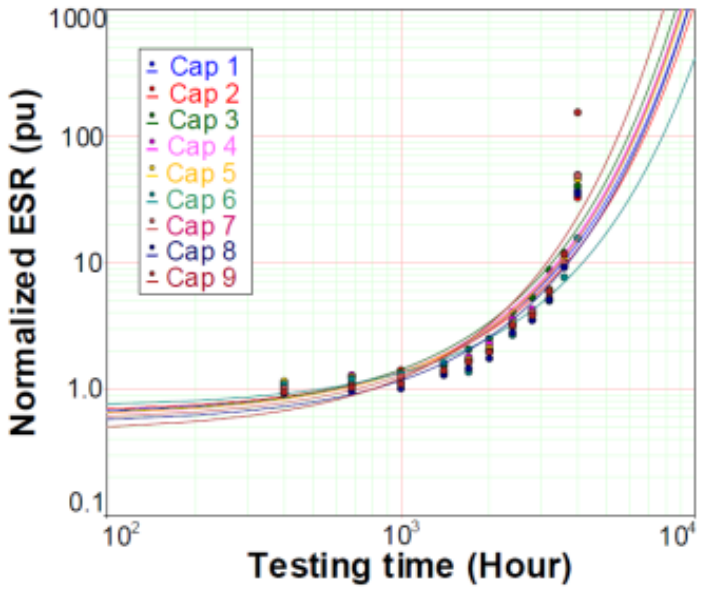
	Al-Caps	MPPF-Caps	MLCC-Caps
Dominant failure modes	wear out		
	open circuit	open circuit	short circuit
Most critical stressors	T_a, V_C, i_C	T_a, V_C, humidity	T_a, V_C, vibration/shock
Self-healing capability	moderate	good	no

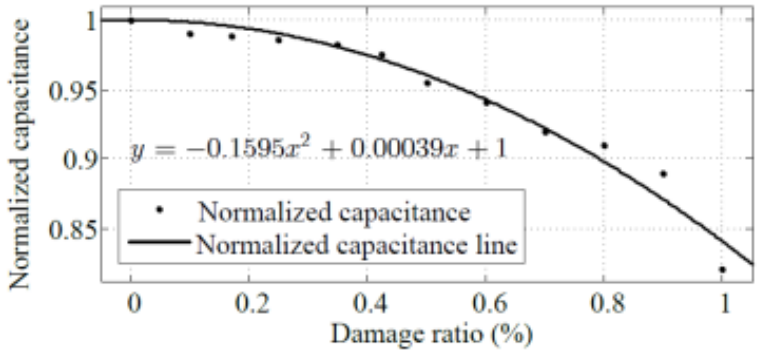
Al-Caps Aluminium Electrolytic Capacitors
MPPF-Caps Metallized Polypropylene Film Capacitors
MLC-Caps Multilayer Ceramic Capacitors

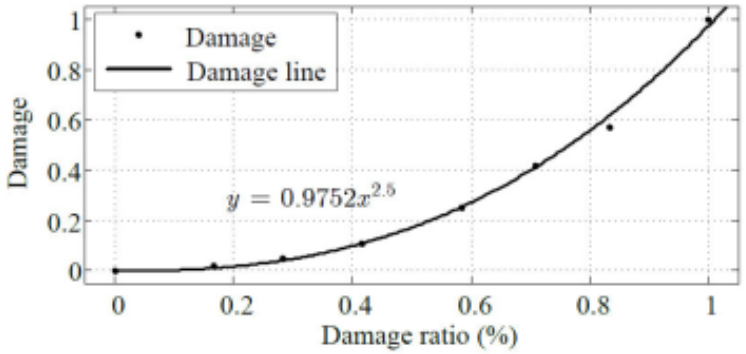
Fonte: H. Wang. "Capacitors in Power Electronics Applications". Ph.D. Course. Aalborg University. 2018.

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

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

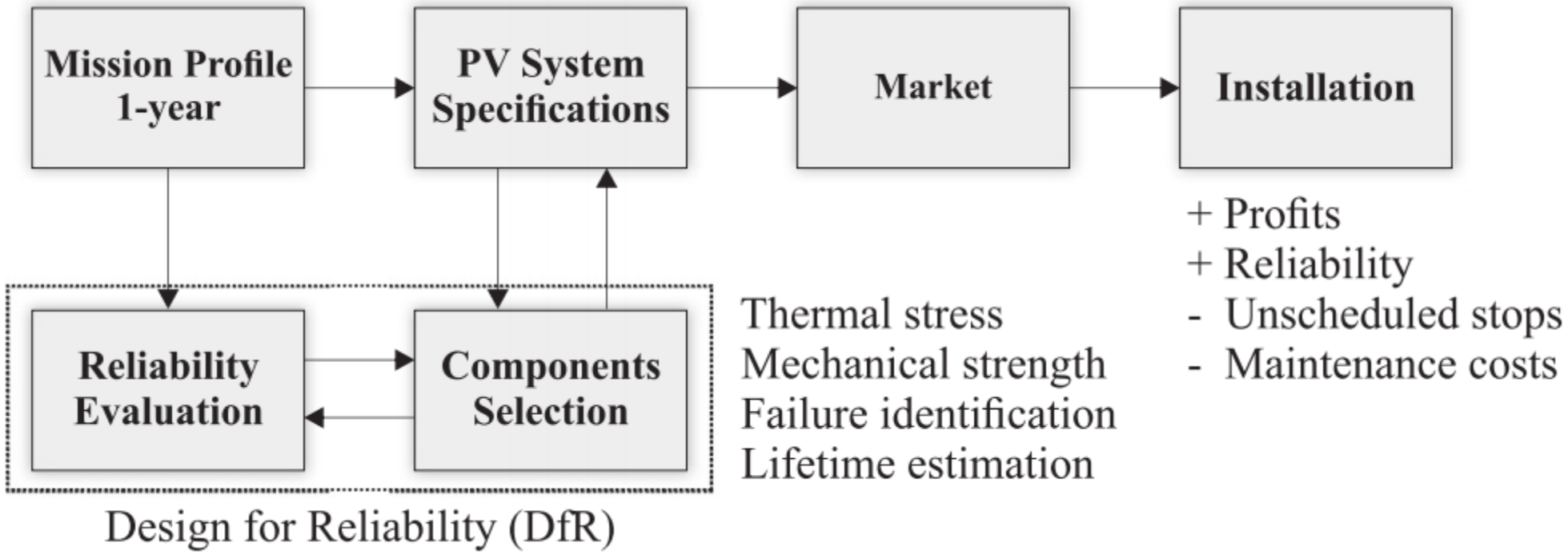
$$L = L_0 \times \left(\frac{V}{V_0}\right)^{-n} \times 2^{\frac{T_0 - T}{10}}$$

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

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

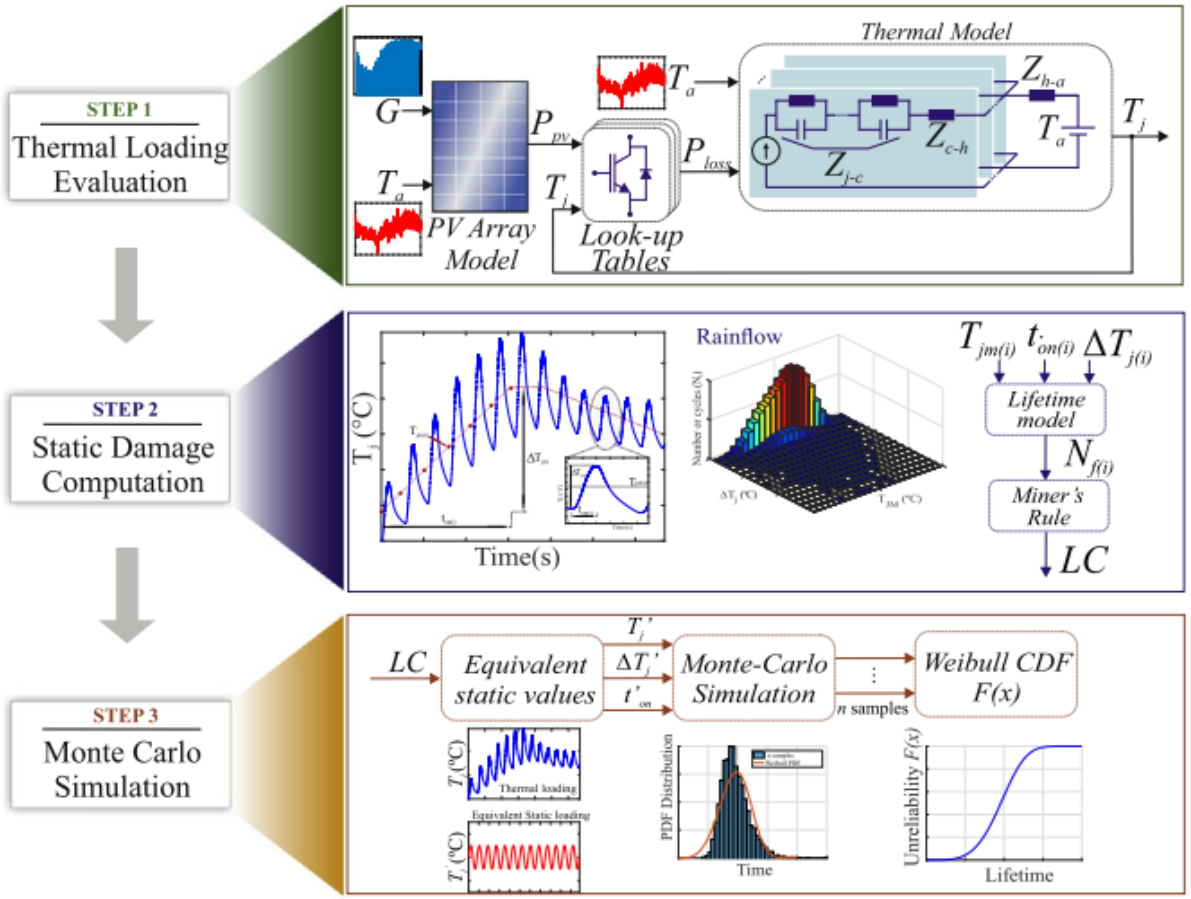
Projeto com foco em confiabilidade



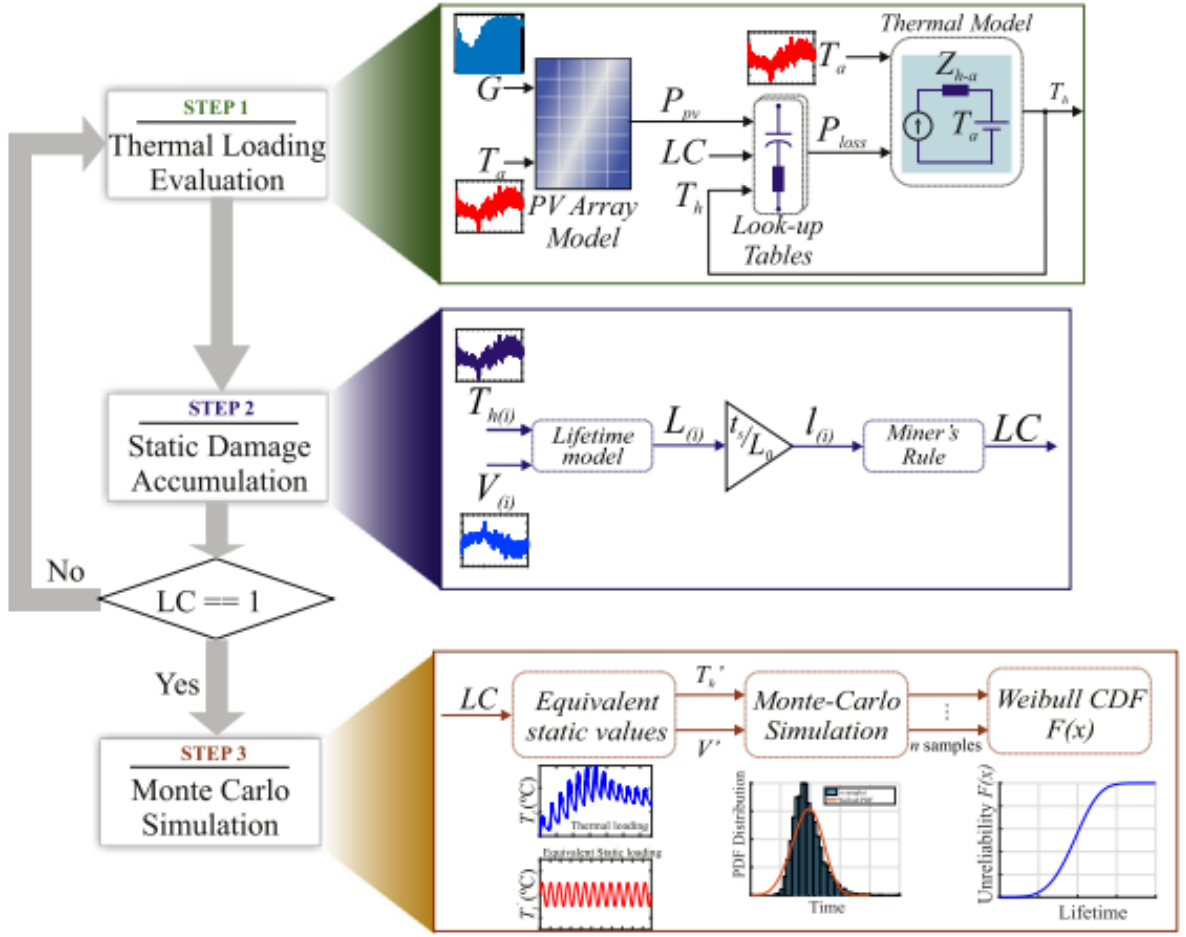
Fonte: E. M. S. Brito et. al. "Impact of meteorological variations on the lifetime of grid-connected PV inverters". Microelectronics Reliability. 2018.

Fluxograma detalhado – Avalição do Wear-out

❑ Semicondutores.

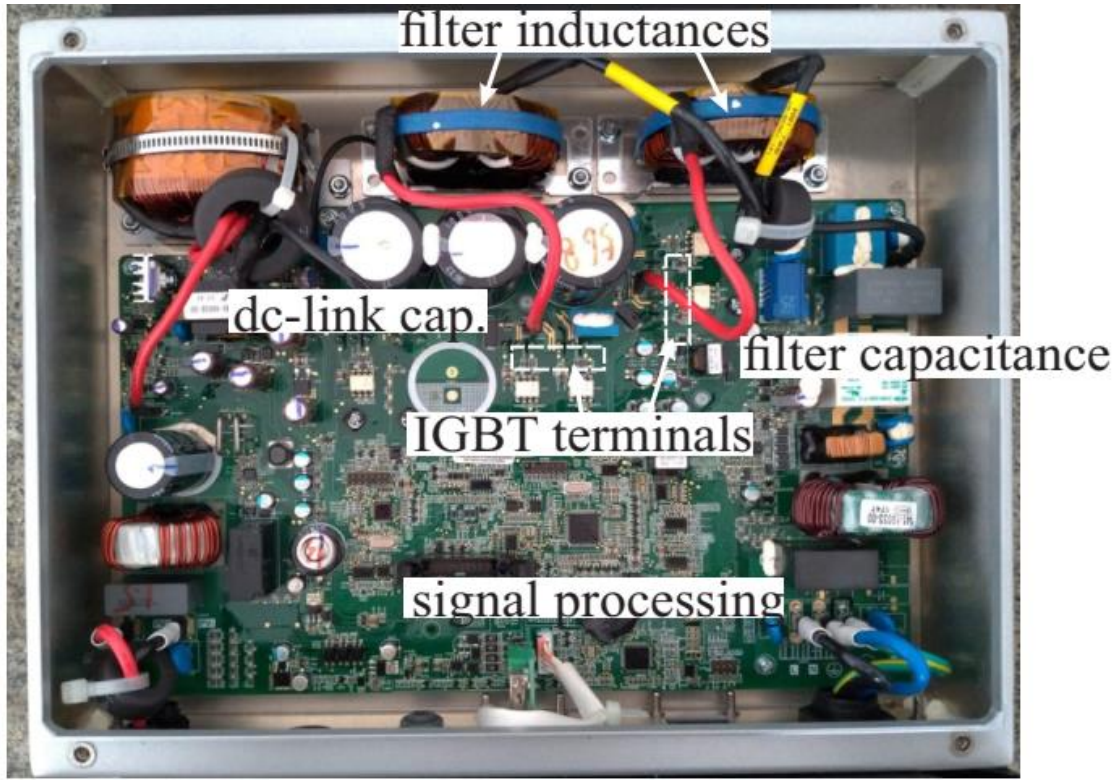


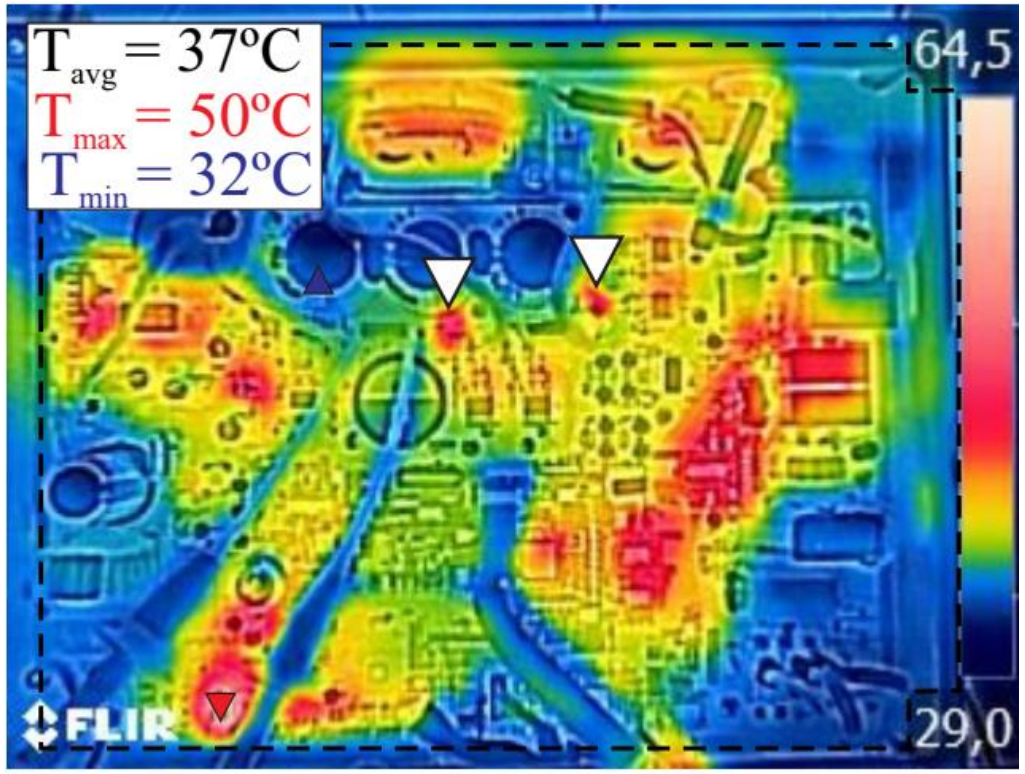
❑ Capacitores.



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

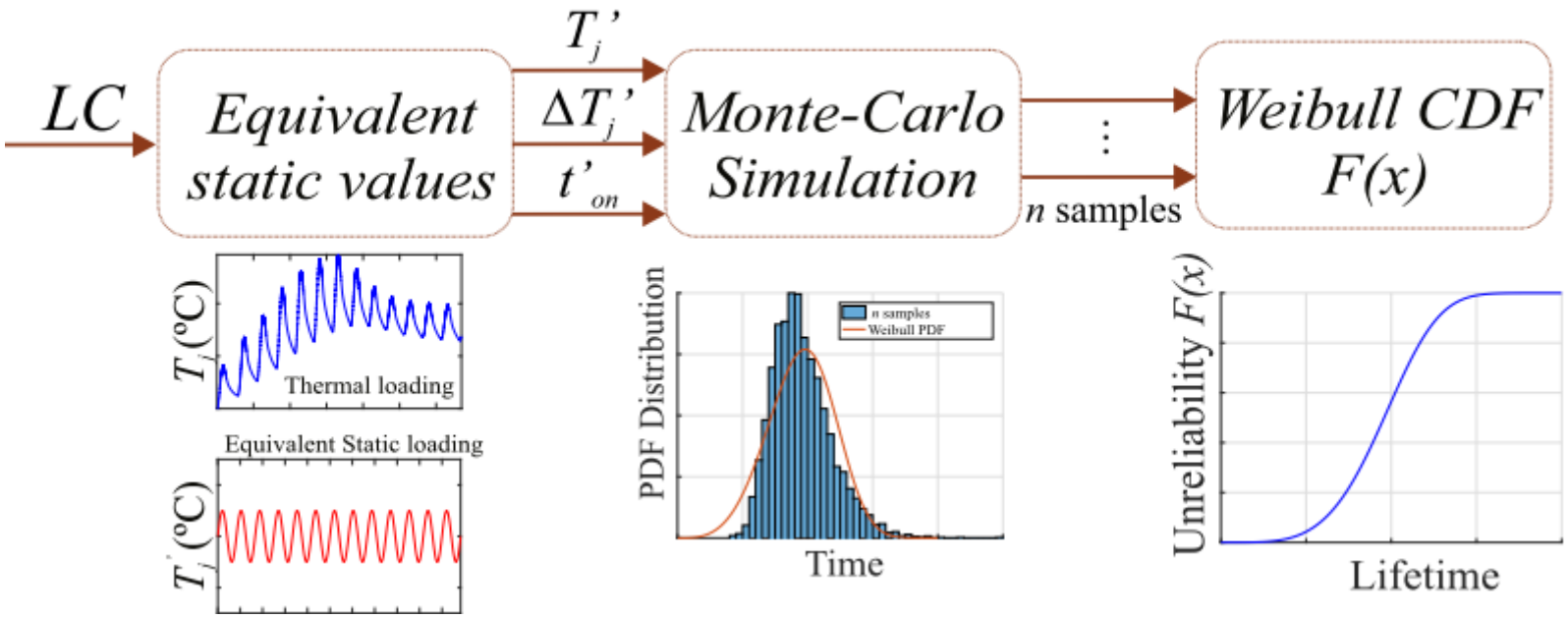
Modelo térmico – acoplamento entre os componentes





- Problema complexo!

Simulação de Monte-Carlo



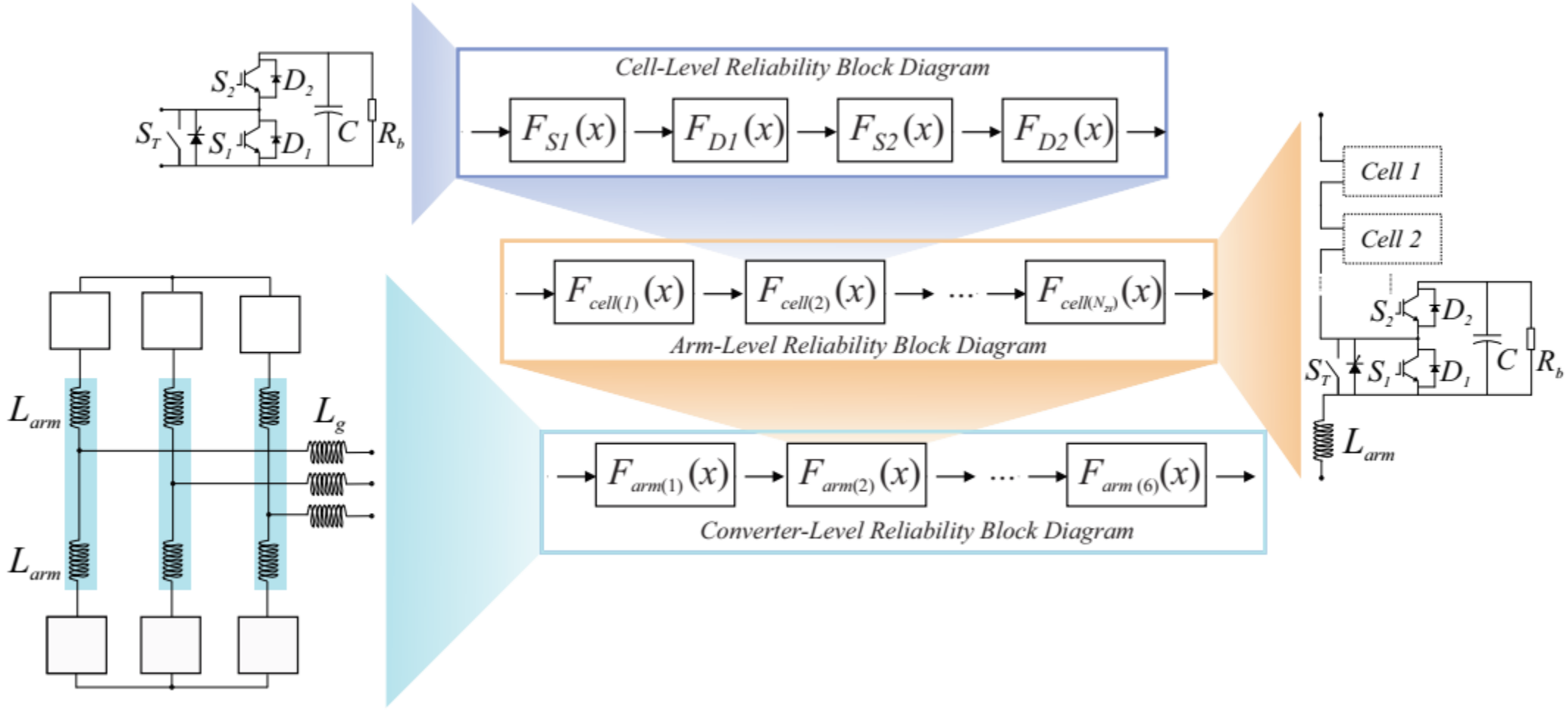
$$f(x) = \frac{\beta}{\eta^{\beta}} x^{\beta-1} \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right]$$

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

- 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

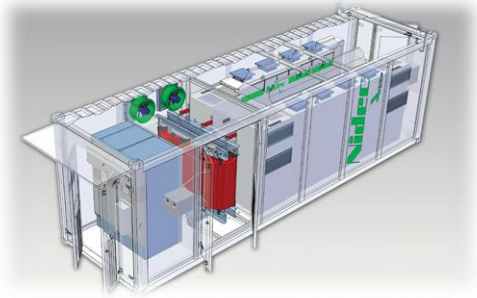
Confiabilidade a nível de sistema



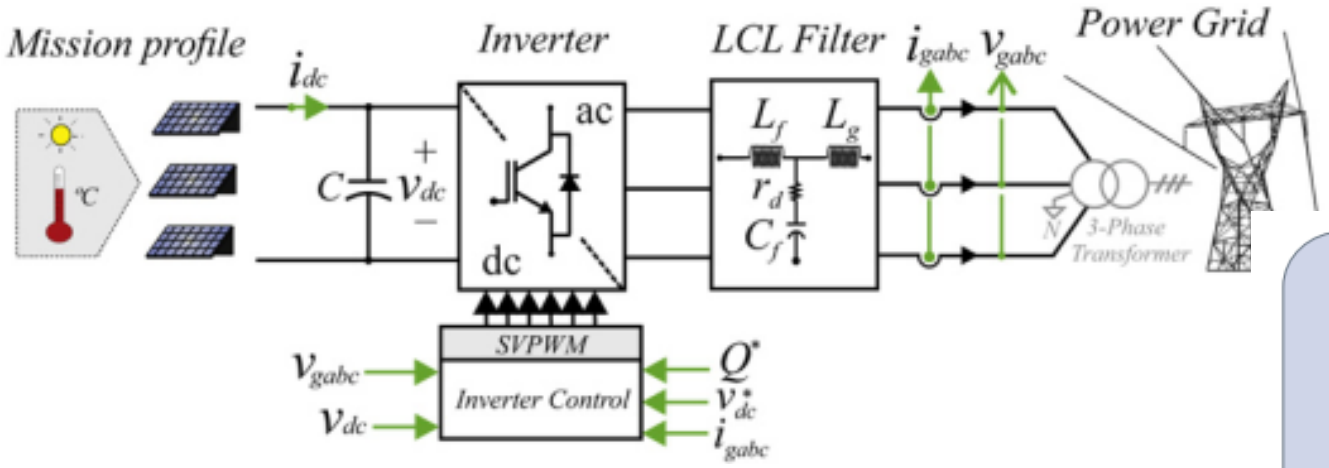
Fonte: A. F. Cupertino "Modeling, Design and Fault-Tolerant Strategies for Modular Multilevel Cascaded Converter-based STATCOMs". PhD Thesis. UFMG. 2019.

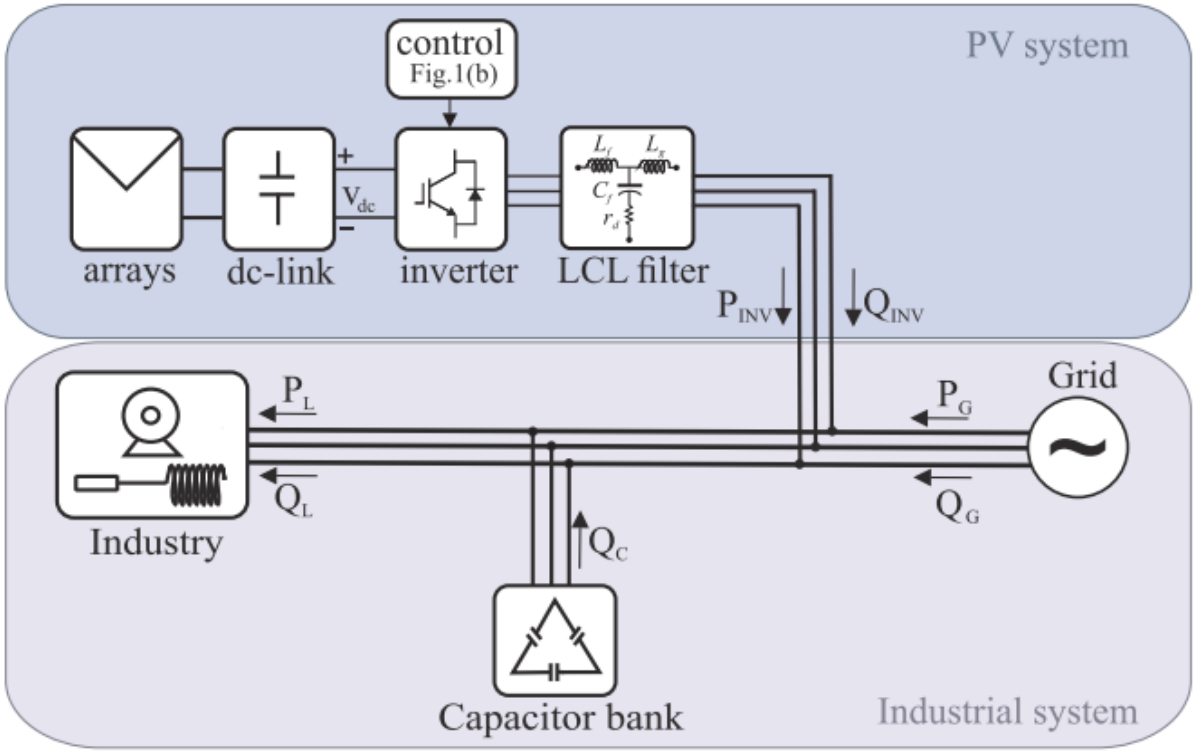
Exemplo – Inversor multifuncional de 25 kVA

Prof. Allan Fagner Cupertino
afcupertino@ieee.org



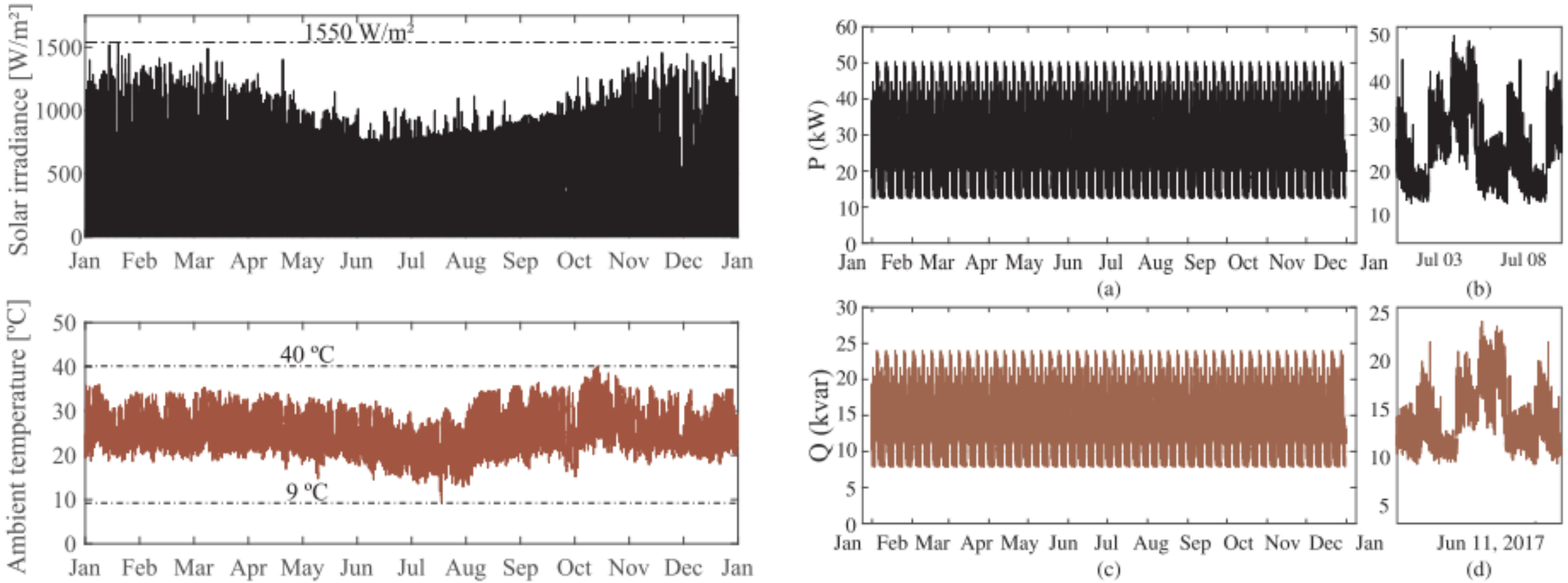
Exemplo 2 – Inversor multifuncional de 25 kVA





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



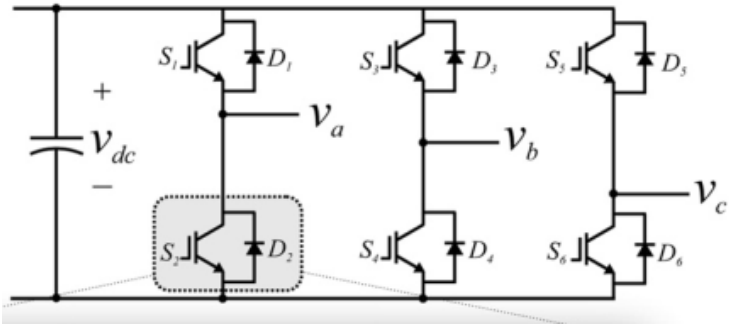
Fonte Lucas S. Gusman. "Design for reliability of multifunctional PV inverters used in industrial power factor regulation". Electrical Power and Energy Systems. 2020.

Projetos considerados

- Projeto 1:

5 x 2 cap. 680 μF/ 400 V

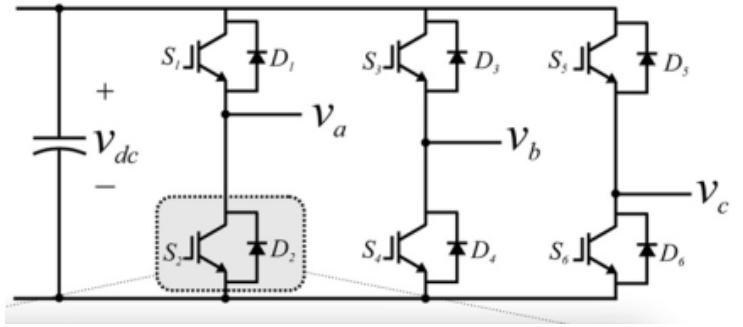
75 A/1200 V



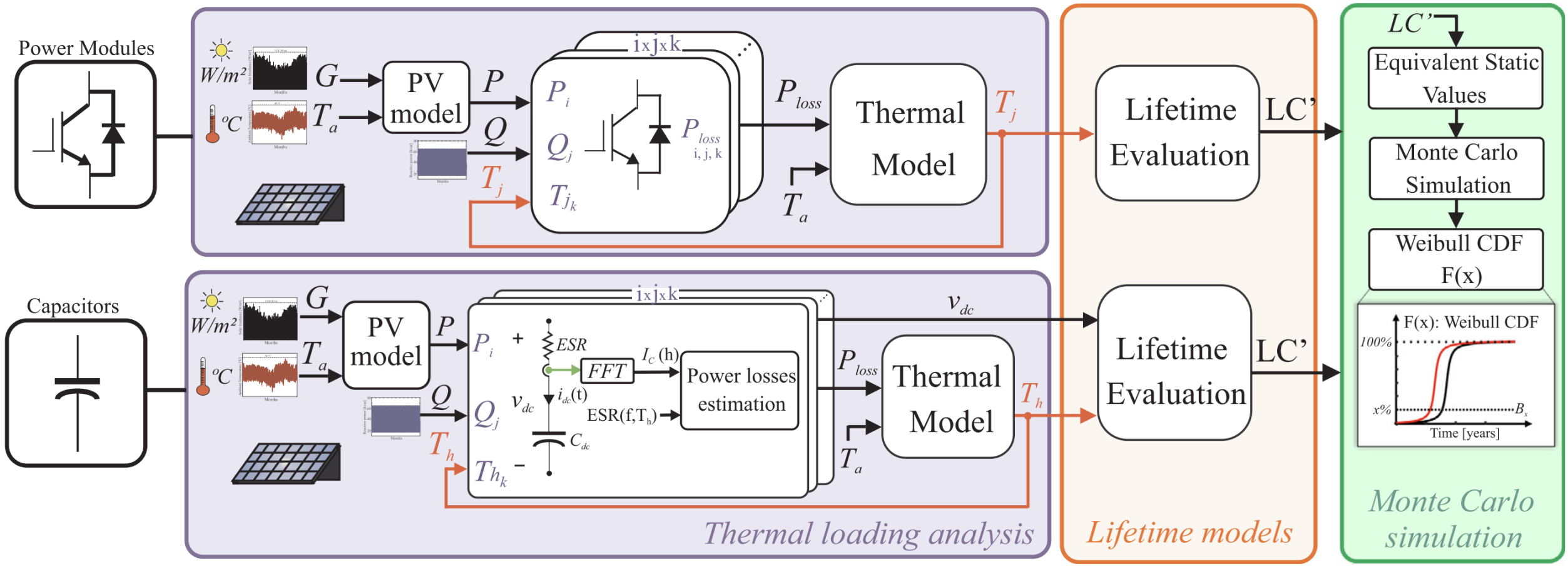
- Projeto 2

6 x 2 cap. 680 μF/ 400 V

100 A/1200 V



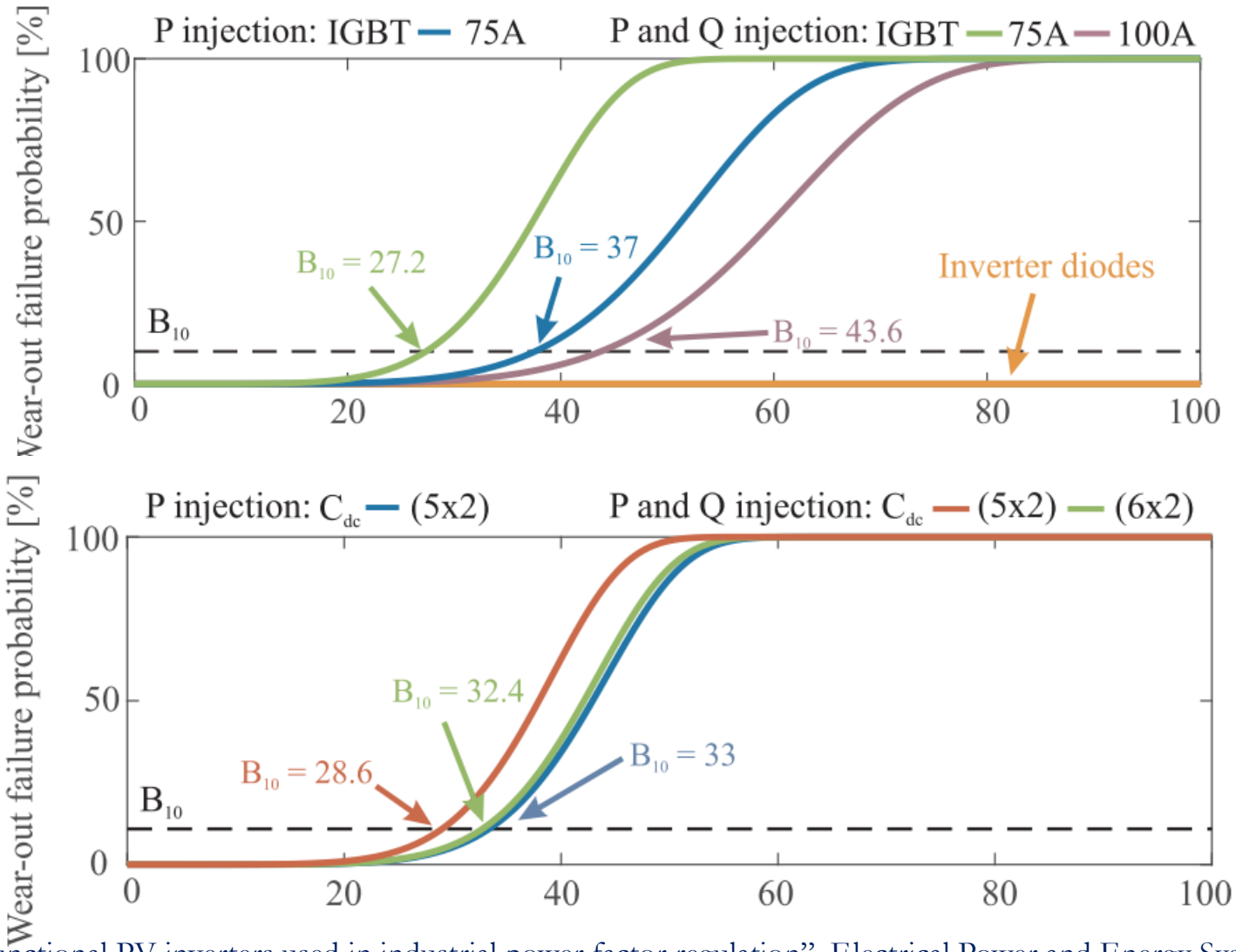
Metodologia



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

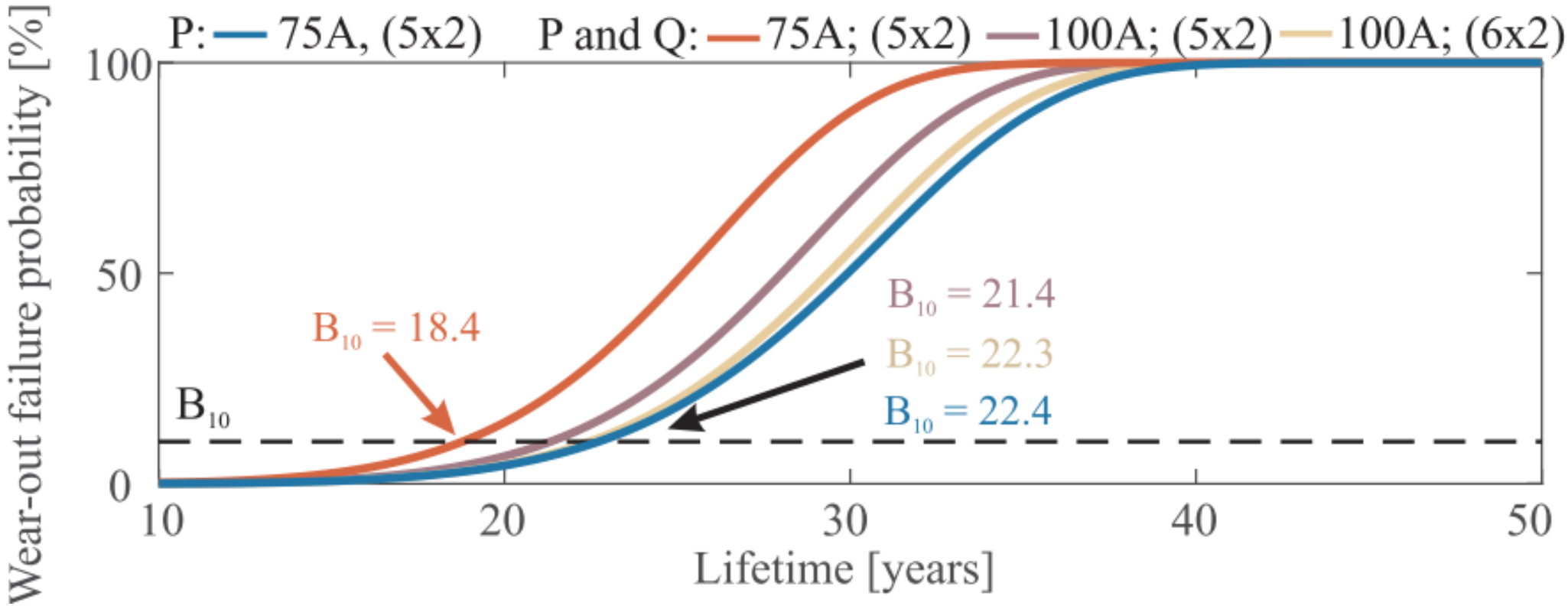
Confiabilidade a nível de componente

- 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.

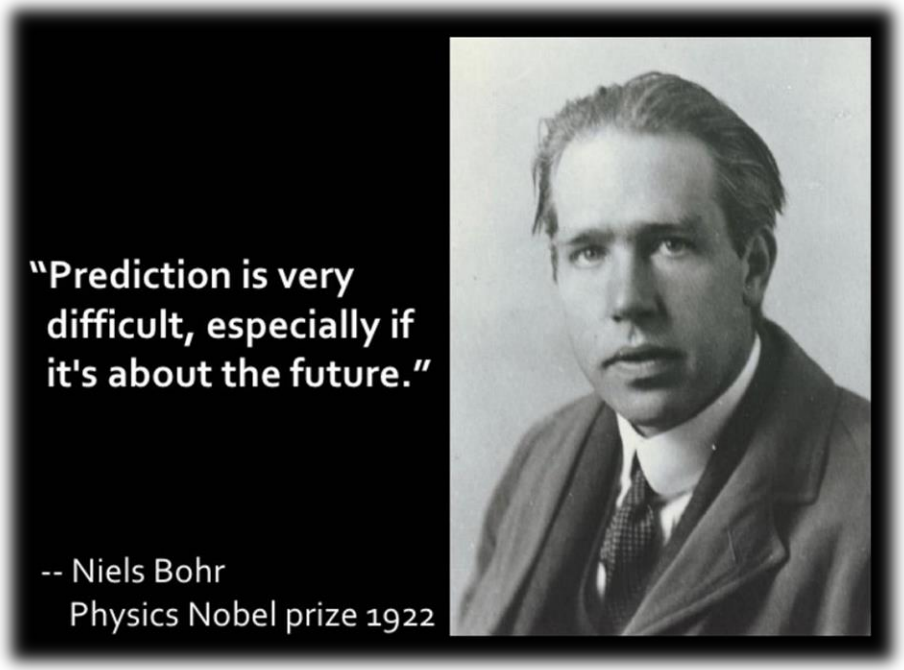
Perfil de irradiância e temperatura



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

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

www.gesep.ufv.br

@GESEP

@gesep_vicosa

Gesep

Pesquise por:
"GESEP UFV"

EStimate - Sistemas Fotovoltaicos

Google Play

Pesquise por:
"EStimate"