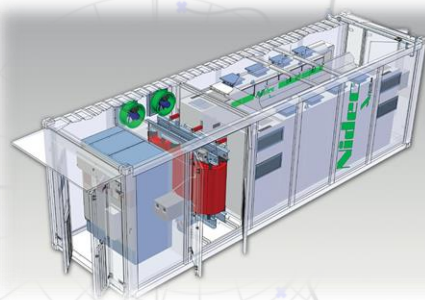




Estágio de conversão de potência (PCS): Classificação e estado da arte

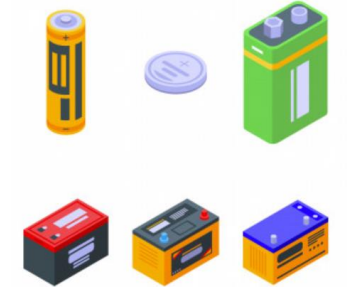
Prof. Allan Fagner Cupertino
afcupertino@ieee.org



Tópicos a serem abordados

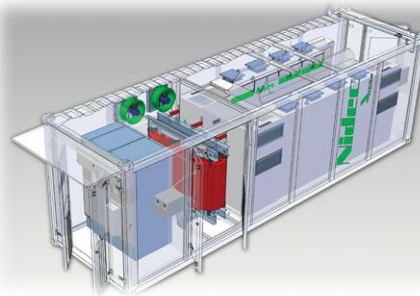
- ❑ Classificação;
- ❑ Topologias tradicionais de estágios de conversão;
- ❑ Topologias em cascata;
- ❑ Exemplos de sistemas comerciais;
- ❑ Desafios e perguntas importantes.



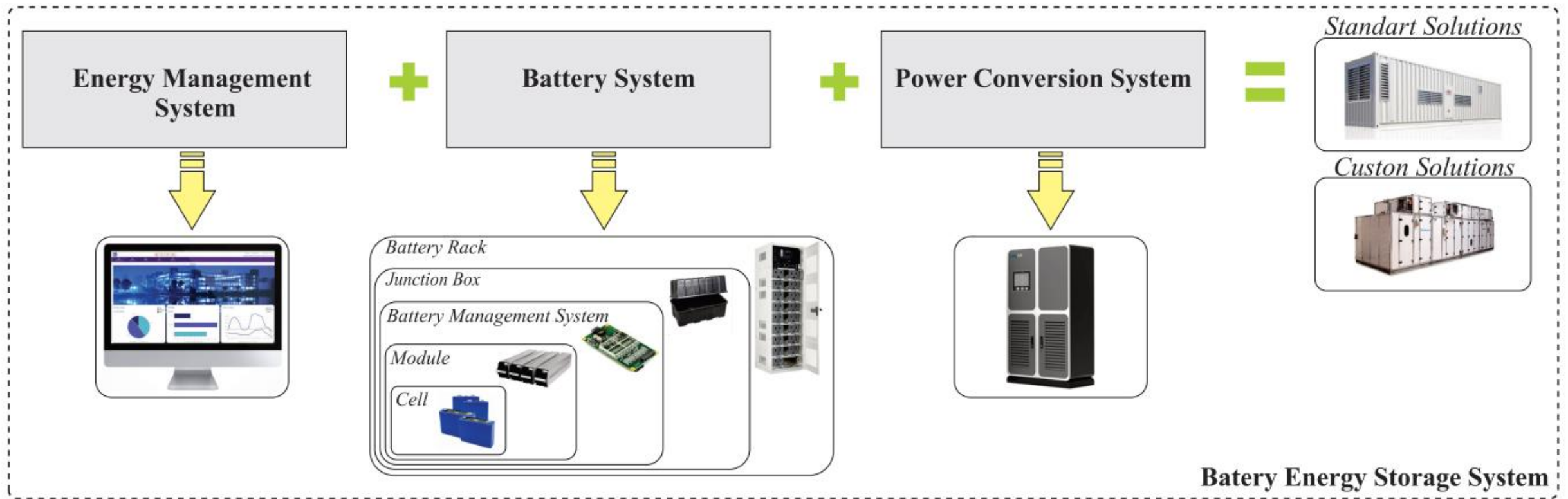


Classificação dos estágios de conversão

Prof. Allan Fagner Cupertino
afcupertino@ieee.org



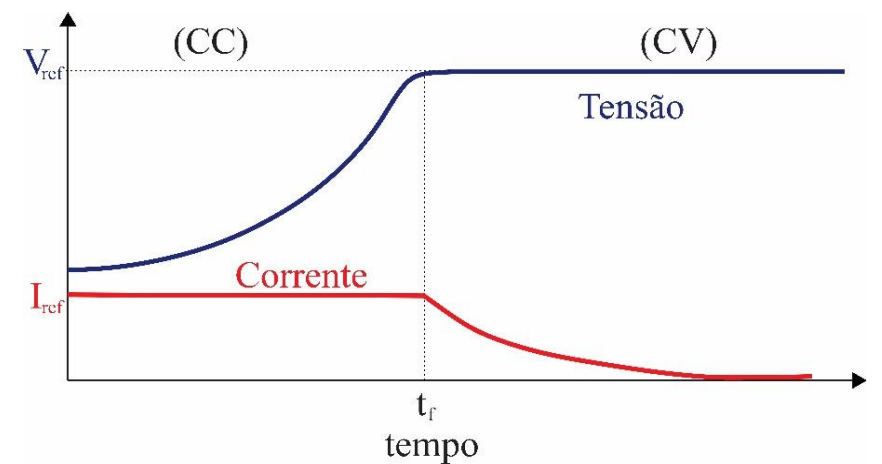
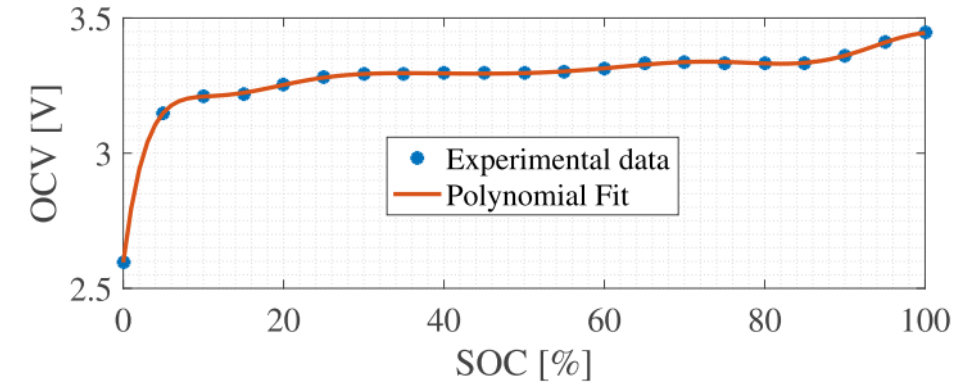
Estrutura de um sistema de armazenamento por baterias



Fonte: Jonathan H. D. G. Pinto, “Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter”, 2020.

Qual a função do PCS?

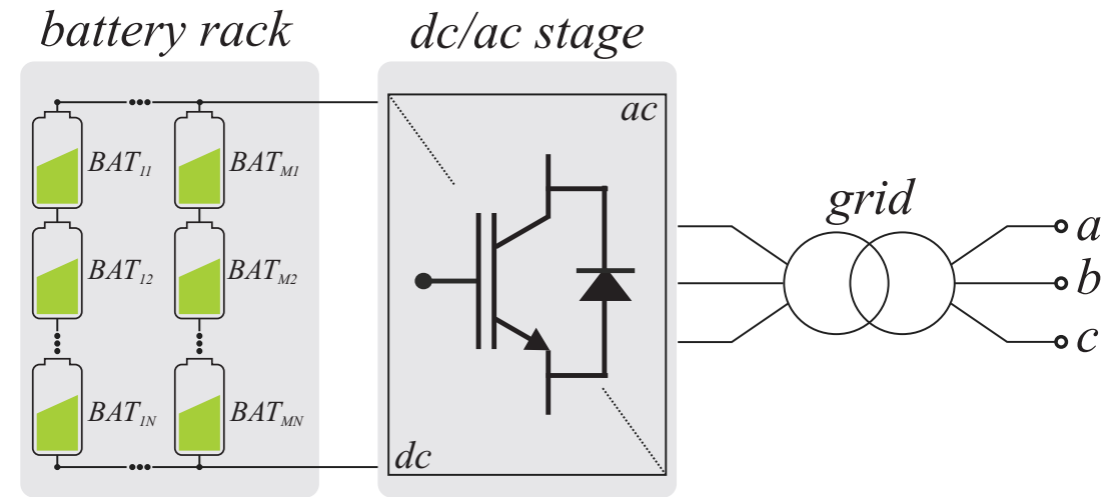
- ❑ Conversão cc/ca;
- ❑ Processo de carga e descarga da bateria;
- ❑ Operação em corrente constante, tensão constante e flutuação;
- ❑ Qual topologia empregar?
- ❑ Como controlar o PCS?



Classificação (GESEP 2020)

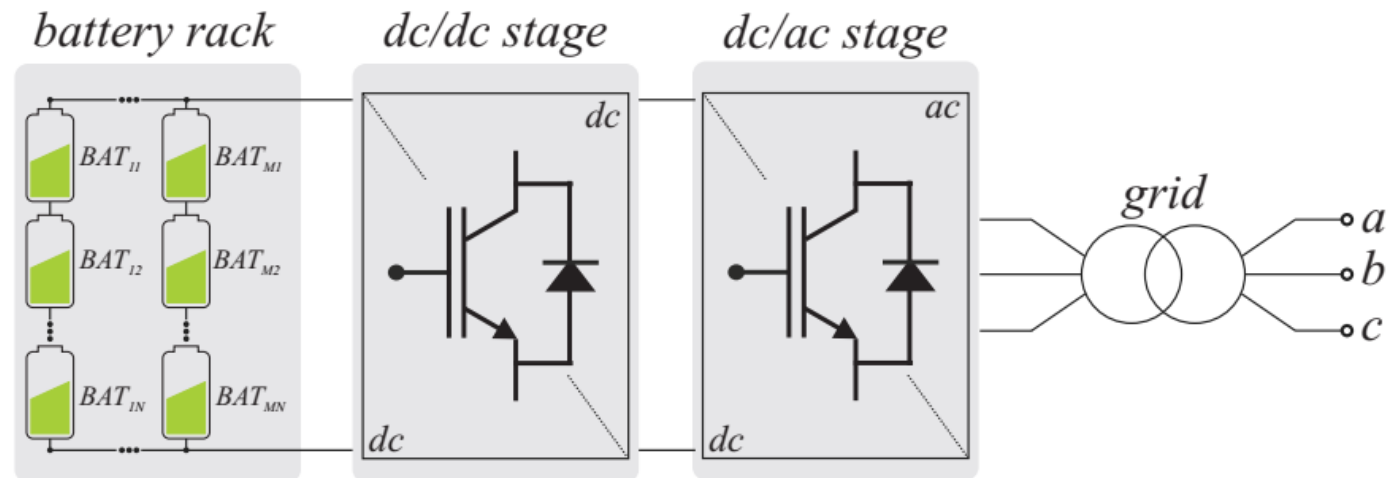
❑ Sistema de único estágio

- Maior simplicidade;
- Menor custo do conversor;
- “Maior eficiência”
- Projeto menos otimizado;
- Ondulação de corrente nas baterias.



❑ Sistema de duplo estágio

- Maior complexidade;
- Maior custo do conversor;
- Projeto mais otimizado;
- “Maiores perdas”;
- Redução da ondulação de corrente.

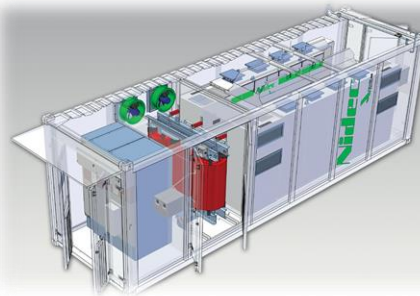


Fonte: Jonathan H. D. G. Pinto, “Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter”, 2020.

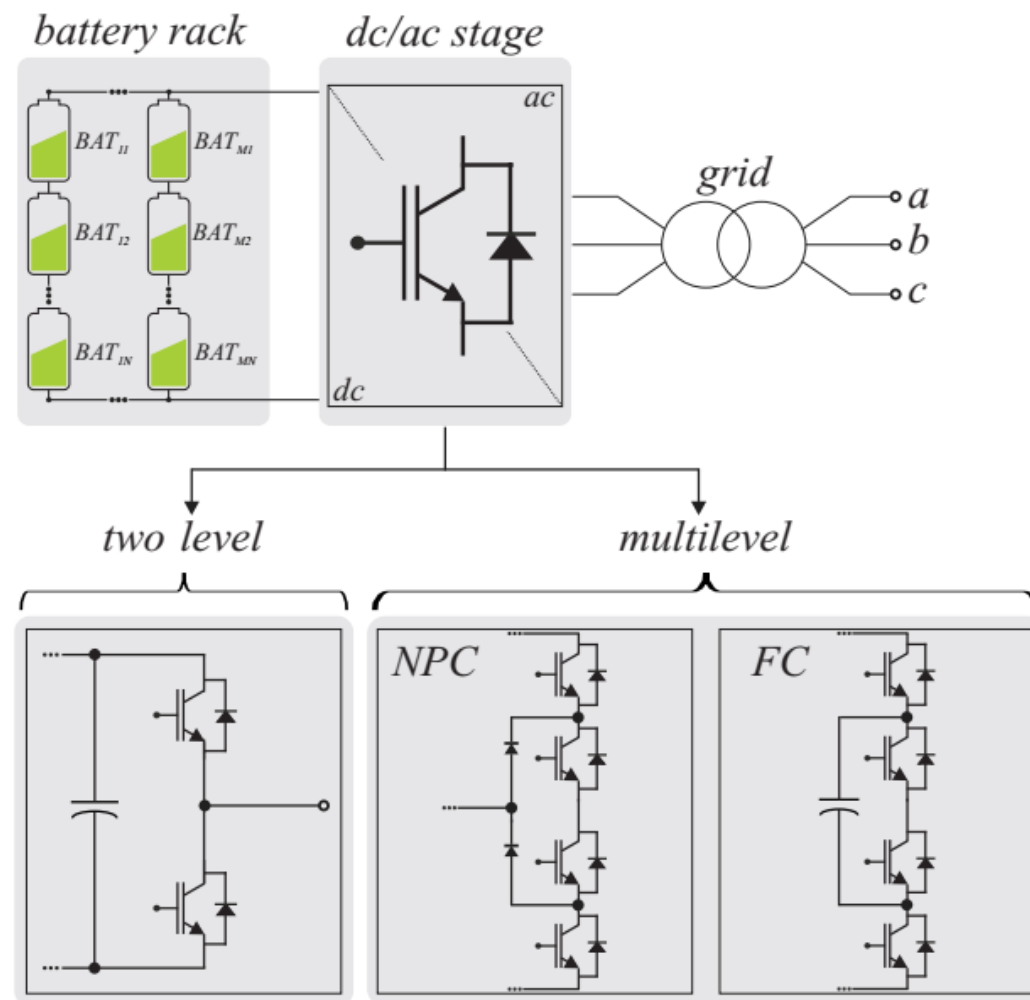


Sistemas de único estágio de conversão

Prof. Allan Fagner Cupertino
afcupertino@ieee.org



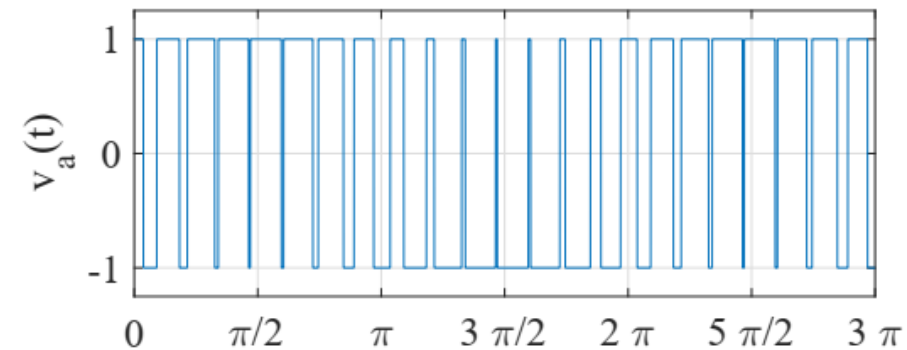
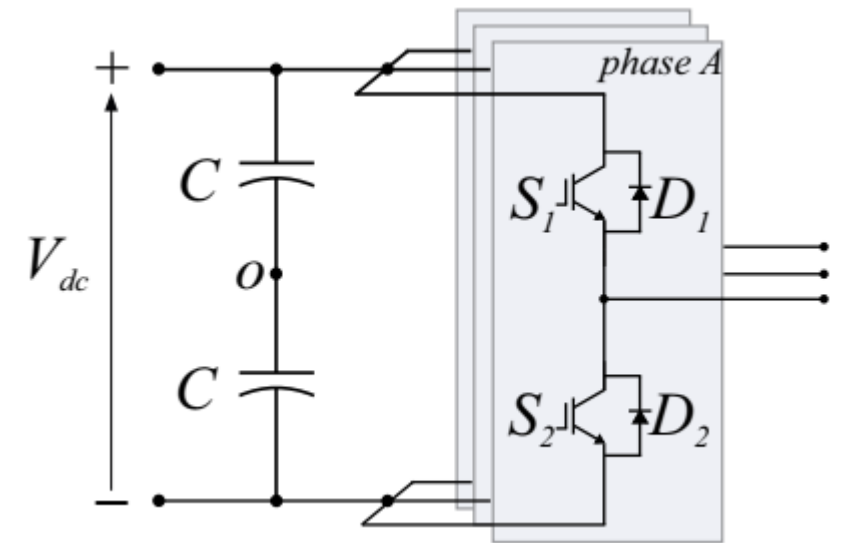
Exemplos – sistemas de único estágio



Fonte: Jonathan H. D. G. Pinto, “Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter”, 2020.

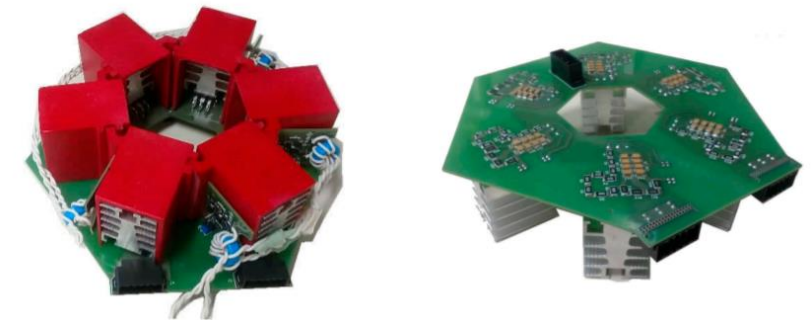
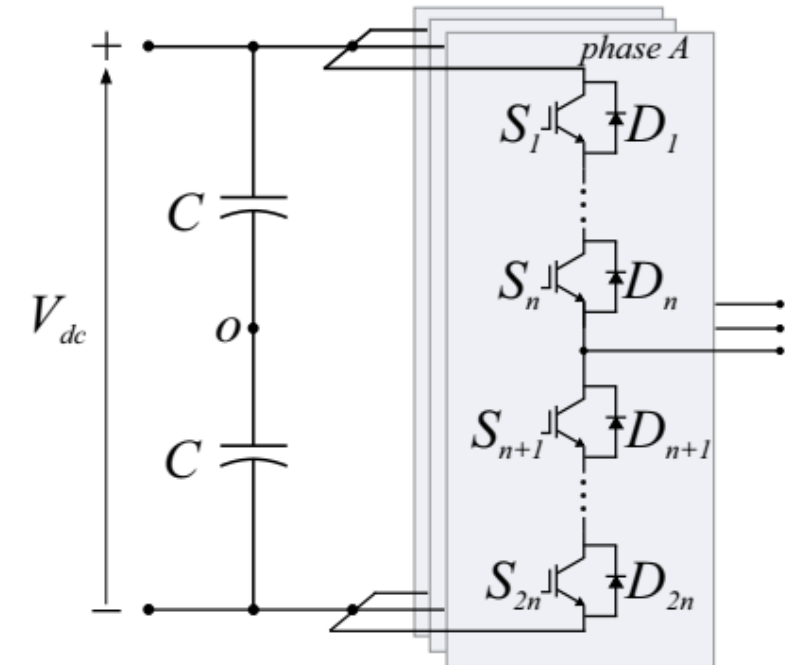
Inversor em ponte completa (dois níveis)

- ❑ Conceito introduzido nos anos 60;
- ❑ Preferível em aplicações de baixa tensão;
- ❑ Tensão de saída com alto dV/dt e tensão de modo comum;
- ❑ Distorção harmônica considerável;
- ❑ Tensão de saída limitada pela capacidade dos interruptores;
- ❑ Pode ser associado a um transformador. ⚠



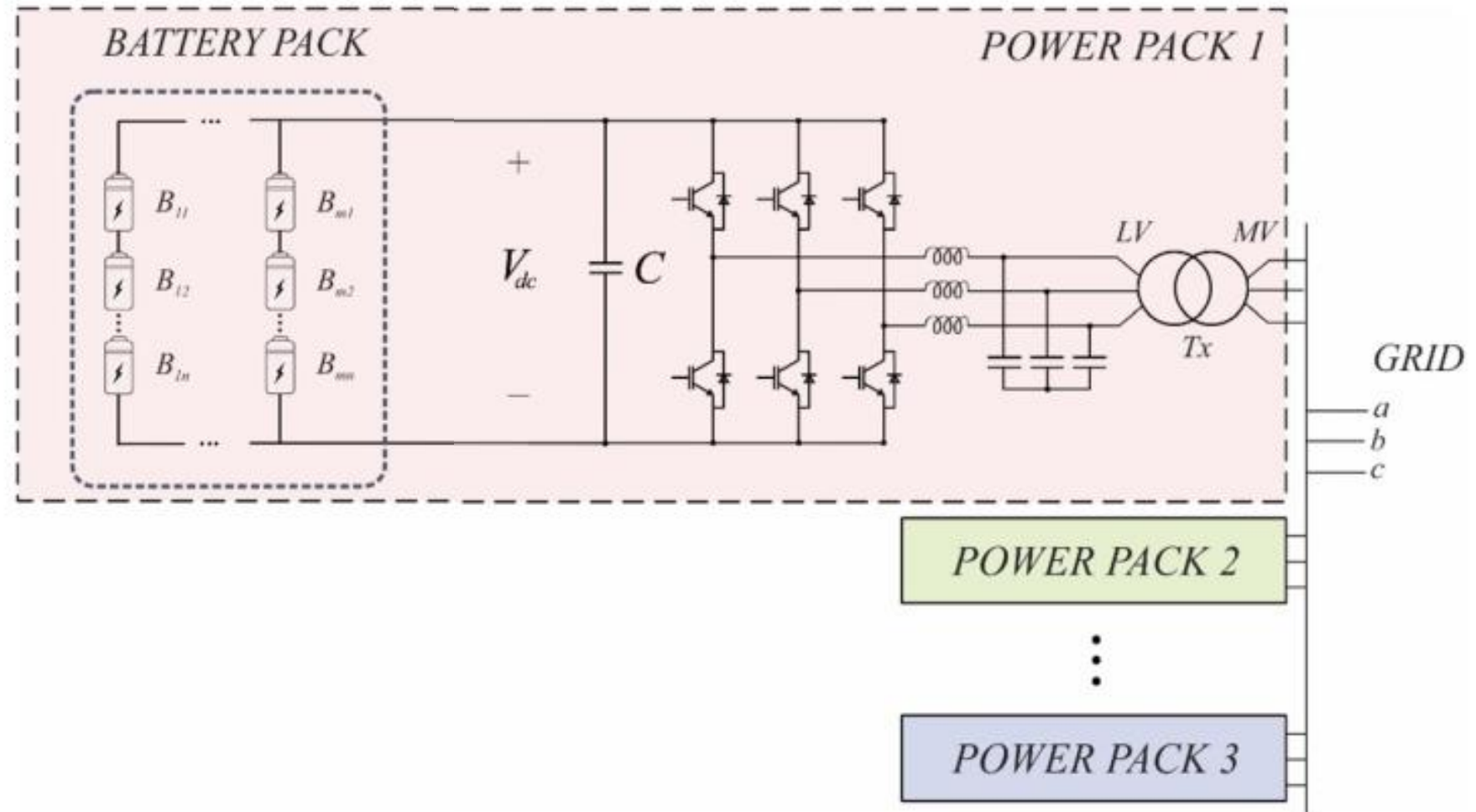
Inversor em ponte completa (dois níveis) com interruptores em série

- ❑ Extensão da capacidade de síntese de tensão;
- ❑ Complexidade da conexão em série de interruptores;
- ❑ Operação tolerante a falha;
- ❑ Solução com custo final “considerável”.



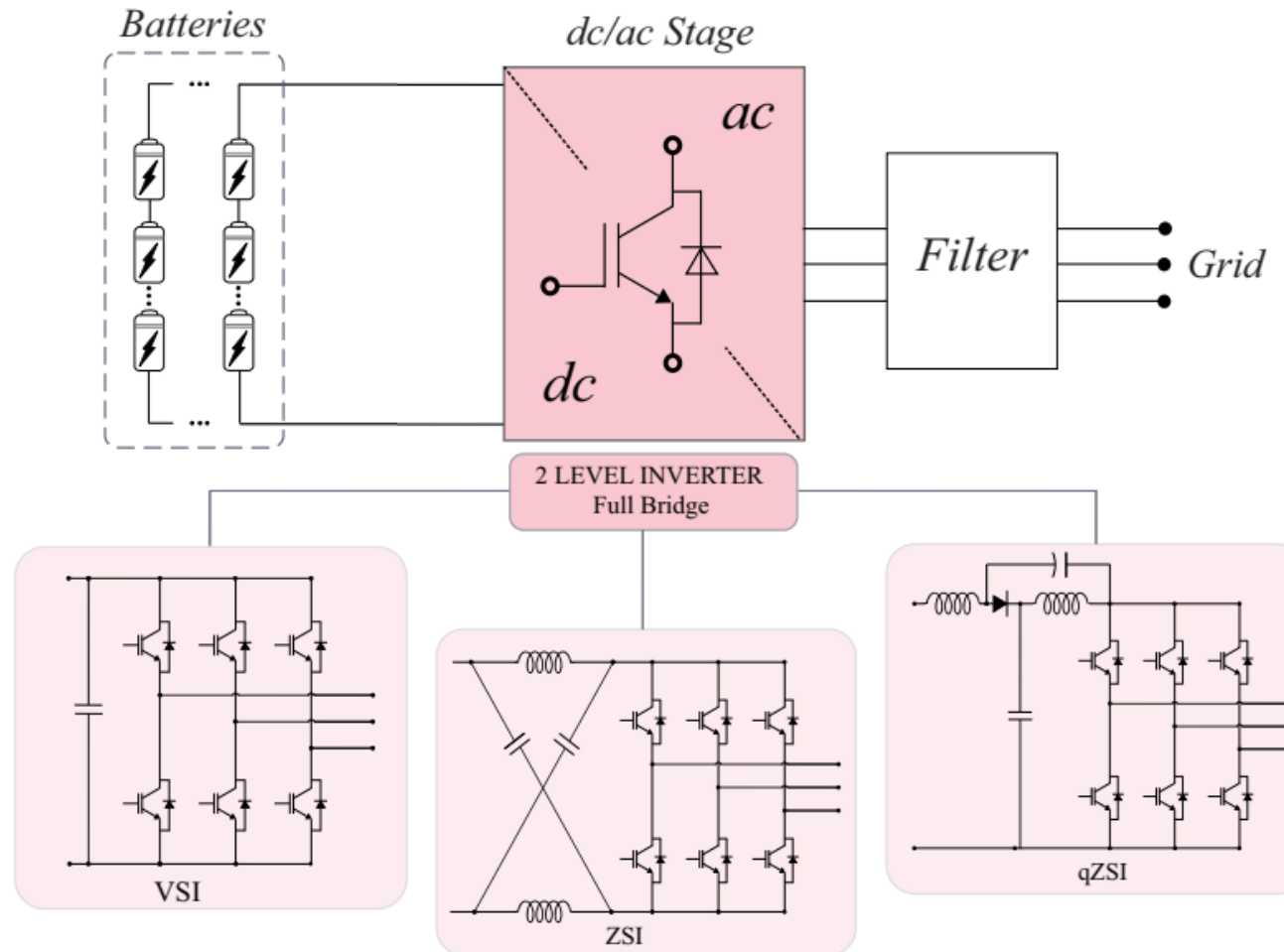
Fonte: G. O. Fortes, M. A. S. Mendes and P. C. Cortizo. “Integrated Solution for Driving Series-Connected IGBTs and Its Natural Intrinsic Balancing”. 2019.

Sistemas de alta potência com conversor de 2 níveis



Fonte: L. S. Xavier, et.al. "Power converters for battery energy storage systems connected to medium voltage systems: a comprehensive review," BMC Energy. 2019.

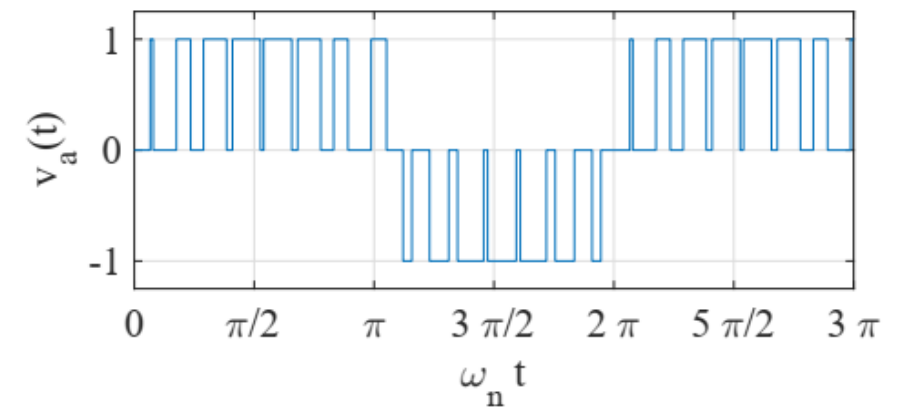
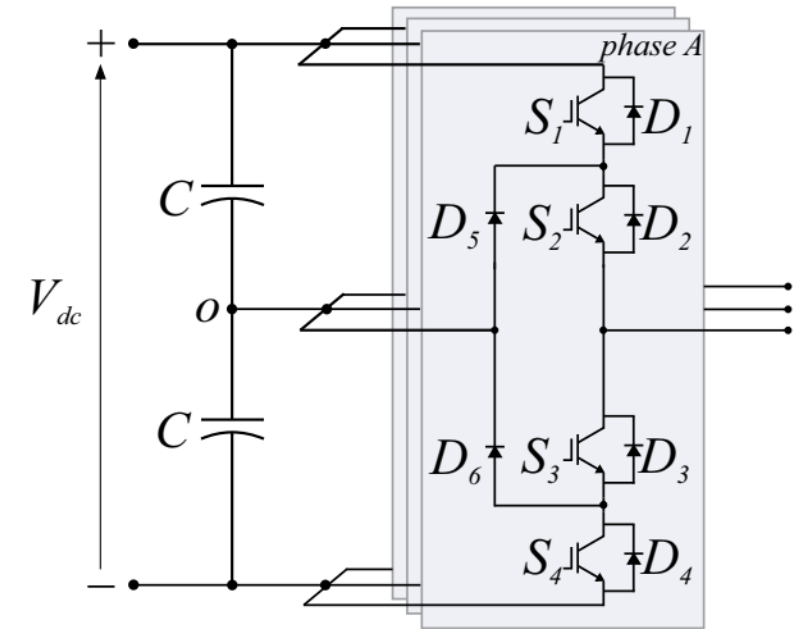
Outras abordagens



Fonte: L. S. Xavier, et.al. "Power converters for battery energy storage systems connected to medium voltage systems: a comprehensive review," BMC Energy. 2019.

Inversor com grampeamento de neutro (NPC)

- ❑ Introduzido na década de 80;
- ❑ Solução com elevado sucesso comercial (3 níveis);
- ❑ Complexidade aumenta com o número de níveis;
- ❑ Balanceamento e **grampeamento**;
- ❑ Projeto mecânico complexo para número elevado;
- ❑ **Desbalanço térmico** entre os IGBT's. ⚠



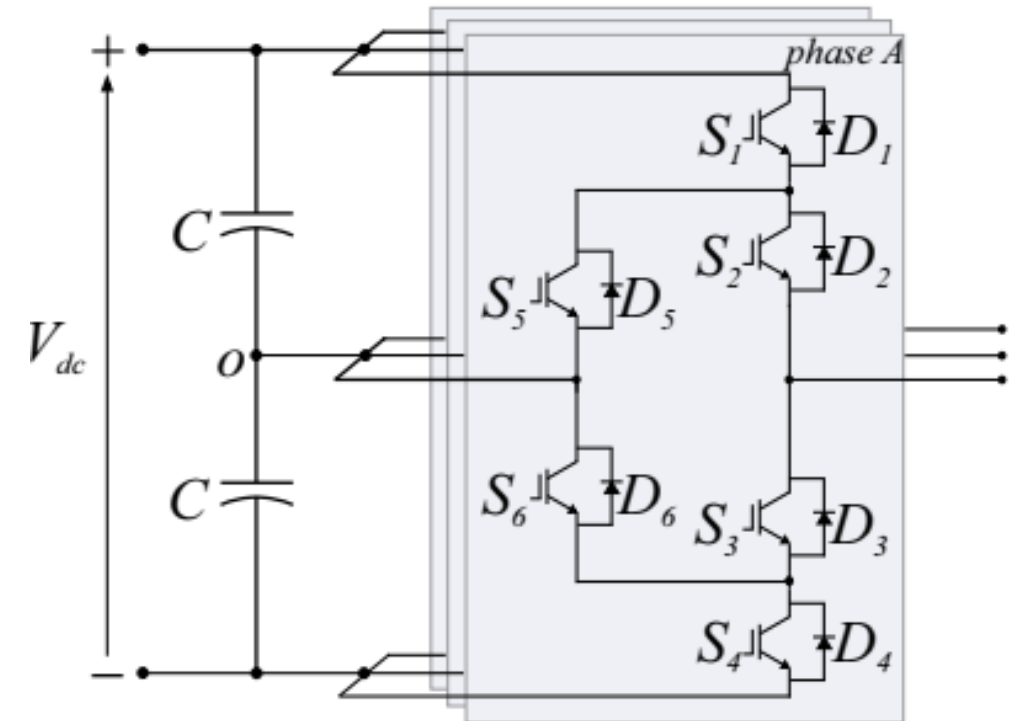
Algumas soluções alternativas - ANPC

❑ Substitui os diodos por interruptores controláveis;

❑ Resolve o problema de desbalanço térmico;

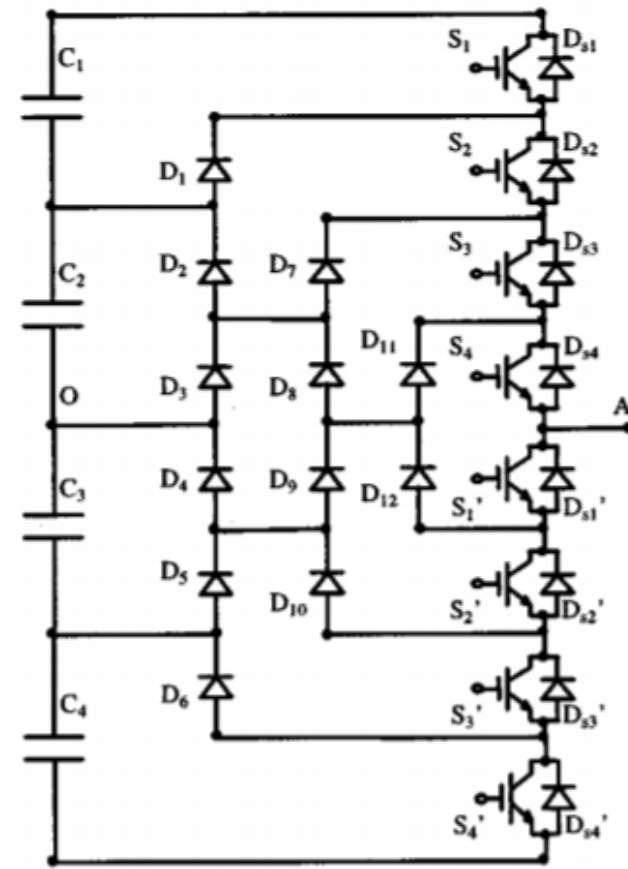
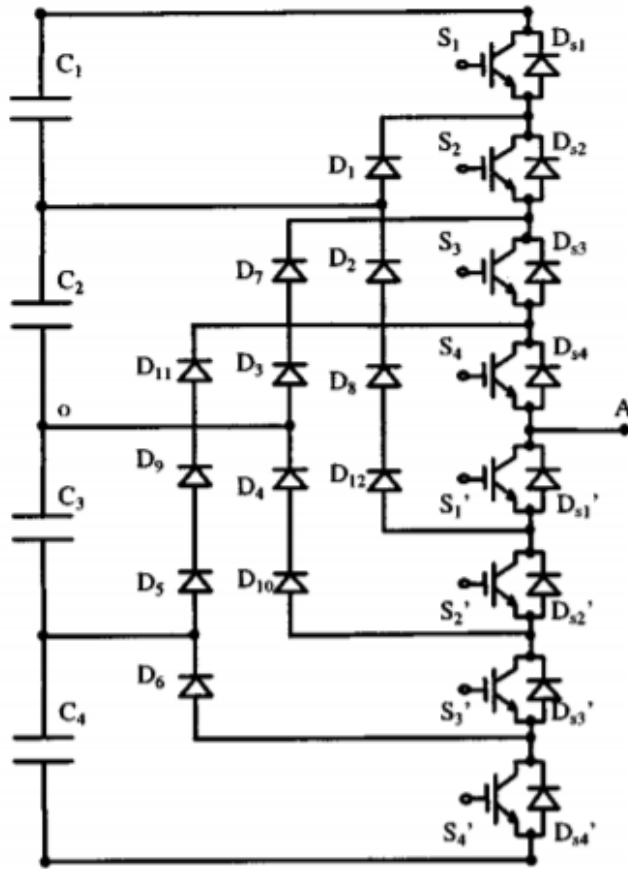
❑ Desvantagens do NPC persistem;

❑ Comercializado por algumas empresas.



Algumas soluções alternativas – NPC modificado

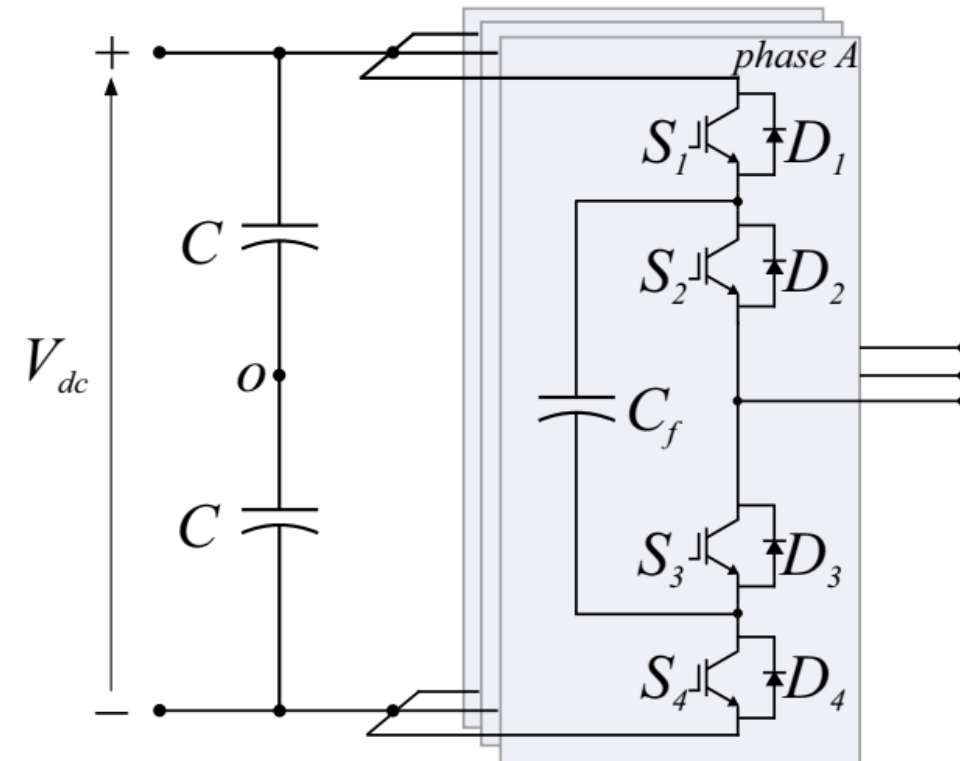
- Elimina a conexão série de diodos.



Fonte: X. Yuan and I. Barbi, "Fundamentals of a new diode clamping multilevel inverter," IEEE Transactions on Power Electronics. 2000.

Inversor com capacitor flutuante

- ❑ Introduzido no começo da década de 90;
- ❑ Adotada por um menor número de fabricantes;
- ❑ Complexidade de montagem para alto número de níveis;
- ❑ Custo dos capacitores;
- ❑ Estratégia de pré-carga dos capacitores.

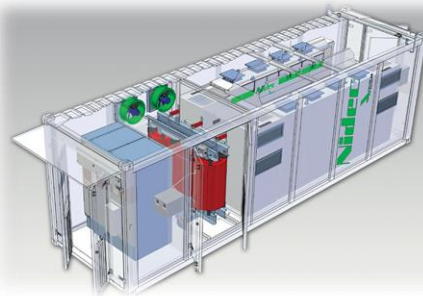


Fonte: X. Yuan and I. Barbi, "Fundamentals of a new diode clamping multilevel inverter," IEEE Transactions on Power Electronics. 2000.

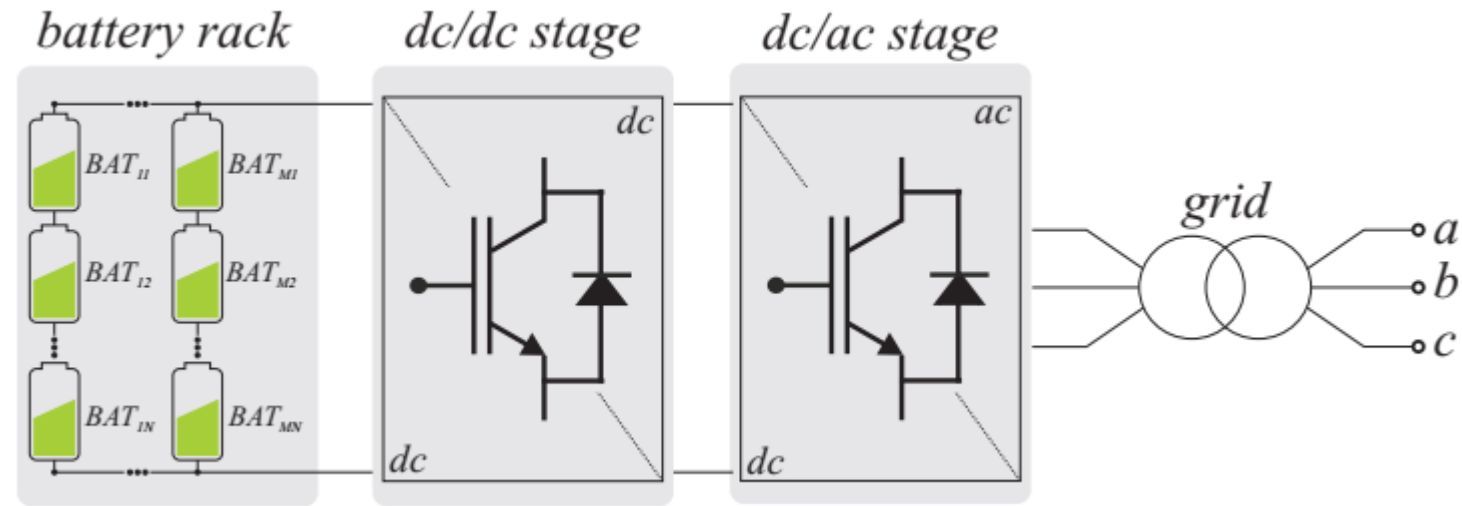


Sistemas de duplo estágio de conversão

Prof. Allan Fagner Cupertino
afcupertino@ieee.org



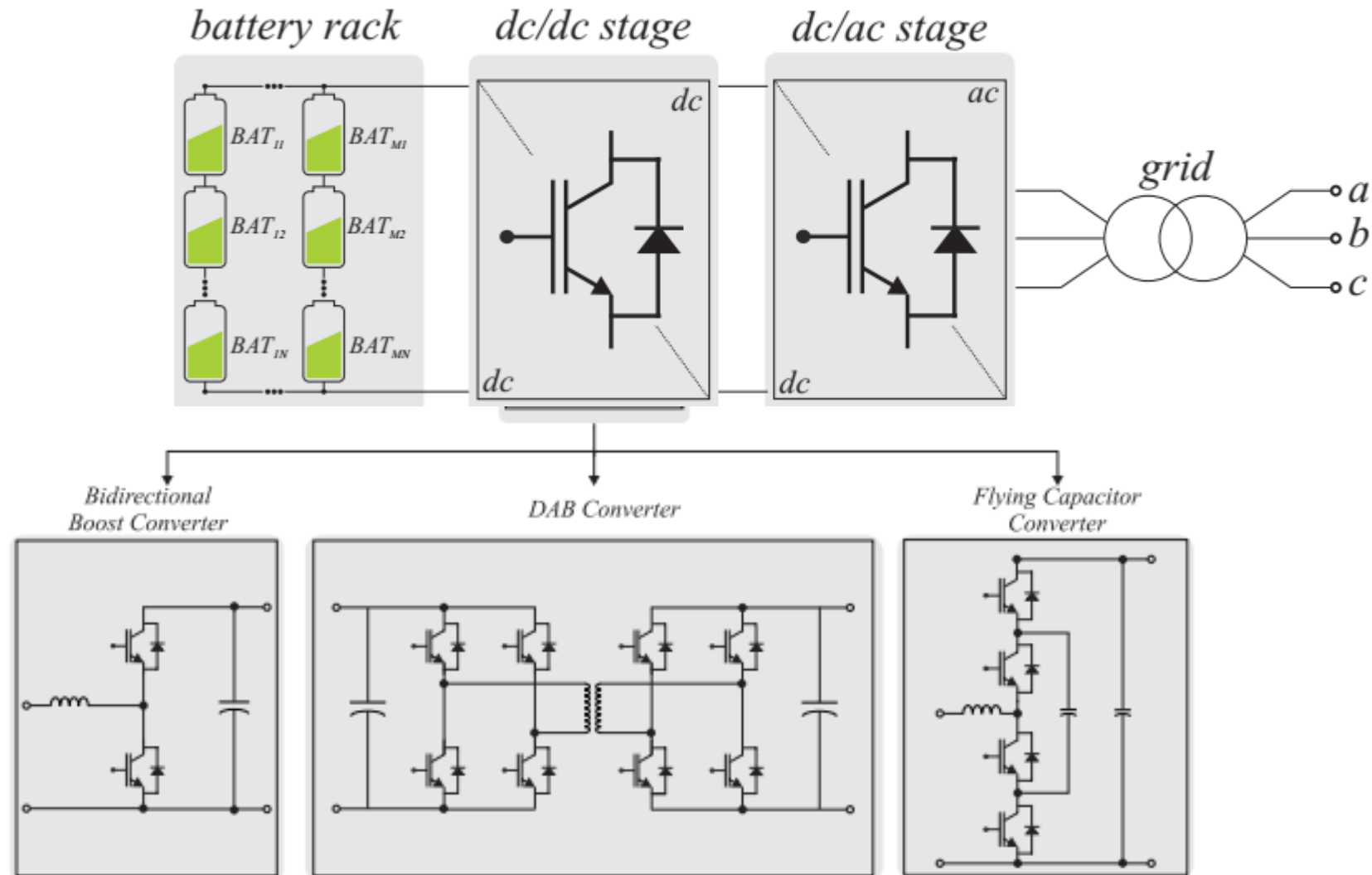
Exemplos – sistemas de duplo estágio



- ❑ Conversor CC/CC deve ser bidirecional;
- ❑ Eficiência e faixa de operação são variáveis importantes;
- ❑ Topologia isolada ou não isolada.

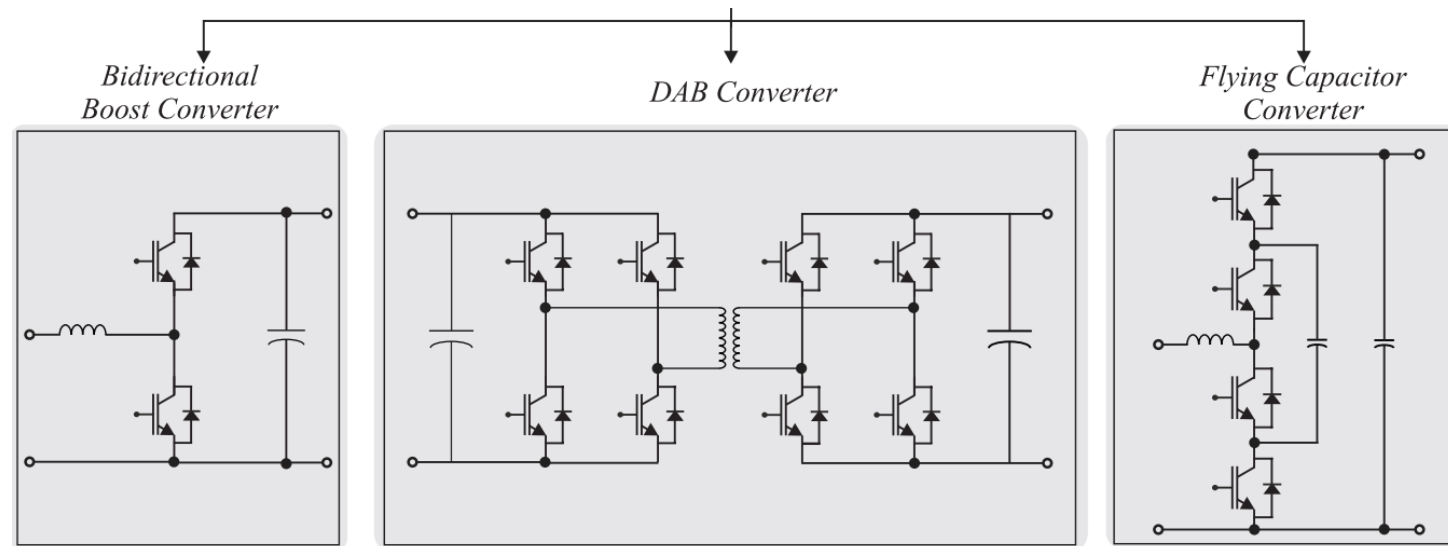
Fonte: Jonathan H. D. G. Pinto, “Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter”, 2020.

Exemplos – sistemas de duplo estágio



Fonte: Jonathan H. D. G. Pinto, “Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter”, 2020.

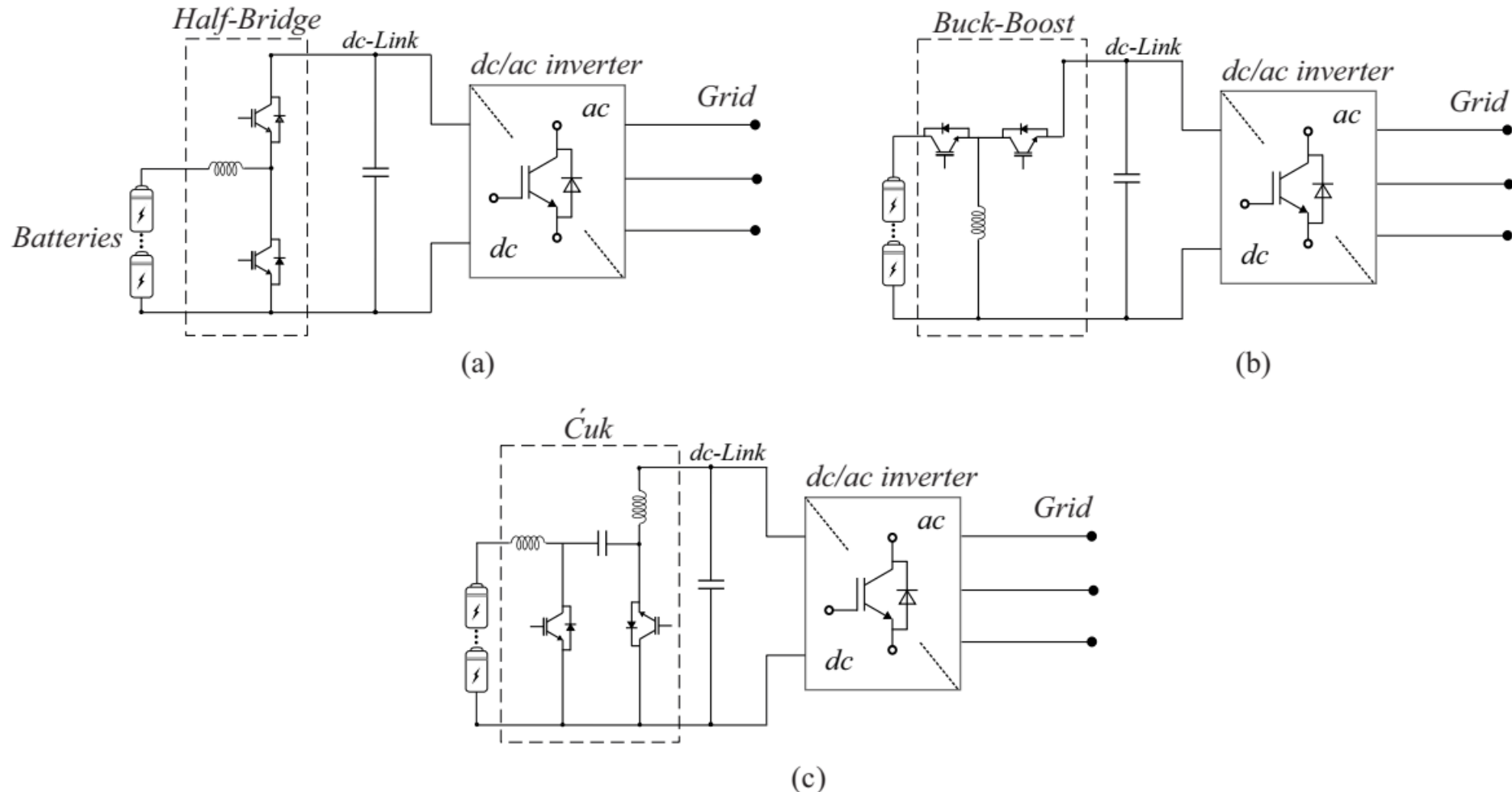
Topologias de conversor CC/CC de destaque



- ❑ Conversor bidirecional: simplicidade;
- ❑ DAB: Elevada eficiência, alto ganho e isolamento galvânica;
- ❑ FC: Elevada eficiência e volume reduzido do indutor (multinível).

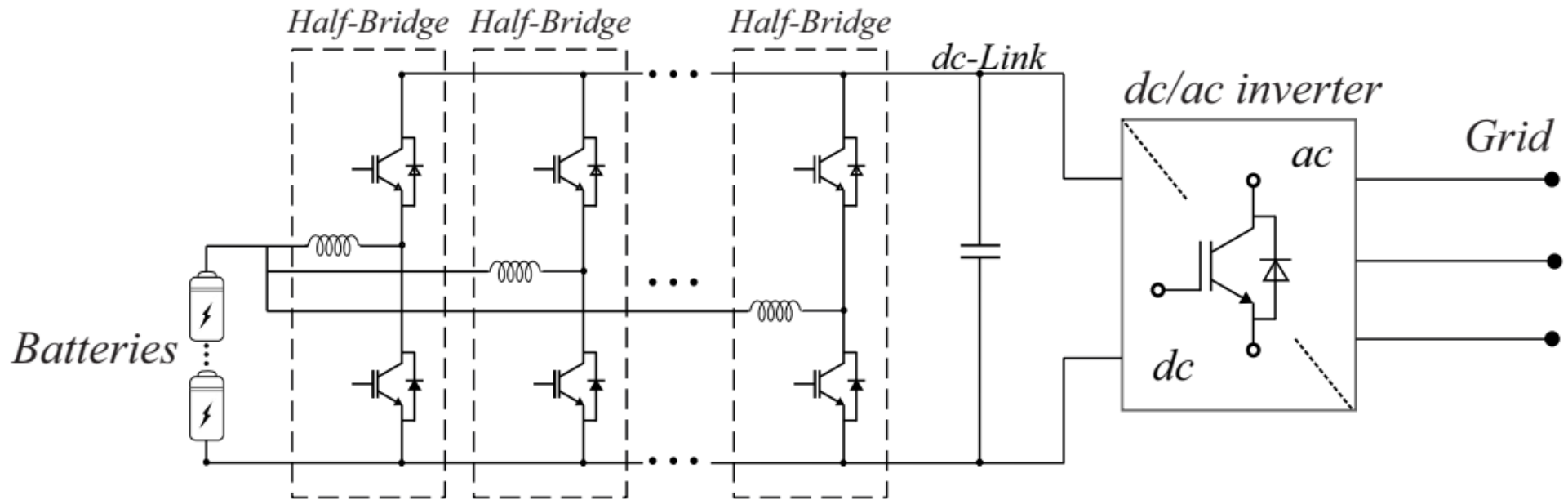
Fonte: Jonathan H. D. G. Pinto, “Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter”, 2020.

Outras abordagens – conversor CC/CC



Fonte: L. S. Xavier, et.al. "Power converters for battery energy storage systems connected to medium voltage systems: a comprehensive review," BMC Energy. 2019.

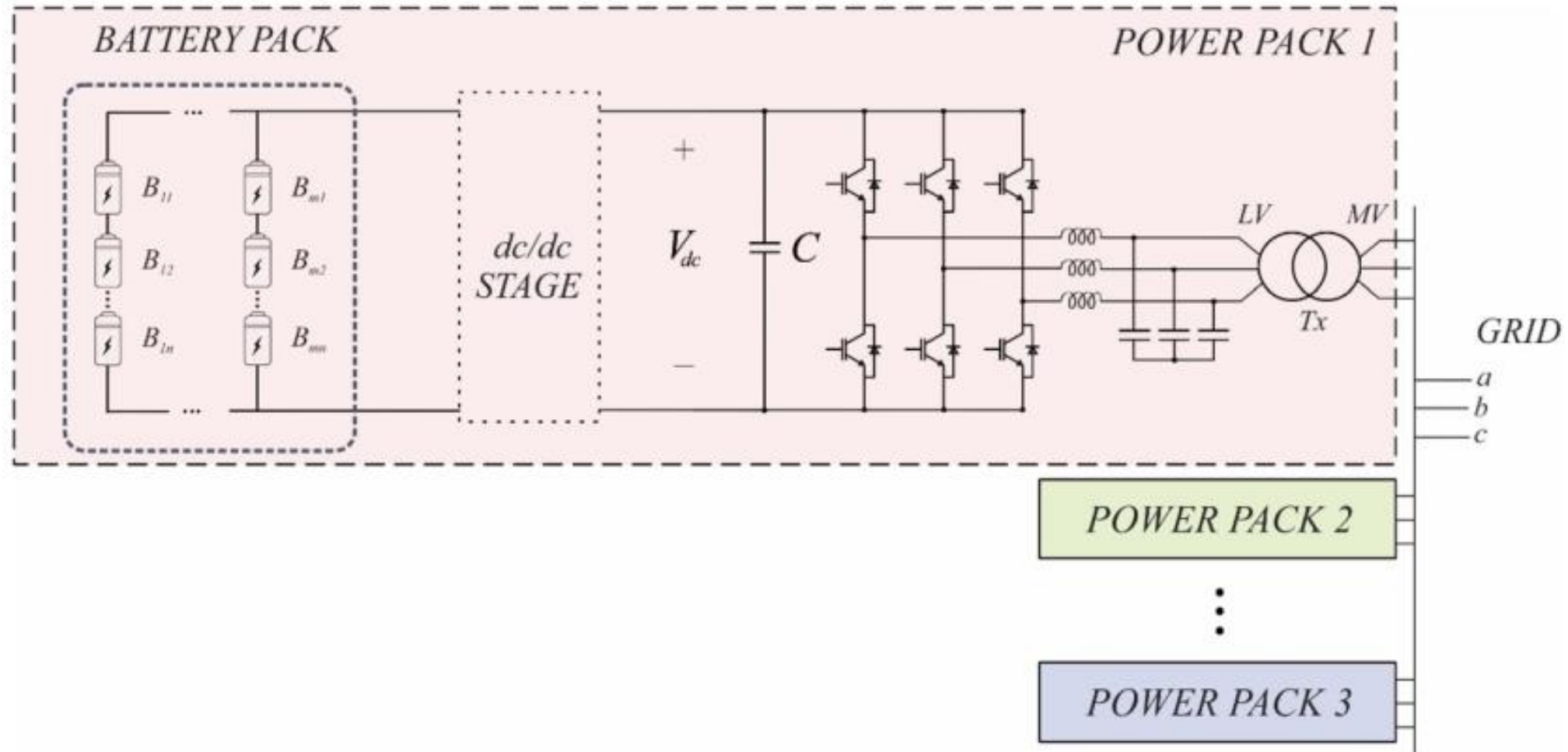
Outras abordagens – conversor entrelaçado



- ❑ Redução da ondulação de corrente na bateria;
- ❑ Pode resultar em um aumento de eficiência e densidade de potência.

Fonte: L. S. Xavier, et.al. "Power converters for battery energy storage systems connected to medium voltage systems: a comprehensive review," BMC Energy. 2019.

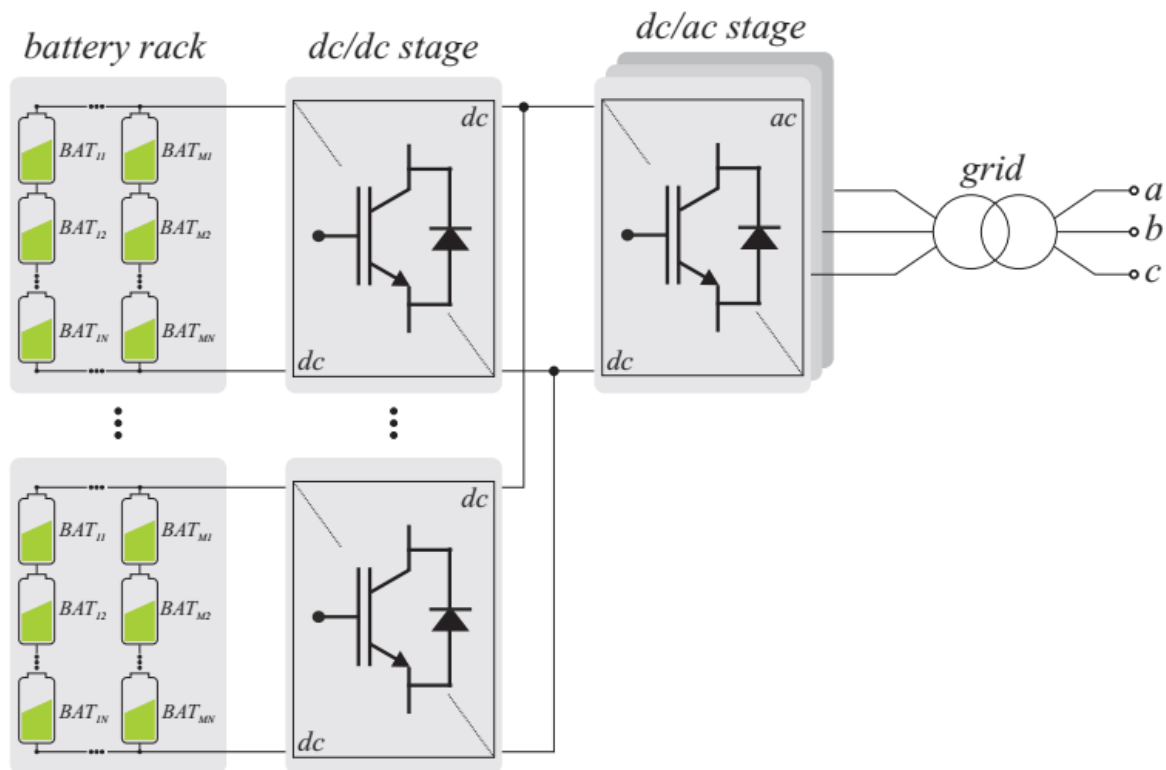
Abordagem para alta potência – vários sistemas em paralelo



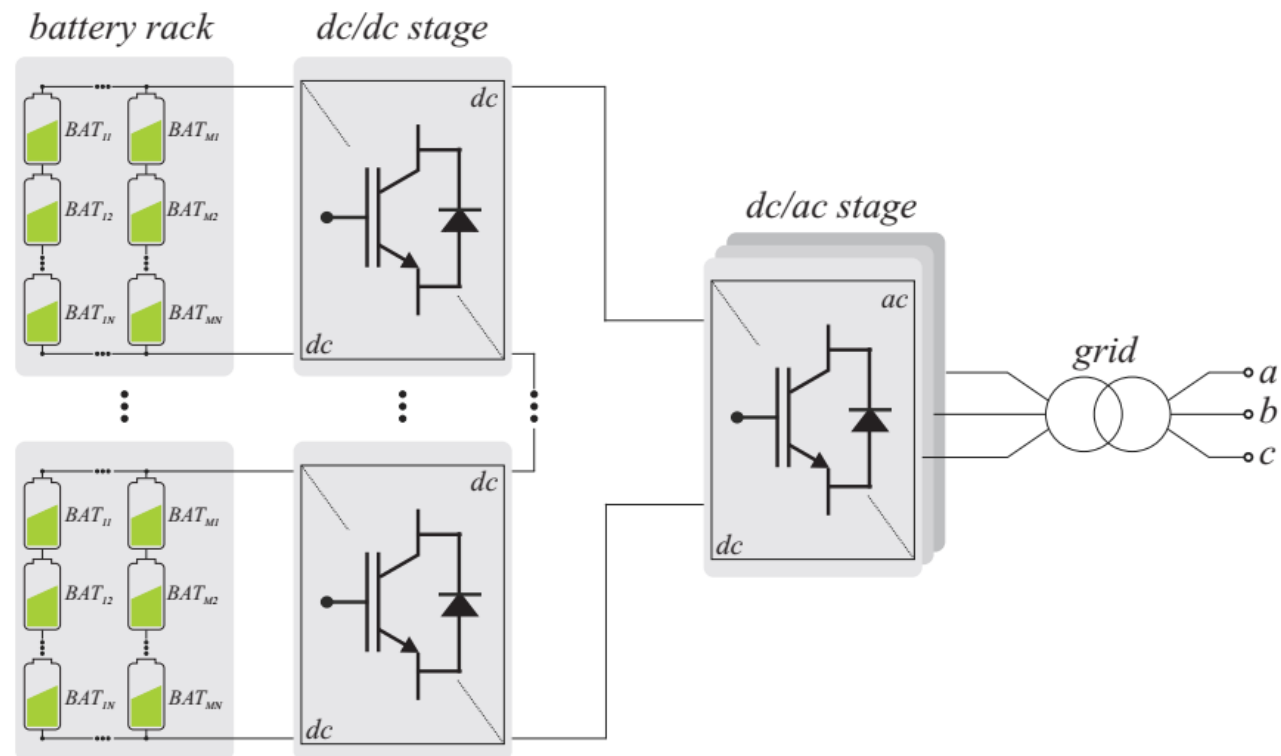
Fonte: L. S. Xavier, et.al. "Power converters for battery energy storage systems connected to medium voltage systems: a comprehensive review," BMC Energy. 2019.

Abordagem para alta potência – vários conversores CC/CC

□ Associação paralela



□ Associação série

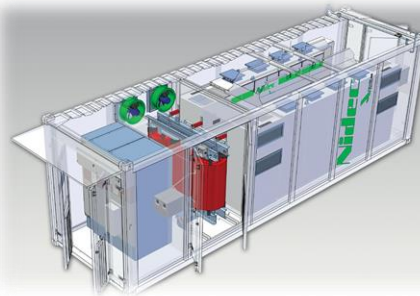


Fonte: Jonathan H. D. G. Pinto, “Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter”, 2020.

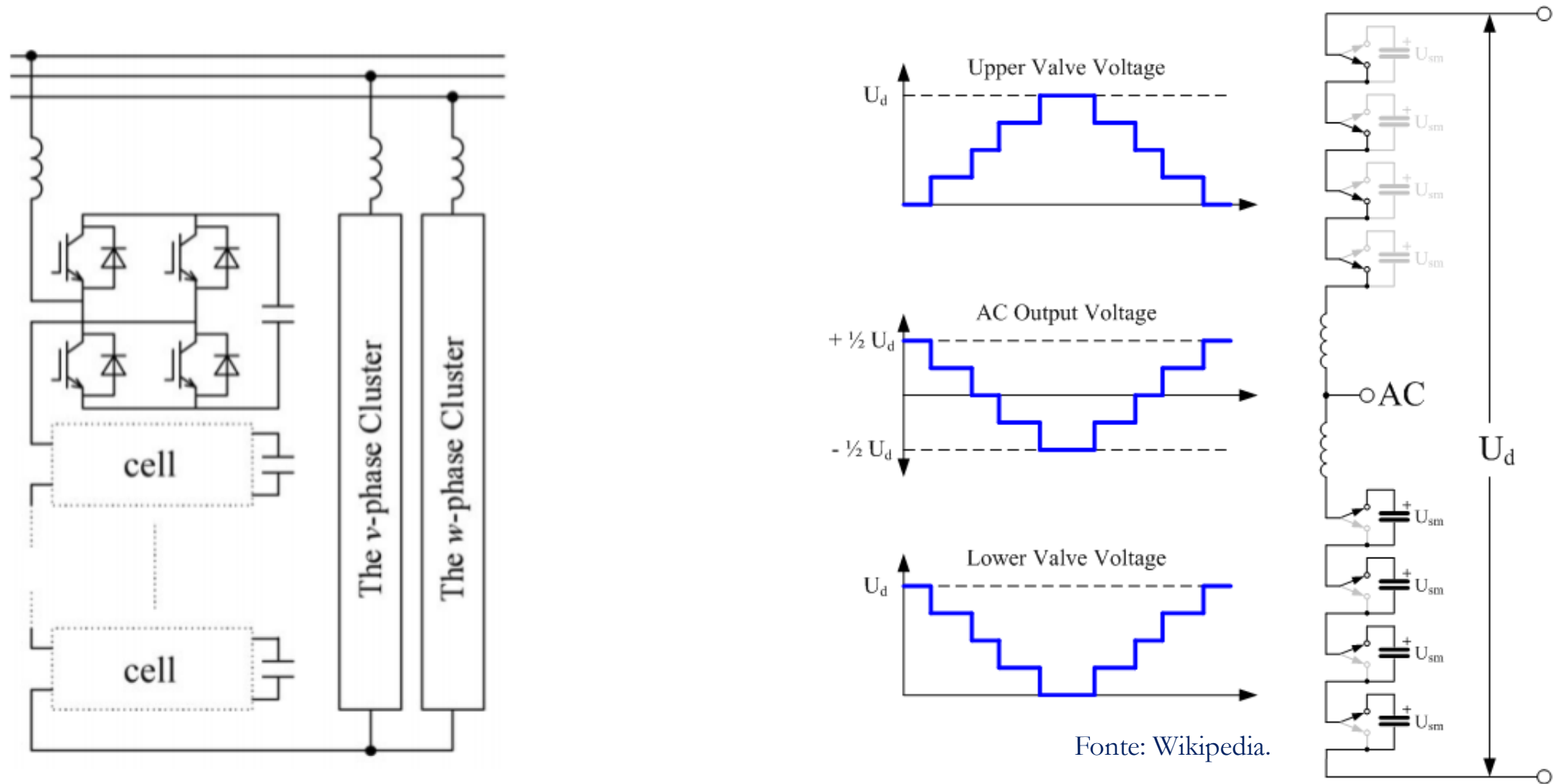


Utilização de conversores em cascata

Prof. Allan Fagner Cupertino
afcupertino@ieee.org



Conceito dos conversores em cascata

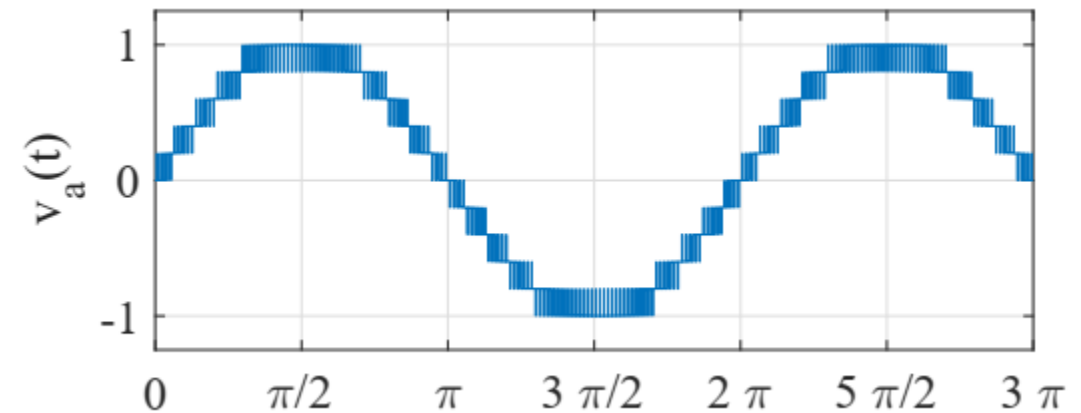


Fonte: Wikipedia.

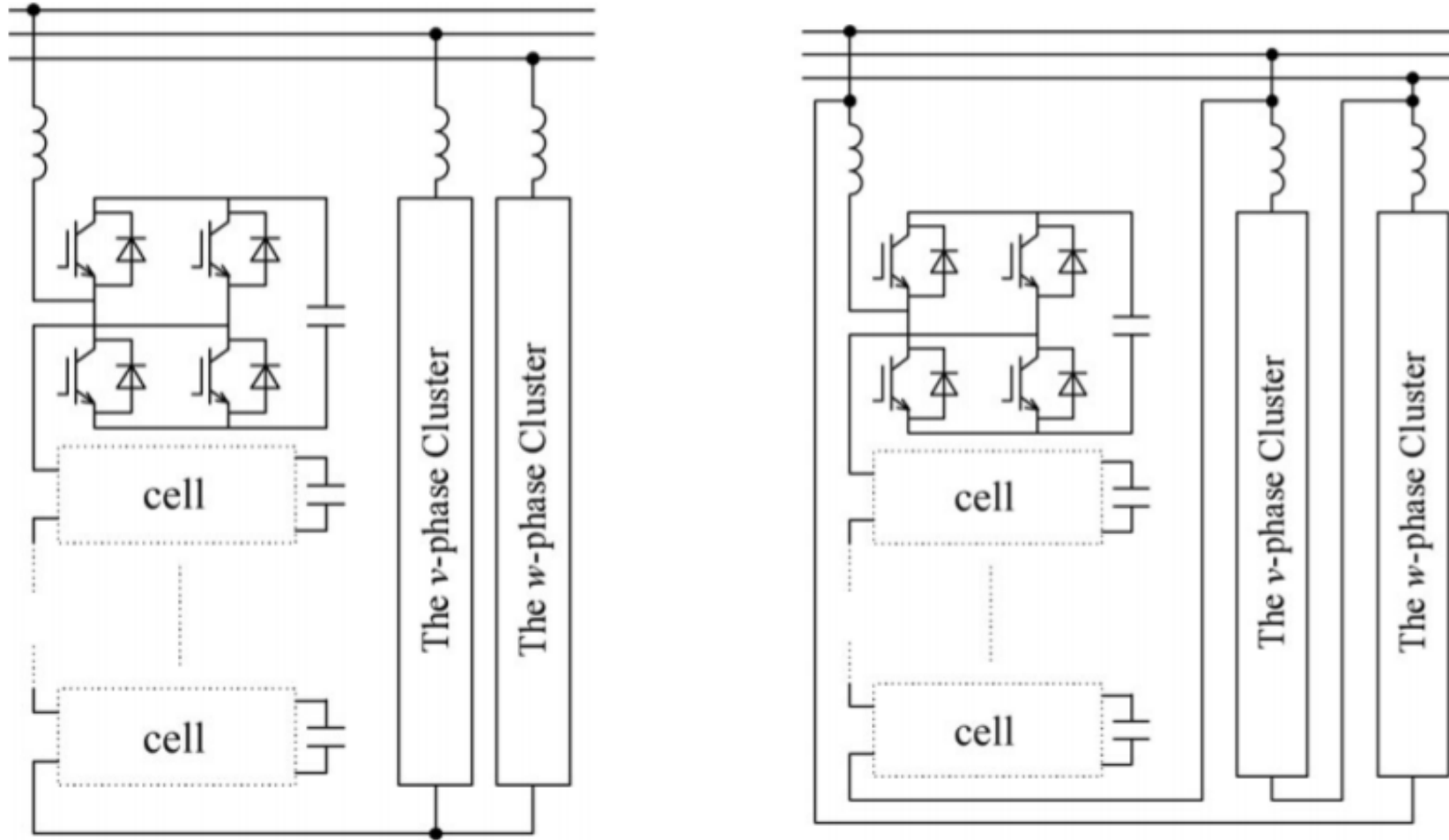
Fonte: H. Akagi, "Classification, Terminology, and Application of the Modular Multilevel Cascade Converter (MMCC)", IEEE Transactions on Power Electronics. 2011.

Vantagens dos conversores em cascata

- ❑ Alta potência e alta tensão com semicondutores maduros;
- ❑ Baixa frequência de comutação → alta eficiência;
- ❑ Nenhum componente de grampeamento;
- ❑ Flexibilidade de projeto;
- ❑ Redundância inerente a estrutura do conversor.



CHB – Cascade H-Bridge Converter

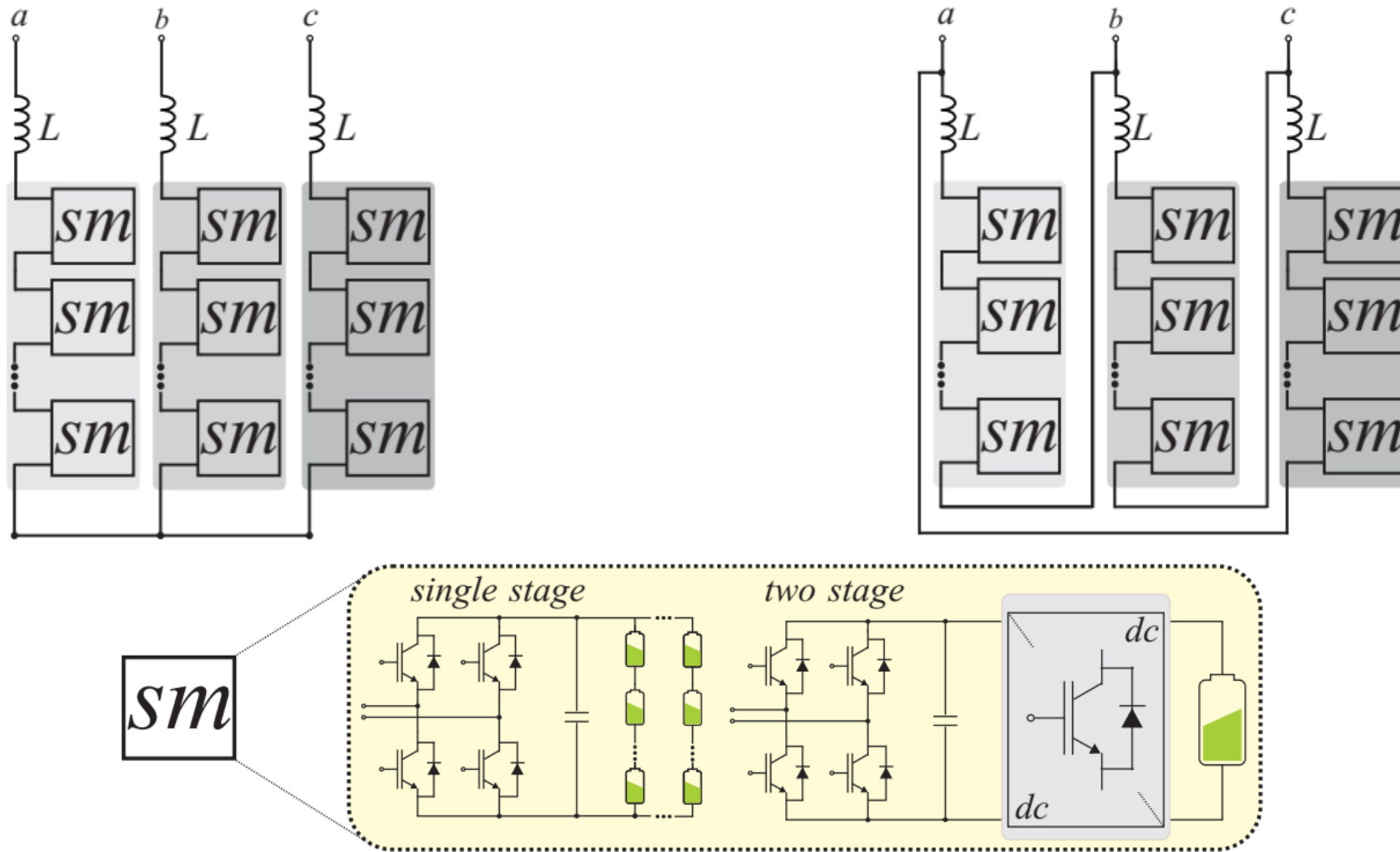


Fonte: H. Akagi, "Classification, Terminology, and Application of the Modular Multilevel Cascade Converter (MMCC)", IEEE Transactions on Power Electronics. 2011.

CHB – Cascade H-Bridge Converter

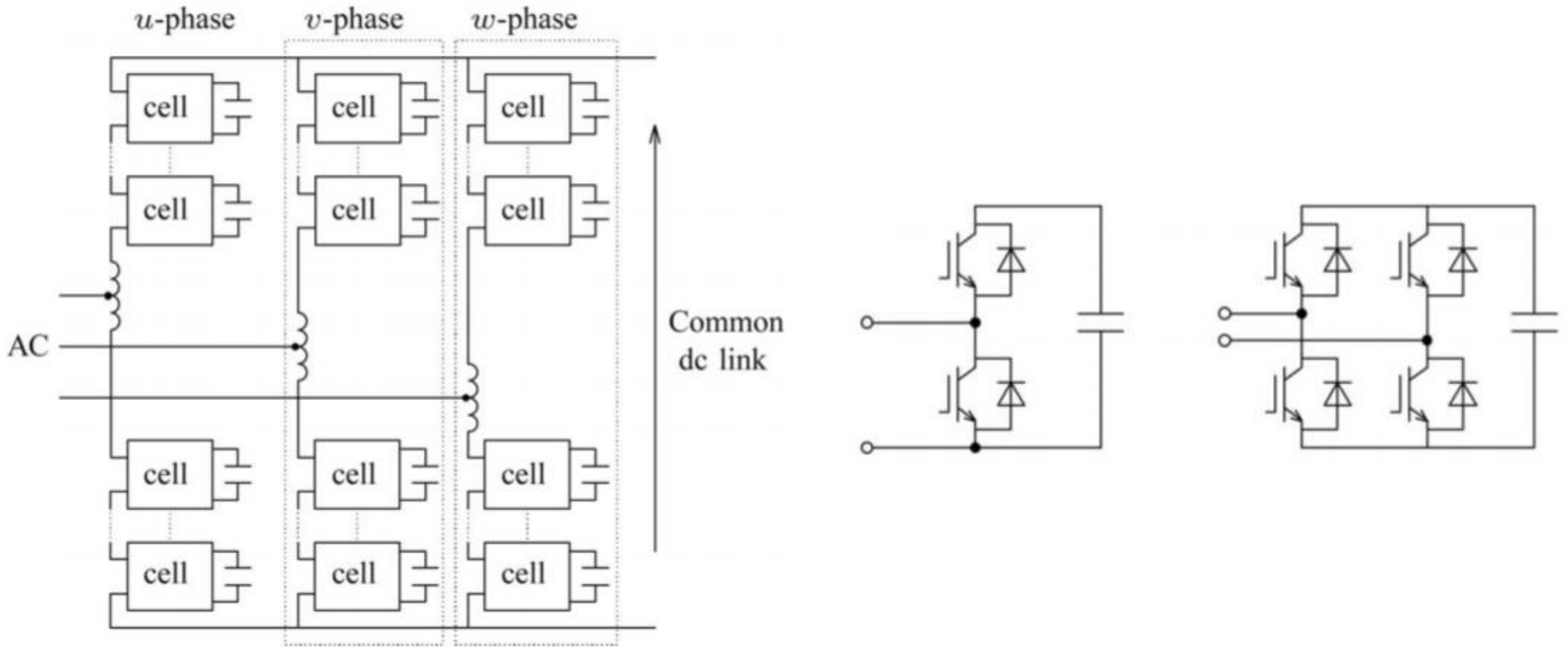
- ❑ Conversor trifásico construído a partir de 3 conjuntos monofásicos;
- ❑ Conversor não apresenta um barramento de corrente contínua;
- ❑ Baterias distribuídas ao longo dos conversores;
- ❑ Pode utilizar abordagem de estágio único ou duplo estágio de conversão.

CHB – Cascade H-Bridge Converter




Fonte: Jonathan H. D. G. Pinto, “Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter”, 2020.

MMC - Modular Multilevel Converter

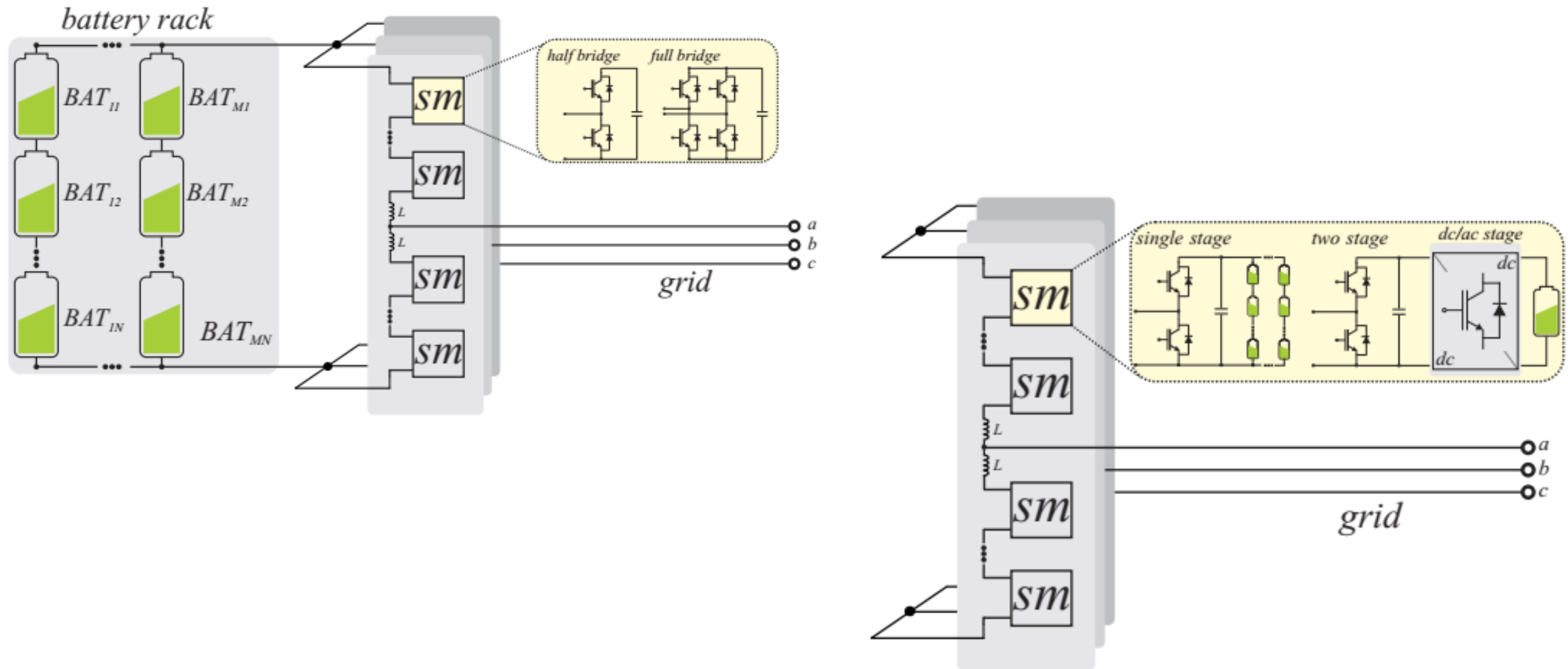


Fonte: Jonathan H. D. G. Pinto, "Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter", 2020.

MMC - Modular Multilevel Converter

- ❑ Conversor trifásico construído a partir de 6 conjuntos monofásicos;
- ❑ Apresenta um barramento de corrente contínua; 
- ❑ Baterias centralizadas ou distribuídas ao longo dos conversores;
- ❑ Pode utilizar abordagem de estágio único ou duplo estágio de conversão;

MMC - Modular Multilevel Converter



Fonte: Jonathan H. D. G. Pinto, "Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter", 2020.

Obrigado pela Atenção



Bons estudos!



Dúvidas: afcupertino@ieee.org



www.gesep.ufv.br



@GESEP



@gesep_vicosa



Gesep



Pesquise por:
“GESEP UFV”



EStimate - Sistemas
Fotovoltaicos

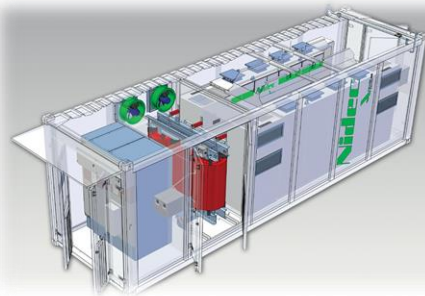


Pesquise por:
“EStimate”



Exemplos de sistemas comerciais

Prof. Allan Fagner Cupertino
afcupertino@ieee.org



Tesla POWERPACK



Power Electronics

Every Powerpack contains 16 individual battery pods, each with an isolated DC-DC converter. Pod architecture and onboard power electronics optimize performance across the array and enable easy swapping at any time.

Fonte: Tesla



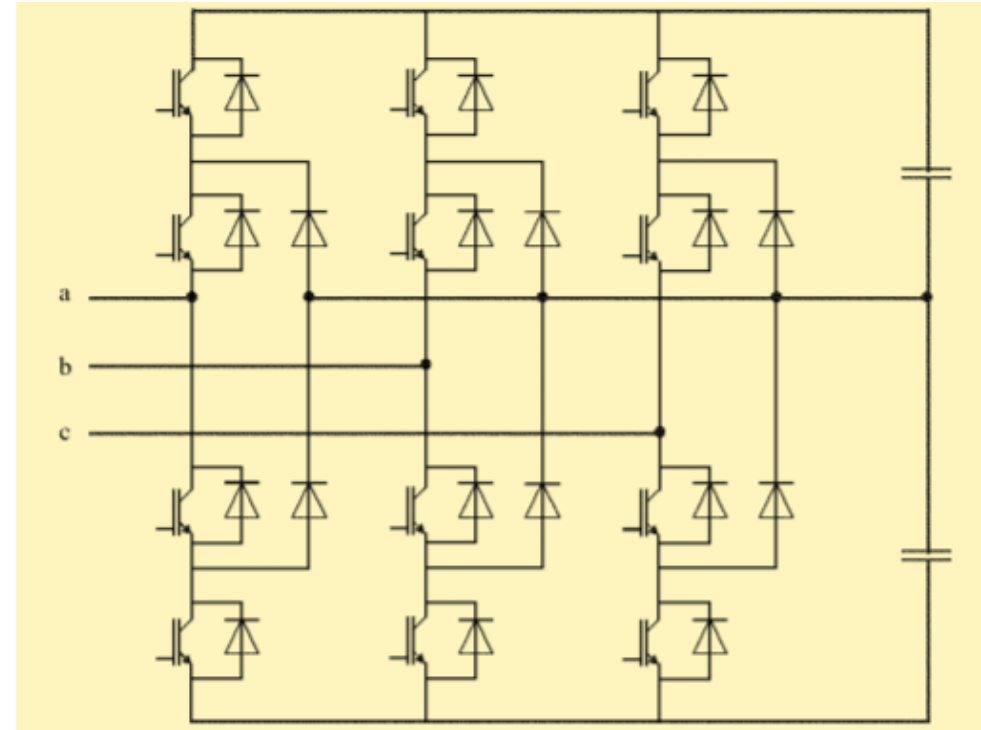
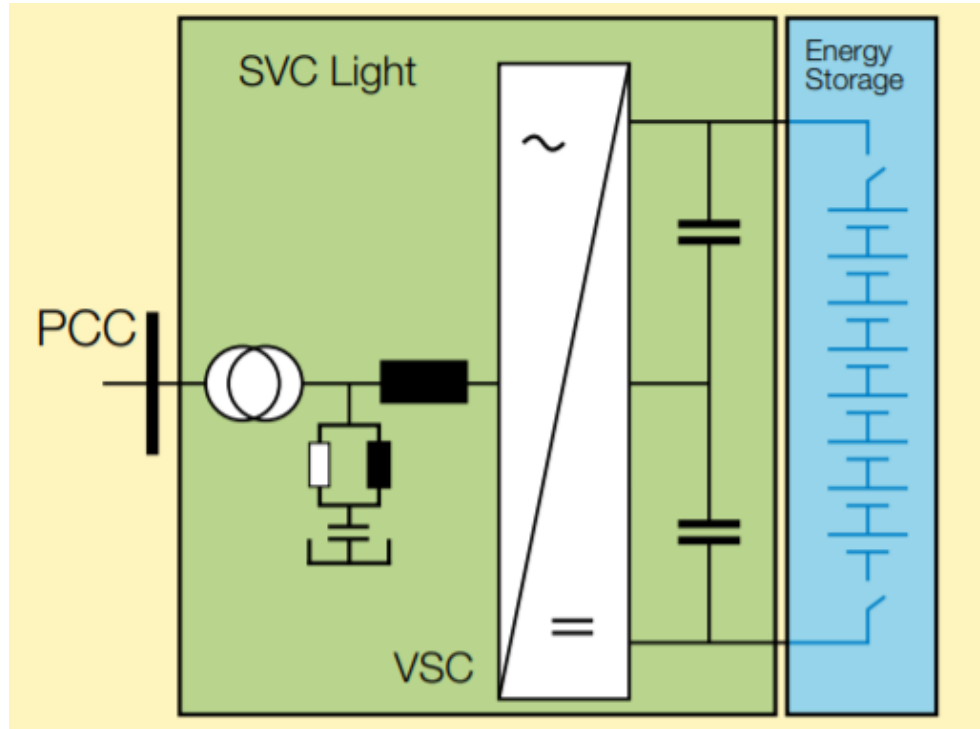
Tesla POWERPACK

Overall System Specs

| | | | |
|--------------------------------|--|--|---|
| AC Voltage | 380 to 480V, 3 phases | Energy Capacity | Up to 232 kWh (AC) per Powerpack |
| Communications | Modbus TCP/IP; DNP3; Rest API | Operating Temperature | -30°C to 50°C / -22°F to 122°F |
| Power | Up to 130 kW (AC) per Powerpack | Enclosures | Pods: IP67 Powerpack: IP35/NEMA 3R Inverter: IP66/NEMA 4 |
| Scalable Inverter Power | From 70kVA to 700kVA (at 480V) | System Efficiency (AC) * | 88% round-trip (2 hour system) 89.5% round-trip (4 hour system) |
| Depth of Discharge | 100% | Certifications | Nationally accredited certifications to international safety, EMC, utility and environmental legislation. |
| Dimensions | Powerpack Unit Length: 1,317 mm (50.9 in) Width: 968 mm (38.1 in) Height: 2,187 mm (86.1 in) Weight: 2,199 kg (4,847 lbs) Powerpack Inverter Length: 1,044 mm (41.1 in) Width: 1,394 mm (54.9 in) Height: 2,191 mm (86.2 in) Weight (max): 1,120 kg (2,470 lbs) | * Net Energy delivered at 25°C (77°F) ambient temperature including thermal control | |

Fonte: Tesla

ABB Dynapeak



Fonte: ABB

ABB Dynapeak



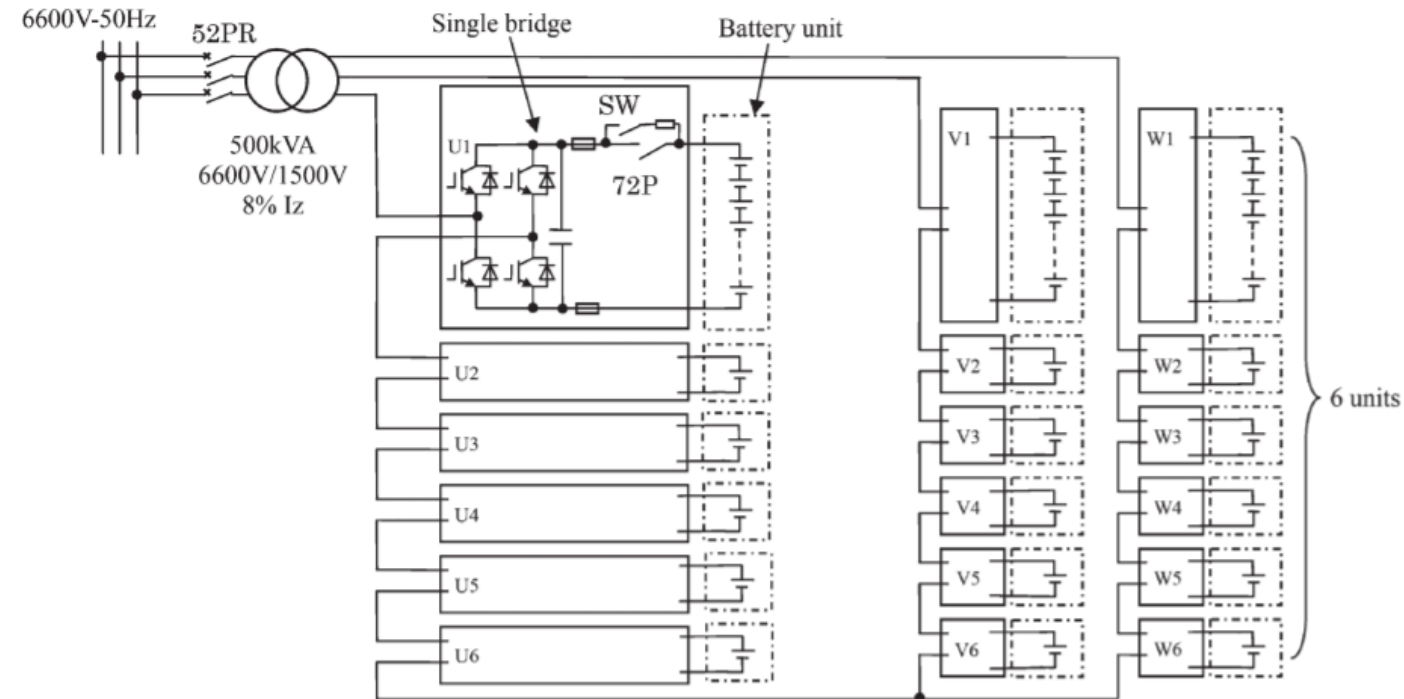
| | |
|---------------------------|--|
| System voltage | 11 kV |
| Reactive power range | 600 kvar inductive to 725 kvar capacitive |
| Energy storage capability | 200 kWh |
| Active power capability | 200 kW during an hour; 600 kW during a few minutes |
| VSC | Rated at 850 kVA; 3-level, neutral point clamped type converter; IGBT based, pulse-width modulated |
| Type of battery | Li-ion |



Fonte: ABB

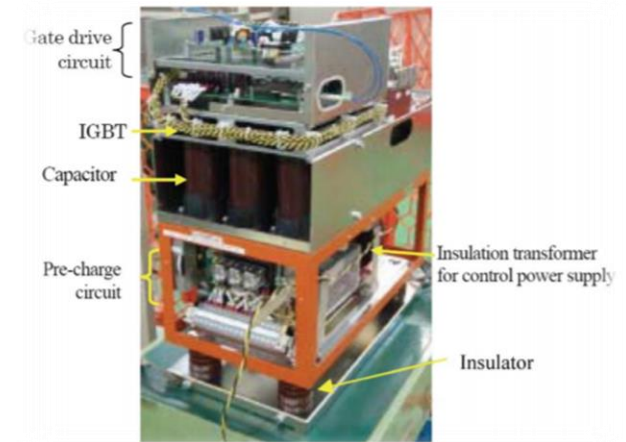
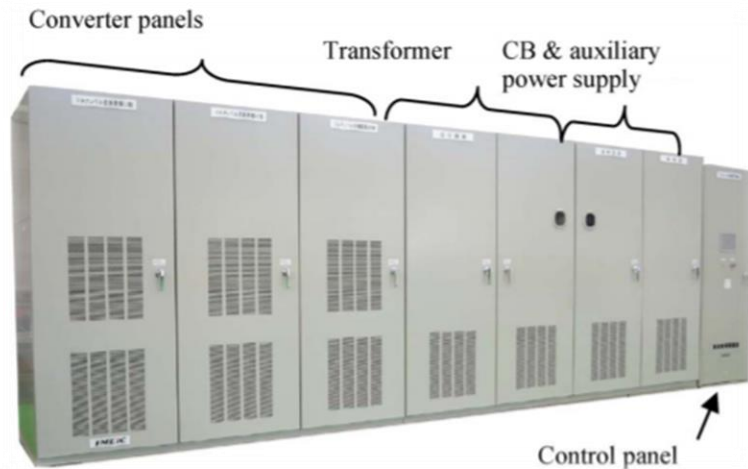
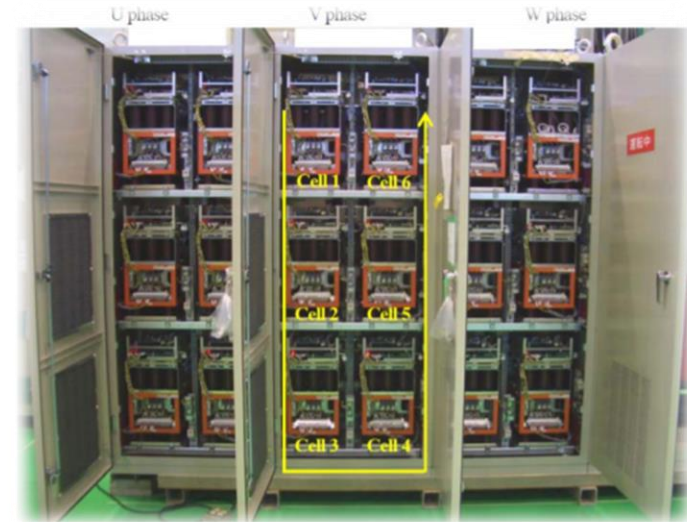
Toshiba-Mitsubishi + Tokyo Institute of Technology

| Items | Actual equipment | Verification test equipment |
|-----------------------------------|---|---|
| Power capacity | 1000 kW | 500 kW |
| Storage energy capacity | 1000 kWh | 238kWh |
| Circuit topology | MMCC-SSBC Modular Multilevel Cascade Converter based on Single-Star Bridge Cells | |
| Cascade number | 6 | 6 |
| Capacity of unit cell | 56 kVA | 28 kVA |
| DC voltage range | 250 V - 380 V | 280 V - 380 V Nominal voltage 331.2V |
| Output AC voltage of converter | 1500 V | 1500 V |
| Grid side AC voltage | 6600 V | 6600 V |
| Power device | 600-V, 600-A IGBT | |
| Configuration of each bridge cell | 1-series, 2-parallel, and 4-arm structure | 1-series, 1-parallel, and 4-arm structure |



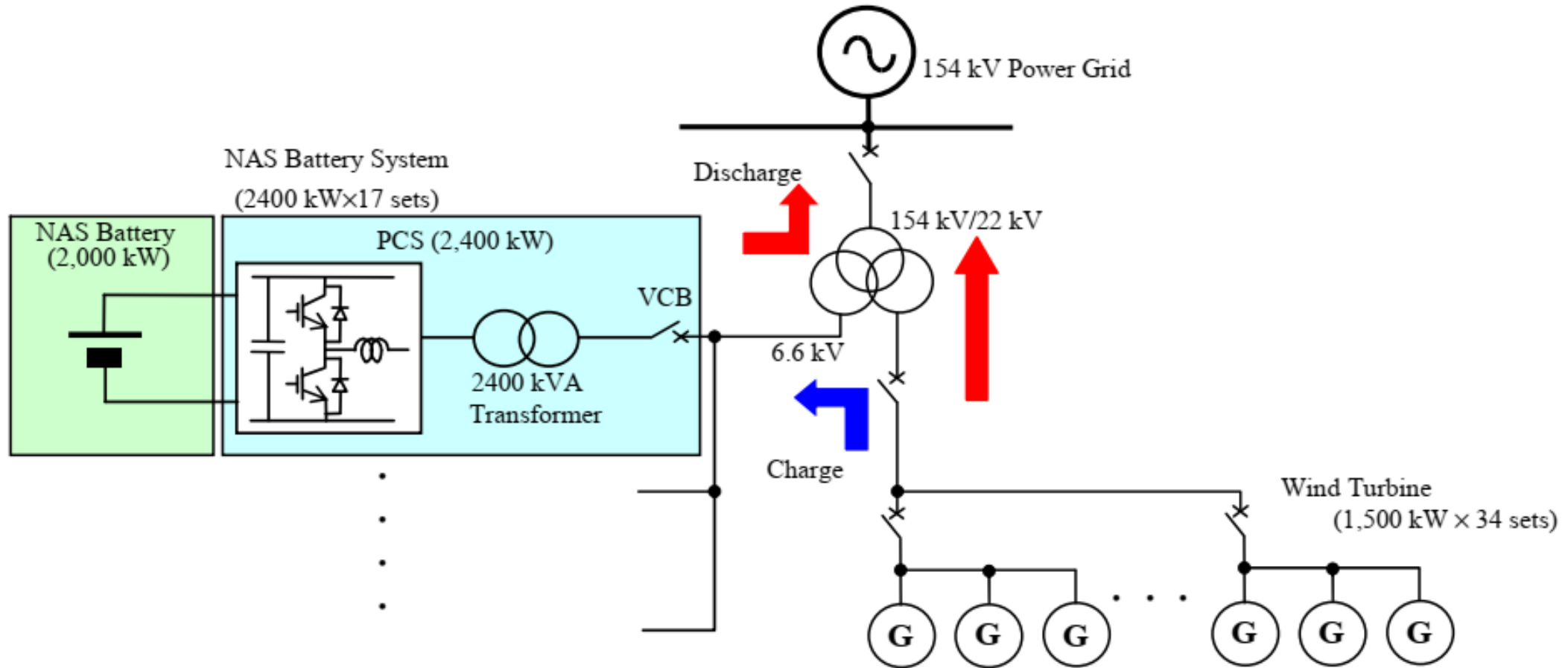
Fonte: N. Kawakami et al., "Development of a 500-kW Modular Multilevel Cascade Converter for Battery Energy Storage Systems," in IEEE Transactions on Industry Applications. 2014.

Toshiba-Mitsubishi + Tokyo Institute of Technology



Fonte: N. Kawakami et al., "Development of a 500-kW Modular Multilevel Cascade Converter for Battery Energy Storage Systems," in IEEE Transactions on Industry Applications. 2014.

Toshiba-Mitsubishi + Japan Wind Development Co.



Fonte: Yukihsa Iijima, Yoshinori Sakanaka, Noriko Kawakami. "Development and Field Experiences of NAS Battery Inverter for Power Stabilization of a 51 MW Wind Farm," IPEC, 2010.

Toshiba-Mitsubishi + Japan Wind Development Co.

| | ITEM | RATED VALUE |
|---|--|--|
| 1 | Inverter rated capacity | 2,400 kW × 17 units |
| 2 | Grid voltage | 6.6 kV - 3Φ - 50 Hz |
| 3 | DC voltage rating (battery voltage) | 470–745 V |
| 4 | Switching device (cooling method) | IGBT (Forced air cooling) |
| 5 | Inverter type | Voltage source self-commutated converter |
| 6 | Switching method | PWM (Pulse Width Modulation) |
| 7 | Efficiency | More than 95 % |



Fonte: Yukihsa Iijima, Yoshinori Sakanaka, Noriko Kawakami. "Development and Field Experiences of NAS Battery Inverter for Power Stabilization of a 51 MW Wind Farm," IPEC, 2010.

Estado da arte – Indústria de sistemas de armazenamento

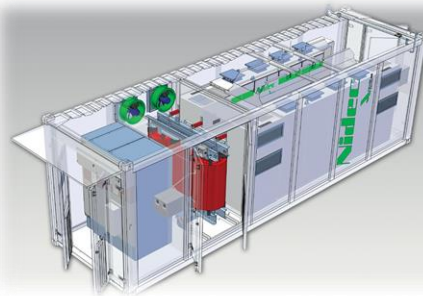
| PE Provider | Power/Energy (MW/MWh) | Topology | Battery Technology | DC-DC Stage | AC/DC Voltage (V) | Module Power Level |
|------------------|-----------------------|----------|--------------------|-------------|--------------------------------------|--------------------|
| ABB | 20/6.67 | 2L/3L | Li-Ion | No | 415–690 V_{ac} ; 975–1200 V_{dc} | 72 kW–1 MW |
| DynaPower | 11/4.4 | 2L/3L | Li-Ion | – | 750–1150 V_{dc} | 1 MVA |
| Enercon | 10/10 | 2L/3L | Li-Ion | Yes | – | 300 kW |
| Extreme Power | 10 / 7.5 | 2L | Advanced Lead Acid | – | 480 V_{ac} ; 750–1200 V_{dc} | 1.5 MVA |
| General Electric | 21/14 | 2L/3L | Lead Acid | – | 480 V_{ac} ; 431–850 V_{dc} | 1.25 MW |
| Mitsubishi | 20/6.33 | 2L/3L | Li-Ion | – | 300 V_{ac} | 0.5 MW |
| Nidec | 12/96 | 2L | NaS | Yes | – | 1.2–2.5 MW |
| Parker SSD | 12/4 | 2L/3L | Li-Ion | No | 400–480 V_{ac} ; 720–1200 V_{dc} | 1.2–2.2 MW |
| S&C Electric | 10/0.14 | 2L/3L | Lead Acid | Yes | 480 V_{ac} ; 460–800 V_{dc} | 1 MW/1.25 MVA |
| Yunicos | 36/24 | 2L/3L | Advanced Lead Acid | – | 415–690 V_{ac} ; 975–1200 V_{dc} | 250 kVA |

Fonte: G. Wang et. al. “A Review of Power Electronics for Grid Connection of Utility-Scale Battery Energy Storage Systems”. IEEE Transactions on Sustainable Energy. 2016



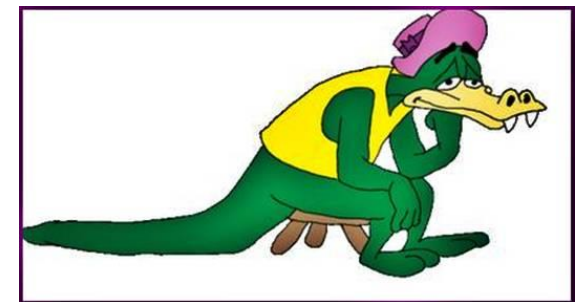
Alguns desafios e perguntas importantes

Prof. Allan Fagner Cupertino
afcupertino@ieee.org

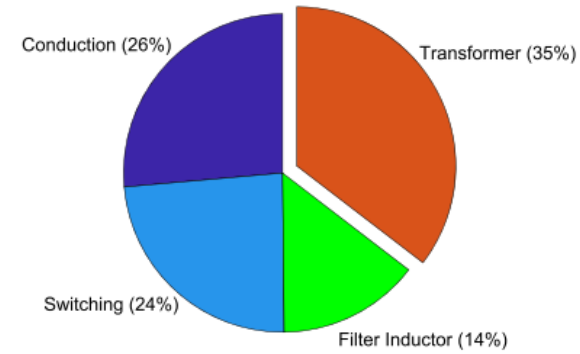
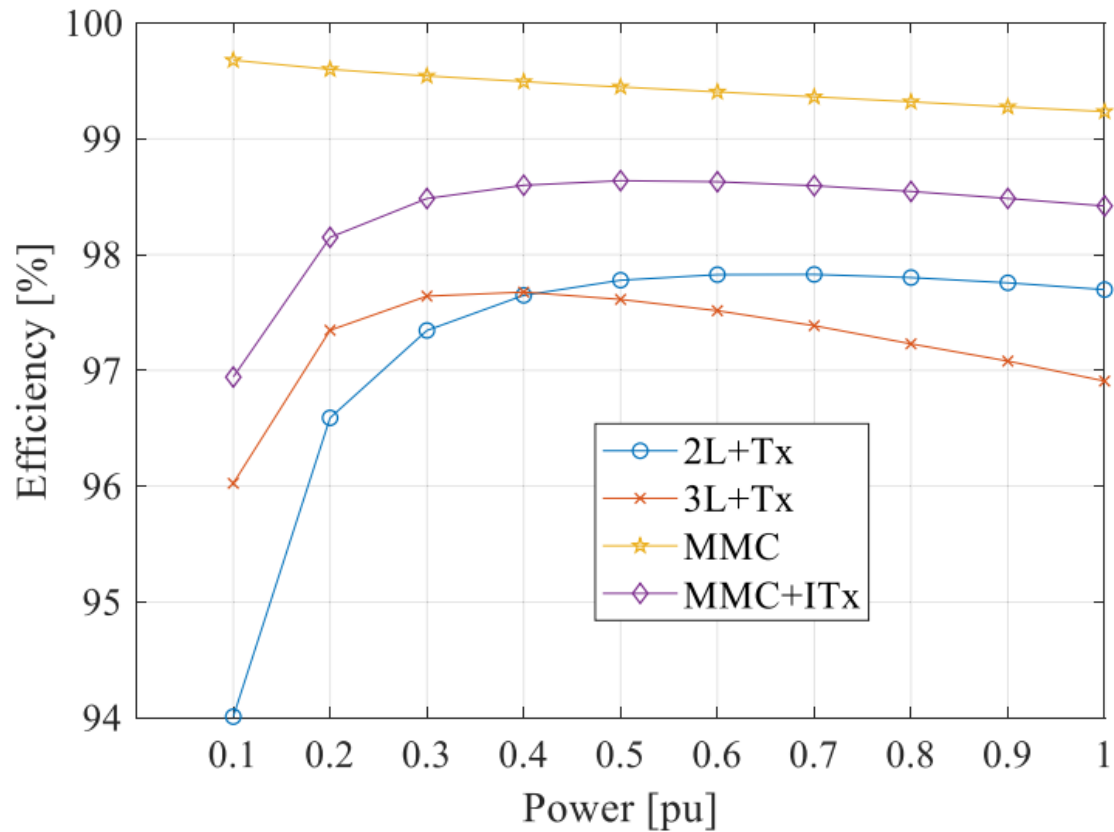


Algumas perguntas importantes

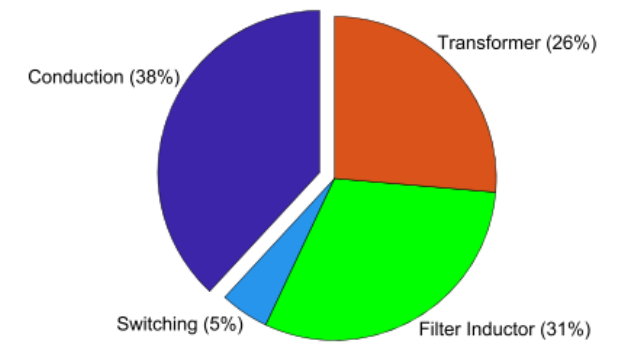
- Qual topologia é mais eficiente?
- Usar conversor CC/CC ou não?
- A ondulação de alta frequência do conversor CC/CC degrada a bateria?
- Abordagem centralizada ou distribuída?



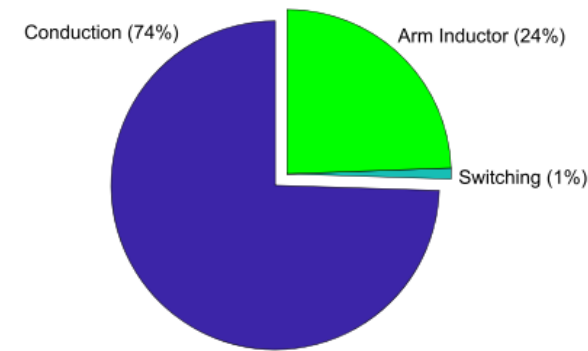
Eficiência de diferentes topologias – Estágio único



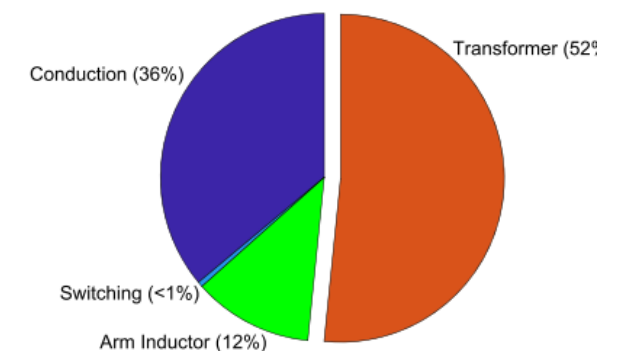
(a)



(b)



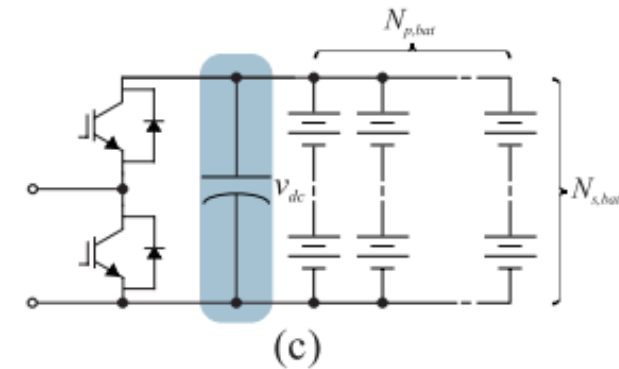
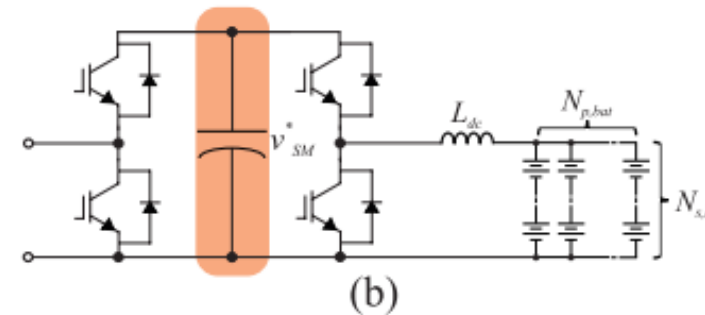
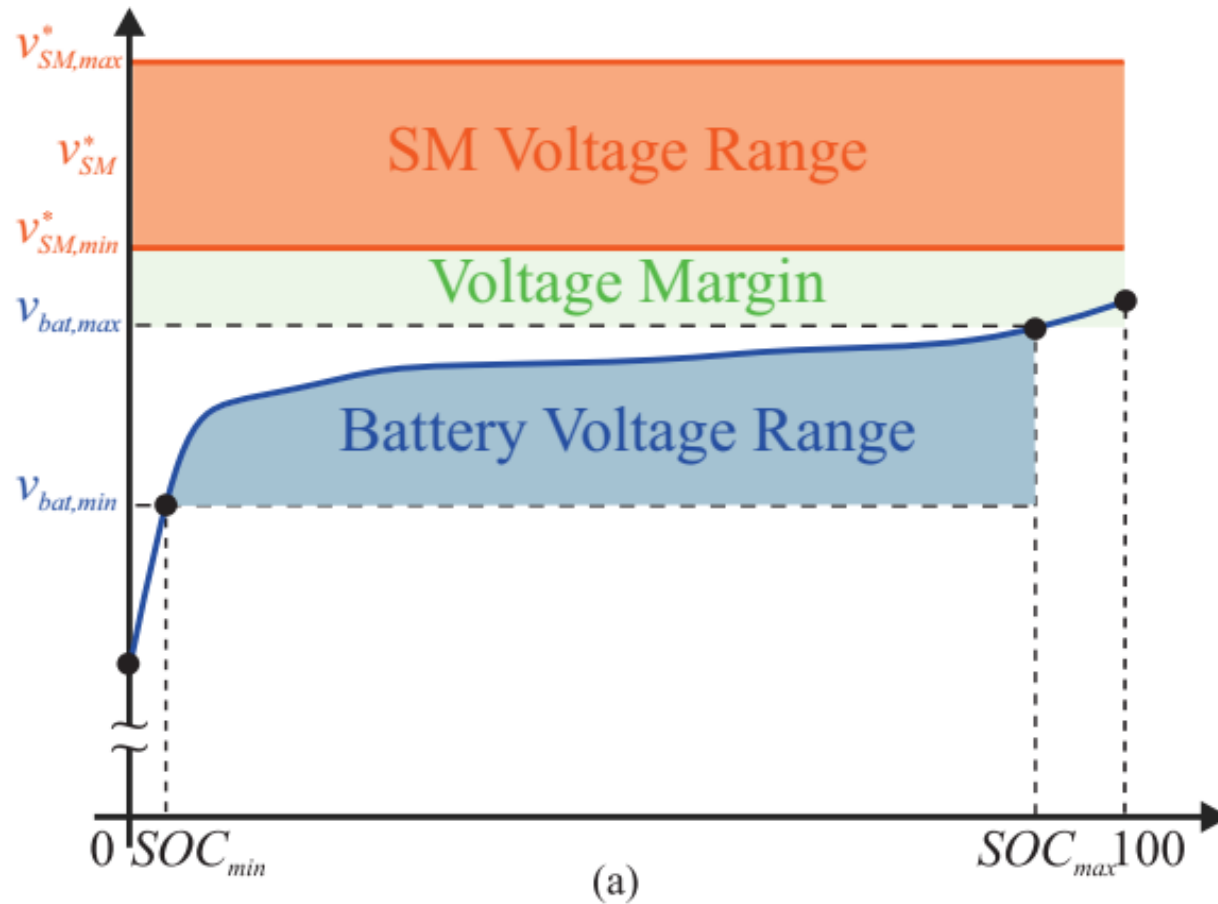
(c)



(d)

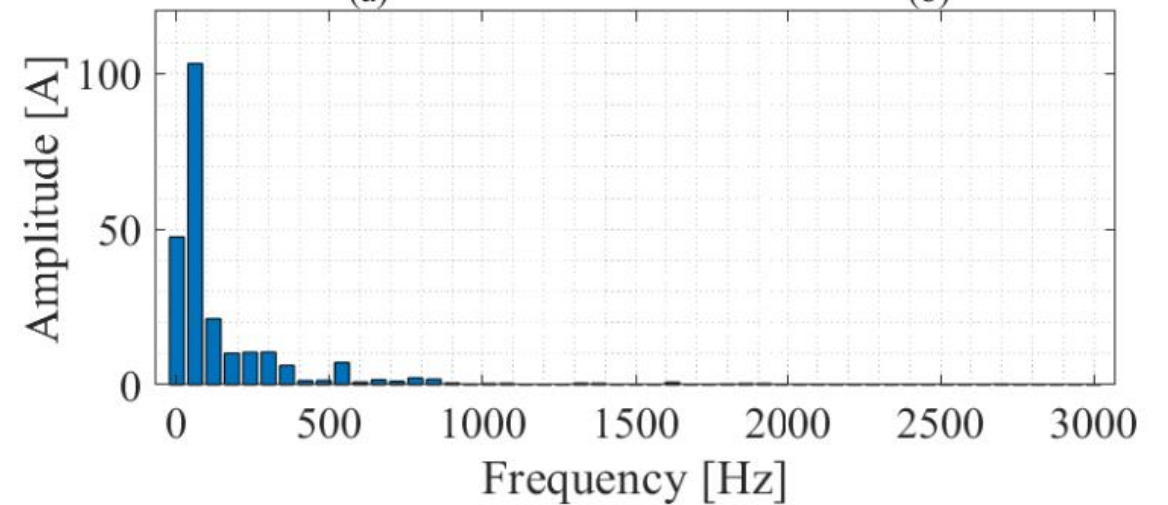
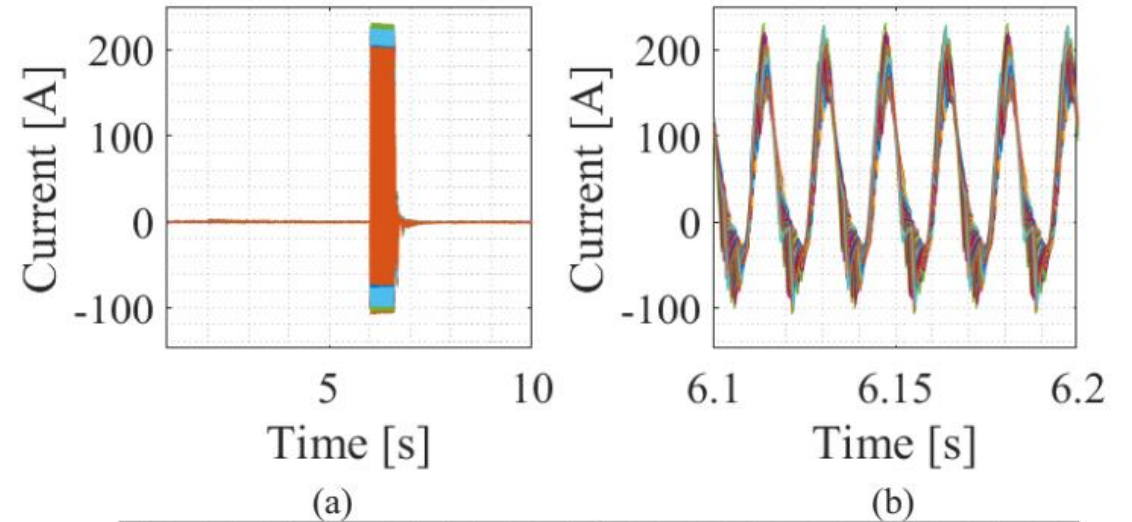
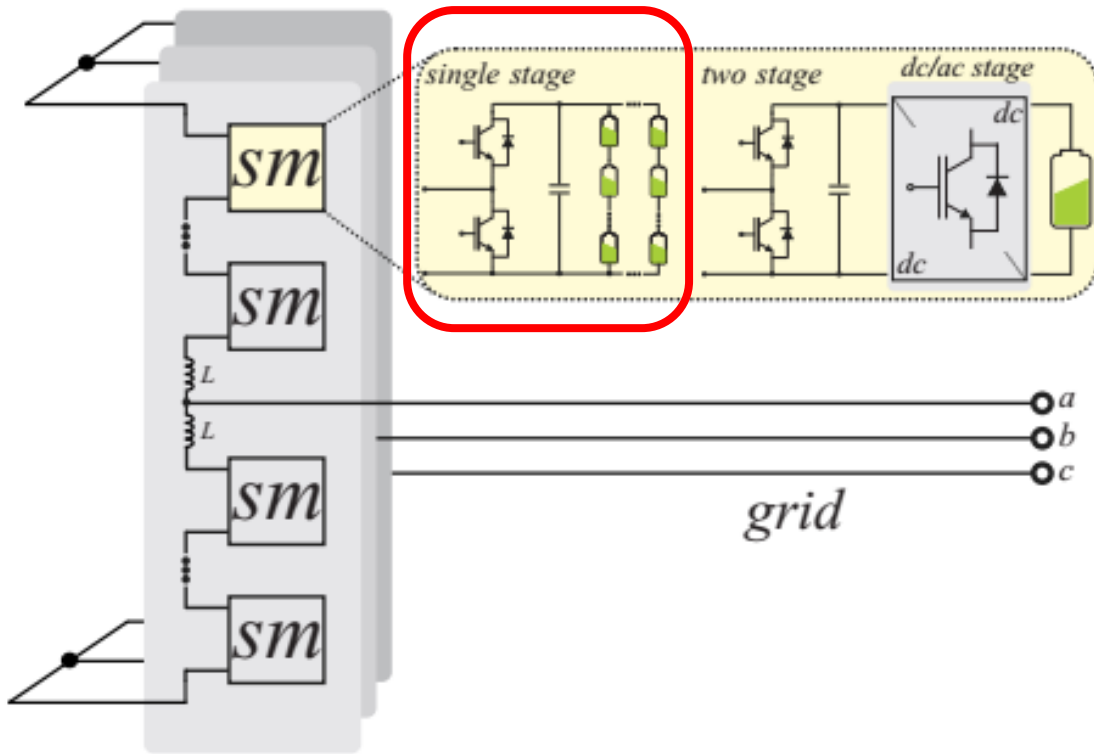
Fonte: L. S. Xavier, et.al. "Power converters for battery energy storage systems connected to medium voltage systems: a comprehensive review," BMC Energy. 2019.

Efeito do conversor CC/CC



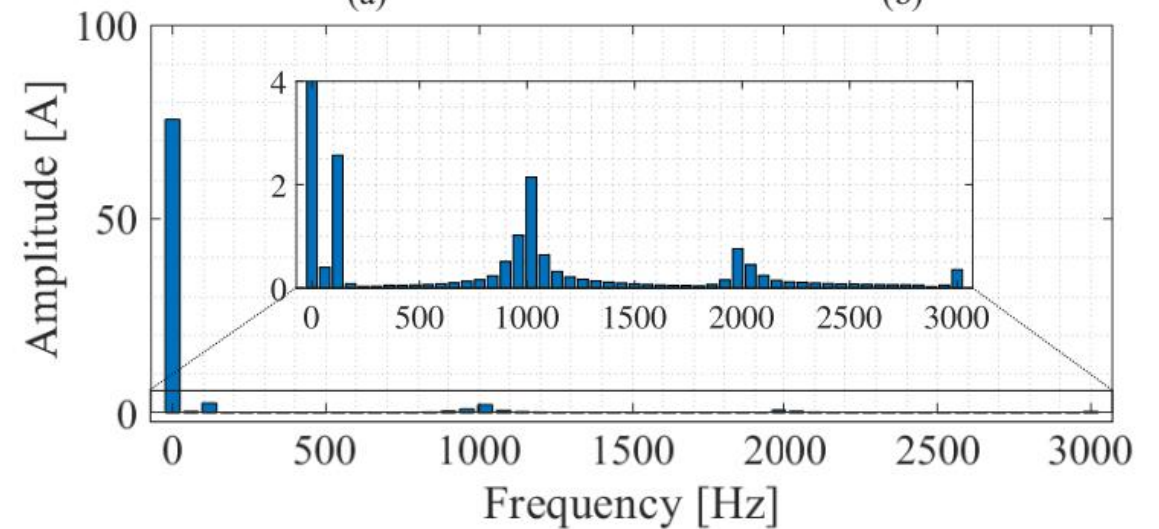
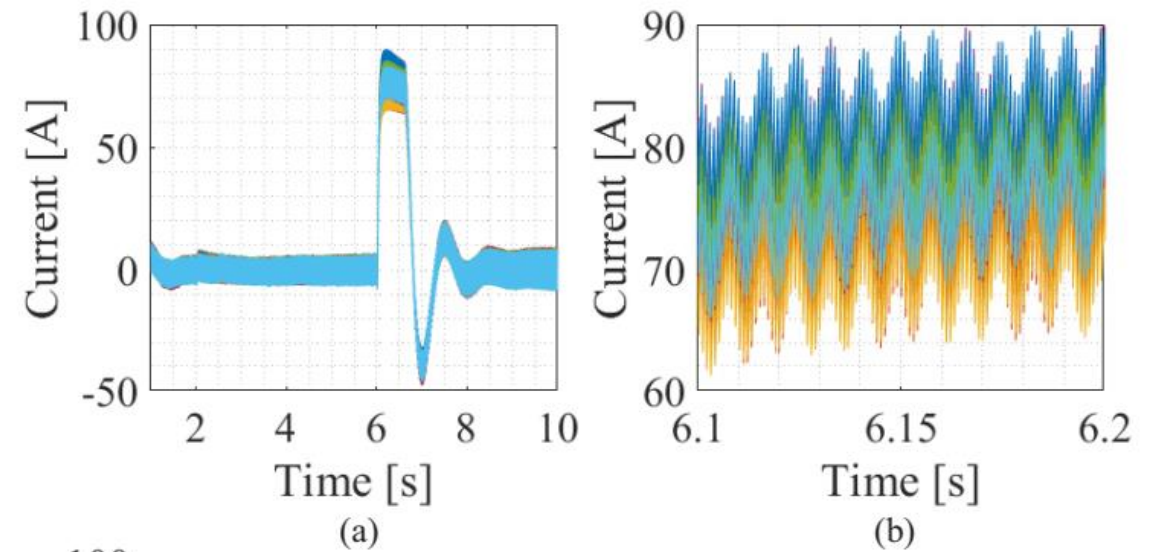
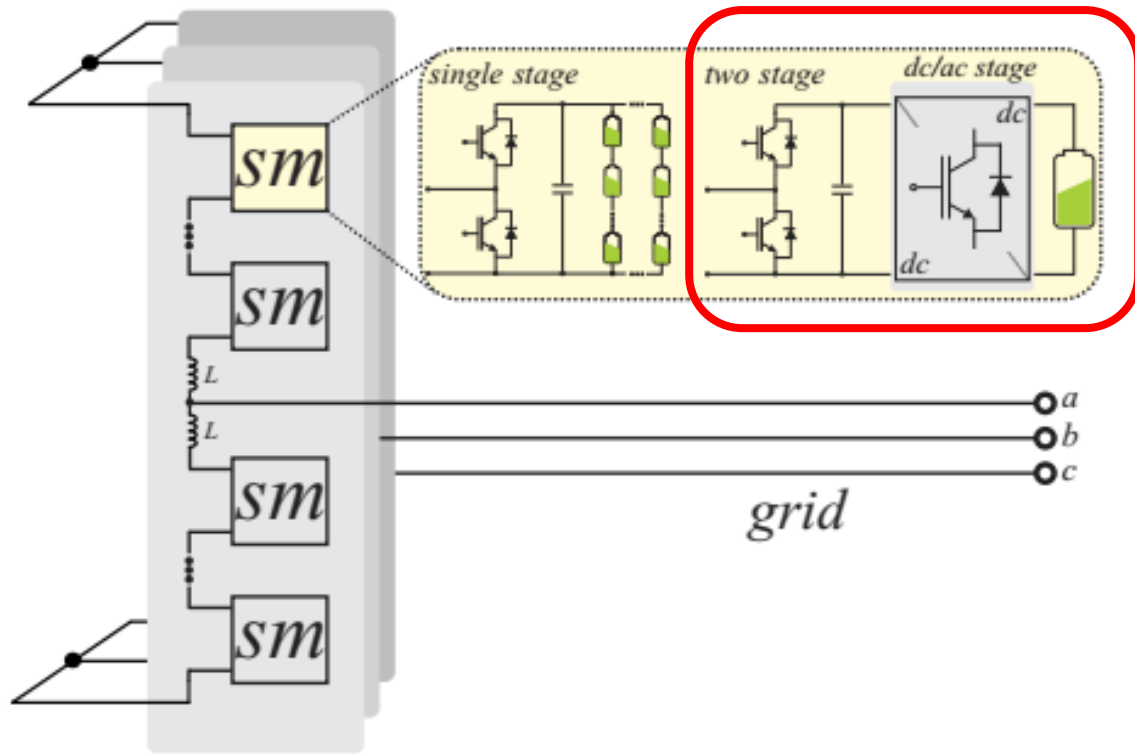
Fonte: Jonathan H. D. G. Pinto et. al., "Optimum Design of MMC-based ES-STATCOM Systems: The Role of the Submodule Reference Voltage," in IEEE Transactions on Industry Applications, Early access.

Comparação – Corrente nas baterias (Estágio único)



Fonte: Jonathan H. D. G. Pinto, “Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter”, 2020.

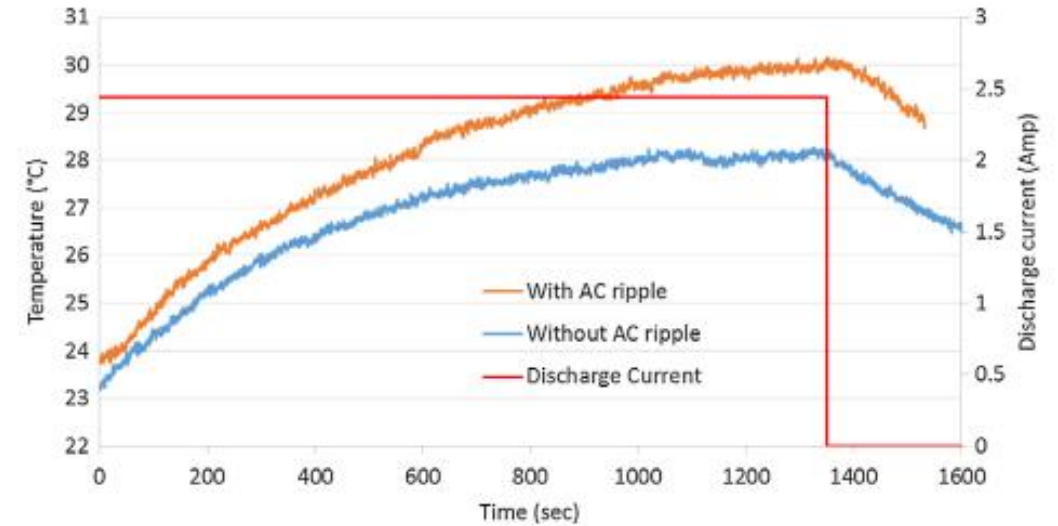
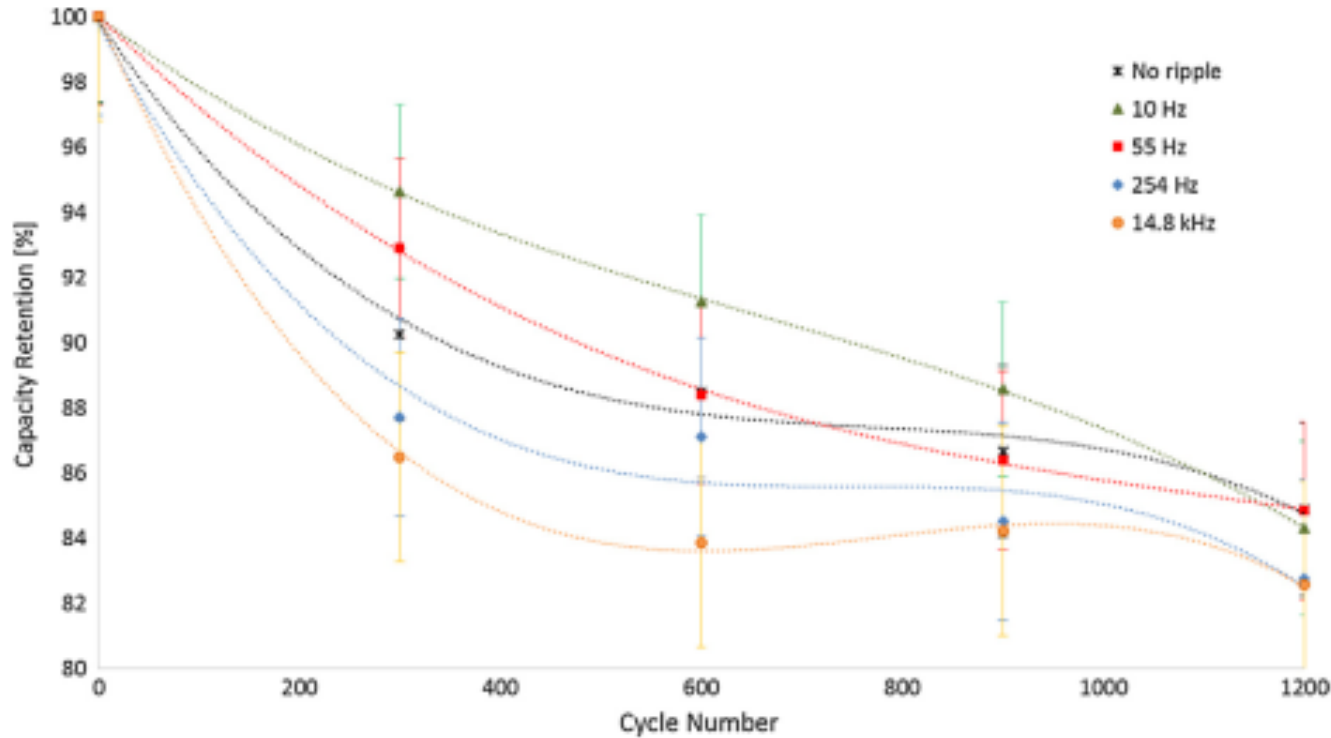
Comparação – Corrente nas baterias (Estágio duplo)



Fonte: Jonathan H. D. G. Pinto, “Modeling, Design and Performance Evaluation of Battery Energy Storage Systems based on Modular Multilevel Converter”, 2020.

Ondulação degrada a bateria?

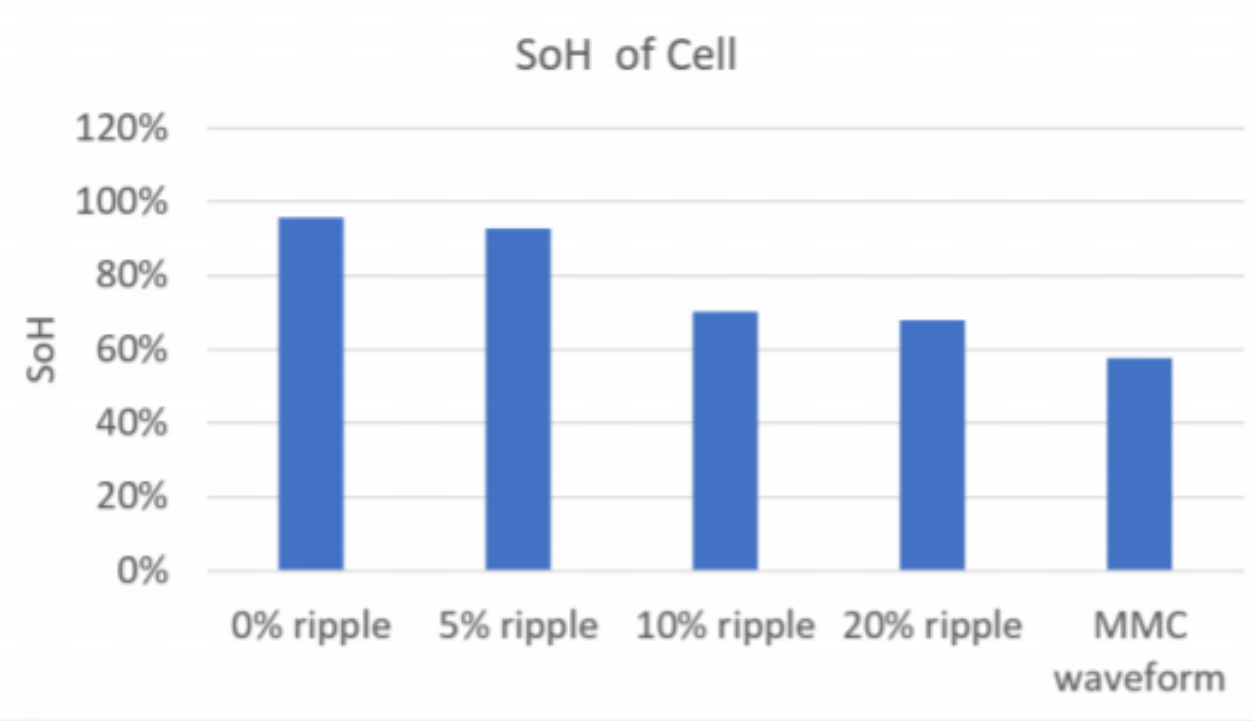
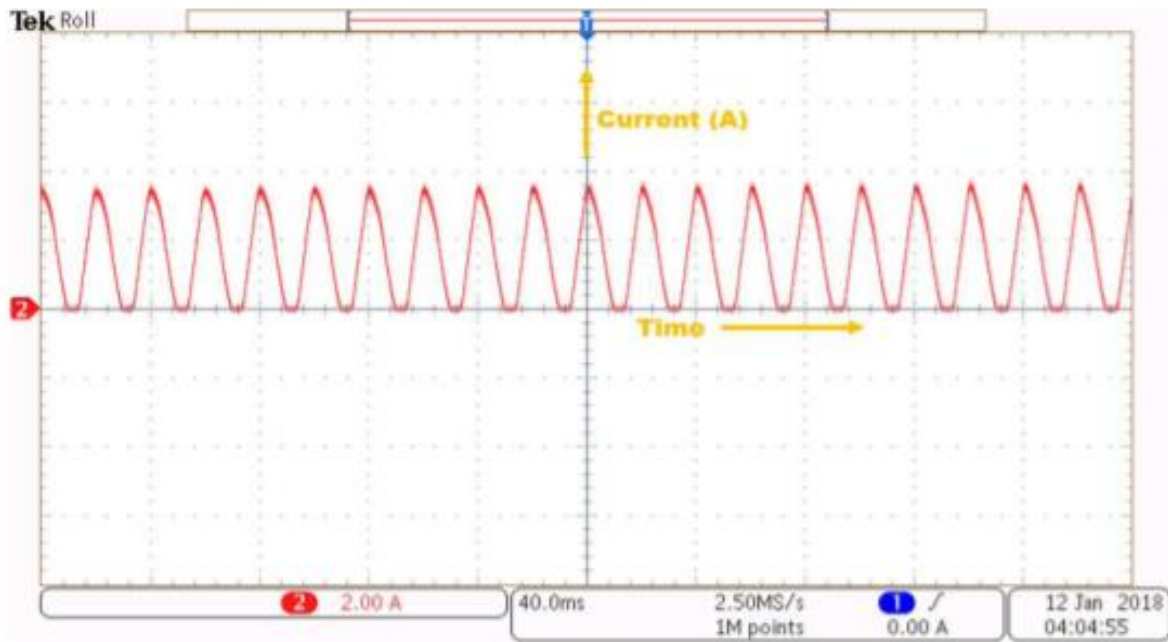
Estudo 1 – Efeito na temperatura



Fonte: K. Uddin et. al. “The effects of high frequency current ripple on electric vehicle battery performance”. Applied Energy. 2016.

Ondulação degrada a bateria?

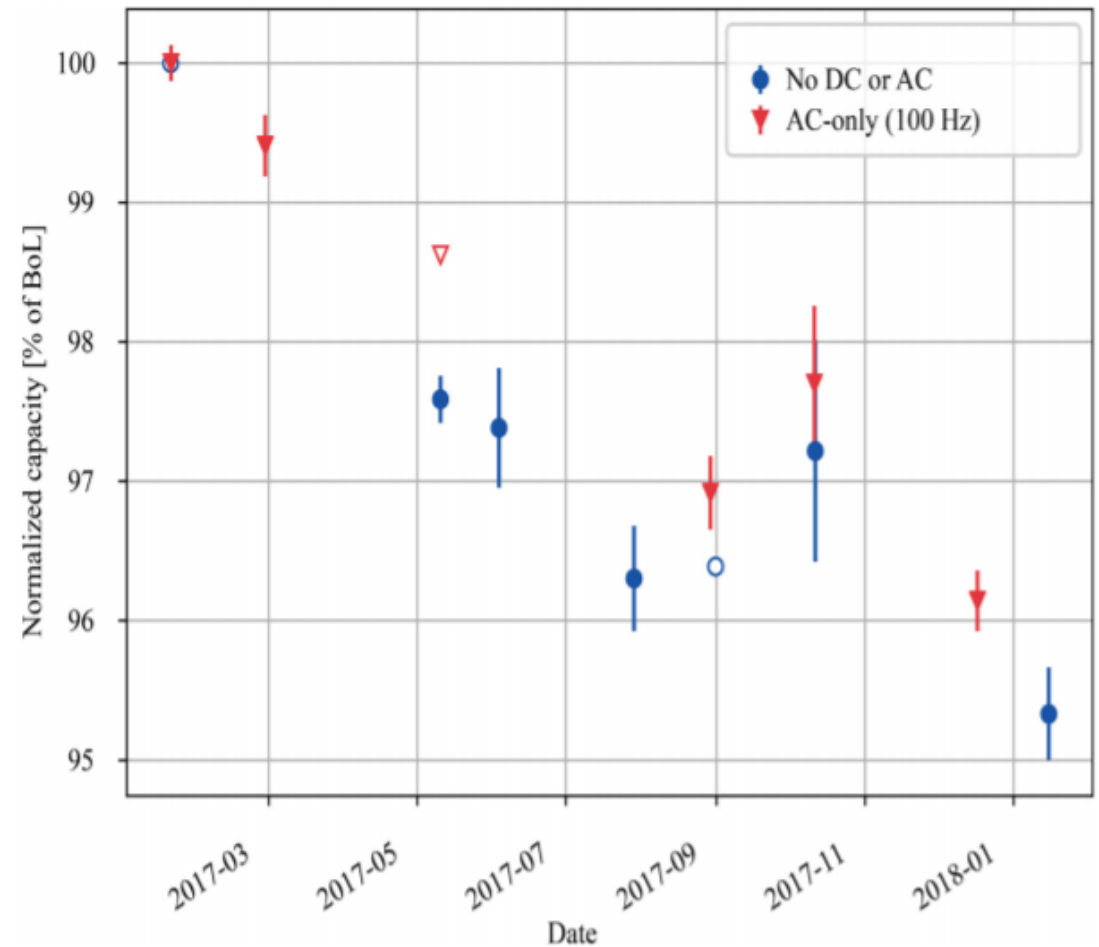
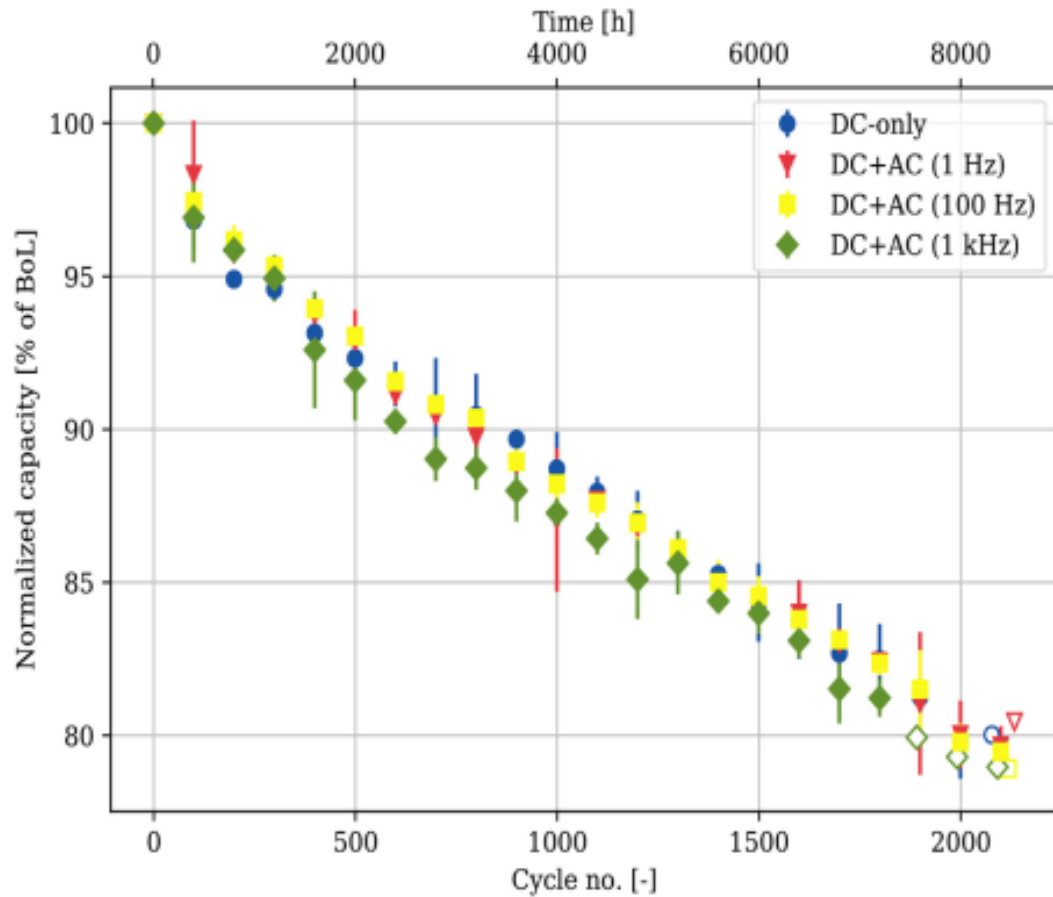
Estudo 2 – Ondulação de baixa frequência elevada



Fonte: I. Puranik et. al. “Impact of Low-Frequency Ripple on Lifetime of Battery in MMC-based Battery Storage Systems”. ECCE. 2018.

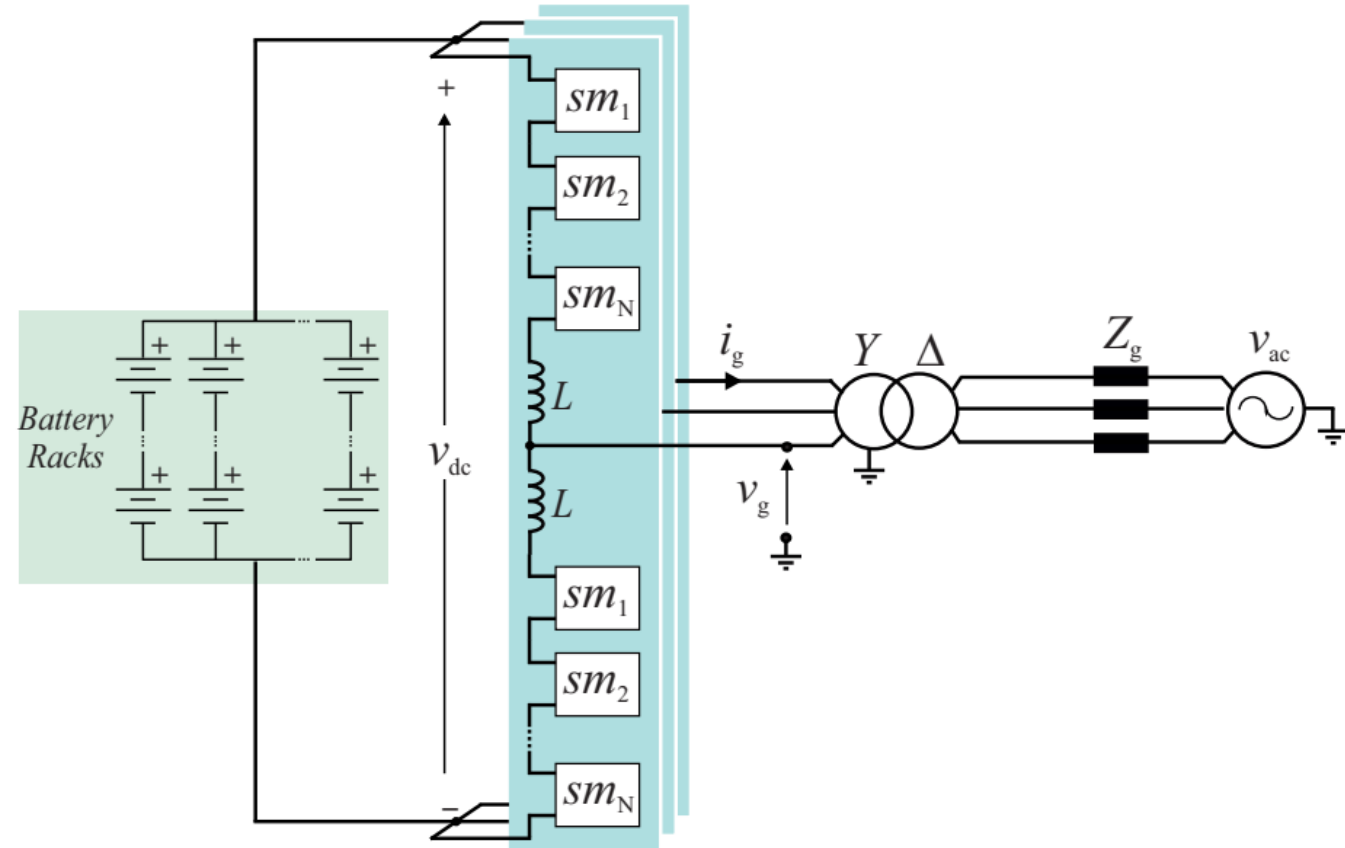
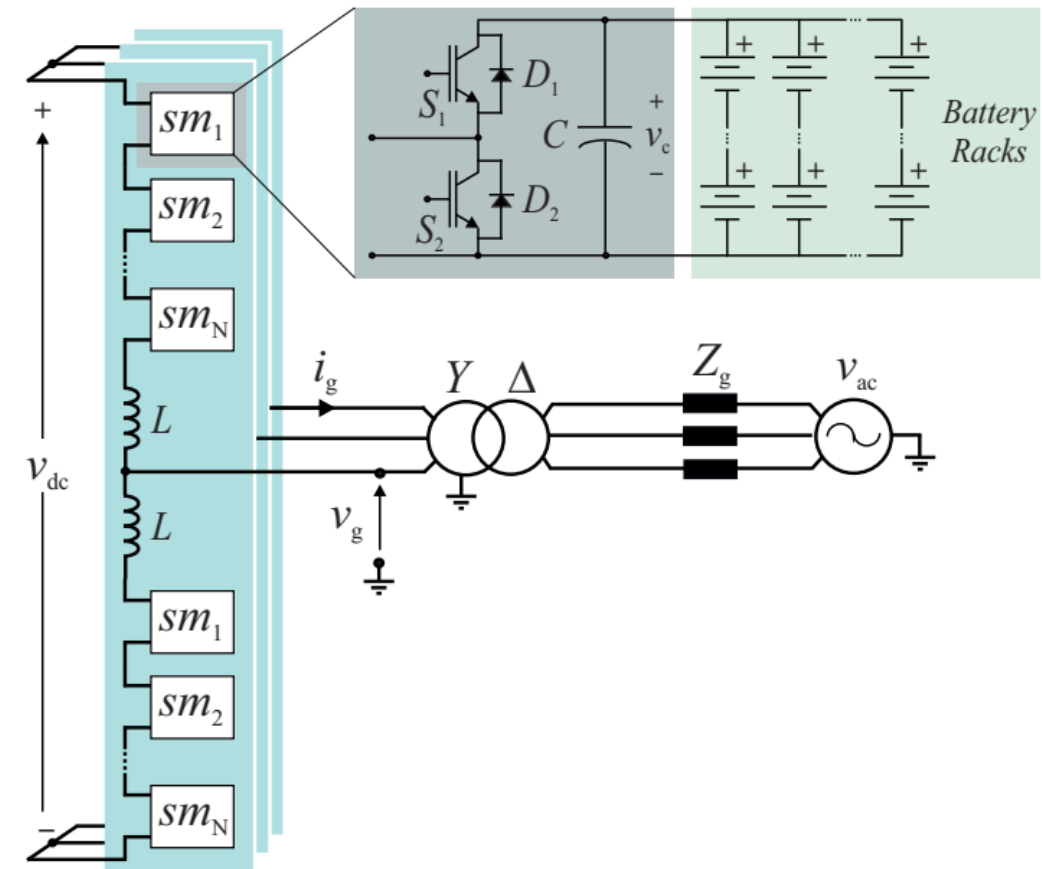
Ondulação degrada a bateria?

Estudo 3 – temperatura constante das baterias



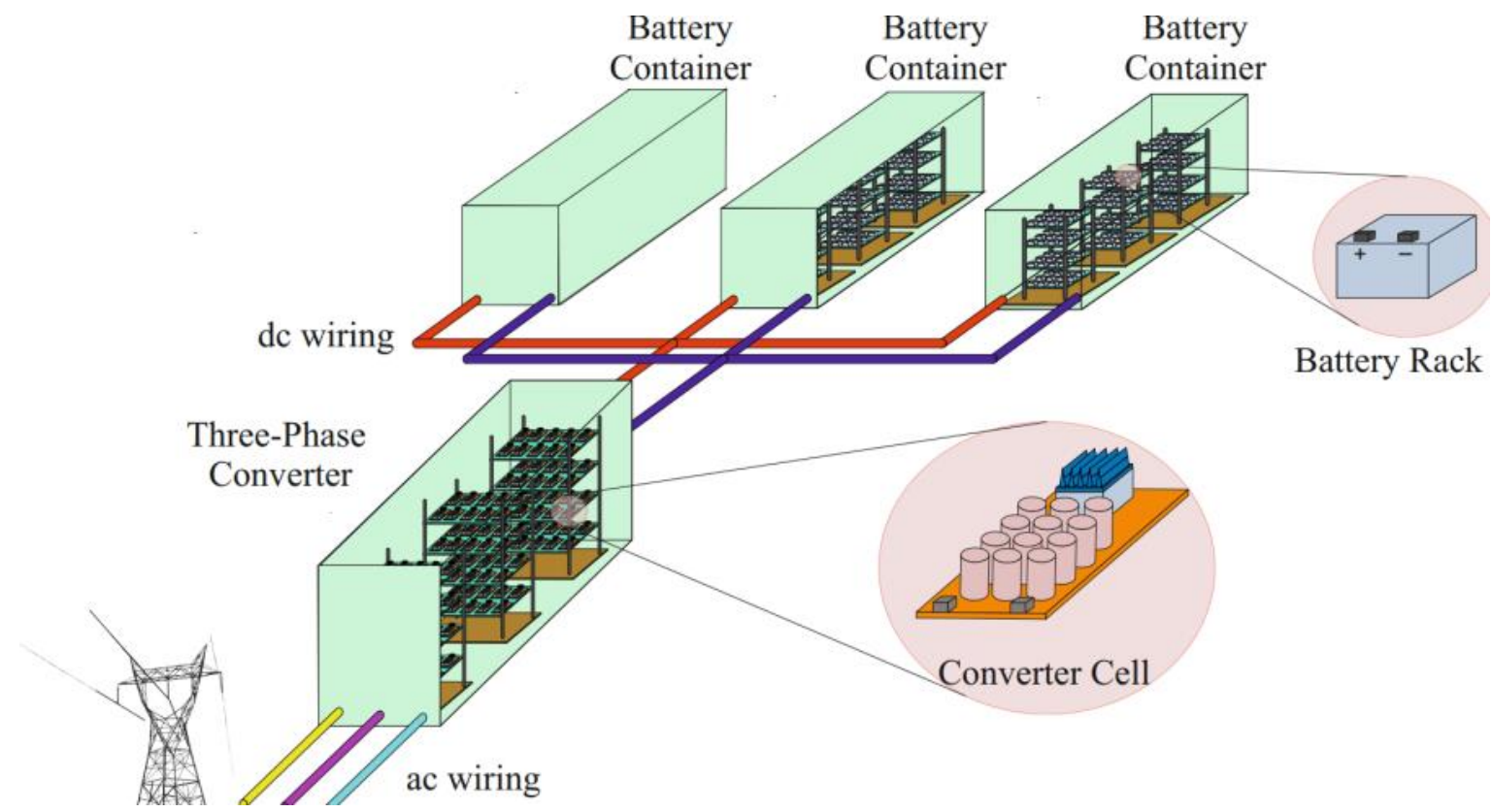
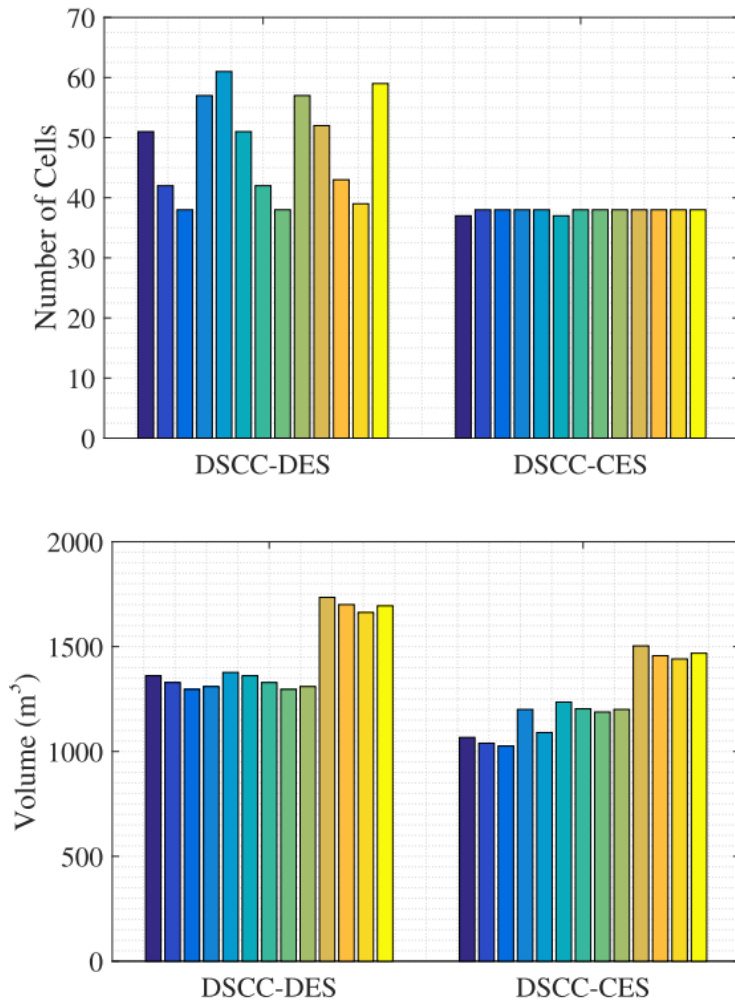
Fonte: A. Bessman, “Aging effects of AC harmonics on lithium-ion cells”, Journal of Energy Storage. 2019.

Abordagem centralizada versus distribuída



Fonte: S. K. Chaudhary et. al. "Benchmarking of Modular Multilevel Converter Topologies for ES-STATCOM Realization". Energies. 2020

Número de baterias – abordagem centralizada versus distribuída



Fonte: S. K. Chaudhary et. al. “Benchmarking of Modular Multilevel Converter Topologies for ES-STATCOM Realization”. Energies. 2020

Obrigado pela Atenção



Bons estudos!



Dúvidas: afcupertino@ieee.org



www.gesep.ufv.br



@GESEP



@gesep_vicosa



Gesep



Pesquise por:
“GESEP UFV”



EStimate - Sistemas
Fotovoltaicos



Pesquise por:
“EStimate”