Advanced Architectures for Next-Generation Battery Energy Storage Systems

Prof. Allan Fagner Cupertino
Federal University of Juiz de Fora

August 12th, 2026

Where is GESEP?

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Presentation outline

Part 1: BESS Technology overview

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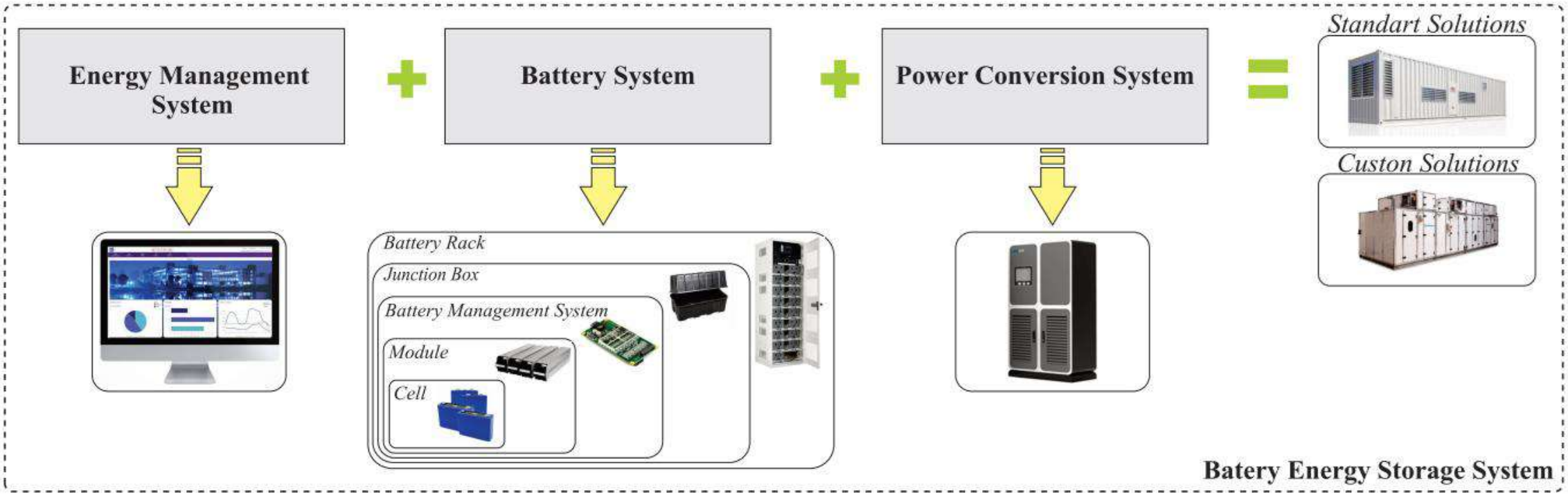
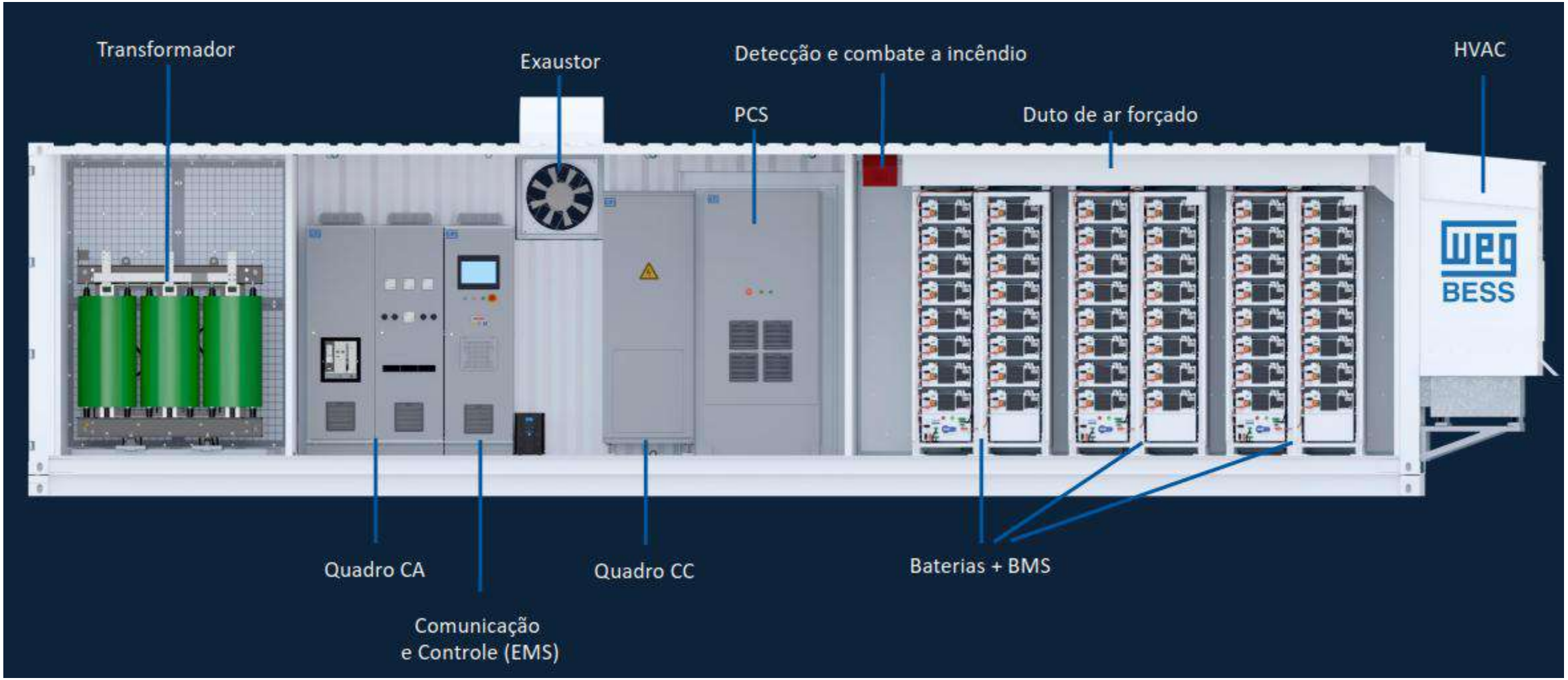
Context and relevance

- Wide integration of renewable energy power plants;
- Inertia challenge;
- High increase of electric mobility;
- Second-life batteries market.
- BESS are fundamental for energy transition.

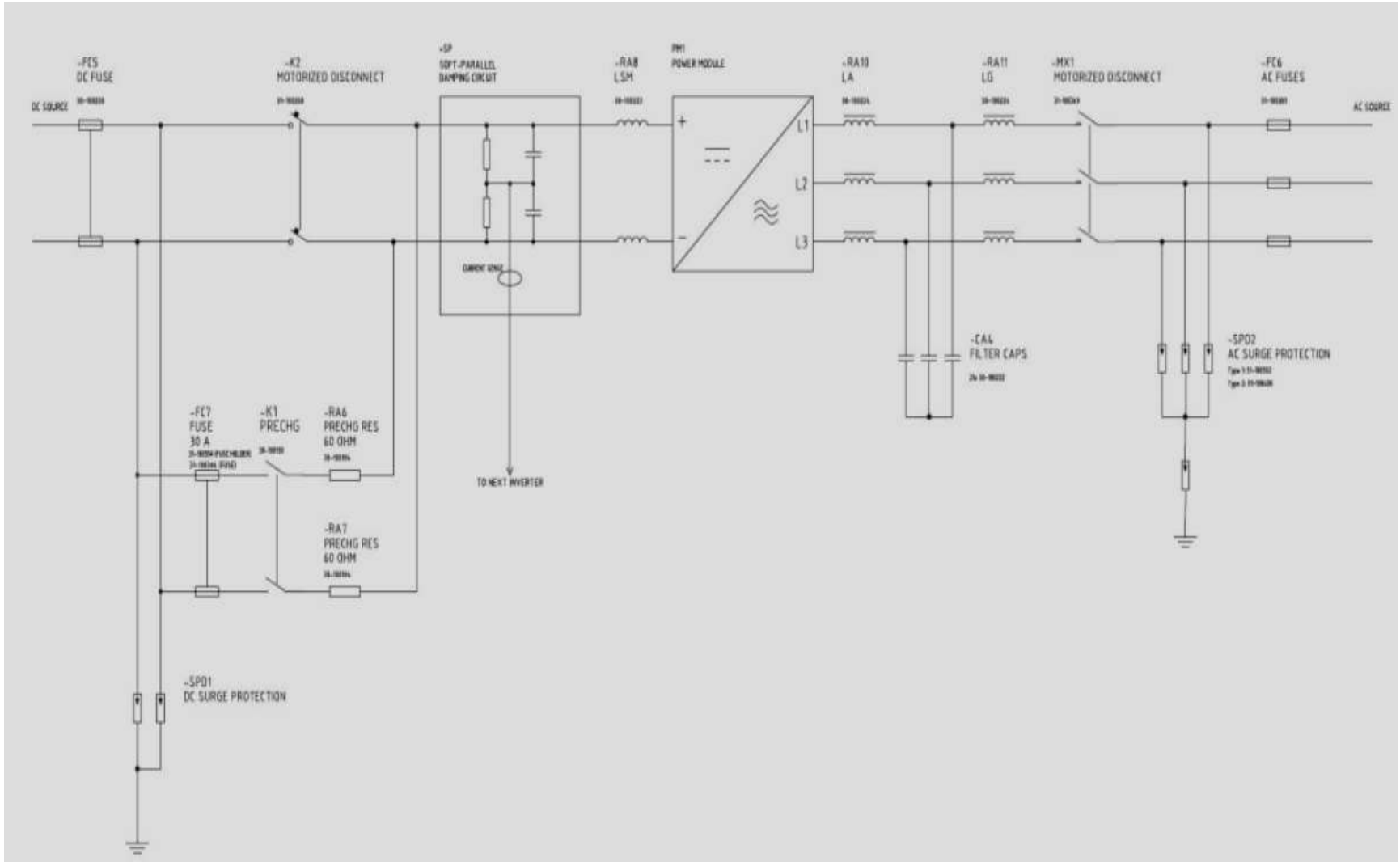
Battery energy storage system



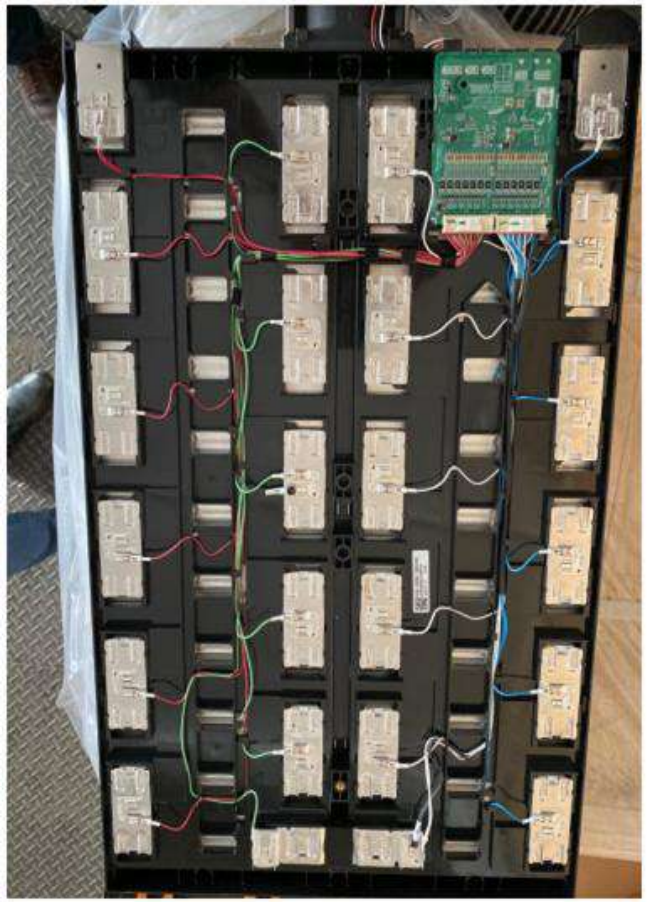
Example of commercial BESS

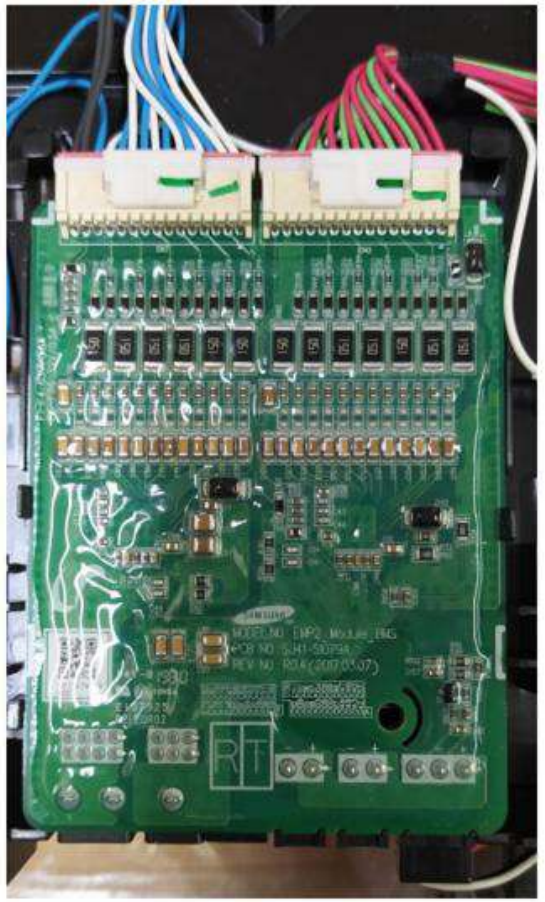


PCS

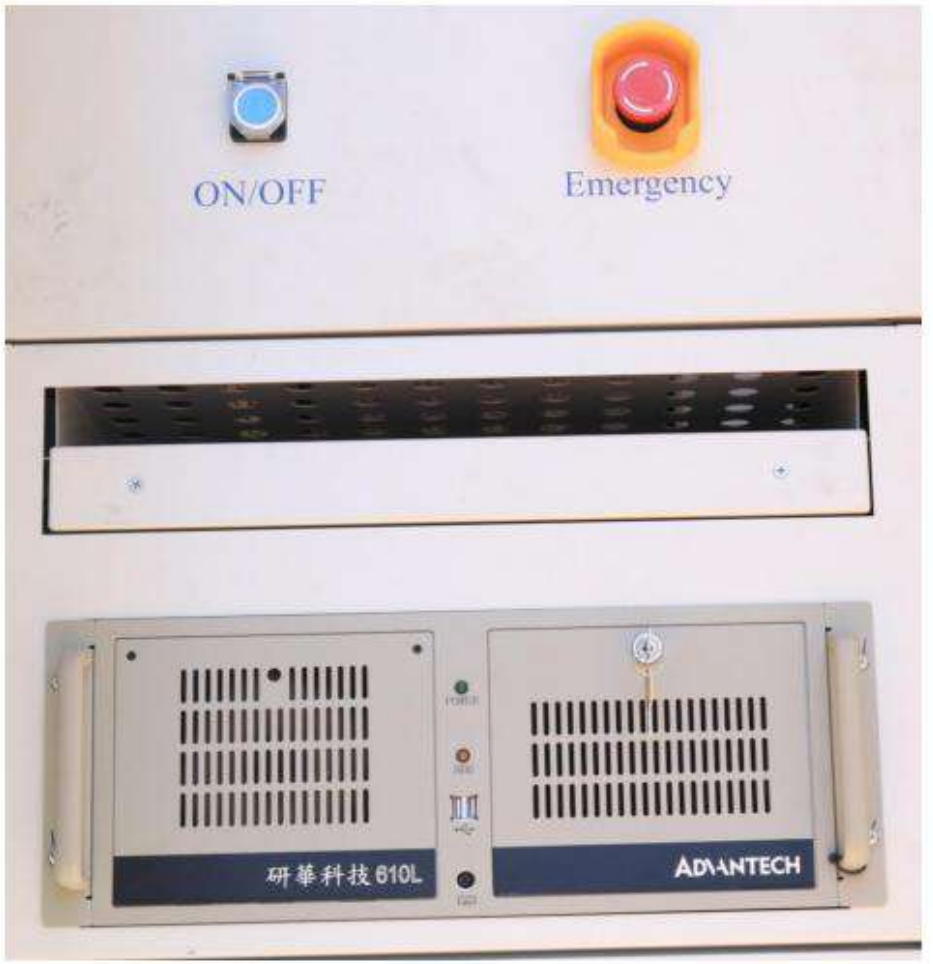

-FC5
DC FUSE
-K2
MOTORIZED DISCONNECT
-SP
SOFT-PARALLEL
DAMPING CIRCUIT
-RA8
LSM
PM1
POWER MODULE
-RA10
LA
-RA11
LG
-MX1
MOTORIZED DISCONNECT
-FC6
AC FUSES
DC SOURCE
AC SOURCE
L1
L2
L3
-CA4
FILTER CAPS
-SPD2
AC SURGE PROTECTION
-FC7
FUSE
30 A
-K1
PRECHG
-RA6
PRECHG RES
60 OHM
-RA7
PRECHG RES
60 OHM
TO NEXT INVERTER
-SPD1
DC SURGE PROTECTION

Storage Unit

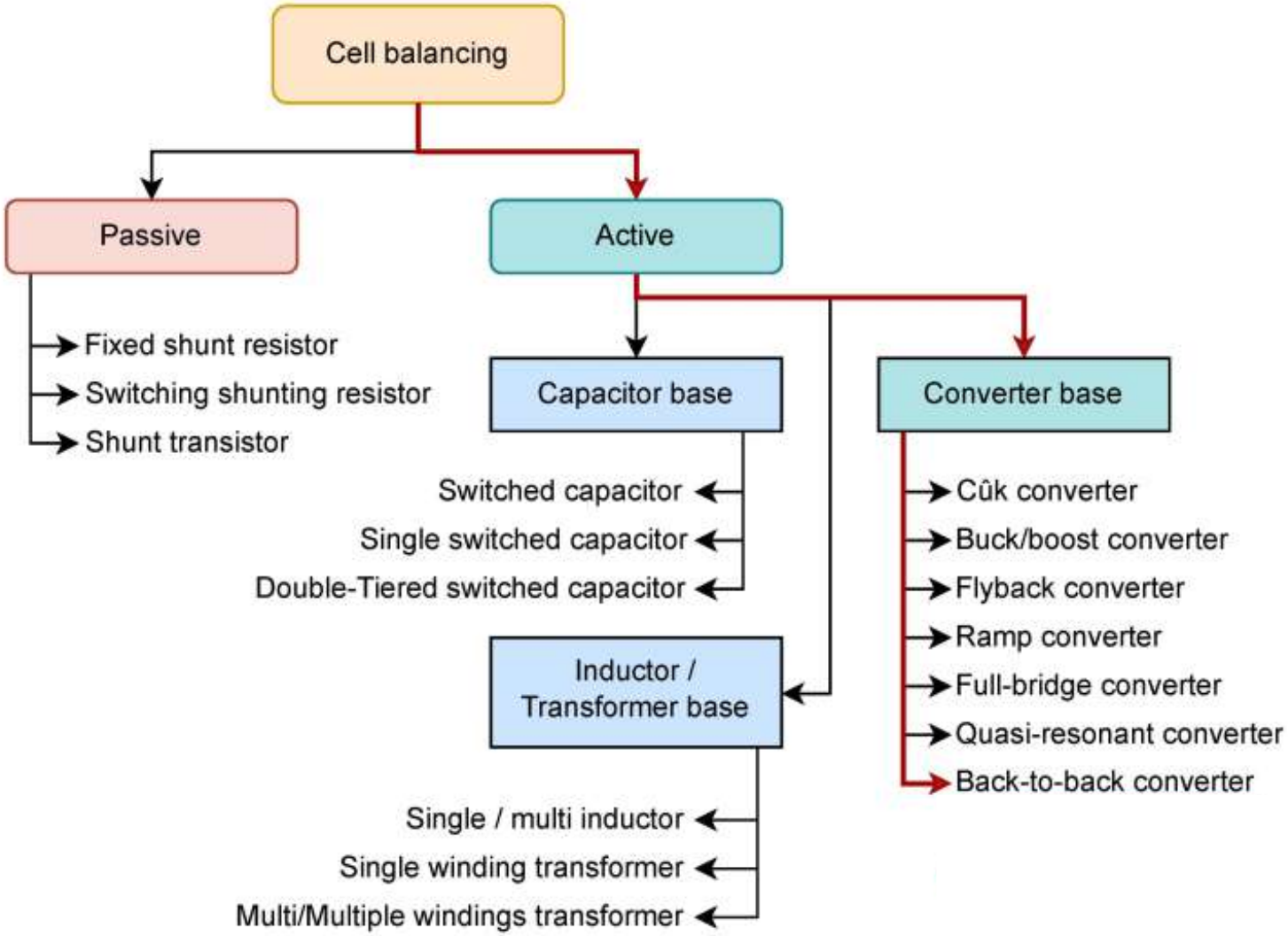




Battery management system



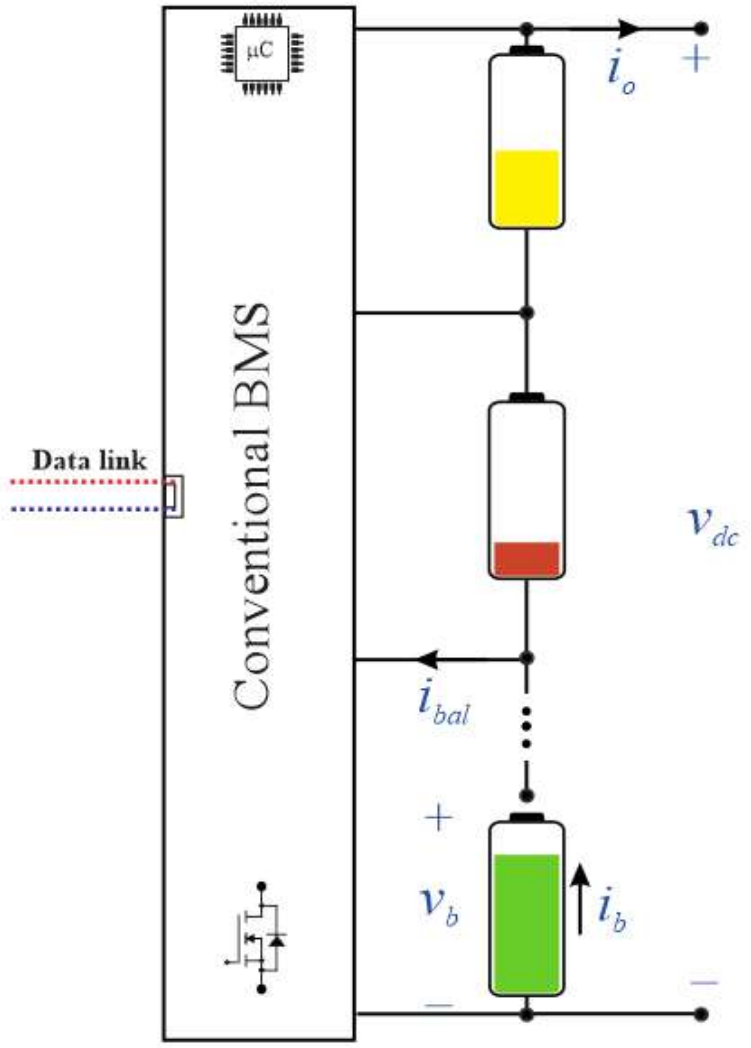
Cell balancing technology overview



Corrêa, T. P., Maia, T. A. C., & Cardoso Filho, B. J. (2023). High-Performance Power Electronic Battery Pack Based on a Back-to-Back Converter. Energies, 16(1), 375. doi: 10.3390/en16010375.

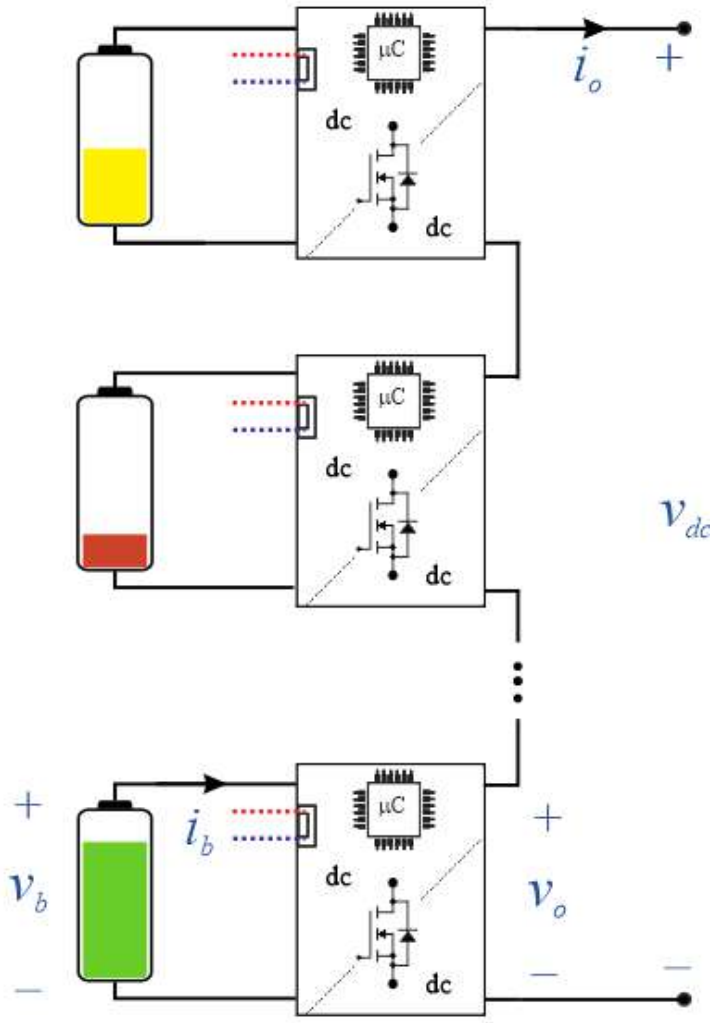
Drawbacks – conventional BESS architecture

- Low fault tolerance;
- Charging using direct current;
- Losses
  - ✓ Balancing process;
  - ✓ Sub-optimum inverter design.
- Safety issues.



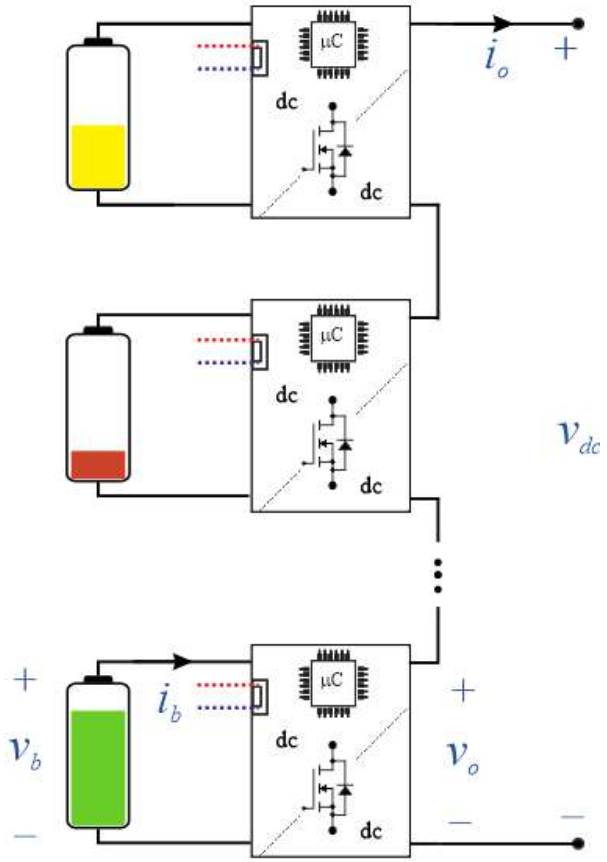
Alternative approach

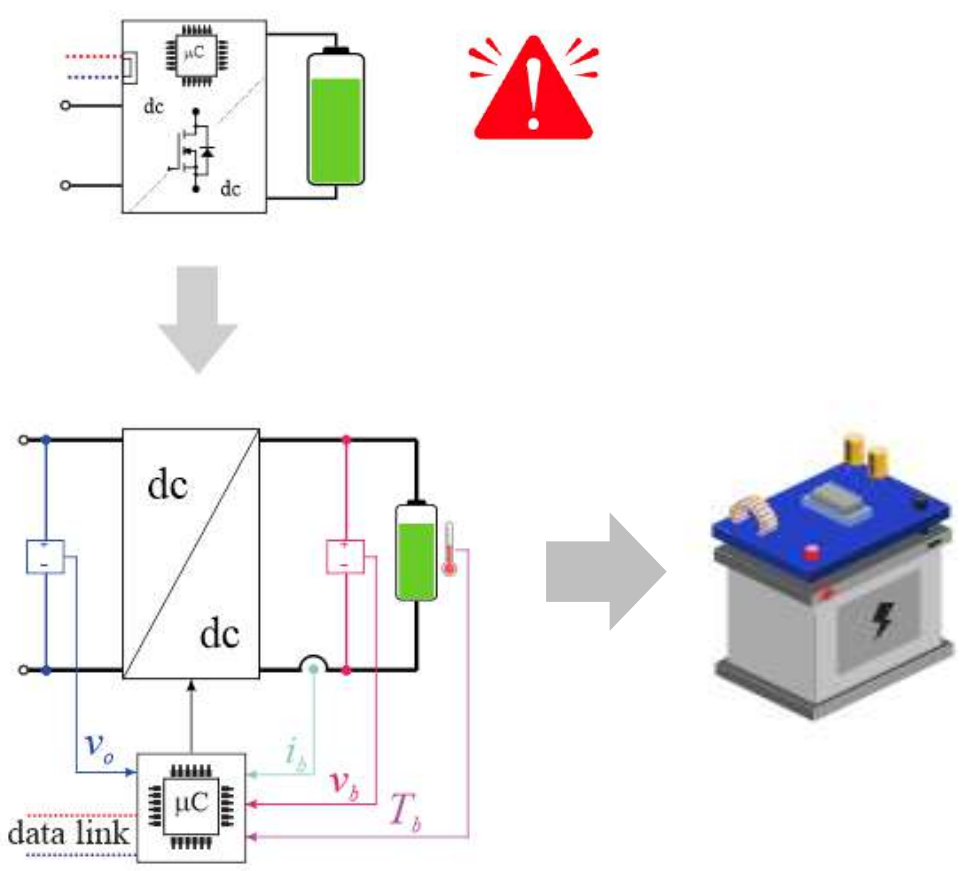
- Power electronics integrated into the battery;
- Same number of terminals of standard approach;
- Compatible with commercial PCS technology;
- Shares PCS and BMS functions;
- Inspired on the modular multilevel converter structure.



Alternative approach

- Smart battery or modular BMS or cascaded dc/dc or BIC or …

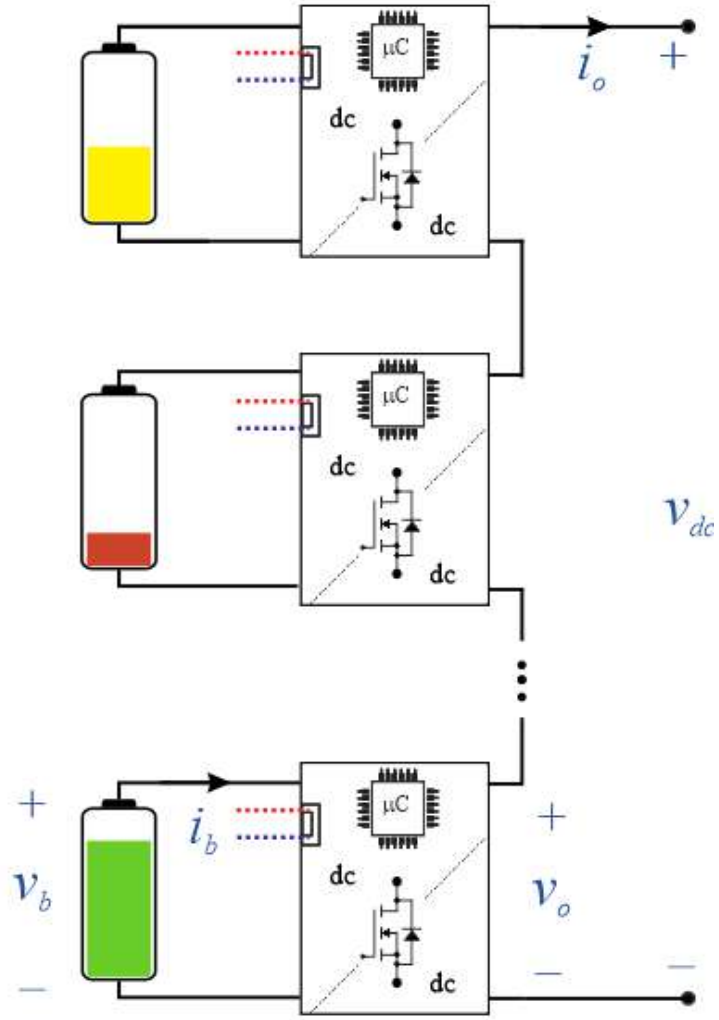




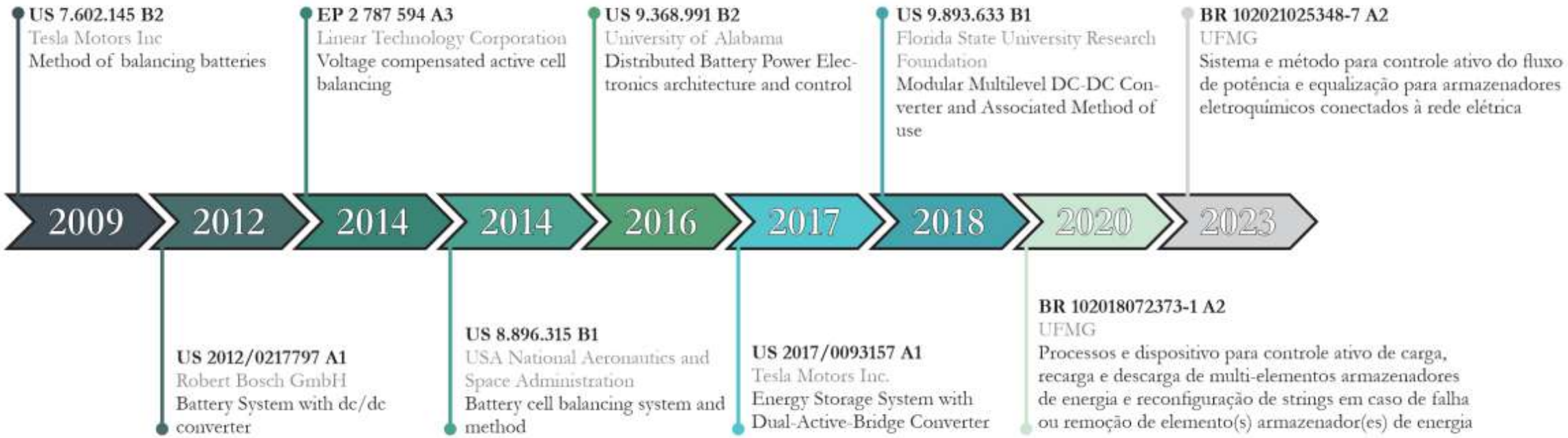
Challenges

- Cost!

- Control strategies and architectures;
- Converter design;
- Is this approach new?



Patents timeline

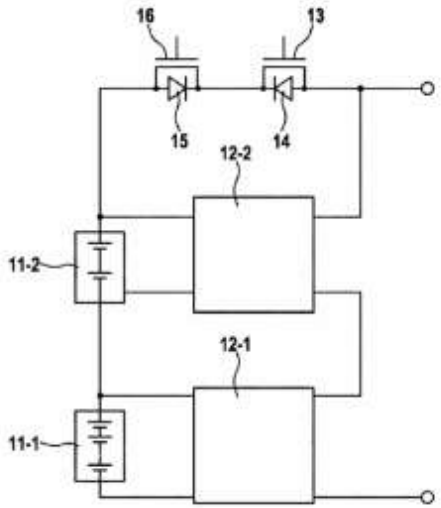


Timeline

2009 2012 2014 2014 2016 2017 2018 2020 2023

BOSCH

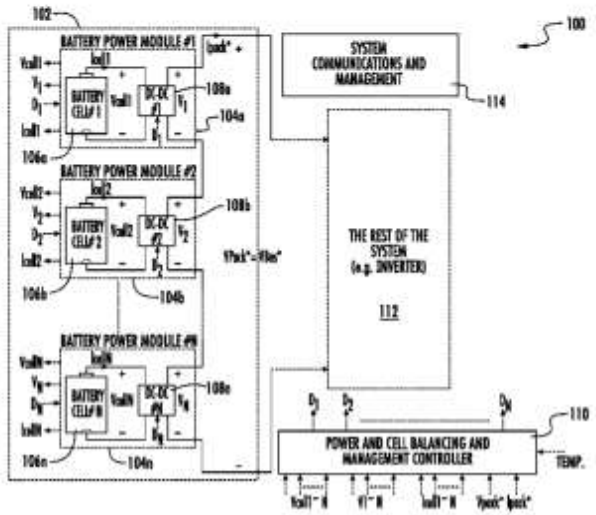
US 2012/0217797 A1
Robert Bosch GmbH
Battery System with dc/dc converter



Timeline

US 9.368.991 B2
University of Alabama
Distributed Battery Power Electronics architecture and control

2009 2012 2014 2014 2016 2017 2018 2020 2023



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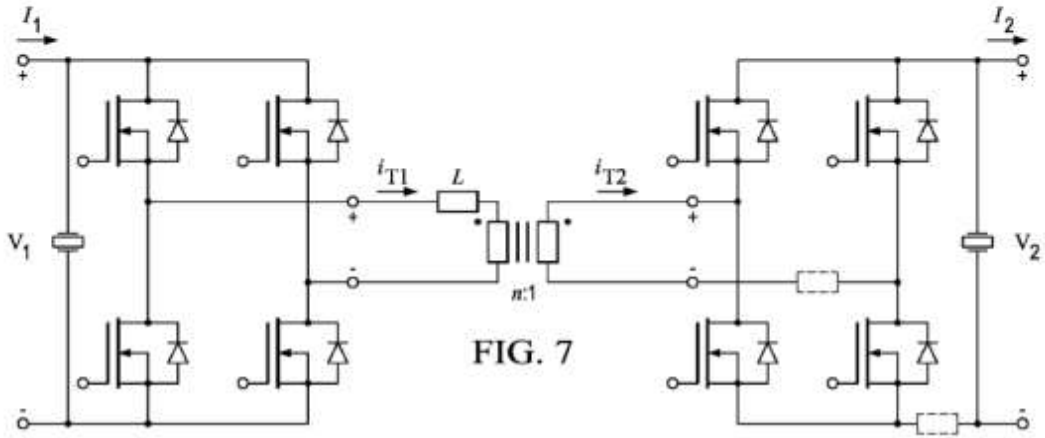
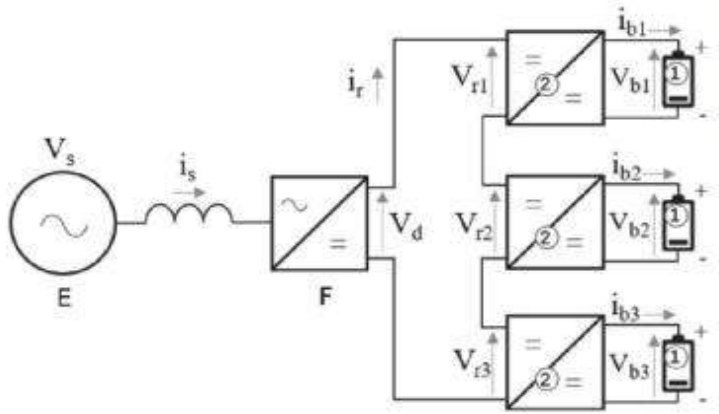


FIG. 7

US 2017/0093157 A1
Tesla Motors Inc.
Energy Storage System with
Dual-Active-Bridge Converter

TESLA

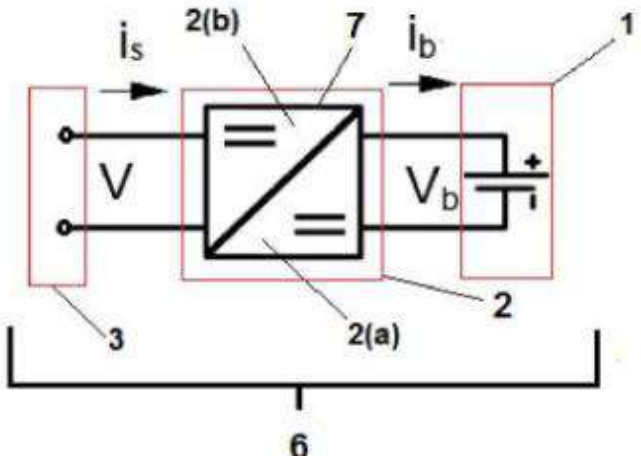
Timeline



2009 | 2012 | 2014 | 2014 | 2016 | 2017 | 2018 | 2020 | 2023

BR 102021025348-7 A2
UFMG
Sistema e método para controle ativo do fluxo de potência e equalização para armazenadores eletroquímicos conectados à rede elétrica

BR 102018072373-1 A2
UFMG
Processos e dispositivo para controle ativo de carga, recarga e descarga de multi-elementos armazenadores de energia e reconfiguração de strings em caso de falha ou remoção de elemento(s) armazenador(es) de energia



Part 2: Smart Battery Fundamentals

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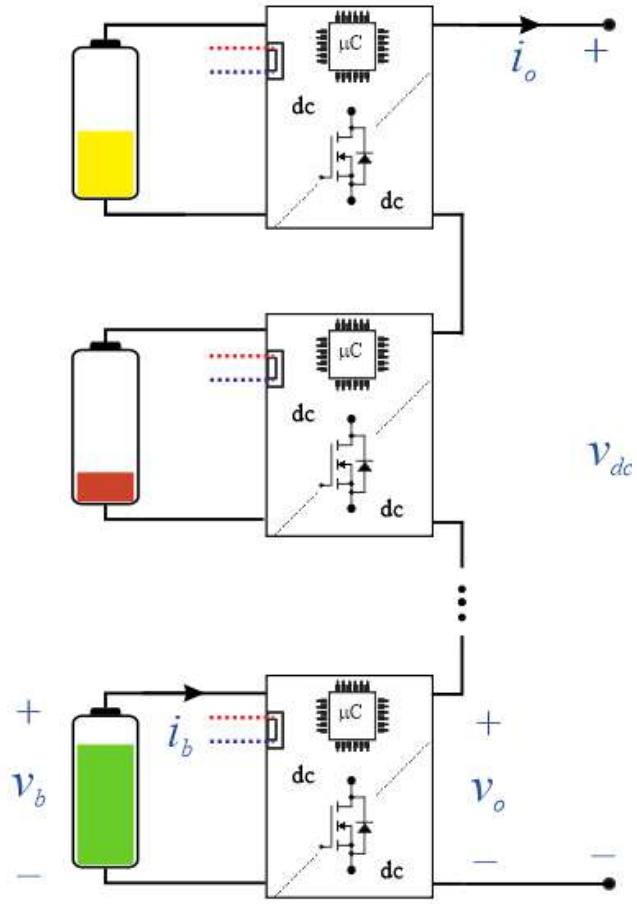
Important assumptions

- BIC behaves as a voltage source;
  - ✓ Output voltage can be controlled.
  - ✓ Usually, two-quadrant topologies are employed.



Important assumptions

- BIC behaves as a voltage source;
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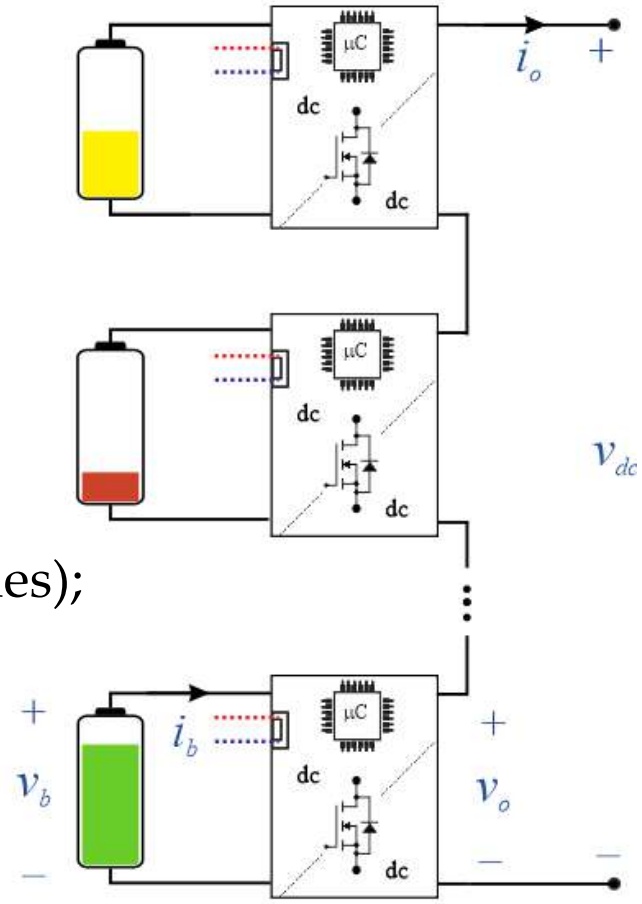
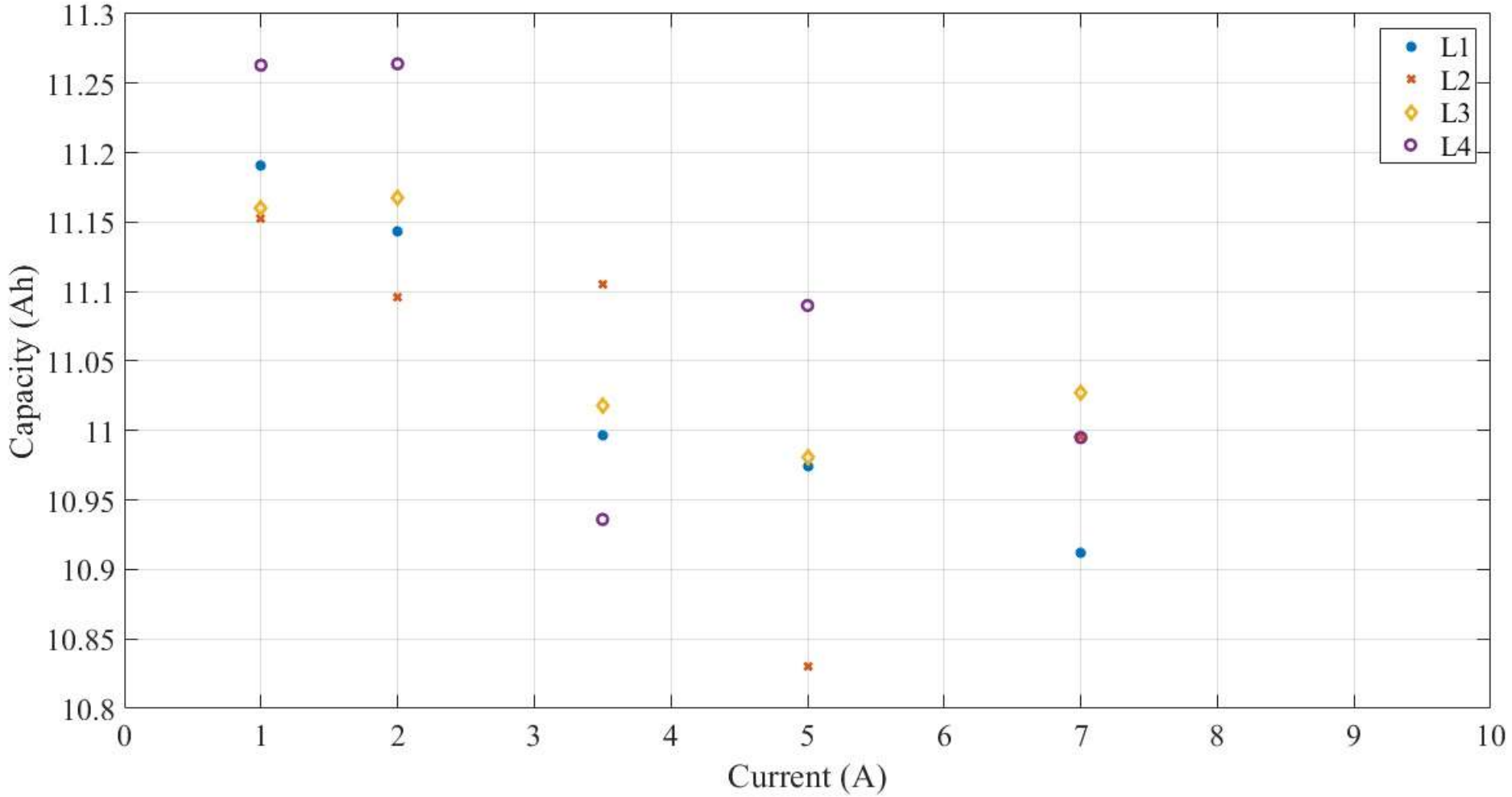
- Batteries are not equal, i.e.:
  - ✓ Different initial states of charge (expected in practice);
  - ✓ Different chemistries and voltages (much more challenging);
  - ✓ Different impedances and capacities (expected even for new batteries);



Capacity measurements – 10 Ah LFP



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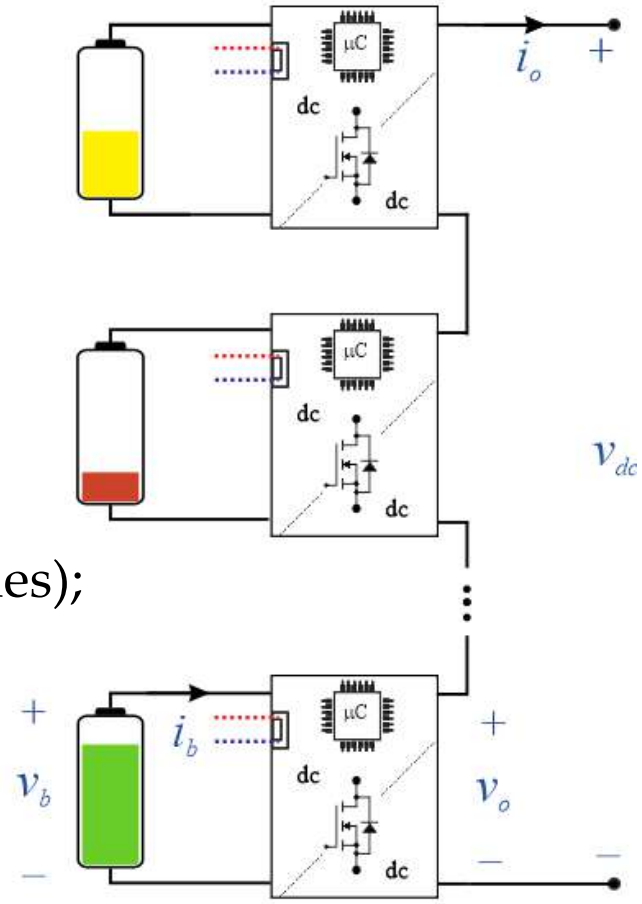
- Control objectives
  - ✓ Output volage regulation;
  - ✓ Constant dc-link voltage;
  - ✓ Active state balancing.



Physics of operation

- Output voltage reference:

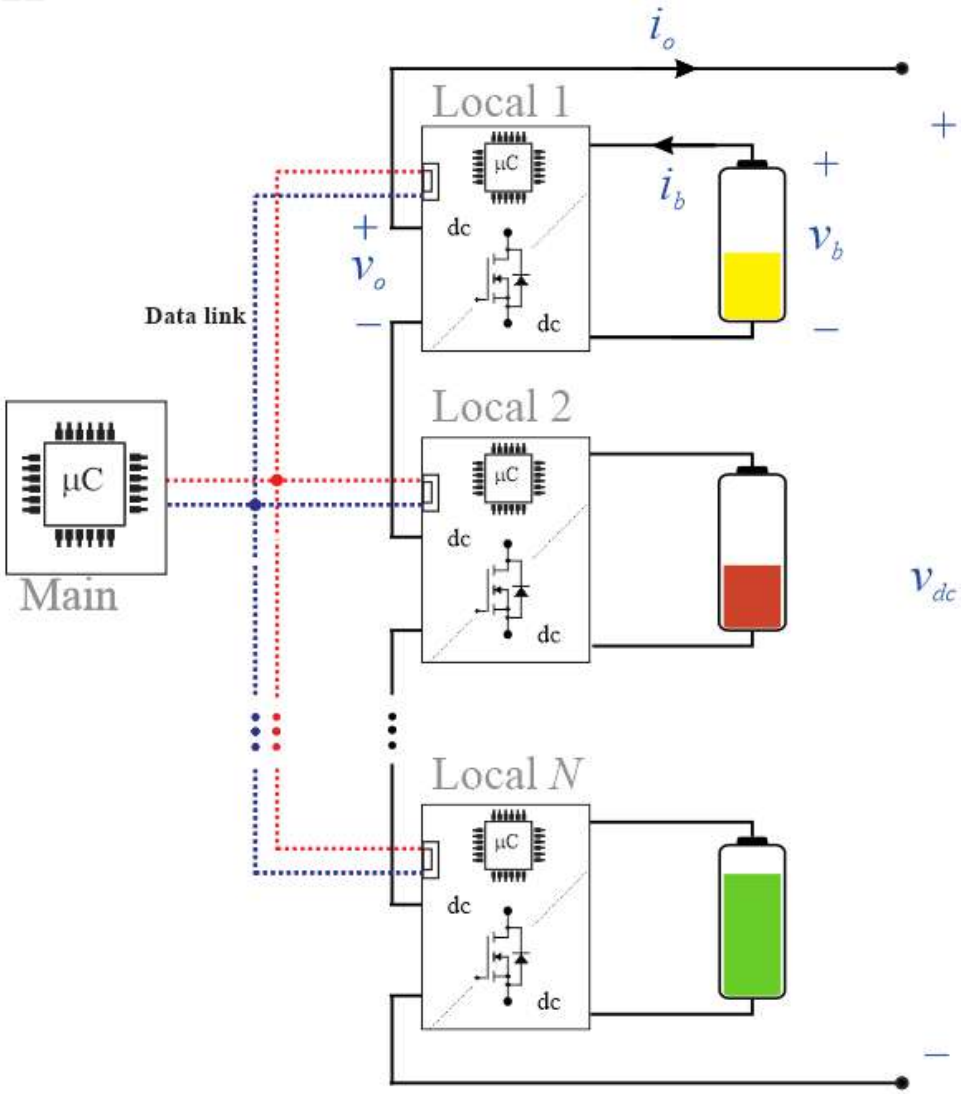
$$v_{o,i} = \frac{v_{dc}^*}{N} + \Delta V_i \qquad \sum_{j=1}^{n} v_{o,j} = v_{dc}^* + \sum_{j=1}^{n} \Delta V_j$$

- If the control algorithm guarantees that:

$$\sum_{j=1}^{n} \Delta V_j = 0$$

- Then,

$$v_{o,i} \approx \frac{v_{dc}^*}{N} \Rightarrow \sum_{j=1}^{n} v_{o,j} = v_{dc}^*$$

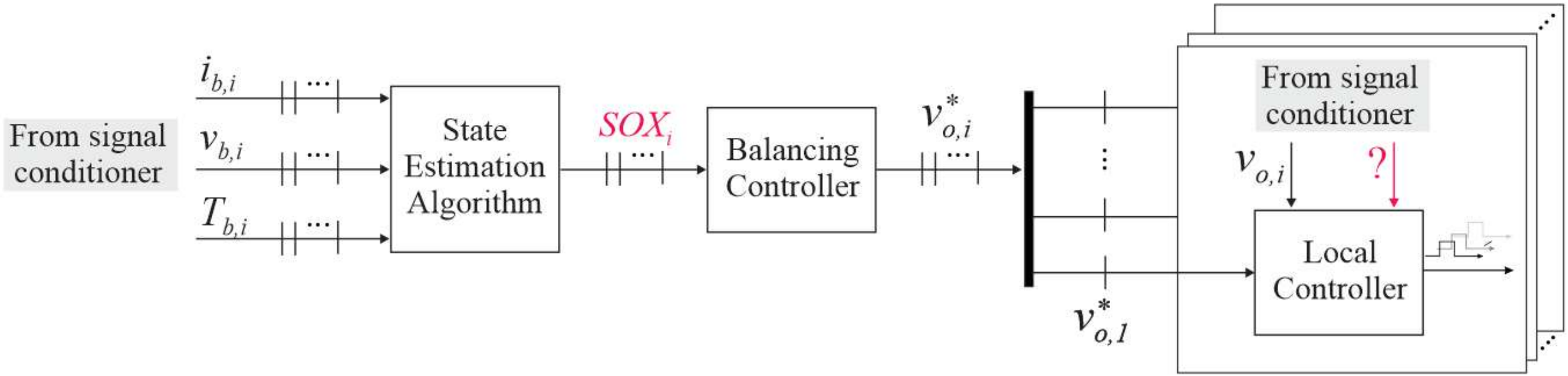


- Dc/dc converter power balance equation:

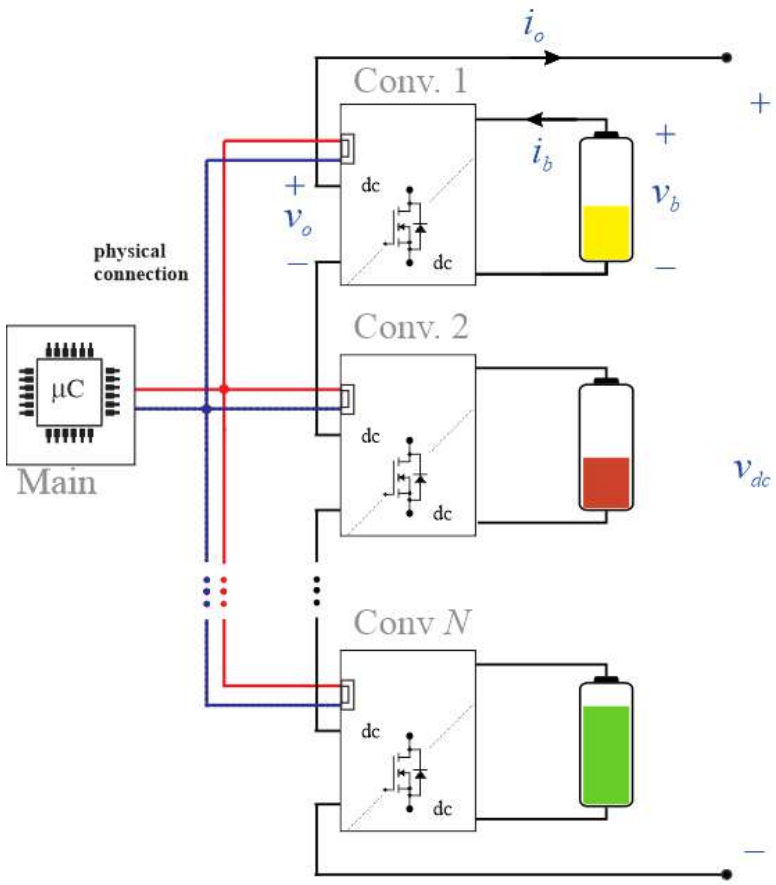
$$p_{b,i} \approx p_{o,i} \Leftrightarrow v_{b,i} \cdot i_{b,i} \Leftrightarrow i_{b,i} = \frac{v_{o,i} \cdot i_o}{v_{b,i}} + \frac{\Delta V_i \cdot i_o}{v_{b,i}}$$

?

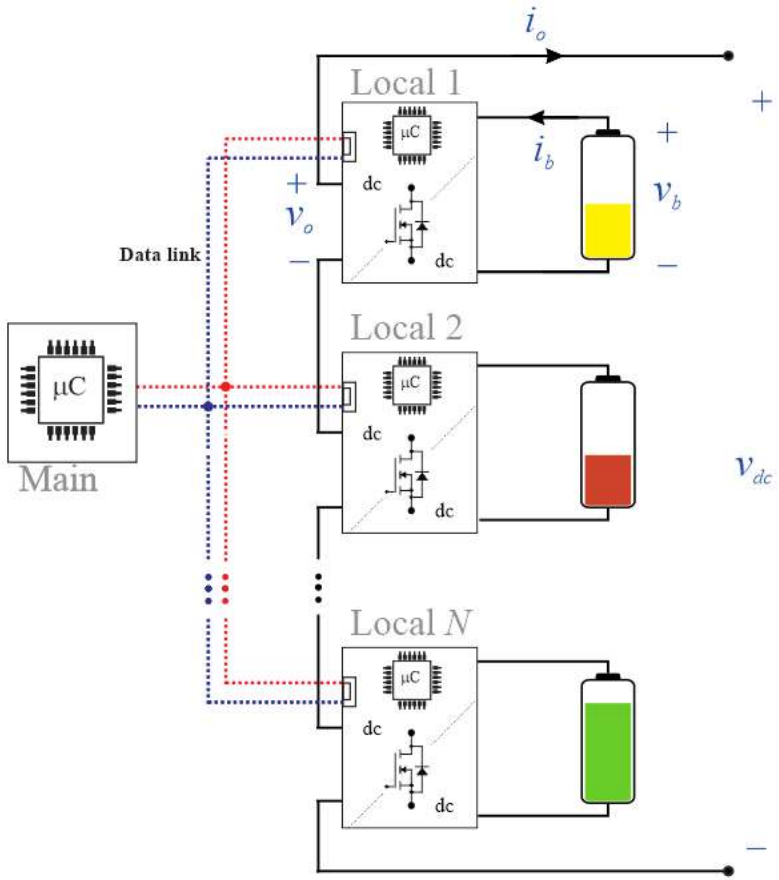
General scheme – SoX balancing



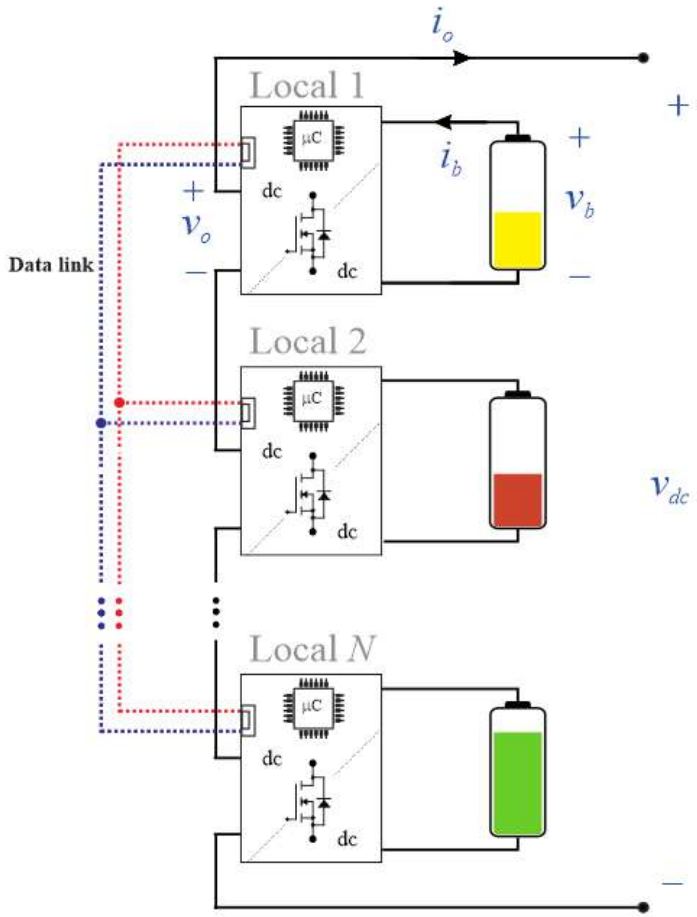
Possible architectures



- Centralized.

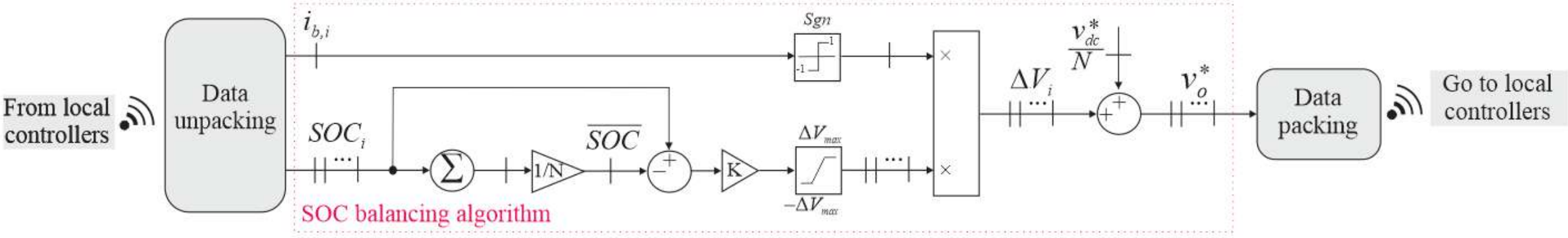


- Leader-follower.



- Decentralized.

Proportional balancing controller



- Balancing voltage contribution:

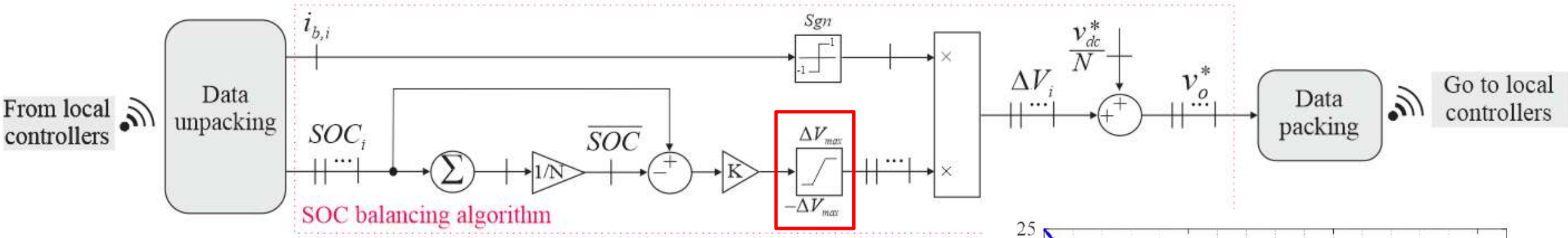
$$\Delta V_i = \mathrm{sgn}(i_{b,i}) \cdot K\left(\overline{SOC} - SOC_i\right) = \pm K\left(\overline{SOC} - SOC_i\right)$$

- It is important to note that:

$$\sum_{j=1}^{n} \Delta V_j = K \sum_{j=1}^{n} \left(\overline{SOC} - SOC_j\right) = 0. \Rightarrow \sum_{j=1}^{n} v_{o,j} = v_{dc}^*$$

[1] J. A. Qahouq and I. Batarseh, "Distributed battery power electronics architecture and control," U.S. Patent 9 368 991 B2, Jun. 14, 2016.
[2] Y. Li and Y. Han, "A module-integrated distributed battery energy storage and management system," IEEE Trans. Power Electron., vol. 31, no. 12, pp. 8260–8270, Dec. 2016..

Converter output voltage saturation

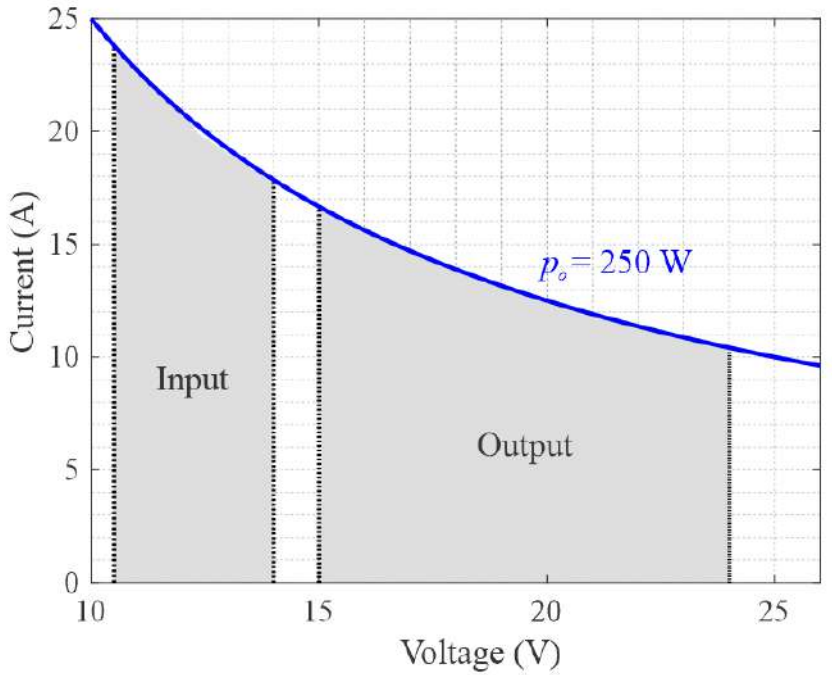


- Converter physical limits;

$$-\Delta V_{max} \leq \Delta V_i \leq \Delta V_{max}$$

- If saturation occurs,

$$\sum_{j=1}^{n} \Delta V_j \neq 0$$



[1] Á. L. C. Amorim et. al., "Steady-state analysis of dc/dc converters applied to smart battery systems," in Proc. Congresso Brasileiro de Automática (CBA), 2024, Art. no. 4702, doi:10.20906/CBA2024/4702.
[2] J. S. d. Oliveira et. al., "Variable-Gain State-of-Charge Balancing Method for Smart Battery Packs," in IEEE Access, vol. 13, pp. 145528-145539, 2025, doi: 10.1109/ACCESS.2025.3597229.

Important analytical results

- Steady-state analysis of SoC balancing

$$v_{o,i} = \frac{v_{dc}^*}{N} + \Delta V_i \Leftrightarrow v_{o_i} \approx \frac{v_{dc}^*}{N}\frac{C_{n,i}}{\overline{C_n}} \quad \text{and} \quad \Delta SOC_i \approx \frac{v_{dc}^*}{KN}\left(\frac{C_{n,i}}{\overline{C_n}} - 1\right)$$

- Transient analysis of SoC balancing

$$\Delta SOC_i(t) \approx \underbrace{\frac{1}{N}\sum_{j=1}^{N} SOC_{i,0} - SOC_{i,0}}_{A} - \underbrace{\frac{K \cdot i_o}{v_b \cdot C_n}}_{B}\int_0^t \Delta SOC_i(t)\, d\tau \Leftrightarrow \Delta SOC_i = A \cdot e^{-B \cdot t}$$

- Condition for constant dc-link voltage during balancing (if K is constant):

$$K \leq \frac{\Delta V_{max}}{|\Delta SOC_{max,0}|}$$

[1] Á. L. C. Amorim et. al., "Steady-state analysis of dc/dc converters applied to smart battery systems," in Proc. Congresso Brasileiro de Automática (CBA), 2024, Art. no. 4702, doi:10.20906/CBA2024/4702.
[2] J. S. d. Oliveira et. al., "Variable-Gain State-of-Charge Balancing Method for Smart Battery Packs," in IEEE Access, vol. 13, pp. 145528-145539, 2025, doi: 10.1109/ACCESS.2025.3597229.

Part 3: Topological overview

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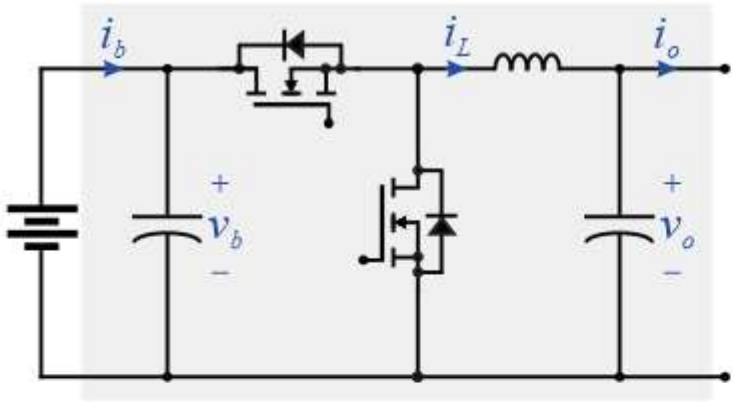
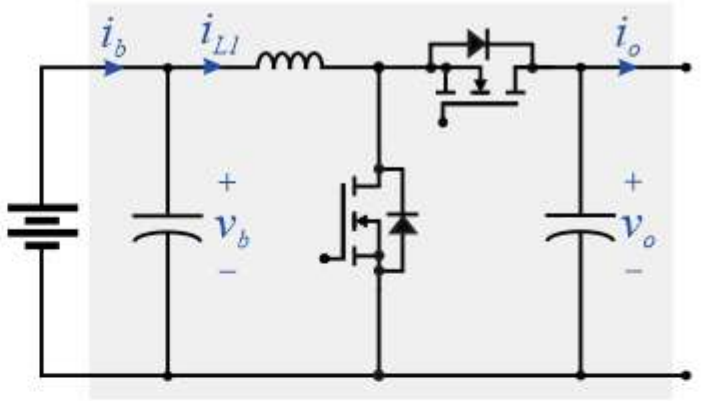
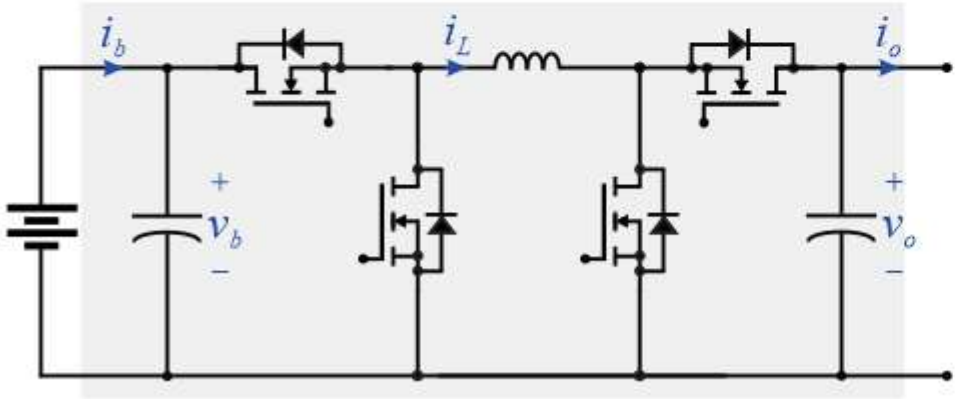
Overview – different topologies



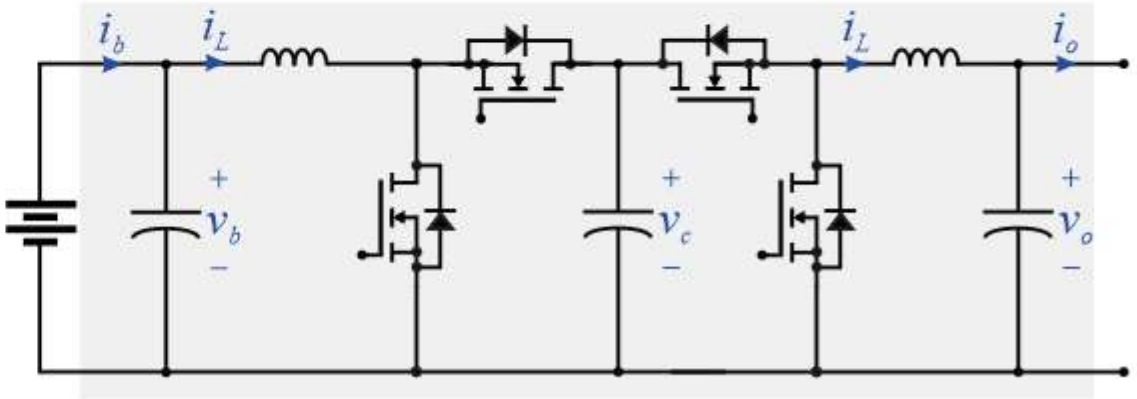
(a)



(b)



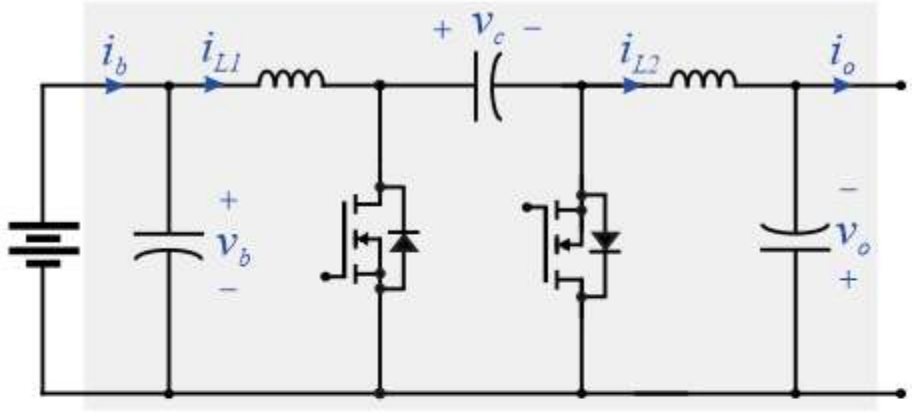
(c)



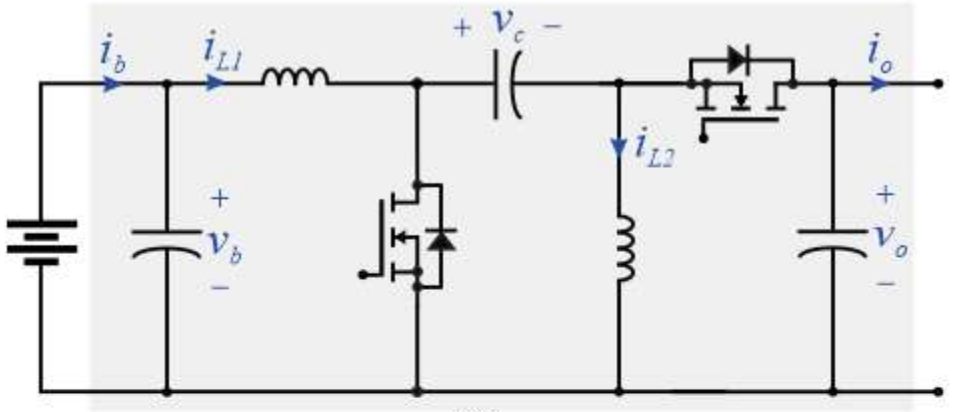
(d)

[1] : B. S. Peixoto, Á. Amorim, R. C. de Barros, M. M. Stopa, P. S. Almeida, and A. F. Cupertino, "On the Balancing Capability of Converter-Integrated Battery Packs: A Topological Benchmark Study," IEEE Open Journal of Power Electronics, under review, 2026..

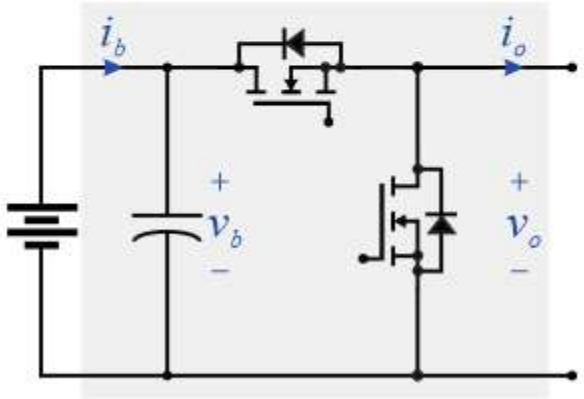
Overview – different topologies (cont.)



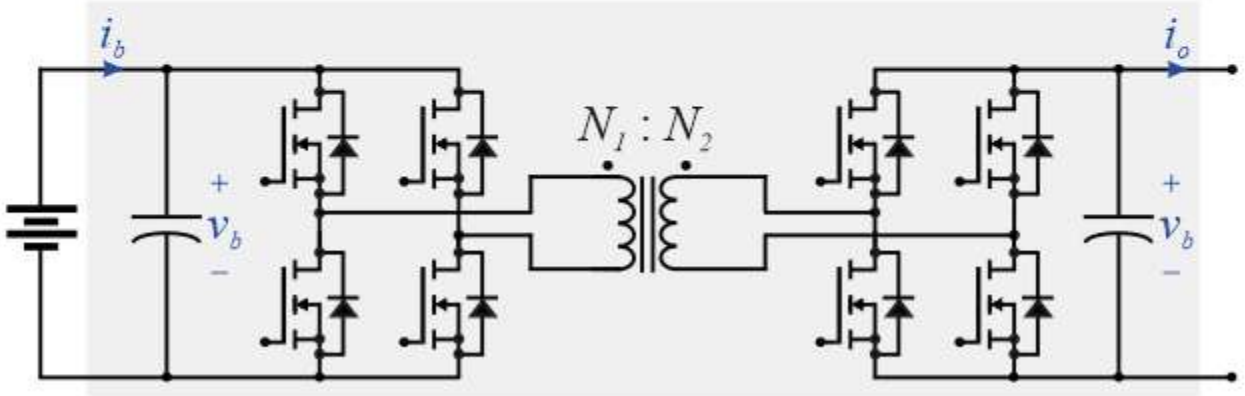
(e)



(f)



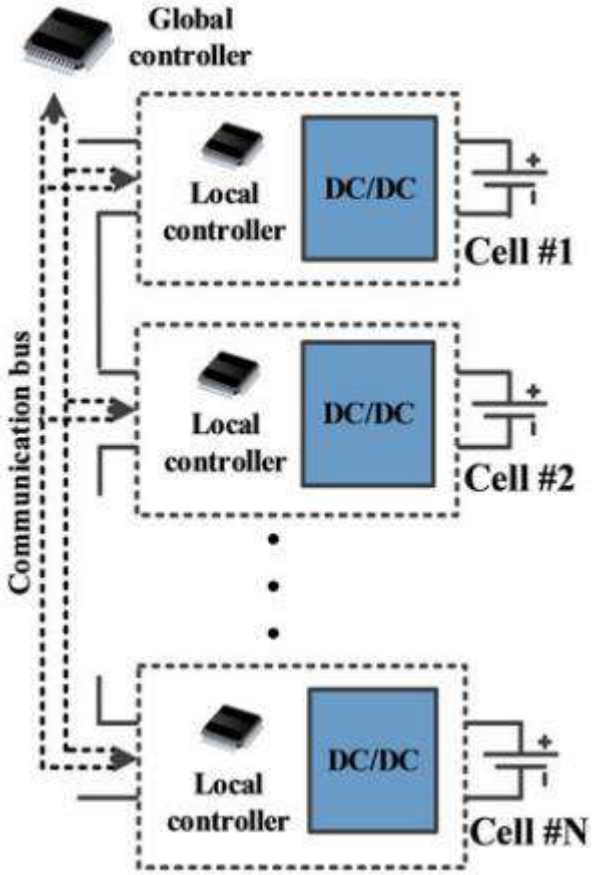
(g)

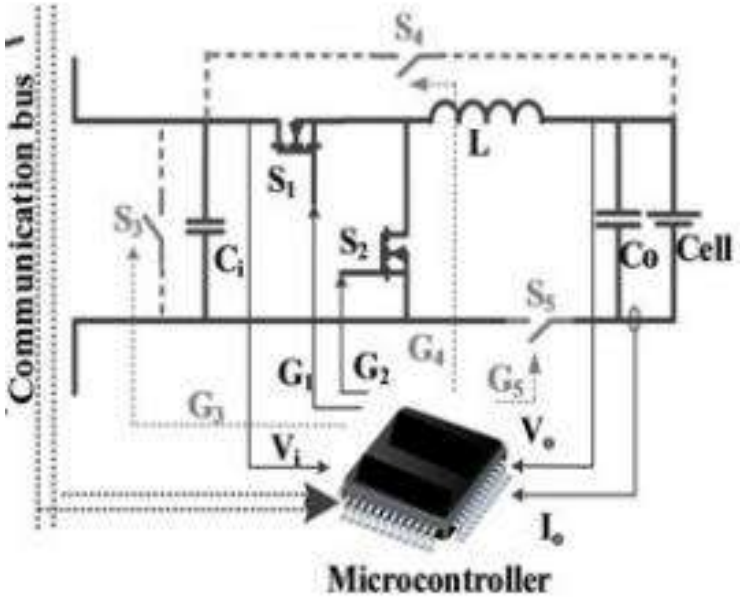


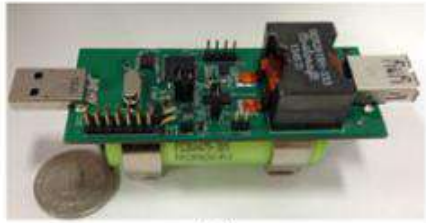
(h)

[1] B. S. Peixoto, Á. Amorim, R. C. de Barros, M. M. Stopa, P. S. Almeida, and A. F. Cupertino, "On the Balancing Capability of Converter-Integrated Battery Packs: A Topological Benchmark Study," IEEE Open Journal of Power Electronics, under review, 2026..

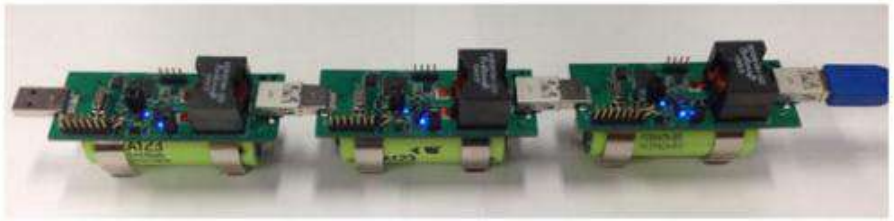
Examples of developments – step-up







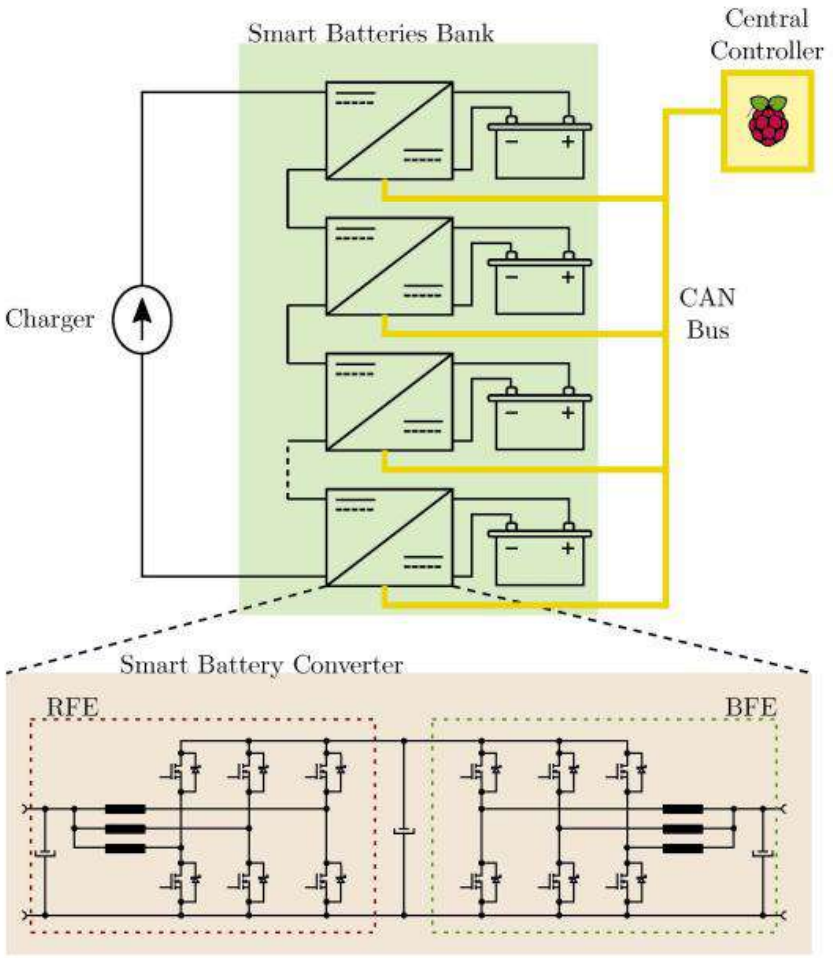
(a)



(b)

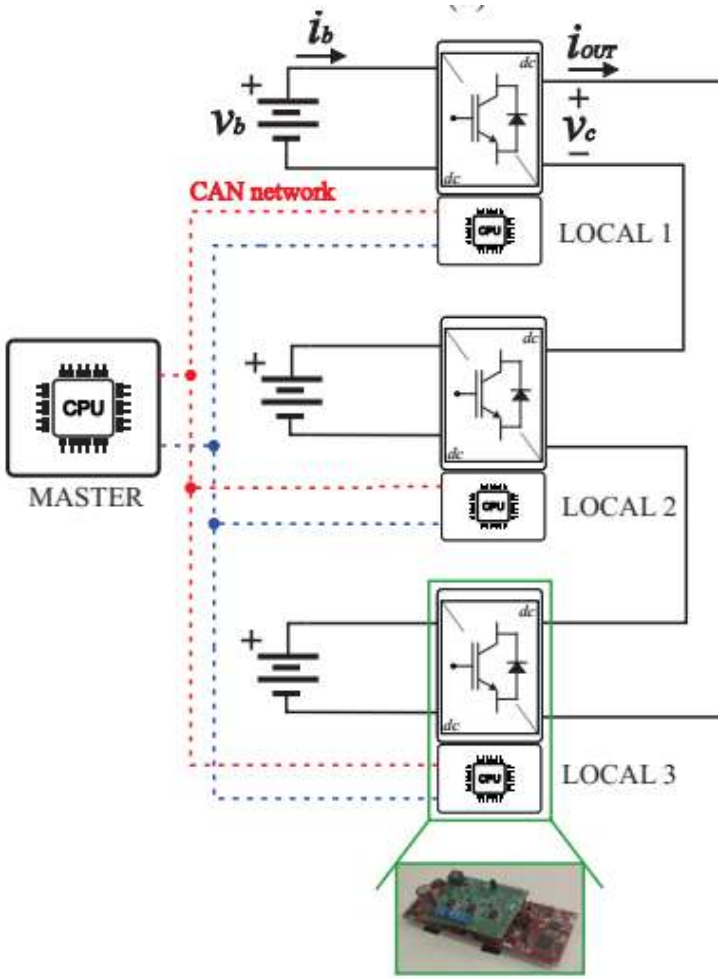
[1] Y. Li and Y. Han, "A Module-Integrated Distributed Battery Energy Storage and Management System," in IEEE Transactions on Power Electronics, vol. 31, no. 12, pp. 8260-8270, Dec. 2016, doi: 10.1109/TPEL.2016.2517150..

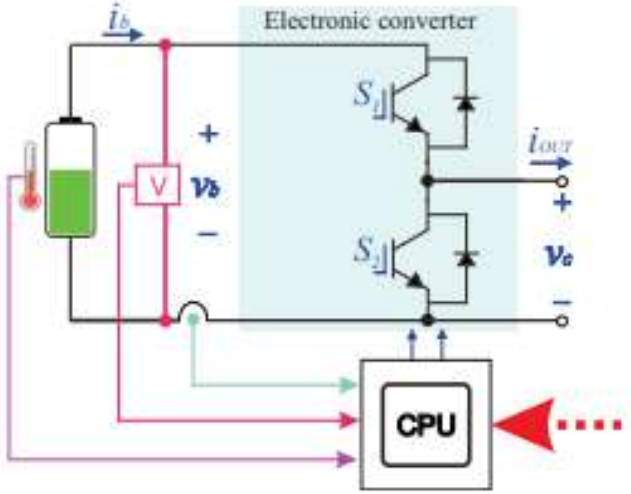
Examples of developments – step-up/step-down

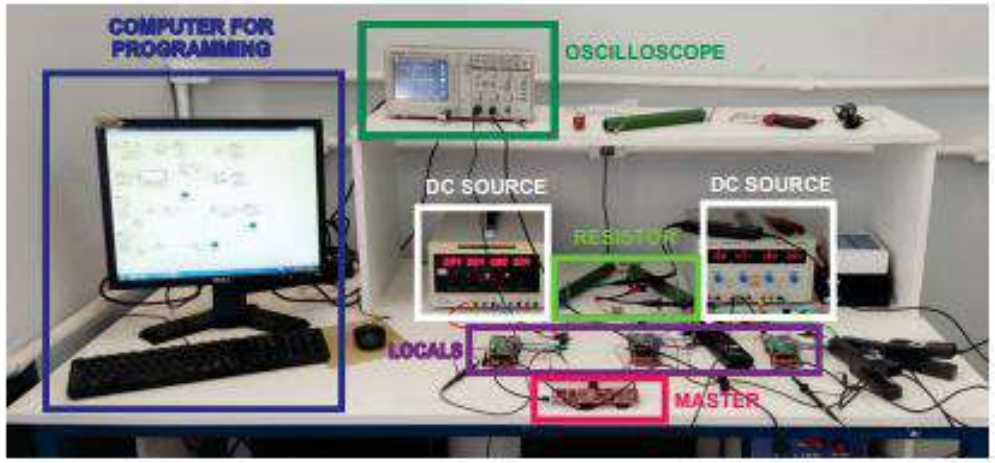


[1] Corrêa, T. P., Maia, T. A. C., & Cardoso Filho, B. J. (2023). High-Performance Power Electronic Battery Pack Based on a Back-to-Back Converter. Energies, 16(1), 375. doi: 10.3390/en16010375

Examples of developments – step-down







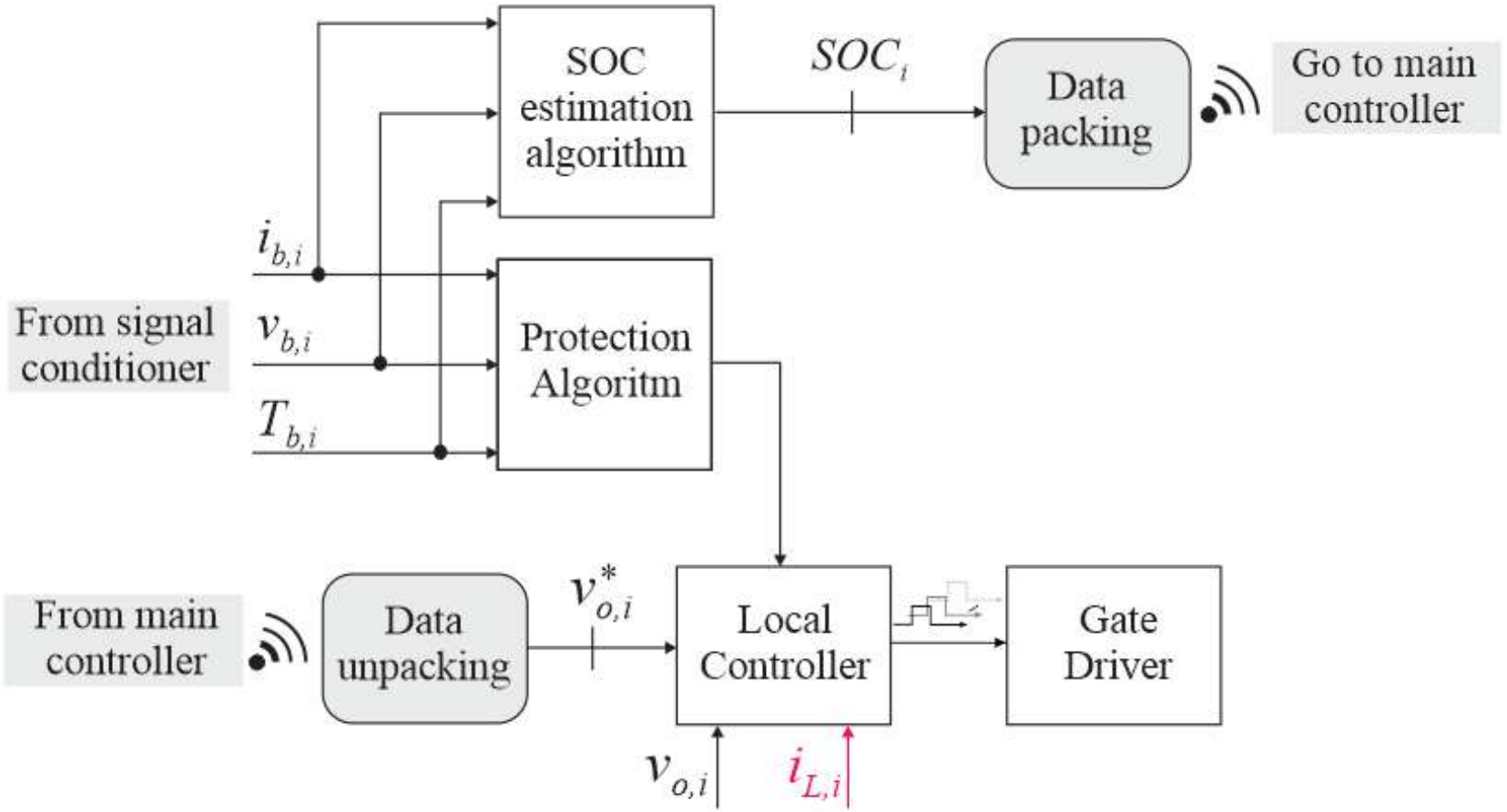
[1] E. F. Rosa, E. M. Da Silveira Brito, H. A. Pereira, R. Teodorescu and A. F. Cupertino, "Pulsed-Current Operation of Smart Batteries Through Warm Redundancy," 2023 IEEE 8th Southern Power Electronics Conference and 17th Brazilian Power Electronics Conference (SPEC/COBEP), Florianopolis, Brazil, 2023, pp. 1-6, doi: 10.1109/SPEC56436.2023.10407654.

Part 4: Control schemes

Prof. Allan Fagner Cupertino

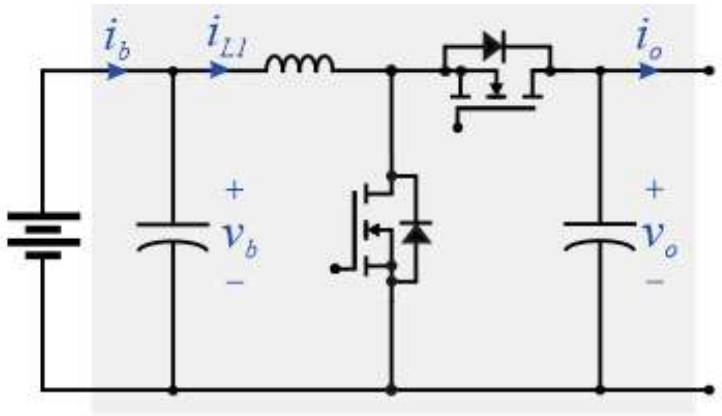
August 12th, 2026

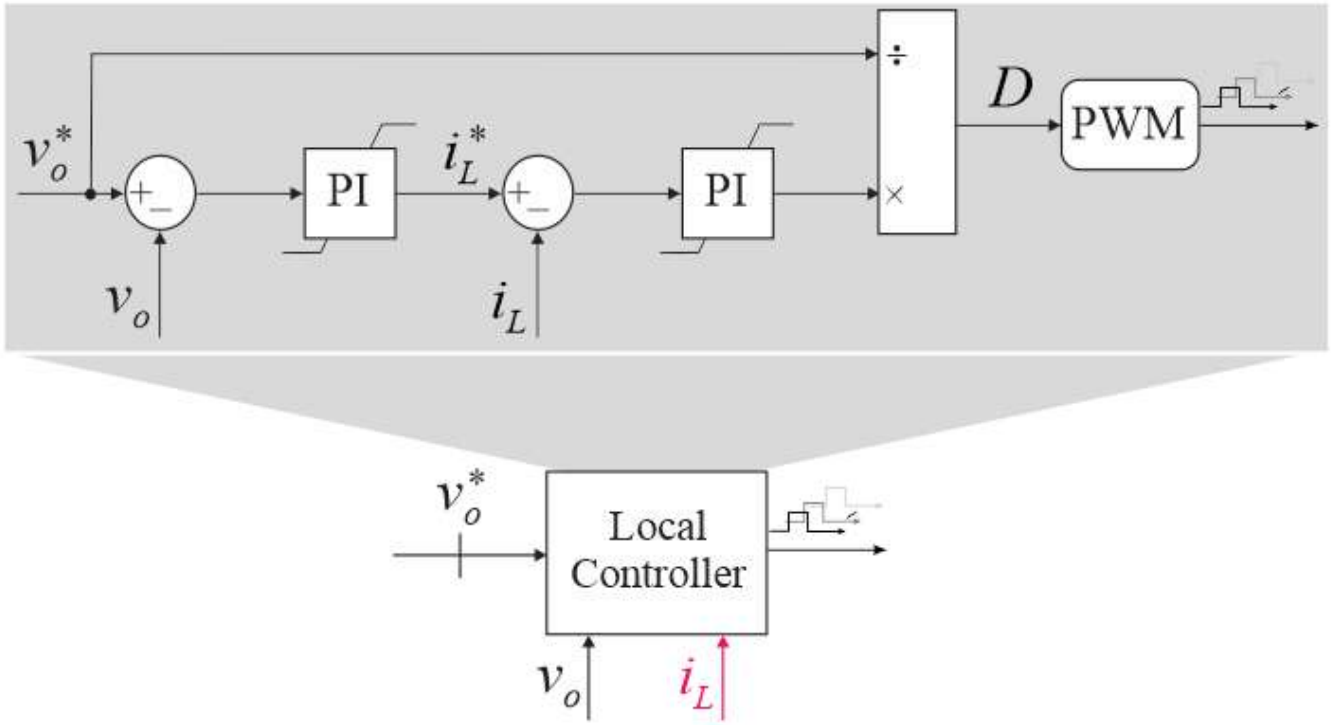
Local control block diagram



[1] E. F. Rosa, E. M. S. Brito, M. M. Stopa, H. A. Pereira, R. Teodorescu and A. F. Cupertino, "A Multifunctional Control Algorithm for Smart Battery Packs," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 14, no. 1, pp. 1071-1084, Feb. 2026, doi: 10.1109/JESTPE.2025.3639787.

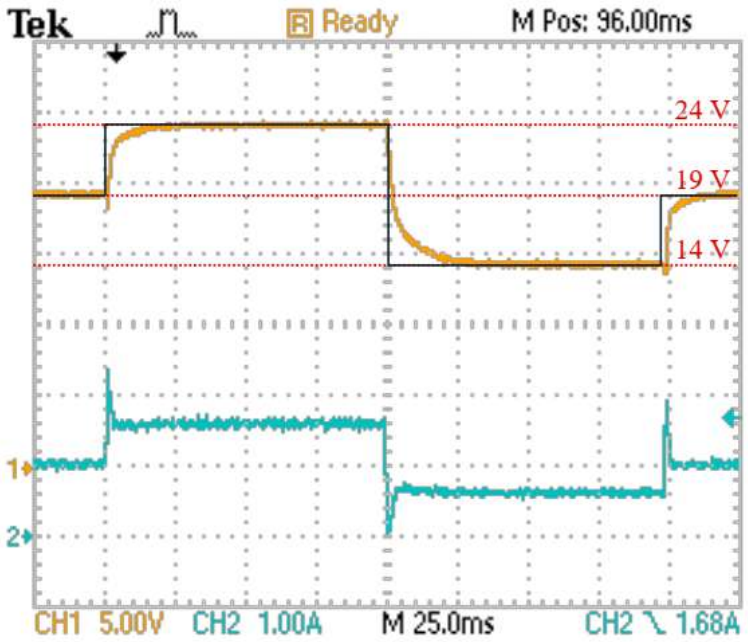
Example: Boost converter

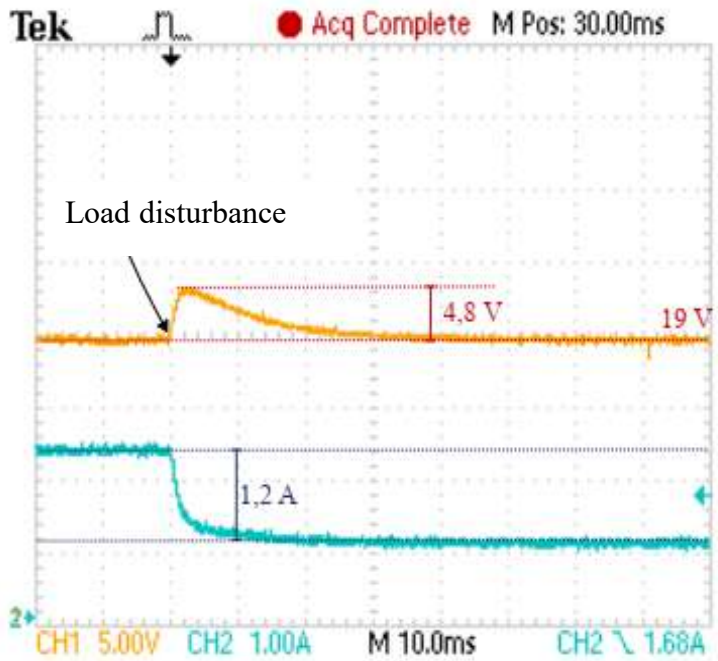


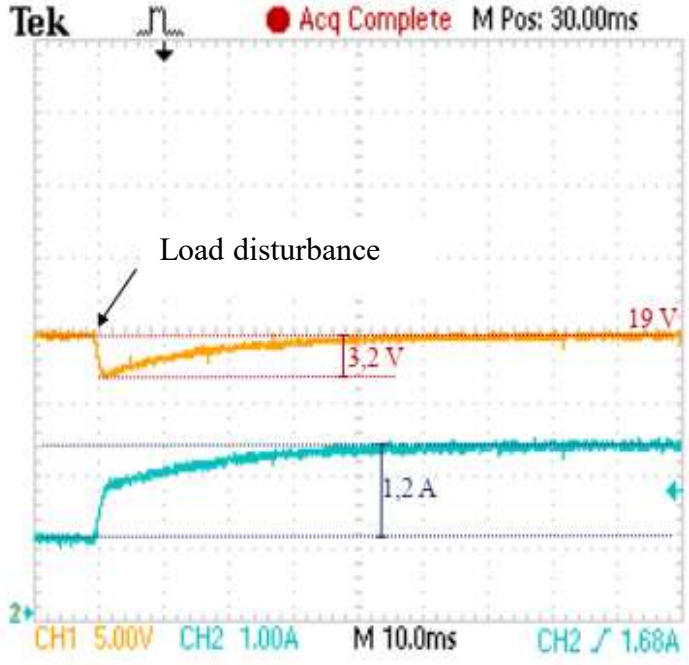


[1] B. De Araujo Coutinho, P. I. De Oliveira Tironi, H. A. Pereira, R. Teodorescu and A. F. Cupertino, "Implementation of a Smart Battery Based on the Dc/Dc Boost Converter," 2023 IEEE 8th Southern Power Electronics Conference and 17th Brazilian Power Electronics Conference (SPEC/COBEP), Florianopolis, Brazil, 2023, pp. 1-8, doi: 10.1109/SPEC56436.2023.10408024.

Experimental results

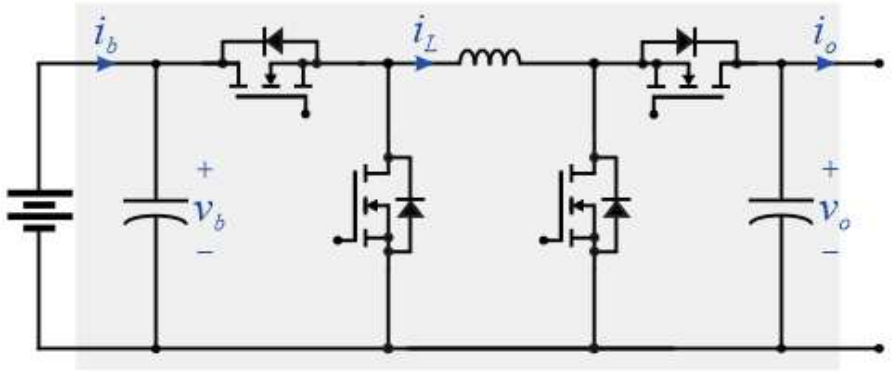


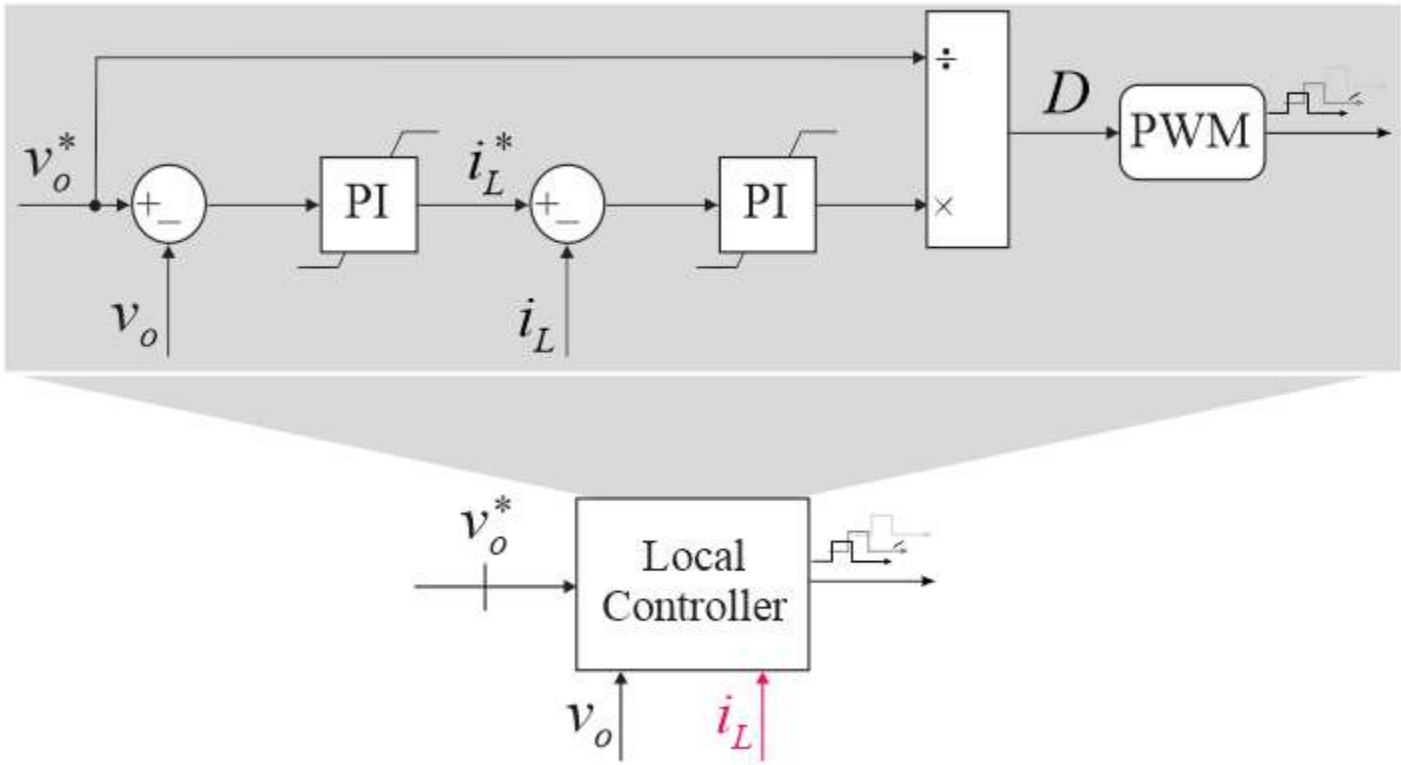




[1] B. De Araujo Coutinho, P. I. De Oliveira Tironi, H. A. Pereira, R. Teodorescu and A. F. Cupertino, "Implementation of a Smart Battery Based on the Dc/Dc Boost Converter," 2023 IEEE 8th Southern Power Electronics Conference and 17th Brazilian Power Electronics Conference (SPEC/COBEP), Florianopolis, Brazil, 2023, pp. 1-8, doi: 10.1109/SPEC56436.2023.10408024.

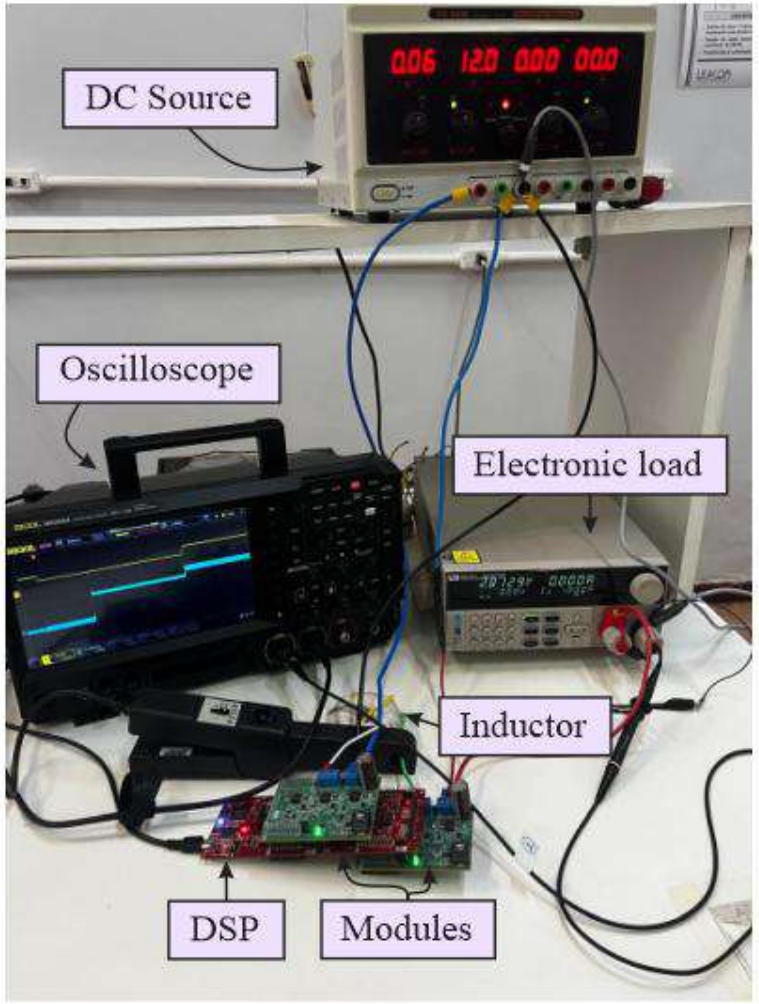
Example: Non-inverting buck-boost converter



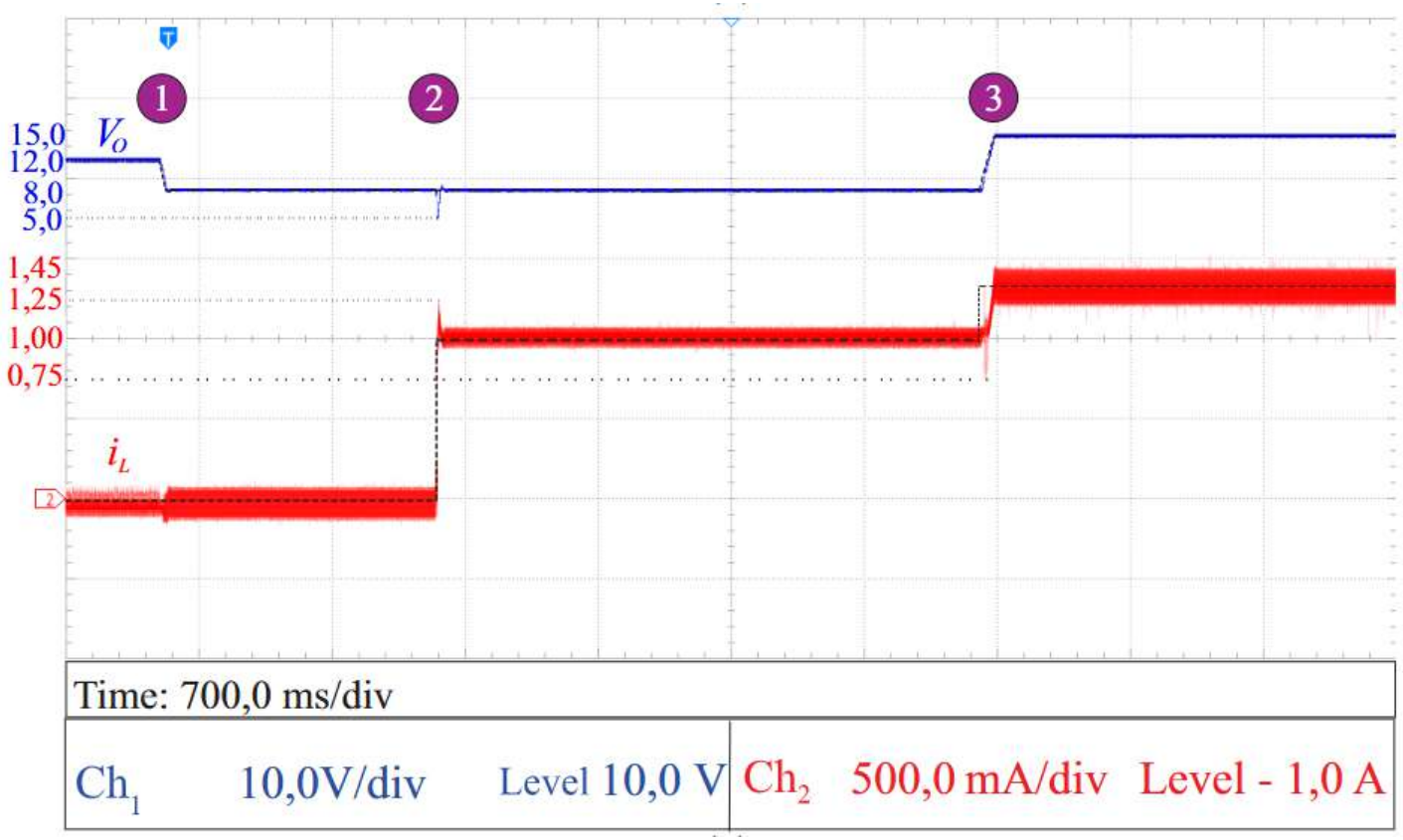


[1] B. S. Peixoto, Á. Amorim, R. C. de Barros, M. M. Stopa, P. S. Almeida, and A. F. Cupertino, "On the Balancing Capability of Converter-Integrated Battery Packs: A Topological Benchmark Study," IEEE Open Journal of Power Electronics, under review, 2025.

Experimental results

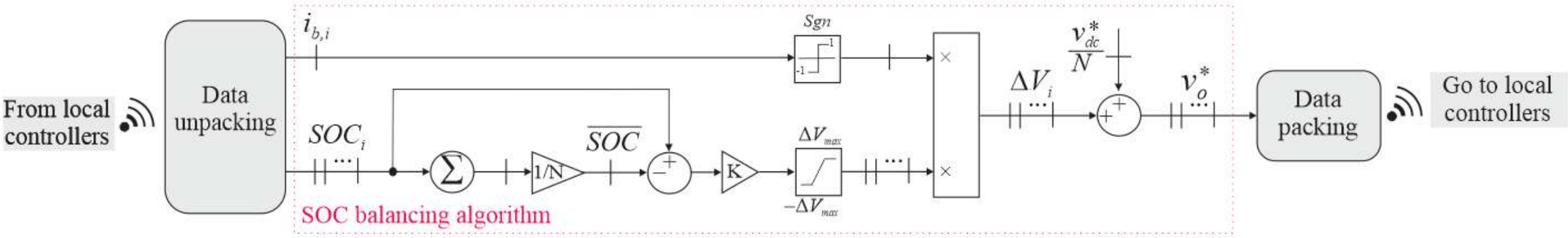


1. Buck mode; 2. Load step; 3. Boost mode.



[1] B. De Araujo Coutinho, P. I. De Oliveira Tironi, H. A. Pereira, R. Teodorescu and A. F. Cupertino, "Implementation of a Smart Battery Based on the Dc/Dc Boost Converter," 2023 IEEE 8th Southern Power Electronics Conference and 17th Brazilian Power Electronics Conference (SPEC/COBEP), Florianopolis, Brazil, 2023, pp. 1-8, doi: 10.1109/SPEC56436.2023.10408024.

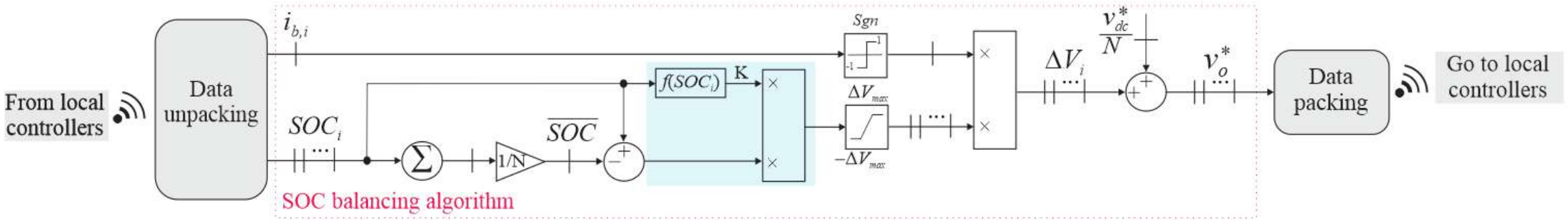
Conventional balancing controller



- Main characteristics (previously analyzed):
  - ✓ **Constant** gain;
  - ✓ **Exponential** reduction of SoC error;
  - ✓ **Expected** steady-state error;
  - ✓ **Guarantees** constant dc-link voltage if $K \leq \frac{\Delta V_{max}}{|\Delta SOC_{max,0}|}$

[1] J. A. Qahouq and I. Batarseh, "Distributed battery power electronics architecture and control," U.S. Patent 9 368 991 B2, Jun. 14, 2016.
[2] Y. Li and Y. Han, "A module-integrated distributed battery energy storage and management system," IEEE Trans. Power Electron., vol. 31, no. 12, pp. 8260–8270, Dec. 2016

Variable gain balancing controller

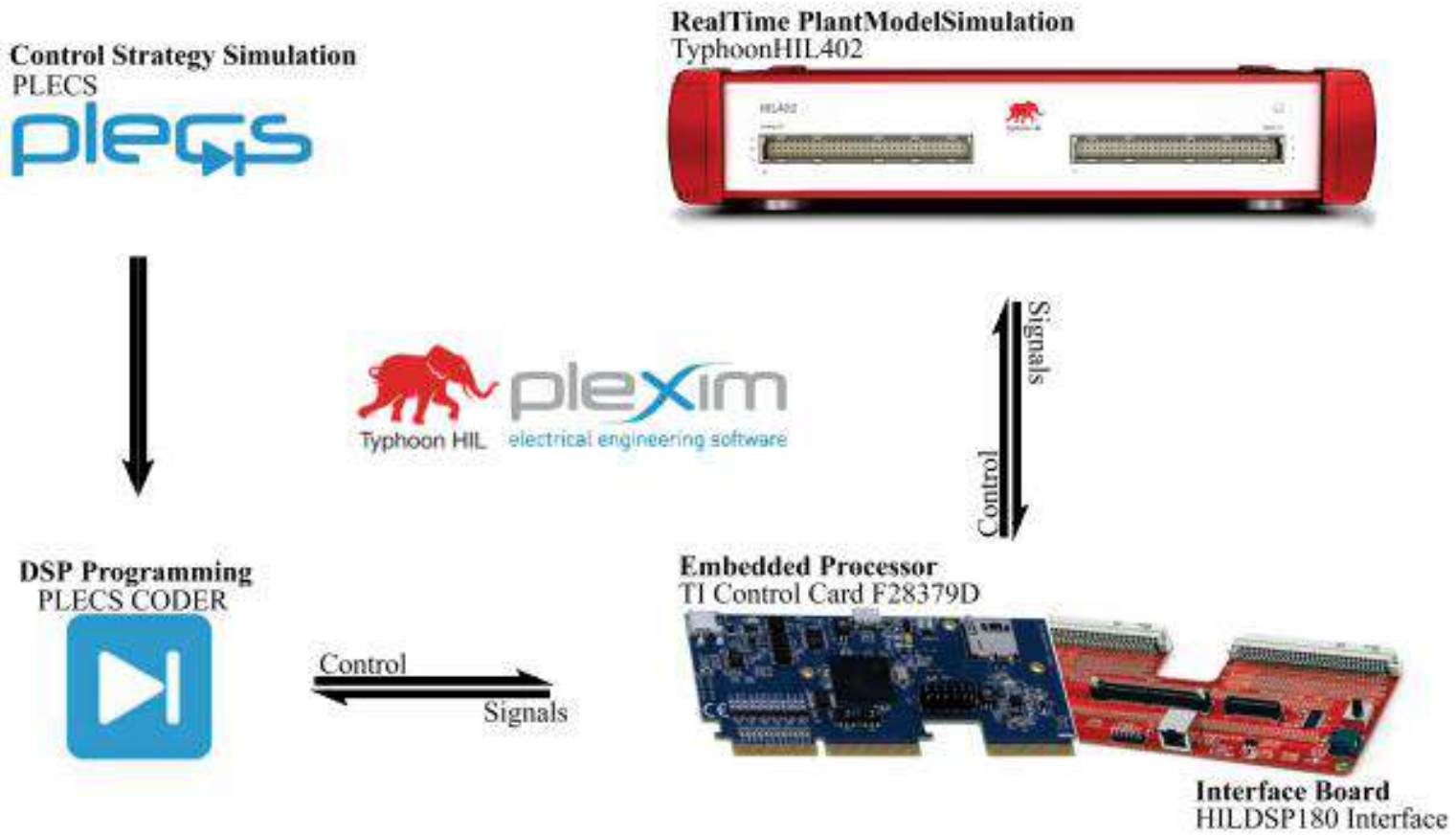


- Main characteristics:
  - ✓ **Variable** gain;
  - ✓ **Linear** reduction of SoC error;
  - ✓ **Lower** Steady-state error;
  - ✓ **Guarantees** constant dc-link voltage.

$$K = f(SOC_i) = \frac{\Delta V_{max}}{|\Delta SOC_{max}(t)|}$$

J. S. d. Oliveira, B. d. A. Coutinho, P. I. d. O. Tironi, A. F. Cupertino, E. M. d. S. Brito and H. A. Pereira, "Variable-Gain State-of-Charge Balancing Method for Smart Battery Packs," in IEEE Access, vol. 13, pp. 145528-145539, 2025, doi: 10.1109/ACCESS.2025.3597229.

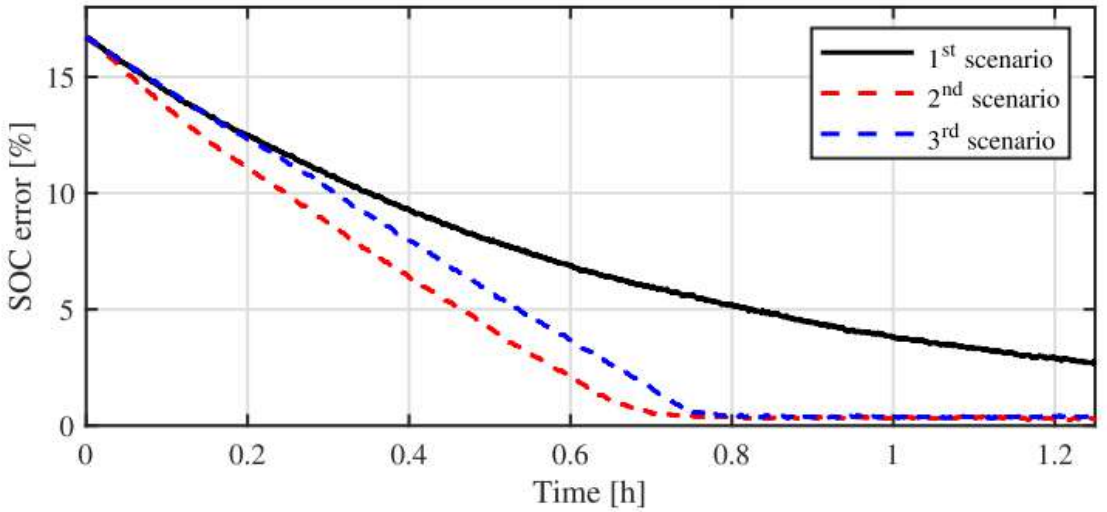
C-HIL validation setup



Á. L. C. Amorim, B. S. Peixoto, A. F. Cupertino, M. M. Stopa, H. A. Pereira, and R. Teodorescu, "Offset compensation network: Improving the control of battery energy storage systems," Int. J. Circuit Theory Appl., vol. 53, no. 8, pp. 4682–4693, Aug. 2025, doi:10.1002/cta.4333.

SoC balancing control results

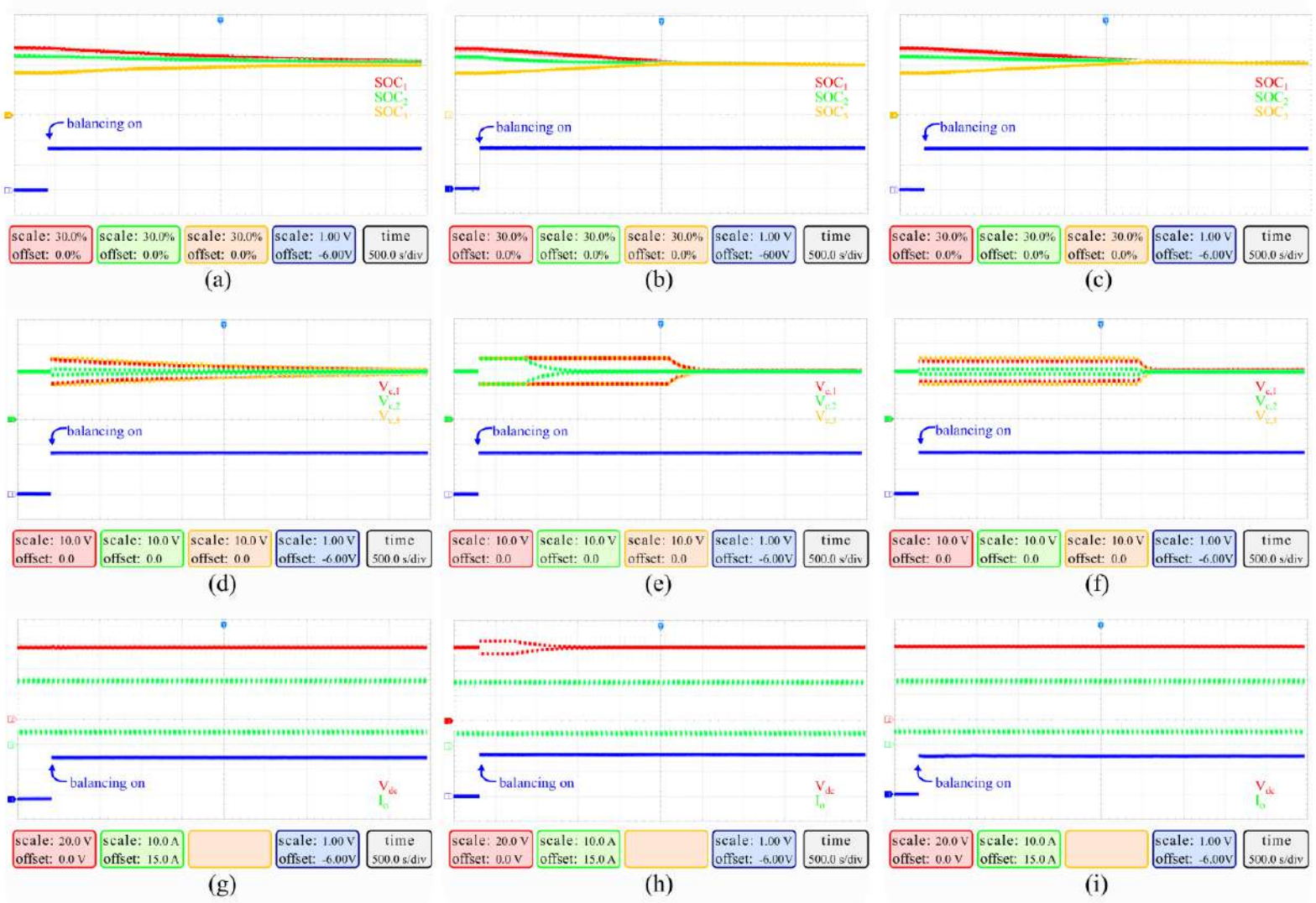
- 3 batteries (12 V, 20 Ah) + boost converters.
- Fixed gain → no full balancing after ~83 min.

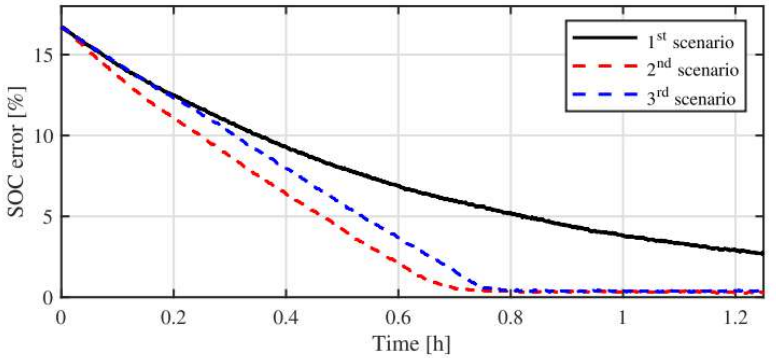


- High fixed gain → balanced in ~46 min, but with dc-link voltage variations.
- Variable gain → balanced in ~54 min, dc-link stable.

J. S. d. Oliveira, B. d. A. Coutinho, P. I. d. O. Tironi, A. F. Cupertino, E. M. d. S. Brito and H. A. Pereira, "Variable-Gain State-of-Charge Balancing Method for Smart Battery Packs," in IEEE Access, vol. 13, pp. 145528-145539, 2025, doi: 10.1109/ACCESS.2025.3597229.

SoC balancing control results





J. S. d. Oliveira, B. d. A. Coutinho, P. I. d. O. Tironi, A. F. Cupertino, E. M. d. S. Brito and H. A. Pereira, "Variable-Gain State-of-Charge Balancing Method for Smart Battery Packs," in IEEE Access, vol. 13, pp. 145528-145539, 2025, doi: 10.1109/ACCESS.2025.3597229.

Part 5: Applications and trends

Prof. Allan Fagner Cupertino

August 12th, 2026

Pulsed current charging for lifetime extension

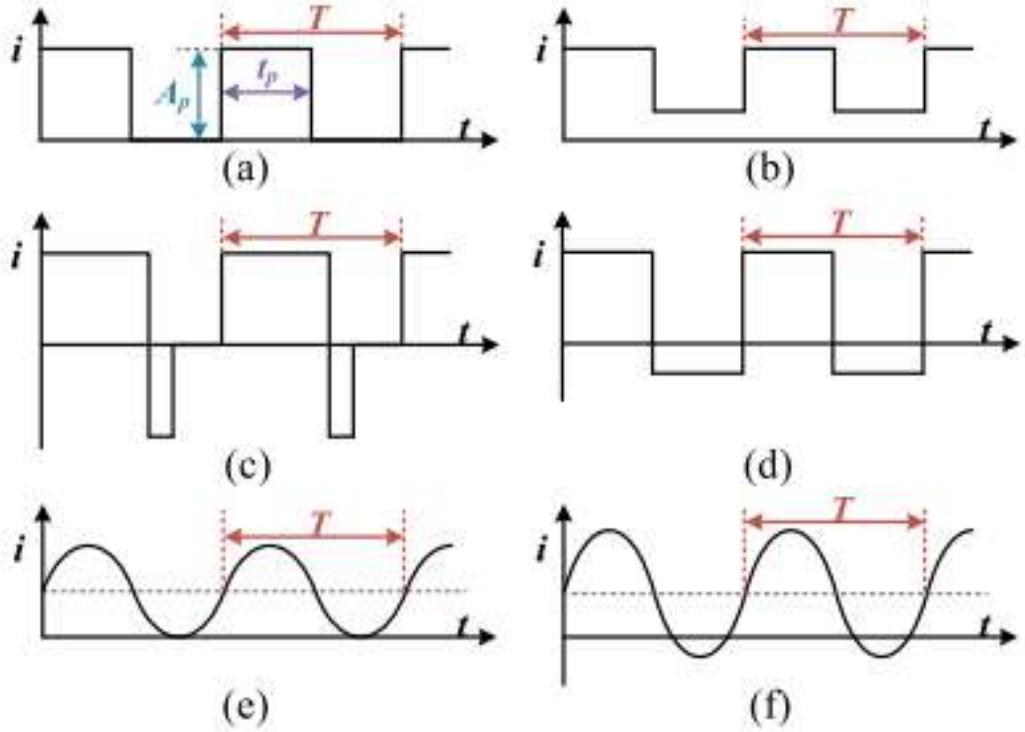


Fig. 1. Six fundamental pulsed current modes. (a) Positive pulsed current (PPC) mode, (b) pulsed current-constant current (PCCC) mode, (c) negative pulsed current (NPC) mode, (d) alternating pulsed current (APC) mode, (e) sinusoidal-ripple current (SRC) mode, and (f) alternating sinusoidal-ripple current (ASRC) mode [15].

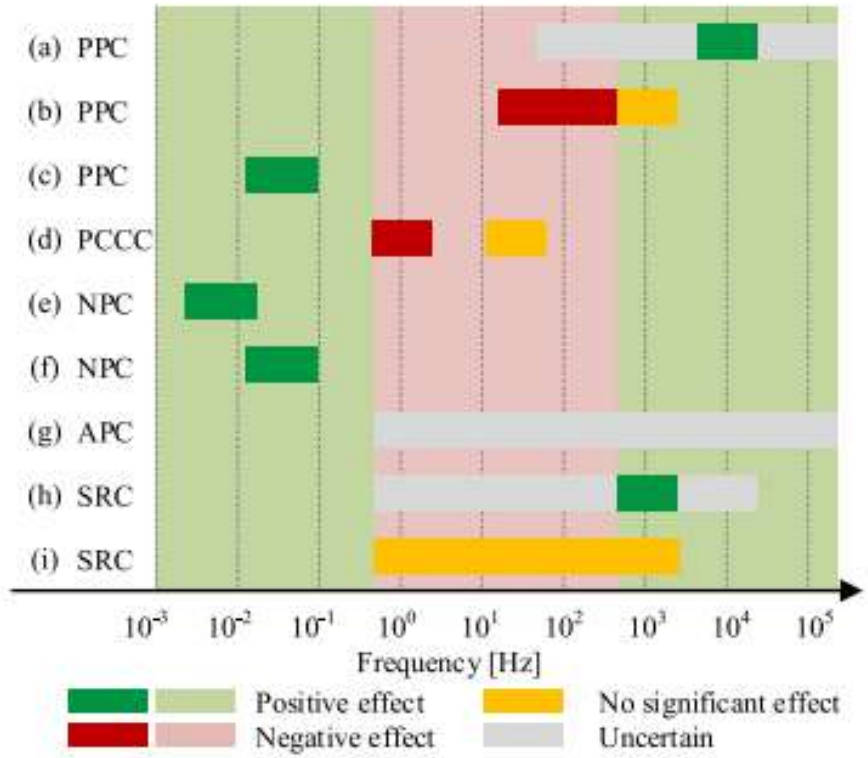
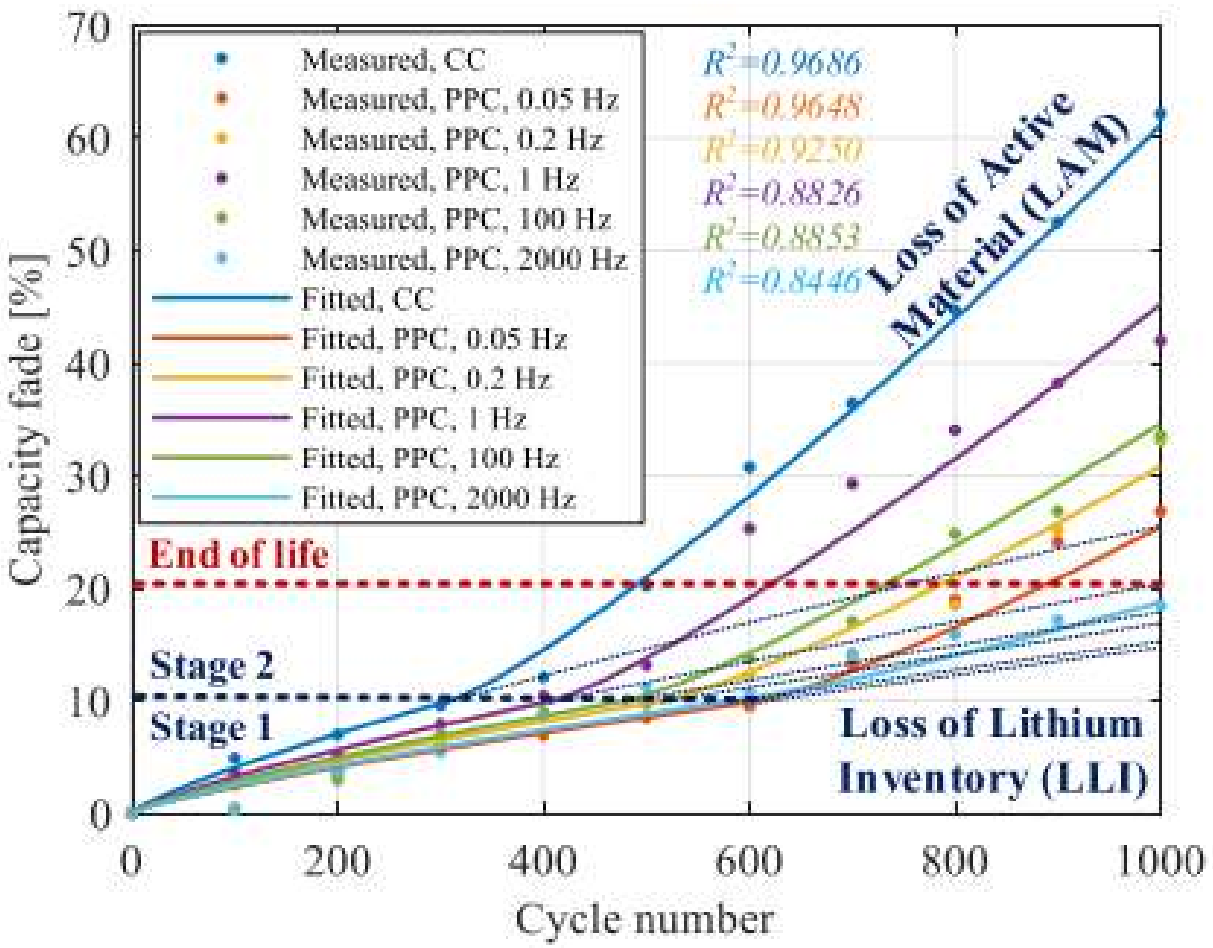
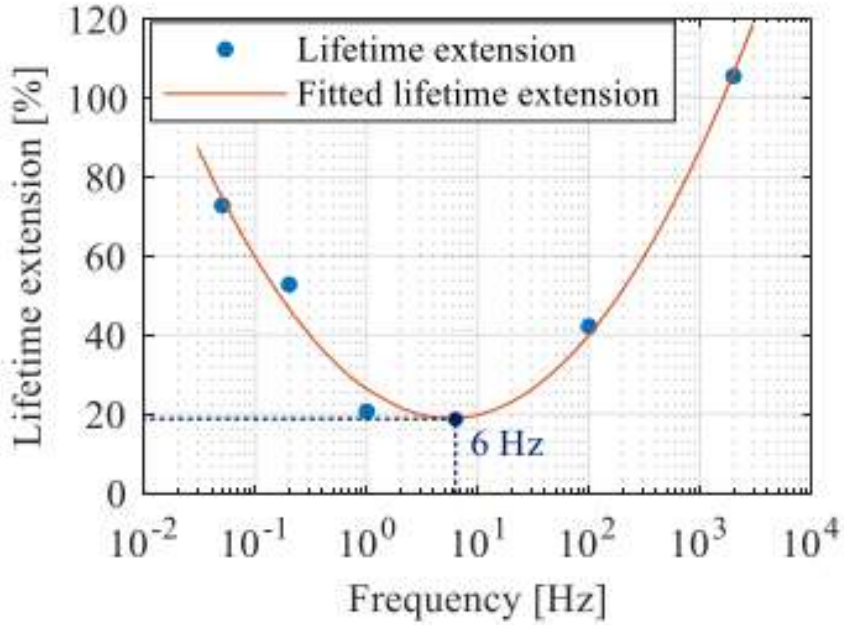


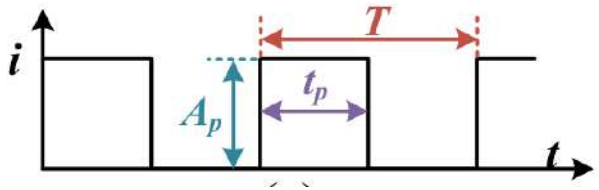
Fig. 2. Effects of the pulsed current charging on lithium-ion battery lifetime considering different frequencies [21]. (a) [8]. (b) [13]. (c) [9]. (d) [14]. (e) [10]. (f) [11]. (g) [23]. (h) [12]. (i) [24].

X. Huang, W. Liu, A. B. Acharya, J. Meng, R. Teodorescu and D. -I. Stroe, "Effect of Pulsed Current on Charging Performance of Lithium-Ion Batteries," in IEEE Transactions on Industrial Electronics, vol. 69, no. 10, pp. 10144-10153, Oct. 2022, doi: 10.1109/TIE.2021.3121726.

Pulsed current charging for lifetime extension

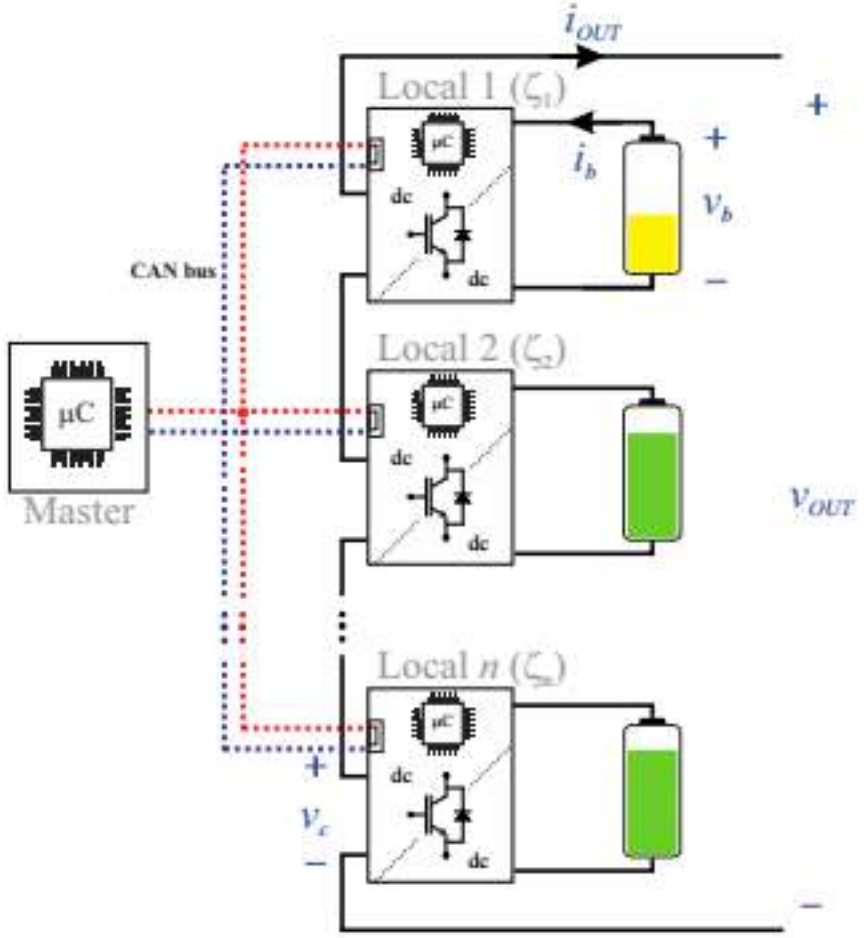


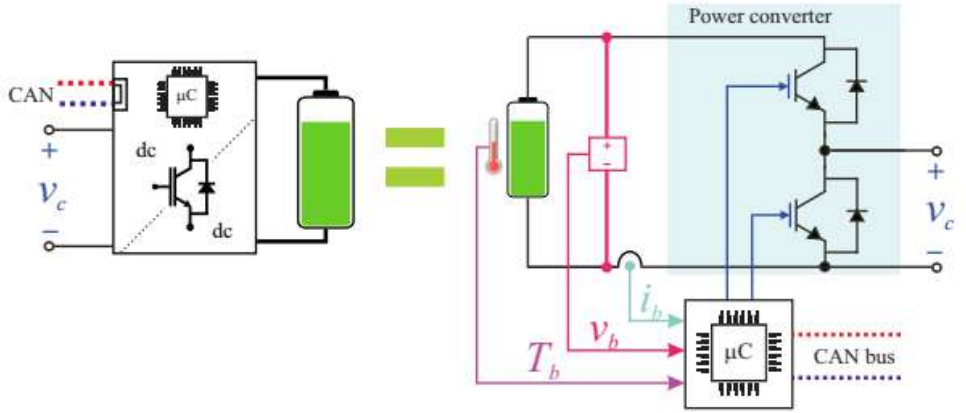




[1] X. Huang et al., "Lithium-Ion Battery Lifetime Extension With Positive Pulsed Current Charging," in IEEE Transactions on Industrial Electronics, 2024, doi: 10.1109/TIE.2023.3250850.
[2] X. Huang et al., "Lifetime Extension of Lithium-Ion Batteries With Low-Frequency Pulsed Current Charging," in IEEE J. Emerg. Sel. Topics Power Electron., 2023, doi: 10.1109/JESTPE.2021.3130424

Half-bridge converter



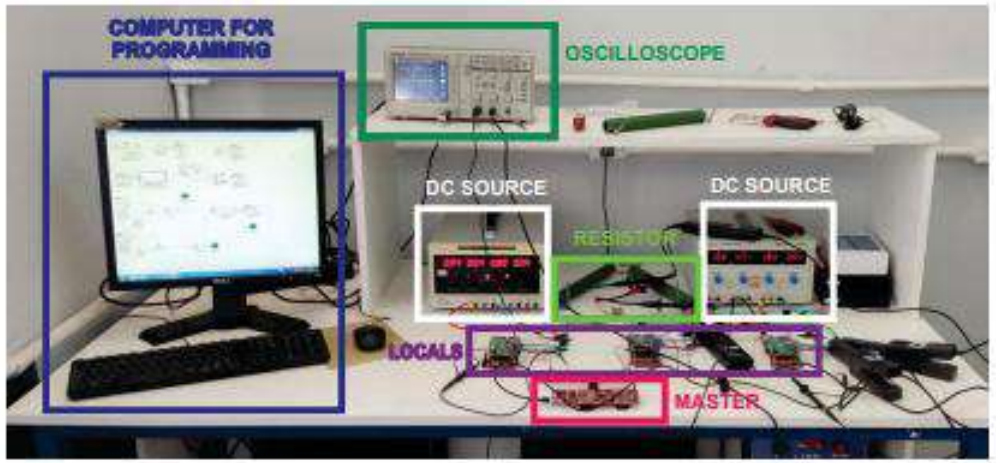


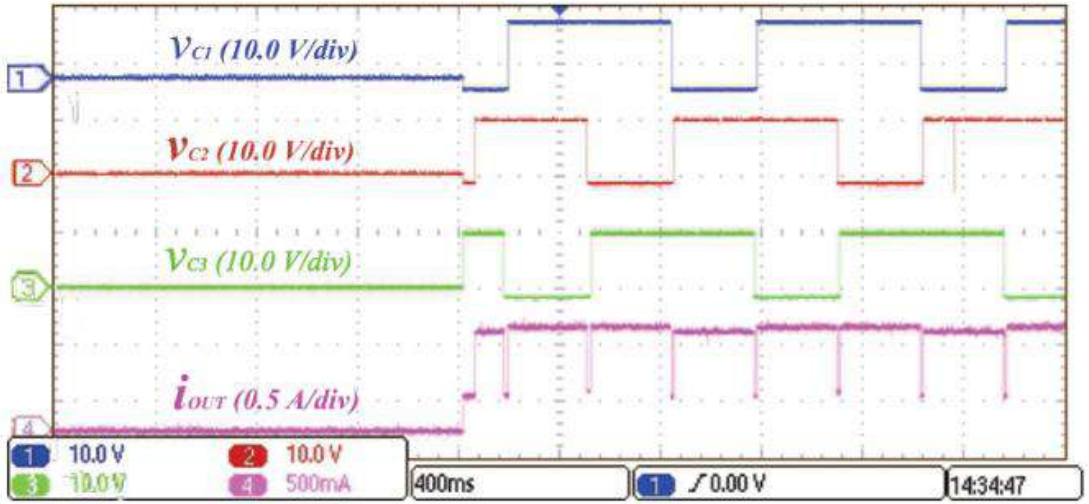
$$D = \frac{n - m}{n}$$

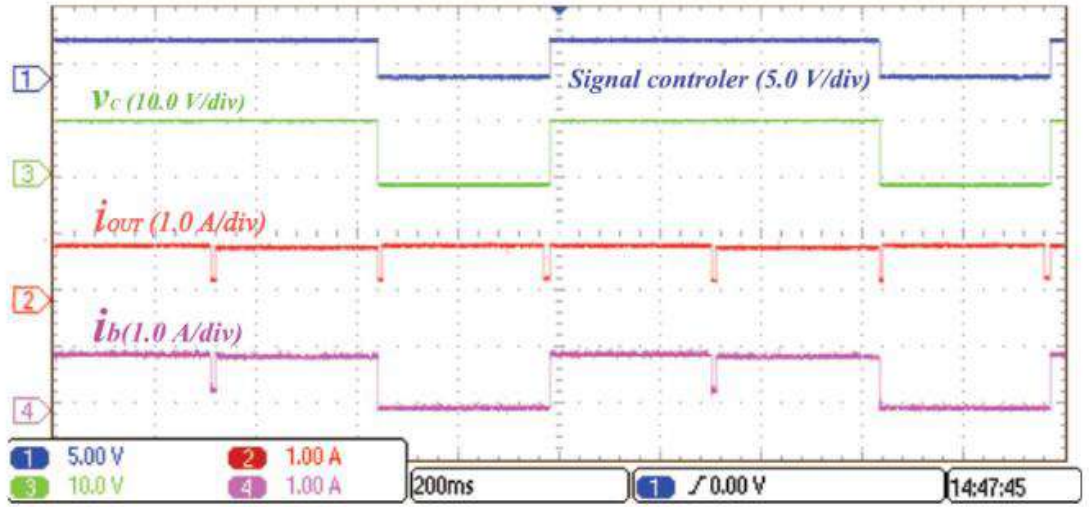
$$f = \frac{1 - D}{t_d} = \frac{m}{nt_d}$$

[1] E. F. Rosa, E. M. S. Brito, M. M. Stopa, H. A. Pereira, R. Teodorescu and A. F. Cupertino, "A Multifunctional Control Algorithm for Smart Battery Packs," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 14, no. 1, pp. 1071-1084, Feb. 2026, doi: 10.1109/JESTPE.2025.3639787.

Pulsed current operation experimental results

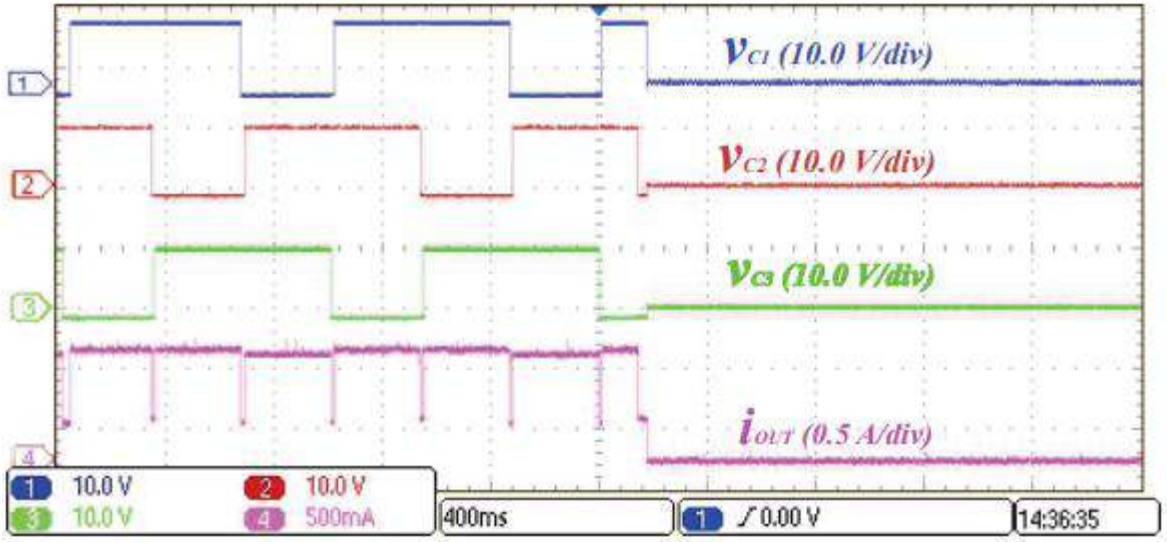






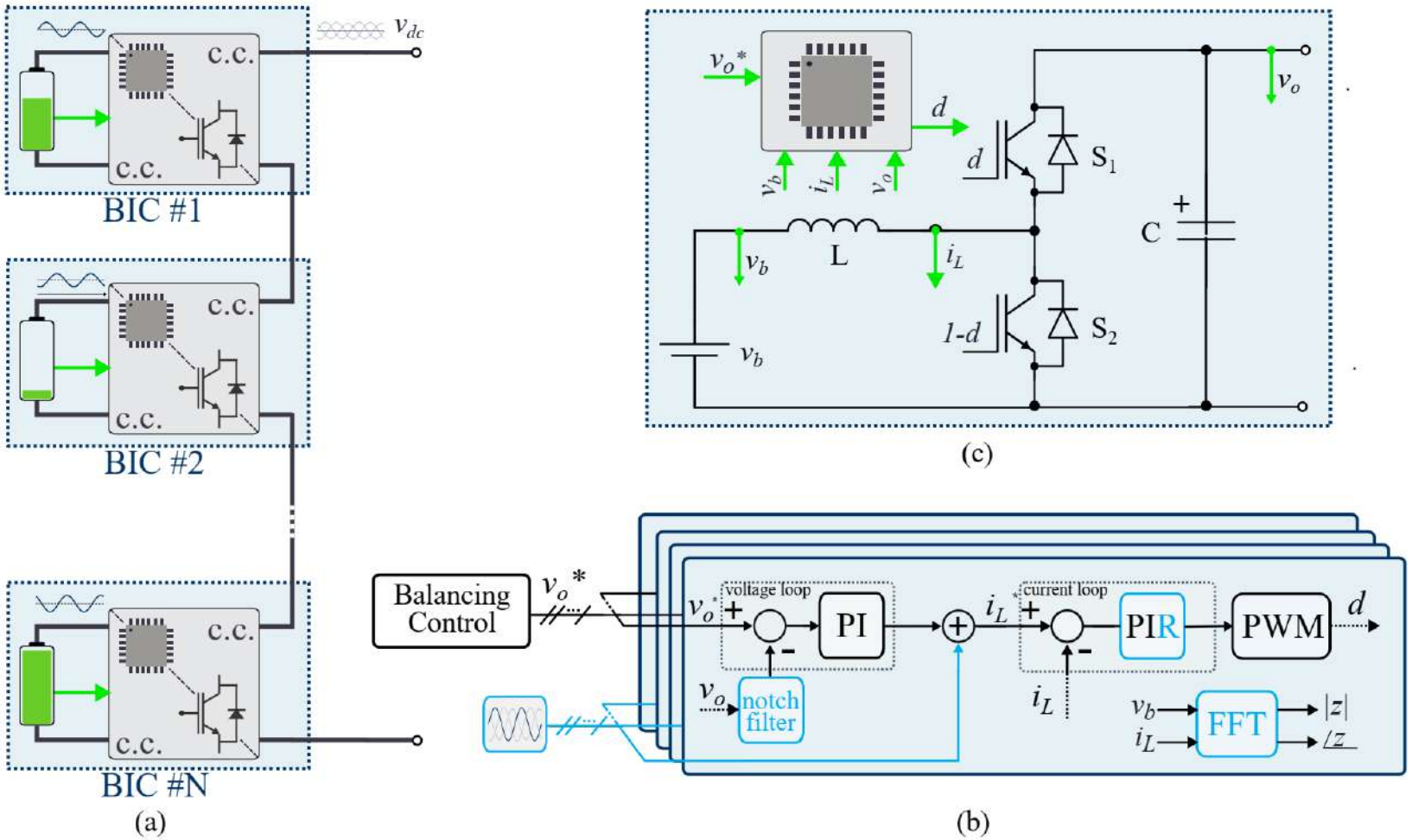
[1] E. F. Rosa, E. M. S. Brito, M. M. Stopa, H. A. Pereira, R. Teodorescu and A. F. Cupertino, "A Multifunctional Control Algorithm for Smart Battery Packs," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 14, no. 1, pp. 1071-1084, Feb. 2026, doi: 10.1109/JESTPE.2025.3639787.

Fault tolerance and safety mode



[1] E. F. Rosa, E. M. S. Brito, M. M. Stopa, H. A. Pereira, R. Teodorescu and A. F. Cupertino, "A Multifunctional Control Algorithm for Smart Battery Packs," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 14, no. 1, pp. 1071-1084, Feb. 2026, doi: 10.1109/JESTPE.2025.3639787.

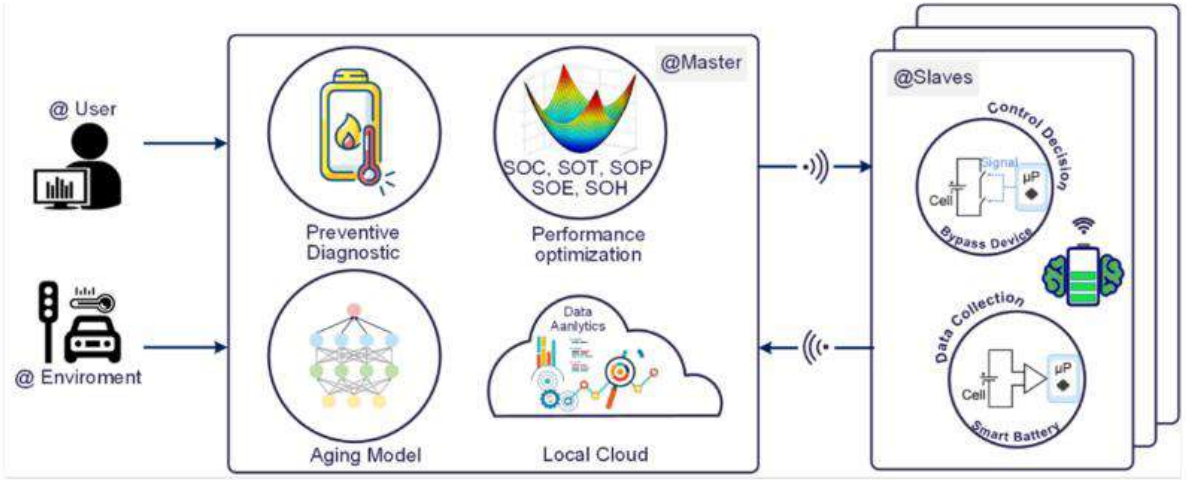
Real time impedance estimation

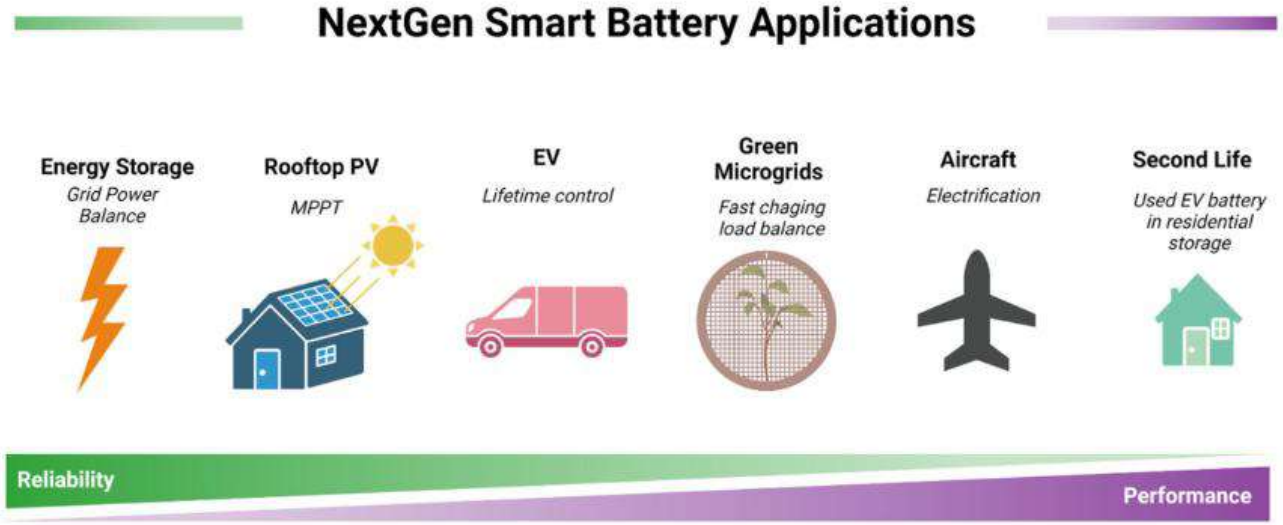


[1] B. de A. Coutinho, L. P. S. do Carmo, M. M. Stopa, V. F. Mendes, H. A. Pereira, and A. F. Cupertino, "An improved injection scheme for impedance estimation in integrated-converter battery packs," in COBEP.2025, pp. 1–8.

Roadmap – Smart Batteries

- Cost: main challenge for wide adoption;
- Control for lifetime extension;
- Second-life friendly;
- AI for smart batteries;





[1] R. Teodorescu, X. Sui, S. B. Vilsen, P. Bharadwaj, A. Kulkarni, and D.-I. Stroe, "Smart Battery Technology for Lifetime Improvement," Batteries, vol. 8, no. 10, Art. no. 169, Oct. 2022, doi: 10.3390/batteries8100169.

Acknowledgement


Q&A


Thank You
Merci
Obrigado
Dyakuyu
Salamat
Arigato
Spasibo
Dank Je
Kiitos
Grazie
Asante
Multumesc
Juspaxar
Mamana
Chokrane
Mochchakkeram
Vinaka
Cam on ban
Maake
Matondo
Dankon
Terma Kasih
Kia Ora
Raibh Maith Agat
Matur Nuwun