IRP7:
Reliability and Availability of Smart Transformers for Cost Effective and High Quality of Services in the Grid

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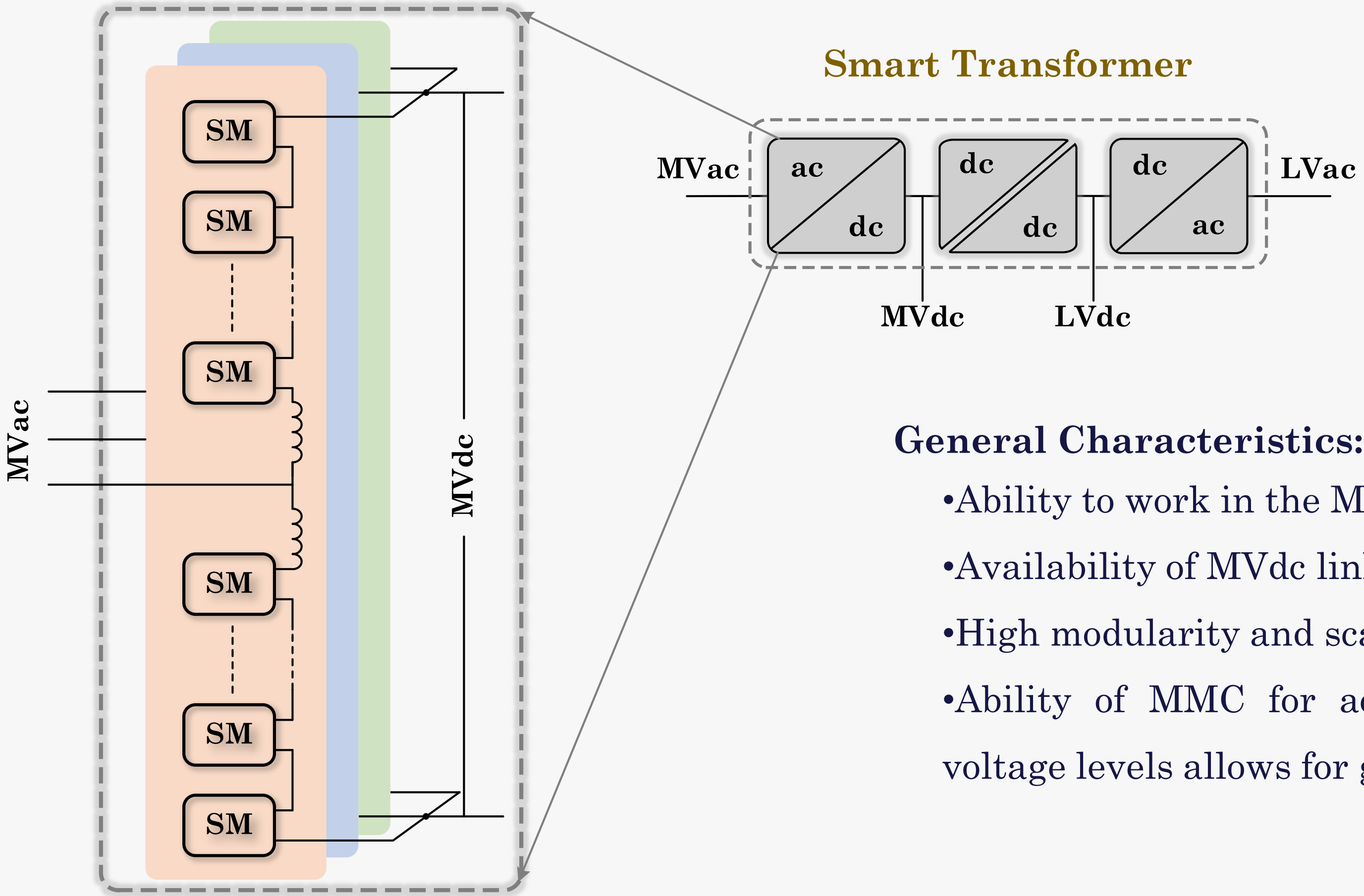
MMC and Smart Transformer

Modular Multilevel Converter (MMC)

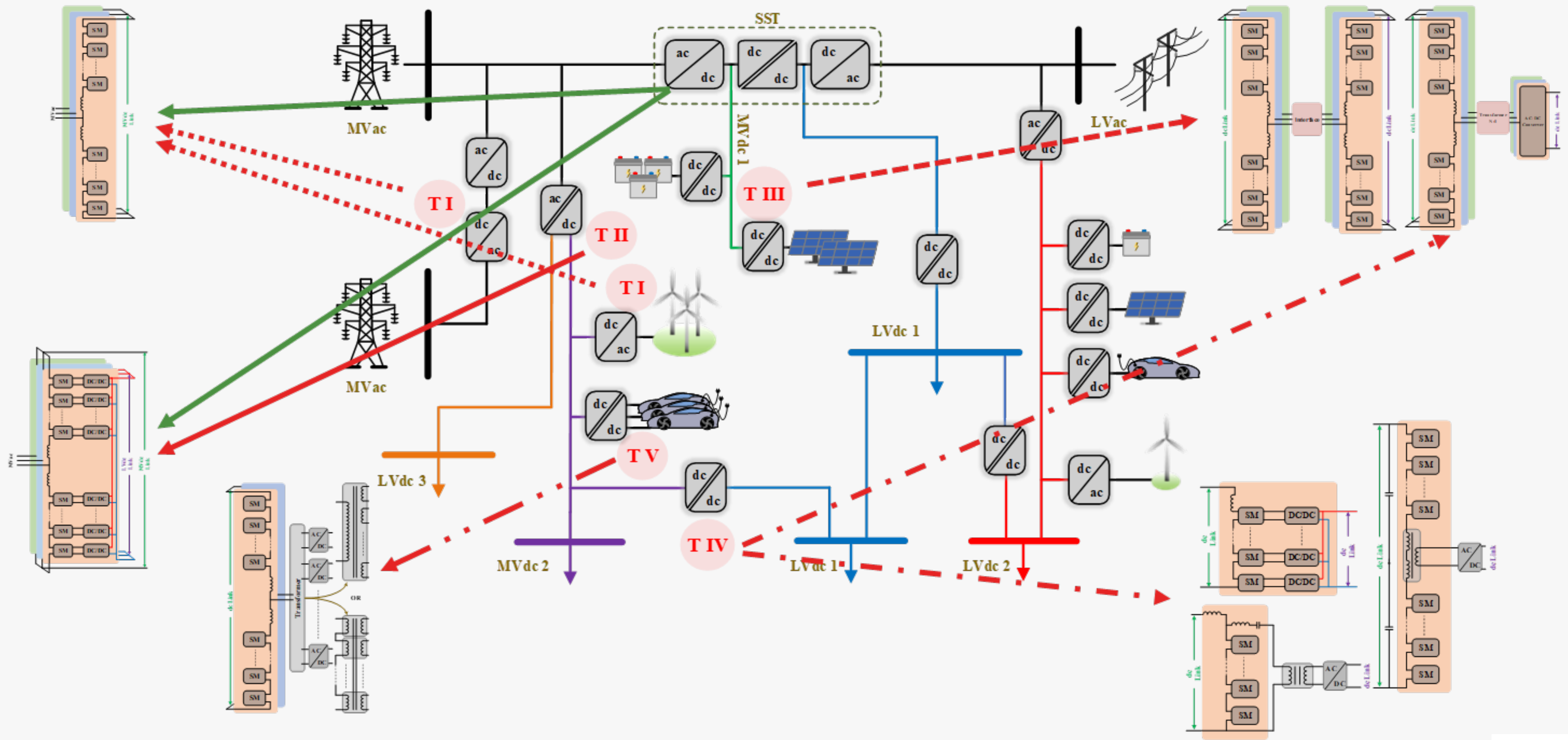


General Characteristics:

- Ability to work in the MV range with low-voltage switches.
- Availability of MVdc link.
- High modularity and scalability.
- Ability of MMC for accommodating a wide range of power and voltage levels allows for greater flexibility.

M. Hassanifar et al., "Modular Multilevel Converters Enabling Multibus DC Distribution," *2023 IEEE 17th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, Tallinn, Estonia, 2023.

Modular Multilevel Converters in Hybrid Grids



M. Hassanifar et al., "Modular Multilevel Converters Enabling Multibus DC Distribution," *2023 IEEE 17th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, Tallinn, Estonia, 2023.

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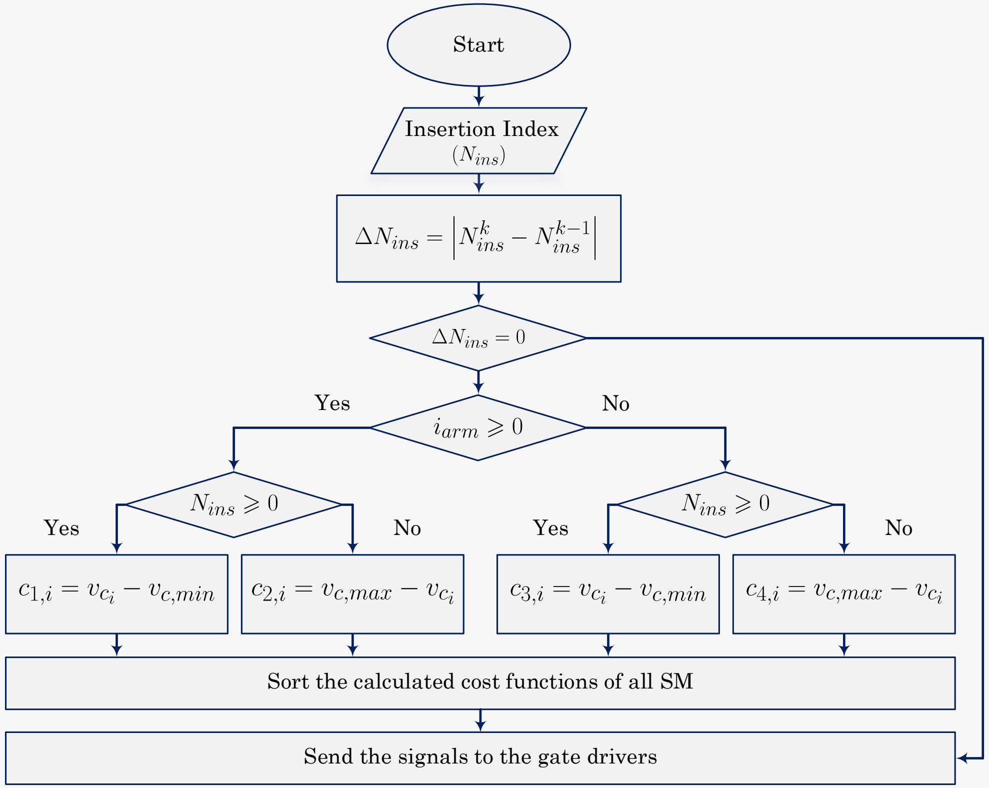
Topic I

Junction Temperature and Capacitor Losses Balancing

Junction Temperature and Capacitor Losses Balancing

Conventional capacitor voltage balancing method takes decision of switching of SMs only based on the capacitor voltages and arm current direction.

The junction temperature of switches and capacitor losses can be added to the voltage balancing method.



Conventional capacitor voltage balancing method

***Proposed method*:**

$$c_1 = (v_c - v_{c,min}) + \alpha(T_{j,D1} - T_{j,D1,min}) + \beta(P_{c,loss} - P_{c,loss,min})$$

$$c_2 = (v_{c,max} - v_c) + \alpha(T_{j,T2} - T_{j,T2,min}) + \beta(P_{c,loss,max} - P_{c,loss})$$

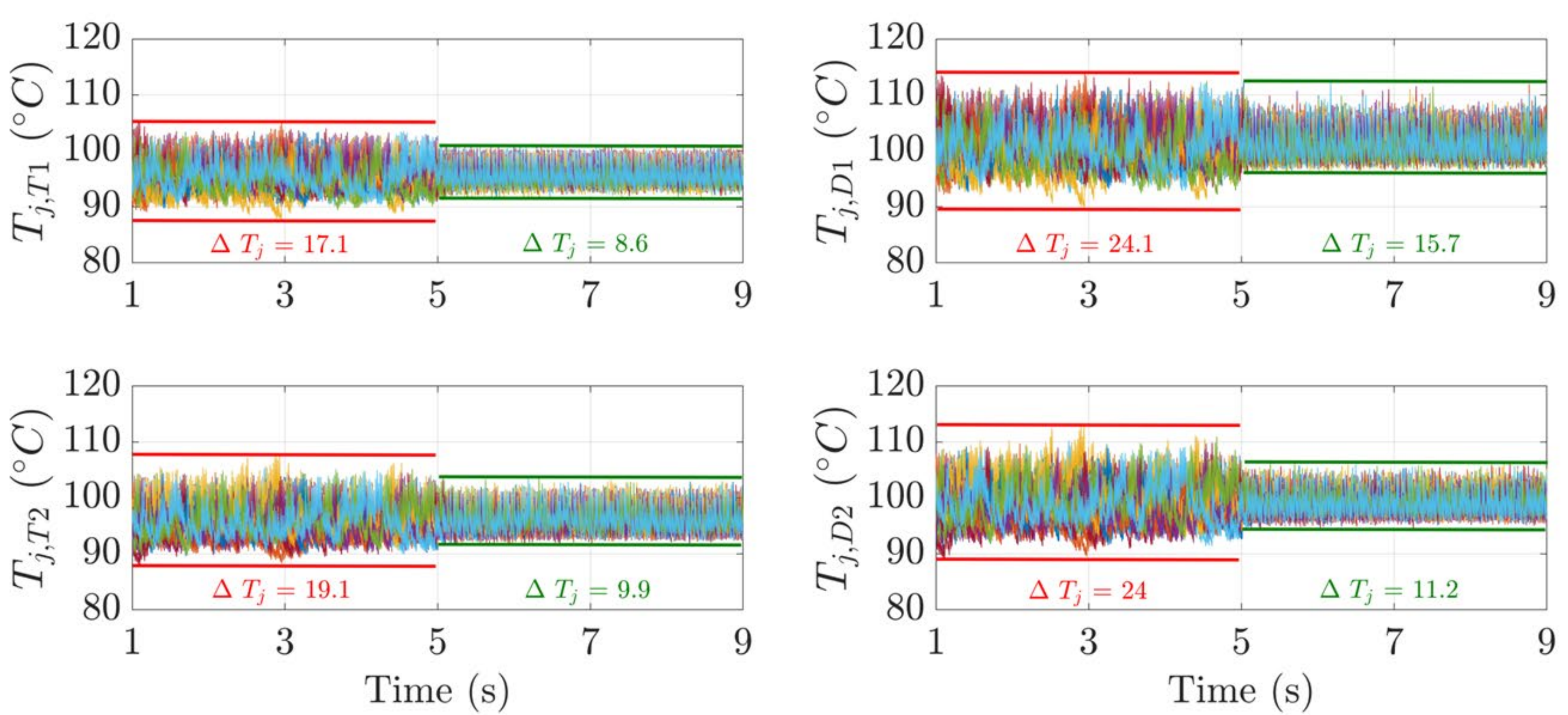
$$c_3 = (v_{c,max} - v_c) + \alpha(T_{j,T1} - T_{j,T1,min}) + \beta(P_{c,loss} - P_{c,loss,min})$$

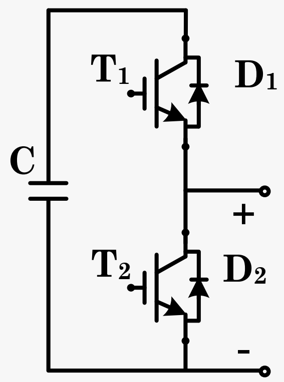
$$c_4 = (v_c - v_{c,min}) + \alpha(T_{j,D2} - T_{j,D2,min}) + \beta(P_{c,loss,max} - P_{c,loss})$$

α : weighting factor α is used to adjust the strength of active thermal balancing
β : weighting factor β is used to adjust the strength of capacitor loss balancing
T_j : matrix of estimated junction temperature
$P_{c,loss}$: Matrix of calculated average capacitor losses in one cycle

Junction Temperature and Capacitor Losses Balancing

Proposed method is applied at *t*=5s

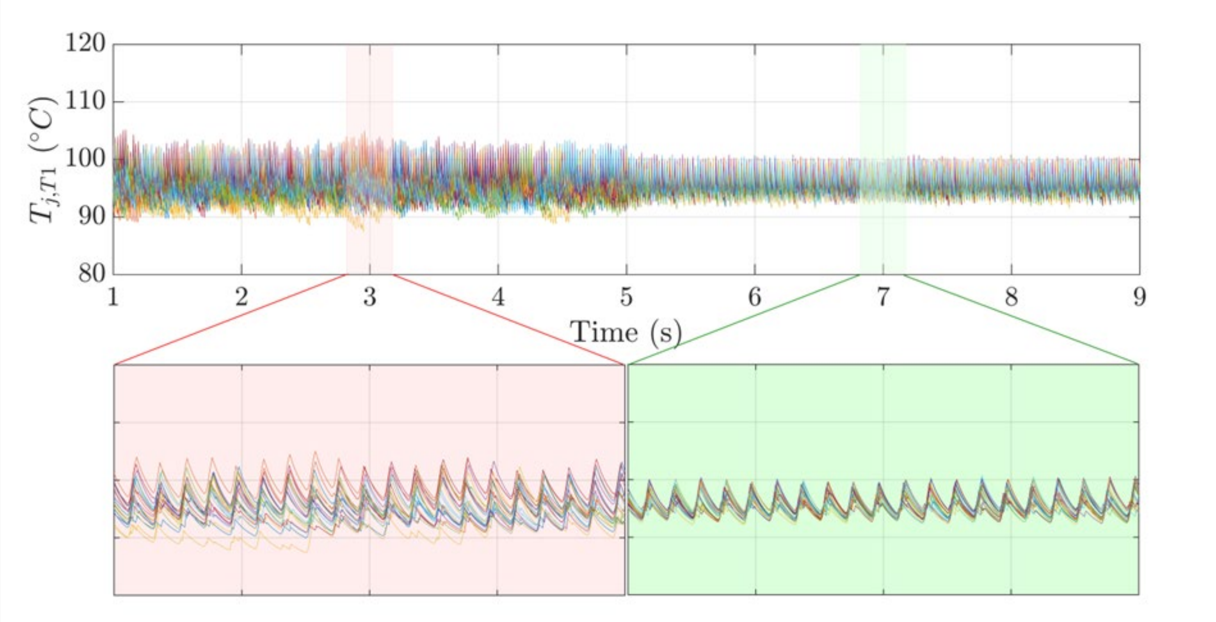




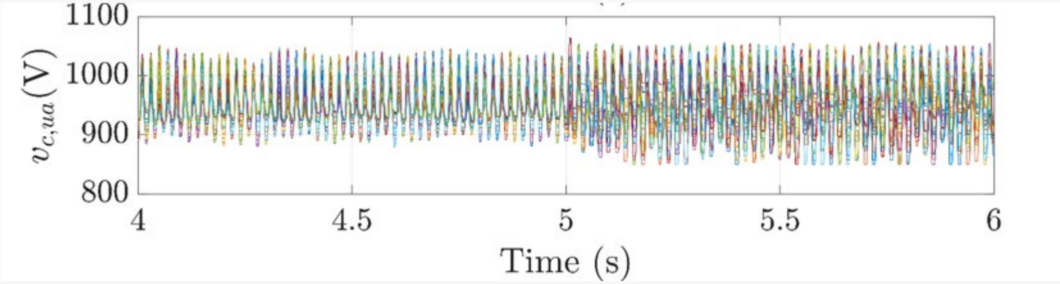
Junction Temperature and Capacitor Losses Balancing

Proposed method is applied at *t*=5s

Adding more factor to the cost function of capacitor voltage balancing can negatively affect the capacitor balancing, however, the capacitors are still well balanced at the desired voltage.

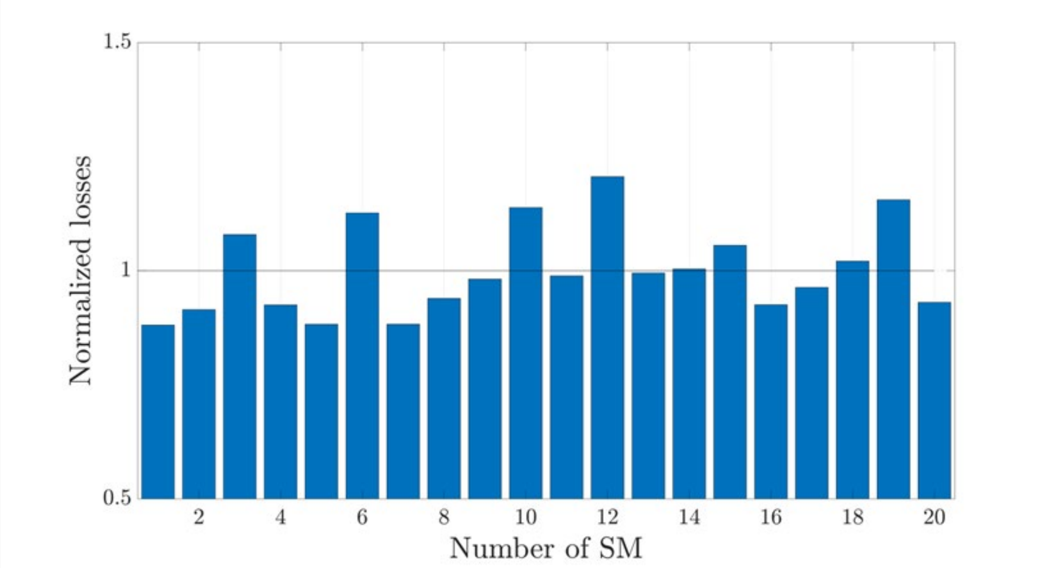


Calculated junction temperature of T1 in conventional balancing and proposed balancing method, which is applied *t*=5 s

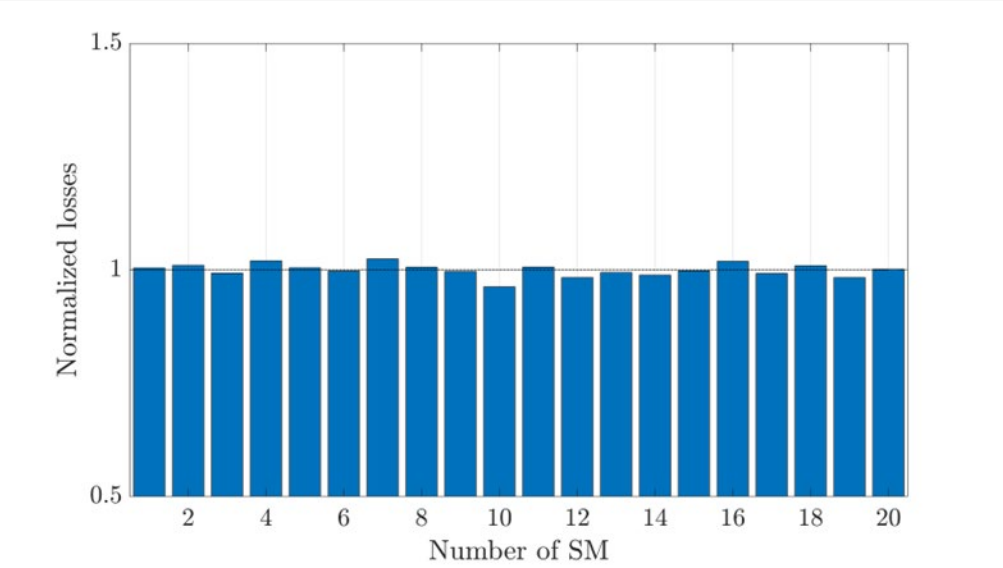


Capacitor voltage balancing in conventional balancing and proposed balancing method, which is applied in *t*=5 s

Junction Temperature and Capacitor Losses Balancing



Normalized capacitor losses in conventional balancing for one arm



Normalized capacitor losses in proposed balancing for one arm

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Topic II

Redundant SMs in Hybrid MMC

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Redundant SMs in hybrid MMC

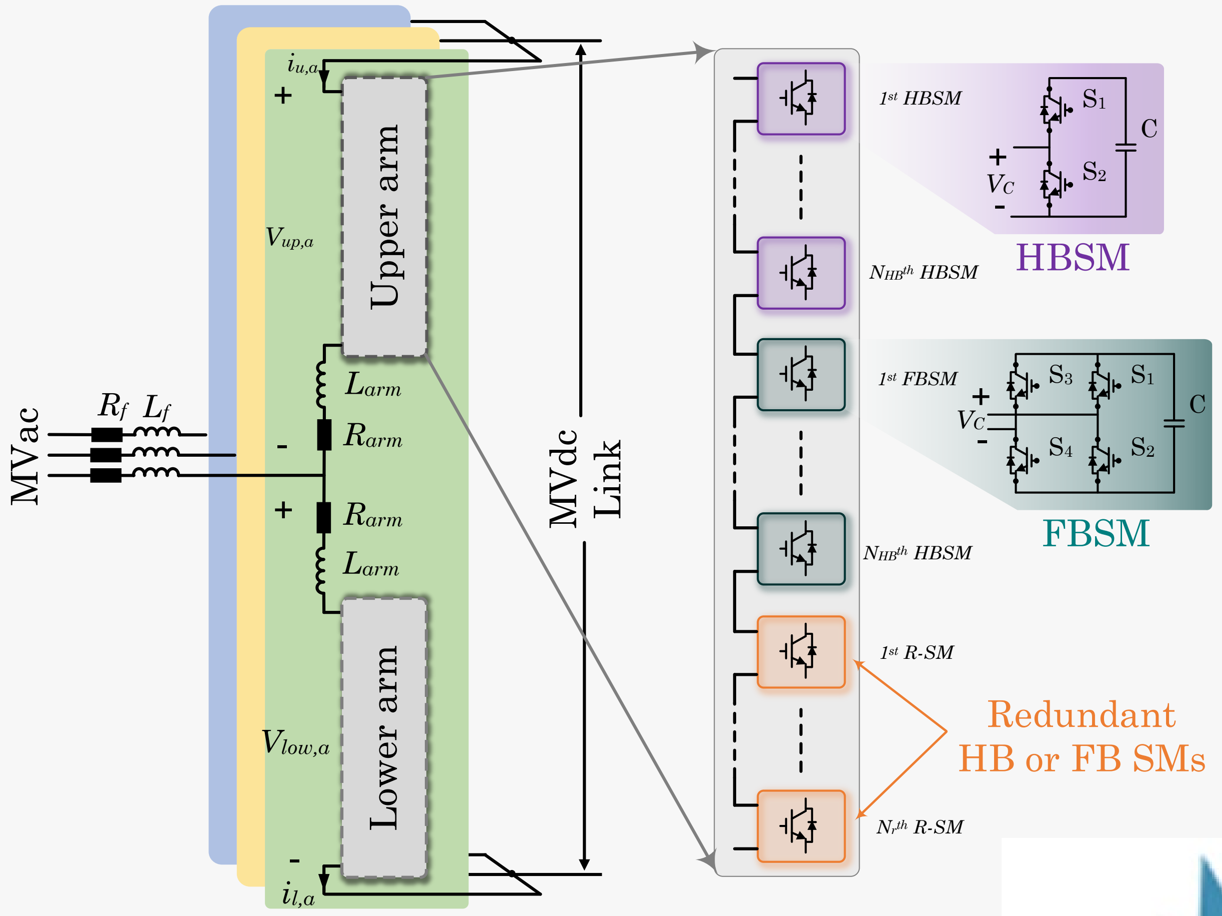
Redundant SMs can be mainly categorized into hot and cold reserve redundancy.

Hot Reserve:

- ❖ high losses
- ❖ better dynamic
- ❖ reducing circulating current
- ❖ reducing capacitor ripple

Cold Reserve:

- ❖ long transient period
- ❖ No impact on the losses of the converter
- ❖ Cause large inrush current after insertion



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Internal Fault-Tolerant of H-MMC

Internal Fault-Tolerant Operation of Hybrid Modular Multilevel Converter by Means of Redundant Submodules

First Objective:

Integration and Operation of Hot Reserve Submodules in Hybrid MMC

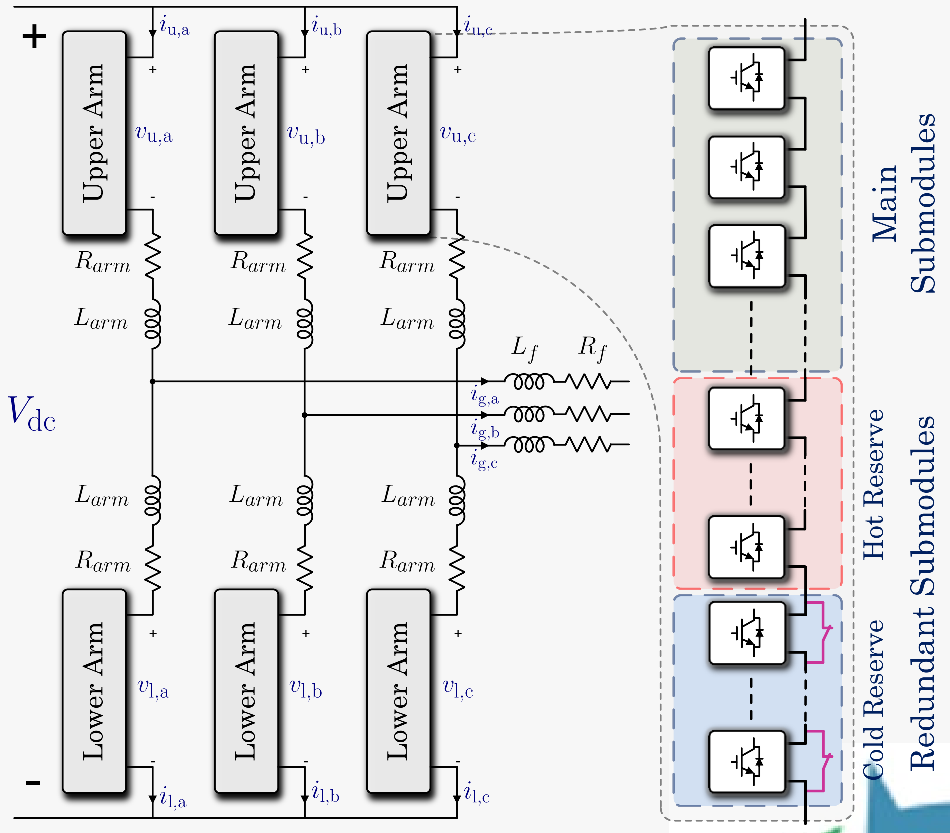
M. Hassanifar, S. Ventura, M. Langwasser, D. D'Amato, V. G. Monopoli and M. Liserre, "Modified Sorting Algorithm for Fault- Tolerant Operation of Hybrid MMC With Hot Reserve Submodules," *2024 IEEE 15th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Luxembourg, Luxembourg, 2024, pp. 1-6

Second Objective:

Development of Controlled Charging Method to Avoid High Inrush Current During Charging of Cold Reserve Submodules

M. Hassanifar, S. Ventura, M. Langwasser, D. D. Amato, V. G. Monopoli and M. Liserre, "Fault Tolerant Control for Medium Voltage Hybrid MMC With Cold Reserve Submodules," *2024 IEEE 15th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Luxembourg, Luxembourg, 2024, pp. 1-6.

M. Hassanifar, D. D'Amato, M. Langwasser and M. Liserre, "Controlled Insertion of Cold Reserve Submodule in Hybrid Modular Multilevel Converter Considering Inrush Current Mitigation," in *IEEE Transactions on Industrial Electronics*.



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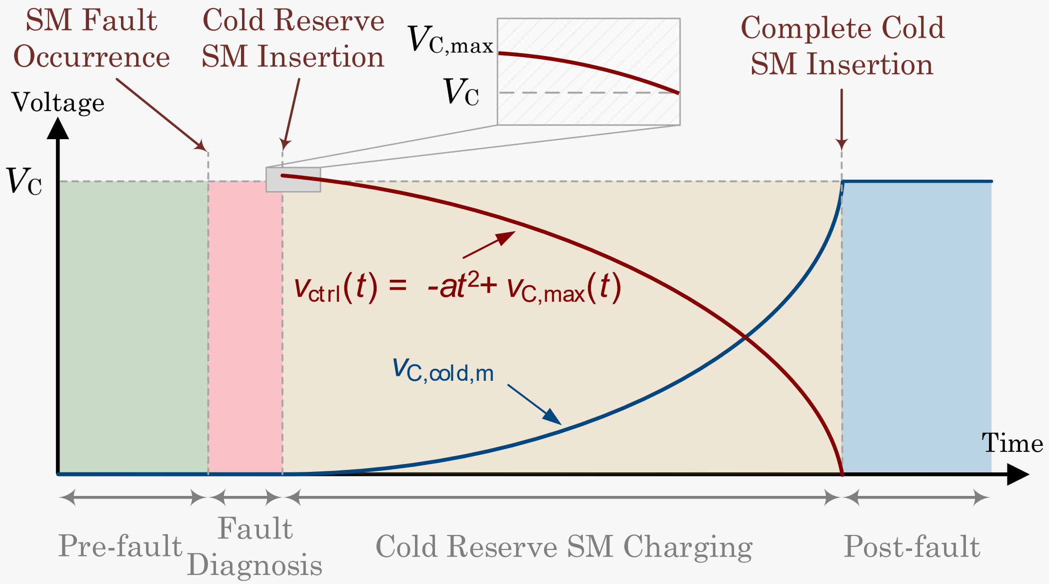
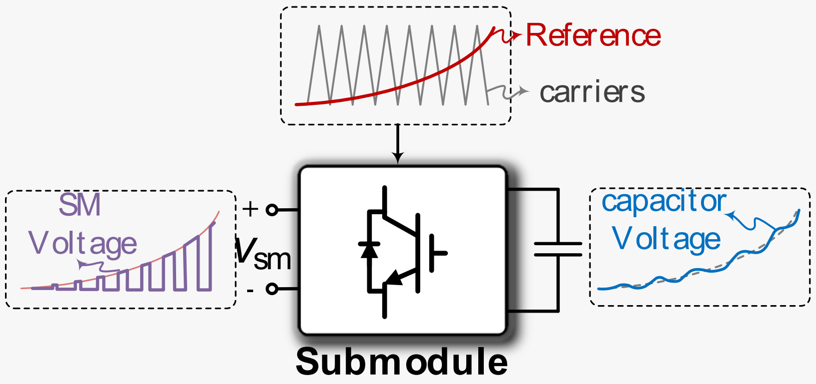
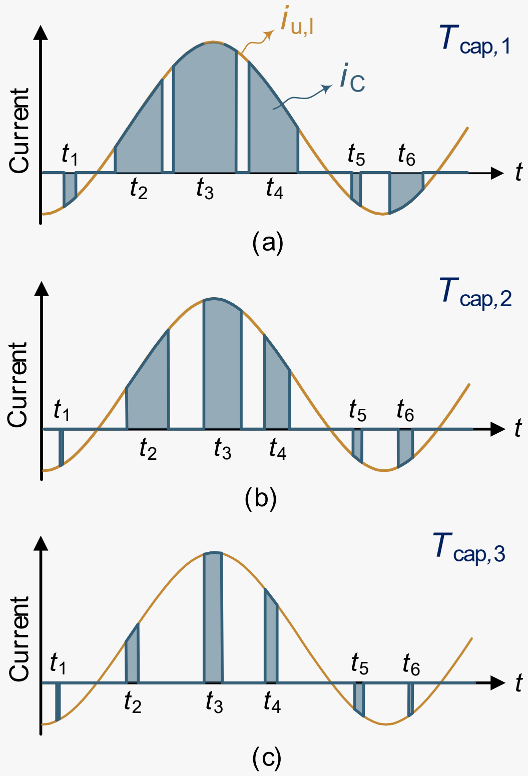
Controlled Cold Reserve SM Charging Method



$$v_{C,cold} = v_{C,cold,m} + V_{ctrl}$$

$$V_{ctrl} = at^2 + bt + c$$





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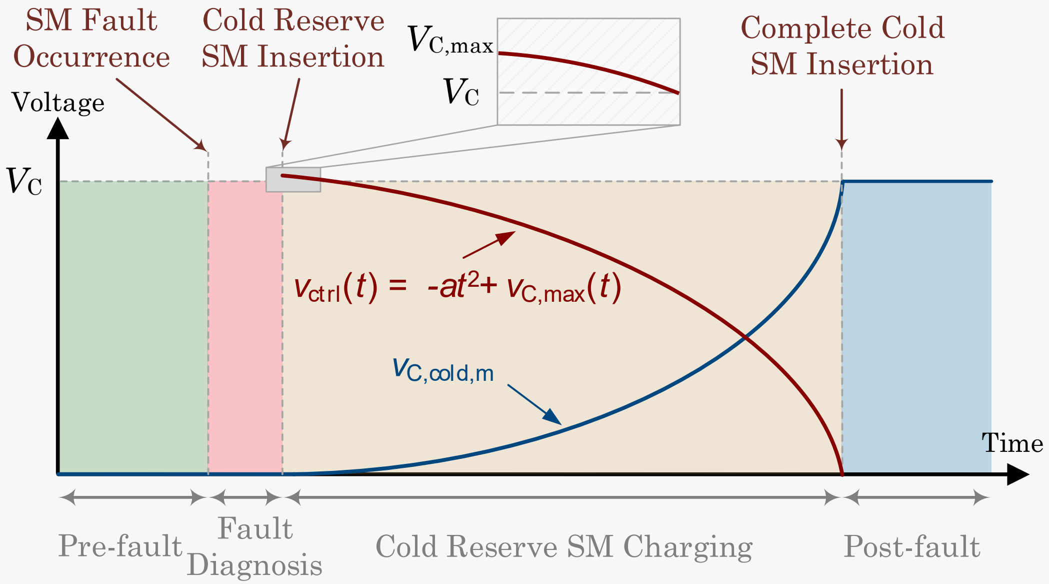
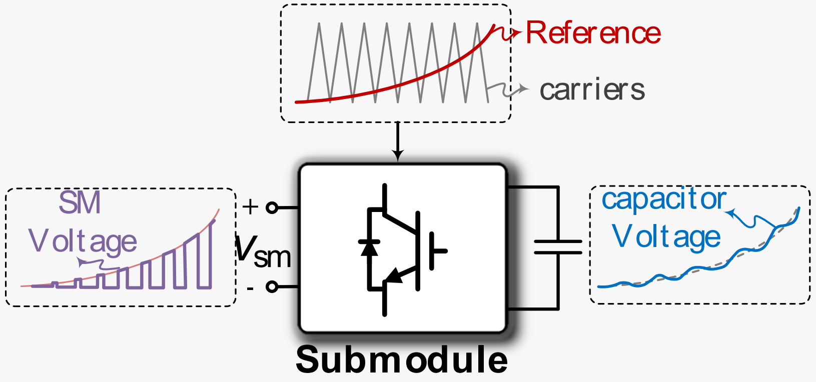
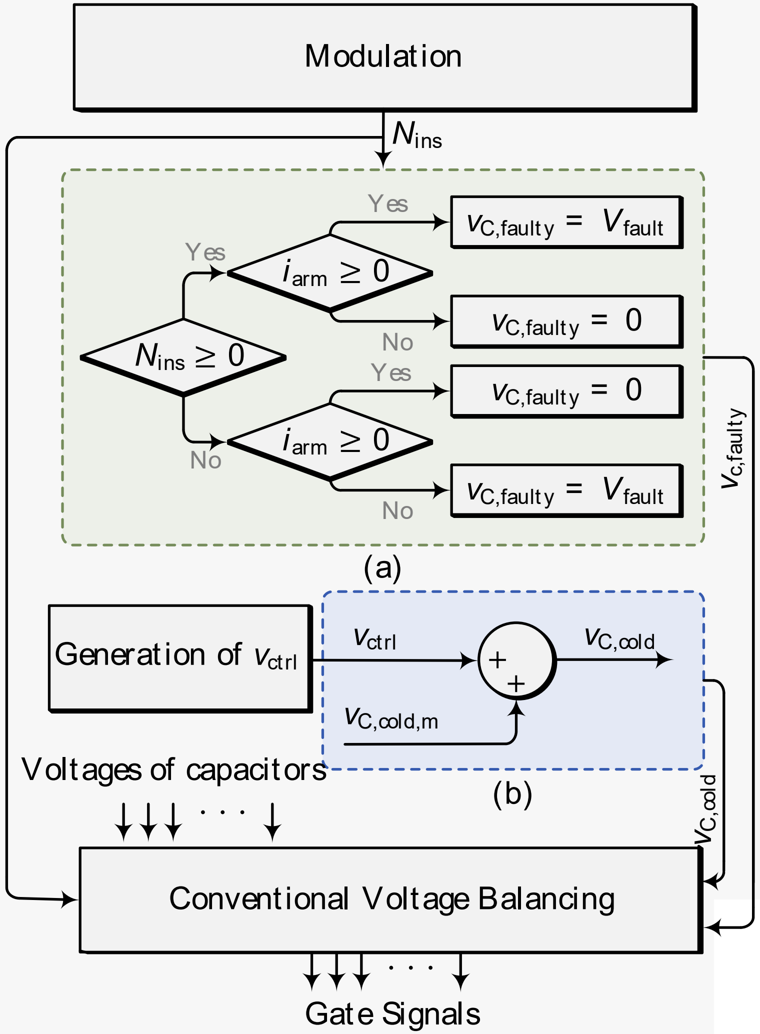
Controlled Cold Reserve SM Charging Method







Topic III

Modular Multilevel Converter Emulator

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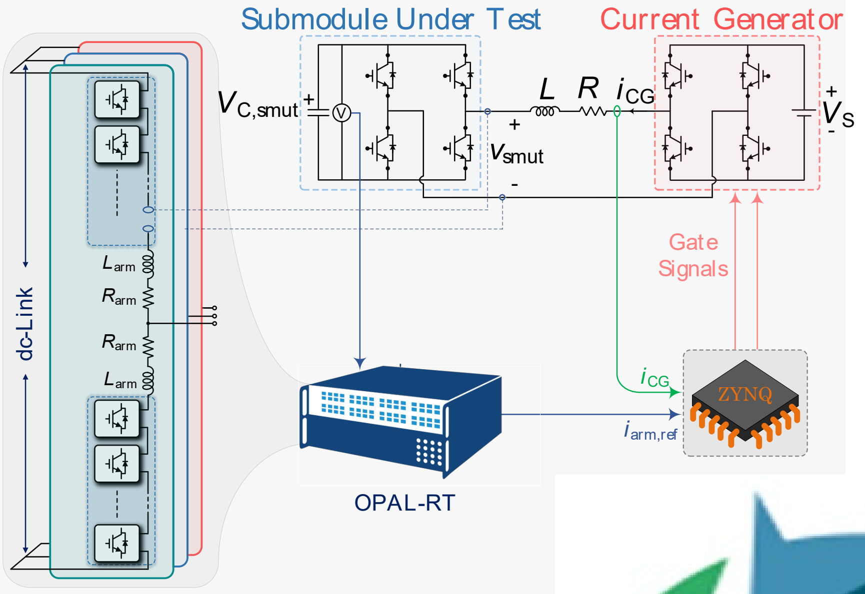
MMC Emulator

❖ Making a real protype for MMC for testing face challenges and limitations:

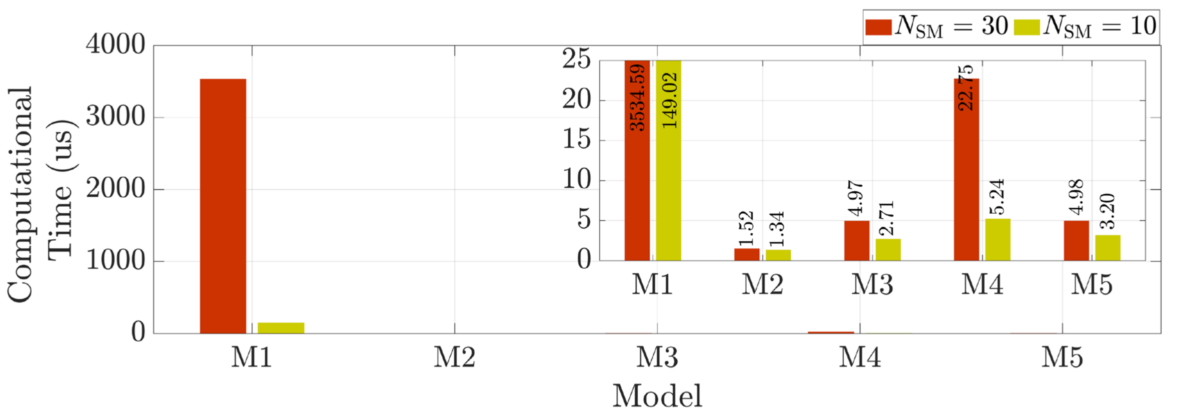
- ➢ High number of components and design complexity
- ➢ High investment cost
- ➢ Large space for full MMC prototype
- ➢ Huge power supply

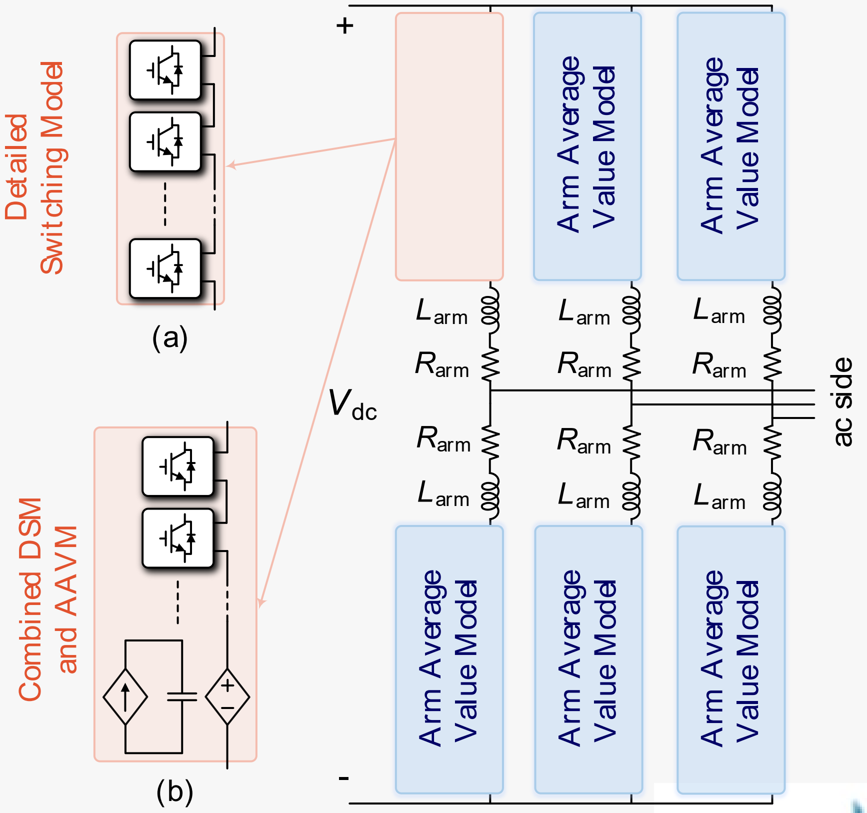
A test bench that emulates the behaviour of the full MMC can be used to study MMC.



MMC emulator is a test bench, which can be used to emulate the behavior of the whole MMC or only to analyze the submodule(s) of the converter.

Using the average models of MMC is critical to avoid high computational burden.





M1: Detailed switching model (DSM)

M2: Arm average value model (AAVM)

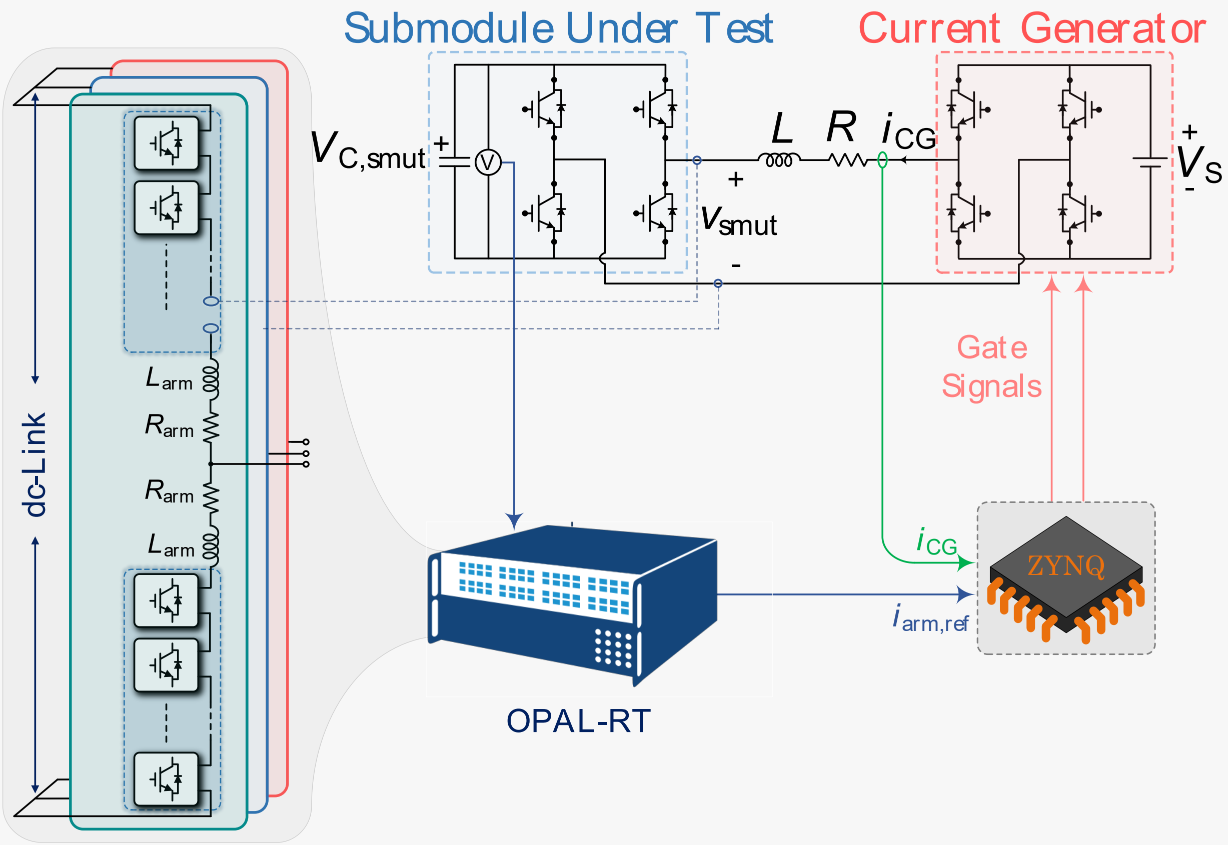
M3: Single SM average value model

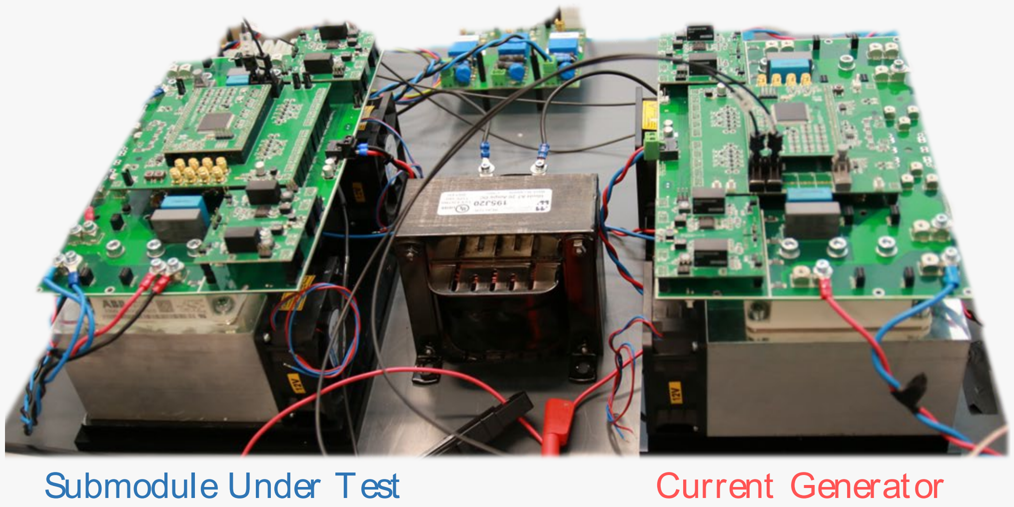
M4: One full arm with DSM and five arms with AAVM

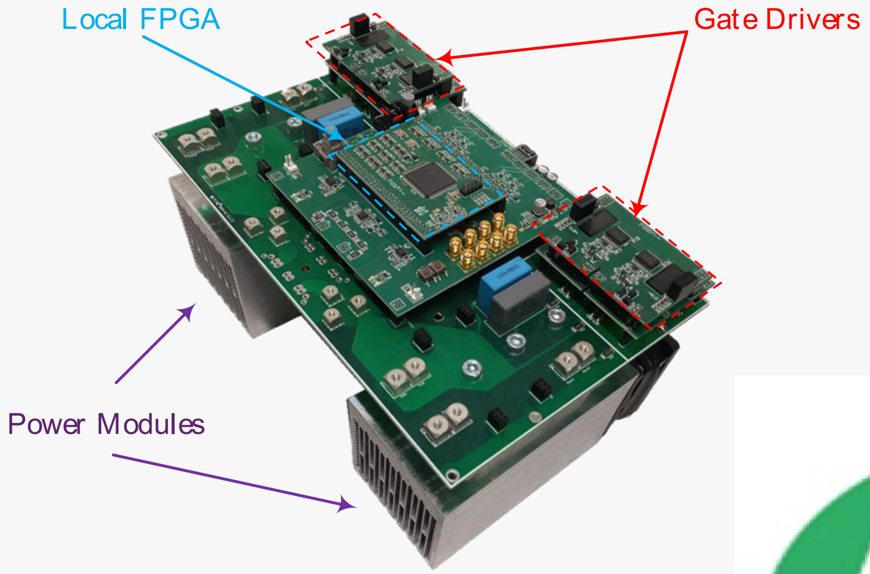
M5: Some SMs in the arm with DSM and the rest of MMC with AAVM

M. Hassanifar, D. D'Amato, M. U. Mutarraf, M. Langwasser and M. Liserre, "Arm Modeling Approaches for Real-Time Simulation of Modular Multilevel Converter," *2025 IEEE Kiel PowerTech*, Kiel, Germany, 2025, pp. 1-7.

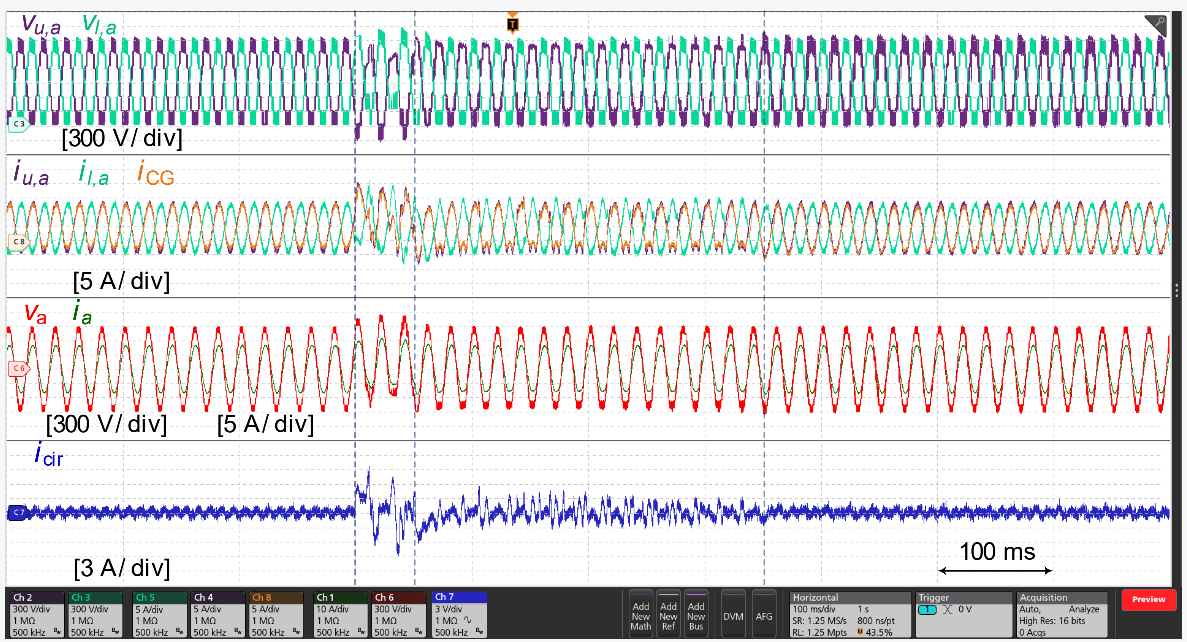
MMC Emulator





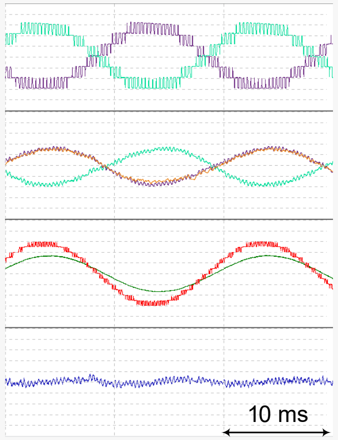


MMC Emulator



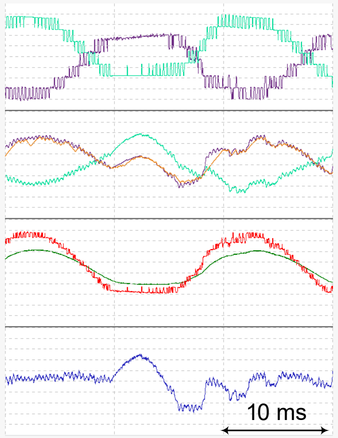
Experimental results during pre-fault, faulty, charging phase of cold reserve SM, and post-fault operation conditions:

Pre-Fault



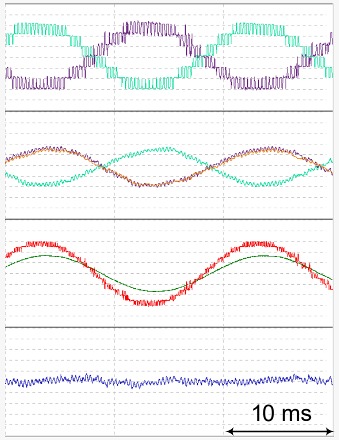
zoomed view of pre-fault condition

Faulty Condition



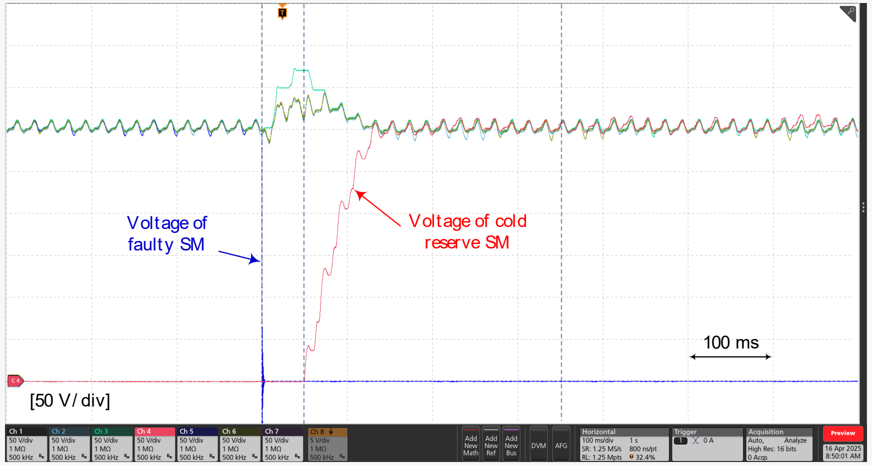
zoomed view of faulty condition

Post-Fault

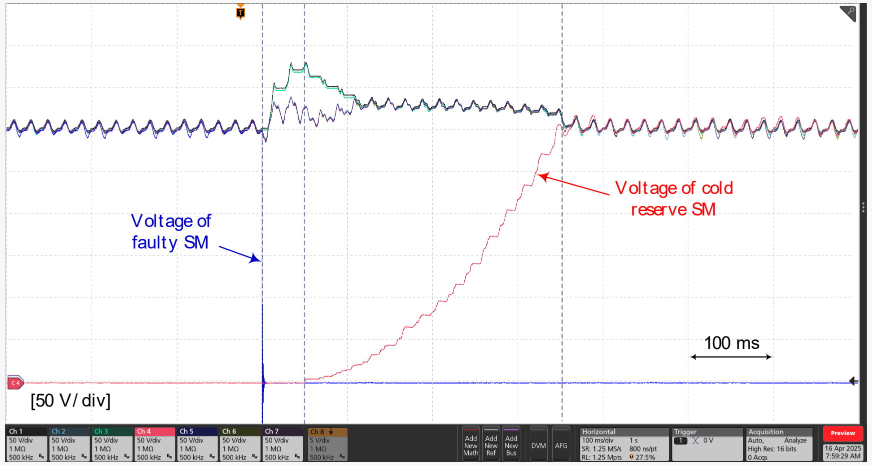


zoomed view of post-fault condition

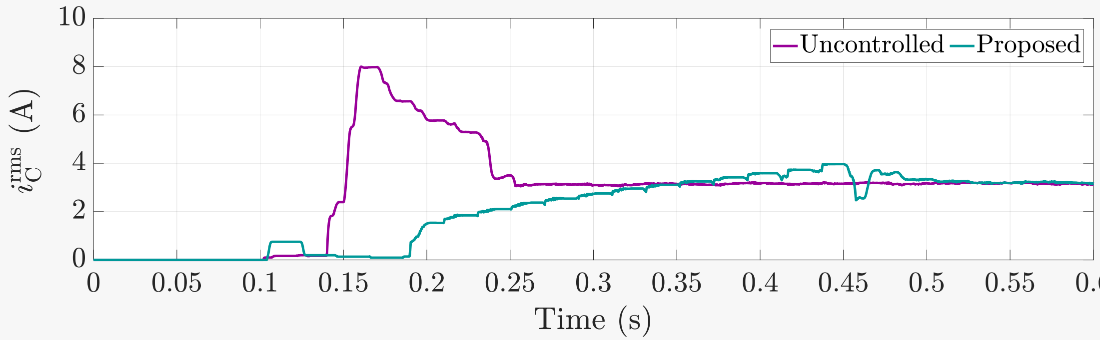
MMC Emulator + Experimental Result of Cold Reserve Insertion



uncontrolled charging of cold reserve SM



proposed cold reserve SM insertion method



Comparison of the RMS values of the inrush current obtained from the proposed charging method and uncontrolled insertion

Condition	Parameter	Uncontrolled	Proposed	Reduction
simulation	Peak Current	812 A	608 A	25.1 %
	Peak RMS Current	375 A	166 A	57.7 %
Experiment	Peak Current	14.9 A	9.3 A	37.5 %
	Peak RMS Current	8 A	3.3 A	58.8 %

M. Hassanifar, D. D'Amato, M. Langwasser and M. Liserre, "Controlled Insertion of Cold Reserve Submodule in Hybrid Modular Multilevel Converter Considering Inrush Current Mitigation," in *IEEE Transactions on Industrial Electronics.*

Outcomes

No.	Title of the Publication	Journal/ Conference	Expected Time of Submission	Status
C1	Modular Multilevel Converters Enabling Multibus DC Distribution	CPE 2023	Feb. 2022	Accepted
C2	Modified Sorting Algorithm for Fault-Tolerant Operation of Hybrid MMC With Hot Reserve Submodules	PEDG 2024	Mar. 2023	Accepted
C3	Fault Tolerant Control for Medium Voltage Hybrid MMC With Cold Reserve Submodules	PEDG 2024	Mar. 2023	Accepted
C4	Arm Modeling Approaches for Real-Time Simulation of Modular Multilevel Converter	Powertech 2025	Sep. 2025	Accepted
J1	Arm Average Value Model of Hybrid MMC, Considering DC Fault and Internal Switch Failures	IEEE TIE	Dec. 2025	Accepted
J2	Capacitor Inrush Current Mitigation for Cold Reserve Submodule Insertion in Hybrid MMC	IEEE TIE	Feb. 2026	Accepted
J3*	Arm Modeling Methods for Real-Time Simulation of MMC	IEEE P.Del.	Sep. 2026	In preparation

Collaborative Publications

+C1	A Data-Driven Condition Monitoring Method for Capacitor in Modular Multilevel Converter (MMC)	ECCE Asia 2024	July. 2024	Accepted
+J1	Monolithic Data-Driven Condition Monitoring Strategy for MMC Considering *C* and ESR	IEEE TPEL	Jan. 2025	Accepted
+C2	Physics-informed neural network for parameter identification: A buck converter case study	ECCE Asia 2025	July. 2025	Accepted
+J2*	A Unified Framework for System-Level Condition Monitoring of Power Electronic Converters	IEEE JESTIE	Sep. 2026	Under Review

Thank you for your attention