PEMC Webinar:
International Workshop on Electric Technologies for Green Airports

Wednesday 28th April 2021

Efficient integration of renewable energy sources for green airports

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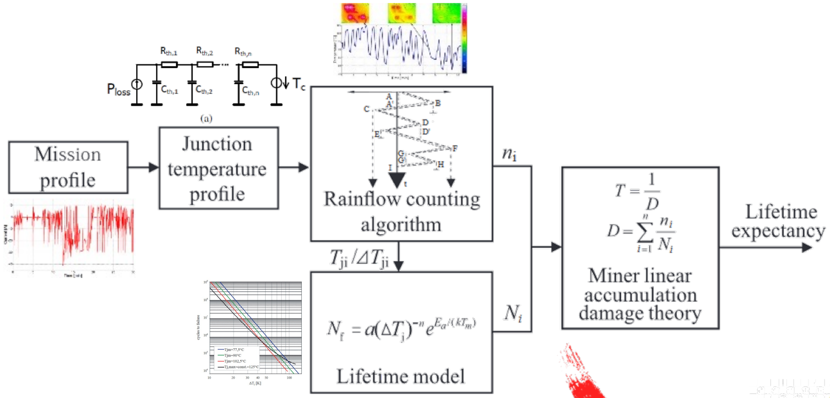
Important remark:

This work is an international collaboration between several research groups:

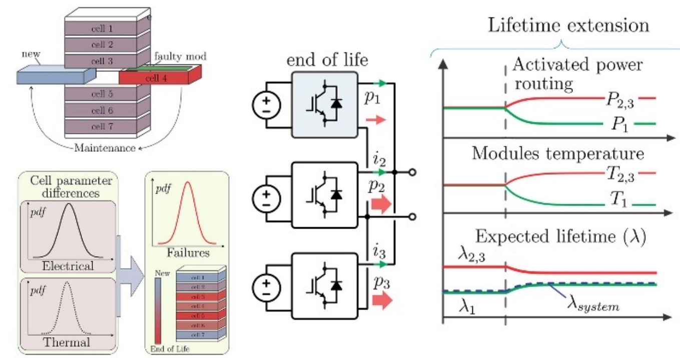
- Prof. Leopoldo G. Franquelo and his team, University of Seville (Spain)
- Prof. Marco Liserre and his team, Christian-Albrechts-Universität zu Kiel (Germany)
- Prof. Giampaolo Buticchi, University of Nottingham at Ningbo (China)
- Prof. Vito Giuseppe Monopoli, Politecnico di Bari (Italy)

Efficient integration of renewable energy sources for green airports

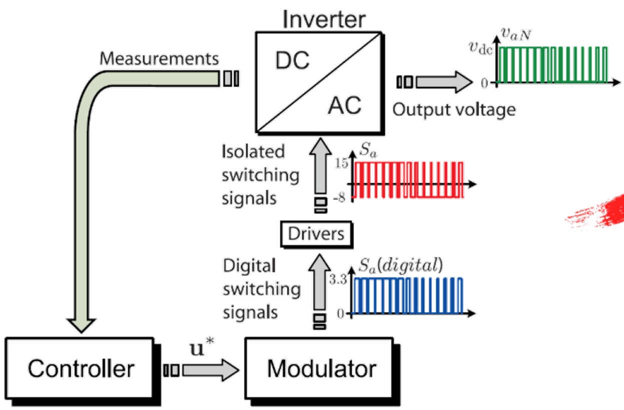
Power devices aging physics



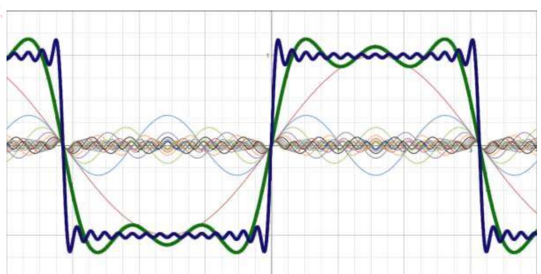
Active thermal control methods



Power Electronics



Harmonic analysis



$$f(t) = \frac{4}{\Pi} \sum_{k=0}^{\infty} \frac{1}{2k+1} \sin 2\Pi(2k+1)t$$

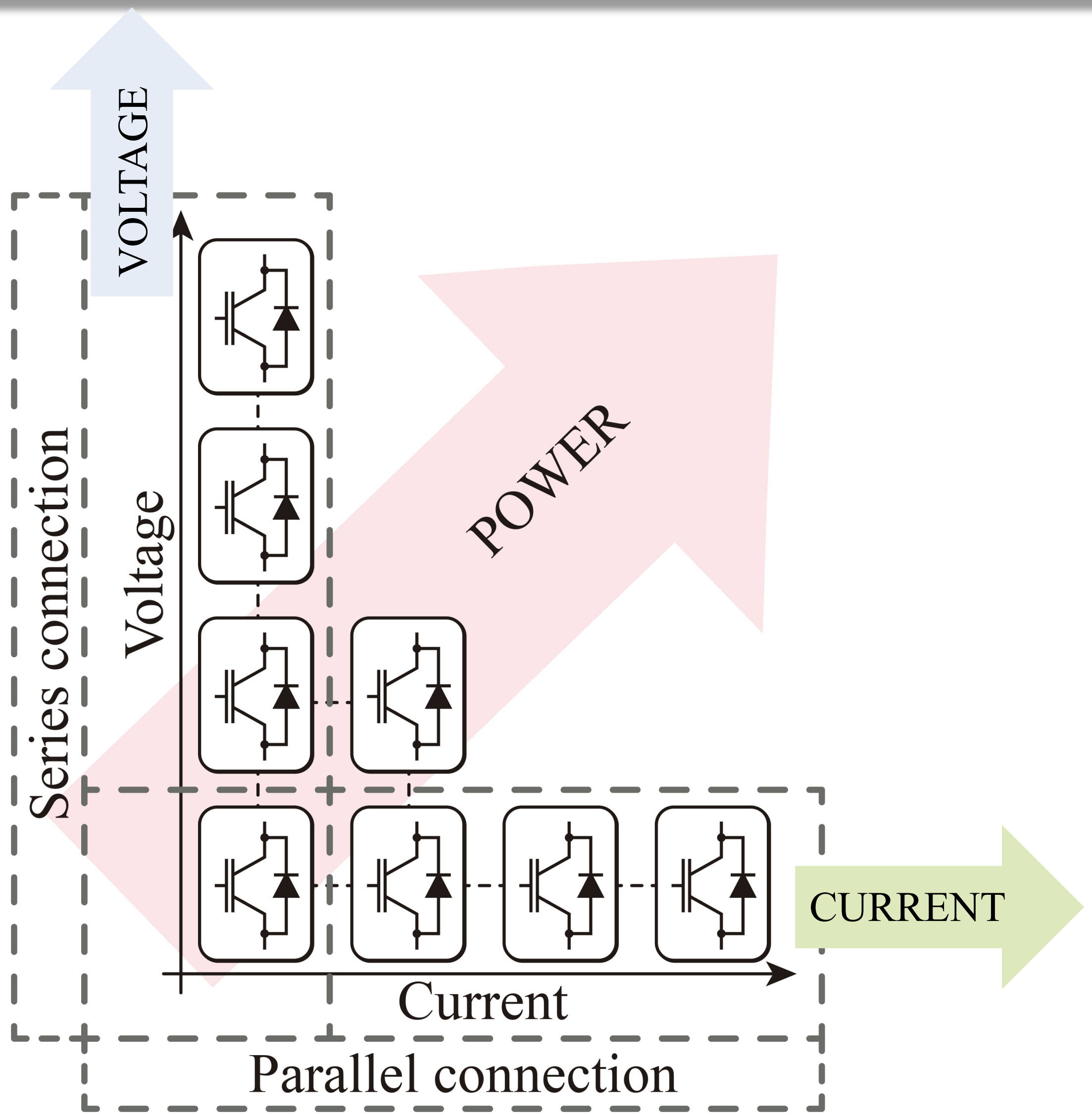
Introduction

Reliability in Power Electronics

- Safety: Growing capacity ➔ Significant impact after failures
- Cost of energy = (Installation + O&M)/Operating time
- Improve reliability of PE ➔ Reduce the cost of energy

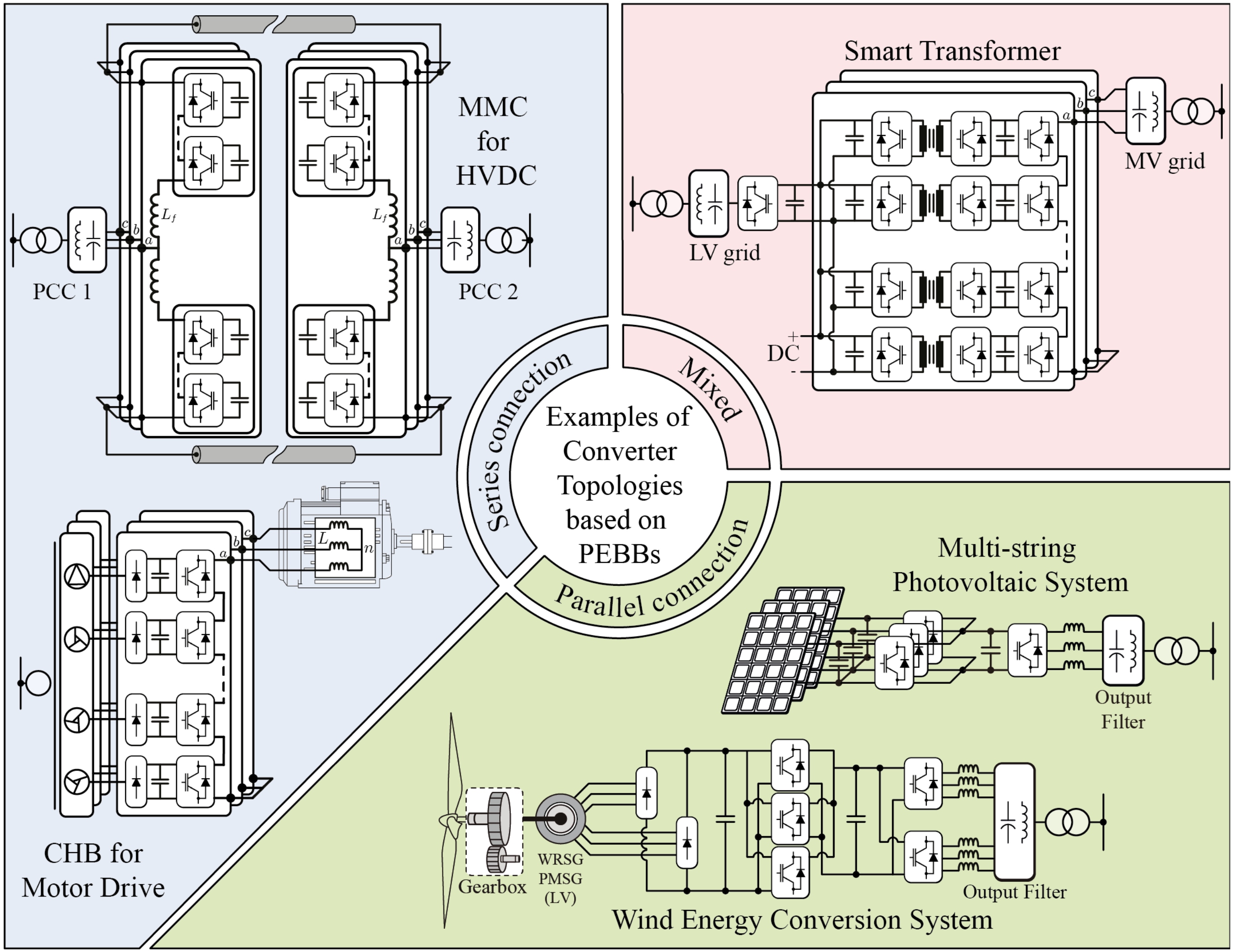
Modular Converters

Basic Concept

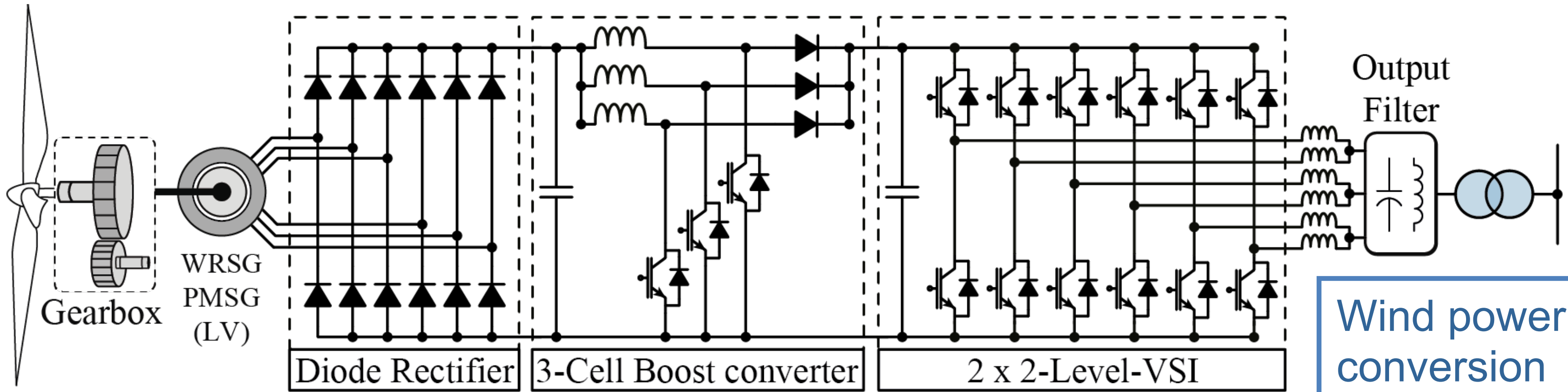


Modular Converters

Some Examples



Wind Power Energy Conversion System with Modular Converters

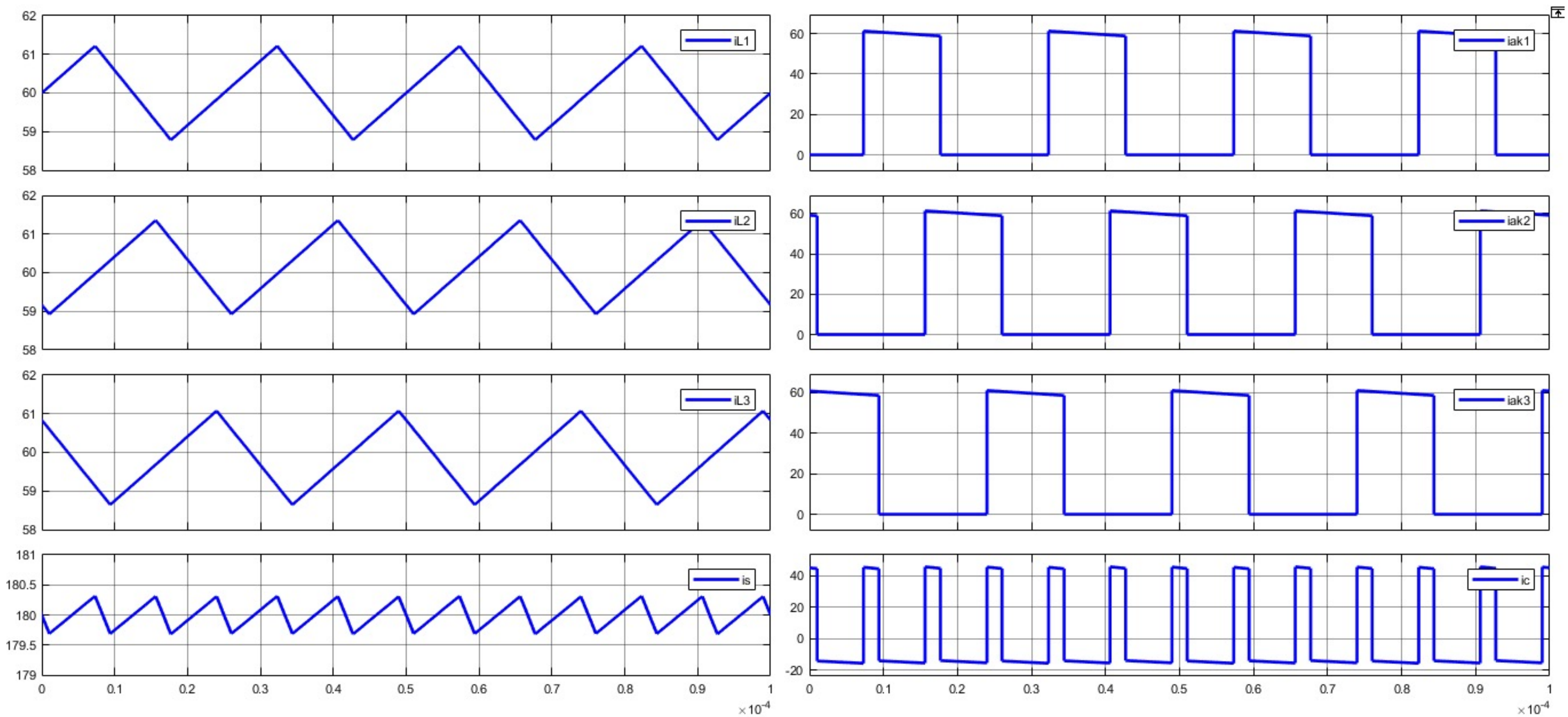


Wind power conversion system

Vensys 60/1200 wind turbine electric schematic

Rated power: 1.2 MW
Rotor diameter: 62 m
Offshore model: no
Swept area: 3,020 m²
Specific area: 2.52 m²/kW
Number of blades: 3
Power control: Pitch
Rated wind speed: 13,5 m/s
Cut-off wind speed: 25 m/s

Conventional PWM Operation of Interleaved Modular Converters



Input currents [A] **Output currents [A]**

Interleaving conventional phase displacement is 360º/N (N is the number of DC-DC modules)

Modular Converters

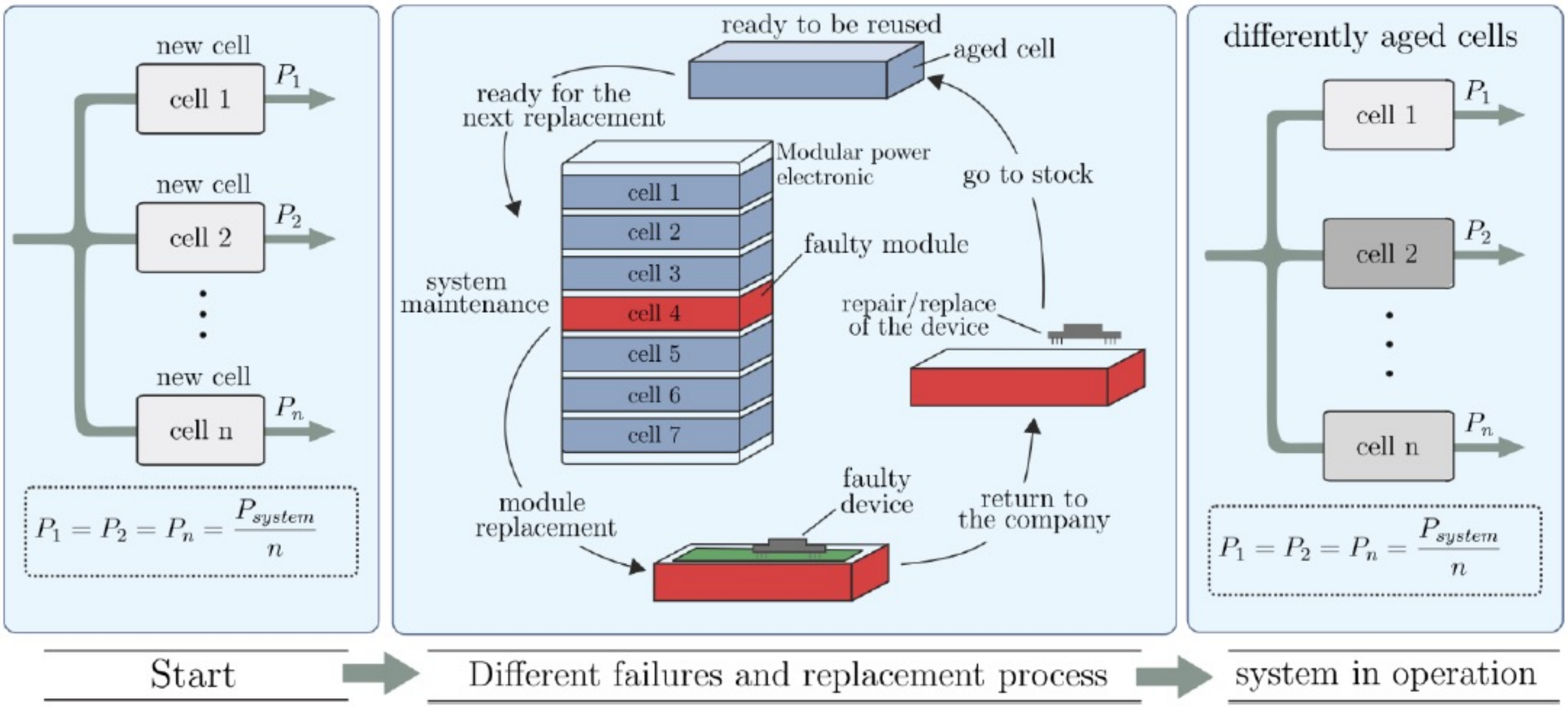
Pros & Cons

MODULAR CONVERTERS FEATURES

- ✓ Inherent fault tolerant capability
- ✓ Output waveforms enhanced quality
- ✓ Reduced output filters
- ✓ Reduced maintenance cost by fast PEBB replacement
- ✓ Standarization in the PEBB design
- ✓ Reduction in the design and manufacturing costs using the same PEBB firmware for different applications

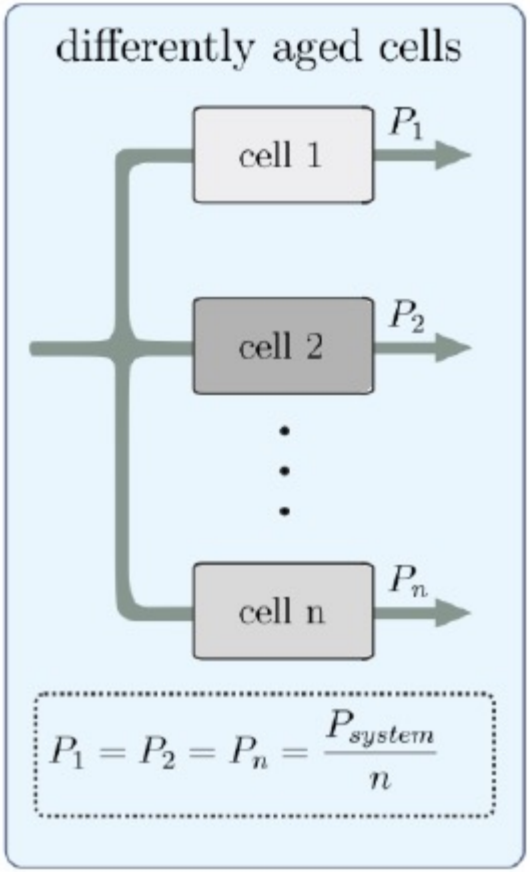
- ✗ Higher initial CAPEX and OPEX
- ✗ More complex hardware/software design including the controllers and the modulation methods
- ✗ Large number of sensors, power converters and drivers
- ✗ Bigger size than non-modular converters

Active Thermal Control (ATC) in Modular Power Converters



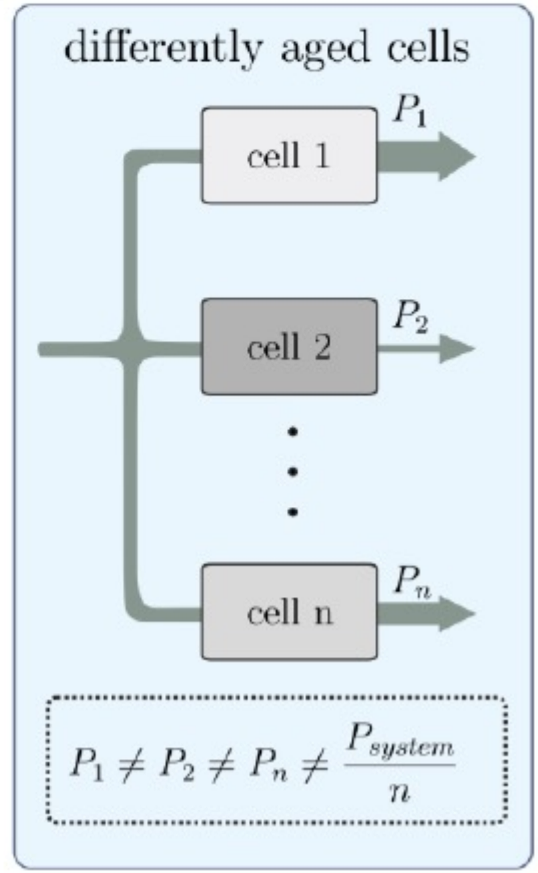
Is the power equalization, inherently obtained by applying the interleaved operation, always optimal ?

Active Thermal Control (ATC) in Modular Power Converters



$$\sum_{i=1}^{n} P_i = P_{system}$$

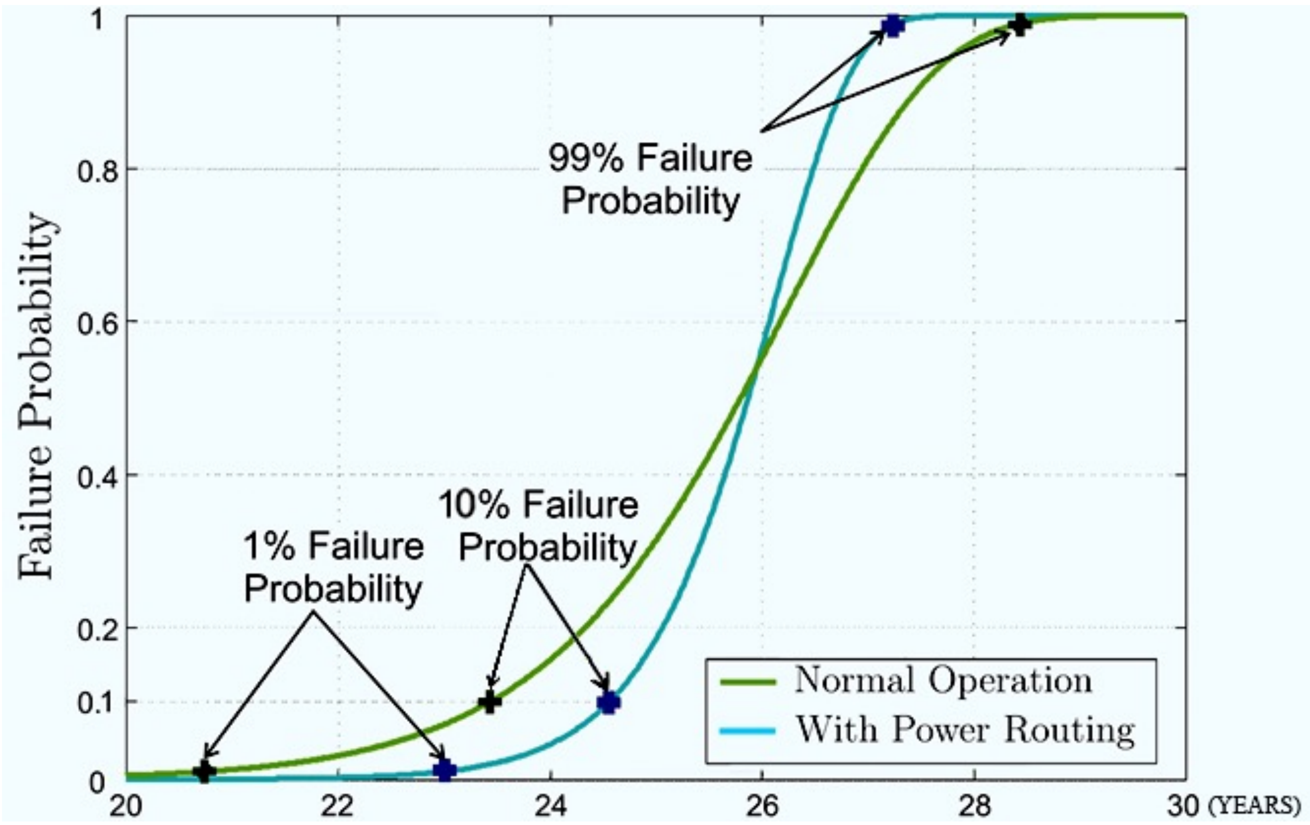
Power Routing



$$\sum_{i=1}^{n} P_i = P_{system}$$

M. Liserre, M. Andresen, L. Costa and G. Buticchi, "**Power Routing in Modular Smart Transformers: Active Thermal Control Through Uneven Loading of Cells**," in *IEEE Industrial Electronics Magazine*, vol. 10, no. 3, pp. 43-53, Sept. 2016.

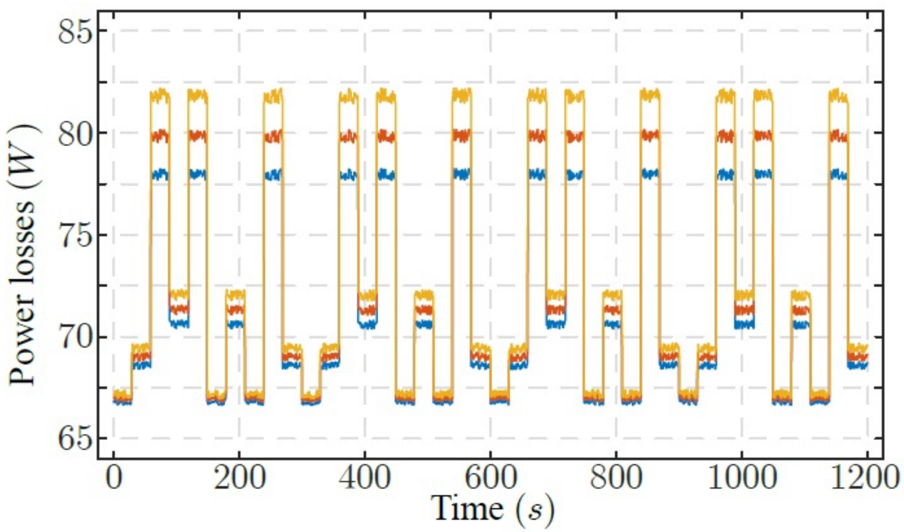
Active Thermal Control (ATC) in Modular Power Converters

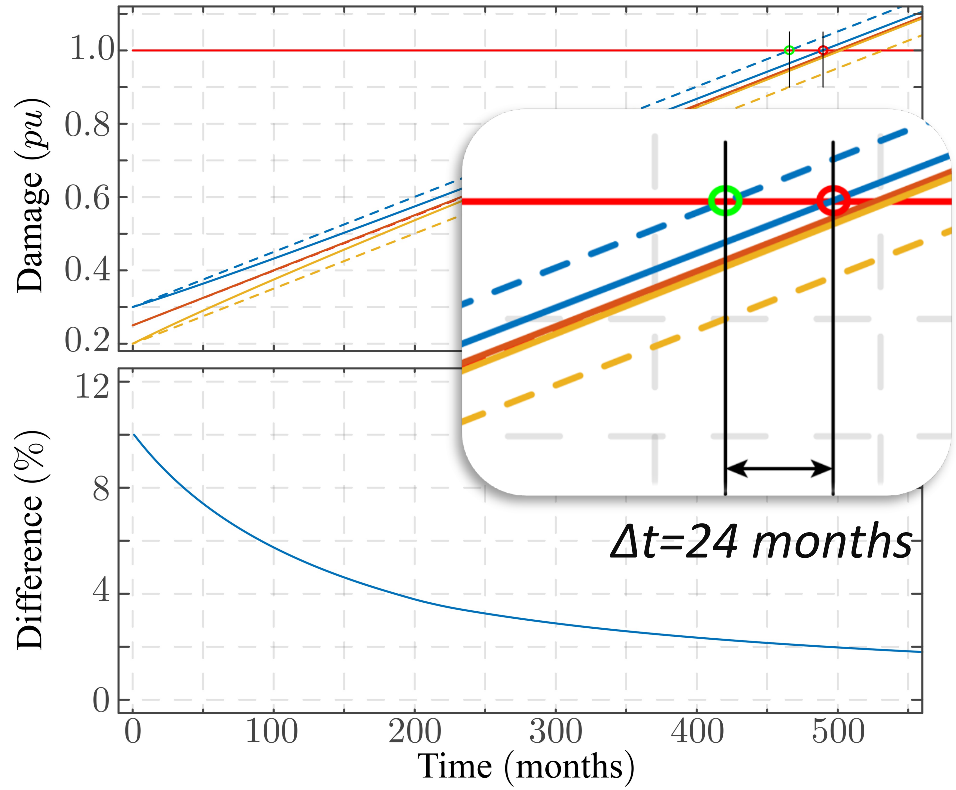


M. Liserre, G. Buticchi, J. I. Leon, A. Marquez, V. Raveendran, Y. Ko, M. Andresen, V. Monopoli and L. G. Franquelo, "**Power Routing: A New Paradigm for Maintenance Scheduling**," in *IEEE Industrial Electronics Magazine*, vol. 14, no. 3, pp. 33-45, Sept. 2020, doi: 10.1109/MIE.2020.2975049.

Lifetime Extension of Power Semiconductors in by applying ATC

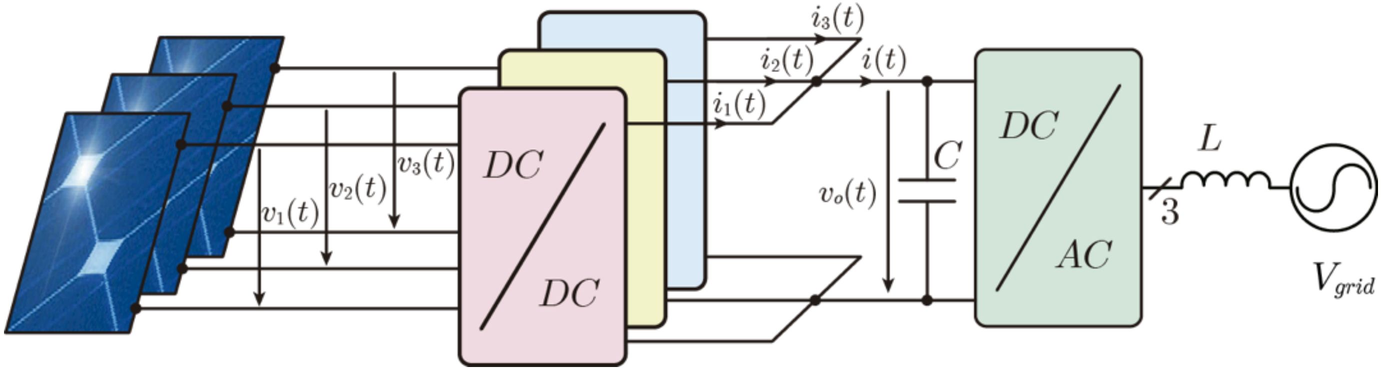
- ATC via power routing improves the power devices average lifetime

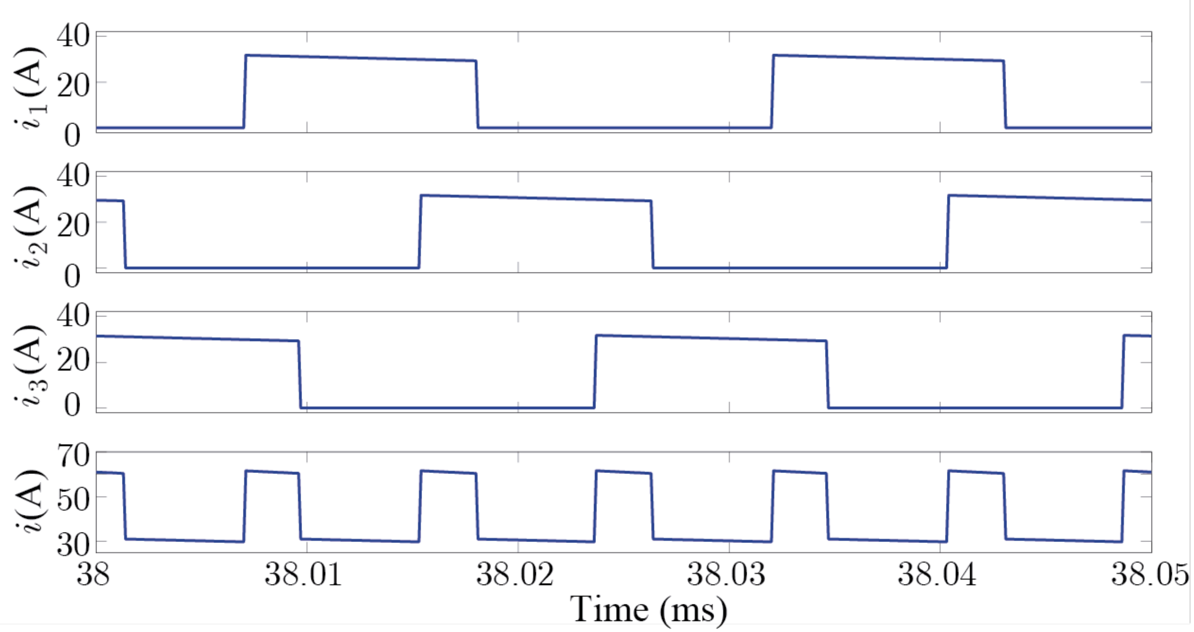




But… is this ATC method via power routing for free? Does it present any drawback??

Solar PV system with Modular Converters. Multi-string PV

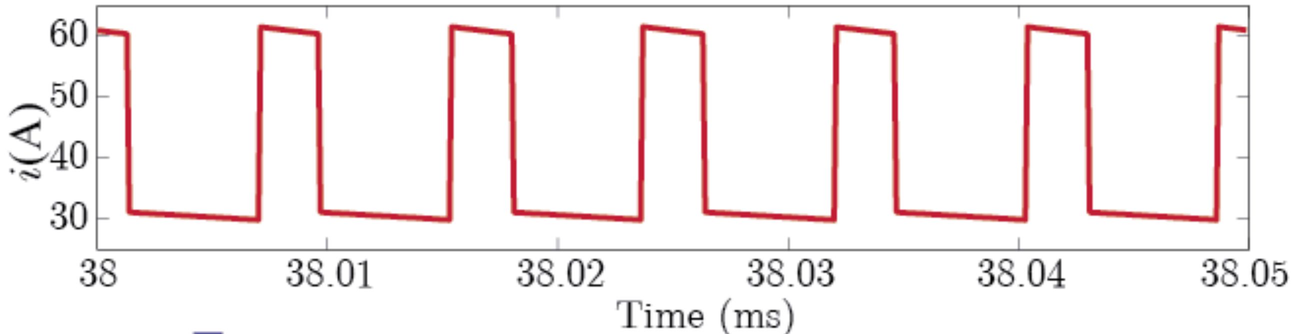


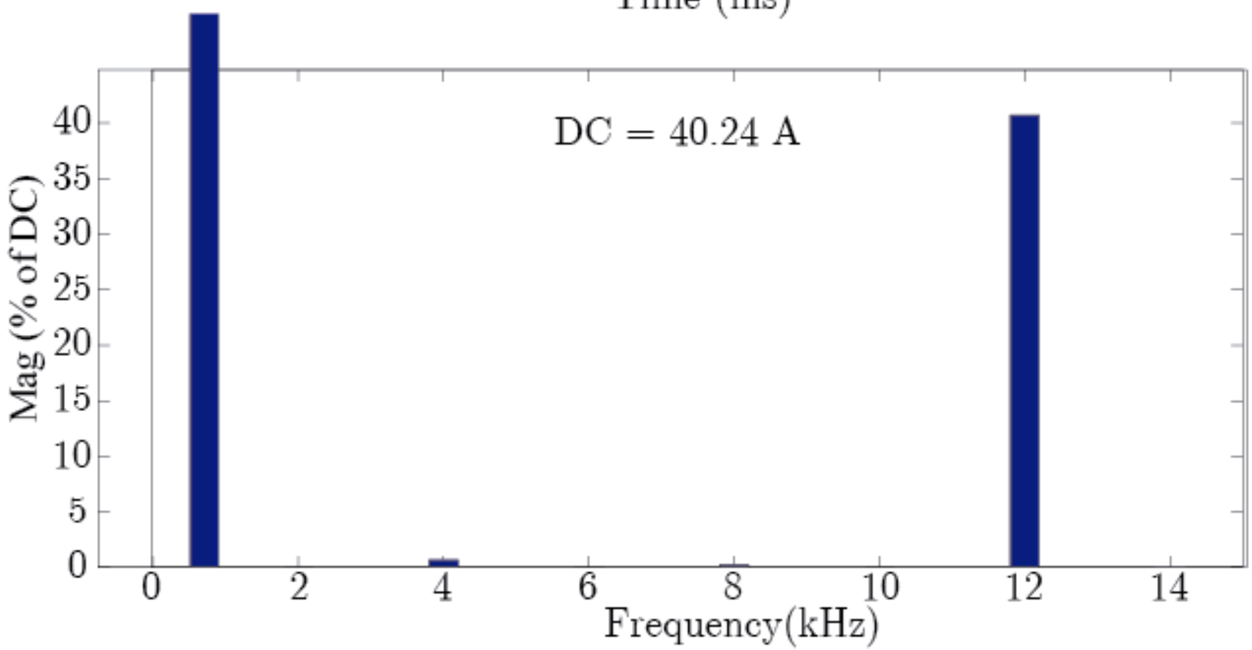


Interleaving conventional phase displacement is 360º/N (N is the number of DC-DC modules)

ATC in Interleaved DC/DC Converters. Solar PV case

- Conventional interleaved operation with balanced operation

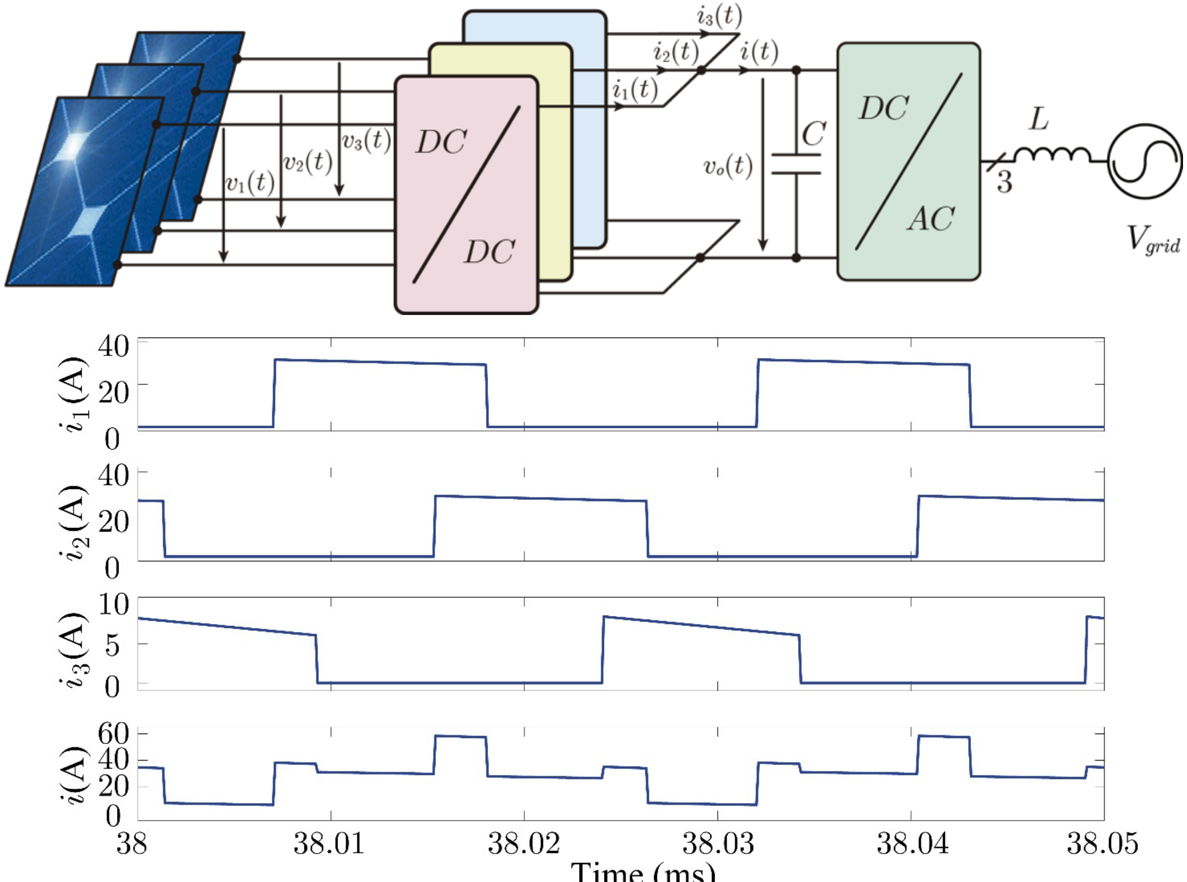




Remark: f_{cr}=4 kHz, three interleaved DC/DC modules

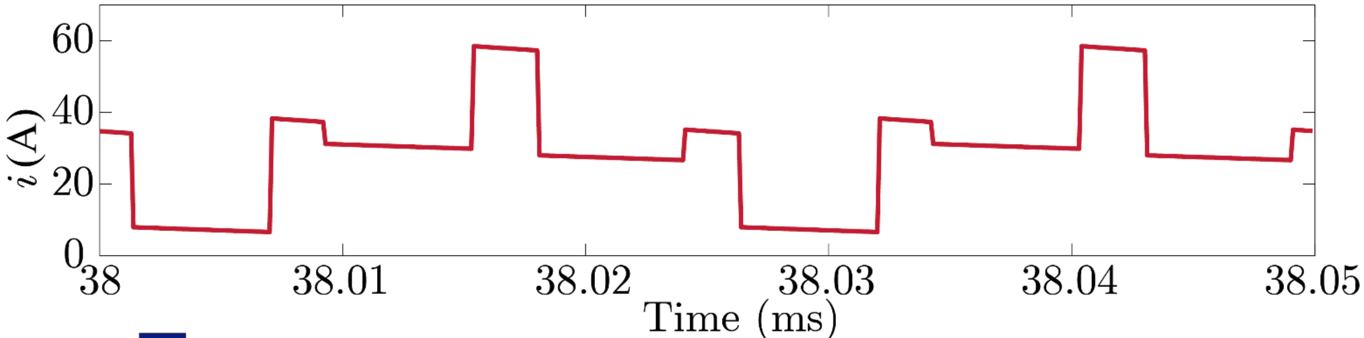
ATC in Interleaved DC/DC Converters. Solar PV case

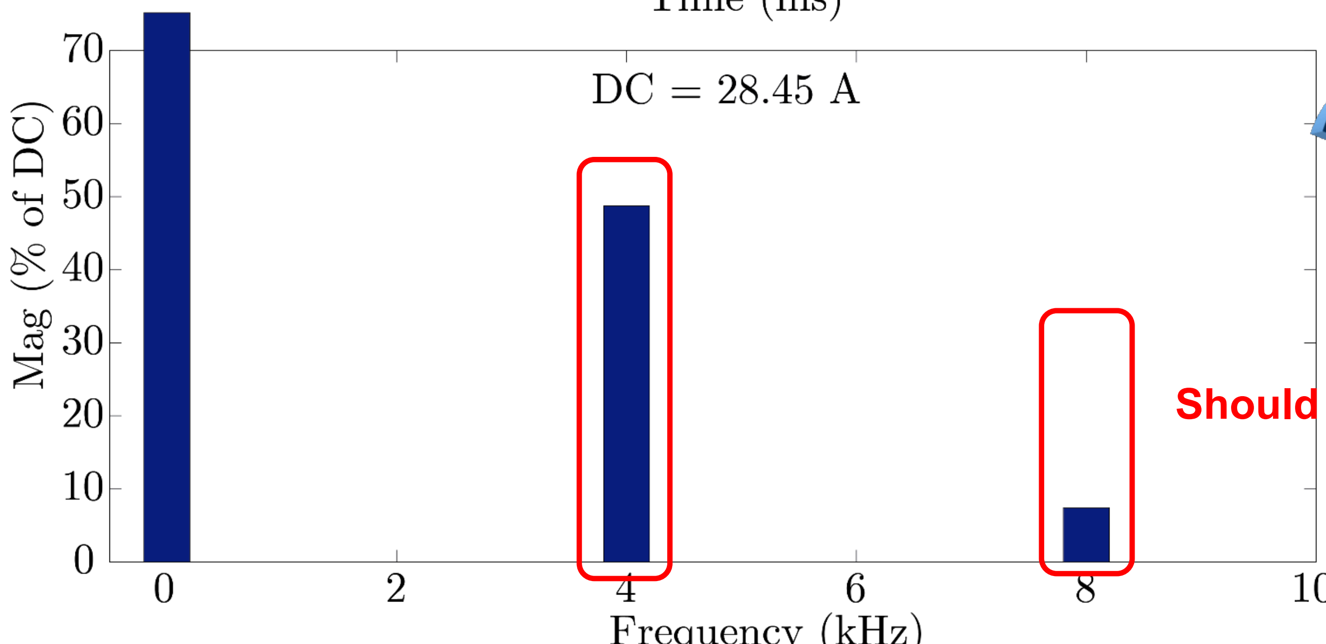
- In the solar PV case, the power routing is imposed by the sun radiation. Let's consider different sun radiation for each PV string…



ATC in Interleaved DC/DC Converters. Solar PV case

- Unbalanced operation using the conventional interleaved angles





Should I be concerned?

Remark: f_{cr}=4 kHz, three interleaved DC/DC modules

Thermal Issues in Power Capacitors

- A widely used lifetime model for capacitors

$$L_c = L_0 \left(\frac{V}{V_0} \right)^{-n} e^{\left(\frac{E_a}{k_B} \left(T_h^{-1} - T_0^{-1} \right) \right)}$$

Observations

- Limited to electrical and thermal stresses
- Other critical stressors, like humidity and mechanical stress are missed

- The capacitor temperature can be estimated taking into account the capacitor power losses P_d

$$T_h = R_{th} P_d + T_a = \Delta T_h + T_a$$

$$P_d = \sum_{h=0}^{\infty} I_{c,h}^2 R_{ESR,h}$$

R_{th} – capacitor termal resistance
P_d – capacitor losses
T_a – ambient temperature
$I_{c,h}$ – h^{th} harmonic of the capacitor current
$R_{ESR,h}$ – h^{th} harmonic value of ESR

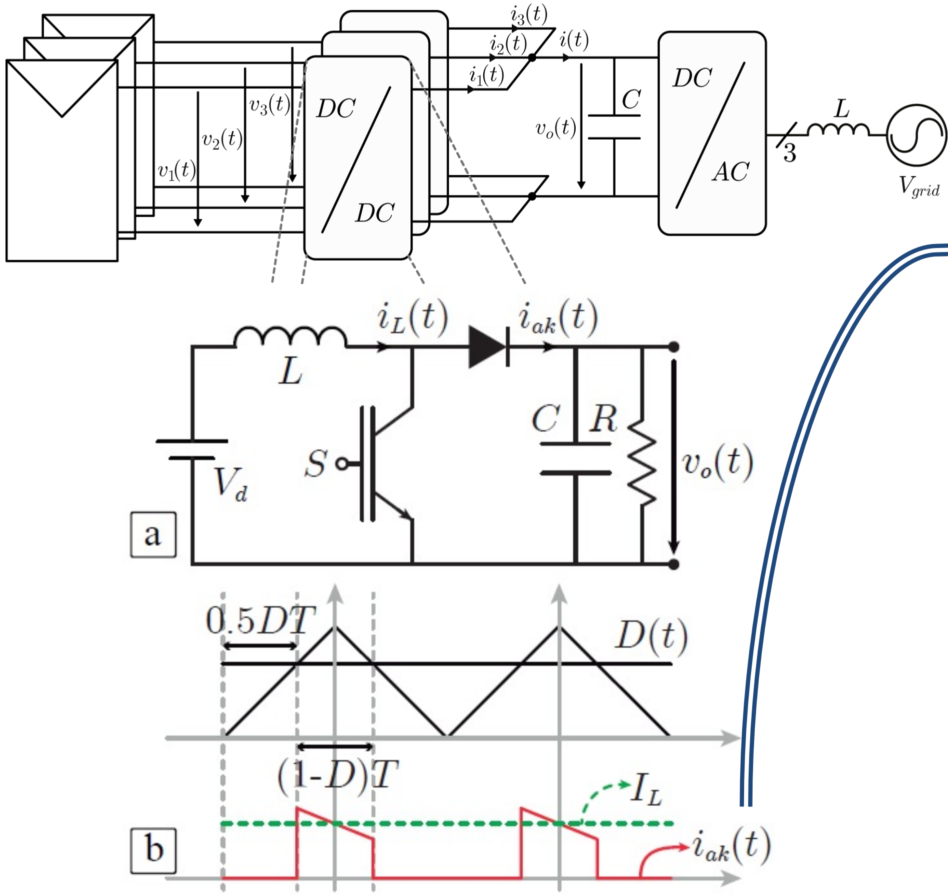
Mitigation of negative effects of power imbalance in modular converters

IDEA

To Modify the typical interleaved operation of modular converters by changing the phase-displacement angles of the PWM method

Output current harmonic description in modular dc/dc converters

- The method is developed taking into account the actual current waveforms without any simplification



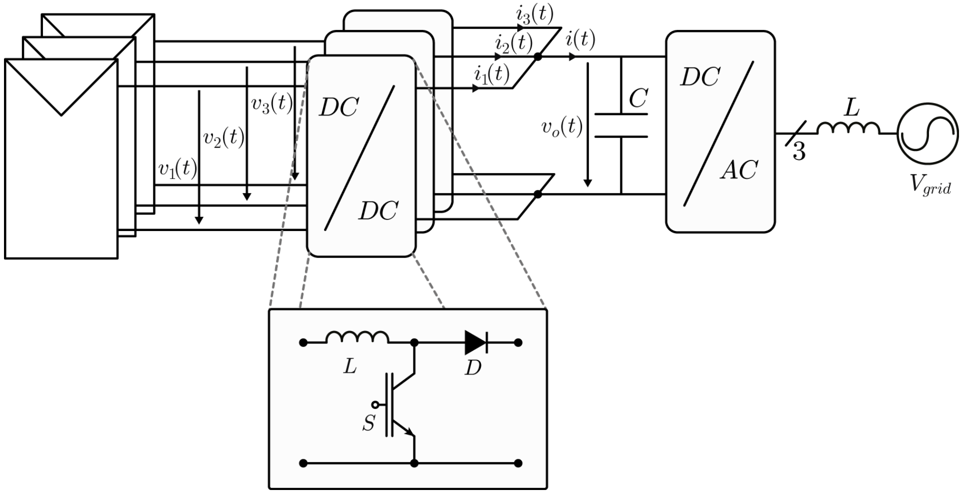
$$i_{c,n}(t) = \cos(n\omega t)\left[\sum_{k=1}^{N} \frac{a_{nk} - b_{nk}\tan(n\phi_k)}{\sqrt{1+\tan(n\phi_k)^2}}\right] + \sin(n\omega t)\left[\sum_{k=1}^{N} \frac{b_{nk} + a_{nk}\tan(n\phi_k)}{\sqrt{1+\tan(n\phi_k)^2}}\right]$$

where:

$$a_n = \frac{2}{T}\int_{-\frac{(1-D)T}{2}}^{\frac{(1-D)T}{2}} (I_L + mt)\cos(n\omega t)dt = \frac{2I_L}{n\pi}\sin(n\pi(1-D))$$

$$b_n = \frac{2}{T}\int_{-\frac{(1-D)T}{2}}^{\frac{(1-D)T}{2}} (I_L + mt)\sin(n\omega t)dt = \frac{mT}{n^2\pi^2}\Big[\sin(n\pi(1-D)) + n\pi(1-D)\cos(n\pi(1-D))\Big]$$

Cost function definition to determine the proper interleaved PWM angles



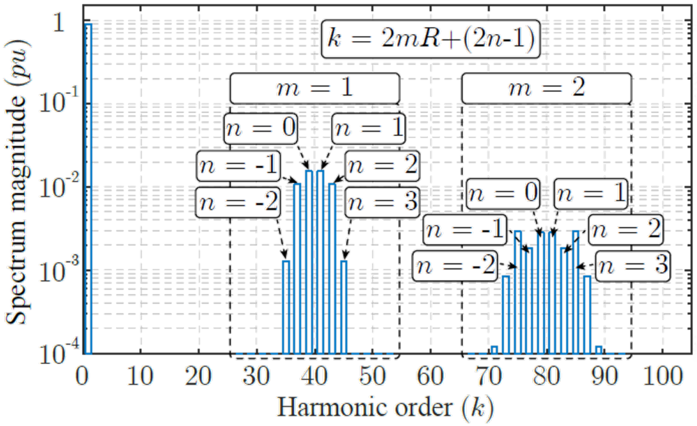
$$\|H_n\| = \left[\left[\sum_{k=1}^{M} \frac{a_{nk} - b_{nk}\tan(n\phi_k)}{\sqrt{1+\tan(n\phi_k)^2}}\right]^2 + \left[\sum_{k=1}^{M} \frac{b_{nk} + a_{nk}\tan(n\phi_k)}{\sqrt{1+\tan(n\phi_k)^2}}\right]^2\right]^{\frac{1}{2}}$$

- In order to extend the output capacitor lifetime, a cost function can be defined (this considers ESR constant with the frequency):

$$\rho = \sum_{n=1}^{m} I_{c,n}^2 = \sum_{n=1}^{m} \|H_n\|^2$$

Variable-angle interleaved PWM method. Obtained results

Parameter	Balanced	Unbalanced
Switching frequency (kHz)	5	5
Inductance (mH)	3.6	3.6
Output voltage V_o (V)	300	300
PV array average voltage V_{PVk} (V)	160	[160, 150, 155]
PV array average current I_{PVk} (A)	10	[10, 5, 8]



Operational conditions	Case
Balanced conditions	I
Unbalanced case, conventional angles	II
Unbalanced case, angles from iterative method with m=1	III
Unbalanced case, angles from iterative method with m=3	IV

Variable-angle interleaved PWM method. Obtained results

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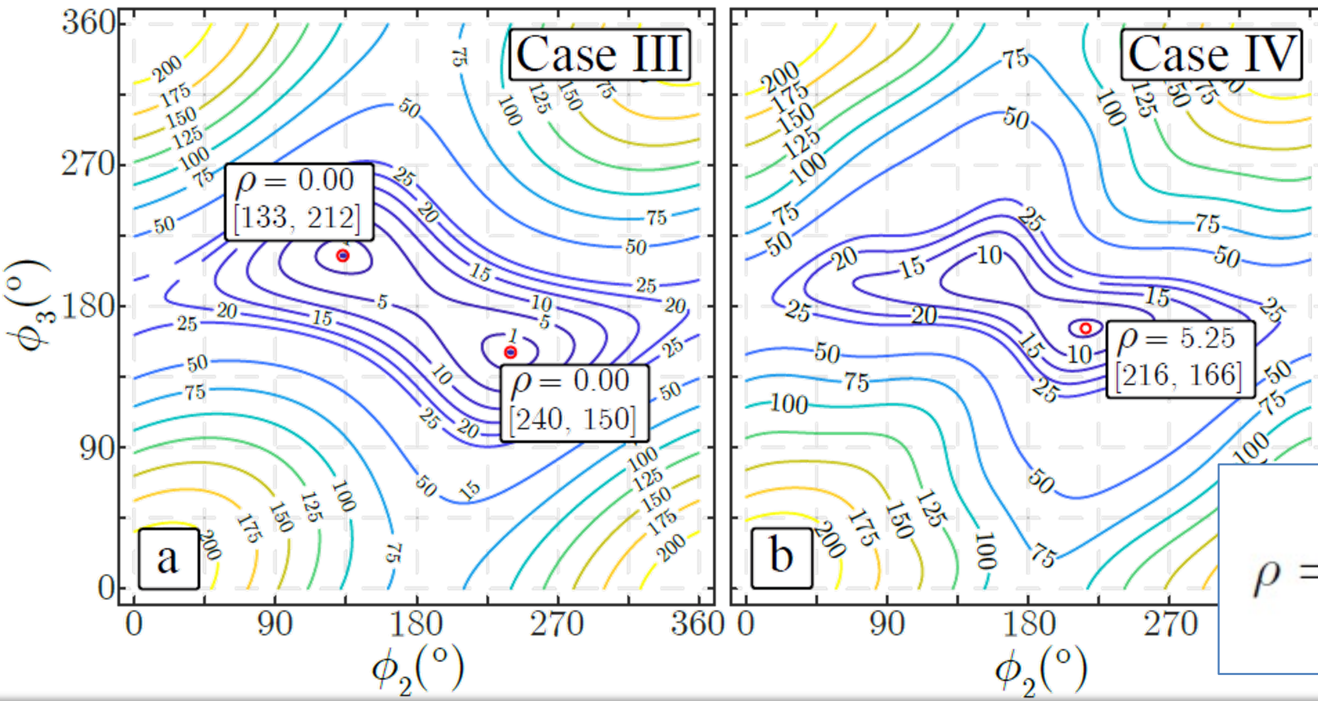

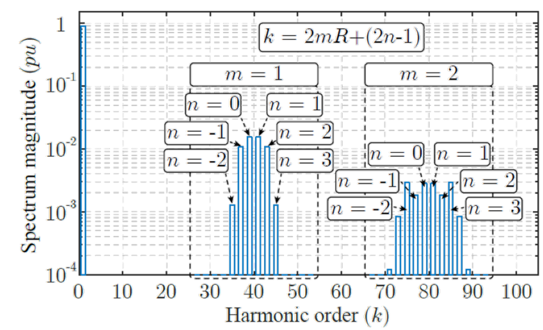

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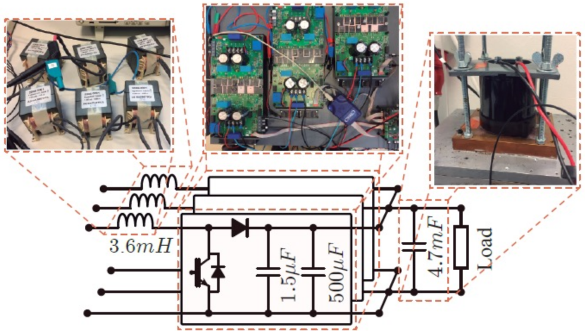

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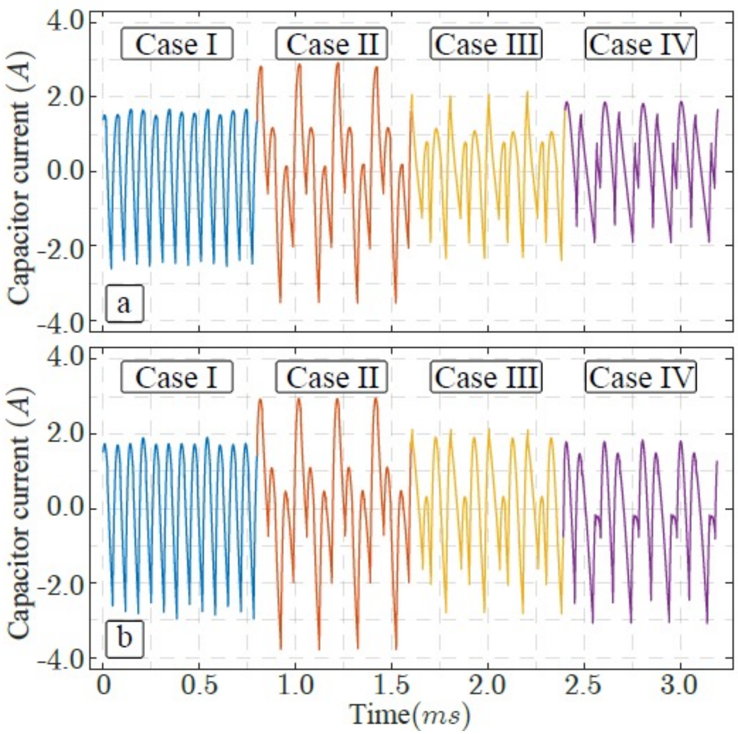
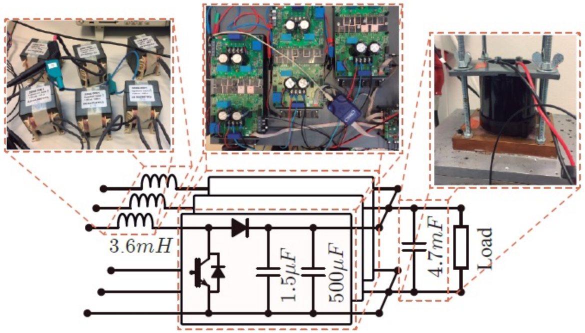


a) b)

Case	$L = 3.6$ mH, $R_{th} = [2,5]$ K/W		$L = 1.8$ mH, $R_{th} = [2,5]$ K/W	
	Normalized $\sum_{h=1}^{m} I_{c,h}^2$	$T_h(°C)$	Normalized $\sum_{h=1}^{m} I_{c,h}^2$	$T_h(°C)$
II	100 %	[31.6,38.9]	100 %	[31.8,39.4]
III	33.29 %	[27.4,30.6]	52.29 %	[28.8,33.6]
IV	33.54 %	[27.4,30.7]	49.54 %	[28.7,33.2]

Variable-angle interleaved PWM method. Obtained results



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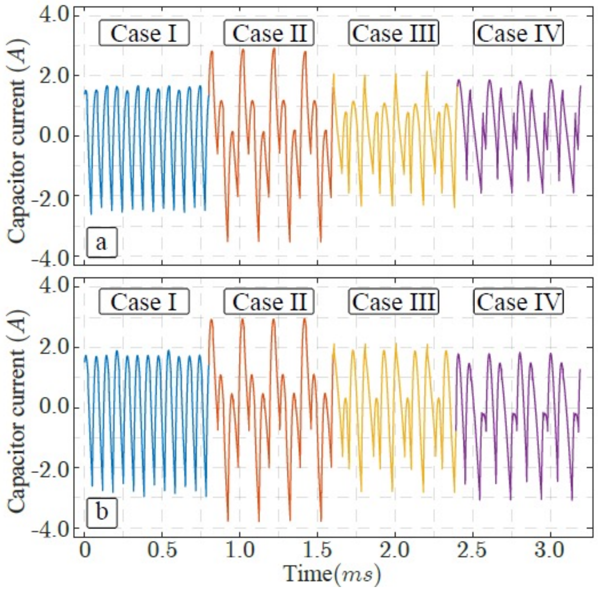


a) b)

	$L = 3.6mH$		$L = 1.8mH$	
Case	$R_{th} = 2K/W$	$R_{th} = 5K/W$	$R_{th} = 2K/W$	$R_{th} = 5K/W$
II	100 %	100 %	100 %	100 %
III	133 %	177 %	123 %	149 %
IV	133 %	177 %	124 %	153 %

Extended lifetime!!!

And… it is for free!!!

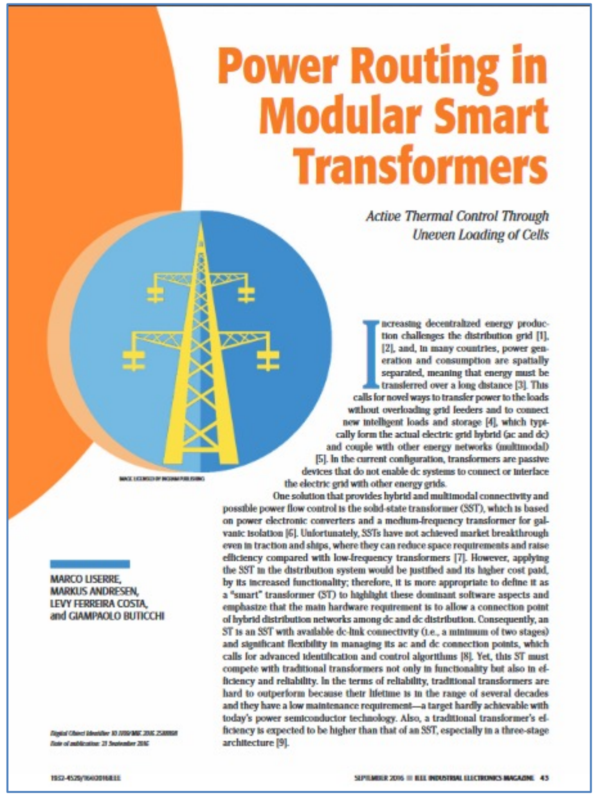
Conclusions

- Modular Converters are a very attractive solution for many power applications looking for fault-tolerant capability, high availability and high operability
- ATC via Power Routing applied to modular converters is an effective method to manage the power devices and capacitors remaining useful lifetime
- However, parallel-connected modular converters with unequal power sharing among the modules present lifetime reduction of output capacitors
- Variable-angle PWM methods mitigate this drawback …

FOR FREE!

Important References: Reliability, ATC, Power Routing

J. Falck, C. Felgemacher, A. Rojko, M. Liserre and P. Zacharias, "**Reliability of Power Electronic Systems: An Industry Perspective**," in *IEEE Industrial Electronics Magazine*, vol. 12, no. 2, pp. 24-35, June 2018.



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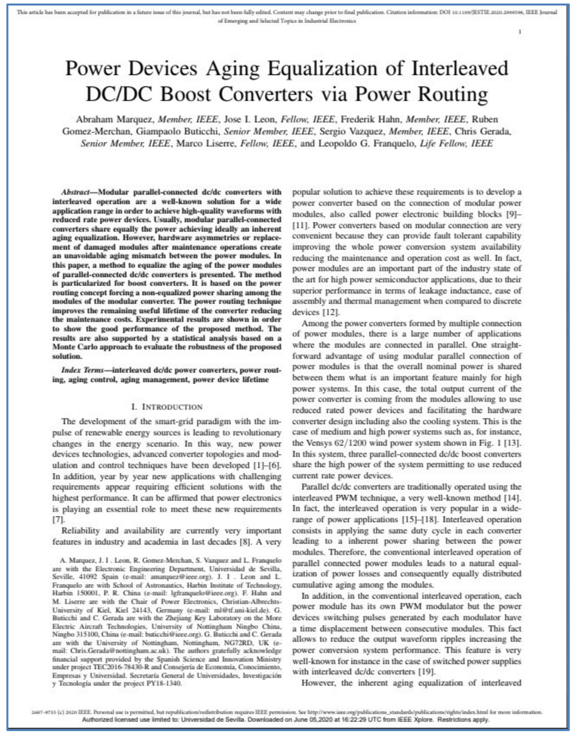

A. Marquez, J. I. Leon, S. Vazquez and L. G. Franquelo, "**Variable-angle interleaved DC-DC converters**," *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, Florence, 2016, pp. 3635-3639.

A. Marquez, J. I. Leon, F. Hahn, R. Gonzalez-Merchan, G. Buticchi, S. Vazquez, C. Geralda, M. Liserre and L. G. Franquelo, "**Power Devices Aging Equalization of Interleaved DC/DC Boost Converters via Power Routing**," in IEEE Journal of Emerging and Selected Topics in Industrial Electronics, doi: 10.1109/JESTIE.2020.2999598.

M. Andresen, A. Marquez, J. I. Leon, Y. Ko, M. Liserre, S. Vazquez and L. G. Franquelo "**Capacitor Lifetime Extension of Interleaved dc-dc Converters for Multi-String Photovoltaic Systems**," European patent P19180419.4/1201.

Important References: ATC methods for DC/AC converters

Improved Harmonic Performance of Cascaded H-Bridge Converters with Thermal Control

Sampling-Time Harmonic Control for Cascaded H-Bridge Converters with Thermal Control

Variable-Angle PS-PWM Technique for Multilevel Cascaded H-Bridge Converters With Large Number of Power Cells

V. G. Monopoli, A. Marquez, J. I. Leon, Y. Ko, G. Buticchi and M. Liserre, "**Improved Harmonic Performance of Cascaded H-Bridge Converters with Thermal Control**," in *IEEE Transactions on Industrial Electronics, vol. 66, no. 7, pp. 4982-4991, July 2019.*

A. Marquez, V. G. Monopoli, J. I. Leon, Y. Ko, M. Liserre, S. Vazquez and L. G. Franquelo " **Sampling-Time Harmonic Control for Cascaded H-Bridge Converters with Thermal Control**," in *Transactions on Industrial Electronics, vol. 67, no. 4, pp. 2776-2785, April 2020.*

A. Marquez, J. I. Leon, R. Portillo, J. Yin, W. Luo, S. Vazquez, S. Kouro and L. G. Franquelo " **Variable-Angle PS-PWM Technique for Multilevel Cascaded H-Bridge Converters with Large Number of Power Cells**," in *IEEE Transactions on Industrial Electronics,* *10.1109/TIE.2020.3000121* .

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Efficient integration of renewable energy sources for green airports

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