

**PEMC Webinar:**  
**International Workshop on Electric Technologies for Green Airports**

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# Efficient integration of renewable energy sources for green airports

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## Important remark:

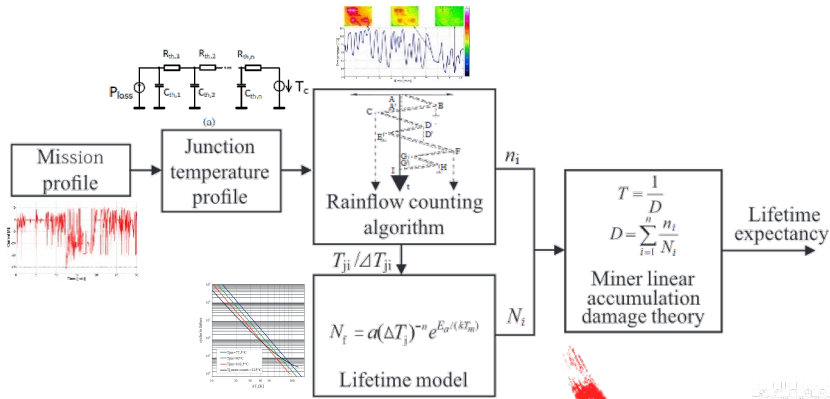
This work is an international collaboration between several research groups:

- 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)

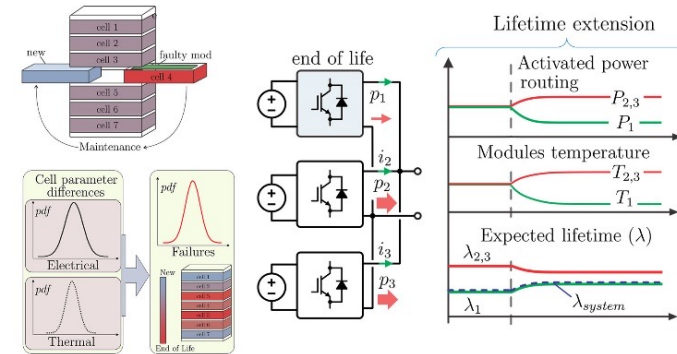


# Efficient integration of renewable energy sources for green airports

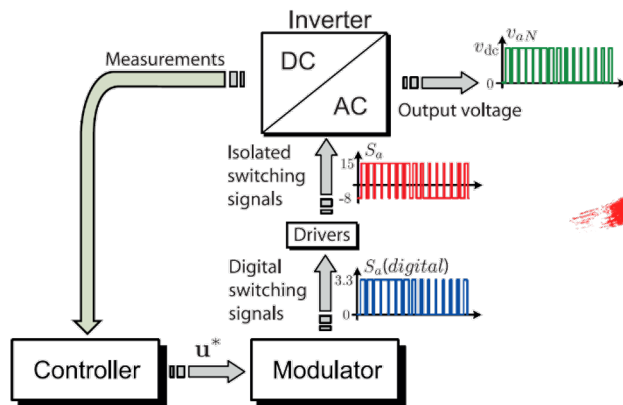
## Power devices aging physics



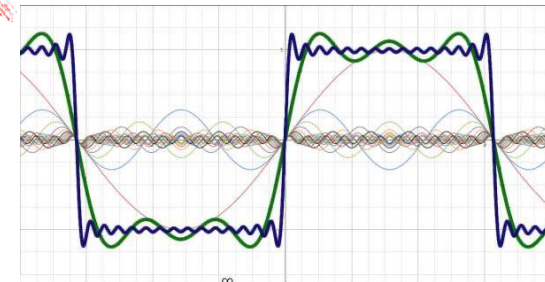
## Active thermal control methods



## 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

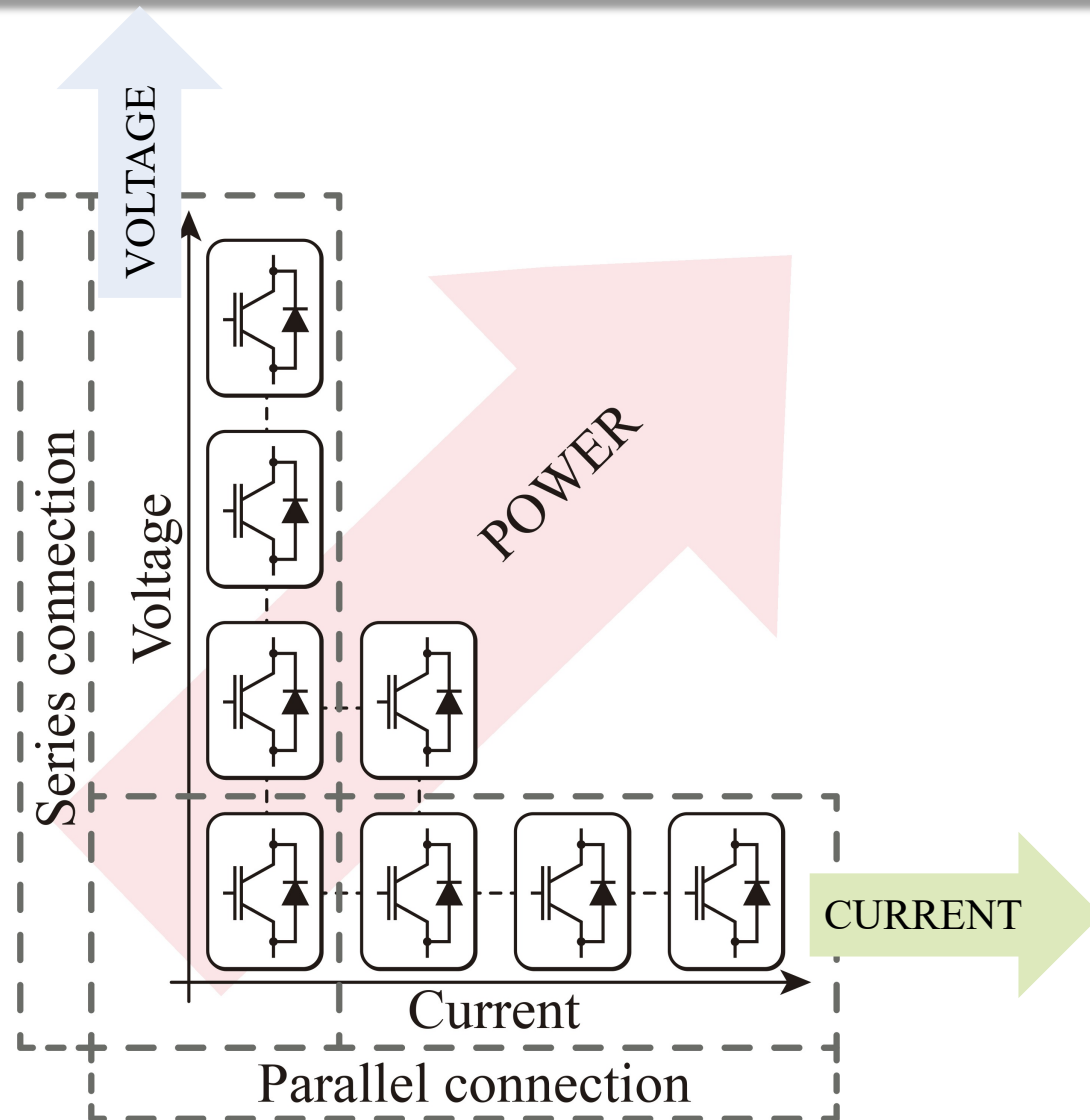


- Safety: Growing capacity ➡ Significant impact after failures
- Cost of energy = (Installation + O&M)/Operating time
- Improve reliability of PE ➡ Reduce the cost of energy



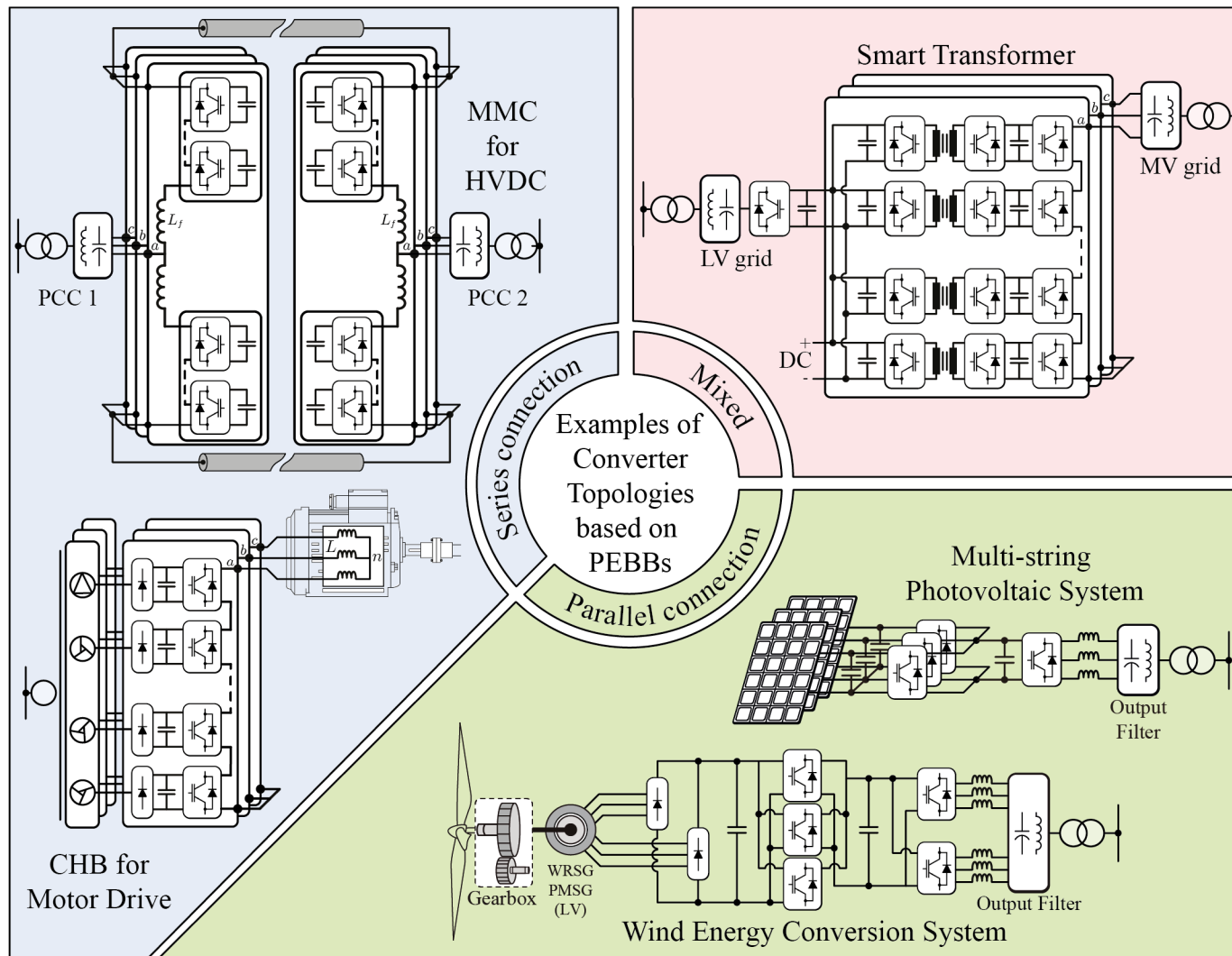
# Modular Converters

## Basic Concept

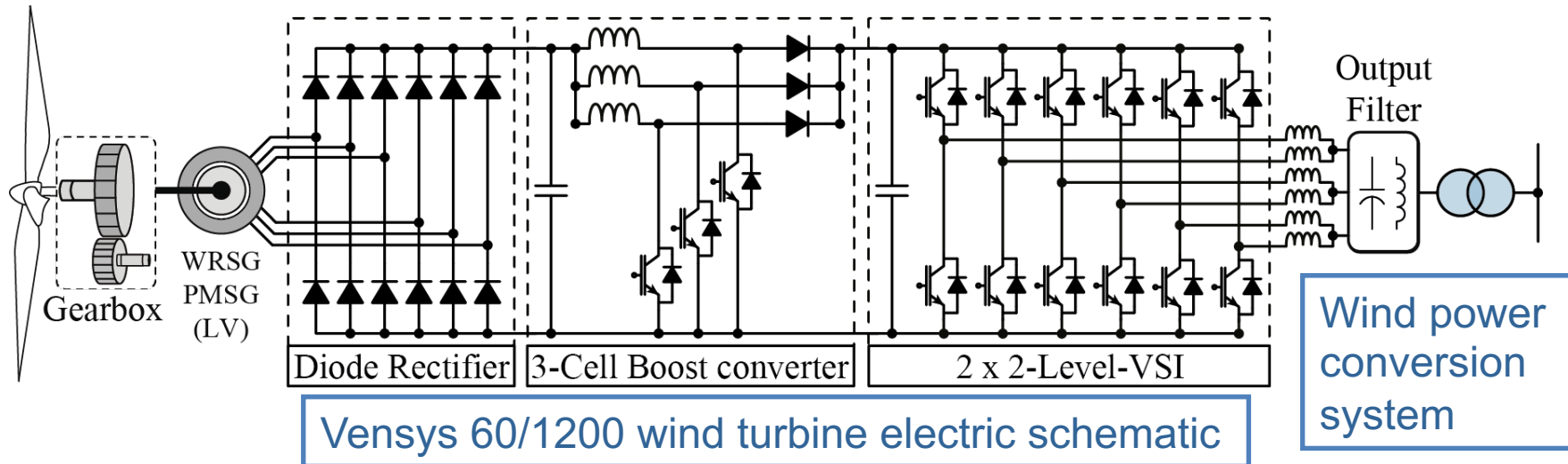


# Modular Converters

## Some Examples

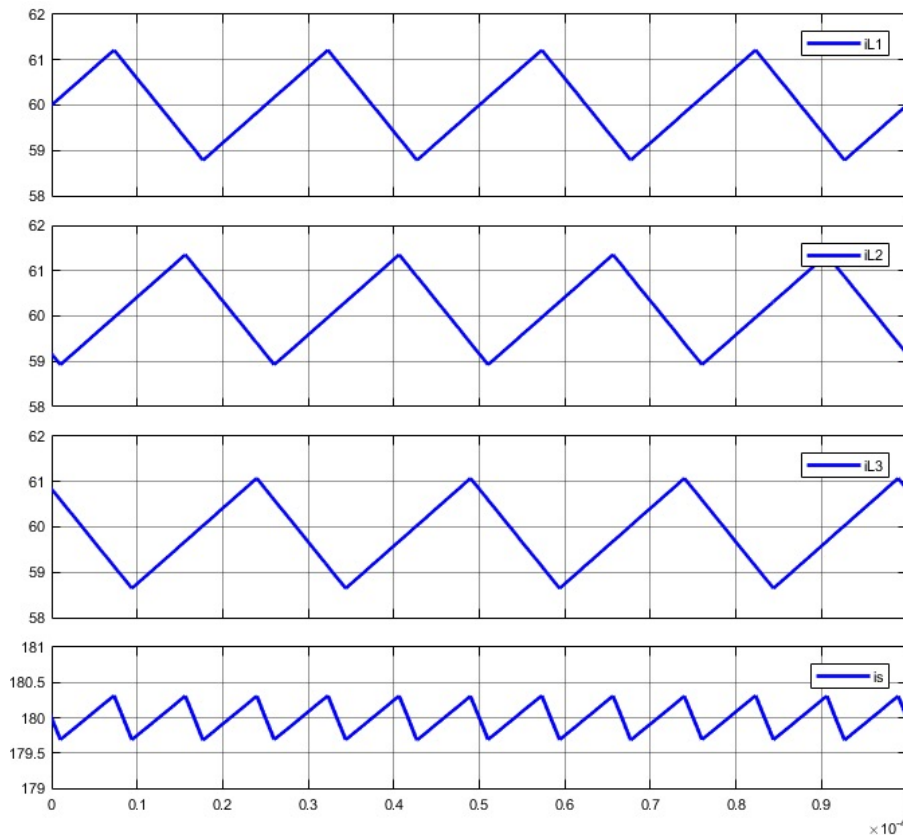


# Wind Power Energy Conversion System with Modular Converters

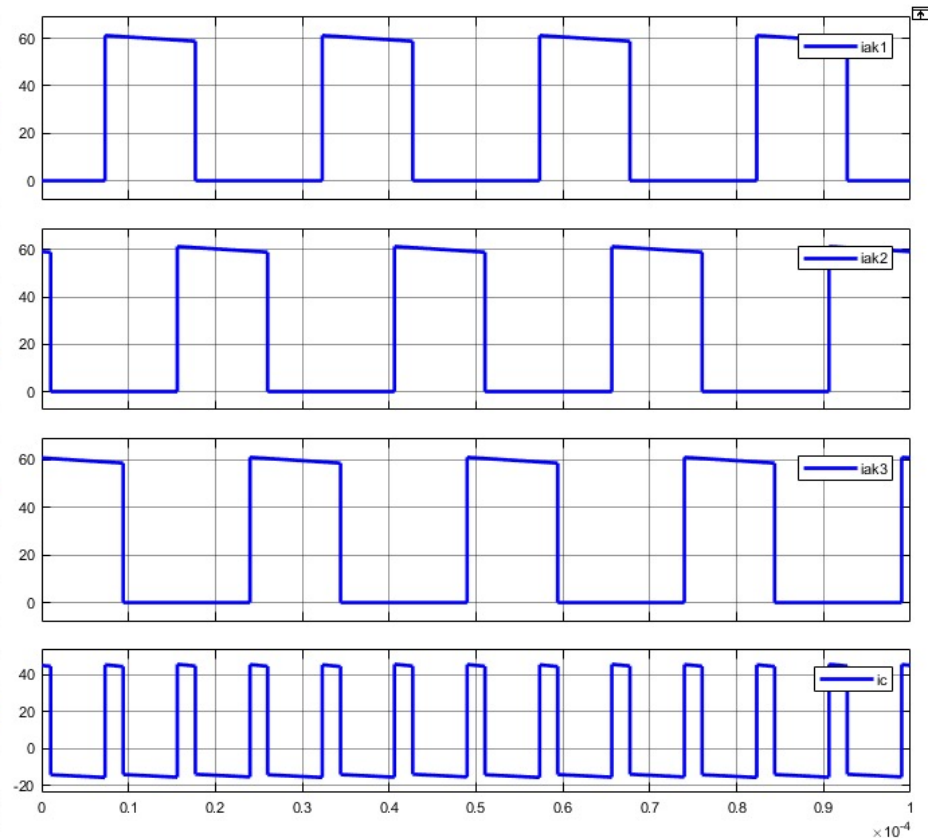


Rated power: 1.2 MW  
 Rotor diameter: 62 m  
 Offshore model: no  
 Swept area: 3,020 m<sup>2</sup>  
 Specific area: 2.52 m<sup>2</sup>/kW  
 Number of blades: 3  
 Power control: Pitch  
 Rated wind speed: 13,5 m/s  
 Cut-off wind speed: 25 m/s

# Conventional PWM Operation of Interleaved Modular Converters



Input currents [A]



Output currents [A]

**Interleaving conventional phase displacement is  $360^\circ/N$  (N is the number of DC-DC modules)**



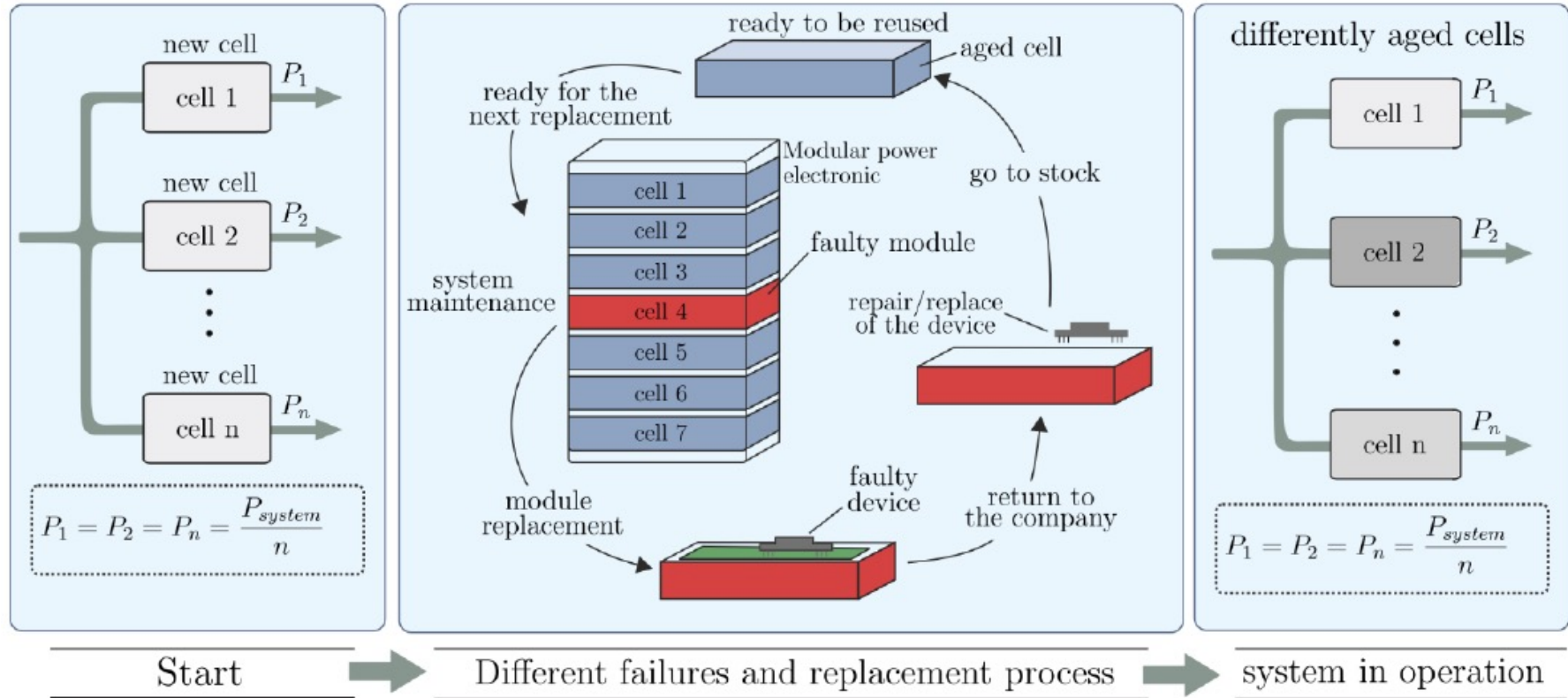
# Modular Converters

## Pros & Cons

### MODULAR CONVERTERS FEATURES

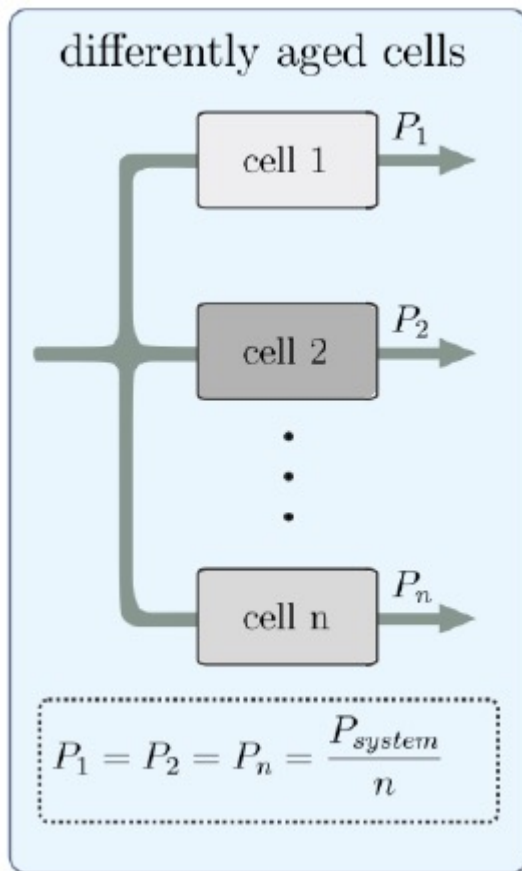
- ✓ Inherent fault tolerant capability
- ✓ Output waveforms enhanced quality
- ✓ Reduced output filters
- ✓ Reduced maintenance cost by fast PEBB replacement
- ✓ Standarization in the PEBB design
- ✓ Reduction in the design and manufacturing costs using the same PEBB firmware for different applications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



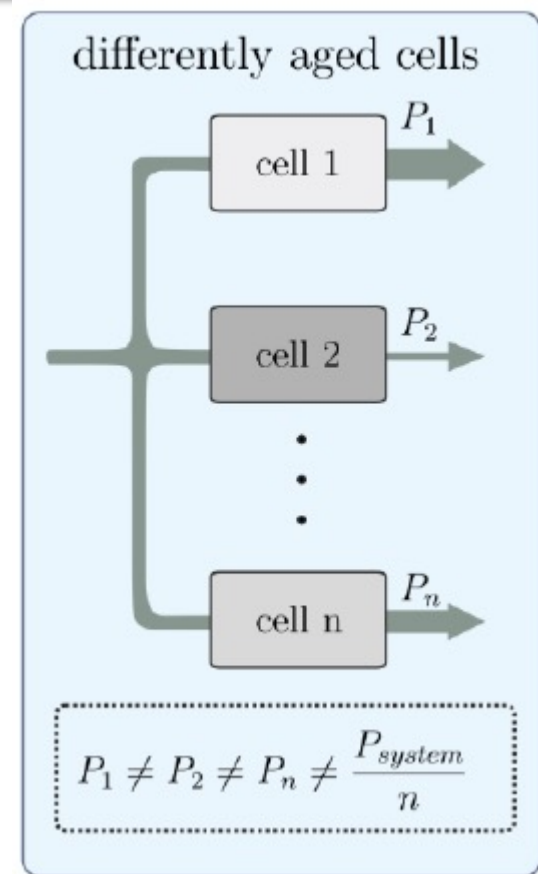
Is the power equalization, inherently obtained by applying the interleaved operation, always optimal ?

# Active Thermal Control (ATC) in Modular Power Converters



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

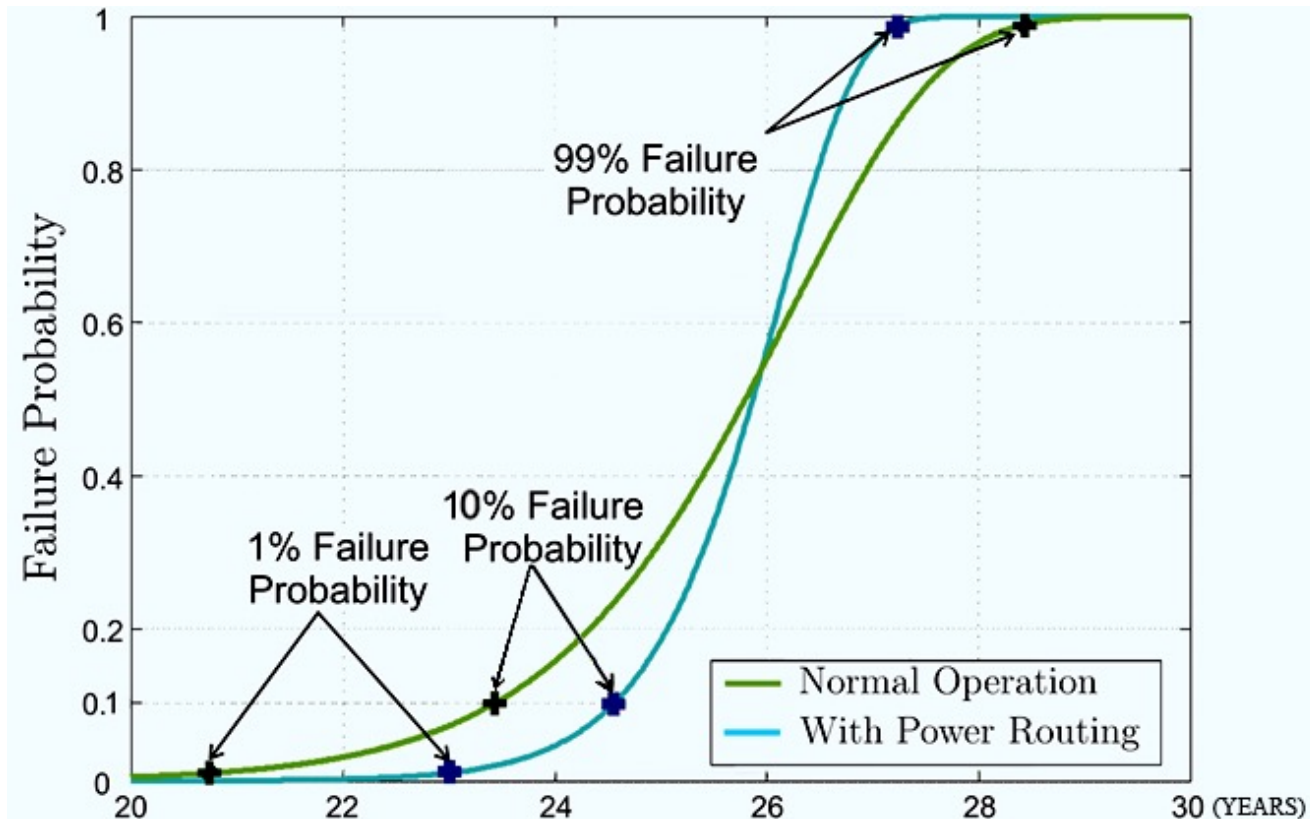
Power Routing



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

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

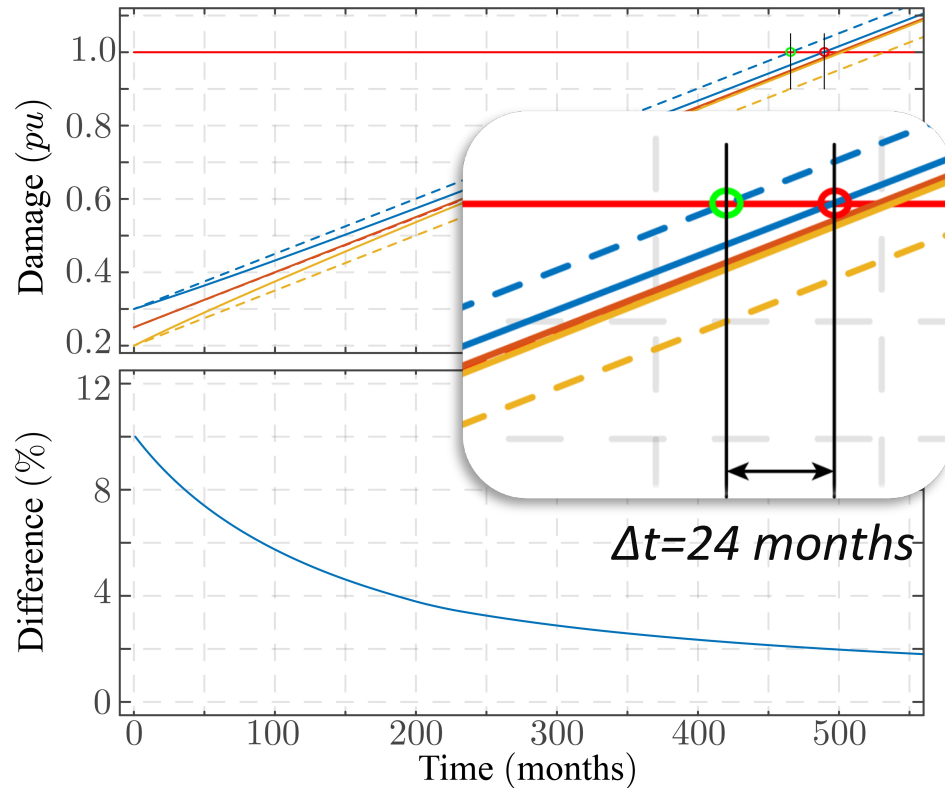
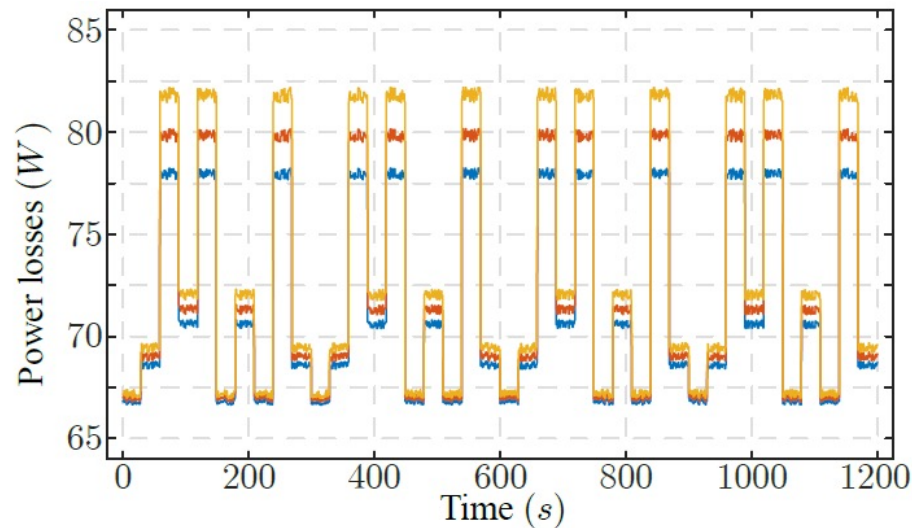


M. Liserre, G. Buticchi, J. I. Leon, A. Marquez, V. Raveendran, Y. Ko, M. Andresen, V. Monopoli and L. G. Franquelo, "**Power Routing: A New Paradigm for Maintenance Scheduling**," in *IEEE Industrial Electronics Magazine*, vol. 14, no. 3, pp. 33-45, Sept. 2020, doi: 10.1109/MIE.2020.2975049.

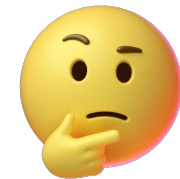


# Lifetime Extension of Power Semiconductors in by applying ATC

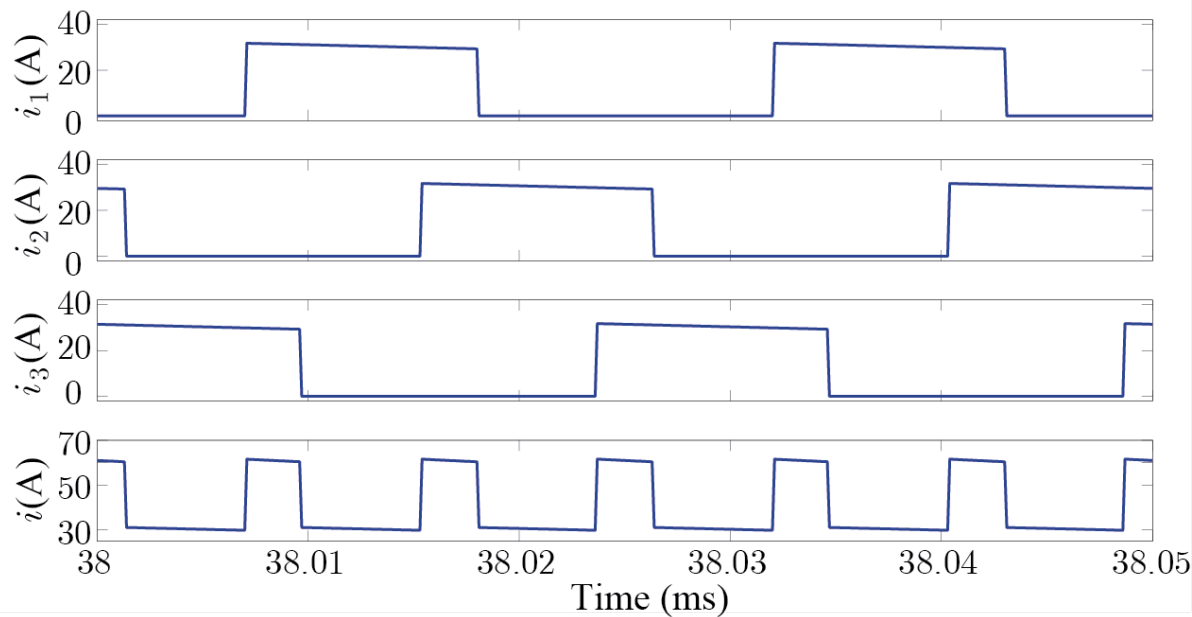
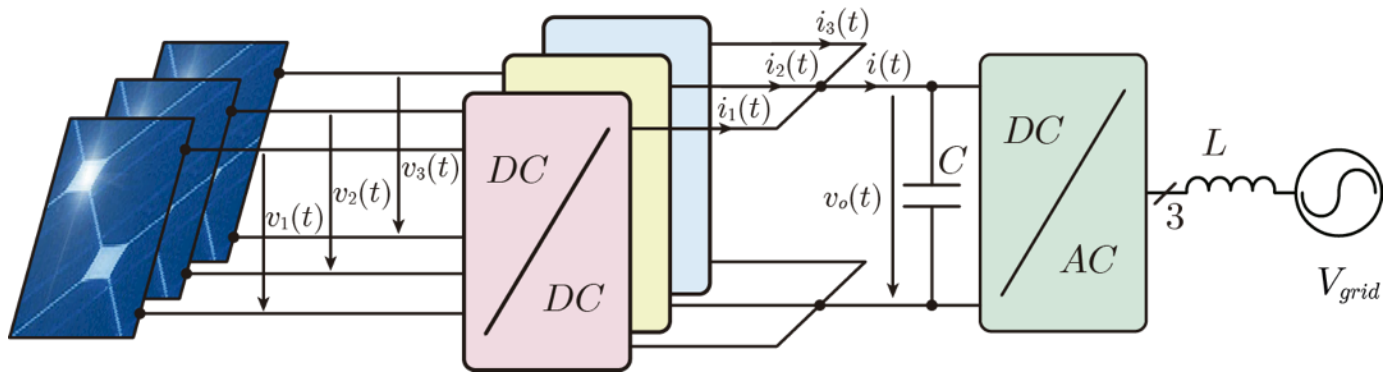
- ATC via power routing improves the power devices average lifetime



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



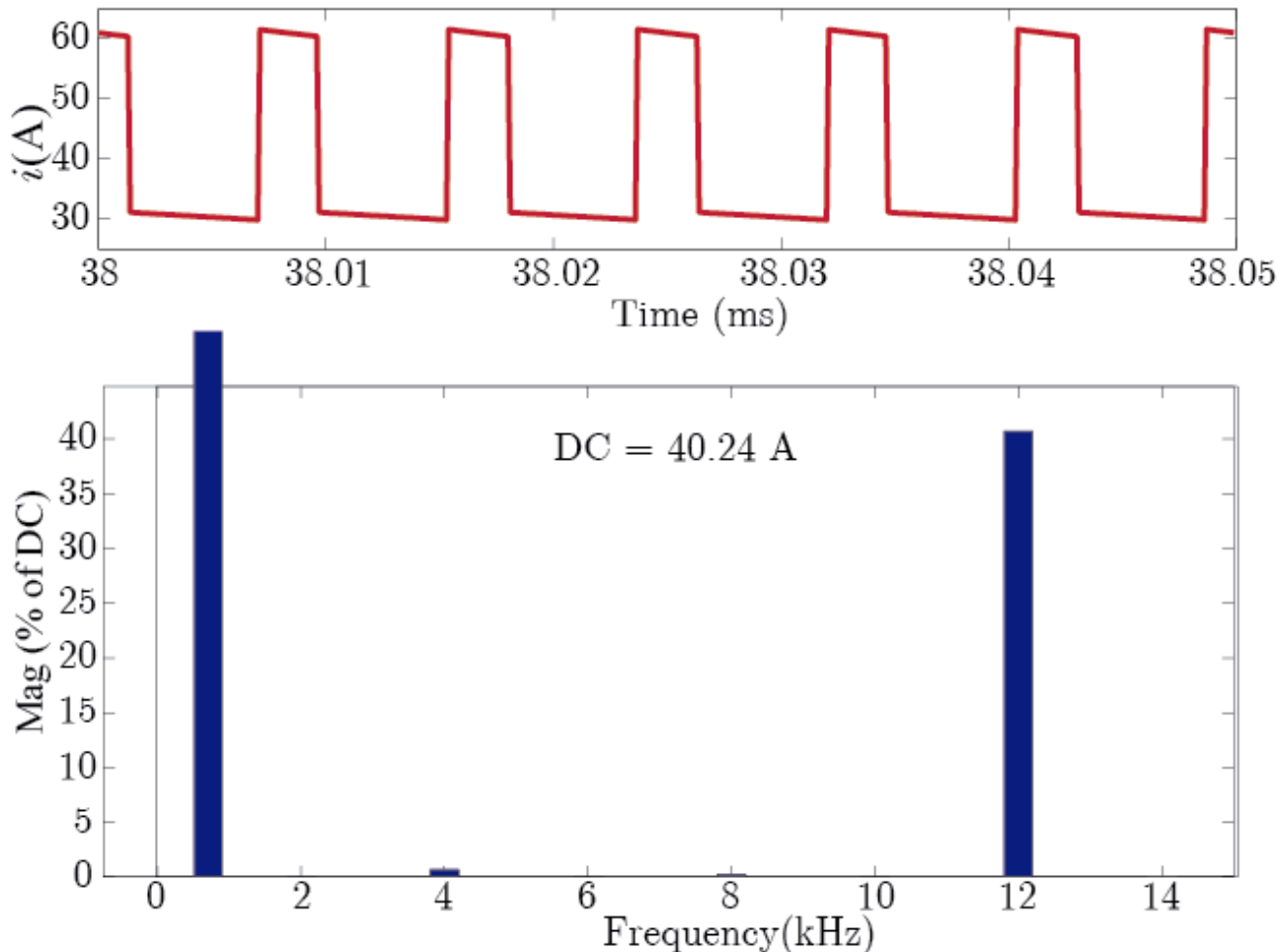
# Solar PV system with Modular Converters. Multi-string PV



**Interleaving conventional phase displacement is  $360^\circ/N$  (N is the number of DC-DC modules)**

# ATC in Interleaved DC/DC Converters. Solar PV case

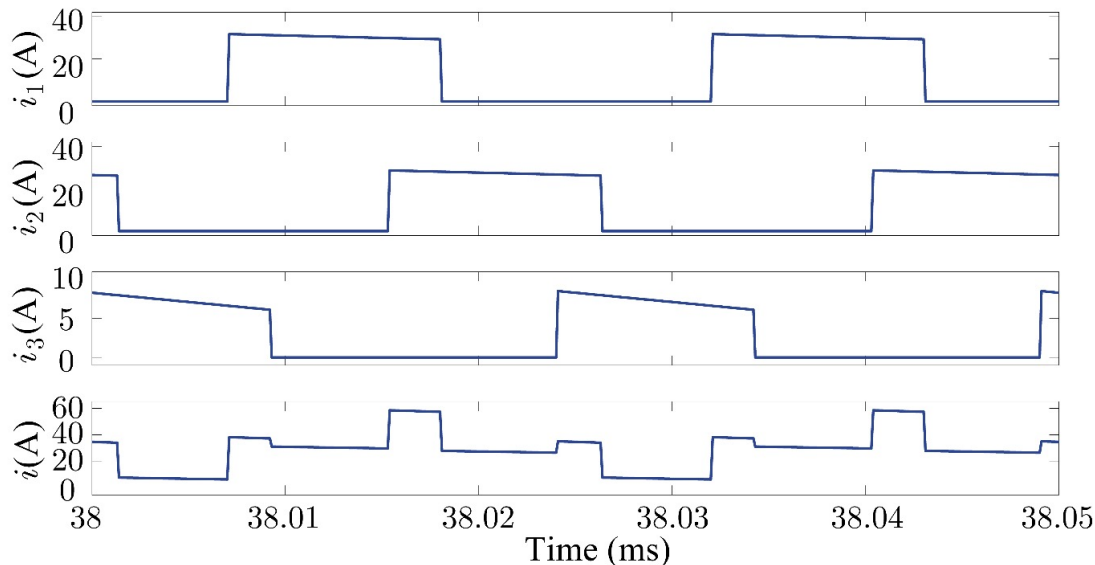
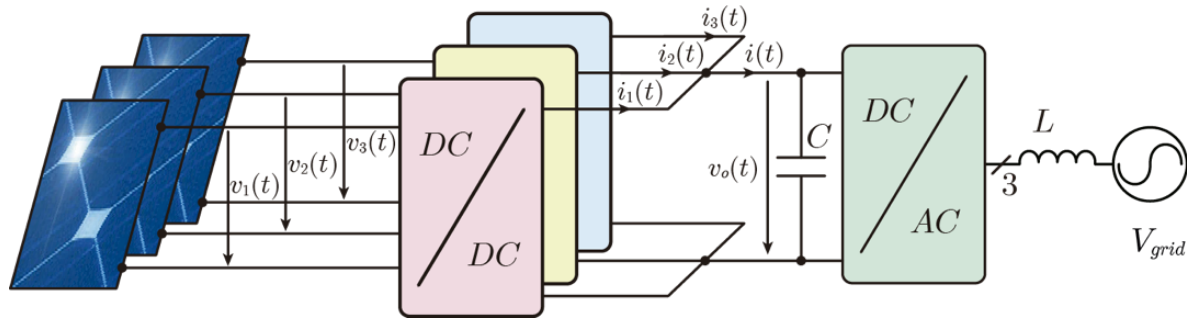
- Conventional interleaved operation with **balanced operation**



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

# ATC in Interleaved DC/DC Converters. Solar PV case

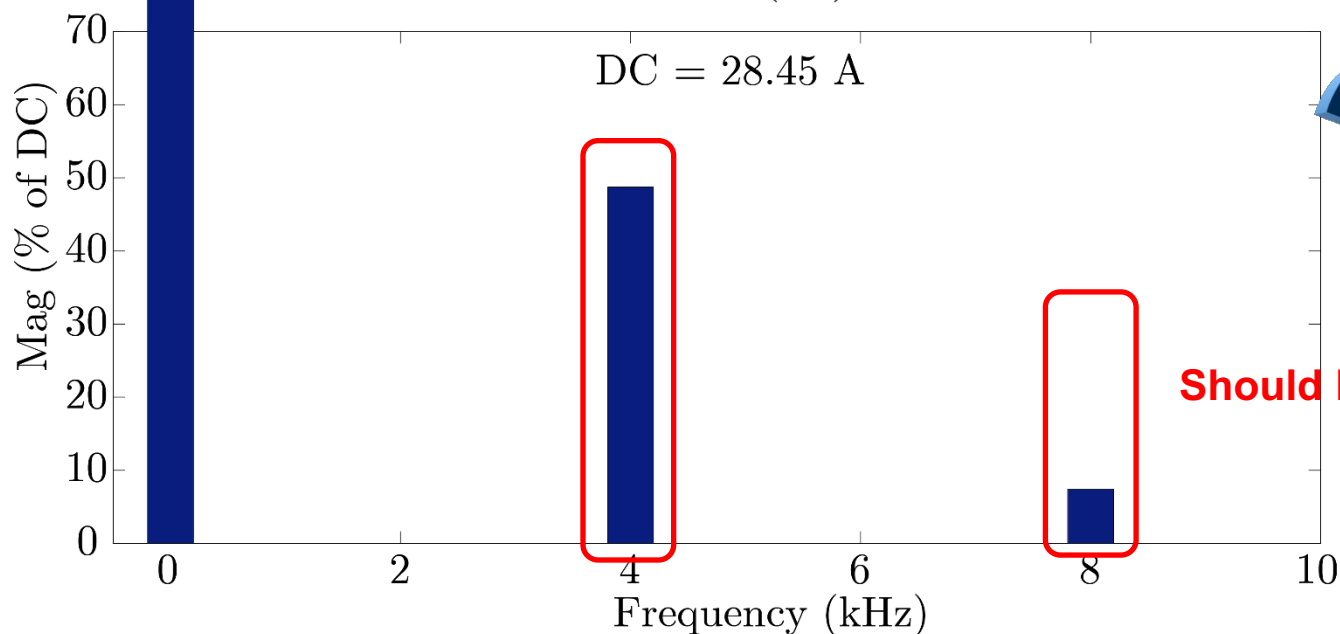
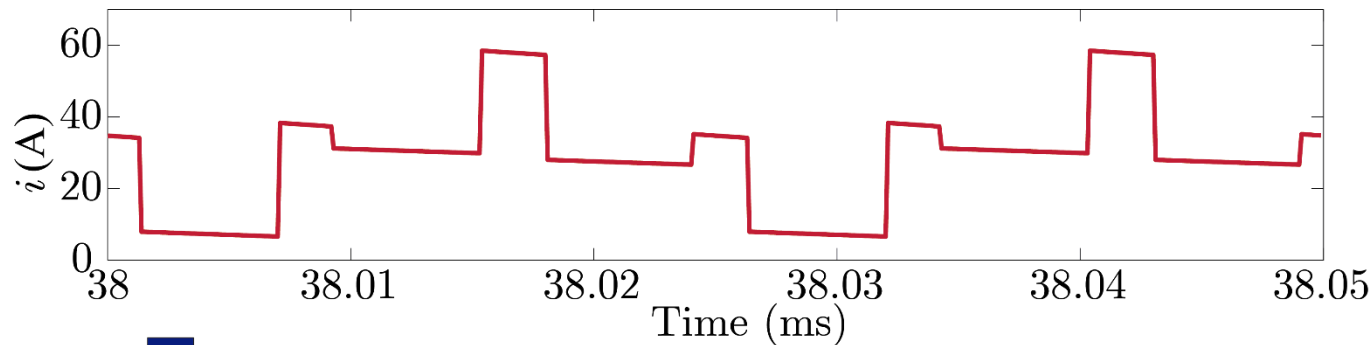
- In the solar PV case, the power routing is imposed by the sun radiation. Let's consider different sun radiation for each PV string...





# 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

- A widely used lifetime model for **capacitors**

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

## 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 thermal resistance

$P_d$  – capacitor losses

$T_a$  – ambient temperature

$I_{c,h}$  –  $h^{\text{th}}$  harmonic of the capacitor current

$R_{ESR,h}$  –  $h^{\text{th}}$  harmonic value of ESR

# Mitigation of negative effects of power imbalance in modular converters

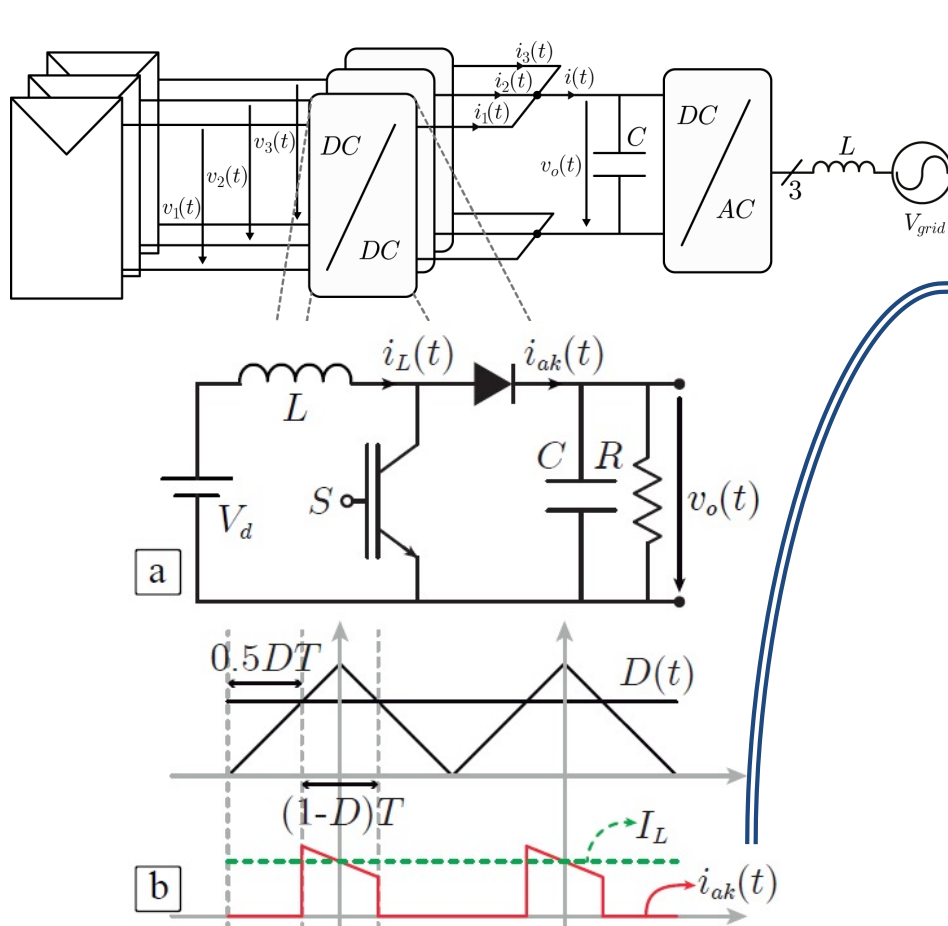


## IDEA

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



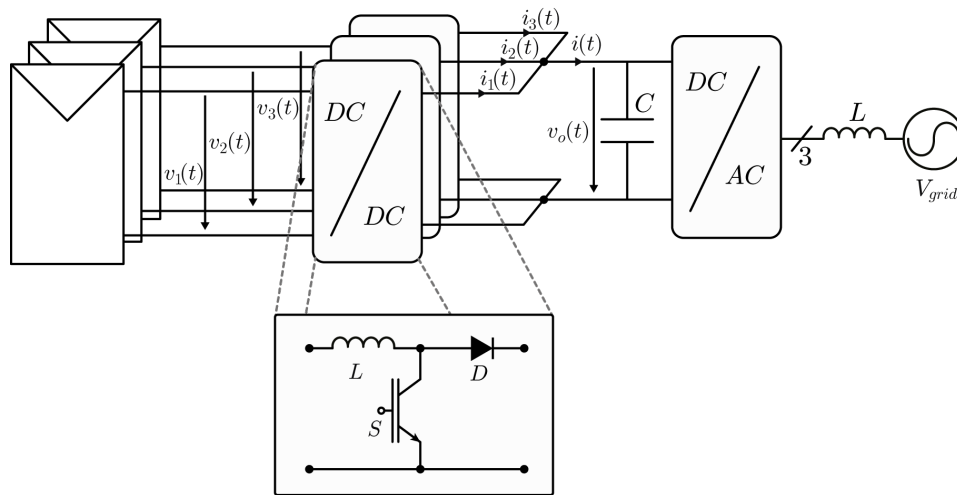
$$i_{c,n}(t) = \cos(n\omega t) \left[ \sum_{k=1}^N \frac{a_{nk} - b_{nk} \tan(n\phi_k)}{\sqrt{1 + \tan(n\phi_k)^2}} \right] + \sin(n\omega t) \left[ \sum_{k=1}^N \frac{b_{nk} + a_{nk} \tan(n\phi_k)}{\sqrt{1 + \tan(n\phi_k)^2}} \right]$$

where:

$$\begin{aligned} a_n &= \frac{2}{T} \int_{-\frac{(1-D)T}{2}}^{\frac{(1-D)T}{2}} (I_L + mt) \cos(n\omega t) dt \\ &= \frac{2I_L}{n\pi} \sin(n\pi(1-D)) \\ b_n &= \frac{2}{T} \int_{-\frac{(1-D)T}{2}}^{\frac{(1-D)T}{2}} (I_L + mt) \sin(n\omega t) dt \\ &= \frac{mT}{n^2\pi^2} \left[ \sin(n\pi(1-D)) \right. \\ &\quad \left. + n\pi(1-D) \cos(n\pi(1-D)) \right] \end{aligned}$$



# 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):

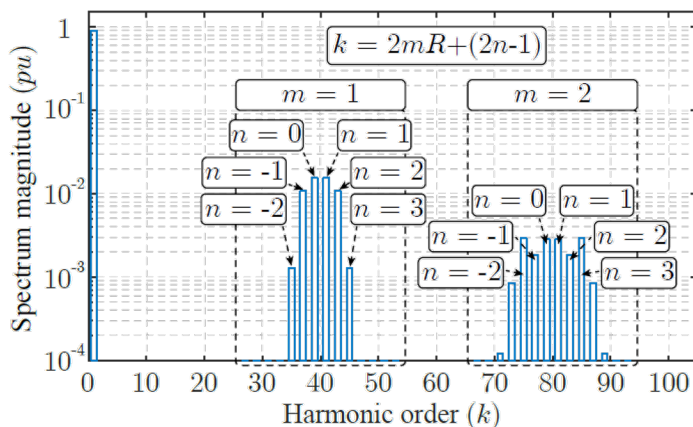
$$\rho = \sum_{n=1}^m I_{c,n}^2 = \sum_{n=1}^m \|H_n\|^2$$

# 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]



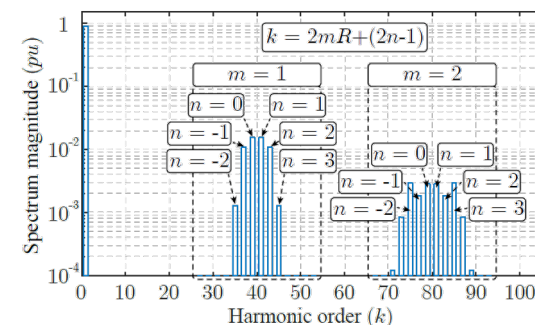
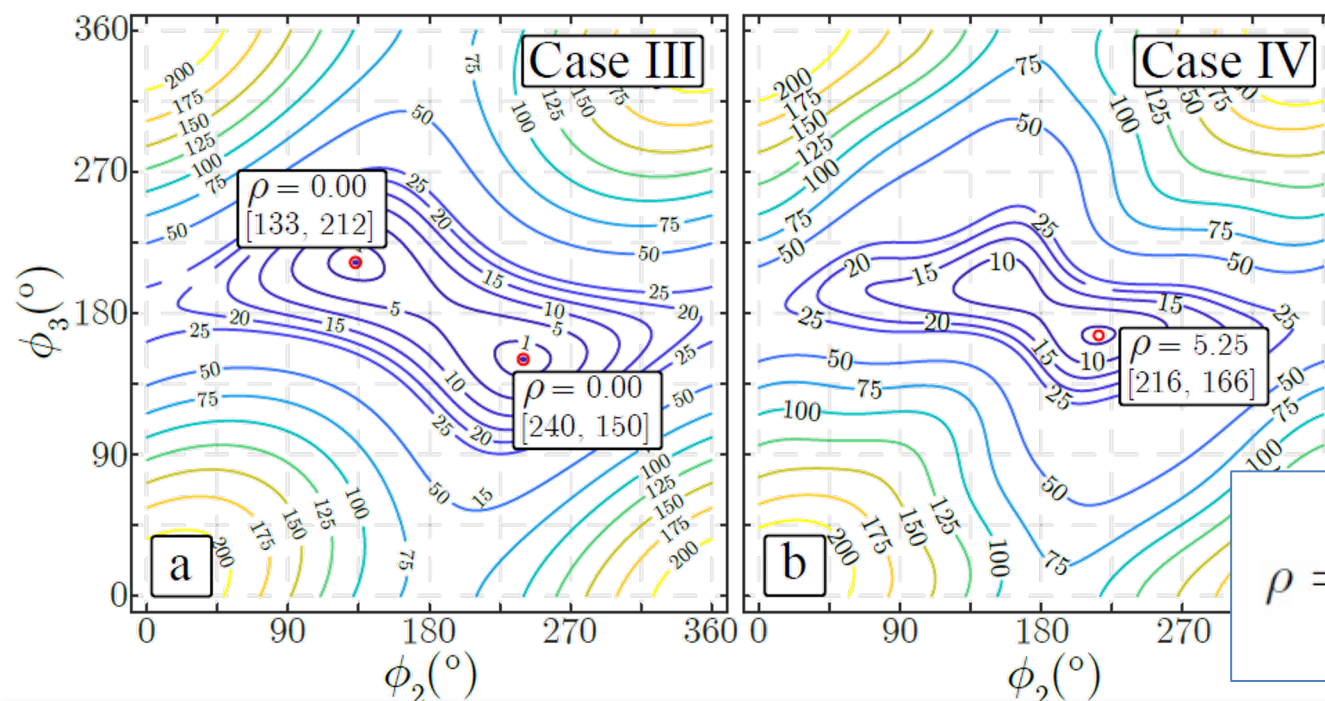
Operational conditions	Case
Balanced conditions	I
Unbalanced case, conventional angles	II
Unbalanced case, angles from iterative method with $m=1$	III
Unbalanced case, angles from iterative method with $m=3$	IV

# Variable-angle interleaved PWM method

## Obtained results



Operational conditions	Case
Balanced conditions	I
Unbalanced case, conventional angles	II
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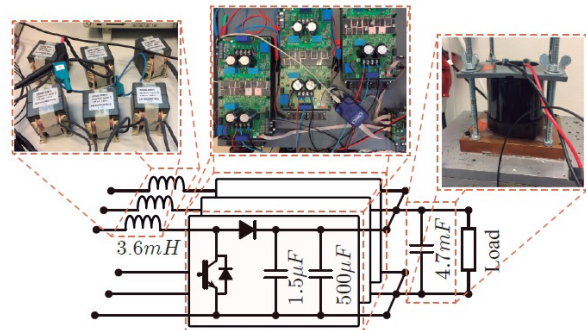


$$\rho = \sum_{n=1}^m I_{c,n}^2 = \sum_{n=1}^m \|H_n\|^2$$

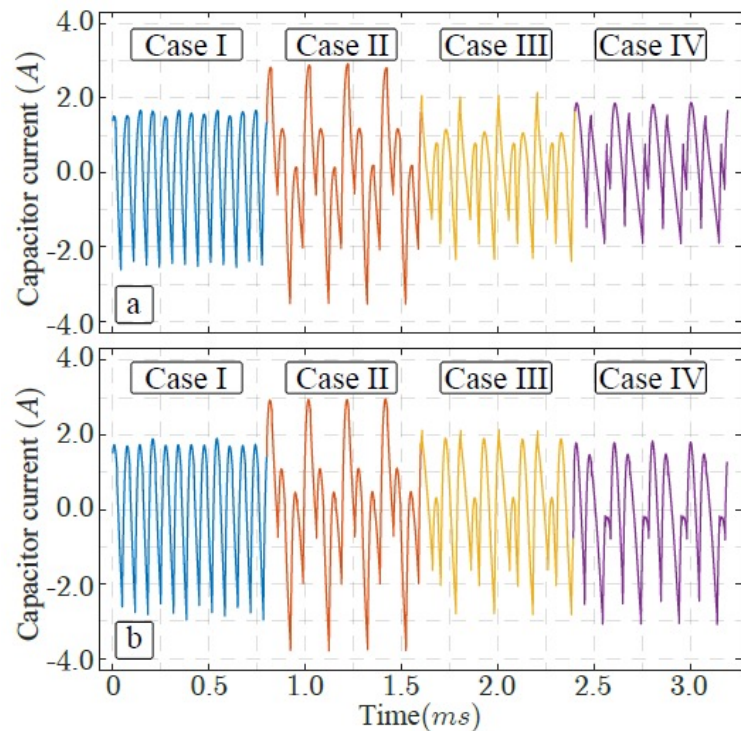


# Variable-angle interleaved PWM method

## Obtained results



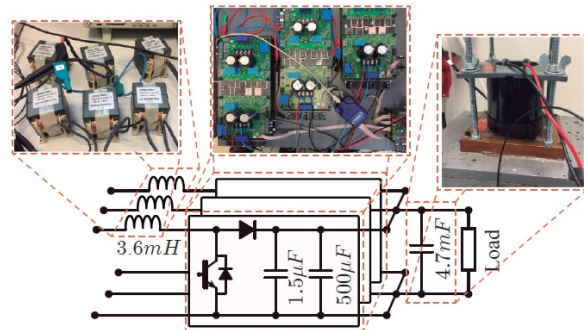
Operational conditions	Case
Balanced conditions	I
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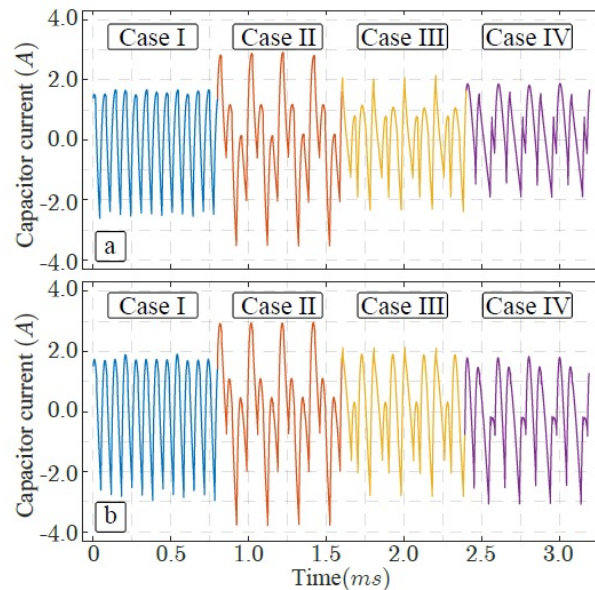
	a)		b)	
	$L = 3.6 \text{ mH}$ $R_{th} = [2, 5] \text{ K/W}$		$L = 1.8 \text{ mH}$ $R_{th} = [2, 5] \text{ K/W}$	
Case	Normalized $\sum_{h=1}^m I_{c,h}^2$	$T_h(^{\circ}\text{C})$	Normalized $\sum_{h=1}^m I_{c,h}^2$	$T_h(^{\circ}\text{C})$
II	100 %	[31.6,38.9]	100 %	[31.8,39.4]
III	33.29 %	[27.4,30.6]	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



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



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

**Extended lifetime!!!**

**And... it is for free!!!**



- 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

## Reliability of Power Electronics Systems

An Industry Perspective

Power electronics systems are used increasingly in a wide range of application fields, such as variable-speed drives, electric vehicles, and renewable energy systems. These elements have become crucial constituents in the further development of such emerging application fields as lighting, more-electric aircraft, and medical systems [1]. Reliable operation over the designed lifetime is essential for any power electronics system [2], particularly because the dependability of power electronics is becoming a prerequisite for system safety in several

key areas, e.g., energy, medicine, and transportation [3]. Demanding operation environments challenge the reliability aspects of power electronics systems [4]. Depending on the application of a specific system, a number of stressors—e.g., high temperatures, temperature cycling, humidity, dust, vibration, electromagnetic interference (EMI), and radiation—can endanger the safe operation of its components. The large number of fragile elements in power electronics systems includes semiconductors, capacitors, inductors, controllers, sensors, and auxiliary devices. The failure of a single part causes downtime and maintenance cost.

The need for dependable systems forces both academia and industry to pursue advances in reliability research [5]. The aim of this article is to identify the industrial challenges for future research and development (R&D) to address in dealing with application-specific reliability issues. The work is based on information obtained by surveying a large pool of power electronics systems reliability experts from industry.

Until now, only a few wider surveys based investigations concerning the dependability aspects of power electronics systems, as seen by experts, have been completed. Most were conducted in the wind power industry and

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Date of publication: 21 June 2018

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1932-4529/2018/0000

## Power Routing in Modular Smart Transformers

Active Thermal Control Through Uneven Loading of Cells



IMAGE COURTESY OF POWER ELECTRONICS

MARCO LISERRE,  
MARKUS ANDRESEN,  
LEVY FERREIRA COSTA,  
and GIAMPAOLO BUTICCHI

Digital Object Identifier 10.1109/IEE.2016.258888  
Date of publication: 21 September 2016

1932-4529/2016/00000000

Increasing decentralized energy production challenges the distribution grid [1], [2], and, in many countries, power generation and consumption are spatially separated, meaning that energy must be transferred over a long distance [3]. This calls for novel ways to transfer power to the loads without overloading grid feeders and to connect new intelligent loads and storage [4], which typically form the actual electric grid hybrid ac and dc) and couple with other energy networks (multimodal) [5]. In the current configuration, transformers are passive devices that do not enable dc systems to connect or interface the electric grid with other energy grids.

One solution that provides hybrid and multimodal connectivity and possible power flow control is the solid-state transformer (SST), which is based on power electronic converters and a medium-frequency transformer for galvanic isolation [6]. Unfortunately, SSTs have not achieved market breakthrough even in traction and ships, where they can reduce space requirements and raise efficiency compared with low-frequency transformers [7]. However, applying the SST in the distribution system would be justified and its higher cost paid, by its increased functionality; therefore, it is more appropriate to define it as a "smart" transformer (ST) to highlight these dominant software aspects and emphasize that the main hardware requirement is to allow a connection point of hybrid distribution networks among dc and ac distribution. Consequently, an ST is an SST with available dc-link connectivity (i.e., a minimum of two stages) and significant flexibility in managing its ac and dc connection points, which calls for advanced identification and control algorithms [8]. Yet, this ST must compete with traditional transformers not only in functionality but also in efficiency and reliability. In the terms of reliability, traditional transformers are hard to outperform because their lifetime is in the range of several decades and they have a low maintenance requirement—a target hardly achievable with today's power semiconductor technology. Also, a traditional transformer's efficiency is expected to be higher than that of an ST, especially in a three-stage architecture [9].

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## Power Routing

A New Paradigm for Maintenance Scheduling

MARCO LISERRE,  
GIAMPAOLO BUTICCHI,  
JOSE IGNACIO LEON,  
ABRAHAM MARQUEZ ALCALDE,  
VIVEK RAVEENDRAN,  
YOUNGJONG KO,  
MARKUS ANDRESEN,  
VITO GIUSEPPE MONOPOLI, and  
LEOPOLDO FRANQUELO

Digital Object Identifier 10.1109/IEE.2020.297040  
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Currently, the necessity of efficient and reliable power systems is also increasing because of the strict requirements that standards and regulations impose, but still costs have to remain low. The monitoring and control of the components' lifetime can lead to reduce maintenance costs. However, overcoming the related challenges is not a straightforward task, as it involves knowledge of power device physics, smart management of electrical quantities, and optimal maintenance planning and scheduling. It represents a multidisciplinary issue being faced in the last decade. As a primary issue to

be considered, it is clear that the evolution of power electronics is playing a principal role in the world in many ways including:

- the development of environmentally friendly and economically affordable clean energy sources, such as wind and solar energy [1]
- the installation and enhancement of facilities to develop a robust, reliable, and high-quality distributed electrical grid, including the smart grid paradigm with distributed energy storage systems [2]–[5]
- efficient and low-cost freight transportation based on electric vehicles, low-fuel-consumption cargo ships, and More Electric Aircraft [6]

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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.

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.

M.Liserre;G.Buticchi;JI.Leon;A. Marquez;V.Raveendran;YJ.Ko;M.Andresen;VG.Monopoli;LG.Franquelo, "Power Routing: A New Paradigm for Maintenance Scheduling," in *IEEE Industrial Electronics Magazine*, vol. 14, no. 3, pp. 33-45, Sept. 2020.

# Important References: ATC methods for DC/DC converters



## Variable-Angle Interleaved DC-DC Converters

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**Abstract.**—The use of interleaved power converters is a mature solution for multiple applications where the power is shared between several power converters. The interleaving method is used in order to improve the quality of the total output current. However, the performance of the complete power system is poor if an ATC operation is present in such power converter. In this paper, a variable-angle interleaving method is presented where the angle to be applied to carry out the interleaving is not fixed, but it is variable and calculated in real time depending on the operational conditions of the overall system. Simulation results are presented in order to demonstrate the good performance of the method.

### 1. INTRODUCTION

Power converters are becoming the key to meet the requirements of a non-stop demand of energy and power. Nowadays, new applications require novel power converters with high performance, high efficiency, high robustness and reduced volume and cost. An important family of power converter solutions is formed by power systems with several converters connected to the same point allowing parallel connection. In this way, each power converter of the power system manages only a part of the power. This solution has high modularity with natural fault tolerant capability improving the reliability of the overall system.

The usual operation of multiple dc-dc converters connected in parallel takes into account the interleaving method well-known since decades [4]–[6]. As an example, the multi-string converter topology for grid-connected large PV applications is shown in Fig. 1 [1]–[3]. In this topology, the PV strings are connected to a common dc-link through dc-dc power converters (usually boost converters). Each dc-dc converter has to achieve the maximum power tracking (MPPT) to maximize the overall power drawn to the grid. The use of multiple dc-dc converters leads to a distributed MPPT at the expense of increasing the number of power converters of the system. All dc-dc converters are operated using independent MPPT strategies and determining the switching signals applying a pulse-width modulation (PWM) method with the same frequency ( $f_{sw}$ ) as [1].

### II. CONVENTIONAL INTERLEAVING TECHNIQUE FOR DC/DC CONVERTERS

In the traditional operation of power converters, the carriers to carry out the pulse-width modulation (PWM) method are not in phase, but they are time displaced. The displacement between carriers in adjacent dc-dc converters is determined by

$$\alpha = \frac{360^\circ}{M} \quad (1)$$

where  $M$  is the number of dc-dc converters connected in parallel.

The dc-dc converters have the same operational conditions if they are connected in parallel themselves having the same input and output voltage. Under this condition, the interleaved operation of dc-dc converters presents several good advantages such as:

- Reduced output current ripple.
- Multiplicative switching frequency of the output current.
- Reduced value of the output capacitance.
- High fault tolerant capability and high reliability.

There are multiple applications where the interleaved operation of dc-dc converters is implemented successfully [7]–[13]. As an example to show the operation of interleaved dc-dc converters, the obtained waveforms of the power system shown in Fig. 1 are shown. In the example, all PV strings operate in the same way because they have the same irradiance value ( $1000 \text{ W/m}^2$ ) leading to the same desired dc-link voltage equal to  $365 \text{ V}$  determined by the MPPT controller. The dc-link voltage (output of the boost converters) is equal to  $600 \text{ V}$  and is controlled by the active front-end connected to the grid. In Fig. 2, the output current of the boost converter  $i_{L1}(t)$  ( $m=1$ ),  $i_{L2}(t)$  and the total output current  $i_L(t)$  are shown.

The interleaved operation of the boost converter makes that (6) presents symmetry having high frequency. Each boost converter operates at  $4 \text{ kHz}$  while the switching frequency  $f_{sw}(t)$  is located at  $12 \text{ kHz}$  (three times the carrier frequency because in the example  $M$  is equal to three). This fact is shown in Fig. 3 where the harmonic spectrum of  $i_L(t)$  is represented.

### III. PROPOSED VARIABLE-ANGLE INTERLEAVING METHOD

In some cases, the dc-dc converters could operate, for instance, in the case of Fig. 1 where each dc-dc converter is connected to a specific PV array. The MPPT control is performed to each array leading to different voltages and power if the radiation is different in each PV array. This leads to a non-equivalent operation of the dc-dc converters. Under this sub-optimal operation, the interleaved operation of the dc-dc converters leads to a degraded performance.

In order to reduce this problem under sub-optimal conditions, a variation of the interleaving technique is introduced in this paper. In essence, the main idea is to calculate analytically the displacement angle to be applied to each dc-dc converter depending on the instantaneous operation point of the overall

## Power Devices Aging Equalization of Interleaved DC/DC Boost Converters via Power Routing

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**Abstract.**—Modular parallel-connected dc-dc converters with interleaved operation are a well-known solution for a wide application range in order to achieve high-quality waveforms with reduced rated power devices. Usually, modular parallel-connected converters share equally the power achieving ideally an inherent aging equalization. However, hardware asymmetries or replacement of damaged modules after maintenance operations create an unavoidable aging mismatch between the power modules. In this paper, a method to equalize the aging of the power modules of parallel-connected dc-dc converters is presented. The method is particularized for boost converters. It is based on the power-routing concept forcing a non-equivalent power sharing among the modules of the modular converter. The power routing technique improves the remaining useful lifetime of the converter reducing the maintenance costs. Experimental results are shown in order to show the good performance of the proposed method. The results are also supported by a statistical analysis based on a Monte Carlo approach to evaluate the robustness of the proposed solution.

**Index Terms.**—Interleaved dc-dc power converters, power routing, aging control, aging management, power device lifetime

### 1. INTRODUCTION

The development of the smart-grid paradigm with the impulse of renewable energy sources is leading to revolutionary changes in the energy scenario. In this way, new power devices technologies, advanced converter topologies and modulation and control techniques have been developed [1]–[6]. In addition, year by year new applications with challenging requirements appear requiring efficient solutions with the highest performance. It can be affirmed that power electronics is playing an essential role to meet these new requirements [7].

Reliability and availability are currently very important features in industry and academia in last decades [8]. A very

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popular solution to achieve these requirements is to develop a power converter based on the combination of modulated power modules, also called power electronic building blocks [9]–[11]. Power converters based on modular connection are very convenient because they can provide fault tolerant capability improving the whole power conversion system availability reducing the maintenance and operation cost as well. In fact, power modules are an important part of the industry state of the art for high power semiconductor applications, due to their superior performance in terms of leakage inductance, ease of assembly and thermal management when compared to discrete devices [12].

Among the power converters formed by multiple connection of power modules, there is a large number of applications where the modules are connected in parallel. One straightforward advantage of using modular parallel connection of power modules is that the overall nominal power is shared between them what is an important feature mainly for high power systems. In this case, the total output current of the power converter is coming from the modules allowing to use reduced rated power devices and facilitating the hardware converter design including also the cooling system. This is the case of medium and high power systems such as, for instance, the Vento G2/1200 wind power system shown in Fig. 1 [13].

In this system, three parallel-connected dc-dc boost converters share the power of the system permitting to use reduced current rated power devices.

Parallel dc-dc converters are traditionally operated using the interleaved PWM technique, a very well-known method [14]. In fact, the interleaved operation is very popular in a wide-range of power applications [15]–[18]. Interleaved operation consists in applying the same duty cycle in each converter leading to a inherent power sharing between the power modules. Therefore, the conventional interleaved operation of parallel-connected power modules leads to a natural equalization of power losses and consequently equally distributed cumulative aging among the modules.

In addition, in the conventional interleaved operation, each power module has its own PWM modulator but the power devices switching pulses generated by each modulator have a time displacement between consecutive modules. This fact allows to reduce the output waveform ripples increasing the power conversion system performance. This feature is very well-known for instance in the case of switched power supplies with interleaved dc-dc converters [19].

However, the inherent aging equalization of interleaved

(19) 

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(54) METHOD FOR CONVERTING ELECTRICAL POWER, COMPUTER PROGRAM AND ELECTRICAL POWER CONVERTER

(57) Method for converting electrical power from a primary electrical supply network into a secondary electrical supply network using an electrical power converter, wherein the electrical power converter comprises a plurality of converter circuits which are operated in an electrically parallel arrangement towards the primary and/or secondary electrical supply network, wherein the power conversion of the converter circuits is operated in an angle control mode controlled by a management unit,

wherein the angle control mode comprises synchronized or interleaved angles between the converter circuits, wherein the synchronized or interleaved angles are modified during runtime of the power converter, characterized in that the synchronized or interleaved angles are determined based upon at least one stator parameter of at least one energy storage component connected to the electrically parallel arrangement of the converter circuits.



Fig. 1

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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



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IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS

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

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**Abstract**—Among multilevel converter topologies, the cascaded H-bridge converter (CHB) is one suitable solution for multiple applications such as flexible ac transmission systems and motor drives. CHB presents a natural high-modularity because it is formed by the serial connection of H-bridges. This paper deals with a CHB where the cells do not have the same aging because the maintenance during the years of operation forces to replace some damaged cells of the converter with new or repaired ones. A method based on clamping one power cell can be used to reduce the power losses of that cell reducing its temperature and increasing its lifetime. However, clamping one cell of the CHB introduces high harmonic distortion around twice the carrier frequency due to the CHB unbalanced operation when a conventional phase-shifted PWM is applied. A deep harmonic distortion analysis of the CHB output voltage with thermal control based on clamping one cell is presented. Using this analysis, the harmonic distortion at twice the carrier frequency is eliminated applying a non-conventional phase-shifted PWM where the switching sequence of consecutive power cells are modified. Experimental results show how the thermal control applying the clamping of a power cell is achieved without the harmonic distortion around twice the carrier frequency is eliminated.

**Index Terms**—Harmonic analysis, Pulse width modulation, Multilevel converters.

### I. INTRODUCTION

The use of multilevel converters has become a reality in the last decades for a wide variety of power applications such as fans, pumps, variable frequency drives, power quality applications and renewable energy integration, among others [1], [2]. One of the most well-known converter topologies is

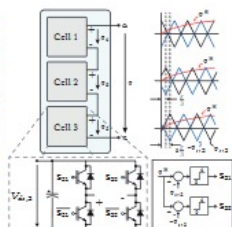


Fig. 1. Three-cell multilevel cascaded H-bridge converter (CHB): Topology and conventional PS-PWM modulation technique.

the cascaded H-bridge converter (CHB), which was proposed by McMurray in 1971 [3]. CHB is composed by the serial connection of H-bridges as shown in Fig. 1 where a three-cell CHB is represented. The basic power cell is usually the H-bridge, however in the literature other power cells like NPC or T-type can be found [4]. In this way, this topology is able to achieve very high nominal voltages with a large number of output voltage levels with high modularity and natural fault-tolerant capability. These good features make the CHB one of the most used topologies for medium and high-voltage applications with an excellent quality in the output voltage and current [5]. In fact, CHB is very popular in countries where medium voltage grids above 6.6 kV.

### A. CHB Converter Description and Operation

The conventional way to operate the CHB is to apply the conventional phase-shifted pulse-width modulation (PS-PWM) method. Each power cell is usually operated by a

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

**Abstract**—Cascaded H-bridge converter (CHB) is a multilevel topology that is a well-suited solution for multiple applications such as flexible ac transmission systems or motor drives. This paper is focused on a CHB where the cells present an aging mismatch. This can be caused by the maintenance operation which forces to replace some damaged cells of the converter with new or repaired ones. In this paper, a new improved approach of the active thermal control (ATC) of the CHB using Discontinuous PWM (D-PWM) is presented. The D-PWM technique is used to reduce the power losses of one cell reducing its average temperature in order to increase its remaining lifetime. However, the combination of D-PWM with traditional Phase-Shifted PWM (PS-PWM) introduces high harmonic distortion in the output voltage of the CHB converter around twice the carrier frequency. A detailed harmonic distortion analysis of the CHB output voltage when the D-PWM based ATC is active is presented. From this analysis, a modification of the traditional PS-PWM is derived to eliminate the harmonic distortion at twice the carrier frequency. Experimental results show how the ATC using D-PWM is achieved whereas the harmonic distortion around twice the carrier frequency is eliminated.

### I. INTRODUCTION

Nowadays, multilevel converter is a mature technology which has been developed since decades [1]. Multilevel converters are used in a extended range of power applications like pumps, fans, power quality applications and also in renewable energy integration [2]. [3]. Among this family, a popular multilevel topology is the cascaded H-bridge converter (CHB) which is shown in Fig. 1 and particularly for a three-cell CHB. This topology was proposed for first time in the early 70's by McMurray [4]. CHB is composed by the serial connection of several H-bridges, often denoted as  $N$ . Traditionally, the basic power cell is the H-bridge, however it is possible to find in the literature other power cells like NPC or T-type [5]. Among other advantages, this topology is very popular because it is able to achieve very high nominal output voltages with a large number of voltage levels providing a high modularity and natural fault-tolerant capability. This fact makes the CHB converter a good candidate to build the Smart Transformer (ST) [6], [7]. The high quality of the output voltage and current make the CHB one of the most used topologies for medium and high-voltage applications [8]. There are many modulation techniques to operate a CHB converter in the literature, from optimized pulses like selective harmonic mitigation [9] to modulation based on multi-carrier [10]. However, CHB has most frequently been operated using the well-known phase-shifted PWM (PS-PWM) technique. Each power cell is operated using a conventional unipolar PWM technique at  $f_c$  kHz. In order to implement the PS-PWM method it is necessary to apply a phase displacement

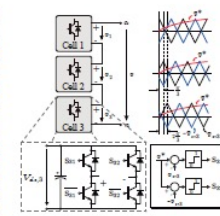


Fig. 1. Three-cell multilevel cascaded H-bridge converter (CHB): Topology and conventional PS-PWM modulation technique.

between triangular carriers of two subsequent power cells. This phase displacement is usually defined as an angle which is equal to  $180^\circ$  ( $\pi$  radians) divided by the number of cells available in each phase, denoted by  $N$  [11]. In order to illustrate this idea, the PS-PWM modulation concept as well as the unipolar modulation technique are represented in Fig. 1. As it is well-known, PS-PWM modulation presents some advantages when it is applied to a CHB converter. As an example, the output voltage presents high equivalent switching frequency because of PS-PWM multiplicative effect. Therefore, assuming a switching frequency of each power cell equal to  $f_c$ , the CHB output voltage features a harmonic behavior that is equivalent to that produced by a converter with a switching frequency of  $Nf_c$  ( $N$  represents the number of cells in the CHB). In addition, it also provides a power equalization between modules [12] because of the voltage references are equal for all cells. Therefore, a natural power losses, temperature and aging distribution is achieved. PS-PWM operation for a CHB is shown in Fig. 2 for two complete periods until  $t = 4$  ms with a 150 Vdc as dc capacitor voltage and a modulation index equal to 0.8.

Power converter failure is mainly caused by the cumulative aging of power devices, which is proportional to the thermal stress they suffered. Thermal stress leads to a fatigue of the materials of which the semiconductor components are composed. In other words, the relaxation of thermal cycles leads to the

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

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**Abstract**—Modular converters such as the multilevel cascaded H-bridge (CHB) are an attractive option for multiple applications mainly because of inherent modularity and fault-tolerant operation. This article is focused on the CHB converter operating with unbalanced conditions (different dc voltages and/or modulation indexes). Under these circumstances, applying the conventional control and modulation strategies, the output voltage harmonic spectrum is degraded. In this article, a generalized variable-angle phase-shifted pulsewidth modulation (PS-PWM) technique for CHB converters with a large number of power modules ( $>3$ ) is presented. The method considers all possible cells' combinations to form groups and assigns the role of each cell in the group. This cell role defines the identifier of the cell in the variable-angle PS-PWM technique. In the steady state, in each group of cells, the harmonic distortion of the CHB output voltage located at twice the carrier frequency  $f_c$  is eliminated, while the distortion at  $4f_c$  is also diminished. Experimental results show how the proposed technique achieves superior harmonic performance without introducing any significant disadvantage.

**Index Terms**—Harmonic analysis, multilevel converters, pulsewidth modulation.

### I. INTRODUCTION

NOWADAYS, multilevel converters are actually a mature technology. In fact, multilevel converters are being applied to multiple applications such as motor drives, flexible ac transmission systems, or solid-state transformers, to name just a few [1]. Among the existing multilevel converters, the cascaded H-bridge (CHB) converter is a very attractive topology. The CHB converter was introduced by McMurray in early 1970s [2], and it is composed of the serial connection of several, and identical, power cells, as shown in Fig. 1. The CHB topology, in each group of cells, the harmonic distortion of the CHB output voltage located at twice the carrier frequency  $f_c$  is eliminated, while the distortion at  $4f_c$  is also diminished. Experimental results show how the proposed technique achieves superior harmonic performance without introducing any significant disadvantage.

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$$\phi_x = (x-1) \frac{\pi}{N}, \quad x = 1, \dots, N \quad (1)$$

where  $N$  denotes the number of cells per phase. The phase angle set is defined with respect to the first cell, as shown in Fig. 1 [16]. The benefits of the PS-PWM technique applied to CHB converters have been well known since decades. The PS-PWM method provides an inherent power equalization between modules, and therefore, the power losses and power devices' junction temperatures are equally distributed [17]. Additionally, the CHB

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**PEMC Webinar:**  
**International Workshop on Electric Technologies for Green Airports**

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# Efficient integration of renewable energy sources for green airports

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