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Applications and Modulation Methods for Modular Converters Enabling Unequal Cell Power Sharing

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Abstract

Modular converters based on the connection of multiple power cells have become a competitive solution for many applications achieving high performance with reduced production and maintenance cost. However, their performance is degraded if the power modules present an unbalanced operation which is a common case in some applications and/or when they implement active thermal control methods. Variable-angle carrier-based PWM strategies face this challenge minimizing the negative impact of unequal power sharing among the cells by improving the output waveforms harmonic quality what has a direct impact on the output filters and/or components' lifetime.

I. INTRODUCTION

In the last decades the increasing power demand has come hand by hand with the non-stop evolution of power systems in order to face the current technical challenges with maximum efficiency, reliability and cost reduction [1]. One of the mainstream solutions to develop power systems with enhanced reliability, scalability, fault tolerant capability and reduced production and maintenance cost is to consider the power converters as modular systems formed by multiple cloned cells connected in series or parallel as shown in

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Fig. 1 [2], [3]. These cloned cells, usually called power electronic building blocks (PEBBs) present inherent reduced cost in terms of PEBB design and manufacturing because the same power cell design can be used to cover different applications [4]–[8]. Also, PEBB-based converters, also called in general modular converters, present reduced maintenance cost because if one PEBB failures, just a direct replacement is needed in order to keep the power system with proper operation.

A. Series-connected PEBB-based Converters

One possible solution to develop modular converters based on the connection of multiple PEBBs is to connect them in series to achieve high voltage ratings [9], [10]. If the voltage rating of a PEBB is V_c, the voltage rating of the complete series-connected PEBB-based converter with N PEBBs is NV_c, what is an interesting feature in applications such as medium-voltage high-power motor drives or high-voltage dc transmission systems [11]. Among the series-connected PEBB-based converters, the cascaded H-bridge converter (CHB) [12] or the modular multilevel converter (MMC) [13], represented in Fig. 1, can be cited. The basic PEBBs of these converters are normally full-bridges or half-bridges for the CHB and the MMC respectively.

B. Parallel-connected PEBB-based converters

A second option to develop modular converters is to connect cloned cells in parallel (parallel connection at the input, output or or even both sides) [14]–[16]. The most important feature of the parallel connection of PEBBs is the equal distribution of the power system nominal current among the modules. For instance, this is the case of the Vensys 60/1200 Wind power system represented in Fig. 1, where parallel-connected boost converters carry out the dc-voltage stage [17]. The advantages obtained by the parallel-connected PEBB-based converters become fundamental in applications where the nominal current rating is above the limits of the power semiconductors, or it is very high forcing to implement the converter with very expensive high-current power devices and hardware. Another interesting parallel-connected PEBB-based converter can be found in residential and industrial photovoltaic applications where several independent PV arrays are connected to a multi-string PV inverter, as shown in Fig. 1 [18], [19]. In this case, a boost converter is connected to each PV array but all boost converters have output parallel connection to the common dc-link of the inverter. Another example can be found in dc power supplies where the output waveforms requirements are strict in terms of reduced ripples [20].

II. PHASE DISPLACEMENT PULSE-WIDTH MODULATION METHODS FOR PEBB-BASED CONVERTERS

A proper operation of series/parallel PEBB-based converters is required in order to squeeze all their potential performance. In most of the cases, they are operated using PWM methods based on the phase displacement of the carriers [21].

Considering a series-connected PEBB-based converter such as the CHB topology, the carrier phase-displacement PWM method is called phase-shifted PWM (PS-PWM) strategy [22], [23]. If a N-cell CHB is considered (assuming that a unipolar PWM method is applied to each H-bridge), the analytical expression of the phasor representing the k-th harmonic component of the CHB output voltage H_k can be determined by adding up all the terms of each PEBB output voltage as follows:

$$H_k = \frac{4\cos\Big([m+n-1]\pi\Big)}{2\pi m}\sum_{x=1}^{N} A_x \tag{1}$$

where the coefficient A_x is defined by

$$\begin{aligned} A_x &= V_x^{dc}\mathcal{J}_{2n-1}\Big(m\pi M_x\Big)e^{j(2m\phi_x)} \\ &= V_x^{dc}\mathcal{J}_{2n-1}\Big(m\pi M_x\Big)\Big[cos(2m\phi_x) + jsin(2m\phi_x)\Big] \end{aligned} \tag{2}$$

It is clear that H_k depends on ϕ_x that represent the carriers phase-displacement of cell x (x=1,...,N). $\mathcal{J}_{2n-1}$ represents the Bessel function of the first kind of order $2n-1$. V_x^{dc} and M_x are the dc voltage and the modulation index of the x-th cell. The coefficients m and n are two indexes that identify each harmonic order k, represented in Fig. 2 fulfilling that $k = 2mR + (2n-1)$, where R is the ratio between the carrier signal frequency f_c and the modulating signal frequency f_m ($R = {}^{f_c}/_{f_m} = 20$). The conventional PS-PWM method applied to the CHB considers carrier phase-displacement angles ϕ_x in the PEBBs equal to [24]:

$$\phi_x = (x-1)\frac{\pi}{N}. \tag{3}$$

On the other hand, considering parallel-connected PEBB-based converters, another PS-PWM method, that is well-known as interleaved operation [25]–[27], is applied where

$$\phi_x = (x-1)\frac{2\pi}{N}. \tag{4}$$

A. Conventional Phase-displacement PWM Methods Performance Under Balanced Operational Conditions

The usual operation of modular converters considers balanced operational conditions for all the PEBBs. Taking the CHB converter as an example, applying the conventional PS-PWM angles, and assuming balanced operational conditions in all PEBBs, i. e., equal dc voltages (V_x^{dc}=V_{dc}), and equal cell reference voltages leading to M_x=M, the CHB operation is optimal in terms of equalized power and equally distributed PEBBs aging. In addition, the application of the PS-PWM method reduces the output voltage ripple (limited to the dc voltage of one cell, V_{dc}) reducing the filtering stage.

In addition, related to the harmonic distortion, from expressions (1) and (2), in order to eliminate one particular k-th harmonic, it has to be fulfilled that

$$H_k = 0 \Rightarrow \begin{cases} \sum_{x=1}^{N} V_x^{dc} \mathcal{J}_{2n-1}\Big(m\pi M_x\Big) cos(2m\phi_x) = 0 \\ \sum_{x=1}^{N} V_x^{dc} \mathcal{J}_{2n-1}\Big(m\pi M_x\Big) sin(2m\phi_x) = 0 \end{cases} \tag{5}$$

By applying the conventional ϕ_x defined in (3) under balanced operational conditions, it can be observed that all the harmonic components in the CHB output voltage with m=1,2,. . .,N-1 are zero (independently of the value of n). In other words, the harmonic distortion is inherently eliminated up to frequencies around $2Nf_c$ [28]. This phenomenon can be observed in Fig. 2, where the cell voltages and the total output voltage (and their corresponding harmonic spectra) of a three-cell CHB with f_c=1 kHz are shown. It can be observed that the cell voltages and the CHB output voltage present the lowest-order harmonic distortion around $2f_c$ and $2Nf_c = 6f_c$ respectively, as expected.

A dual case can be found if a parallel-connected PEBB-based converter is considered. In the interleaved operation of a N-cell parallel-connected PEBB-based converter such as the parallel-boost converters in the multi-string application, the output current ripple is limited leading to a superior harmonic performance [29]. In this case, the output current harmonic spectrum presents the first harmonic distortion around Nf_c. As an example, a dc/dc converter based on three parallel-connected boost interleaved converter has been tested. The obtained PEBB currents and the total output current and their corresponding harmonic spectra are represented in Fig. 2.

B. Conventional Phase-displacement PWM Methods Performance Under Unbalanced Operational Conditions

The balanced operation of PEBB-based converters is not always present. On one hand, there are applications where the balanced operation of PEBB-based converters is inherently impossible. An example is the multi-string converter shown in Fig. 1. The input of each boost converter is an independent PV string that, in general, presents a unique solar radiation and temperature leading to an inherent unbalanced operation. On the other hand, PEBB-based converters present an unbalanced operation if an active thermal control method, such as the power routing method, is applied [30]. This is a recent research topic that takes into account the actual state of health of the PEBBs to manage their power smartly in order to extend their lifetime reducing the maintenance cost [31].

In any case, if a modular converter operates under unbalanced conditions (i.e. unequal dc voltages and/or unequal modulation indices in the PEBBs), the performance applying the conventional carrier phase-displacement PWM methods is degraded leading to higher output waveform ripples and low-order harmonic distortion. Good features such as the inherent equalized power and equally distributed PEBBs aging are also lost [32]. As an example to show this phenomenon, considering a three-cell CHB converter, Fig. 3 illustrates what happens if the converter operates under the unbalanced conditions applying the conventional PS-PWM technique. It results that the low-order side-bands harmonic components of the CHB output voltage are not canceled anymore. The main consequence of this fact is the necessity of increasing the output filter size, weight and cost.

The same negative phenomenon appears if a parallel-connected PEBB-based converter is operated with unbalanced conditions as can be also observed in Fig. 3. The parallel-connected PEBB-based converter presents an output current with higher ripple and degraded harmonic performance. This creates different drawbacks depending on the converter specific application. In the case of the multi-string PV converter shown in Fig. 1, the unbalanced operation of the parallel-connected dc/dc stage leads to a degraded harmonic performance of the current that flows through the dc-link capacitor of the PV inverter. This critically affects to its remaining useful lifetime making its lifespan shorter than expected.

III. VARIABLE-ANGLE MULTICARRIER PWM METHODS FOR MODULAR CONVERTERS

In order to address the issue of the harmonic performance worsening for the PEBB-based converters operated with unbalanced operational conditions, a modification in the modulation strategy, that is called

Variable-Angle Phase-Shifted PWM (VAPS-PWM) technique, has been developed [33]–[36]. The main concept underlying this new approach is based on adapting the ϕ_x values according to the converter operational conditions. Doing it cleverly, the low-order side-bands harmonics of the output waveforms can be mitigated even under unbalanced operational conditions. The VAPS-PWM methods were initially introduced for modular converters with three PEBBs, which is the focus of this section. In Section IV, the methods are extended to be used in modular converters with larger number of PEBBs.

A. Fundamental-Period Based VAPS-PWM Method for Three-Cell PEBB-based Converters

As a first approach of a VAPS-PWM method, the strategy considered a three-cell CHB aiming to eliminate the most important low-order harmonic component, that is described by $m = 1$ and $n = 1$ in (5). In this approach the harmonic analysis is conducted adopting the modulating signal fundamental period as time-window and using a double fourier integral [24] to determine the analytical expression of the harmonics to be canceled and hence the required ϕ_x values [33], [34] leading to the expression introduced in Fig. 4. The main advantage of this approach is based on the capability of optimizing the converter harmonic performance with low computational burden taking into account the relatively large fundamental period window. As an example, this method has been applied to a three-cell CHB with the operational conditions shown in Fig. 4. It can be observed that the dominant low-order harmonic component defined by m=1 and n=1 is canceled.

The methodology used for the series-connected PEBB-based converter such as the CHB, can be applied in a similar manner to parallel-connected modular converters. In this case, the VAPS-PWM method considers the converter output current as the waveform to be analyzed in order to determine its corresponding side-bands harmonic expression. Once this is known, ϕ_x can be determined with the objective of eliminating the most dominant low-order harmonic component or, in general, improving its harmonic content. In order to show this concept, Fig. 6 is included where the current that is flowing through the output capacitor in a three-cell parallel-connected boost converter is represented. Different operational conditions are imposed in the converter applying the conventional interleaved angles and those obtained by the VAPS-PWM method. In this case, the VAPS-PWM strategy applies the ϕ_x angles in order to minimize the current harmonic components even under unbalanced operational conditions. As it can be observed in Fig. 6, applying the VAPS-PWM strategy, the first harmonic group (Case III) or the three first harmonic groups (Case IV) of the capacitor current harmonic spectrum are reduced. This fact has a decisive positive impact in the output capacitor average temperature leading to extend its expected lifetime.

B. Sampling-Time Based VAPS-PWM Method for Three-Cell PEBB-based Converters

An alternative approach of the harmonic analysis of a modular converter can be derived taking into account the carrier signal period as time-window [35]. Every carrier period it is possible to determine the time-based phasor ($h_k(t)$) representing the k-th harmonic component of the output waveform, as introduced in Fig. 4 where D_x is the duty cycle applied to PEBB number x. It is important to notice that in this method, the parameter k is defined related to the PEBB output waveform effective switching frequency what means that k=1 represents the most dominant lowest-order harmonic component. Taking this fact into account, a VAPS-PWM method can be developed in order to eliminate the harmonic distortion located at the first harmonic group by forcing $h_1(t) = 0$. Doing this, the envelope of that signal is eliminated what leads to the elimination of the complete harmonic group described by $m = 1$ with any value of n. In addition, a prompt and rapid optimization of the converter harmonic performance is achieved also during transients. The ϕ_x determination every carrier signal period, introduced in Fig. 4, does not represent a limitation of the applicability of the method in three-PEBB modular converters because the computational burden is very reduced.

As an example to show the performance of this method, it has been applied to the three-cell CHB with the operational conditions summarized in Fig. 4. The obtained results show that in the CHB output voltage the harmonic group defined by m=1 is highly mitigated. On the other hand, the method can be also applied to parallel-connected PEBB-based converters considering the output current as the waveform to be analyzed [37].

IV. VARIABLE-ANGLE MULTICARRIER PWM METHODS FOR MODULAR CONVERTERS IF $N > 3$

A. Fundamental-Period Based VAPS-PWM Method Implemented with Artificial Intelligence

The fundamental-period based VAPS-PWM method introduced in Section III-A presents two challenges. On one hand, this strategy just achieves the elimination of one specific harmonic component (defined by m=1 and n=1). The method lets the other components completely uncontrolled what could cause a distortion increase in other frequencies. On the other hand, applying the method to converters with $N > 3$, the angles ϕ_x are very complex to be determined in an analytical manner as can be observed in [38].

In order to overcome both issues, it is possible to adapt the method looking for the ϕ_x that minimize a well-defined cost function ρ that includes not only one specific harmonic but the harmonics of interest in an specific application [39]. Typically, a well-suited option to define ρ is to use the weighted total harmonic distortion (WTHD) which is a good figure of merit to improve the design of the output low-pass filter as it is introduced in Fig. 5, where harmonics up to N-1 are included in the cost function (but other figures of merit can also be used). In any case, any mathematical search algorithm can be used to look for the minimum value of the cost function [39], [40]. In [39], the Exchange Market Algorithm (EMA) was used to determine ϕ_x to minimize the cost function in a CHB with four, five and six cells. Some of the obtained results (represented in Fig. 5) show that, applying this VAPS-PWM method, an improved CHB output voltage harmonic spectrum is obtained.

B. Extension of the Sampling-Time Based VAPS-PWM Method

In the case of the sampling-time based VAPS-PWM method addressed in Section III-B, as the number of cells increases, it becomes progressively more difficult to determine the ϕ_x values imposing $h_k(t) = 0$. In this case, an efficient way to come to a valid solution is to force some conditions to ϕ_x in order to simplify the mathematical approach fitting with the solution given if N=3 introduced in Fig. 4 [41]. As an example, if N=4 and forcing $h_1(t) = 0$, the resulting equations to be solved are complex. However, the angle ϕ_1 can be fixed to one specific value in order to reduce the number of angles to be determined. Doing this, the obtained solution if N=3 would be valid but it represents only one of the infinite solutions to achieve the harmonic cancellation. Another way to simplify the calculations when N is large is to associate the cells forming groups of three cells and again using the well-known analytical solution when N=3. In this method, the carrier phase-displacement angles are determined in order to eliminate the envelope of the harmonics $A\rfloor_k$ introduced in Fig. 5. In particular, in [41] the ϕ_x values are obtained eliminating the envelope of the lowest-order side-bands harmonic (k=1) and minimizing the envelopes of other side-bands harmonic groups (defined by k=1 and k=2). The obtained enhanced CHB total output voltage harmonic spectrum applying this VAPS-PWM method considering a six-cell CHB converter is represented in Fig. 5. Another strategy to implement a sampling-time based VAPS-PWM method is based on a geometrical approach that also achieves similar results [42]. In any case, the elimination of the first group of harmonic components lead to an increase of the magnitude higher harmonic groups compared to the result obtained by applying the fundamental-period VAPS-PWM method.

V. FUTURE TRENDS

In many current and future applications, strict requirements in terms of fault tolerant capability, extended lifespan converters and reduced maintenance cost will lead to consider modular converters as the most attractive solution. Current limitations related to communications bandwidth and hardware management and control complexity are step by step being overcome by applying more powerful monitoring and control systems including cloud computing and the integration of cyber-physical systems [43].

The evolution of such kind of systems comes hand by hand with new algorithms based on artificial intelligence, machine learning and big data that can be applied to complex systems to be optimized [44], [45]. In this way, the actual limitations of the VAPS-PWM methods when the number of cells is large could be overcome. These algorithms based on these new approaches can be the core of new modulation methods in order to avoid such complex calculations that are nowadays required. More complex targets could be considered in the search for the most appropriate carrier phase-displacement angles of VAPS-PWM in order to achieve for instance the common-mode voltage and circulating currents minimization, reduce electromagnetic interference noise or take into account actual grid codes and standards.

VI. CONCLUSIONS

Modular converters are specially suitable for many applications taking advantage of the PEBB concept in order to minimize the production and maintenance cost achieving high performance by applying advanced control and modulation methods.However, to exploit the full potential of the modular topologies, unbalanced operation shall be allowed which brings new challenges in terms of low-order side-bands harmonic distortion reducing the expected performance of the system. A new family of modulation methods based on multicarrier PWM strategies but applying variable carrier phase-displacement angles has been recently developed. The application of these modulation techniques achieves the enhancement of the converters harmonic performance permitting to obtain optimal solutions even with unbalanced operational conditions. For instance, these methods make possible to apply, without any drawback, the lifetime extension methods based on active thermal control techniques. This will speed up the possibility to optimally apply modular systems to any existing and future application.

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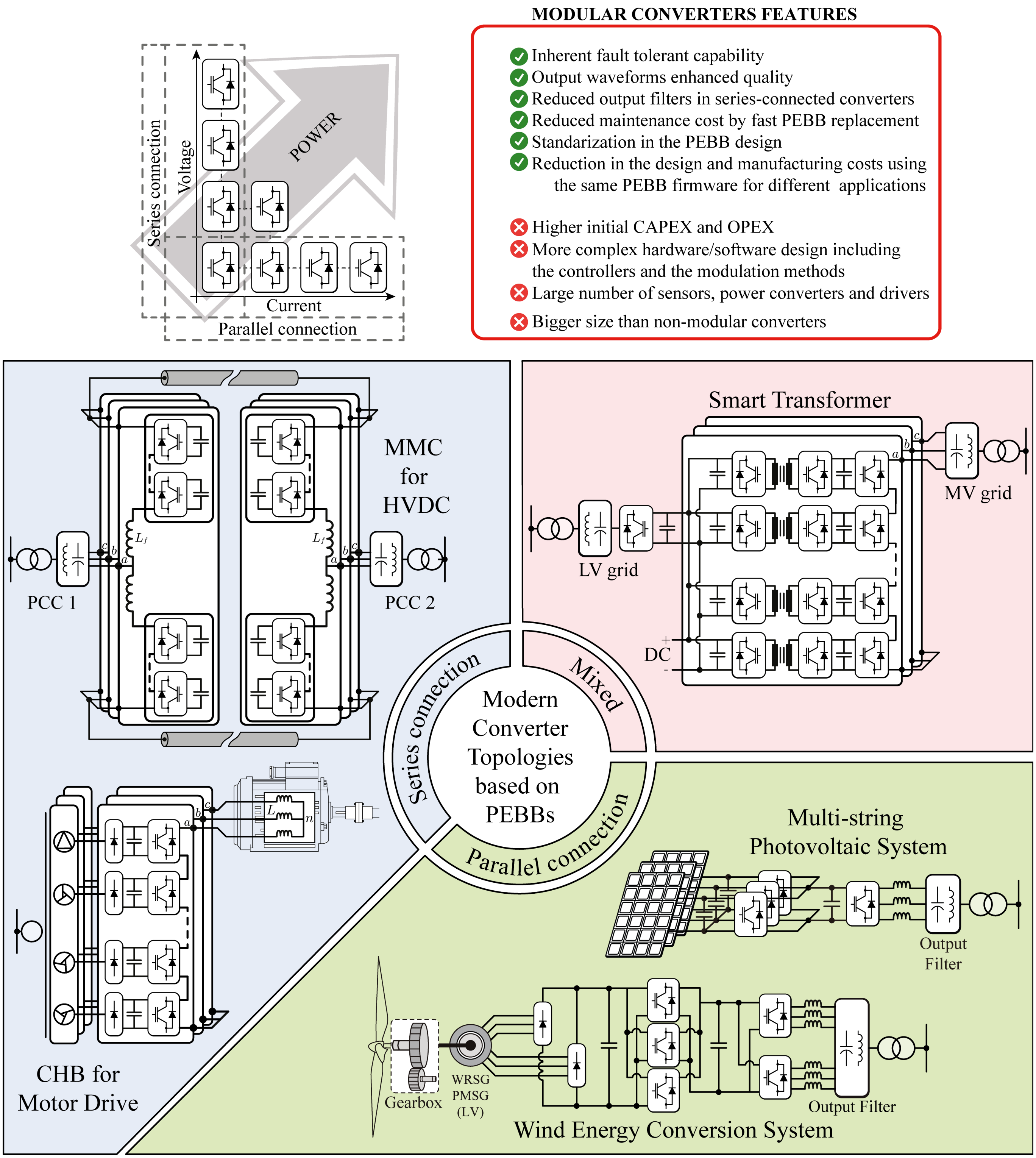


MODULAR CONVERTERS FEATURES

- ✓ Inherent fault tolerant capability
- ✓ Output waveforms enhanced quality
- ✓ Reduced output filters in series-connected converters
- ✓ 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

Fig. 1: Concept of modular converters: advantages and drawbacks. Several examples of series- and/or parallel-connected PEBB-based converters

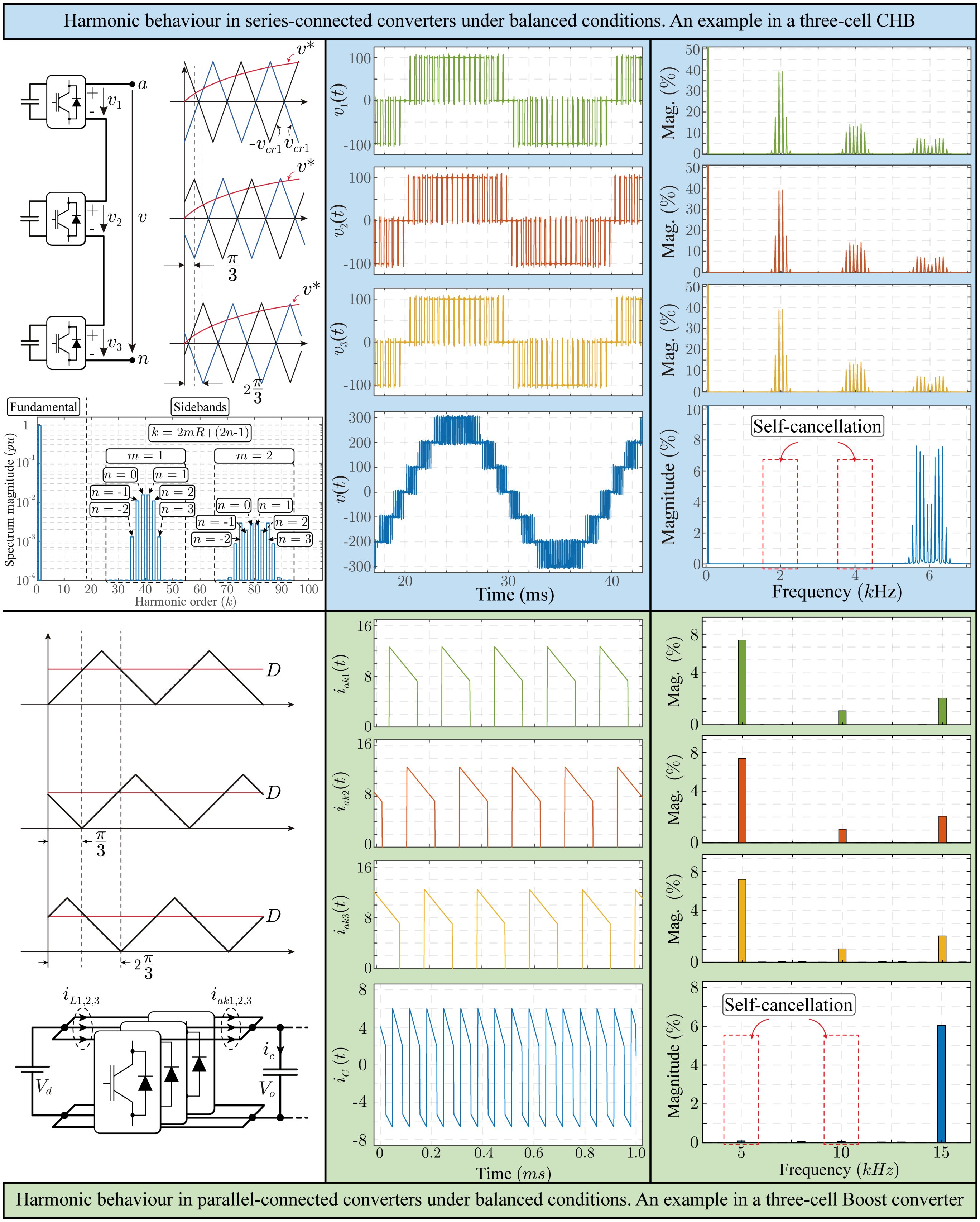
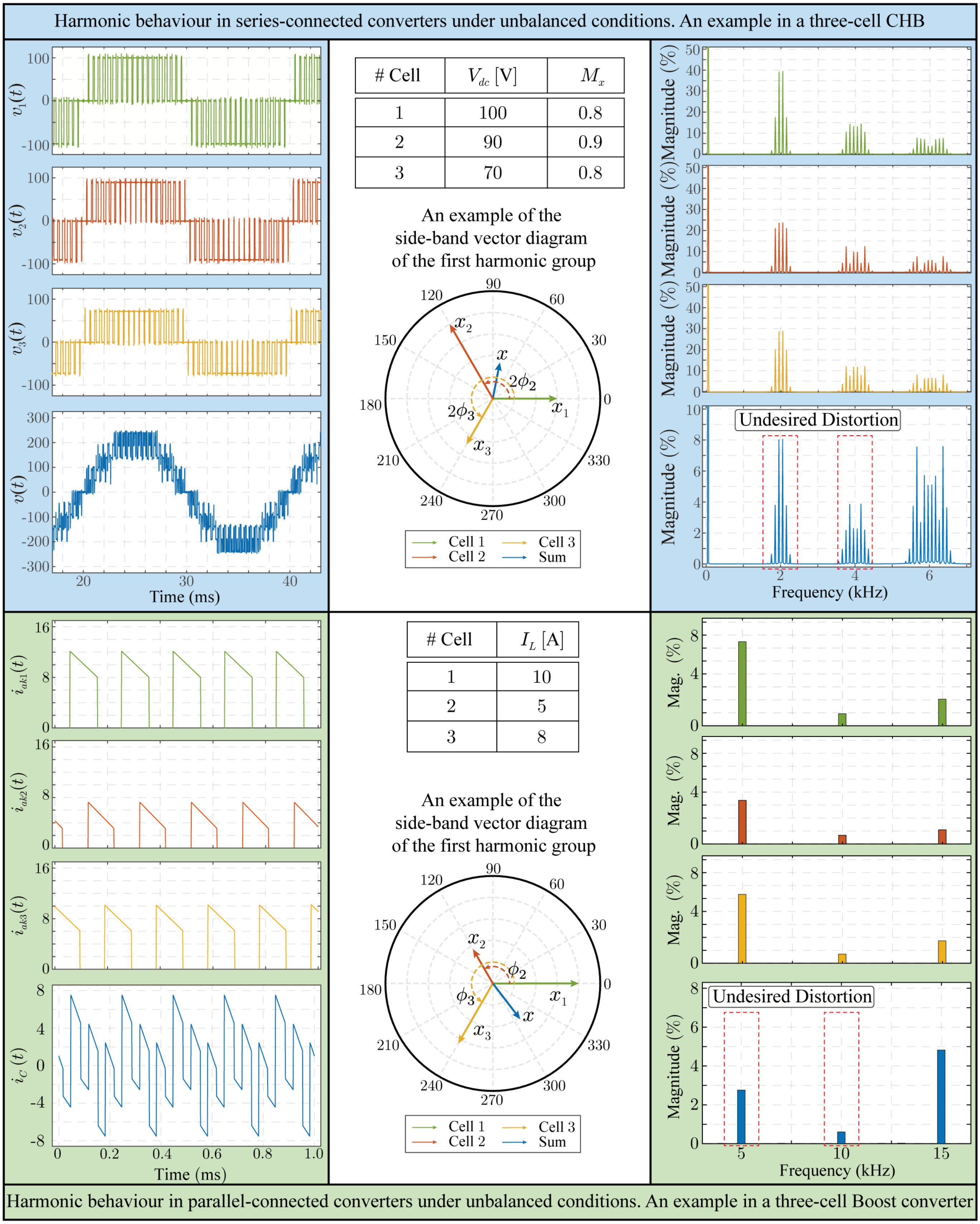


Fig. 2: Balanced operation of PEBB-based converters applying the conventional PS-PWM methods. Up: results of a three-cell CHB with f_c equal to 1 kHz. PEBB voltages and CHB output voltage with their corresponding harmonic spectra. Bottom: results of a three-cell parallel boost converters with f_c equal to 5 kHz. PEBB currents and total output current with their corresponding harmonic spectra



# Cell	V_{dc} [V]	M_x
1	100	0.8
2	90	0.9
3	70	0.8

# Cell	I_L [A]
1	10
2	5
3	8

Fig. 3: Unbalanced operation of three-cell CHB and three-cell parallel boost converters applying the conventional carrier phase displacement PWM methods with carrier frequency equal to 1 kHz and 5 kHz respectively. PEBB voltages/currents and total output voltage/current with their corresponding harmonic spectra

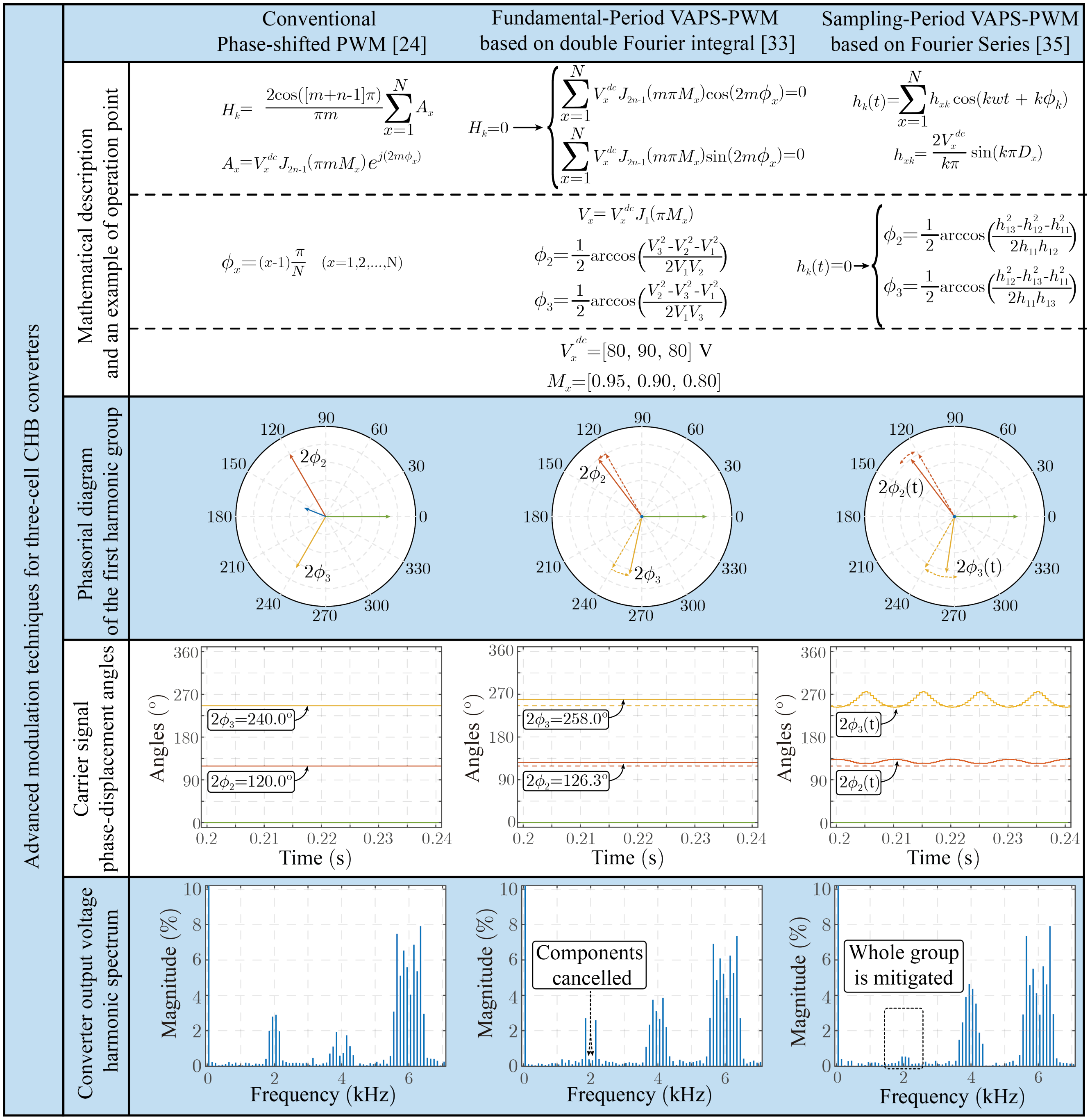


Fig. 4: Basic concepts and results applying PWM methods for three-cell CHB converters. From left to right: conventional PS-PWM, fundamental-period VAPS-PWM and sampling-time VAPS-PWM strategies

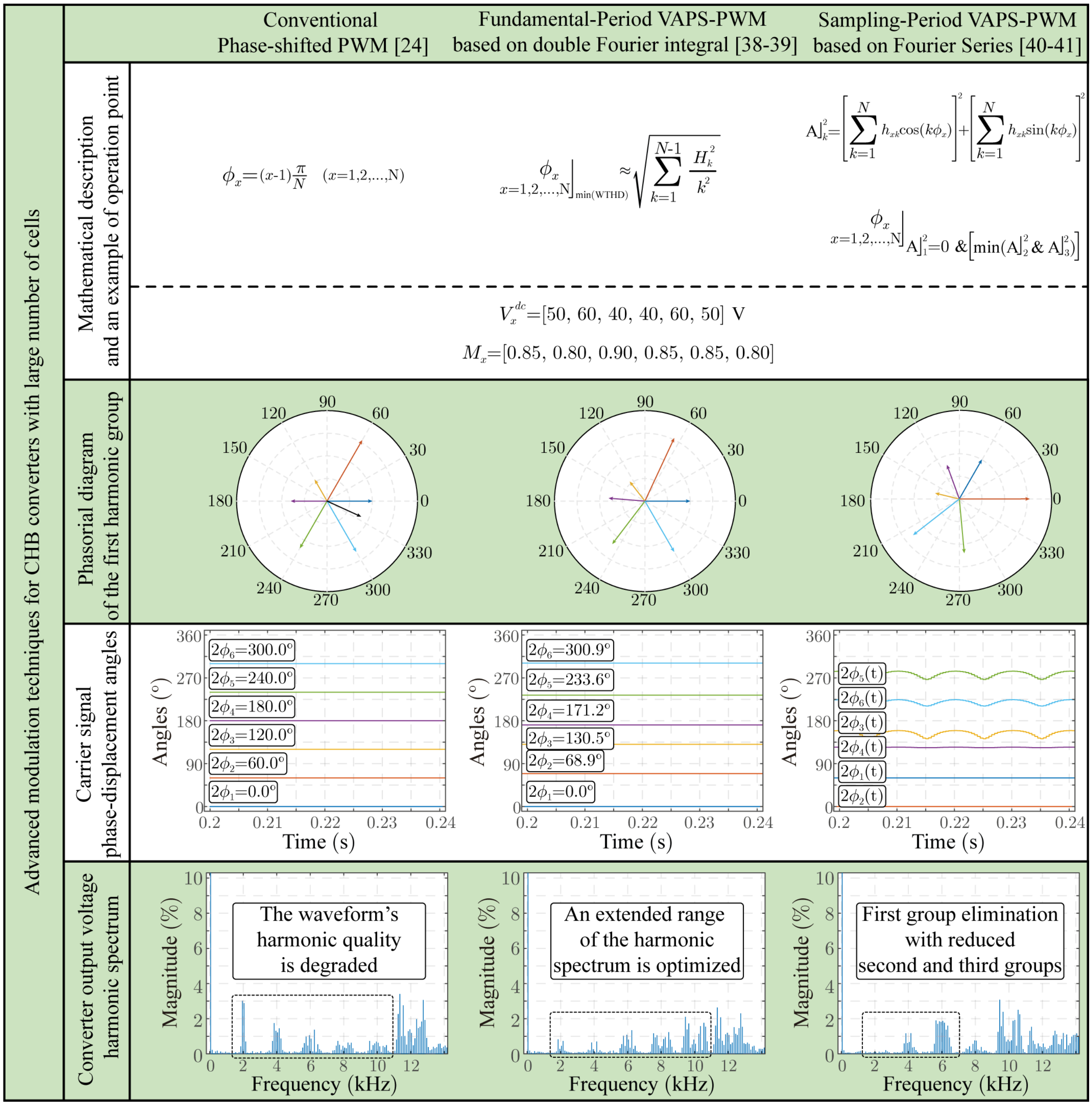


Fig. 5: Basic concepts and results applying PWM methods for six-cell CHB converters. From left to right: conventional PS-PWM, fundamental-period VAPS-PWM and sampling-time VAPS-PWM strategies

Parameter	Balanced	Unbalanced	Operational conditions & PS-PWM method	Case
Switching frequency (kHz)	5	5	Balanced case, conventional interleaving	I
			Unbalanced case, conventional interleaving	II
Output voltage V_o (V)	300	300	Unbalanced case, VAPS-PWM method reducing the first harmonic group	III
Power managed by the PEBBs (W)	1600	[1600,750,1240]	Unbalanced case, VAPS-PWM method reducing the first three harmonic groups	IV

L=3.6mH

Case	I	II	III	IV
$I_{c,1}$	0.03	1.50	0.06	0.79
$I_{c,2}$	0.01	0.13	0.63	0.88
$I_{c,3}$	1.70	1.52	1.06	0.37
$\Sigma_{k=1}^{3} I_{c,k}^{2}$	3.20	4.57	1.52	1.53

L=1.8mH

Case	I	II	III	IV
$I_{c,1}$	0.02	1.57	0.14	0.79
$I_{c,2}$	0.06	0.17	1.19	1.19
$I_{c,3}$	1.92	1.51	1.03	0.57
$\Sigma_{k=1}^{3} I_{c,k}^{2}$	3.69	4.77	2.49	2.36

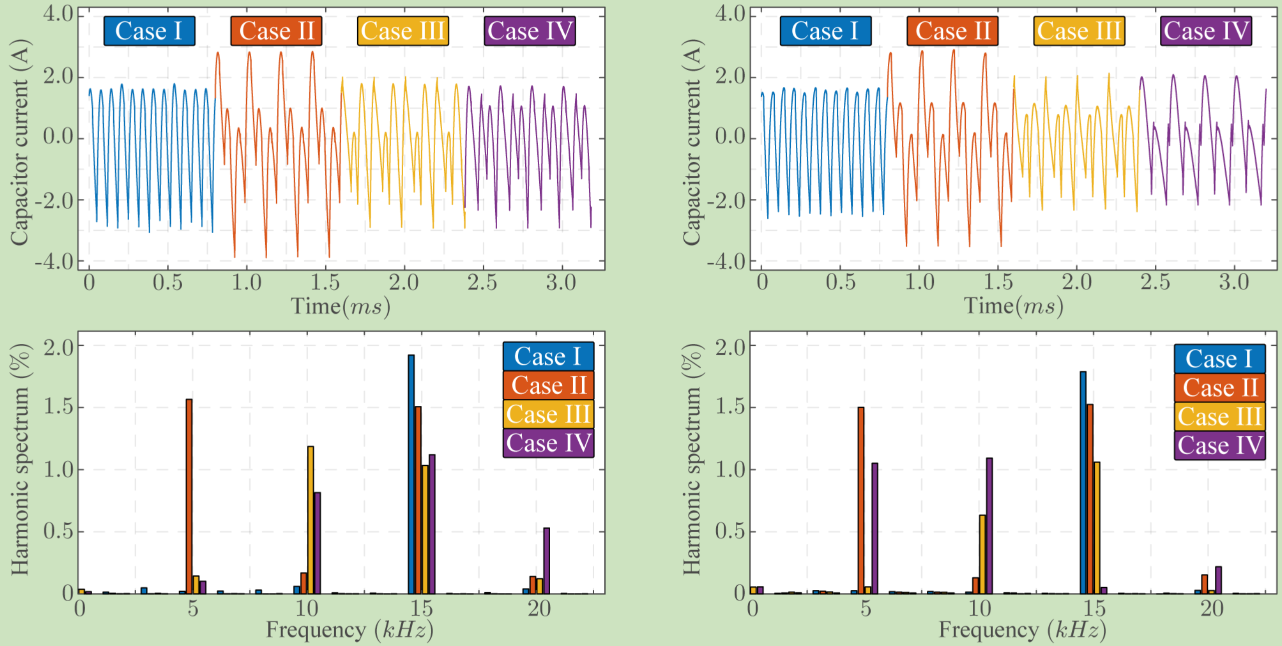


Fig. 6: Experimental results of a three-cell parallel-connected boost converter working under balanced and unbalanced operational conditions applying the conventional interleaved PWM technique and the VAPS-PWM method

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