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Power Balancing in Cascaded H-Bridge and Modular Multilevel Converters Under Unbalanced Operation: A Review

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ABSTRACT Multilevel Voltage-Source Converters (VSC) based on modular structures are envisioned as a prominent alternative for grid and industry applications. Foremost among these are the Cascaded H-Bridge (CHB) and the Modular Multilevel Converter (MMC). In this context, depending on the application and the power conversion structure, unbalanced operating conditions can be asked to the converter. Previous investigations regarding the operation and the solutions for modular structures under unbalanced conditions have already addressed this topic, but information is dispersed over a wide number of sources. This paper identifies, classifies, and analyzes the intercluster active power balancing strategies for the adequate operation of the most commonly used modular structures in some typical unbalanced operating scenarios: the Static Synchronous Compensator (STATCOM) under unbalanced voltage and/or current conditions, the unequal power generation in large-scale photovoltaic (PV) power plants, and the uneven power distribution in a battery energy storage system (BESS). Each of the applications has been independently studied so as to provide a comprehensive analysis of the alternative techniques found in the specialized literature, clearly explaining their respective strengths and drawbacks. Several future challenges have been identified during the study, which will involve greater research effort in this key research topic.

INDEX TERMS Battery energy storage system (BESS), cascaded H-bridge (CHB), modular multilevel converter (MMC), photovoltaic (PV), static synchronous compensator (STATCOM), unbalanced operation, multilevel voltage-source converter (VSC), zero-sequence injection.

I. INTRODUCTION

The dependency on fossil fuel-based conventional generation or the poor energy quality supplied by an aged power grid, among others, have led to an unsustainable energy system. In the last decades, the rapid increment in the energy consumption and the concern about climate change [1] have motivated great research effort to discover alternative generation systems [2] and technology solutions for their integration in the power system [3], [4].

In this framework, traditional power systems are evolving due to the progressive integration of distributed renewable energy-sources (RES), such as the solar photovoltaic (PV) and wind power plants (WPP). These non-conventional sources have actively contributed to reduce greenhouse gas emissions, increase the grid power capacity, prevent the saturation of lines, reduce electricity prices, and improve the overall efficiency [5]. However, the integration of RES into the power grid implies certain challenges due to their non-dispatchable nature compared to conventional generation systems [6]. Such systems often use power electronic converters for grid-connection instead of synchronous generators, making power systems become converter-dominated [3]–[6]. The development of self-commutated semiconductor devices [7], accompanied with the emergence of multilevel Voltage-Source Converter (VSC) topologies [8], allow power converters to face demanding operating requirements that massive RES integration imply [9].

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Besides common advantages of multilevel VSCs [8], those based on modular structures are considered as one of the most attractive topologies available for grid and industry applications. They play a key role in the integration of RES [10] or large power consuming industrial loads [11].

Power electronic converter-based power grid makes it increasingly necessary to count on power equipment with higher voltage and power rating [12]. In this context, since their scalable attributes, multilevel VSCs based on modular structures are nowadays the most promising alternatives commercially available for that purpose. Furthermore, the use of modular structures allows the transformerless connection to the grid with improved power quality [13]. In the last decade they have gained more and more attention both from the research community and converter manufacturers [14], [15].

Modular structures are frequently used as Static Synchronous Compensator (STATCOM) to facilitate the RES integration into the power grid [5], by helping to meet the requirements imposed by transmission and distribution system operators. The STATCOM provides fast dynamic reactive power support and improves the supply quality [16]. It is also used to compensate unbalanced loads in large industry applications such as mining or metal processing [15]. When the STATCOM was proposed, first thyristor-based [17], and later VSC-based [18], it was defined as a converter connected in parallel to the power grid which delivers or absorbs ac reactive power [19]. Today, the technical literature calls "STATCOM" the power equipment that provides a wide variety of functionalities [20]. The authors of this paper consider the STATCOM as the regulating static device which does not exchange net energy with the power grid.

Due to its modular configuration, modular structures are also the most interesting solutions for large-scale PV integration [21]–[23]. Connecting them to different power cells, modular structures allow to separate PV module strings, controlling each one separately and maximizing the PV power generation.

With a fairly similar philosophy, modular converters are also very suitable for battery energy storage system (BESS) applications [24], [25]. BESS are of vital importance in order to handle with the stochastic attributes of RES and facilitate their grid-integration [26]. Each battery unit is connected independently to separate power cells, and depending on the state-of-charge (SOC) of each one, an unequal active power distribution is enabled, where some battery units can be consuming and others delivering energy [27].

Among the challenging operating scenarios that a converter-dominated power system implies, the unbalanced operation should be highlighted; a new scenario that power converters have not dealt with before. On the one hand, dealing with the unbalanced generation of RES supposes a challenge when delivering balanced currents into the power grid [28]. On the other hand, requirements from grid codes are changing and start to demand negative-sequence injection capability from the converters connected to their power grid [20], [29], [30]. The unbalanced operation is an issue that the converter must face, either in transmission or in distribution systems. Single-phase loads such as traction drives, arc-furnaces or adjustable speed drives are one of the causes of an unbalanced current scenario [15]. The voltage unbalance may arise, for instance, from asymmetric grid faults [31] or unbalanced loads. The unbalance may ask the converter to give negative-sequence current and/or voltage to balance the current and/or the voltage at the point of common coupling (PCC).

Despite their advantages, multilevel VSCs based on modular structures present some drawbacks under unbalanced conditions. In order to overcome these, different control solutions have been proposed in the specialized literature. However, the information around the operation and the solutions for modular structures under unbalanced conditions is very disperse, and has not been previously reviewed or classified. Therefore, the aim of this paper is to perform a comprehensive review of the problems that the unbalanced operation suppose for multilevel VSCs based on modular structures, to classify the proposed solutions, and to identify future challenges.

The unbalanced operation is a trending issue, and it will have a large impact in the future electrical system. The classification and analysis of the most important modular converter structures, as well as their operation under unbalanced conditions will support researchers and developers to adopt the most appropriate solution. This will contribute to achieving a more robust future power grid.

The rest of this paper is organized as follows. Initially, a brief overview of the multilevel VSCs based on modular structures is performed in Section II, stating their most important features. Section III analyzes the problem of the unbalanced operation. Section IV collects a wide literature review where the adopted solutions for unbalanced operation are identified, analyzed, and classified. Finally, in Section V and Section VI the future challenges and main conclusions raised during the study are summarized, respectively.

II. OVERVIEW OF MODULAR VSC STRUCTURES

In 1993, Robicon Corporation brought to the industry a MV high-power motor drive multilevel inverter with a pulse-width modulation (PWM) strategy [32]; the emergence of what nowadays is known as "Cascaded H-Bridge (CHB) multilevel converter" [14]. In order to deliver energy to all the cascaded power cells, the presented ac-dc converter required a multiwinding line-frequency transformer [33]. A decade later, Marquardt and his group introduced a novel power conversion structure called "Modular Multilevel Converter" (MMC) [34], which was based on the series-connection of single-phase 2L VSC-based power cells (also known as half-bridge cells). In this converter configuration, the phase leg (called "phase cluster" in this paper) is separated into two equal parts to be able to generate positive and negative voltage levels at the ac side. The MMC has received increased attention since early 2000s, particularly for HVDC systems [35]–[37].

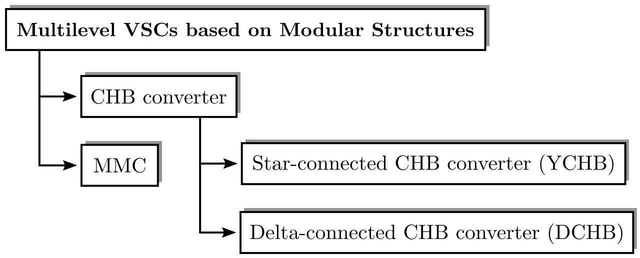

FIGURE 1. **Classification of multilevel VSCs based on modular structures.**

Since multilevel VSCs based on modular structures were proposed in the literature, there has been confusion regarding terminology within this family. Because both circuit configurations stand out due to their "modular" and "multilevel" features, Akagi classified the CHB converter and its connection configurations within the MMC family [15]. After this publication, many authors have used this criterion to distinguish and classify modular converter structures. Nevertheless, the authors of this paper understand the MMC as the particular converter topology presented by Marquardt [34]. Hence, modular converter structures are grouped separately in this review: on the one hand, the Cascaded H-Bridge (CHB) multilevel converter; on the other hand, the Modular Multilevel Converter (MMC), either with half-bridge or full-bridge power cells. In both converter groups, any VSC-based power cell topology is considered. Fig. 1 shows the simplified classification of the multilevel VSCs based on modular structures discussed in this paper.

As the ac voltage is proportional to the number of power cells, these structures are scalable, and direct power grid-connection is often feasible without a bulky step-up transformer [8], [14], [15]. Due to the multilevel waveform, the power quality is improved compared to non-modular VSC topologies [13].

A. CASCADED H-BRIDGE

The Cascaded H-Bridge (CHB) multilevel converter is composed of multiple units of single-phase full-bridge (or H-bridge) power cells, connected in cascade on their ac side [8]. This topology requires isolated dc energy-sources to feed each H-bridge (HB) [14]. This is not a drawback when the energy-source is also modular, but may require a multiwinding transformer with diode rectifier if it is not the case.

In the case of unbalanced operation, the main disadvantage of CHBs is the lack of a common three-phase dc-link, and thereby the difficulty in exchanging energy among phase clusters [38]. Consequently, countermeasures must be taken in order to preserve the balancing of dc-link capacitors. Different intercluster balancing methods have been proposed in the specialized literature, depending on the circuit configuration and the application. Hence, these solutions will have an impact on the overall rating of the converter, especially in terms of voltage and current requirements.

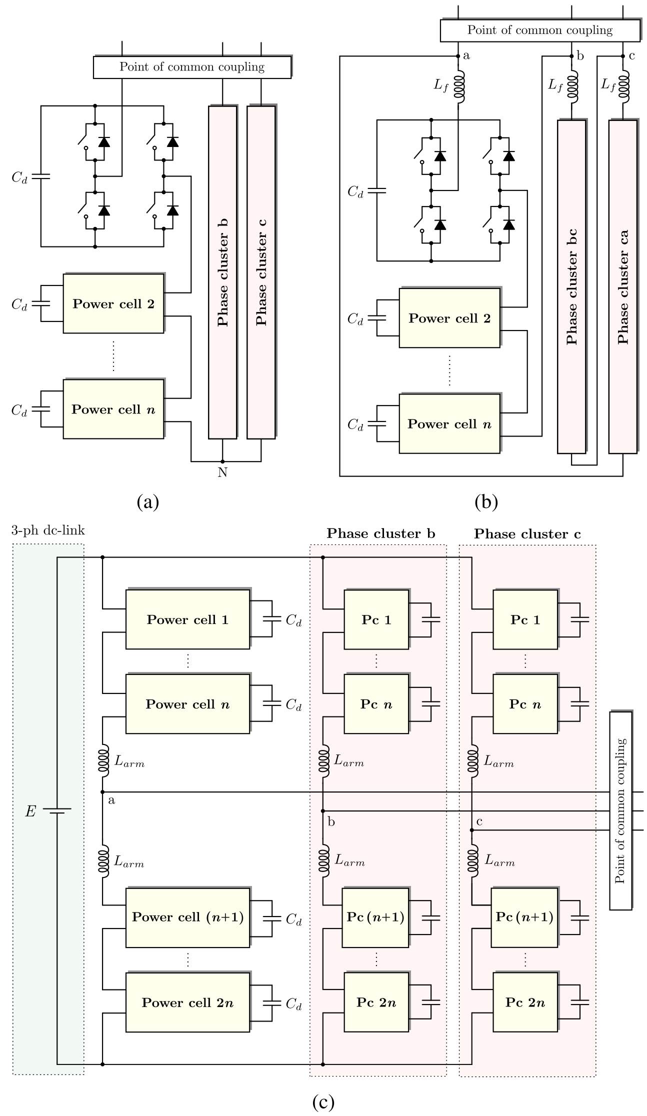

FIGURE 2. **Simplified circuit diagrams of multilevel VSCs based on modular structures. (a) YCHB, (b) DCHB, and (c) MMC.**

Fig. 2 (a) and (b) depict two circuit configurations belonging to the CHB: the star-connected CHB converter (YCHB), and the delta-connected CHB converter (DCHB). When employing the YCHB, the converter phase cluster is rated at the line-to-neutral voltage. Thus, when compared with the DCHB, either the switching devices can be sized at lower blocking voltage rating, or the number of the cascaded power cells can be reduced to obtain the same ac voltage level. Equivalent behavior can be found in terms of current for the DCHB. Another feature to consider is that the DCHB requires a solution (e.g., control loops or magnetic elements) to minimize circulating current inside the delta [15].

B. MODULAR MULTILEVEL CONVERTER

The Modular Multilevel Converter (MMC) is composed of two sets of star-connected converters in which the ac sides of multiple cascaded power cells (regardless their topology)

TABLE 1. Electrical characteristics of the multilevel VSCs based on modular structures under study. All the values are normalized with reference to the YCHB configuration.

Converter structure	YCHB	DCHB	MMC
PCC voltage	1 p.u.	$1/\sqrt{3}$ p.u.	1 p.u.
PCC current	1 p.u.	$\sqrt{3}$ p.u.	1 p.u.
Rated power	1 p.u.	1 p.u.	1 p.u.
Number of power cells	n	n	$2n$
Number of switches	Sw^{YCHB}	Sw^{YCHB}	Sw^{YCHB}

are interconnected to constitute each phase cluster [39], [40]. It is also known as "double-star-configured MMC" [15]. Fig. 2 (c) shows the circuit configuration of the classical MMC.

Unlike CHB configurations, the power cells constituting each phase cluster of the MMC share a common three-phase dc energy-source. If the same power cell voltage is used, to achieve the same voltage rating in ac terminals, the MMC needs twice as many power cells per phase cluster than a CHB. However, the MMC can be built with half-bridge power cells while the CHB needs full-bridge power cells [40]. In this manner, the number of switching devices is the same for the three structures. Table 1 summarizes the main per unit (p.u.) electrical characteristics of the converter structures considered in this paper, which provides a general idea of the number of power cells and/or the transformer conversion ratio that need to be used for each structure.

The MMC may also require a solution to control the circulating current between the upper and lower arms of each phase cluster [41]. In case of unbalanced operation, this current may have an impact on the MMC current rating [42], assuming that the converter has been dimensioned for balanced operation (where circulating currents of different harmonic orders also exist).

Multilevel VSCs based on modular structures must face any operating requirement and fulfill the standards imposed by grid codes [9], [30], [43]; in which the unbalanced operation is a mandatory requirement. Section III discusses the issue of working under unbalanced conditions in different applications.

III. PROBLEM OF THE UNBALANCED OPERATION

Together with the increase in the installation of MV converters, unbalanced operation is an increasingly frequent requirement faced by power electronic converters. Depending on the application scenario, the type of unbalance the modular structure must deal with is different.

Generally speaking, the instantaneous active power [44] in each phase cluster of the power converter ($p_\text{a}, p_\text{b}, p_\text{c}$) contains both an average ($\bar{P}_\text{a}, \bar{P}_\text{b}, \bar{P}_\text{c}$) and an oscillating ($\tilde{p}_\text{a}, \tilde{p}_\text{b}, \tilde{p}_\text{c}$) term (see Appendix A):

$$p_{ph}(t) = \bar{P}_{ph} + \tilde{p}_{ph}(t) \quad \text{where} \quad ph = \text{a,b,c}. \tag{1}$$

The oscillating term is generated due to the single-phase nature of power converters. This term oscillates at twice the power grid frequency (2ω) with a zero average value. Under unbalanced conditions, the average active power ($\bar{P}_{ph}$) in each phase cluster can be expressed as

$$\begin{aligned}\bar{P}_{ph} = {} & \underbrace{\frac{V^+I^+}{2}\cos\left(\delta_v^+ - \theta_i^+\right)}_{\bar{P}_{ph}^{++}} + \underbrace{\frac{V^-I^-}{2}\cos\left(\delta_v^- - \theta_i^-\right)}_{\bar{P}_{ph}^{--}} \\ & + \underbrace{\frac{V^+I^-}{2}\cos\left(\delta_v^+ - \theta_i^- + k\frac{4\pi}{3}\right)}_{\bar{P}_{ph}^{+-}} \\ & + \underbrace{\frac{V^-I^+}{2}\cos\left(\delta_v^- - \theta_i^+ - k\frac{4\pi}{3}\right)}_{\bar{P}_{ph}^{-+}} \end{aligned} \tag{2}$$

being $k = 0, -1, 1$ for $ph = $ a,b,c, respectively. V^+, V^-, δ_v^+ and δ_v^- denote the converter phase positive- and negative-sequence voltage phasor amplitudes and angles. Likewise, I^+, I^-, θ_i^+ and θ_i^- are the amplitudes and angles of current phasors.

From (2) different expressions are distinguished. Terms $\bar{P}_{ph}^{++}$ and $\bar{P}_{ph}^{--}$ correspond to the positive- and negative-sequence average active power expressions. These terms are common in the three phases. Terms $\bar{P}_{ph}^{+-}$ and $\bar{P}_{ph}^{-+}$ represent the average active power due to the cross-interaction of positive- and negative-sequence voltage and current components.

A. STATCOM SCENARIO

The Static Synchronous Compensator (STATCOM) using multilevel VSCs is finding increased utilization in transmission and distribution grids [45]–[48]. The typical applications of the STATCOM could be the improvement of the power system stability, the power factor ($\cos\phi$) correction, the regulation of line voltages, active power filtering (APF), mitigation of voltage flicker, unbalanced load compensation and low-voltage ride-though (LVRT) [16]. The main characteristic of STATCOM applications is that there is no need of any energy-source [19], since, neglecting losses, the net active power transfer between the power converter and the application is zero ($\bar{P}_\text{a} + \bar{P}_\text{b} + \bar{P}_\text{c} = 0$).

When there is no interaction between positive- (v^+, i^+) and negative-sequence (v^-, i^-) components (i.e., only term $\bar{P}_{ph}^{++}$ or $\bar{P}_{ph}^{--}$ exists), the average active power which flows into each phase cluster of the STATCOM is zero. In contrast, when the STATCOM operates under unbalanced voltage and/or current conditions, terms $\bar{P}_{ph}^{+-}$ and/or $\bar{P}_{ph}^{-+}$ appear in (2), which are also different in each phase cluster. These new terms cancel out in the ac side, but may appear in the single-phase dc side. Thus, each phase cluster might give or absorb active power different from zero ($\bar{P}_\text{a} \neq \bar{P}_\text{b} \neq \bar{P}_\text{c} \neq 0$).

On the one hand, in the case of CHB configurations (see Fig. 2 (a) and (b)), where each power cell of the converter

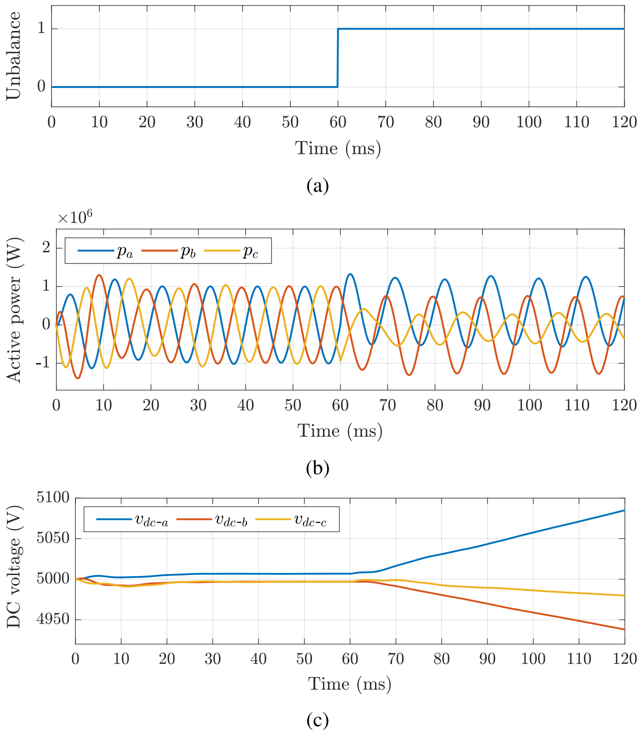

FIGURE 3. Impact of an unbalance on the YCHB STATCOM. (a) Unbalance, (b) phase cluster active power, and (c) phase cluster dc-link capacitor voltage. The effect in the DCHB is almost identical.

has its own single-phase dc-link, an external dc energy-source is required. In STATCOM application, where there is no need of any dc energy supply for each cascaded power cell, dc-link capacitor balancing cannot be guaranteed under unbalanced conditions, and hence, dc-link voltage drift appears. Fig. 3 shows an example of the impact of an unbalance on the phase cluster instantaneous active powers, and on dc-link capacitor voltages of a YCHB STATCOM. For clarity of the illustration, the plotted voltages are low-pass filtered in order to remove the double-frequency component (2ω). Each phase cluster is composed of a single power cell for the sake of simplicity. Thus, countermeasures have to be taken in order to correct this uneven active power distribution among phase clusters. The unbalance of the dc voltage may cause higher semiconductor stress or increase in total harmonic distortion (THD) at ac voltage and currents [49], or even can make the converter exceed its operating limits. In this case, the control strategy has to keep dc-link capacitor voltages in each phase cluster adjusted to the reference. This solution may suppose a de-rating in the converter output power.

On the other hand, structures with a common dc-link for three phase clusters do not need any energy-source connected to this dc-link in STATCOM application, whatever the unbalance is. That is, the sum of terms $\bar{P}_{ph}^{+-}$ and $\bar{P}_{ph}^{-+}$ of (2) in the three phase clusters is zero ($\bar{P}_{\rm a}+\bar{P}_{\rm b}+\bar{P}_{\rm c}=0$). This is the case of the MMC (see Fig. 2 (c)). However, as the phase cluster active power may differ from zero ($\bar{P}_{\rm a} \neq \bar{P}_{\rm b} \neq \bar{P}_{\rm c} \neq 0$), different dc circulating currents appear in each phase cluster; as a result of the potential difference between the neutral points of each set of star-connected converters forming the MMC (E). Therefore, the control strategy needs to cancel out these dc circulating currents to guarantee the dc-link voltage balancing in each phase cluster [50].

B. LARGE-SCALE PV POWER PLANT SCENARIO

Multilevel VSCs based on modular structures may be required to operate with active power. This can be the case of large-scale PV power plants, where the active power flows unidirectionally from the PV modules to the power grid.

Among all practical multilevel VSC topologies, the CHB converter is considered as one of the most suitable structures for large PV integration. In this case the active power is supplied directly by the PV modules with no need of extra energy-sources. The separate low-voltage PV strings can be modularly connected to each cascaded power cell. This allows easy extension to reach higher voltage and power levels, thus making it feasible to connect a large-scale PV power plant to a MV grid with a single converter. The main reasons for choosing the CHB structure for large-scale PV integration are: 1) individual maximum power point tracking (MPPT) algorithm alternatives; 2) improved high-power quality; 3) power cell fault redundancy; and even 4) the transformerless direct grid-connection [21], [22]. Some of these characteristics cannot be achieved with the MMC.

The CHB converter is typically designed considering that equal amount of active power is delivered to each phase cluster. Nevertheless, this assumption does not hold for large-scale PV applications. Even if the number of PV modules connected to each power cell is the same, and they are of the same characteristics, the active power supplied to each power cell will differ ($\bar{P}_{\rm a} \neq \bar{P}_{\rm b} \neq \bar{P}_{\rm c}$). This unequal power distribution occurs as a result of the dependence of the PV string generation on local weather conditions, or other causes such as partial shading due to near objects or cloud movement, unequal module temperature, manufacturing tolerances, dirt, or inhomogeneous module degradation [51].

As a consequence of the unequal power generation in large-scale PV power plants, the three-phase grid currents will become unbalanced if countermeasures are not taken [28]. As grid standards demand balanced grid current injection [9], [52], the control strategy has to redistribute equally the active power among phase clusters.

C. BESS SCENARIO

Another application where an active power is needed is the battery energy storage system (BESS). These systems play a key role in order to handle with the non-dispatchable attributes of RES and facilitate their grid-integration. They can even provide inertia services to the grid. In this case, the active power can flow bidirectionally, either from the batteries to the application or vice versa.

Modular structures are the most interesting alternatives for BESS [24], [25]. The isolated dc-links of each power cell are connected to separate battery strings, and thus, an independent management of each battery unit forming the BESS installation is achieved. Due to this reason, each of the converter phase clusters can absorb or deliver an unequal active power ($\bar{P}_a \neq \bar{P}_b \neq \bar{P}_c$) [27].

As well as PV power plants, in order to absorb/deliver only positive-sequence average active power from/to the ac- or dc-source, a control strategy needs to be added.

Although the aim of the application differs, the operation principle under unbalanced conditions is the same, either a STATCOM application, large-scale PV power plant, or BESS: to maintain the dc-link capacitor voltages balanced, or to supply/absorb balanced currents. That is, to set the average active power of each phase cluster to the reference value. Section IV deals with the techniques used for that purpose.

IV. INTERCLUSTER ACTIVE POWER BALANCING IN MODULAR VSC STRUCTURES

The unbalanced operation of multilevel VSCs based on modular structures involves some drawbacks to be addressed, as mentioned in Section III. The countermeasures adopted depend on the converter structure and the application.

A. STATCOM UNDER UNBALANCED VOLTAGE AND/OR CURRENT CONDITIONS

As (2) shows, different average active power is derived in each phase cluster due to the cross-interaction between positive- and negative-sequence voltage and/or current components. This involves a non-zero average active power in each phase cluster of the STATCOM ($\bar{P}_a \neq \bar{P}_b \neq \bar{P}_c \neq 0$).

In order to quantify the degree of current unbalance, the ratio k_{ipn} is defined [12]:

$$\text{for } I^+ \geq I^- \rightarrow \ k_{ipn} = \frac{I^-}{I^+} \ \rightarrow \ 0 \leq k_{ipn} \leq 1 \tag{3}$$

$$\text{for } I^+ \leq I^- \rightarrow \ k_{ipn} = 2 - \frac{I^+}{I^-} \ \rightarrow \ 1 \leq k_{ipn} \leq 2 \tag{4}$$

Equation (3) is applied when i^+ predominates, and (4) when i^- does. $k_{ipn} = 0$ states that the current sequence is only positive (balanced condition); $k_{ipn} = 1$ that both components exist and are of equal magnitude; and $k_{ipn} = 2$ expresses that the converter is only supplying negative-sequence current. Fig. 4 shows the evolution of the positive- and negative-sequence current amplitudes as a function of k_{ipn} and the phase shift between both sequences ($\theta_{ipn} = \theta_i^- - \theta_i^+$).

Analogously, the phase shift between both voltage sequences ($\delta_{vpn} = \delta_v^- - \delta_v^+$) and the ratio of voltage unbalance (k_{vpn}) can be defined:

$$\text{for } V^+ \geq V^- \rightarrow \ k_{vpn} = \frac{V^-}{V^+} \ \rightarrow \ 0 \leq k_{vpn} \leq 1 \tag{5}$$

$$\text{for } V^+ \leq V^- \rightarrow k_{vpn} = 2 - \frac{V^+}{V^-} \rightarrow 1 \leq k_{vpn} \leq 2 \tag{6}$$

Three main unbalanced scenarios can be identified which the STATCOM may have to deal with:

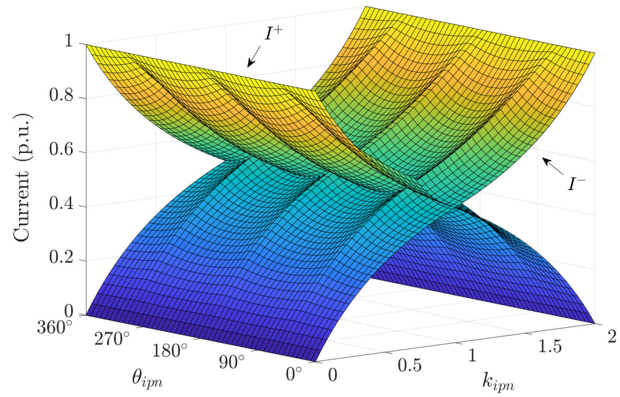

FIGURE 4. Positive- and negative-sequence current amplitudes at nominal phase cluster current, as a function of k_{ipn} and θ_{ipn}. The same could be applied to the voltage.

- *Negative-sequence current withstanding*. Sometimes, the STATCOM is only used for dynamic power factor correction or regulation of line voltages (usually in weak grids). In this scenario, the STATCOM must not be disconnected from the power grid. However, the converter can be demanded by the corresponding grid code to withstand a small amount of negative-sequence voltage (v^-) in the PCC (e.g., $k_{vpn} \approx 0.02$) [30]. As Fig. 5 (a) shows, this v^- generates a negative-sequence current (i^-) through the STATCOM, which should be capable of copping with [53], [54].
- *Unbalanced load compensation*. The STATCOM may be required to compensate unbalanced loads, such as arc-furnaces, single-phase loads, etc. In this scenario, ideally, the power grid supplies positive-sequence voltage (v^+) in the PCC, while the load absorbs negative-sequence current (i^-). The STATCOM provides positive- and negative-sequence voltage (v^+, v^-) and current (i^+, i^-), so the grid is only required of positive-sequence current (i^+) (see Fig. 5 (b)) [38], [55], [56].
- *Low-voltage ride-through (LVRT)*. As Fig. 5 (c) depicts, when a voltage sag or an unbalanced fault occurs, in the worst case, both positive- and negative-sequence voltage components (v^+, v^-) may appear in the PCC [57]–[60]. Thus, the STATCOM needs to provide positive- and negative-sequence voltage (v^+, v^-) and current (i^+, i^-) in order to compensate for the power grid asymmetry. In Germany, for example, the technical requirement imposes i^- injection so as to reduce v^- during a fault [43].

Apart from these typical unbalanced scenarios, other ones may also appear under certain operating requirements of the STATCOM. However, they could be grouped within the above-mentioned scenarios.

1) PHASE CLUSTER AVERAGE ACTIVE POWER CANCELLATION IN THE CHB-BASED STATCOM

When CHB configurations with single-phase dc-links are used for the STATCOM and operating under unbalanced

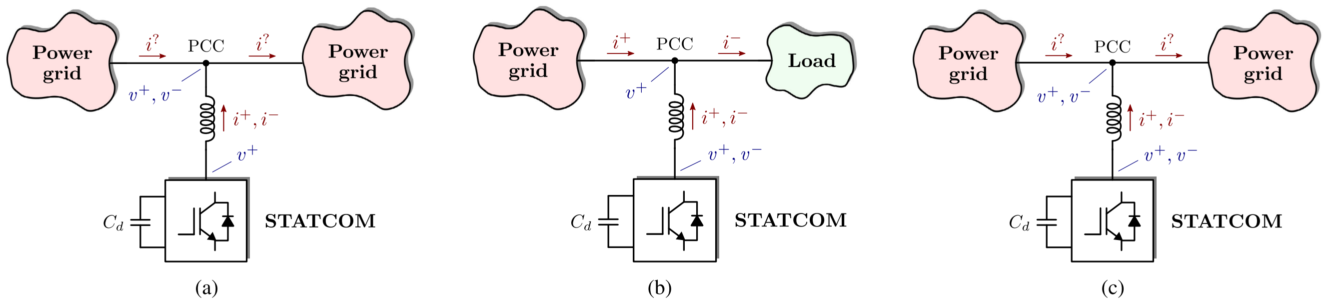

FIGURE 5. **Typical unbalanced scenarios of the STATCOM application. (a) Negative-sequence current withstanding, (b) unbalanced load compensation, and (c) low-voltage ride-through (LVRT).**

voltage ($k_{vpn} > 0$) and/or current ($k_{ipn} > 0$) conditions, the derived average active power term in each power cell and each phase cluster must be cancelled ($\bar{P}_a = \bar{P}_b = \bar{P}_c = 0$). The adopted power balancing strategy needs to guarantee constant dc-capacitor voltages. This means that apart from ensuring an equal active power distribution among phase clusters *(intercluster balancing)*, power cells forming each phase cluster need to be balanced from their dc voltage point of view *(intracluster balancing)*.

This paper deals with the "intercluster active power balancing" [54], which aims to redistribute the active power equally among the three phase clusters so as to preserve the dc-link voltages adjusted to the reference value. In turn, the "intracluster active power balancing" in CHBs needs to be addressed regardless of whether it is an unbalanced scenario or not [49], [51], [61]; therefore, it is not covered in this review article.

The CHB converter topology was introduced by Peng and Lai at the end of the 90's as a promising converter structure for STATCOM application [62], [63]. It was expected to be the best alternative suitable for MV applications, due to its modular structure, a transformerless connection and output filter size reduction. These first designs were based on the YCHB, composed of full-bridge power cells [64]–[66].

The use of the STATCOM for rebalancing issues was well established [67]–[73]. However, most of the papers published previously addressed the unbalanced operation of non-modular converter structures. In 2004, Peng proposed the DCHB converter as the alternative to the YCHB for STATCOM application under unbalanced conditions [55]. In contrast to the star, the delta configuration allowed to compensate unbalanced loads while compensating also the reactive power (Q). The author proposed an "admittance compensation theory", an active solution to force the phase cluster average active powers to zero. This technique was based on calculating the converter current magnitude and phase by means of an analogous YCHB converter. References [74], [75] analyzed the possibility of controlling the circulating current flowing inside the DCHB. An intercluster active power balancing solution was addressed for the DCHB STATCOM [55], [74], [75], but not yet for the star structure.

Akagi and coauthors presented a transformerless YCHB STATCOM with pulse-width modulation (PWM) [76], handling the dc capacitor voltage unbalance by independently cancelling the average active power of each individual phase cluster. However, this paper does not contemplate any unbalanced situation. Reference [77] presented a control method based on the injection of negative-sequence current (i^-) to operate under unbalanced grid voltage conditions.

Betz and Summers proposed a pioneering compensation control concept based on the injection of fundamental-frequency zero-sequence voltage (YCHB), and zero-sequence current (DCHB) [78]–[80]. The aim was to cancel the terms $\bar{P}_{ph}^{+-}$ and $\bar{P}_{ph}^{-+}$ of (2), by means of an additional zero-sequence term ($\bar{P}_{0\text{-}ph}^{\text{YCHB}}$ in case of the YCHB, and $\bar{P}_{0\text{-}ph}^{\text{DCHB}}$ in case of the DCHB):

$$\begin{aligned}\bar{P}_{ph} = & \underbrace{\frac{V^+I^+}{2}\cos\left(\delta_v^+ - \theta_i^+\right)}_{\bar{P}_{ph}^{++}} + \underbrace{\frac{V^-I^-}{2}\cos\left(\delta_v^- - \theta_i^-\right)}_{\bar{P}_{ph}^{--}} \\ & + \underbrace{\frac{V^+I^-}{2}\cos\left(\delta_v^+ - \theta_i^- + k\frac{4\pi}{3}\right)}_{\bar{P}_{ph}^{+-}} \\ & + \underbrace{\frac{V^-I^+}{2}\cos\left(\delta_v^- - \theta_i^+ - k\frac{4\pi}{3}\right)}_{\bar{P}_{ph}^{-+}} \\ & + \bar{P}_{0\text{-}ph}^{\text{YCHB}} + \bar{P}_{0\text{-}ph}^{\text{DCHB}} \end{aligned} \quad (7)$$

On the one hand, when the YCHB converter operates under unbalanced voltage and/or current conditions, a fundamental-frequency zero-sequence voltage (v_0) is added to the converter star point N (see Fig. 7 (a)). The addition of this component does not affect the three-phase voltages and currents at the converter output, and allows two degrees of freedom; its amplitude (V_0), and angle (δ_{v_0}):

$$v_0(t) = V_0 \sin(\omega t + \delta_{v_0}) \quad (8)$$

The aim is to find a suitable V_0 and δ_{v_0} so as to generate an active power ($\bar{P}_{0\text{-}ph}^{\text{YCHB}}$) which cancels out the effect of the non-zero average active power at each phase cluster (terms $\bar{P}_{ph}^{+-}$ and $\bar{P}_{ph}^{-+}$):

$$\bar{P}_{0\text{-}ph}^{\text{YCHB}} = \frac{V_0 I^+}{2}\cos\left(\delta_{v0} - \theta_i^+ - k\frac{2\pi}{3}\right) + \frac{V_0 I^-}{2}\cos\left(\delta_{v0} - \theta_i^- + k\frac{2\pi}{3}\right) = -\bar{P}_{ph}^{+-} - \bar{P}_{ph}^{-+} \tag{9}$$

where $k = 0, -1, 1$ for $ph =$ a,b,c, respectively. Defining some constant terms (see Appendix B.1), the expressions of δ_{v0} and V_0 can be deduced [53], [81]:

$$\tan\delta_{v0} = \frac{K_1^{\text{a}}K_2^{\text{b}} - K_1^{\text{b}}K_2^{\text{a}}}{K_1^{\text{b}}K_3^{\text{a}} - K_1^{\text{a}}K_3^{\text{b}}} \tag{10}$$

$$V_0 = \frac{-K_1^{ph}}{K_2^{ph}\cos\delta_{v0} + K_3^{ph}\sin\delta_{v0}} \tag{11}$$

Fig. 6 shows how the injected zero-sequence voltage component in the YCHB STATCOM corrects the effect of the current unbalance on the instantaneous phase cluster active powers. However, depending on the ratios k_{vpn} and/or k_{ipn}, the injection of v_0 could lead the converter voltage exceeding its rated level. As a consequence, the YCHB must be over-rated in terms of voltage in order to let a wide voltage margin to guarantee the nominal ac voltage at the PCC; otherwise, the STATCOM should be disconnected from the power grid. The voltage over-rating can be achieved either serializing more power cells, or increasing the power cell dc-link voltage.

On the other hand, if the DCHB converter is used, the delta configuration allows unbalanced operation by letting a fundamental-frequency zero-sequence current (i_0) circulate inside the delta (see Fig. 7 (b)), without affecting the three-phase voltages and currents at the converter ac side. Similar to the YCHB, the circulating fundamental-frequency zero-sequence current allows two degrees of freedom, in terms of its amplitude (I_0), and angle (θ_{i0}):

$$i_0(t) = I_0\sin(\omega t + \theta_{i0}) \tag{12}$$

The additional zero-sequence active power term ($\bar{P}_{0\text{-}ph}^{\text{DCHB}}$) cancels out the active power terms delivered in each phase cluster due to the cross-interaction between positive- and negative-sequence components (terms $\bar{P}_{ph}^{+-}$ and $\bar{P}_{ph}^{-+}$):

$$\bar{P}_{0\text{-}ph}^{\text{DCHB}} = \frac{V^+ I_0}{2}\cos\left(\delta_v^+ - \theta_{i0} + k\frac{2\pi}{3}\right) + \frac{V^- I_0}{2}\cos\left(\delta_v^- - \theta_{i0} - k\frac{2\pi}{3}\right) = -\bar{P}_{ph}^{+-} - \bar{P}_{ph}^{-+} \tag{13}$$

where $k = 0, -1, 1$ for $ph =$ ab,bc,ca. Following the same criteria adopted for the star, θ_{i0} and I_0 are calculated as (see Appendix B.2) [53], [81]:

$$\tan\theta_{i0} = \frac{K_1^{\text{ab}}K_2^{\text{bc}} - K_1^{\text{bc}}K_2^{\text{ab}}}{K_1^{\text{bc}}K_3^{\text{ab}} - K_1^{\text{ab}}K_3^{\text{bc}}} \tag{14}$$

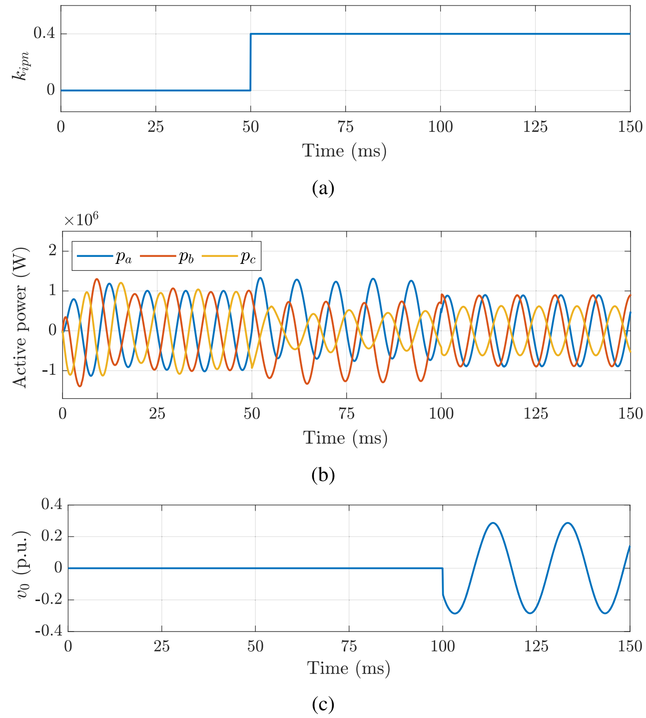

FIGURE 6. Phase cluster average active power cancellation in the YCHB STATCOM using the fundamental-frequency zero-sequence voltage injection ($k_{vpn} = 0$). The unbalance starts at $t = 50$ ms, and the intercluster active power balancing is activated at $t = 100$ ms. (a) Ratio of current unbalance, (b) phase cluster active power, and (c) zero-sequence voltage.

$$I_0 = \frac{-K_1^{ph}}{K_2^{ph}\cos\theta_{i0} + K_3^{ph}\sin\theta_{i0}} \tag{15}$$

In an equivalent way to the YCHB, the injected i_0 will involve a current de-rating in the DCHB converter.

In the first approach, Betz and Summers developed the zero-sequence injection expressions and discussed the technique under unbalanced current conditions, assuming terminal voltages of the STATCOM to be balanced [78] ($k_{vpn} = 0$, $k_{ipn} > 0$). Later, they studied the same solution when the output voltages were unbalanced [79] ($k_{vpn} > 0$, $k_{ipn} > 0$). These papers concluded that a duality exists between the YCHB voltage rating and DCHB current rating under unbalanced operation [78], [79]. The method was integrated in a novel control strategy in [80].

The previously proposed negative-sequence current injection method for the YCHB STATCOM [77] was compared with the fundamental-frequency v_0 injection, considering the latter as the best technique for LVRT (see Fig. 5 (c)) [82]. Both methods can be combined together depending on the unbalanced voltage sag depth [82]–[84]. However, the negative-sequence currents for voltage balance purpose will be injected into the power grid inevitably, which is not preferred from the power quality point of view [85]. Accordingly, the scientific literature shows that the fundamental-frequency v_0 injection is the most widespread

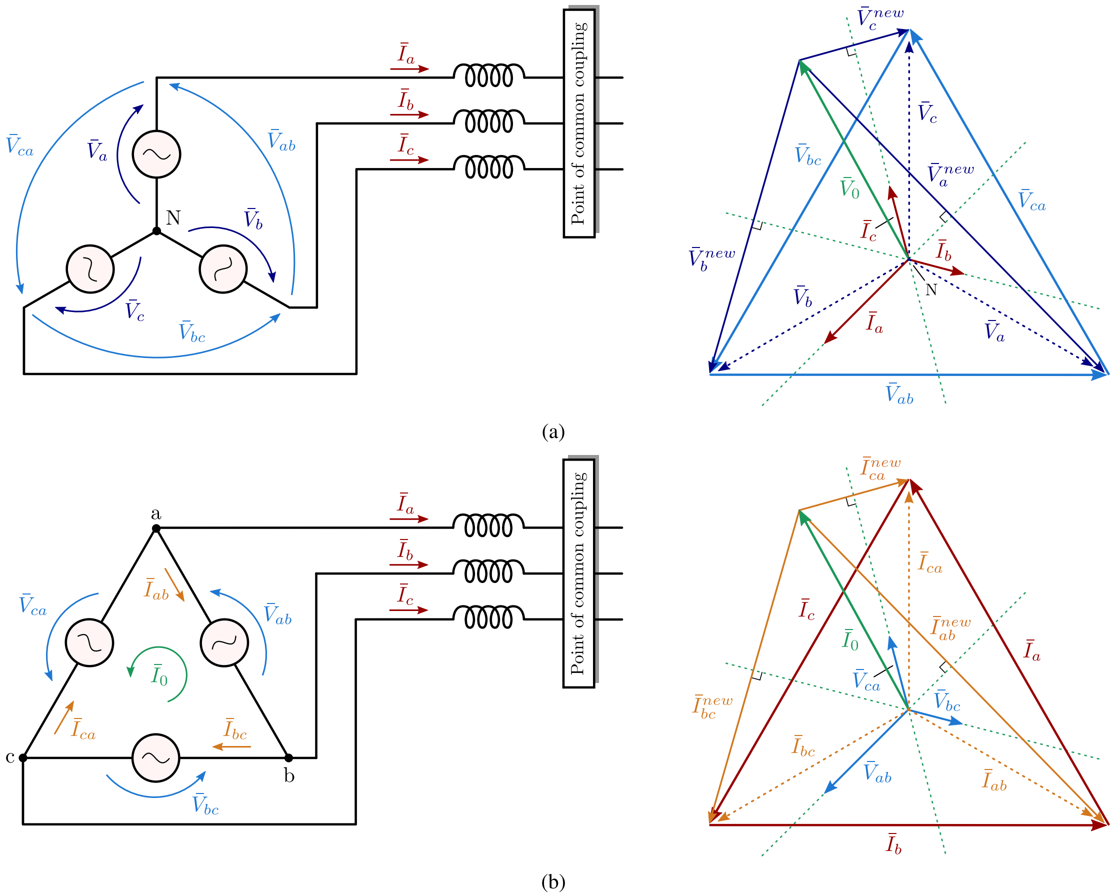

FIGURE 7. Phasor diagrams of the fundamental-frequency zero-sequence injection. (a) YCHB STATCOM under unbalanced current conditions ($k_{vpn} = 0$, $k_{ipn} > 0$), and (b) DCHB STATCOM under unbalanced voltage conditions ($k_{ipn} = 0$, $k_{vpn} > 0$).

technique to address any unbalanced operating point with the YCHB STATCOM [38], [85]–[95].

Several authors have studied the technique of injecting a circulating fundamental-frequency i_0 for the unbalanced operation of the DCHB STATCOM. In [55], a control method is presented for intercluster active power balancing, but no feedback loop is formed to control the circulating current among the delta-connected clusters. References [96]–[100] present a control strategy for the DCHB STATCOM considering both unbalanced operation and circulating zero-sequence current control.

2) COMPARISON OF YCHB AND DCHB STATCOMs

CHB structures are interesting for STATCOM applications under unbalanced operation. This has led many authors to individually analyze and compare the limitations and the operating ranges of the YCHB and DCHB.

Behrouzian and Bongiorno [53], [101] investigated the capabilities of the YCHB and DCHB STATCOM under unbalanced current ($k_{vpn} = 0$, $k_{ipn} > 0$) and voltage conditions ($k_{ipn} = 0$, $k_{vpn} > 0$), respectively. For that purpose, analytical expressions of the injected fundamental-frequency zero-sequence voltage (in case of YCHB) and current (in case of DCHB) were developed. The authors concluded that the utilization of these STATCOM configurations for negative-sequence injection presents some limitations. That is, due to a singularity that exists in the solution for the calculation of the zero-sequence components, there are special operating points for both YCHB and DCHB STATCOMs, where v_0 and i_0 are unable to set the average active power in each phase cluster to zero. These operating points are $k_{ipn} = 1$ for the star, and $k_{vpn} = 1$ for the delta. These two singular points demand infinite V_0 for the YCHB, and infinite I_0 for the DCHB in order to reach the dc-capacitor voltage balancing. The authors identified that the phase shift between current components ($\theta_{ipn} = \theta_i^- - \theta_i^+$) in the YCHB, and the phase shift between voltage components ($\delta_{vpn} = \delta_v^- - \delta_v^+$) in the DCHB have also an impact in the zero-sequence components to be injected. The results presented confirm the mentioned duality between the two configurations; the impact of k_{ipn} in the YCHB (when $k_{vpn} = 0$) is equivalent to the impact of k_{vpn} in the DCHB (when $k_{ipn} = 0$). Other authors led to similar conclusions [102], [103].

Even the duality between both configurations is interesting, comparing the YCHB and the DCHB STATCOMs in the same operating scenario is a fair approach. References [54], [81], [103] compared the two CHB-based circuit configurations under balanced voltage and unbalanced current conditions ($k_{vpn} = 0,\ k_{ipn} > 0$), which is a negative-sequence current withstanding scenario (see Fig. 5 (a)). In this application, the duality between the two configurations exposed previously is lost: the DCHB requires less I_0 than the V_0 demanded by an equivalent YCHB STATCOM for a certain ratio of current unbalance (k_{ipn}). This conclusion has motivated several authors to investigate the delta configuration for unbalanced load compensation [56], [104]. Some researchers also analyzed the DCHB STATCOM for LVRT purposes [57], [58].

3) MMC STATCOM UNDER UNBALANCED OPERATING CONDITIONS

Apart from CHB-based circuit configurations, the MMC is also considered an interesting alternative to operate in unbalanced scenarios as STATCOM [15]. Although the MMC needs twice as many power cells than CHB configurations to reach the same output voltage, it presents more degrees of freedom in its circulating current control strategy [50].

As with CHB structures, this paper deals with the ''intercluster active power balancing''. Since both the ''intracluster active power balancing'' [105] and the active power balancing between the upper and lower arms of the MMC need to be addressed regardless of whether it is an unbalanced scenario or not [106], they are not analyzed in this paper.

Equation (7) can be extended to the MMC, by including an additional average active power term ($\bar{P}^{\mathrm{MMC}}_{dc\text{-}ph}$):

$$\bar{P}_{ph} = \bar{P}^{++}_{ph} + \bar{P}^{--}_{ph} + \bar{P}^{+-}_{ph} + \bar{P}^{-+}_{ph} + \bar{P}^{\mathrm{MMC}}_{dc\text{-}ph} \tag{16}$$

Hagiwara and Akagi proposed a control method for the MMC STATCOM under unbalanced conditions [107]–[109], both theoretically and experimentally. In this approach, the circulating current control of the MMC introduces an internal dc voltage in each phase cluster ($v_{z\text{-}ph}$), which drives a dc circulating current ($i_{z\text{-}ph}$) with the aim of cancelling out the dc circulating current generated due to the non-zero average active power at each phase cluster (terms $\bar{P}^{+-}_{ph}$ and $\bar{P}^{-+}_{ph}$):

$$P^{\mathrm{MMC}}_{dc\text{-}ph} = v_{z\text{-}ph} \cdot i_{z\text{-}ph} = -\bar{P}^{+-}_{ph} - \bar{P}^{-+}_{ph} \tag{17}$$

In an equivalent manner to the zero-sequence injection in CHB configurations, by controlling i_z in each phase cluster of the MMC the active power can be redistributed among the phase clusters, and hence the charge of dc-link capacitors can remain adjusted to the reference value [110]–[119]. Considering that the arm inductance (L_{arm}) is almost purely inductive (see Fig. 2 (c)), the generated v_z is negligible under unbalanced conditions, and does not imply any de-rating.

Some technical papers can be found which compare CHB and MMC configurations for STATCOM application under unbalanced conditions. In [110], the authors analyze the capability of the YCHB, DCHB and MMC for compensating unbalanced loads or LVRT operation (see Fig. 5). The paper concludes that the MMC is the preferable option in the above mentioned scenarios. References [114], [119] compare the negative-sequence compensation capability between the MMC and the DCHB configuration in LVRT application. The authors concluded that the compensation capability of the MMC is higher than the DCHB, considering both are rated for the same output power (double total energy storage for the MMC). Finally, [59] compares the performances of the YCHB, DCHB and MMC for STATCOM in large-scale offshore WPPs, with special focus on LVRT capability under asymmetrical grid faults. This publication concludes that the full-bridge MMC is the most attractive structure por that purpose (with similar total cost and volume).

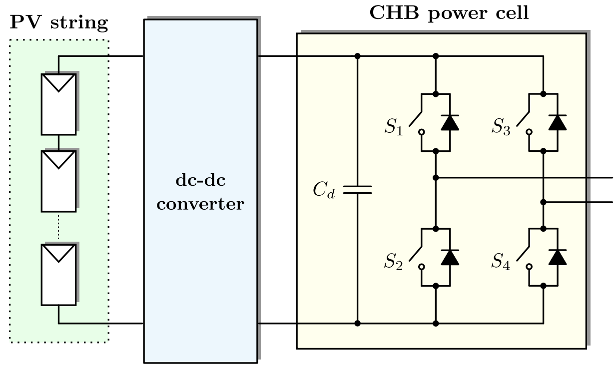

FIGURE 8. Scheme of a single-phase power cell connected to a PV string by a dc-dc converter.

Table 2 presents a classification (studied converter structures and typical unbalanced scenarios) of the most relevant references analyzed in Subsection IV-A for STATCOM application.

B. LARGE-SCALE PV POWER PLANTS UNDER UNBALANCED GENERATION

As mentioned in Subsection III-B, the CHB converter is one of the most attractive structures for large-scale PV integration [120]. The MMC is not commonly used in this type of applications. Fig. 8 illustrates the scheme of a single-phase CHB power cell connected to a PV string by a dc-dc converter. The dc-dc stage allows independent MPPT in order to maximize the power extraction from the PV string. CHB power cells can be cascaded, and then the three phase clusters can be connected either in star (Fig. 2 (a)), or in delta (Fig. 2 (b)).

During balanced operation, the PV power delivered to each CHB power cell is equal; thus, the active power in each of the three phase clusters of the converter is equal to the other two ($\bar{P}_{\mathrm{a}} = \bar{P}_{\mathrm{b}} = \bar{P}_{\mathrm{c}}$). In this scenario, the three-phase currents injected to the PCC will be balanced ($k_{ipn} = 0$). The converter is controlled to generate balanced phase cluster voltages ($k_{vpn} = 0$). As the aim of a PV power plant is to maximize the active power extraction, it operates with a power factor as close to the unity as possible ($\cos\phi \approx 1$).

However, the PV power generation levels in each power cell are unlikely to be equal, especially in a large geographically-dispersed power plant. Hence, the PV power delivered to each phase cluster of the CHB converter can

TABLE 2. Classification of multilevel VSCs based on modular structures for STATCOM application and typical unbalanced operating scenarios. The crosses (×) indicate which converter structure and scenario are discussed in each reference*.

Reference	Converter structure			Operating scenario		
	YCHB	DCHB	MMC	Negative-sequence current withstanding	Unbalanced load compensation	Low-voltage ride-through (LVRT)
[38], [85], [86], [88]	×				×	
[77], [82]–[84], [87], [90]–[95]	×					×
[96]		×		×		
[55], [56], [97]–[99], [104]		×			×	
[57], [58]		×				×
[53], [54], [78], [80], [81], [101], [103]	×	×		×		
[102]	×	×		×	×	
[79]	×	×				×
[111]–[113], [115]–[118]			×			×
[110]	×	×	×		×	
[114], [119]		×	×			×
[59]	×	×	×			×

*Authors of the papers may not necessarily use this terminology.

become unequal ($\bar{P}_a \neq \bar{P}_b \neq \bar{P}_c$). This uneven power generation in large-scale PV power plants involves an unbalanced current injection into the PCC ($k_{ipn} > 0$) [28]. Specific control strategies are thus needed so as to supply balanced three-phase currents to the power grid [9], [52]. This problem is analogous to the one recognized in the unbalanced operation of the STATCOM application, as seen in Subsection IV-A.

1) INTERCLUSTER ACTIVE POWER BALANCING IN LARGE-SCALE PV POWER PLANTS

The objective of the power balancing in large-scale PV power plants consists of delivering three-phase balanced currents to the power grid ($k_{ipn} = 0$), even with unbalanced PV power generation in each power cell. The required control is applied at two levels: 1) intercluster active power balancing, which is used when each phase cluster delivers a different amount of power; and 2) individual or intracluster active power balancing, which is applied when each power cell in the same phase cluster delivers a different amount of power [51]. This review covers the first one.

References [21], [22], [121] presented an intracluster power balancing technique of a CHB power cell-based single-phase converter for PV integration. These first approaches did not face the intercluster balancing. In 2012, Townsend [122] proposed the utilization of the technique introduced by Betz and Summers for dc-capacitor voltage balancing in a STATCOM [78]–[80] for PV applications: the *Fundamental-Frequency Zero-Sequence Injection*. This technique was called FFZSI by [123] for PV integration, and it is the same technique analyzed in Subsection IV-A.

The injected fundamental-frequency zero-sequence voltage (v_0) in the YCHB, expressed in (8), is able to rebalance the three-phase grid currents [9], even with an unbalanced three-phase PV power generation [122]–[126]. However, the FFZSI involves the increasing of the resultant converter output voltage, which can easily exceed the limit set by the dc side as the power unbalance increases. Once the voltage limit is reached, the converter saturates, and three-phase balanced grid currents cannot be guaranteed. The available dc-voltage can be increased by means of a voltage over-rating, which should not be the preferable option. Reference [127] proposes a converter topology that can avoid the zero-sequence injection by adjusting the active power which parallel connected dc-dc converters feed into each phase cluster. Henceforth, the references that followed this one tried to achieve both the maximum output ac voltage, and the intercluster active power balancing.

The *Weighted Min-Max* (WMM) zero-sequence voltage injection was proposed for the YCHB in [28], and implemented in [128]. The zero-sequence voltage is generated by using simple comparisons of weighted positive-sequence voltage references [129]. Nevertheless, in references [124], [130] it is stated that the WMM zero-sequence injection is not able to provide sufficiently accurate results since it synthesizes an incorrect fundamental-frequency zero-sequence component. Due to this fact, the system dynamic performance is reduced.

An effective method to improve the dc voltage utilization in a three-phase VSC is the third-harmonic injection (THI). Holmes and Lipo [131] deduced that a THI of 1/6 of the fundamental-frequency component achieves the highest ac output voltage without overmodulation (when $k_{vpn} = 0$).

TABLE 3. Classification of CHB configurations and zero-sequence injection methods for large-scale PV integration. The crosses (×) indicate which configuration and injection method are covered in each reference.

	Converter structure		Zero-sequence injection method							
Reference	YCHB	DCHB	FFZSI	SWZSI	WMM	DTHI	THSWI	RTHI	DMM	OSZI
[122], [125], [126]	×		×							
[133]–[135]	×	×	×							
[28], [128]	×				×					
[132]	×		×			×				
[51]	×					×		×	×	
[123], [130]	×									×
[124]	×		×		×	×			×	×
[129]	×	×	×	×	×	×	×			×

Based on this, Yu *et al.* [132] proposed to combine the optimal injection of the positive-sequence voltage with the optimal one of the zero-sequence:

$$v_0^{\mathrm{DTHI}}(t) = \underbrace{V_0 \sin(\omega t + \delta_{v_0})}_{v_0} + \underbrace{\frac{V_0}{6}\sin(3\omega t + 3\delta_{v_0})}_{v_{0_3}} + \underbrace{\frac{V^+}{6}\sin(3\omega t + 3\delta_v^+)}_{v_3^+} \tag{18}$$

The method is called *Double Third-Harmonic Injection* (DTHI). As (18) shows, in addition to the fundamental-frequency zero-sequence component (v_0) of (8), its third-harmonic component (v_{0_3}) and the third-harmonic component of the phase cluster positive-sequence voltage (v_3^+) are also injected. These two third-harmonic terms reduce the peak value of the resultant phase voltages without affecting the injected fundamental-frequency zero-sequence. In this manner, the power balancing capabilities are improved in comparison to the FFZSI [51], [124], [132]. The DTHI was also applied to extend the operating ranges of CHB STATCOMs under unbalanced current conditions [54].

The DTHI is derived considering that the overall optimal THI is equal to the sum of the optimal THI of its positive-sequence and its fundamental-frequency components ($v_{ph_3} \neq v_{0_3} + v_3^+$). However, this superposition principle does not apply in this situation. From this conclusion, an improvement of the DTHI was proposed: the *Reduced Third-Harmonic Injection* (RTHI) [51]. With this injection, the third-harmonic terms (v_{0_3} and v_3^+) are injected to the most vulnerable phase cluster so as to reduce its maximum voltage. If this injection increases the voltage of another phase cluster, the injection level is reduced from $1/6$; this is why it is called RTHI.

Very similar to WMM zero-sequence injection, the *Double Min-Max* (DMM) zero-sequence injection was proposed [51], [124] as another improvement of the DTHI. This method consists of injecting the derived min-max sequence of the positive-sequence as well as that of the required fundamental-frequency zero-sequence. Since the superposition principle can be applied by this injection, the separation of both min-max sequences is allowed [51].

Reference [129] proposed the *Square-Wave Zero-Sequence Injection* (SWZI) [131] for PV power balancing: an injection of a fundamental zero-sequence square wave $4/\pi$ times larger than its peak value. A combination of third-harmonic and square-wave was also proposed under the name *Third-Harmonic Square-Wave Injection* (THSWI) to further reduce the phase cluster peak reference voltage [129].

As [130] states, all the zero-sequence injection methods proposed by Yu *et al.* lacked of satisfying both conditions for the injection technique to be optimal: 1) its fundamental-frequency component should be equal to that of FFZSI; and 2) its harmonic component should make the converter output voltage peak as low as possible to avoid saturation. Thus, they proposed the method that would satisfy both conditions; the *Optimal Zero-Sequence Injection* (OZSI) [123], [124], [130]. This method extends the power balancing capabilities of the converter by making full use of the available voltage [130].

Comparative studies of the power balancing capabilities of zero-sequence injection methods proposed for large-scale PV integration by CHB structures are also a novel approach [51], [124], [129]. Table 3 classifies the zero-sequence injection methods analyzed.

2) COMPARISON OF YCHB AND DCHB FOR PV INTEGRATION

In order to address the phase cluster PV power balancing in a CHB converter, a zero-sequence voltage (YCHB) or a zero-sequence current (DCHB) must be added. Both of them (v_0 or i_0) are expected to increase as the power unbalance between phase cluster becomes more severe. This fact involves a converter over-rating in terms of voltage for the star case, and in terms of current for the delta one [133]. As in the field of STATCOM application, this has motivated some authors to individually analyze and compare the power balancing capabilities of the YCHB and DCHB.

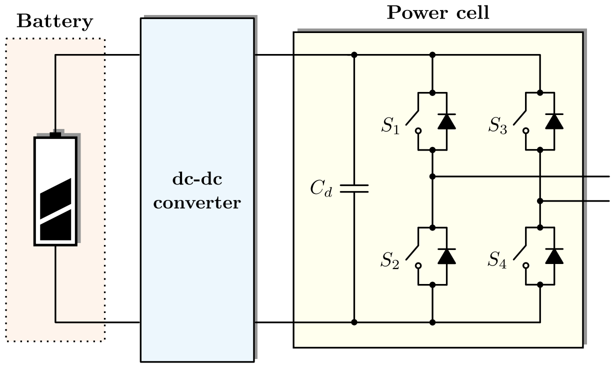

FIGURE 9. Scheme of a single-phase power cell connected to a battery by a dc-dc converter.

Most of the references focused on the FFZSI of the YCHB. The main drawback of this method is that the power balancing capability is limited by the available dc voltage in each phase cluster. Due to this fact, as seen in Subsection IV-A, some studies have extended slightly the operating range of the YCHB by means of injecting a wide variety of non-sinusoidal zero-sequence voltage components (see Table 3).

The DCHB configuration started to draw attention as a promising alternative for PV integration [129], [133]–[135]. As these references identify, the limiting factor in the delta case is the maximum phase cluster current that flows through each cascaded power cell. The p.u. zero-sequence current asked to the DCHB is smaller than the p.u. zero-sequence voltage asked to the YCHB for the same power unbalance scenario. This fact makes the DCHB superior to the YCHB. In the worst case-scenario (when zero power is delivered to one phase cluster while the other two generate the rated power), the DCHB converter needs around 15% of current over-rating so as to supply balanced currents. A bit of extra current rating on the phase cluster allows the DCHB to tolerate any level of power unbalance among phase clusters.

C. UNEQUAL ACTIVE POWER DISTRIBUTION IN BESS

Multilevel VSCs based on modular structures are a promising family for BESS [13], [15], [25], [136]–[141]. These structures are modular, and thus scalable to medium- and high-voltage levels, necessary for the high-power rating demanded by grid applications. Modular structures allow the distribution of energy storage units among the converter power cells. Fig. 9 shows the scheme of a single-phase power cell connected to a battery unit by a dc-dc converter.

Very similar to large-scale PV power plants, during balanced operation, all battery units absorb/deliver an equal active power. Thus, the active power is distributed equally among the three phase clusters ($\bar{P}_\mathrm{a} = \bar{P}_\mathrm{b} = \bar{P}_\mathrm{c}$). This means that the three-phase current absorbed/delivered from/to the PCC will be balanced ($k_{ipn} = 0$).

In the practical use of a BESS, an uneven active power distribution among multiple battery units and phase clusters is more usual ($\bar{P}_\mathrm{a} \neq \bar{P}_\mathrm{b} \neq \bar{P}_\mathrm{c}$), as a result of manufacturing tolerances, uneven temperature conditions or differences in ageing [142]. The intercluster active power balancing allows each of the three clusters to absorb or deliver an unequal active power without exchanging negative-sequence currents with the PCC [27]. This time the zero-sequence voltage or current has to be calculated in order to achieve the desired active power distribution among the phase clusters. This issue is also analogous to the unbalanced operation identified for STATCOM (see Subsection IV-A) and large-scale PV power (see Subsection IV-B) applications.

Maharjan and Akagi proposed the utilization of the YCHB converter for BESS [27], [142]–[144]. As these references state, the star configuration is preferable to the delta in this applications, so as to minimize the number of power cells connected in cascade. For phase cluster active power balancing, these papers applied the technique introduced by Betz and Summers for dc-capacitor voltage balancing in the unbalanced operation of the STATCOM [78]–[80]. The authors add a fundamental-frequency v_0 expressed in (8), in such a way as to absorb/deliver three-phase balanced current in spite of operating all the power cells at different power levels. Two philosophies are distinguished: 1) phase cluster voltage balancing control [142]–[144], which has the function of balancing the three mean dc voltages of the three phase clusters; and 2) phase cluster state-of-charge (SOC) balancing [27], which has the function of balancing the three mean SOC values of the three phase clusters. The latter provides more effective utilization of battery energy. But still, both methods allow unequal power distribution among three phase clusters, without causing any change in the line-to-line voltages; thus, balanced currents are absorbed/delivered. Reference [145] describes a SOC balancing-based real-scale YCHB BESS.

The dc circulating current between the phase clusters and the three-phase dc-link of the MCC is able to exchange active power among phase clusters. This current can be used to compensate the unequal power distribution in an MMC BESS. Hence, without affecting the converter output, the phase cluster SOC balancing can also be reached [146], [147]. That is, a dc portion of the circulating current can guarantee that all phase clusters present the same average SOC. Some references can be found which also face asymmetrical grid faults by the MMC BESS [148], [149]. Reference [150] proposed to integrate a RES with a BESS by an MMC. In this application, the circulating dc current facilitates the active power transfer between phase clusters and the three-phase dc-link, being able to cope with the fluctuating power generated by RES.

V. FUTURE CHALLENGES

Although several works focus on the operation of multilevel VSCs based on modular structures under unbalanced conditions, there still are some future challenges that, to the authors' knowledge, have not been covered in depth. This section collects the most important future research topics that have been identified in this study.

Either grid-connected or industry applications, STATCOMs are being asked for new operating scenarios which demand negative-sequence injection capability. Different converter structures have been proposed for that purpose, analyzing them mostly independently. As far as the authors of this paper know, the power de-rating applied to each structure as a result of the intercluster active power balancing has not been clearly evaluated and fairly compared. Besides, the unbalanced operating scenarios identified in some references do not correspond each other in the nomenclature. Another open point can be considered the injection of novel zero-sequence components proposed for PV integration in order to increase the STATCOM power rating.

With regard to large-scale PV integration, only CHB configurations have been analyzed in the specialized literature. The possible extension to the MMC structure has not been reported yet, which might be a promising research topic. Moreover, new grid codes may demand unbalanced voltage and/or currents in the PCC, in order to support an asymmetrical grid fault or LVRT. The analysis of unbalanced PV power generation during unbalanced PCC conditions is a key research topic for the future power grid.

The utilization of multilevel VSCs based on modular structures for BESS has not been so widely covered as STATCOM or PV applications. While large-scale PV integration aims to maximize the active power extraction, BESS need to supply/absorb active power depending on the application demands. It is remarkable that the DCHB configuration, which is a competitive solution for other unbalanced scenarios, has not been examined in BESS applications. Besides, even some references about the MMC have been found, the utilization of this structure has not been completely justified in the specialized literature.

VI. CONCLUSION

Multilevel VSCs based on modular structures are envisioned as essential components of the future power grid. Due to their modular and scalable features, enable high-output voltage with low-voltage inputs. Besides, unbalanced condition is a mandatory scenario that these structures must operate in different applications such as STATCOM, large-scale PV power plants, or BESS.

This paper performs a comprehensive review of the problems that the unbalanced operation in different applications suppose for multilevel VSCs based on modular structures, classifying the proposed intercluster active power balancing strategies, and identifying future challenges. The authors consider that this paper provides a proposal for researchers to develop further studies.

As main conclusion, an equivalency between the three analyzed applications can be arisen. In the same way, an equivalency between intercluster active power balancing techniques applied to the YCHB, DCHB and MMC can be found. However, the extrapolation of one scenario/technique/structure to another one is not completely covered in the specialized literature. Accordingly, a deeper research in this topic is considered necessary.

APPENDIX A

The instantaneous active power in each phase cluster of the power converter can be calculated by the inner product of the phase cluster voltage and current [44]:

$$p_{ph}(t) = v_{ph}(t) \cdot i_{ph}(t) \tag{A.1}$$

Assuming an unbalanced scenario, the converter phase cluster voltage can be expressed as

$$v_{ph}(t) = V^+ \sin\left(\omega t + \delta_v^+ + k\frac{2\pi}{3}\right) + V^- \sin\left(\omega t + \delta_v^- - k\frac{2\pi}{3}\right) \tag{A.2}$$

and the current as

$$i_{ph}(t) = I^+ \sin\left(\omega t + \theta_i^+ + k\frac{2\pi}{3}\right) + I^- \sin\left(\omega t + \theta_i^- - k\frac{2\pi}{3}\right) \tag{A.3}$$

where $k = 0, -1, 1$ for ph = a,b,c in the YCHB and the MMC, and for ph = ab,bc,ca in the DCHB, respectively. Applying the following trigonometric identity,

$$\sin\alpha \sin\beta = \cos(\alpha - \beta) - \cos(\alpha + \beta) \tag{A.4}$$

expression (A.1) can be developed:

$$\begin{aligned} p_{ph}(t) = &\underbrace{\frac{V^+I^+}{2}\cos\left(\delta_v^+ - \theta_i^+\right)}_{\bar{P}_{ph}^{++}} + \underbrace{\frac{V^+I^-}{2}\cos\left(\delta_v^+ - \theta_i^- + k\frac{4\pi}{3}\right)}_{\bar{P}_{ph}^{+-}} \\ &+ \underbrace{\frac{V^-I^+}{2}\cos\left(\delta_v^- - \theta_i^+ - k\frac{4\pi}{3}\right)}_{\bar{P}_{ph}^{-+}} + \underbrace{\frac{V^-I^-}{2}\cos\left(\delta_v^- - \theta_i^-\right)}_{\bar{P}_{ph}^{--}} \\ &- \underbrace{\frac{V^+I^+}{2}\cos\left(2\omega t + \delta_v^+ - \theta_i^+ + k\frac{4\pi}{3}\right)}_{\tilde{p}_{ph}^{++}} - \underbrace{\frac{V^+I^-}{2}\cos\left(2\omega t + \delta_v^+ + \theta_i^-\right)}_{\tilde{p}_{ph}^{+-}} \\ &- \underbrace{\frac{V^-I^+}{2}\cos\left(2\omega t + \delta_v^- + \theta_i^+\right)}_{\tilde{p}_{ph}^{-+}} - \underbrace{\frac{V^-I^-}{2}\cos\left(2\omega t + \delta_v^- - \theta_i^- - k\frac{4\pi}{3}\right)}_{\tilde{p}_{ph}^{--}} \end{aligned} \tag{A.5}$$

APPENDIX B

A. CONSTANT TERMS FOR THE ZERO-SEQUENCE VOLTAGE CALCULATION IN THE YCHB

$$\begin{aligned} K_1^{ph} &= V^+I^- \cos\left(\delta_v^+ - \theta_i^- + k\frac{4\pi}{3}\right) \\ &\quad + V^-I^+ \cos\left(\delta_v^- - \theta_i^+ - k\frac{4\pi}{3}\right) \\ K_2^{ph} &= I^+ \cos\left(\theta_i^+ + k\frac{2\pi}{3}\right) \\ &\quad + I^- \cos\left(\theta_i^- - k\frac{2\pi}{3}\right) \\ K_3^{ph} &= I^+ \sin\left(\theta_i^+ + k\frac{2\pi}{3}\right) \\ &\quad + I^- \sin\left(\theta_i^- - k\frac{2\pi}{3}\right) \end{aligned} \quad \text{(B.1)}$$

where $k = 0, -1, 1$ for $ph =$ a,b,c, respectively [53].

B. CONSTANT TERMS FOR THE ZERO-SEQUENCE CURRENT CALCULATION IN THE DCHB

$$\begin{aligned} K_1^{ph} &= V^+I^- \cos\left(\delta_v^+ - \theta_i^- + k\frac{4\pi}{3}\right) \\ &\quad + V^-I^+ \cos\left(\delta_v^- - \theta_i^+ - k\frac{4\pi}{3}\right) \\ K_2^{ph} &= V^+ \cos\left(\delta_v^+ + k\frac{2\pi}{3}\right) \\ &\quad + V^- \cos\left(\delta_v^- - k\frac{2\pi}{3}\right) \\ K_3^{ph} &= V^+ \sin\left(\delta_v^+ + k\frac{2\pi}{3}\right) \\ &\quad + V^- \sin\left(\delta_v^- - k\frac{2\pi}{3}\right) \end{aligned} \quad \text{(B.2)}$$

where $k = 0, -1, 1$ for $ph =$ ab,bc,ca, respectively [53].

REFERENCES

[1] *Going Climate-Neutral by 2050: A Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate-Neutral EU Economy*, European Comission, Brussels, Belgium, 2019.
[2] M. H. Nehrir, C. Wang, K. Strunz, H. Aki, R. Ramakumar, J. Bing, Z. Miao, and Z. Salameh, "A review of hybrid renewable/alternative energy systems for electric power generation: Configurations, control, and applications," *IEEE Trans. Sustain. Energy*, vol. 2, no. 4, pp. 392–403, 2011.
[3] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galván, R. C. P. Guisado, M. A. M. Prats, J. I. Leon, and N. Moreno-Alfonso, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1002–1016, Jun. 2006.
[4] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.
[5] H. Abu-Rub, M. Malinowski, and K. Al-Haddad, *Power Electronics for Renewable Energy Systems, Transportation and Industrial Application*. Hoboken, NJ, USA: Wiley, 2014.
[6] F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1184–1194, Sep. 2004.
[7] J. Rabkowski, D. Peftitsis, and H. P. Nee, "Silicon carbide power transistors: A new era in power electronics is initiated," *IEEE Ind. Electron. Mag.*, vol. 6, no. 2, pp. 17–26, Jun. 2012.
[8] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. G. Franquelo, B. Wu, J. Rodriguez, M. A. Pérez, and J. I. Leon, "Recent advances and industrial applications of multilevel converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2553–2580, Aug. 2010.
[9] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources With Associated Electric Power Systems Interfaces*, Standard 1547-2018, 2018.
[10] L. M. Tolbert and F. Z. Peng, "Multilevel converters as a utility interface for renewable energy systems," in *Proc. Power Eng. Soc. Summer Meeting*, Jul. 2000, pp. 1271–1274.
[11] S. Kouro, J. Rodriguez, B. Wu, S. Bernet, and M. Perez, "Powering the future of industry: High-power adjustable speed drive topologies," *IEEE Ind. Appl. Mag.*, vol. 18, no. 4, pp. 26–39, Jul. 2012.
[12] I. Marzo, J. A. Barrena, and A. Sanchez-Ruiz, "Methodology to evaluate converter structures based on 3L NPC PEBBs," in *Proc. IECON 46th Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2020, pp. 4107–4114.
[13] Y. Cheng, C. Qian, M. L. Crow, S. Pekarek, and S. Atcitty, "A comparison of diode-clamped and cascaded multilevel converters for a STATCOM with energy storage," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1512–1521, Oct. 2006.
[14] M. Malinowski, K. Gopakumar, J. Rodríguez, and M. A. Pérez, "A survey on cascaded multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 7, pp. 2197–2206, Jul. 2010.
[15] H. Akagi, "Classification, terminology, and application of the modular multilevel cascade converter (MMCC)," *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3119–3130, Nov. 2011.
[16] K. R. Padiyar and A. M. Kulkarni, "Modeling and analysis of FACTS and HVDC controllers," in *Dynamics and Control of Electric Transmission and Microgrids*. Hoboken, NJ, USA: Wiley, 2019, pp. 145–194.
[17] L. Gyugyi, "Reactive power generation and control by thyristor circuits," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 1976, pp. 174–184.
[18] Y. Sumi, Y. Harumoto, T. Hasegawa, M. Yano, K. Ikeda, and T. Matsuura, "New static VAR control using force-commutated inverters," *IEEE Trans. Power Appar. Syst.*, vol. PAS-100, no. 9, pp. 4216–4224, Sep. 1981.
[19] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components," *IEEE Trans. Ind. Appl.*, vol. IA-20, no. 3, pp. 625–630, May 1984.
[20] M. Zubiaga, A. Sanchez-Ruiz, E. Olea, E. Unamuno, A. Bilbao, and J. Arza, "Power capability boundaries for an inverter providing multiple grid support services," *Energies*, vol. 13, no. 17, pp. 1–14, 2020.
[21] E. Villanueva, P. Correa, J. Rodríguez, and M. Pacas, "Control of a single-phase cascaded H-bridge multilevel inverter for grid-connected photovoltaic systems," *IEEE Trans. Power Electron.*, vol. 56, no. 11, pp. 4399–4406, Nov. 2009.
[22] S. Kouro, B. Wu, A. Moya, E. Villanueva, P. Correa, and J. Rodriguez, "Control of a cascaded H-bridge multilevel converter for grid connection of photovoltaic systems," in *Proc. 35th Annu. Conf. IEEE Ind. Electron.*, Nov. 2009, pp. 3976–3982.
[23] A. I. Elsanabary, G. Konstantinou, S. Mekhilef, C. D. Townsend, M. Seyedmahmoudian, and A. Stojcevski, "Medium voltage large-scale grid-connected photovoltaic systems using cascaded H-bridge and modular multilevel converters: A review," *IEEE Access*, vol. 8, pp. 223686–223699, 2020.
[24] G. Wang, G. Konstantinou, C. D. Townsend, J. Pou, S. Vazquez, G. D. Demetriades, and V. G. Agelidis, "A review of power electronics for grid connection of utility-scale battery energy storage systems," *IEEE Trans. Sustain. Energy*, vol. 7, no. 4, pp. 1778–1790, Oct. 2016.
[25] S. K. Chaudhary, A. F. Cupertino, R. Teodorescu, and J. R. Svensson, "Benchmarking of modular multilevel converter topologies for ES-STATCOM realization," *Energies*, vol. 13, no. 13, pp. 1–22, 2020.
[26] J. P. Barton and D. G. Infield, "Energy storage and its use with intermittent renewable energy," *IEEE Trans. Energy Convers.*, vol. 19, no. 2, pp. 441–448, Jun. 2004.
[27] L. Maharjan, S. Inoue, H. Akagi, and J. Asakura, "State-of-charge (SOC)-balancing control of a battery energy storage system based on a cascade PWM converter," *IEEE Trans. Power Electron.*, vol. 24, no. 6, pp. 1628–1636, Jun. 2009.

[28] S. Rivera, B. Wu, S. Kouro, H. Wang, and D. Zhang, "Cascaded H-bridge multilevel converter topology and three-phase balance control for large scale photovoltaic systems," in *Proc. 3rd IEEE Int. Symp. Power Electron. Distrib. Gener. Syst. (PEDG)*, Jun. 2012, pp. 690–697.

[29] Y. Yang, F. Blaabjerg, and H. Wang, "Low-voltage ride-through of single-phase transformerless photovoltaic inverters," *IEEE Trans. Ind. Appl.*, vol. 50, no. 3, pp. 1942–1952, May/Jun. 2014.

[30] *Electromagnetic Compatibility (EMC)—Part 2-4: Environment—Compatibility Levels in Industrial Plants for Low-Frequency Conducted Disturbances*, document IEC 61000-2-4, 2004.

[31] P. Rodriguez, A. V. Timbus, R. Teodorescu, M. Liserre, and F. Blaabjerg, "Flexible active power control of distributed power generation systems during grid faults," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2583–2592, Oct. 2007.

[32] P. W. Hammond, "Medium voltage PWM drive and method," U.S. Patent 5 625 545 A, 1997, pp. 1–21. [Online]. Available: https://patents.google.com/patent/US5625545A/en

[33] P. W. Hammond, "A new approach to enhance power quality for medium voltage AC drives," *IEEE Trans. Ind. Appl.*, vol. 33, no. 1, pp. 202–208, Jan./Feb. 1997.

[34] A. Lesnicar and R. Marquardt, "An innovative modular multilevel converter topology suitable for a wide power range," in *Proc. IEEE Bologna Power Tech Conf.*, Jun. 2003, pp. 1–6.

[35] S. Allebrod, R. Hamerski, and R. Marquardt, "New transformerless, scalable modular multilevel converters for HVDC-transmission," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2008, pp. 174–179.

[36] R. Marquardt, "Modular multilevel converter: An universal concept for HVDC-networks and extended DC-bus-applications," in *Proc. Int. Power Electron. Conf. (ECCE ASIA)*, Jun. 2010, pp. 502–507.

[37] A. Nami, L. Jiaqi, F. Dijkhuizen, and G. D. Demetriades, "Modular multilevel converters for HVDC applications: Review on converter cells and functionalities," *IEEE Trans. Power Electron.*, vol. 30, no. 1, pp. 18–36, Jan. 2015.

[38] Q. Song and W. Liu, "Control of a cascade STATCOM with star configuration under unbalanced conditions," *IEEE Trans. Power Electron.*, vol. 24, no. 1, pp. 45–58, Jan. 2009.

[39] S. Du, A. Dekka, B. Wu, and N. Zargari, *Modular Multilevel Converters: Analysis, Control, and Applications*. Hoboken, NJ, USA: Wiley, 2018.

[40] M. A. Perez, S. Bernet, J. Rodriguez, S. Kouro, and R. Lizana, "Circuit topologies, modeling, control schemes, and applications of modular multilevel converters," *IEEE Trans. Power Electron.*, vol. 30, no. 1, pp. 4–17, Jan. 2015.

[41] J. Pou, S. Ceballos, G. Konstantinou, V. G. Agelidis, R. Picas, and J. Zaragoza, "Circulating current injection methods based on instantaneous information for the modular multilevel converter," *IEEE Trans. Ind. Electron.*, vol. 62, no. 2, pp. 777–788, Feb. 2015.

[42] M. Vasiladiotis, N. Cherix, and A. Rufer, "Impact of grid asymmetries on the operation and capacitive energy storage design of modular multilevel converters," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 6697–6707, Nov. 2015.

[43] *Technical Connection Rules for High-Voltage (VDE-AR-N 4120)*, Verband der Elektrotechnik Elektronik Informationstechnik (VDE), Bremen, Germany, 2018.

[44] H. Akagi, E. H. Watanabe, and M. Aredes, *Instantaneous Power Theory and Applications for Power Conditioning*. Hoboken, NJ, USA: Wiley, 2007.

[45] P. Rao, M. L. Crow, and Z. Yang, "STATCOM control for power system voltage control applications," *IEEE Trans. Power Del.*, vol. 15, no. 4, pp. 1311–1317, Oct. 2000.

[46] D. Soto and T. C. Green, "A comparison of high-power converter topologies for the implementation of FACTS controllers," *IEEE Trans. Ind. Electron.*, vol. 49, no. 5, pp. 1072–1080, Nov. 2002.

[47] M. Molinas, J. A. Suul, and T. Undeland, "Low voltage ride through of wind farms with cage generators: STATCOM Versus SVC," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1104–1117, May 2008.

[48] H. P. Mohammadi and M. T. Bina, "A transformerless medium-voltage STATCOM topology based on extended modular multilevel converters," *IEEE Trans. Power Electron.*, vol. 26, no. 5, pp. 1534–1545, May 2011.

[49] J. A. Barrena, L. Marroyo, M. Á. R. Vidal, and J. R. T. Apraiz, "Individual voltage balancing strategy for PWM cascaded H-bridge converter-based STATCOM," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 21–29, Jan. 2008.

[50] J. Li, G. Konstantinou, H. R. Wickramasinghe, and J. Pou, "Operation and control methods of modular multilevel converters in unbalanced AC grids: A review," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 7, no. 2, pp. 1258–1271, Jun. 2019.

[51] Y. Yu, G. Konstantinou, B. Hredzak, and V. G. Agelidis, "Power balance of cascaded H-bridge multilevel converters for large-scale photovoltaic integration," *IEEE Trans. Power Electron.*, vol. 31, no. 1, pp. 292–303, Jan. 2016.

[52] Y. Yang, P. Enjeti, F. Blaabjerg, and H. Wang, "Wide-scale adoption of photovoltaic energy: Grid code modifications are explored in the distribution grid," *IEEE Ind. Appl. Mag.*, vol. 21, no. 5, pp. 21–31, Sep./Oct. 2015.

[53] E. Behrouzian and M. Bongiorno, "Investigation of negative-sequence injection capability of cascaded H-bridge converters in star and delta configuration," *IEEE Trans. Power Electron.*, vol. 32, no. 2, pp. 1675–1683, Feb. 2016.

[54] O. J. K. Oghorada and L. Zhang, "Unbalanced and reactive load compensation using MMCC-based SATCOMs with third-harmonic injection," *IEEE Trans. Ind. Electron.*, vol. 66, no. 4, pp. 2891–2902, Apr. 2019.

[55] F. Z. Peng and J. Wang, "A universal STATCOM with delta-connected cascade multilevel inverter," in *Proc. IEEE 35th Annu. Power Electron. Spec. Conf.*, Jun. 2004, pp. 3529–3533.

[56] P.-H. Wu, H.-C. Chen, Y.-T. Chang, and P.-T. Cheng, "Delta-connected cascaded H-bridge converter application in unbalanced load compensation," *IEEE Trans. Ind. Appl.*, vol. 53, no. 2, pp. 1254–1262, Mar. 2017.

[57] Z. He, F. Ma, Q. Xu, Y. Chen, C. Li, M. Li, J. M. Guerrero, and A. Luo, "Reactive power strategy of cascaded delta-connected STATCOM under asymmetrical voltage conditions," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 5, pp. 784–795, Jun. 2017.

[58] P.-H. Wu, Y.-T. Chen, and P.-T. Cheng, "The delta-connected cascaded H-bridge converter application in distributed energy resources and fault ride through capability analysis," *IEEE Trans. Ind. Appl.*, vol. 53, no. 5, pp. 4665–4672, Sep. 2017.

[59] T. Tanaka, K. Ma, H. Wang, and F. Blaabjerg, "Asymmetrical reactive power capability of modular multilevel cascade converter based STATCOMs for offshore wind farm," *IEEE Trans. Power Electron.*, vol. 34, no. 6, pp. 5147–5164, Jun. 2019.

[60] Y. Peng, Y. Li, K. Y. Lee, Y. Tan, Y. Cao, M. Wen, Y. Shen, M. Zhang, and W. Li, "Coordinated control strategy of PMSG and cascaded H-bridge STATCOM in dispersed wind farm for suppressing unbalanced grid voltage," *IEEE Trans. Sustain. Energy*, vol. 12, no. 1, pp. 349–359, Jan. 2021.

[61] Z. Liu, B. Liu, S. Duan, and Y. Kang, "A novel DC capacitor voltage balance control method for cascade multilevel STATCOM," *IEEE Trans. Power Electron.*, vol. 27, no. 1, pp. 14–27, Jan. 2012.

[62] F. Z. Peng, J.-S. Lai, J. W. McKeever, and J. VanCoevering, "A multilevel voltage-source inverter with separate DC sources for static VAr generation," *IEEE Trans. Ind. Appl.*, vol. 32, no. 5, pp. 1130–1138, Sep./Oct. 1996.

[63] F. Z. Peng and J.-S. Lai, "Dynamic performance and control of a static VAr generator using cascade multilevel inverters," *IEEE Trans. Ind. Appl.*, vol. 33, no. 3, pp. 748–755, May 1997.

[64] Y. Liang and C. O. Nwankpa, "A new type of STATCOM based on cascading voltage-source inverters with phase-shifted unipolar SPWM," *IEEE Trans. Ind. Appl.*, vol. 35, no. 5, pp. 1118–1123, Sep. 1999.

[65] S. Sirisukprasert, A. Q. Huang, and J.-S. Lai, "Modeling, analysis and control of cascaded-multilevel converter-based STATCOM," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jul. 2003, pp. 2561–2568.

[66] C. K. Lee, J. S. K. Leung, S. Y. R. Hui, and H. S. H. Chung, "Circuit-level comparison of STATCOM technologies," *IEEE Trans. Power Electron.*, vol. 18, no. 4, pp. 1084–1092, Jul. 2003.

[67] C. Hochgraf and R. H. Lasseter, "Statcom controls for operation with unbalanced voltages," *IEEE Trans. Power Del.*, vol. 13, no. 2, pp. 538–544, Apr. 1998.

[68] C. A. C. Cavaliere, E. H. Watanabe, and M. Aredes, "Multi-pulse STATCOM operation under unbalanced voltages," in *Proc. IEEE Power Eng. Soc. Winter Meeting. Conf.*, Jan. 2002, pp. 567–572.

[69] N. I. A. Wahab, N. Mariun, A. Mohamed, and M. Mohamad, "Response of D-STATCOM under unbalanced voltage condition caused by SLG fault," in *Proc. Student Conf. Res. Dev. (SCOReD)*, Aug. 2003, pp. 395–400.

[70] G. Escobar, A. M. Stankovic, and P. Mattavelli, "An adaptive controller in stationary reference frame for D-StatCom in unbalanced operation," *IEEE Trans. Ind. Electron.*, vol. 51, no. 2, pp. 401–409, Apr. 2004.

[71] L. Xu, B. R. Andersen, and P. Cartwright, "VSC transmission operating under unbalanced AC conditions—Analysis and control design," *IEEE Trans. Power Del.*, vol. 20, no. 1, pp. 427–434, Jan. 2005.
[72] Y. Liu and F. L. Luo, "Trinary hybrid multilevel inverter used in STATCOM with unbalanced voltages," *IEE Proc.-Electr. Power Appl.*, vol. 152, no. 5, pp. 1203–1222, Sep. 2005.
[73] B. Blazic and I. Papic, "Improved D-StatCom control for operation with unbalanced currents and voltages," *IEEE Trans. Power Del.*, vol. 21, no. 1, pp. 225–233, Jan. 2006.
[74] K. Fujii, U. Schwarzer, and R. W. De Doncker, "Comparison of hard-switched multi-level inverter topologies for STATCOM by loss-implemented simulation and cost estimation," in *Proc. IEEE 36th Conf. Power Electron. Spec.*, Jun. 2005, pp. 340–346.
[75] K. Fujii, R. W. De Doncker, and S. Konishi, "A novel DC-link voltage control of PWM-switched cascade cell multi-level inverter applied to STATCOM," in *Proc. 14th IAS Annu. Meeting. Conf. Rec. Ind. Appl. Conf.*, Oct. 2005, pp. 961–967.
[76] H. Akagi, S. Inoue, and T. Yoshii, "Control and performance of a transformerless cascade PWM STATCOM with star configuration," *IEEE Trans. Ind. Appl.*, vol. 43, no. 4, pp. 1041–1049, Jul./Aug. 2007.
[77] N. Hatano and T. Ise, "A configuration and control method of cascade H-bridge STATCOM," in *Proc. IEEE Power Energy Soc. Gen. Meeting Convers. Del. Electr. Energy 21st Century*, Jul. 2008, pp. 1–8.
[78] R. Betz, T. Summers, and T. Furney, "Symmetry compensation using a H-bridge multilevel STATCOM with zero sequence injection," in *Proc. Conf. Rec. IEEE Ind. Appl. Conf. 41st IAS Annu. Meeting*, Oct. 2006, pp. 1724–1731.
[79] R. E. Betz and T. J. Summers, "Using a cascaded H-bridge STATCOM for rebalancing unbalanced voltages," in *Proc. 7th Int. Conf. Power Electron.*, Oct. 2007, pp. 1–6.
[80] T. Summers, R. E. Betz, and G. Mirzaeva, "Phase leg voltage balancing of a cascaded H-bridge converter based STATCOM using zero-sequence injection," in *Proc. 13th Eur. Conf. Power Electron. Appl.*, Sep. 2009, pp. 1–10.
[81] O. J. K. Oghorada and L. Zhang, "Analysis of star and delta connected modular multilevel cascaded converter-based STATCOM for load unbalanced compensation," *Int. J. Electr. Power Energy Syst.*, vol. 95, pp. 341–352, Feb. 2018.
[82] N. Hatano and T. Ise, "Control scheme of cascaded H-bridge STATCOM using zero-sequence voltage and negative-sequence current," *IEEE Trans. Power Del.*, vol. 25, no. 2, pp. 543–550, Apr. 2010.
[83] Y. Shi, B. Liu, Y. Shi, and S. Duan, "Individual phase current control based on optimal zero-sequence current separation for a star-connected cascade STATCOM under unbalanced conditions," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 2099–2110, Mar. 2016.
[84] H.-C. Chen, P.-H. Wu, C.-T. Lee, C.-W. Wang, C.-H. Yang, and P.-T. Cheng, "A flexible DC voltage balancing control based on the power flow management for star-connected cascaded H-bridge converter," *IEEE Trans. Ind. Appl.*, vol. 52, no. 6, pp. 4946–4954, Nov. 2016.
[85] D. Lu, J. Zhu, J. Wang, J. Yao, S. Wang, and H. Hu, "A simple zero-sequence-voltage-based cluster voltage balancing control and the negative sequence current compensation region identification for star-connected cascaded H-bridge STATCOM," *IEEE Trans. Power Electron.*, vol. 33, no. 10, pp. 8376–8387, Oct. 2018.
[86] W. Liu, X. Zhao, Q. Song, and X. Zhang, "Research on unbalance load compensation by cascaded STATCOM with star configuration," in *Proc. IECON 38th Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2012, pp. 734–738.
[87] K. Sano and M. Takasaki, "A transformerless D-STATCOM based on a multivoltage cascade converter requiring no DC sources," *IEEE Trans. Power Electron.*, vol. 27, no. 6, pp. 2783–2795, Jun. 2012.
[88] L. Tan, S. Wang, P. Wang, Y. Li, Q. Ge, H. Ren, and P. Song, "High performance controller with effective voltage balance regulation for a cascade STATCOM with star configuration under unbalanced conditions," in *Proc. 15th Eur. Conf. Power Electron. Appl. (EPE)*, Sep. 2013, pp. 1–10.
[89] M. Zhang and Q. Wang, "Implementation of a cascade D-STATCOM under unbalanced conditions," in *Proc. Int. Power Electron. Appl. Conf. Expo.*, Nov. 2014, pp. 788–793.
[90] C.-T. Lee, B.-S. Wang, S.-W. Chen, S.-F. Chou, J.-L. Huang, P.-T. Cheng, H. Akagi, and P. Barbosa, "Average power balancing control of a STATCOM based on the cascaded H-bridge PWM converter with star configuration," *IEEE Trans. Ind. Appl.*, vol. 50, no. 6, pp. 3893–3901, Nov. 2014.
[91] J. I. Y. Ota, Y. Shibano, N. Niimura, and H. Akagi, "A phase-shifted-PWM D-STATCOM using a modular multilevel cascade converter (SSBC)—Part I: Modeling, analysis, and design of current control," *IEEE Trans. Ind. Appl.*, vol. 51, no. 1, pp. 279–288, Jan. 2015.
[92] J. I. Y. Ota, Y. Shibano, and H. Akagi, "A phase-shifted PWM D-STATCOM using a modular multilevel cascade converter (SSBC)—Part II: Zero-voltage-ride-through capability," *IEEE Trans. Ind. Appl.*, vol. 51, no. 1, pp. 289–296, Jan. 2015.
[93] H. C. Chen, P. H. Wu, C. T. Lee, C. W. Wang, C. H. Yang, and P. T. Cheng, "Zero-sequence voltage injection for DC capacitor voltage balancing control of the star-connected cascaded H-bridge PWM converter under unbalanced grid," *IEEE Trans. Ind. Appl.*, vol. 51, no. 6, pp. 4584–4594, Dec. 2015.
[94] O. J. K. Oghorada and L. Zhang, "Control of a modular multilevel converter STATCOM for low voltage ride-through condition," in *Proc. IECON 42nd Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2016, pp. 3691–3696.
[95] Y. Neyshabouri, S. K. Chaudhary, R. Teodorescu, R. Sajadi, and H. Iman-Eini, "Improving the reactive current compensation capability of cascaded H-bridge based STATCOM under unbalanced grid voltage," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 1466–1476, Jun. 2020.
[96] M. Hagiwara, R. Maeda, and H. Akagi, "Negative-sequence reactive-power control by a PWM STATCOM based on a modular multilevel cascade converter (MMCC-SDBC)," *IEEE Trans. Ind. Appl.*, vol. 48, no. 2, pp. 720–729, Mar./Apr. 2012.
[97] S. Du, J. Liu, J. Lin, and Y. He, "Control strategy study of STATCOM based on cascaded PWM H-bridge converter with delta configuration," in *Proc. 7th Int. Power Electron. Motion Control Conf.*, Jun. 2012, pp. 345–350.
[98] S. Du, J. Liu, J. Lin, and Y. He, "A novel DC voltage control method for STATCOM based on hybrid multilevel H-bridge converter," *IEEE Trans. Power Electron.*, vol. 28, no. 1, pp. 101–111, Jan. 2013.
[99] M. Nieves, J. M. Maza, J. M. Mauricio, R. Teodorescu, M. Bongiorno, and P. Rodriguez, "Enhanced control strategy for MMC-based STATCOM for unbalanced load compensation," in *Proc. 16th Eur. Conf. Power Electron. Appl.*, Aug. 2014, pp. 1–10.
[100] S. Ouyang, J. Liu, and H. Chen, "Arm current stress reduction technique for a delta-connected solid state transformer using zero-sequence current injection," *IEEE Trans. Power Electron.*, vol. 36, no. 11, pp. 12234–12250, Nov. 2021.
[101] E. Behrouzian, M. Bongiorno, and H. Z. D. L. Parra, "Investigation of negative sequence injection capability in H-bridge multilevel STATCOM," in *Proc. 16th Eur. Conf. Power Electron. Appl.*, Aug. 2014, pp. 1–10.
[102] D. Basic, M. Geske, and S. Schroeder, "Limitations of the H-bridge multilevel STATCOMs in compensation of current imbalance," in *Proc. 17th Eur. Conf. Power Electron. Appl. (EPE ECCE-Eur.)*, Sep. 2015, pp. 1–10.
[103] U. Hameed, H. Sadiq, H. A. Khalid, M. U. Khan, and M. Ali, "Investigation of zero sequence injection method for balancing of multi-level Cascaded-H bridge inverter," in *Proc. Int. Conf. Comput., Electron. Electr. Eng. (ICE Cube)*, Nov. 2018, pp. 1–6.
[104] R. Luo, Y. He, and J. Liu, "Research on the unbalanced compensation of delta-connected cascaded H-bridge multilevel SVG," *IEEE Trans. Ind. Electron.*, vol. 65, no. 11, pp. 3439–3444, Mar. 2018.
[105] G. Liang, H. D. Tafti, G. G. Farivar, J. Pou, C. D. Townsend, G. Konstantinou, and S. Ceballos, "Analytical derivation of intersubmodule active power disparity limits in modular multilevel converter-based battery energy storage systems," *IEEE Trans. Power Electron.*, vol. 36, no. 3, pp. 2864–2874, Mar. 2021.
[106] G. A. Reddy and A. Shukla, "Circulating current optimization control of MMC," *IEEE Trans. Ind. Electron.*, vol. 68, no. 4, pp. 2798–2811, Apr. 2021.
[107] M. Hagiwara and H. Akagi, "Control and experiment of pulsewidth-modulated modular multilevel converters," *IEEE Trans. Power Electron.*, vol. 24, no. 7, pp. 1737–1746, Jul. 2009.
[108] M. Hagiwara, R. Maeda, and H. Akagi, "Theoretical analysis and control of the modular multilevel cascade converter based on double-star chopper-cells (MMCC-DSCC)," in *Proc. Int. Power Electron. Conf. (ECCE ASIA)*, Jun. 2010, pp. 2029–2036.
[109] M. Hagiwara, R. Maeda, and H. Akagi, "Negative-sequence reactive-power control by the modular multilevel cascade converter based on double-star chopper-cells (MMCC-DSCC)," in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2010, pp. 3949–3954.

[110] S. Du and J. Liu, "A brief comparision of series-connected modular topology in STATCOM application," in *Proc. IEEE ECCE Asia Downunder*, Jun. 2013, pp. 456–460.
[111] J.-W. Moon, C.-S. Kim, J.-W. Park, D.-W. Kang, and J.-M. Kim, "Circulating current control in MMC under the unbalanced voltage," *IEEE Trans. Power Del.*, vol. 28, no. 3, pp. 1952–1959, Jul. 2013.
[112] S. Li, X. Wang, Z. Yao, T. Li, and Z. Peng, "Circulating current suppressing strategy for MMC-HVDC based on nonideal proportional resonant controllers under unbalanced grid conditions," *IEEE Trans. Power Electron.*, vol. 30, no. 1, pp. 387–397, Jan. 2015.
[113] J.-W. Moon, J.-W. Park, D.-W. Kang, and J.-M. Kim, "A control method of HVDC-modular multilevel converter based on arm current under the unbalanced voltage condition," *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 529–536, Apr. 2015.
[114] C. Xu, K. Dai, X. Chen, and Y. Kang, "Unbalanced PCC voltage regulation with positive- and negative-sequence compensation tactics for MMC-DSTATCOM," *IET Power Electron.*, vol. 9, no. 15, pp. 2846–2858, Dec. 2016.
[115] Y. Liang, J. Liu, T. Zhang, and Q. Yang, "Arm current control strategy for MMC-HVDC under unbalanced conditions," *IEEE Trans. Power Del.*, vol. 32, no. 1, pp. 125–134, Feb. 2017.
[116] J. Wang, J. Liang, C. Wang, and X. Dong, "Circulating current suppression for MMC-HVDC under unbalanced grid conditions," *IEEE Trans. Ind. Appl.*, vol. 53, no. 4, pp. 3250–3259, Jul./Aug. 2017.
[117] G. Tsolaridis, E. Kontos, S. K. Chaudhary, P. Bauer, and R. Teodorescu, "Internal balance during low-voltage-ride-through of the modular multilevel converter STATCOM," *Energies*, vol. 10, no. 7, pp. 1–18, 2017.
[118] Z. Ou, G. Wang, and L. Zhang, "Modular multilevel converter control strategy based on arm current control under unbalanced grid condition," *IEEE Trans. Power Electron.*, vol. 33, no. 5, pp. 3826–3836, May 2018.
[119] A. F. Cupertino, J. V. M. Farias, H. A. Pereira, S. I. Seleme, and R. Teodorescu, "Comparison of DSCC and SDBC modular multilevel converters for STATCOM application during negative sequence compensation," *IEEE Trans. Ind. Electron.*, vol. 66, no. 3, pp. 2302–2312, Mar. 2019.
[120] V. Sridhar and S. Umashankar, "A comprehensive review on CHB MLI based PV inverter and feasibility study of CHB MLI based PV-STATCOM," *Renew. Sustain. Energy Rev.*, vol. 78, pp. 138–156, Oct. 2017.
[121] J. Chavarria, D. Biel, F. Guinjoan, C. Meza, and J. J. Negroni, "Energy-balance control of PV cascaded multilevel grid-connected inverters under level-shifted and phase-shifted PWMs," *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 98–111, Jan. 2013.
[122] C. D. Townsend, T. J. Summers, and R. E. Betz, "Control and modulation scheme for a cascaded H-bridge multi-level converter in large scale photovoltaic systems," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2012, pp. 3707–3714.
[123] Y. Yu, G. Konstantinou, B. Hredzak, and V. G. Agelidis, "Optimal zero sequence injection in multilevel cascaded H-bridge converter under unbalanced photovoltaic power generation," in *Proc. Int. Power Electron. Conf. (IPEC-Hiroshima ECCE ASIA)*, May 2014, pp. 1458–1465.
[124] Y. Yu, G. Konstantinou, C. D. Townsend, and V. G. Agelidis, "Comparison of zero-sequence injection methods in cascaded H-bridge multilevel converters for large-scale photovoltaic integration," *IET Renew. Power Gener.*, vol. 11, no. 5, pp. 603–613, Apr. 2017.
[125] R. P. Aguilera, P. Acuna, Y. Yu, G. Konstantinou, C. D. Townsend, B. Wu, and V. G. Agelidis, "Predictive control of cascaded H-bridge converters under unbalanced power generation," *IEEE Trans. Ind. Electron.*, vol. 64, no. 1, pp. 4–13, Jan. 2017.
[126] H. D. Tafti, A. I. Maswood, G. Konstantinou, C. D. Townsend, P. Acuna, and J. Pou, "Flexible control of photovoltaic grid-connected cascaded H-bridge converters during unbalanced voltage sags," *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6229–6238, Aug. 2018.
[127] C. D. Townsend, Y. Fu, G. Konstantinou, and V. G. Agelidis, "Cascaded H-bridge multilevel PV topology for alleviation of per-phase power imbalances and reduction of second harmonic voltage ripple," *IEEE Trans. Power Electron.*, vol. 31, no. 8, pp. 5574–5586, Aug. 2016.
[128] B. Xiao, L. Hang, J. Mei, C. Riley, L. M. Tolbert, and B. Ozpineci, "Modular cascaded H-bridge multilevel PV inverter with distributed MPPT for grid-connected applications," *IEEE Trans. Ind. Appl.*, vol. 51, no. 2, pp. 1722–1731, Mar./Apr. 2015.
[129] P. Sochor and H. Akagi, "Theoretical comparison in energy-balancing capability between star- and delta-configured modular multilevel cascade inverters for utility-scale photovoltaic systems," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 1980–1992, Mar. 2016.
[130] Y. Yu, G. Konstantinou, B. Hredzak, and V. G. Agelidis, "Power balance optimization of cascaded H-bridge multilevel converters for large-scale photovoltaic integration," *IEEE Trans. Power Electron.*, vol. 31, no. 2, pp. 1108–1120, Feb. 2016.
[131] D. G. Holmes and T. A. Lipo, *Pulse Width Modulation for Power Converters: Principles and Practice*. Hoboken, NJ, USA: Wiley, 2003.
[132] Y. Yu, G. Konstantinou, B. Hredzak, and V. G. Agelidis, "On extending the energy balancing limit of multilevel cascaded H-bridge converters for large-scale photovoltaic farms," in *Proc. Australas. Universities Power Eng. Conf. (AUPEC)*, Sep. 2013, pp. 1–6.
[133] Y. Yu, G. Konstantinou, C. D. Townsend, R. P. Aguilera, and V. G. Agelidis, "Delta-connected cascaded H-bridge multilevel converters for large-scale photovoltaic grid integration," *IEEE Trans. Ind. Electron.*, vol. 64, no. 11, pp. 8877–8886, Nov. 2017.
[134] P. Sochor and H. Akagi, "Energy-balancing control of a delta-configured modular multilevel cascade inverter for utility-scale photovoltaic systems," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2015, pp. 4706–4713.
[135] Y. Yu, G. Konstantinou, C. D. Townsend, R. P. Aguilera, B. Hredzak, and V. G. Agelidis, "Delta-connected cascaded H-bridge multilevel photovoltaic converters," in *Proc. IECON 41st Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2015, pp. 2229–2234.
[136] C. Qian and M. L. Crow, "A cascaded converter-based StatCom with energy storage," in *Proc. IEEE Power Eng. Soc. Winter Meeting. Conf.*, Jan. 2002, pp. 544–549.
[137] L. Baruschka and A. Mertens, "Comparison of cascaded H-bridge and modular multilevel converters for BESS application," in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2011, pp. 909–916.
[138] M. Schroeder, S. Henninger, J. Jaeger, A. Rašić, H. Rubenbauer, and H. Leu, "Integration of batteries into a modular multilevel converter," in *Proc. EPE 15th Eur. Conf. Power Electron. Appl.*, Sep. 2013, pp. 1–12.
[139] T. Soong and P. W. Lehn, "Evaluation of emerging modular multilevel converters for BESS applications," *IEEE Trans. Power Del.*, vol. 29, no. 5, pp. 2086–2094, Oct. 2014.
[140] W. Cao, Y. Xu, Y. Han, and B. Ren, "Comparison of cascaded multilevel and modular multilevel converters with energy storage system," in *Proc. IEEE 11th Conf. Ind. Electron. Appl. (ICIEA)*, Jun. 2016, pp. 290–294.
[141] E. Chatzinikolaou and D. J. Rogers, "A comparison of grid-connected battery energy storage system designs," *IEEE Trans. Power Electron.*, vol. 32, no. 9, pp. 6913–6923, Sep. 2017.
[142] L. Maharjan, T. Yamagishi, and H. Akagi, "Active-power control of individual converter cells for a battery energy storage system based on a multilevel cascade PWM converter," *IEEE Trans. Power Electron.*, vol. 27, no. 3, pp. 1099–1107, Mar. 2012.
[143] L. Maharjan, S. Inoue, and H. Akagi, "A transformerless energy storage system based on a cascade multilevel PWM converter with star configuration," *IEEE Trans. Ind. Appl.*, vol. 44, no. 5, pp. 1621–1630, Sep./Oct. 2008.
[144] L. Maharjan, T. Yamagishi, and H. Akagi, "Discussions on a battery energy storage system based on a cascade PWM converter with star configuration," in *Proc. Int. Power Electron. Conf. (ECCE ASIA)*, Jun. 2010, pp. 2043–2049.
[145] N. Kawakami, S. Ota, H. Kon, S. Konno, H. Akagi, H. Kobayashi, and N. Okada, "Development of a 500-kW modular multilevel cascade converter for battery energy storage systems," *IEEE Trans. Ind. Appl.*, vol. 50, no. 6, pp. 3902–3910, Nov./Dec. 2014.
[146] N. Li, F. Gao, T. Hao, Z. Ma, and C. Zhang, "SOH balancing control method for the MMC battery energy storage system," *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6581–6591, Aug. 2018.
[147] A. F. Cupertino, W. C. S. Amorim, H. A. Pereira, S. I. Seleme, Jr., S. K. Chaudhary, and R. Teodorescu, "High performance simulation models for ES-STATCOM based on modular multilevel converters," *IEEE Trans. Energy Convers.*, vol. 35, no. 1, pp. 474–483, Mar. 2020.
[148] L. Zhang, F. Gao, and N. Li, "Control strategy of MMC battery energy storage system under asymmetrical grid voltage condition," *Proc. Chin. J. Electr. Eng.*, vol. 2, no. 2, pp. 76–83, Dec. 2016.
[149] Q. Chen, R. Li, and X. Cai, "Analysis and fault control of hybrid modular multilevel converter with integrated battery energy storage system," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 5, no. 1, pp. 64–78, Mar. 2017.
[150] T. Soong and P. W. Lehn, "Internal power flow of a modular multilevel converter with distributed energy resources," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 4, pp. 1127–1138, Dec. 2014.

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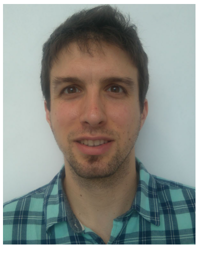

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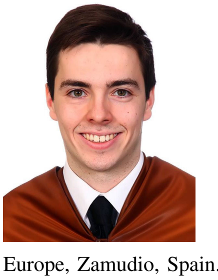

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