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# **Study of Applications of a Modular Multilevel SSBC Converter to a Distribution STATCOM and a Battery Energy Storage System**

**A DISSERTATION SUBMITTED TO  
THE DEPARTMENT OF ELECTRICAL AND ELECTRONIC  
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AND THE COMMITTEE ON GRADUATE STUDIES  
OF TOKYO INSTITUTE OF TECHNOLOGY  
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS  
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**By  
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# Abstract

This dissertation describes applications of a modular multilevel SSBC converter to a Distribution STATCOM (D-STATCOM) and a Battery Energy Storage System (BESS), both intended for installation on a 6.6-kV distribution power system. An SSBC-based D-STATCOM needs no step-down transformer, thus making it more compact and lightweight than a conventional D-STATCOM. An SSBC enables a BESS to have multiple low-voltage battery strings, thus improving its availability and reliability. A three-phase downscaled pulse-width modulated SSBC converter is design and constructed to verify the operation of a 140-V, 10-kVA, 50-Hz D-STATCOM and a 140-V, 10-kW, 21-kWh, 50-Hz BESS. Experimental results confirm both D-STATCOM and BESS operation when ac mains voltages are balanced and their ride-through capability against voltage sags, frequency deviations, and phase jumps.



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# Chapter 1

## Introduction

### 1.1 Background

The modern era of Power Electronics started in 1958 with the invention of the silicon-controlled rectifier (SCR), also known as the “thyristor,” by General Electric Company. In the 60’s and 70’s, the thyristor was put on the market by several manufacturers, thus spurring the substitution of mechanical and mercury-arc-based devices with silicon-based ones. Although the term “power electronics” was used amongst a part of electrical engineers and research scientists, it encompassed a wide range of disciplines related to electronics, power engineering, and control. In 1974, William E. Newell urged electrical engineers and research scientists to recognize and use the term “power electronics” as an emerging discipline in electrical engineering.

During the 80’s, the gate-turn off (GTO) thyristor started to substitute the SCR in power electronics applications. Developed in the 70’s, the GTO had the turn-off capability through its gate terminal. Such feature eliminated the need of complex circuits to perform forced-commutation, such as the McMurray inverter. In the 80’s, the invention of the insulated gate bipolar junction (IGBT) transistor become an important milestone on power electronics. It combined the bipolar current injection of the bipolar junction transistor (BJT) and the structure of the recently developed metal-oxide-semiconductor field-effect transistor (MOSFET) [1]. Following developments have enhanced the reliability and performance of the IGBT, making it a major element in power electronics

applications and in high-power medium-voltage power conversion systems .

The dawn of innovative technologies in semiconductor devices brought new possibilities for circuit topologies in applications of power electronics, or power conversion systems. The advance of the digital control, by the means of digital signal process (DSP) boards and field-programmable gate array (FPGA) technology, made it possible the implementation of novel and efficient strategies to drive complex power conversion systems. Applications have been extensively studied, allowing higher voltage and power ratings, improvements in performance and reliability, and the reduction of passive and magnetic components [2, 3]. Nowadays, power electronics is present in nearly every system that converts electricity in its different forms, ranging from watts to gigawatts [3, 4].

Wide-gap semiconductor devices, such as those based on silicon carbide (SiC) and gallium nitride (GaN), are expected to operate at higher frequencies and temperature. The use of such devices is expected to bring an increase on power density and overall system efficiency [5]. Emerging applications in unexplored fields have also spurred the development of new technologies [4]. In the context of crescent interest in renewable energy sources, power electronics have also drawn considerable attention. Power-electronics-based solutions are indispensable both to deliver electricity adequately and to ensure the power quality in electric power systems with a massive presence of renewable energy sources.

### 1.1.1 Renewable Sources and Grid Stability

The depletion of fossil fuels has spurred the interest of governments, power utilities and industries toward alternative energy sources. In addition, environmental agencies have urged governments to deal with the issue of global warming. Such factors turned in reality an enormous production of electricity by renewable energy sources around the globe. As an example, photovoltaics in Germany reached a nominal installed power capacity of 38.5 GW, and they have been responsible of generating around 34.9 TWh in 2014. This amount of electricity corresponded to approximately 6.5 % of the total annual production [6].

Fig. 1.1 shows the evolution of the cumulative installed capacity of wind-power genera-

tion and photovoltaics in the world [7,8]. In the beginning wind-power generation was the renewable energy source of choice due to its scalability and simple technology. Initially relegated for small-scale power generation, photovoltaics became prominent on electrical power systems in the mid-2000's. The ongoing trend moves toward utility-scale photovoltaics, where large-scale plants are connected to transmission and distribution power systems.

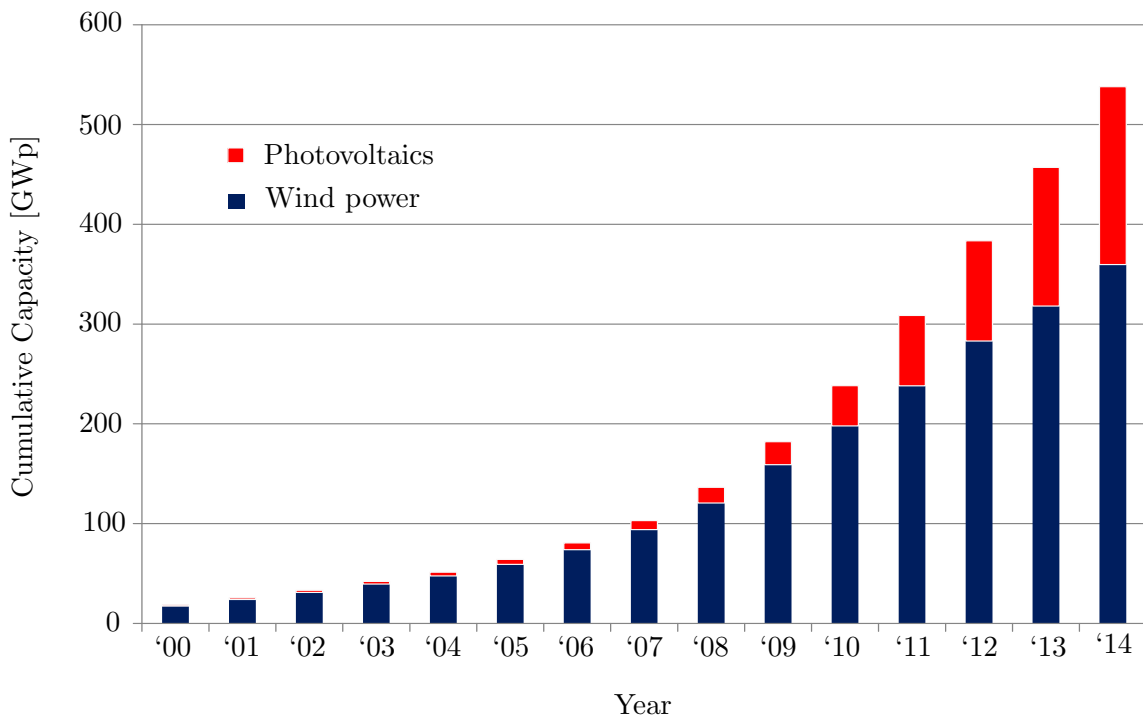


**Fig. 1.1:** Global cumulative installed capacity of wind-power generation and photovoltaics between 2000-2014 [7,8].

Massive penetration of wind-power generation and photovoltaics in electrical power systems have brought higher efficiency and flexibility to electricity generation. Nevertheless, such renewable energy sources produce electricity dependently of weather conditions, thus making their power profile to vary intermittently. In spite of this characteristic, methods for forecasting long-term generation of wind-power and photovoltaics can be applied to forecast the power variation. The installation of renewable energy sources in wide areas could also reduce variation of electricity generation [9].

However, concerns arise on the stability of the distribution power system when consid-

ering short-time range operation. The unbalancing among distribution feeders may result in a reverse power flow to a distribution substation that would jeopardize protection schemes of distribution power systems [10]. The intermittent electricity from renewable energy sources may bring voltage fluctuations and frequency deviations. Voltage fluctuations, mainly in the short-time range, can be expected in low-voltage distribution power systems with a high penetration of photovoltaics [10, 11]. Frequency deviations may increase when total installed power of renewable energy sources in a local system is high, because governor-based frequency regulation becomes less effective [12, 13].

### 1.1.2 Static Synchronous Compensator and Battery Energy Storage System in Distribution Power Systems

A static synchronous compensator (STATCOM) is a flexible and versatile FACTS<sup>1</sup> device that draws reactive power from a electric power system. A STATCOM intended for installation in a distribution power system, also referred as a distribution STATCOM (D-STATCOM), is suitable for reactive-power support in distribution feeder with high penetration of renewable energy sources. The STATCOM can provide reactive power compensation, voltage regulation, increase of transient stability, and support on voltage stability after faults occurrences.

Energy storage systems (ESS) have been pointed out as an essential solution for the supporting the installation of wind-power generation and photovoltaics by drawing active power from electric power system [11, 15, 16]. An ESS dealing with frequency compensation, reduction of power output oscillation, load leveling, peak shaving, and so on, becomes essential for supporting the penetration of renewable energy sources. Battery energy storage systems (BESS) have become the preferred option owing to its scalability, modularity, and compact size, which facilitates its construction and installation [17].

Fig. 1.2 shows equivalent single-phase diagrams of a D-STATCOM and of a BESS. Fig. 1.2(a) depicts a D-STATCOM connected to a tie line between the ac mains and an auxiliary bus. The D-STATCOM consists basically of a dc-to-ac power conversion system coupled to the line through an ac inductor or a transformer. The ultimate function is to

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<sup>1</sup>“FACTS” is an acronym for Flexible AC Transmission Systems [14].

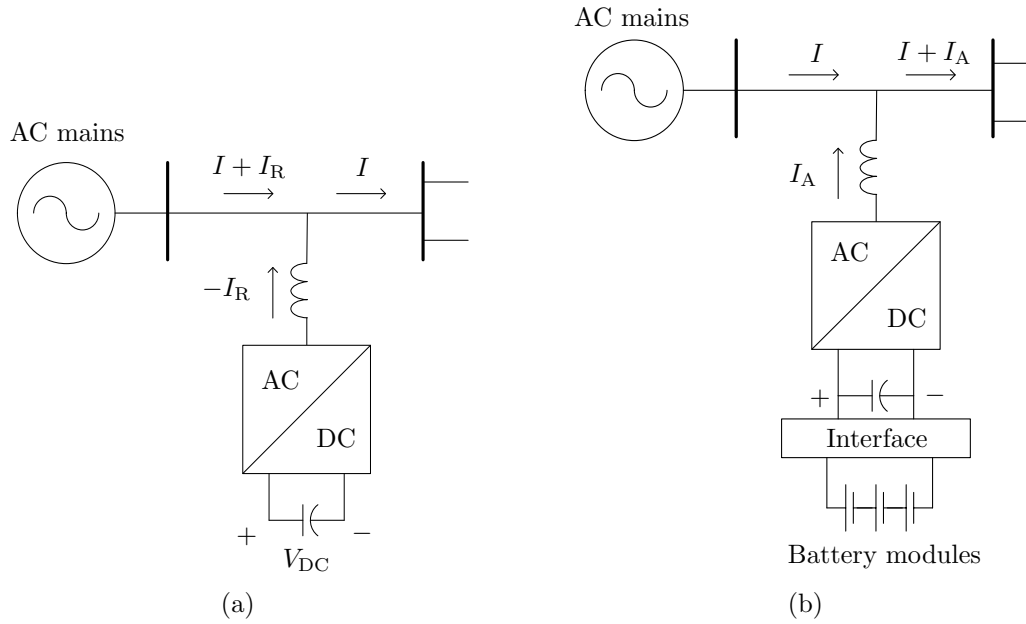


**Fig. 1.2: Basic functionality of a D-STATCOM and a BESS. (a) Distribution STATCOM. (b) Battery energy storage system.**

draw reactive currents from the tie line, thus allowing a increase on the transmitted power and support of the buses voltage [14]. An energy storage is theoretically not necessary on the dc-link of the power conversion system because the D-STATCOM only draws reactive power. Nevertheless, capacitors with a small unit capacitance value are used practically. Fig. 1.2(b) depicts a BESS shunt-connected to a tie line among the ac mains and an auxiliary bus. Similarly to the D-STATCOM, the BESS consists of a dc-to-ac power conversion system. On the other hand, because the BESS draws active power from the tie line, an energy storage system consisting of battery modules is connected to the dc-link. The choice of the interface between the battery storage unit and the dc-link depends on the power conversion system circuit configuration.

The present dissertation deals with the power conversion system of a D-STATCOM and of a BESS intend to installation on distribution power systems. Presently, multilevel converters are considered as the most promising circuit topology for medium-voltage and high-power applications in transmission and distribution power systems. The so-called “multilevel modular SSBC converter [18]” is a circuit topology of multilevel converter suitable solution for both D-STATCOM and BESS. A transformerless D-STATCOM can

be derived from the modular multilevel SSBC converter. Reduction on size and on weight can be achieved, thus making it possible the installation on electric poles directly. A BESS based in the modular multilevel SSBC converter has its batteries distributed in multiple low-voltage modules, thus resulting in a flexible, robust, and reliable solution.

## 1.2 Research Objectives

This dissertation describes applications of a modular multilevel cascade converter based on single-star bridge cells (MMCC-SSBC), or *modular multilevel SSBC converter* simply, to a distribution STATCOM (D-STATCOM) and a battery energy storage system (BESS), both intended for installation on a 6.6-kV distribution power system.

A three-phase downscaled phase-shifted-carrier pulse-width modulated (PWM) SSBC converter with a per-cluster cascade count of six ( $N = 6$ ) is designed and constructed to verify the operation of a 140-V, 10-kVA, 50-Hz D-STATCOM and a 140-V, 10-kW, 21-kWh, 50-Hz BESS. Experimental verification is performed to confirm operation of both D-STATCOM and BESS when ac mains voltages are balanced, and when they ride through voltage sags, frequency deviations, and phase jumps.

The present dissertation presents the following research ideas:

### ■ Improvement of SSBC current control through the “all-cells update” method:

The phase-shifted-carrier pulse-width modulation produces a time delay which affects the current control of the SSBC converter. A method based in multiple updates of a voltage reference called “all-cells update” method can be applied, which improves the current control performance considerably.

### ■ Improvement of cluster-balancing control of the D-STATCOM through a

**mean-average filter (MAF):** The SSBC-based D-STATCOM yields a 100-Hz oscillating component on its dc capacitor voltages intrinsically, which affects the cluster-balancing control. A moving-average filter (MAF) can be applied instead of a conventional low-pass filter (LPF) for mitigating the oscillating component, thus improving the cluster-balancing control considerably.

- **Improvement of availability and flexibility of the BESS by increasing number of low-voltage battery modules:** A high number of low-voltage battery modules in a SSBC-based BESS can actually increase the overall system reliability, because the SSBC can still operate even when a failure of a single or more battery module occurs. A proper design can yield a choice of the number of battery modules per cluster and the terminal voltage of a battery module to achieve the desirable system availability.
- **Capability of D-STATCOM and BESS to ride-through voltage sags, phase jumps and frequency oscillations:** As the D-STATCOM and the BESS are connected to a actual distribution power system, they are subjected to the occurrence of voltage sags, phase jumps and frequency oscillations. The capability to ride through these occurrences is highly desirable.

## 1.3 Thesis Organization

- ◆ **Chapter 1** is the present chapter. It introduces the background and motivation of this research. Massive penetration of renewable energy sources have spurred concerns on the stability of distribution power systems. D-STATCOMs and BESS are expected to play an important role of regulating voltage oscillations and frequency deviations caused by the electricity mismatches between supply and demand. This motivates the author to study both applications to a 6.6-kV distribution power system.
- ◆ **Chapter 2** presents a brief literature review of multilevel converters, D-STATCOMs and BESSs. Multilevel converters have attracted considerable attention of power electronics engineers and researchers for high-power medium-voltage applications. Applications of such converters to D-STATCOM and BESS are revisited in this chapter. Moreover, requirements related to ride-through capability are presented and discussed.
- ◆ **Chapter 3** describes the SSBC-based D-STATCOM and BESS, and the experimental downscaled model with a per-cluster cascade count of  $N = 6$  used for experiments is

presented. This chapter also described the current control of the SSBC when using phase-shifted-carrier PWM, which is applicable to both D-STATCOM and BESS.

- ◆ **Chapter 4** describes the control strategies and operation of the D-STATCOM based on the SSBC converter. Attention is paid to the improvement of the cluster-balancing control. The MAF has a better performance in eliminating the 100-Hz component from the capacitor voltages than a LPF-based method.
- ◆ **Chapter 5** reviews the control strategies and operation of the BESS based on the SSBC converter. Attention is paid to the enhanced reliability achieved by using multiple low-voltage battery modules. Moreover, a simple method of power estimation is presented to implement the active-power control of individual cells without the use of dc current sensors.
- ◆ **Chapter 6** finally presents experimental verification of the ride-through capability of both D-STATCOM and BESS. Results showed that both applications not only have ZVRT capability, but they can also ride through frequency deviations and phase jumps.
- ◆ **Chapter 7** summarizes the dissertation contents and lists further research on the topic of the SSBC converter applied to D-STATCOM and BESS.

# Chapter 2

## Literature Review

### 2.1 Introduction

The present chapter presents a literature review on applications of multilevel converters to D-STATCOM and BESS. Firstly, a brief historic review of the most prominent topologies of multilevel converters is made. The chapter then discusses the D-STATCOM and BESS based on conventional topologies and on multilevel converters. The chapter finishes with a discussion of the ride-through capability of the two applications. Focus is given on the occurrences of voltage sags, frequency deviations and phase jumps on distribution power systems.

### 2.2 Multilevel Converters for Medium Voltage Applications

Fig. 2.1 shows a single-leg circuit of a three-phase two-level inverter and line-to-neutral voltage waveform. The two-level inverter is the most commonly used topology in medium-voltage industrial and power utilities applications. Fig. 2.1(a) shows a single-leg of a three-phase two-level inverter with series-connected switching devices. Currently, high-power valves consisting of series-connected devices are used to overcome the existing limitations of blocking voltage. Nevertheless, snubber circuits should be used to equal the voltage applied in each series-connected device [19]. Fig. 2.1(b) shows a two-level voltage

waveform observed on the ac terminals. The high-voltage excursion on the ac terminals brings a considerable voltage stress on the switching devices, and bulky passive filters are necessary in order to mitigate the voltage harmonics.

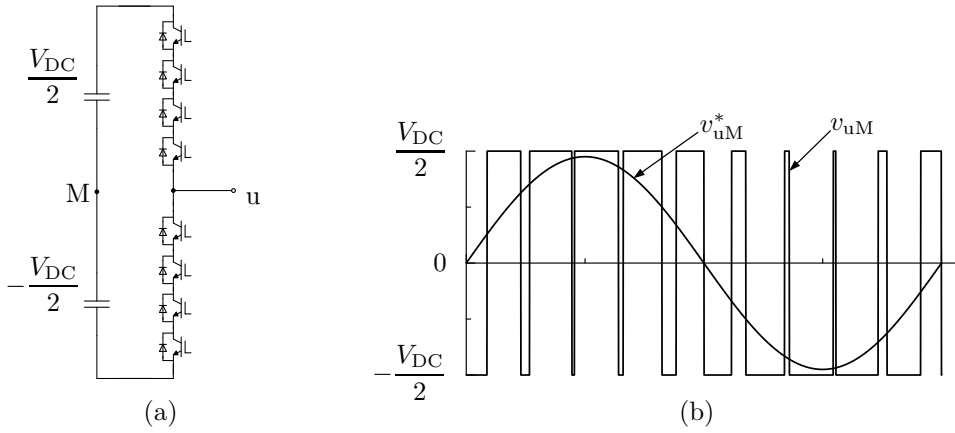


**Fig. 2.1: Two-level inverter. (a) Single-leg of a three-phase two-level inverter. (b) Line-to-neutral voltage on ac terminals.**

The so-called “multilevel converters,” or “multilevel inverters,” have as main characteristic the synthesis of a voltage waveform with small dc voltage levels. They evolved from the need of achieving a high quality voltage waveform on the converter ac terminals. The synthesized voltage waveforms by a multilevel converter yields considerably less harmonic content when compared to that of a typical two-level voltage source.

The invention of the three-level neutral-pointed clamped (NPC) inverter by Nabae *et al.* in the 80’s spurred the interest for multilevel converters [20]. Since then, new developments on topologies have been proposed and research by power electronics engineers and researchers. The so-called “flying capacitor multilevel inverter” or “capacitor-clamped inverter” was presented in 1992 by Meynard *et al.* [21,22]. In 1995, Peng *et al.* presented the so-called “cascaded multilevel inverter” applied to a static VAR compensator [23,24]. The “cascaded multilevel inverter” was based on the cascade connection of multiple basic modules consisting of a bridge cell circuit.

This section briefly revises the neutral-point clamped and the flying-capacitor multilevel inverters, and then describes the “modular multilevel cascade converters (MMCC)” circuit classification made for topologies that uses the cascade connection of basic modules.

### 2.2.1 Neutral-Point Clamped Inverter

Fig. 2.2 shows the neutral-point clamped (NPC) inverter presented by Nabae *et al.* in 1981 [20]. Other nomenclature is the “diode-clamped multilevel inverter,” which pays attention on how the voltage-clamping characteristic is achieved [25]. This circuit is also known as “three-level inverter” because its terminals produce a PWM voltage that ranges between  $V_{DC}$  and 0 V, and between 0 V and  $-V_{DC}$ . The NPC is widely credited by researchers and engineers as the stem of multilevel converters.

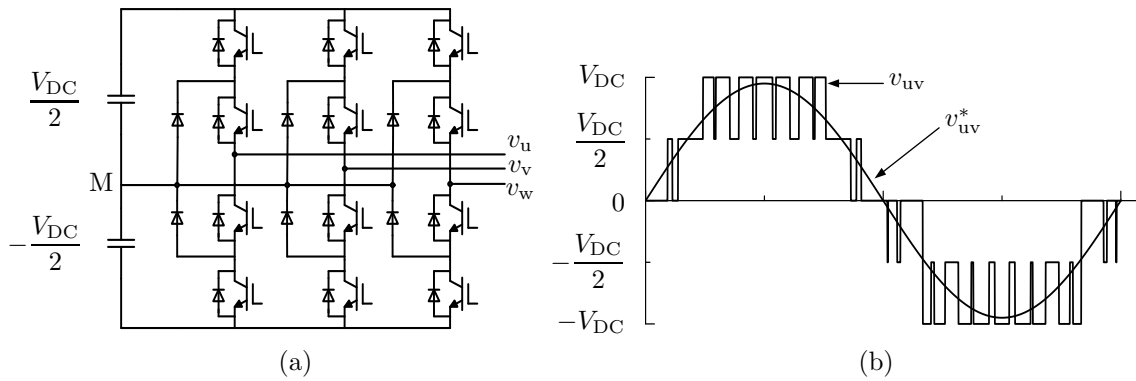


**Fig. 2.2:** Neutral-point clamped inverter. (a) Circuit of a three-phase three-level NPC inverter. (b) Line-to-line voltage on ac terminals.

Fig. 2.2(a) shows a three-phase three-level NPC inverter and Fig. 2.2(b) shows typical voltage waveforms. Note that Fig. 2.2(b) shows a line-to-line waveform consisting of five voltage levels. The multilevel voltage waveforms have less harmonic content than a conventional two-level inverter [20, 26]. The NPC inverter has some disadvantages when compared to other circuit topologies. A voltage imbalance appears among the dc capacitors for a number of levels higher or equal to four. The topology also needs a high number of clamping diodes, and brings an unequal loss distribution among switching devices. Nevertheless, the three-level NPC inverter has been widely adopted and applied to high-power and medium-voltage applications, such as motor drive and grid connected applications.

### 2.2.2 Flying Capacitor Inverter

Fig. 2.3 shows the flying, or floating, capacitor inverter proposed by Meynard *et al.* [21]. It is also referred as “capacitor-clamped multilevel inverter,” because the voltage-clamping characteristic is achieved by floating capacitors located among the switching devices [25]. Self-balancing of capacitor voltages is achievable when proper modulation and control methods are used [27, 28].

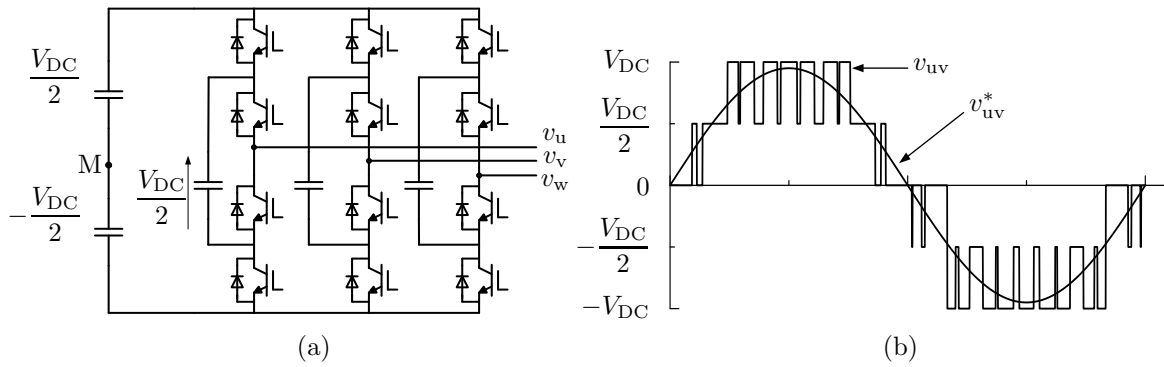


**Fig. 2.3: Flying capacitor inverter. (a) Circuit of three-phase three-level flying capacitor inverter. (b) Line-to-line voltage on ac terminals.**

Fig. 2.3(a) shows a three-phase three-level flying capacitor inverter and Fig. 2.3(b) shows typical voltage waveforms. Note that Fig. 2.3(b) shows a five-level line-to-line voltage waveform. Ideally, the flying capacitor inverter would produce a voltage waveform similar to that of the NPC inverter [21].

The flying capacitor inverter has been applied mainly to motor drive in industrial and traction applications [29]. Nevertheless, it needs a considerable number of clamping capacitors, and high capacitance values should be used when the switching frequency is low. Another disadvantage is related to parasitic components when switching frequency is very high. Moreover, it has been showed that the flying capacitor inverter loses its self-balancing characteristic when only reactive power is drawn from its ac terminals, thus restricting its applications [30–32].

### 2.2.3 Modular Multilevel Cascaded Converters

Modular multilevel cascade converters have gained considerable attention among power electronics engineers and researchers in the 90's. Fig. 2.4 shows a single-leg circuit of a three-phase five-level cascade converter [23, 24]. The cascade converter consists on series connections of individual basic modules. Fig. 2.4(a) shows a cascade connection of two basic modules consisting of H-bridge circuits. Nevertheless, different circuits can be used as basic modules [33]. Fig. 2.4(b) shows the line-to-neutral voltage waveforms.

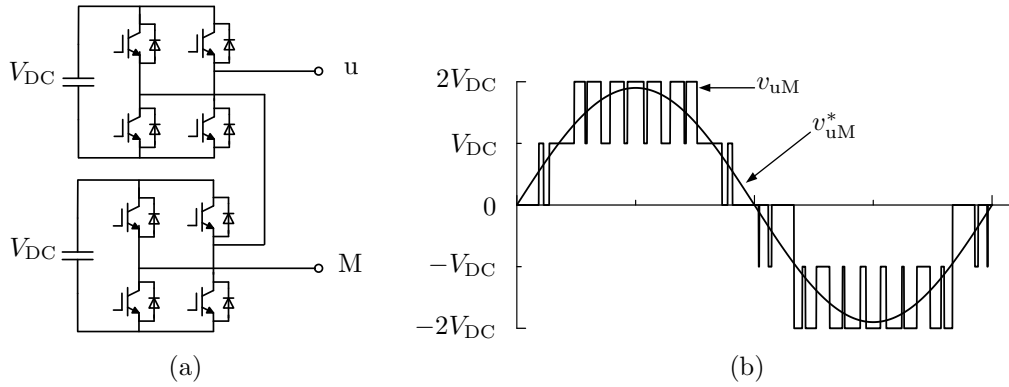


**Fig. 2.4: Basic configuration of a cascaded converter [24]. (a) Single leg of a three-phase five-level cascaded converter. (b) Line-to-neutral voltage on ac terminals.**

In 1995, Peng and Lai [23] presented a STATCOM based on the cascaded connection of full-bridge modules. Initially known as “cascaded multilevel inverter (CMI),” the topology is often referred as the “cascade H-bridge inverter.” In 1997, Robicon Corporation presented a motor drive consisting on a cascade connection of H-bridges and a multiwinding transformer that feed each H-bridge through three-phase diode rectifiers. Both inventions have patents granted in 1997 [34, 35]. Until then the concept of “modular” and “multilevel” converters was named by researchers engaging in applications related to plasma engineering [36–38]. In 2003, Lesnicar and Marquardt proposed the so-called “modular multilevel converter (MMC),” and then this concept was later extended by Glinka and Marquadt in [39]. Initially aimed to HVDC applications, the MMC was then extended to other high-power medium-voltage applications, such as motor drives and BTB systems.

As the CMI and the MMC gained more popularity, power electronics engineers and

researches engaged in exploring possibilities of the circuit modularity for synthesizing multilevel waveforms. Manjrekar *et al.* proposed the use of asymmetrical dc sources for the cascade multilevel inverter [40,41]. Teodorescu *et al.* presented a motor drive consisting of three-phase inverters instead of full-bridge modules [42]. Steimer *et al.* [43] and Veenstra *et al.* [44] proposed hybrid topologies of modular multilevel converters for motor drives. Recently, a novel circuit configuration called “Hexverter” intended to ac-to-ac power conversion was proposed by Baruschka and Mertens [45], and experimental verification of a loop-power-flow-controller application was presented by Tsuruta *et al.* [46]. Moreover, other commercially-available applications followed the launch of the motor drive launched by Robicon Corporation [47]. Siemens AG have presented HVDC applications based on the MMC [48–50], and a STATCOM based on a CMI [51]. Alston have presented solutions for grid-connected applications based on modular multilevel converters as well [52,53].

### Classification and Terminology of MMCC family

As the CMI and MMC become more prominent as a solution for high-power medium-voltage applications, technical papers related on “multilevel inverters” have been published and commercial solutions for high-power medium-voltage converters have been launched. However, the terms “multilevel converters,” “multilevel inverters,” or “cascaded multilevel converters” can refer to an wide range of circuit configurations. For example, even though the multilevel inverter proposed by Marquadt [33] was named as “modular multilevel converter,” the same term could be perfectly applied to the “Robicon inverter [47]” because its circuit configuration consists of cascade connection of multiple modules with a low-voltage rating basically. Moreover, companies and industries have their own nomenclature as trademarks. Nevertheless, the use of specific commercial names may cause confusion to engineers and researchers engaging in the multilevel converters.

Fig. 2.5 shows a classification for modular multilevel cascaded converters (MMCC) proposed by Akagi [18] and extended by Kawamura *et al.* [54]. Figs. 2.6–2.8 show the circuit configurations. This classification identifies each member of the MMCC family by grouping them accordingly to their circuit configuration and their basic modular cell.

This terminology is then adopted by the author of this dissertation.

Modular Multilevel Cascaded Converter (MMCC) Family.

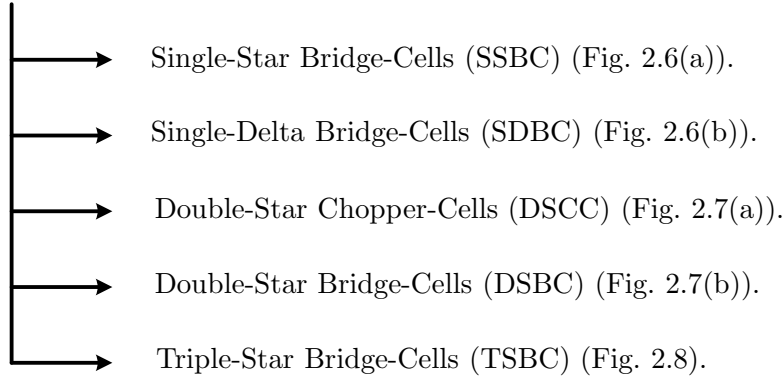


**Fig. 2.5: Classification of the MMCC circuit family proposed by Akagi [18] and extended by Kawamura *et al.* [54].**

Fig. 2.6(a) shows the modular multilevel cascade converter based on single-star bridge cells or a modular multilevel SSBC converter, while Fig. 2.6(b) shows the modular multilevel cascade converter based on single-delta bridge cells or a modular multilevel SDBC converter. The reason for naming is that the SSBC and SDBC converters are characterized by a star- and a delta-connection among its three clusters, respectively. Here, note that the term “cluster” refers to a string of series-connected bridge-cells, as it is done in [18].

Firstly presented by Peng *et al.* in [23] and [24], both SSBC and SDBC converters are also referred in the literature as “cascade H-bridge inverter” or “cascade multilevel inverter.” The SSBC and SDBC have three-phase ac terminals, which make them suitable to grid-connected applications, such as STATCOMs and battery energy storage systems (BESS). The SSBC can add a common zero-sequence voltage to the each cluster voltage that can be used for voltage-balancing control of dc capacitors of a STATCOM [55] and for SOC-balancing control of battery modules of a BESS [56]. Analogously, a common circulating current flows among the clusters of the SDBC, making it suitable to STATCOMs that compensate negative-sequence currents [57]. The three-ac-terminals configuration makes the SSBC and SDBC not suitable to motor drives a priori, but exceptions are applicable when multiple dc sources are available as presented by Tolbert *et al.* [58] and

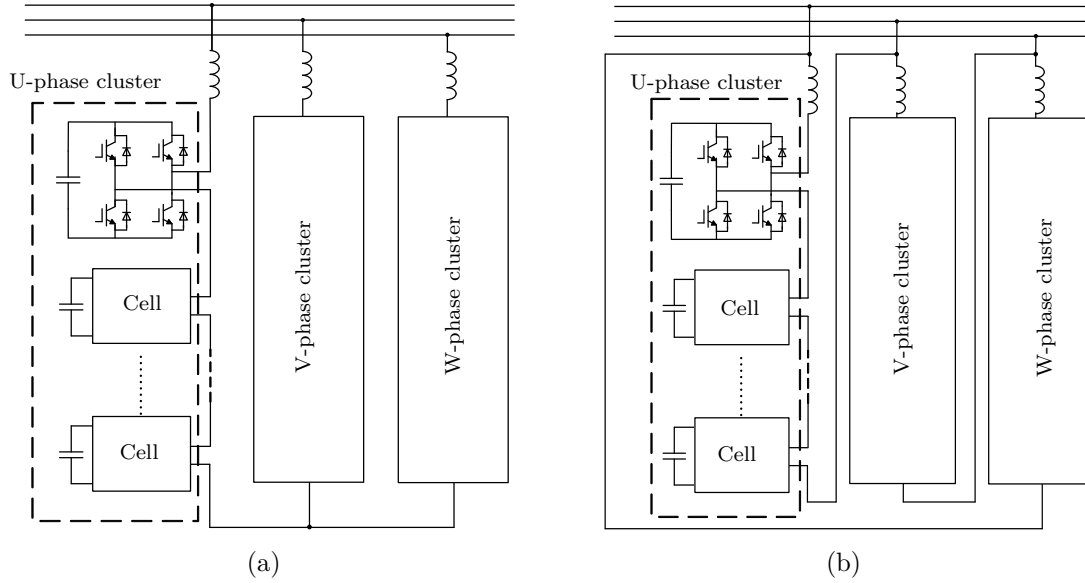


**Fig. 2.6: Two members of MMCC family. (a) The modular multilevel SSBC converter. (b) The modular multilevel SDBC converter.**

Hammond [47].

Fig. 2.7(a) shows the modular multilevel cascade converter based on double-star chopper cells or a modular multilevel DSCC converter, while Fig. 2.7(b) shows the modular multilevel cascade converter based on double-star bridge cells or a modular multilevel DSBC converter. Both converters are also known as “modular multilevel converters,” being the DSCC presented firstly in [33], and then extended to the DSBC by the authors of [39]. They can be visualized as two sets of star-connected SSBC-based circuits. As for the DSCC, the low-voltage side of multiple bidirectional chopper cells are series-connected in one arm, while the ac side of bridge cells are series-connected to form one arm in the DSBC.

Apart from the three-phase ac terminals, the DSCC and DSBC have a two-line terminal resulting from the star-connected points. This makes both converters suitable to a motor drive, because this terminal can connect to a dc voltage supply. Although Fig. 2.7 depicts the use of a single ac inductor in each arm, both DSCC and DSBC with coupled buffer inductors have advantages when applied to motor drives [18].

Other important feature of the DSCC and DSBC is the presence of circulating currents

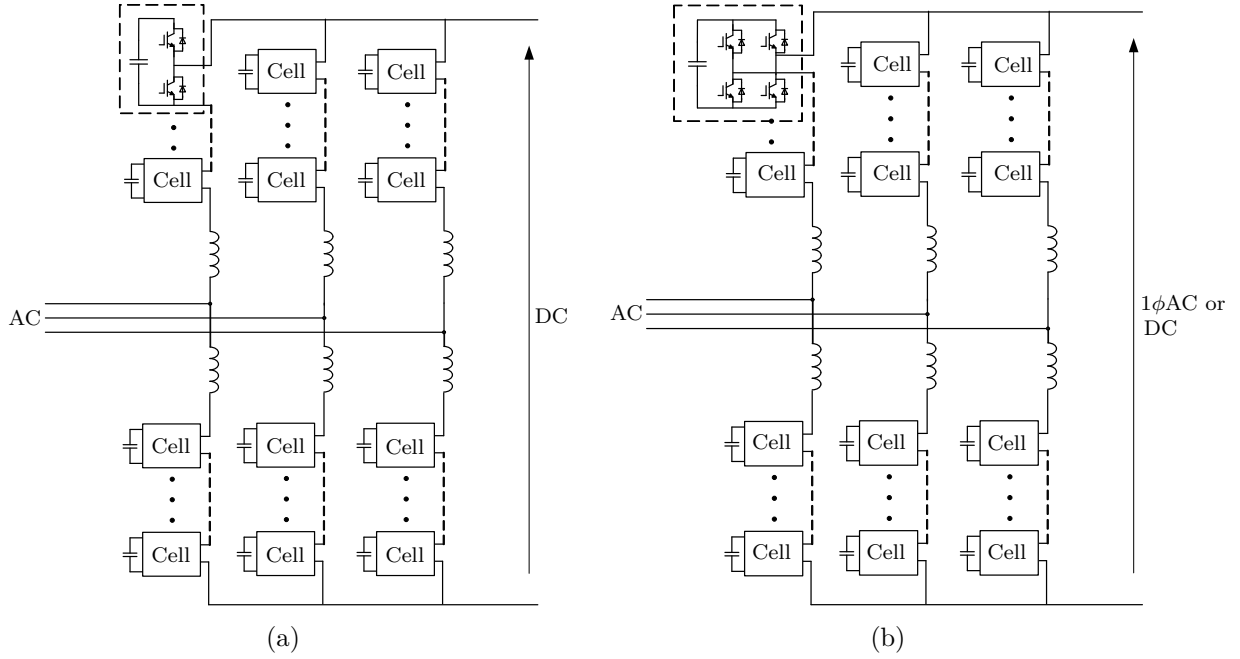


**Fig. 2.7: Two members of the MMCC family. (a) The modular multilevel DSCC converter. (b) The modular multilevel DSBC converter.**

flowing among their positive and negative arms. Such currents play an important role on power exchange among the clusters, and between the two set of terminal connections [59]. In a practical point of view, the DSCC is applicable to motor drives without the need of regenerative braking, HVDC conversion stations, and BTB systems [60–63]. On the other hand, the DSBC can withstand a broad voltage variation on the dc-link voltage. This characteristic makes the DSBC suitable to a three-to-single-phase ac-to-ac power conversion [64–66], and to power conversion systems intended for renewable energy sources such as wind power generation [67].

Fig. 2.8 shows the modular multilevel cascade converter based on triple-star chopper cells or a modular multilevel TSBC converter. Firstly presented by the authors of [68], it is also known as “modular multilevel matrix converter [69, 70].” Here, a subconverter is equivalent to an SSBC converter as shown in Fig. 2.6(a). Two three-phase ac terminals characterize the TSBC converter, allowing it to achieve ac-to-ac ( $3\phi$ -to- $3\phi$ ) bidirectional power conversion. The capability of drawing or feeding sinusoidal three-phase currents with any power factor on both two terminals makes the TSBC converter a candidate to

high-power medium-voltage motor applications with regenerative braking [54].

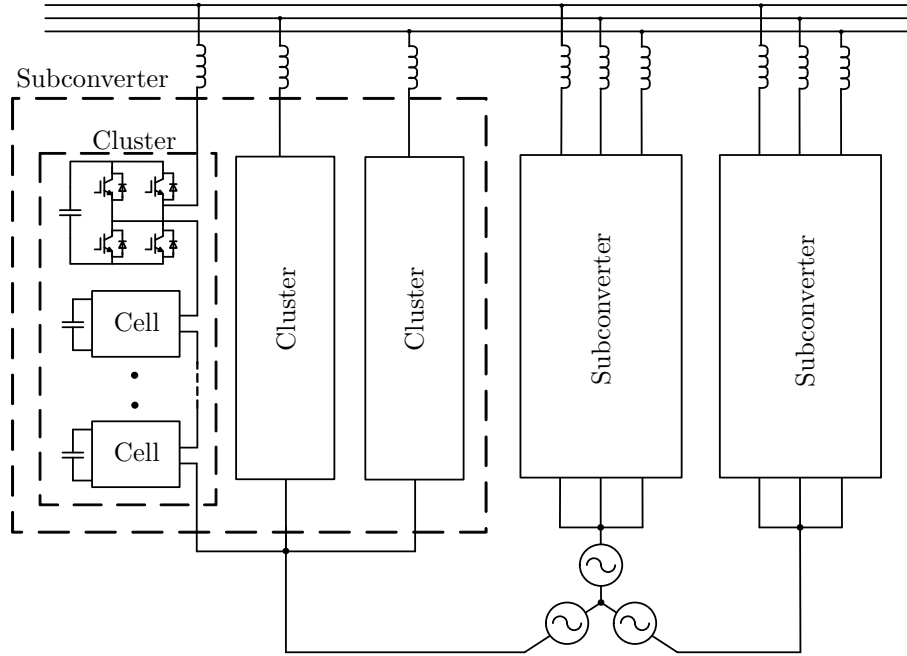


Fig. 2.8: The modular multilevel TSBC converter [54].

## 2.3 Static Synchronous Compensator in Distribution Power Systems

A traditional method for reactive compensation in power systems is commonly made through installation of capacitor banks. More advanced solutions are based on the combination of thyristors, capacitor and inductors, such as thyristor-switched capacitors (TSC), thyristor-controlled reactors (TCR) and the thyristor-controlled series compensator (TCSC) [14, 71, 72]. Such solutions are cost-effective, but they lack flexibility and their performance depends on the ac mains voltage.

The static synchronous compensator, or simply static compensator (STATCOM), is a very well-known solution for large-capacity reactive compensation applications. Accordingly to “The Authoritative Dictionary of IEEE Standards Terms [73],” the STATCOM can be described as “a static synchronous generator operated as a shunt-connected static

var compensator (SVC), whose capacitive or inductive output current can be controlled independently of the ac system voltage.”

Fig. 2.9 presents the circuit configuration of the first STATCOM commissioned commercially, located in Japan [74]. The STATCOM is rated at 80 MVA and 154 kV, and consists of a 48-pulse inverter combined with a step-up transformer, a multiwinding phase-shifted transformer, and eight 10-MVA voltage-source inverters. Here, the use of multiwinding transformer is necessary to properly reduce the currents harmonics to permissible levels. Moreover, it brings voltage matching between the ac mains voltage and the nominal ac voltage of the voltage-source inverters.

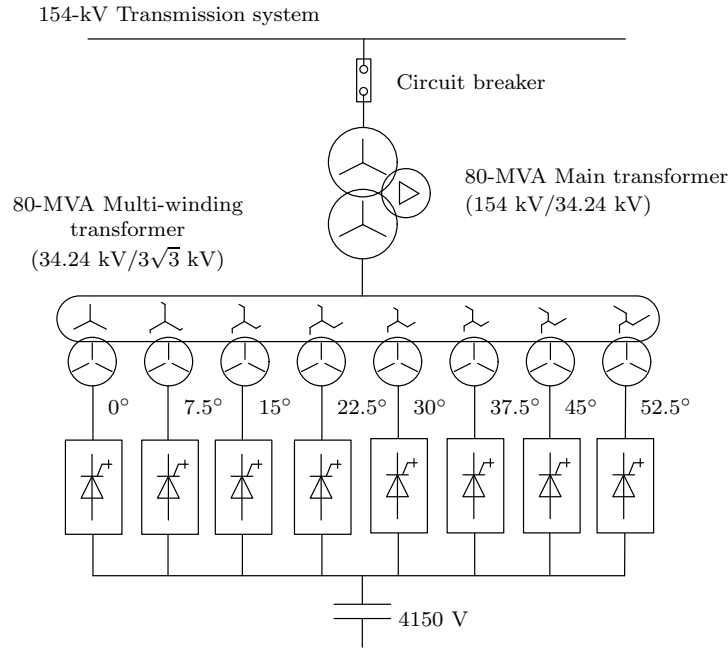


**Fig. 2.9: The 80-MVA STATCOM installed at Inuyama substation [74].**

Distribution STATCOM (D-STATCOM) are intended for installation on medium-voltage industrial grids or distribution power systems. Fig. 2.10 shows a D-STATCOM using a typical two-level voltage-source converter (VSC) [75]. D-STATCOMs are usually designed with a step-down transformer for voltage matching [72,75,76]. Moreover, a shunt harmonic filter is installed in the ac terminals of the STATCOM so its currents comply with harmonic standards.

Reed *et al.* [77] have presented a 5-MVA, 4.16-kV STATCOM for flicker compensation in industrial plants. This STATCOM consisted of a transformer with a voltage ratio

of 4.16 kV/300 V and parallel-connected IGBT-based two-level voltage-source converter (VSC). Commercially-available D-STATCOMs consist in equivalent solutions. In some cases an NPC inverter is applied instead of VSC [78–80].

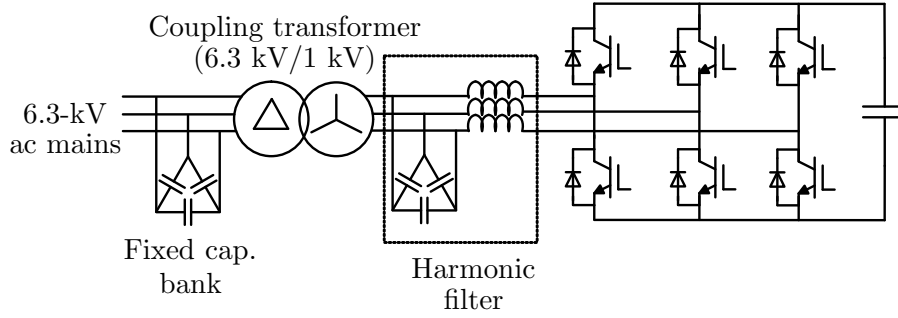


Fig. 2.10: A D-STATCOM based on a two-level voltage-source converter [75].

### 2.3.1 Applications of Multilevel Converter to Distributed Static Synchronous Compensator

In principle, a D-STATCOM requires the use of a step-down transformer [72, 75–77, 79, 80]. The transformer provides the necessary voltage matching between the converter and the grid voltage. However, the transformer usually weights from 3000 kg to 4000 kg, while a three-level NPC converter may weight from 1000 kg to 2000 kg [81]. The suppression of the transformer could make the D-STATCOM compact, thus making it possible to be installed in poles within a distribution feeder in urban zones. A pole-installed, lightweight, and size-reduced D-STATCOM would be competitive in terms of compactness when compared to thyristor-based solutions. In this scenario, multilevel converters become prospective candidates to D-STATCOM applications.

Fig. 2.11 shows a five-level NPC-based pulse-width modulated D-STATCOM [81]. A D-STATCOM based on an NPC converter has been proposed by Hochgraf *et al.* [82] including simulated results, and Akagi *et al.* [81] described experimental verification of a 200-V, 10-kVA STATCOM including a proposal of a voltage-balancing auxiliary circuit. A transformerless five-level NPC-based D-STATCOM brings higher complexity and cost due to its clamping diodes and dc capacitors. However, better harmonic performance and reduced electromagnetic-interference (EMI) emissions can offset such costs.

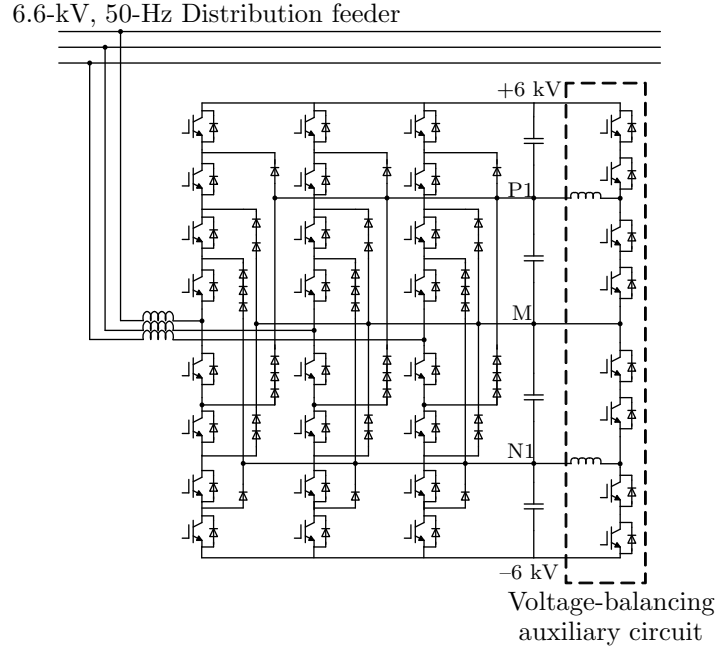


**Fig. 2.11: A transformerless STATCOM based on the five-level diode-clamped converter [81].**

Fig. 2.12 shows a transformerless D-STATCOM based on the MMCC-SSBC [24, 55, 83–89]. An SSBC-based STATCOM yields three-phase multilevel voltage waveforms with low-voltage steps. This results in requiring no shunt harmonic filter at the ac side of the STATCOM. Moreover, the modularity facilitates an eventual expansion of cascaded bridge cells. The SSBC-based D-STATCOM is studied in this dissertation, with further details presented in chapter 3.

Fig. 2.13 shows a transformerless STATCOM based on the MMCC-SDBC [53, 90]. Peng and Wang proposed it in 2004 as an “universal statcom [90].” In the SDBC-based STATCOM, a zero-sequence current circulates among the delta-connected clusters [57]. As a result, the SDBC-based STATCOM is capable to compensate negative-sequence reactive power and low-frequency power oscillations, making it suitable to STATCOM applications for arc furnaces and flicker effect. Experimental results of a 100-V, 5-kV downscaled model were presented by Hagiwara *et al.* [57]. Former Alston T&D presented a field application of the SDBC-based STATCOM for a transmission system [53]. Nevertheless, a drawback is the increase of bridge cells by 70% when compared to the SSBC-based STATCOM considering the same ac mains voltage, power ratings, and switching devices.

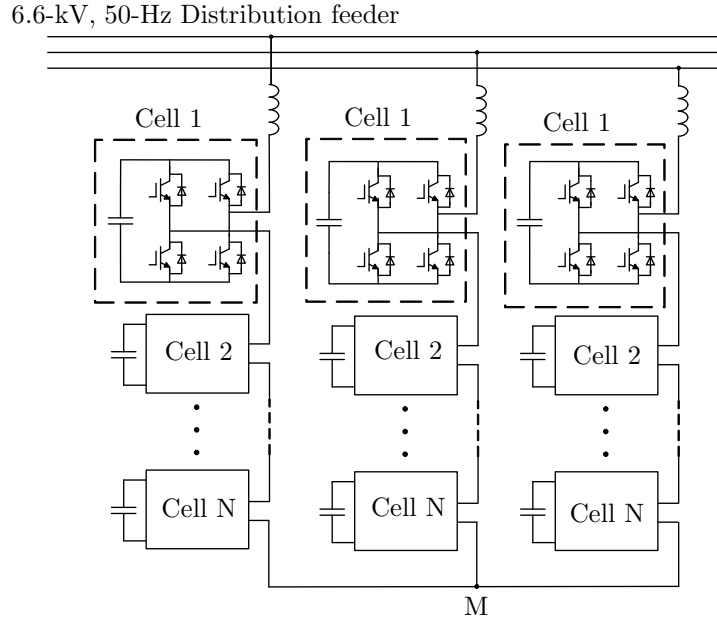


Fig. 2.12: A transformerless D-STATCOM based on an SSBC converter [55].

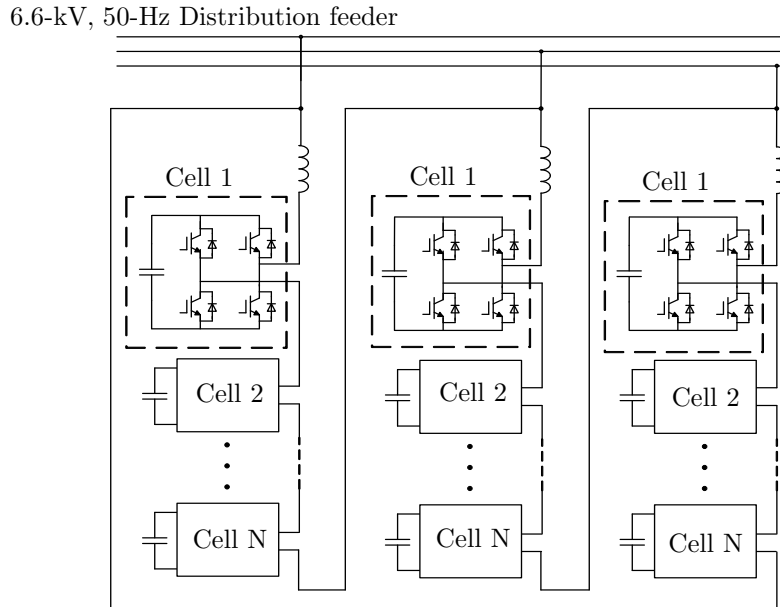


Fig. 2.13: A transformerless STATCOM based on an SDBC converter for a 6.6-kV industrial power system [91].

Fig. 2.14 shows an alternative implementation of the D-STATCOM based on an asymmetrical SSBC. Such circuit configuration with asymmetry among the bridge-cells dc voltages was firstly proposed by Manjrekar *et al.* [40,41] for motor drives. The asymmetrical SSBC-based D-STATCOM consists of three clusters with three bridge cells with different dc capacitor voltages among them. The bridge cells are divided in high-voltage cell (HV), medium-voltage cell (MV), and low-voltage cell (LV). Low switching frequency is applied to the HV and MV cells, while LV cell switches in a higher frequency. The asymmetry among the dc capacitor voltages makes it possible to produce a voltage waveform with more steps than a standard SSBC. As for disadvantages, the asymmetrical SSBC does not have the same modularity as the standard SSBC because the switching devices have different ratings depending on the type of cell. Sano *et al.* [92] presented experimental waveforms for a 220-V, 10-kVA asymmetrical-SSBC-based D-STATCOM. Koyama *et al.* [93] presented experimental verification of a 6.6-kV, 100-kVA D-STATCOM based on the asymmetrical SSBC using both silicon (Si) and silicon-carbide (SiC) devices.

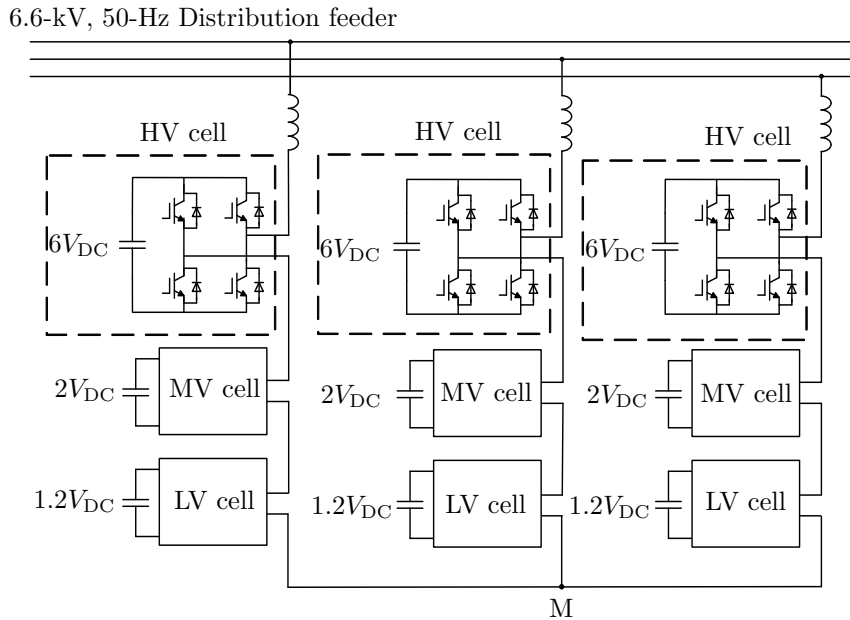


**Fig. 2.14:** A transformerless D-STATCOM based on an asymmetrical MMCC-SSBC with a dc voltage ratio of 6:2:1.2 [92].

## 2.4 Battery Energy Storage Systems in Power Systems

The use of energy storage systems (ESS) bring various benefits in transmission and distribution power systems [15, 94]. As an ESS draws active power from the grid, it can regulate the grid frequency locally and aid on maintaining voltage stability. ESS can perform local regulation of the load peak and the surplus of generated energy in distribution systems with distributed generation. This makes ESS as a key-enabling technology to support the spread of renewable energy sources in power systems.

As for technologies in ESS, pumped-hydro-power-based energy storage [95] and lead-acid battery technologies [96] are well known and mature solutions. Attention is being drawn in recent technologies, such as compressed air energy storage [97], nickel- [98] and lithium-based battery technologies [99], regenerative fuel cells [100, 101], and redox-flow batteries [102]. Super-capacitor technology and super magnetic energy storage (SMES) are still novel and potential alternatives, but they still lack reliability and satisfactory performance [15, 103].

Battery Energy Storage Systems (BESS) stands as a cost-efficient, reliable, and well-established technology for ESS in distribution power systems. Valve-regulated lead-acid (VRLA) batteries have been firstly applied in energy storage systems [104]. BESS using sodium-sulfur (NaS) batteries were also demonstrated for balancing power output of wind-power plants [105, 106]. The present trend goes toward lithium-based batteries and on redox-flow-type batteries [17].

Fig. 2.15 shows the circuit configuration of a 10-MW GTO-based BESS installed and commissioned in Chino, CA, USA, in 1988 [104]. Early BESS intended for distribution power systems consisted on the combination of 18-, 24-, 36-, or 48-pulse converters with a three-phase zig-zag transformer [104, 107]. The BESS consist of lead-acid batteries, and can perform reactive power control, voltage and frequency regulation, and load-peak-shave compensation. Nevertheless, the use of multiple complicated phase-shifted windings brings various difficulties to the design and construction of the zig-zag transformer, thus resulting in issues of insulation reliability. This would make zig-zag transformers prone

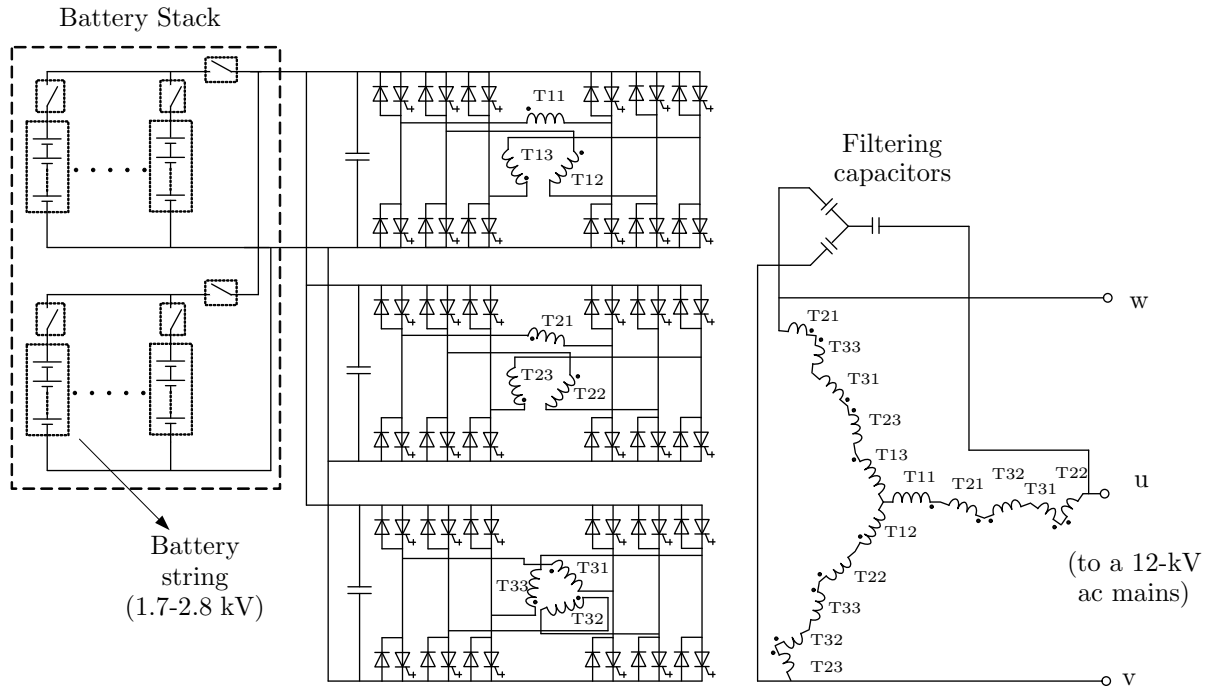


Fig. 2.15: The 10-MVA BESS installed in Chino [104].

to failures.

### 2.4.1 Applications of Multilevel Converters to Battery Energy Storage Systems

Nowadays, a commercially-available BESS consists mainly of parallel connection of two- or three-level converters [108–113]. Fig. 2.16 shows a possible configuration of a BESS consisting of an NPC converter and a batter stack connected to its dc terminals. Usually lithium-ion battery modules consist of series connection of low-voltage battery cells [99]. Parallel connection of multiple battery strings, each of which is based on series-connected battery modules, should be done to achieve high power ratings. However, increasing the number of the parallel series-connected battery strings brings complexity and lack of reliability to the whole system.

Fig. 2.17 shows a BESS based on a modular multilevel SSBC converter [56, 114–121]. This thesis discusses this BESS in details in chapter 5.

The SSBC converter is suitable for a BESS in terms of cost, practicability and flexibility [18]. The cascaded connection of bridge cells produces three-phase multilevel voltage

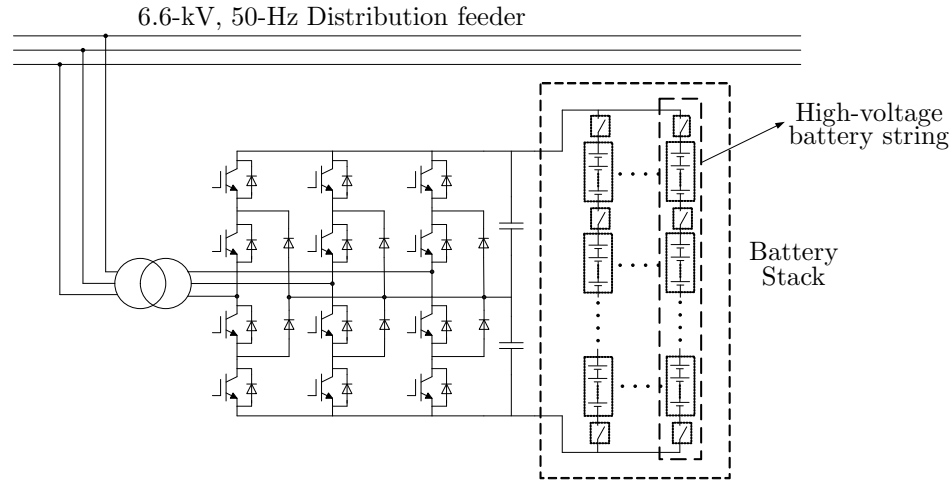


**Fig. 2.16:** A battery energy storage system based on an NPC converter [109, 111].

waveforms with low-voltage steps, thus resulting in an almost sinusoidal voltage waveform. Even if the simplest three-phase transformer for a grid connection were necessary for galvanic isolation and voltage matching, it would be much less expensive and more reliable than a complicated zig-zag transformer with multiple phase-shifted windings.

Tolbert *et al.* [58] firstly described an SSBC using battery modules as separated dc voltage sources for a motor drive. Some research papers have discussed SSBC-based BESS configurations including simulated results [114–116]. Maharjan *et al.* [56] introduced phase-shifted-carrier pulsewidth modulation (PWM) to an SSBC-based BESS, and verified the effectiveness of state-of-charge (SOC) balancing control. Fault-tolerant control strategy and active-power control of individual bridge cells have also been proposed in [117] and [118], respectively. Baruschka and Mertens have disclosed experimental waveforms for steady-state operation of an SSBC-based BESS equipped with lead-acid battery modules [119]. Chen *et al.* have presented a 30-kW, 220-V, 65-kWh SSBC-based BESS equipped with lithium-ion (Li-ion) battery modules [120]. Kawakami *et al.* presented experimental waveforms of steady-state operation, transient response, and low-voltage-ride-through (LVRT) capability for a grid-scale 500-kW, 1.5-kV, 238-kWh SSBC-based BESS using Li-ion battery modules [121].

The application of other members from the MMCC family to a BESS has been investigated owing to their prominent advantages when used for high-power and medium-voltage converters. Fig. 2.18 shows a BESS based on a modular multilevel DSCC converter that

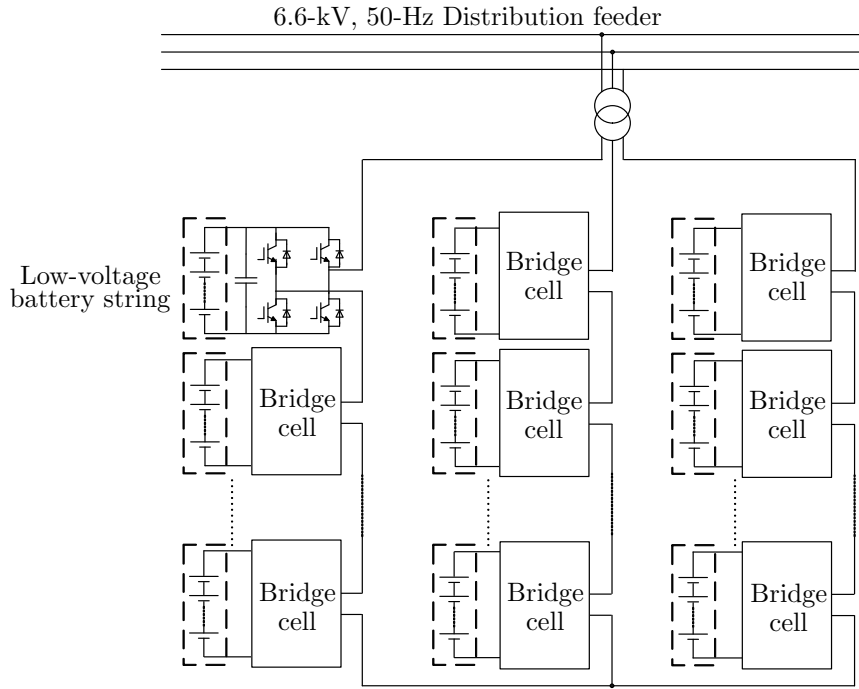


**Fig. 2.17: A BESS based on a modular multilevel SSBC converter [56,117,118].**

has each cell unit equipped with a low-voltage battery module [122–126]. Fig. 2.18(b) shows the basic cell for this system. Note that an extra chopper is used to suppress low-frequency oscillations on the battery modules current. The system modularity allows the use of multiple individual low-voltage battery modules.

Fig. 2.19 shows a possible application of a modular multilevel DSCC converter for BESS applications [119]. Here, a central high-voltage battery stack is connected to the dc-link, differently from the BESS in Fig. 2.18.

Fig. 2.20 shows the circuit configuration of a BESS based on a three-phase modular push-pull converter (MPC) presented by Hagiwara *et al.* [127]. Galvanic isolation is achieved by the use of three single-phase transformers with center-tapped windings in their secondary side. Analysis showed that a MPC-based BESS requires a dc-link voltage lower than that of the BESS in Fig. 2.19. This feature makes the MPC a suitable alternative for BESS using low-voltage and large-current batteries.

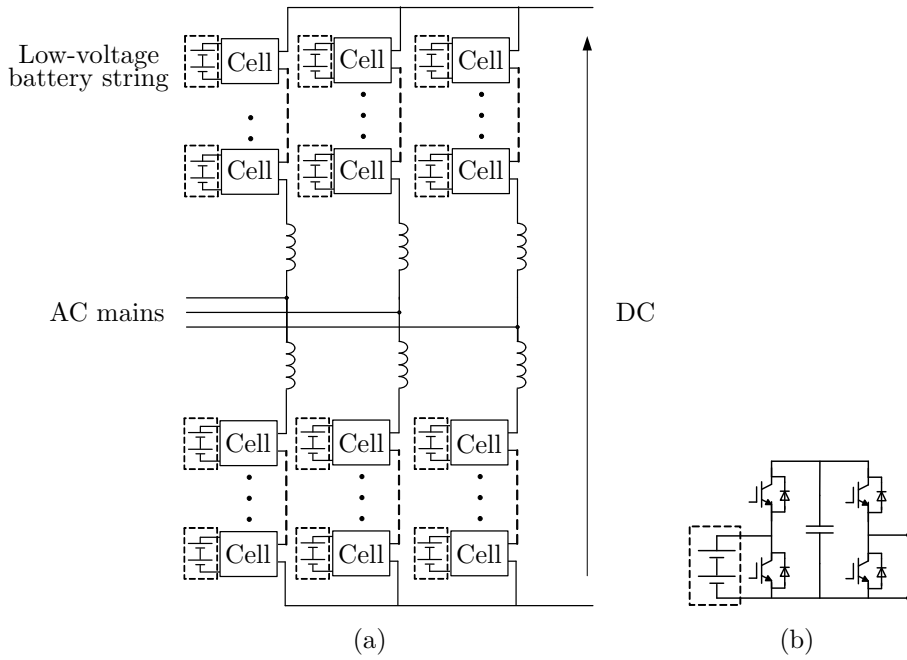


**Fig. 2.18:** A modular multilevel DSCC converter with low-voltage battery strings on each cell [123,125,126]. (a) Main circuit. (b) Basic cell circuit with a low-voltage battery string.

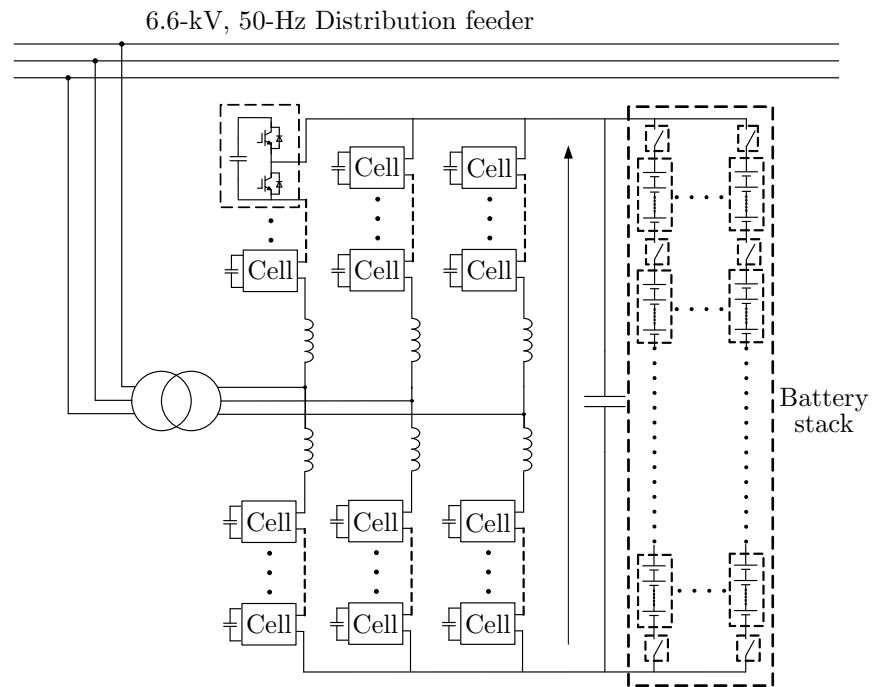


**Fig. 2.19:** A modular multilevel DSCC converter with a battery stack on the dc-link [119].

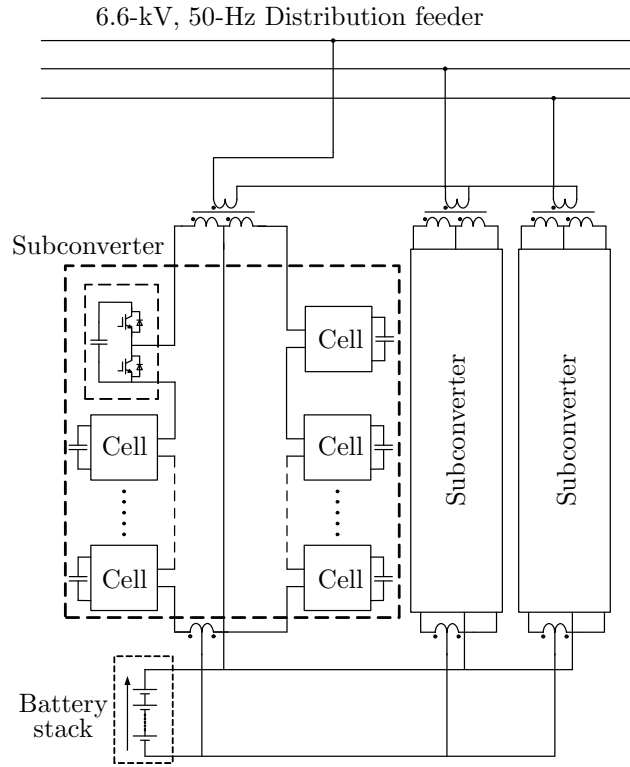


**Fig. 2.20:** A modular push-pull PWM converter (MPC) applied to a BESS [127].

## 2.5 Voltage Sags, Phase Jumps, and Frequency Deviations on Distribution Power Systems

Either a D-STATCOM or a BESS connected to an electrical power system are susceptible to disturbances that may bring an inadvertent halt to their operation. Although a protection system must operate for safety reasons, it is difficult to assess the disruption level of a disturbance occurrence. If the occurrence is cleared in a short-time, the inadvertent shutdown of a grid-connected equipment brings avoidable economic losses. The capability to ride through the occurrence of grid disturbances becomes then necessary for the D-STATCOM and the BESS to improve their reliability and availability.

The so-called “low-voltage ride-through (LVRT) capability” refers to is the capability to ride through voltage sags, and it is extensively covered in literature and in reliability standards [128, 129]. Nevertheless, occurrences of phase jumps and frequency deviation also affect the operation of grid-connected equipment [130, 131].

The ride-through capability of both D-STATCOM and BESS based on an SSBC con-

verter is verified experimentally in chapter 6. This section briefly reviews and discusses the occurrence of voltage sags, phase jumps and frequency deviations.

### 2.5.1 Voltage Sags

Voltage sag, also known as voltage dip, is defined as a temporary decrease in the voltage amplitude on the ac mains. A difference should be made between a voltage sag and an interruption. The interruption corresponds to a total loss of voltage, owing to the disconnection of the electricity source feeding a given load or feeder. This usually happens during fault occurrences within the feeder when protection systems, e.g. a relay, clear the fault and interrupt the electricity. On the other hand, the voltage sag is usually related to a remote fault occurrence on the electrical power system [128, 132, 133].

Fig. 2.21 shows two situations when a voltage sag appears in a distribution feeder. Fig. 2.21(a) illustrates when a fault occurs in a transmission line. Usually, a fault is caused by short-circuits, by accidents, or by atmospheric electrical discharges. Until the faulted line is cleared by the protection relay T1, a voltage sag appears on the distribution feeders because a short-circuit current flows to the fault location [134]. The voltage of the distribution feeders is restored when T1 opens. Fig. 2.21(b) illustrates the case when a remote fault occurs within the distribution power system. When a fault occurs in the distribution feeder numbered 2, the feeder voltage reduces and a short-circuit current starts to flow. As a consequence, a voltage sag appears on feeder numbered 1. When the protection relay D2 opens, the voltage in feeder numbered 1 is restored. The protection relay D1 remains closed because the fault occurs outside of its operation range. The feeder numbered 2 is then reconnected when the fault is cleared [128, 129, 132].

### Low- and Zero-Voltage Ride-Through Capability

From the position of a power utility, grid-connected equipment is expected to ride through voltage sags occurrences to maintain system stability. The inadvertent failure due to a voltage sag could result in chain-reaction failures. This applies to inverter-based power conversion systems especially, such as distributed generation, renewable energy sources, D-STATCOMs, BESSs, and so on. In other words, low-voltage-ride-through

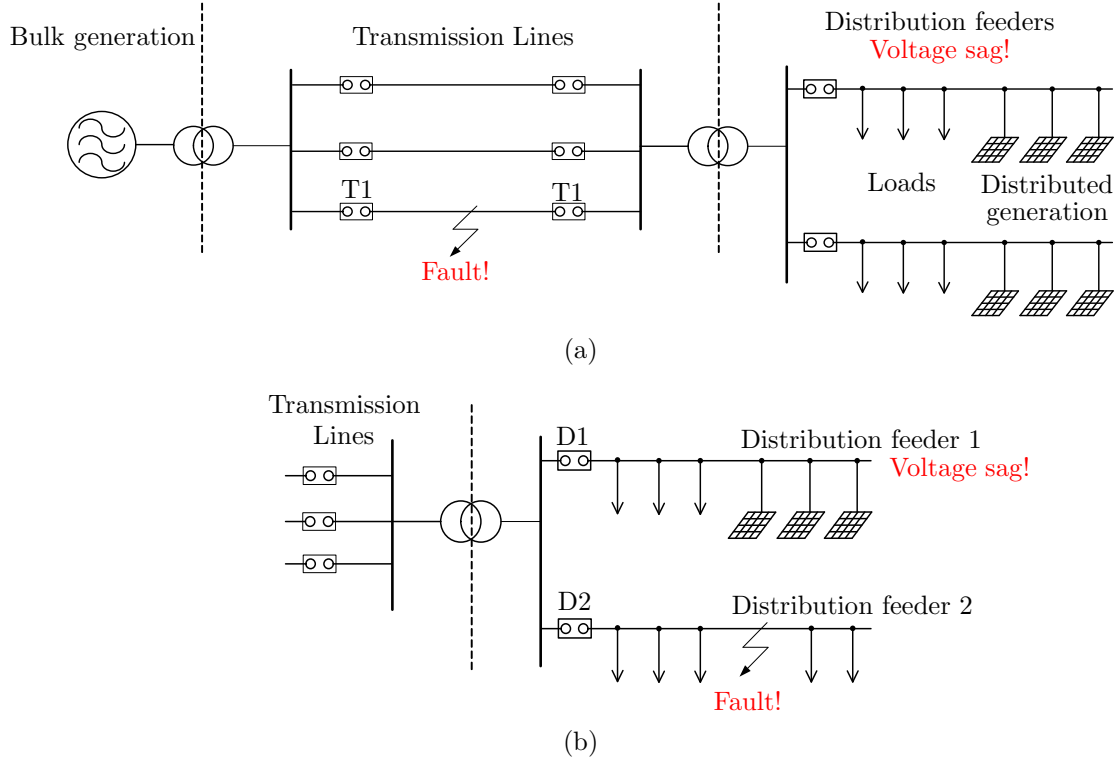


**Fig. 2.21: Two possible situations of voltage sag occurrence in distribution power systems. (a) Fault on transmission lines. (b) Fault on a parallel distribution feeder.**

(LVRT) capability is expected from such systems [135, 136].

Fig. 2.22 shows some of LVRT requirements issued by power utilities for distributed power generation. Current standards in Japan follows the same trend in Europe, which requires that distributed generation based on renewable energy sources to have not only LVRT, but also zero-voltage-ride-through (ZVRT) capability [137] [135]. Approved in 2013, a standard by the North American Electric Reliability Corporation (NERC) also requires ZVRT capability of wind-power-based distributed generation [136]. Reference [138] shows the LVRT requirements in UK grid system, and [139] refers to the Brazilian LVRT requirements. Note that no ZVRT capability is required neither in [138] nor in [139].

### Supportive Roles of D-STATCOM and BESS

A D-STATCOM performs regulation of voltage stability in distribution feeders. Nevertheless, D-STATCOM is also required to performs supportive roles in case of faults and

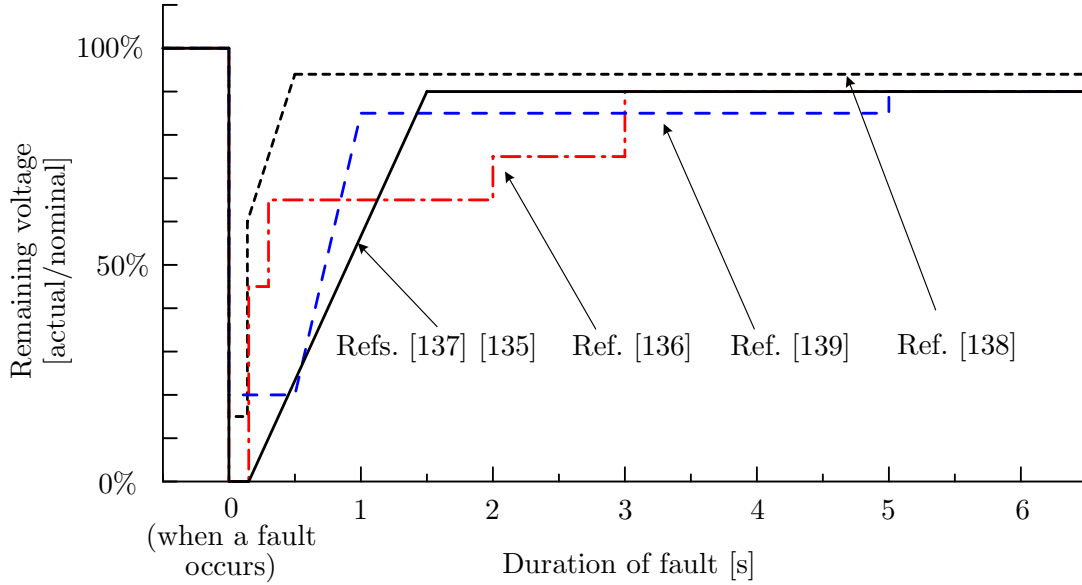


**Fig. 2.22: Examples of requirements for Low- and Zero-Voltage Ride-Through capability of grid-connected converters.**

voltage sags. A D-STATCOM can increase the transmissible power and maintain a high margin for transient stability of a feeder. This is important after a fault clearance, when a faster voltage recovery can be achieved by injecting reactive power to compensate the difference between the electrical transmitted power and the feeder supplied power [14, 140]. Other important role is the power oscillation damping in undamped distribution feeders. The injection of reactive power allows the transmitted power of a feeder to vary dynamically, so that low-frequency oscillations of active power can be damped.

A BESS can perform supportive roles during voltage sags and after fault clearances as well [14, 15]. Although depending on its ratings and on the feeder characteristics, the BESS could compensate a voltage sag by supplying power to the loads in a distribution feeder.

The present dissertation deals with the low- and zero-voltage ride-through capabilities of the both D-STATCOM and BESS only. Supportive roles can be achieved through specific control strategies applied to a D-STATCOM and BESS [14]. Nevertheless, a fast transient response of the power conversion system ensures that the D-STATCOM and the BESS can perform the designed supportive roles.

### 2.5.2 Frequency Deviations

The system frequency in distribution power systems is regulated by the bulk power generation automatically through the governing system of large synchronous generators. The response of governor regulation to a local frequency deviation is slow, in the range of seconds or minutes, because of the scale of both bulk power generation and transmission systems

Recent studies have showed that the combination of the typical governor response time and the recent development of consumer loads and distributed generation may increase frequency deviation occurrences in distribution power systems [13, 131, 141]. The increase on frequency deviation can inadvertently halt inverter-based generation and power utility equipments set to operate in a restricted frequency range. Distribution and transmission systems could be jeopardized by a chain reaction resulting from massive disconnection of inverter-based distributed generation. The capability of grid-connected inverters and converters to withstand frequency deviations becomes necessary to maintain system stability. Government agencies in USA have named such capability as “frequency ride-through” to draw attention for necessary revision of requirements related to stable operation range of frequency in transmission and distribution power systems [142, 143]. In Japan, the frequency deviation has been considered as an important issue in distribution power systems. Recent guidelines have proposed grid-connected converters to have capability to not only withstand voltage sag occurrences, but also a sudden increase of the system frequency [137].

Fig. 2.23 illustrates the guidelines for riding through frequency deviations in Japan [137]. For a 50-Hz distribution power system, a inverter-based distributed generation or battery energy storage system should not disconnect from the ac mains during a step change of 0.8 Hz, as shown in Fig. 2.23(a), and should not disconnect during a frequency change of  $\pm 2$  Hz/s, as shown in Fig. 2.23(b).

### 2.5.3 Phase Jumps on Distribution Power Systems

Voltage sags can be characterized by the drop of the voltage magnitude and the time duration [129]. Nevertheless, the phase of one or more voltages may also change during

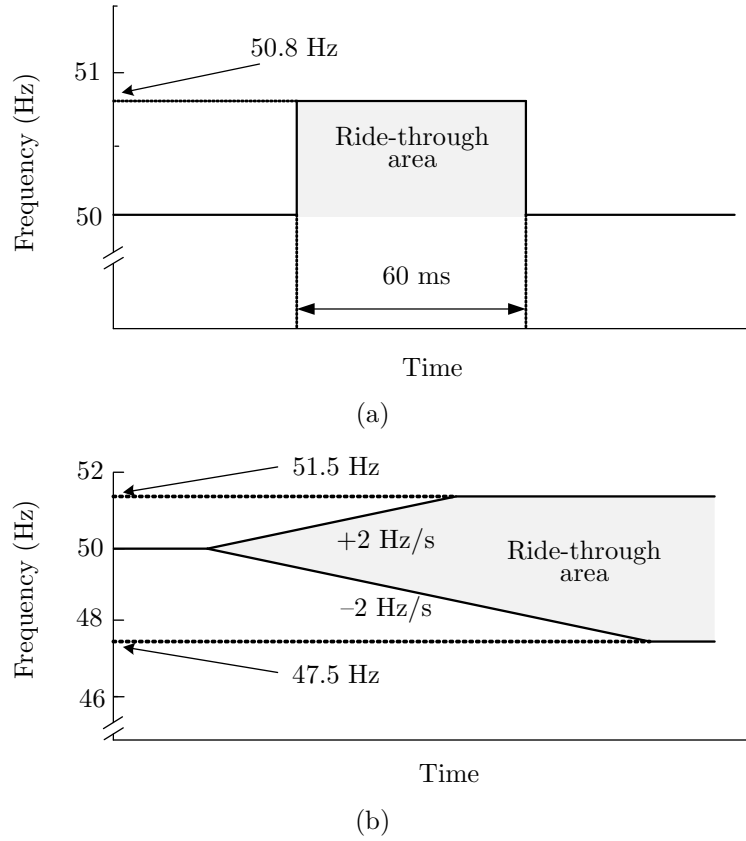


**Fig. 2.23: Ride-through capability against frequency deviations for a fundamental frequency of 50 Hz [137]. (a) Step change on frequency. (b) Ramp change on frequency.**

the occurrence of a voltage sag. This effect is usually referred as “phase jump.” Some references describe and discuss the characterization and the calculation of phase jumps during voltage sags in details [130, 134, 144, 145]. Moreover, the sudden variation on the power generated by renewable energy sources can also bring rapid change of phase angle. This phase change can also be characterized as a “phase jump.”

Phase jumps on the ac mains voltage can be related to three main reasons:

- the so-called “impedance ratio” of the faulted line and the distribution feeder under consideration is different. As a result, a phase jump is induced on the distribution feeder voltage during a fault occurrence on a remote line [130, 134].
- an asymmetrical voltage sag caused by a single or a double-phase fault occurrence induces a phase jump appears on the line-to-line voltages [92, 130, 134].

- when renewable energy sources are tied to the power system by long transmission or distribution cables, sudden variation of generated power may change the voltage phase angle significantly.

Fig. 2.24 shows a simplified equivalent single-phase voltage-divider model to illustrate the occurrence of phase jumps due to the “impedance ratio.” Here, a three-phase short-circuit occurs on the faulted line, causing a voltage sag on the point of common coupling  $V_{PCC}$ .

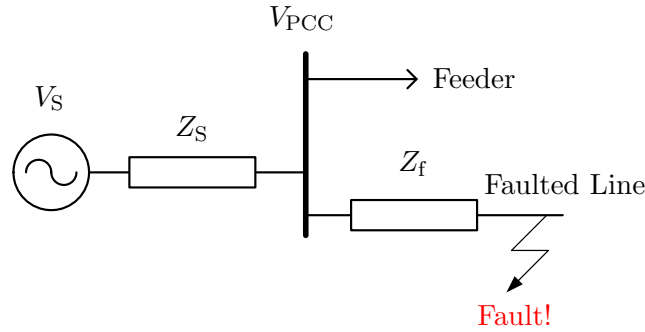


**Fig. 2.24: Voltage-divider model for voltage sags [134].**

From Fig. 2.24,  $V_{PCC}$  is given by

$$V_{PCC} = V_S \frac{Z_f}{Z_f + Z_S} = \bar{V}_{PCC} \angle \phi_{PCC}, \quad (2.1)$$

where  $V_S$  is voltage before the fault,  $Z_S$  is the equivalent source impedance, and  $Z_f$  is the equivalent impedance of the faulted line. Let  $Z_S = R_S + j\omega X_S$  and  $Z_f = R_f + j\omega X_f$ . The following expression is obtained for the angle  $\phi_{PCC}$ :

$$\phi_{PCC} = \arctan \left( \frac{X_f}{R_f} \right) - \arctan \left( \frac{X_f + X_S}{R_f + R_S} \right). \quad (2.2)$$

From (2.2), the value of the resulting angle corresponds to the phase jump during a fault. If the faulted line is a transmission line, both  $Z_S$  and  $Z_f$  can be considered small, so the phase jump is minimized. If the faulted line is a distribution feeder, the ratio  $X_S/R_S$  is larger due to a distribution transformer, while  $X_f/R_f$  is usually much smaller, considering only line cables. This may lead to a significant phase jump [146].

Fig. 2.25 illustrates the phase jump due to asymmetrical voltage sag. In the primary side of the transformer, a voltage sag of 50% of depth occurs on  $v_u^Y$ , while  $v_v^Y$  and  $v_w^Y$  do not change. The line-to-line voltages on the primary side  $v_{uv}^Y$  and  $v_{wu}^Y$  have their angle changed, and  $v_{vw}^Y$  has no change. The voltages  $v_u^\Delta$  and  $v_v^\Delta$  in the secondary side have a decrease in magnitude and a change in phase angle. Note that in the case of a symmetrical voltage sag, no changes occur on the phase angles neither of the line-to-line voltages on the primary side nor of the line-to-neutral voltage of the secondary side.

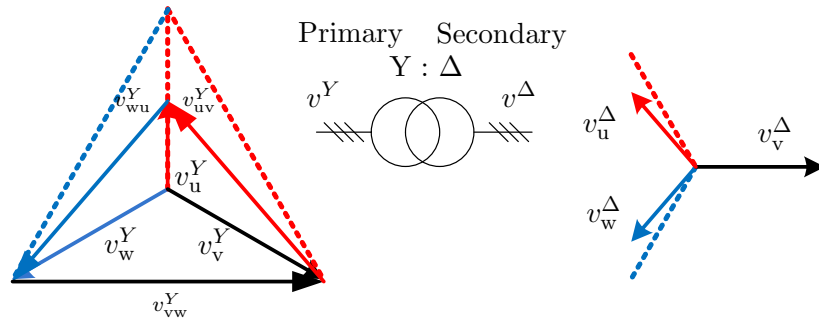


**Fig. 2.25: Phase jump induced by a wye-delta transformer during a single-phase voltage sag with 50% of depth.**

The power generated by wind-power plants and photovoltaics has sudden variations because of different conditions of wind and solar irradiation. When connected to so-called “weak grids” or to power systems by long transmission lines, the power variation may induce a significant phase change because the equivalent system impedance is high. Moreover, temporary changes on the transmission circuit, such as maintenance or after faults, bring an increase of the system impedance value. During this period, phase jumps may become significant in transmission lines and in distribution power systems.

Although recognize as a issues for grid-connected inverters, no recommendation exist for riding through phase jumps [129, 144]. Nonetheless, field data have shown that phase jump occurrences during voltage sag are usually in the range of  $\pm 15^\circ$  [134, 144, 145]. Also, even for the case when the difference on the impedance ratio of  $Z_S$  and  $Z_f$  is high, simulated results in [146] showed that the equivalent phase jump on the positive sequence component of the ac mains voltage is between  $0^\circ$  and  $-15^\circ$  for the most common voltage sag situations.

## 2.6 Summary

This chapter presented a brief literature review on applications of multilevel converters to D-STATCOM and BESS. Especial focus was made on the multilevel converters that have been considered as prominent solutions for high-power medium-voltage applications. Finally, a review on the occurrence of voltage sags, frequency deviations and phase jumps on distribution power systems were presented with attention on the ride-through capability against such grid disturbances.



## Chapter 3

# The SSBC Converter Applied to a D-STATCOM and a BESS: Experimental Setup and Current Control

### 3.1 Introduction

This chapter deals with the modular multilevel cascaded converter based on single-star bridge cells (MMCC-SSBC), or the modular multilevel SSBC converter more simply. The SSBC converter and its application to a distribution STATCOM (D-STATCOM) and a battery energy storage system (BESS) are described and detailed. Both SSBC-based D-STATCOM and SSBC-based BESS have advantages which make them suitable for installation to 6.6-kV distribution power systems. The experimental downscaled systems of both D-STATCOM and BESS are then described. A detailed description on the current control strategy of the SSBC is carried out. Attention is paid to the implementation of the “all-cells update” method when the phase-shifted-carrier phase-width modulation (PWM) is used. The modeling, design and analysis of the current control are carried out and confirmed by simulated and experimental results. The current control can be applied for both D-STATCOM and BESS in a similar way.

## 3.2 Modular Multilevel Cascaded Converter Based on Single-Star Bridge Cells

Fig. 3.1 shows a modular multilevel SSBC converter. The SSBC converter is characterized by the star-connection of three clusters connected through a common point. Each cluster is formed by a series, or cascaded, connection of multiple bridge cells. The SSBC presents some advantages, specially when intended for grid-connected applications:

- Higher voltage and power ratings can be achieved, making it suitable to high-power and medium-voltage applications.
- Reasonable assessment of the cascaded count of bridge cells and the blocking voltages of switching devices allows a “transformerless” connection to the ac mains.
- Multilevel voltage waveform eliminate the need of a harmonic filter.
- Use of multiple bridge cells brings modularity, facilitating design and layout.

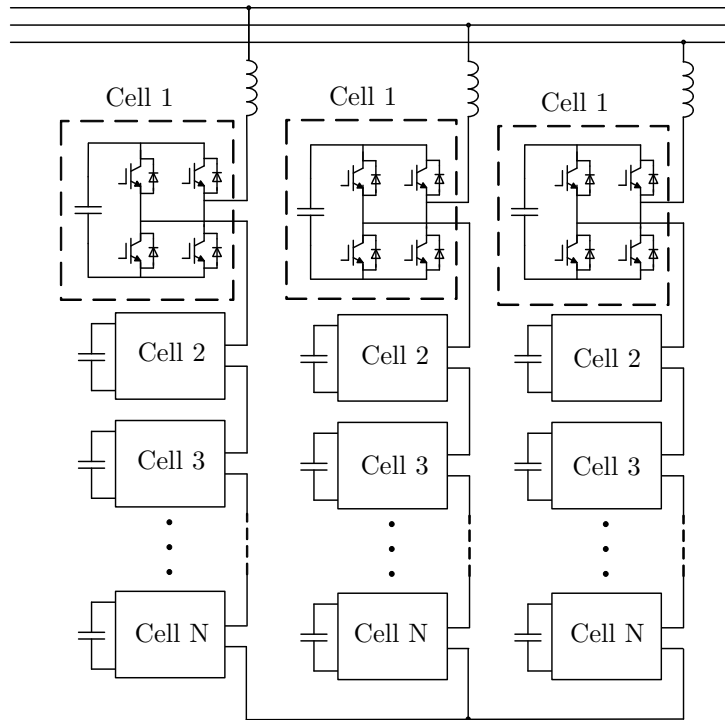


Fig. 3.1: The modular multilevel SSBC converter.

The authors of [23] and [47] firstly presented applications of the SSBC converter to STATCOM and motor drives. Since then, the SSBC converter have attracted considerable attention from power electronics researchers and engineers around the globe.

Fig. 3.2(a) shows the SSBC converter applied to a STATCOM proposed by Peng *et al.* [23, 24, 34]. The STATCOM had multiple bridge cells equipped with separated dc sources on their dc side. Stair-case modulation (SCM) method is used to synthesize multilevel voltage waveforms on the converter ac side. Fig. 3.2(b) shows the commercially-available motor drive presented by Robicon Corporation, presently part of Siemens AG [35, 47]. A multiwinding transformer connects the ac mains to the multiples units consisted of a diode rectifier, a dc capacitor, and a H-bridge cell. The diode rectifier provides the energy to feed the motor and the ac side of the SSBC converter drives the motor.

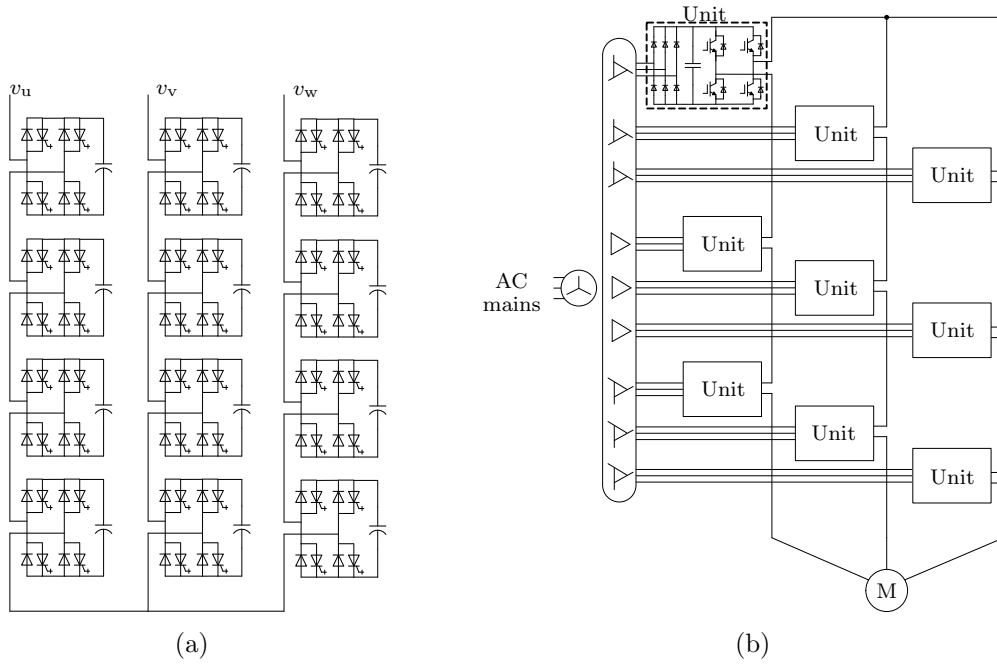


**Fig. 3.2: Early applications of a modular multilevel SSBC converter. (a) The SSBC applied to VAR compensation as depicted in [23]. (b) The SSBC applied to driving a 2.4-kV motor as depicted in [47].**

Since its proposal, the SSBC converter has been proved to be most suitable for STATCOM applications [24, 55, 83–89]. Moreover, its advantages and modularity makes it a prospective candidate to a battery energy storage system (BESS) [56, 115–121]. The present thesis focus on the SSBC-based applications to distribution STATCOMs and

BESSs.

Nevertheless, other applications of the SSBC converter are reported in literature. Sandells *et al.* [147] and Wang *et al.* [148] have proposed an unified power flow controller (UPFC) using two SSBC converters. Yang *et al.* [149] disclosed experimental waveforms of a prototype of a grid-scale SSBC-based UPFC. The SSBC converter may be also applied to small-scale PV installations [150,151]. Nevertheless, because of its merits to high-power medium-voltage applications, the SSBC would be more suitable to large utility-scale PV installations [152–154].

### 3.2.1 Application of an SSBC Converter to a D-STATCOM

Fig. 3.3 illustrates a 6.6-kV distribution feeder with a D-STATCOM. Recently, power utilities are concerned on the ac mains voltage stability along a radial distribution feeder when it has a considerable penetration of renewable energy sources [10,19]. The installation of D-STATCOM on the end of a feeder is a suitable solution by regulating the voltage by compensating the reactive power along the feeder [14].

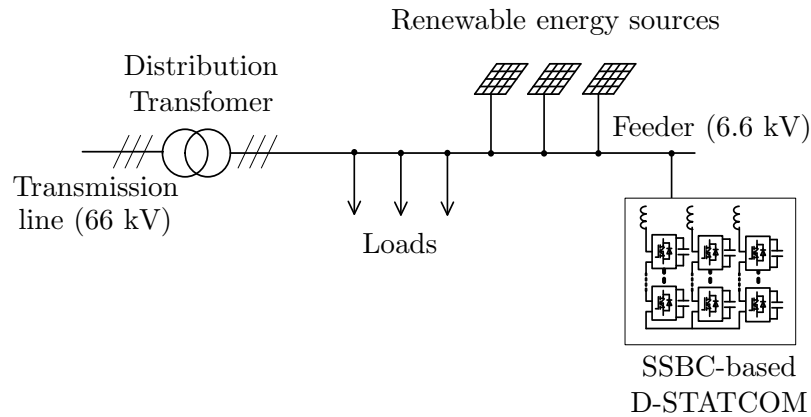


**Fig. 3.3: An SSBC-based D-STATCOM within a 6.6-kV distribution feeder.**

The SSBC is the most basic and suitable for the distribution static synchronous compensator (D-STATCOM) among the MMCC family members [18]. A configuration with  $N$  bridge cells per cluster is presented in Fig. 3.1. The SSBC-based D-STATCOM is a suitable equipment to perform reactive power compensation in a distribution power system [24, 55, 83–89]. It can also perform ancillary roles, such as voltage regulation, power

damping control, and stability control [14].

Although an SDBC converter could also be applied to the D-STATCOM, the number of bridge cells increases by 70% when considering the same voltage and power ratings, and the same semiconductor devices. If a same cascade count is considered, the voltage rating of IGBTs would increase by 70%. As for a STATCOM within a distribution feeder, the solution based on the SSBC converter is the most suitable and cost-effective.

The SSBC-based D-STATCOM yields three-phase multilevel voltage waveforms with low voltage steps, thus resulting in eliminating a harmonic filter at the ac side of the STATCOM. Moreover, the modularity facilitates an eventual expansion of cascaded bridge cells. As a result, when it is applied to power distribution systems with nominal voltages of 6.6 kV in Japan and 13.8 kV in the USA, a reasonable compromise between the blocking voltage of switching devices and the cascaded bridge-cell count per cluster enables to eliminate a medium-voltage line-frequency transformer from the D-STATCOM.

### 3.2.2 Application of an SSBC Converter to a Battery Energy Storage System

The SSBC-based BESS is characterized by allowing a low-voltage battery string to be installed on the dc side of each bridge cell. As a result, the overall failure rate of the BESS is actually reduced because the SSBC-based BESS can continue operating seamlessly even when a battery string becomes unhealthy or faulty.

Fig. 3.4(a) shows the circuit configuration for a conventional BESS combining a central converter with multiple battery strings connected in parallel. A commercial BESS employs a two- or three-level neutral-point clamped (NPC) converter as the central converter [109–111]. The parallel connection showed in Fig. 3.4(a) is required for the battery strings, each of which consists of series-connected battery modules. Thus, desirable power and energy ratings can be obtained by connecting multiple battery strings in parallel [110, 111, 155]. However, parallel and series connections of many battery modules inherently bring complexity to the battery management system. High-level supervisory control must be applied along with the battery management system (BMS) coupled in every battery module to guarantee proper operation [156]. Besides, an eventual failure of a single battery

module interrupts the operation of the battery string. It drastically restrains available power and energy ratings and may force the disconnection of the BESS from the ac mains. Moreover, a serious concern arises in suppressing faulty dc currents from battery strings with high dc voltages [155].

Fig. 3.4(b) shows the circuit configuration of an SSBC-based BESS. Battery strings, each of which consists of a low-voltage battery module, are connected individually to each SSBC bridge cell. Since the dc voltage of each bridge cell is reduced when compared to that of the central converter shown in Fig. 3.4(a), it is possible to apply a low-voltage battery string on each bridge cell. Modularity in the SSBC-based BESS allows flexible operation by monitoring either the SOC condition of each battery module [56] or the active-power flow for each bridge cell [118]. Moreover, the SSBC-based BESS can keep seamless operation even when a battery module in a string becomes unhealthy or faulty. Note that a transformer should be utilized to attend safety requirements of galvanic isolation.

Fig. 3.5 illustrates an SSBC-based BESS installed within a 6.6-kV distribution feeder. The main functions of the BESS are frequency regulation and to support local dispatching by drawing active power from the feeder [15,121]. The BESS can also perform supportive roles during and after faults. Note that the BESS is located on the point of common coupling of the secondary side of the distribution transformer [16].

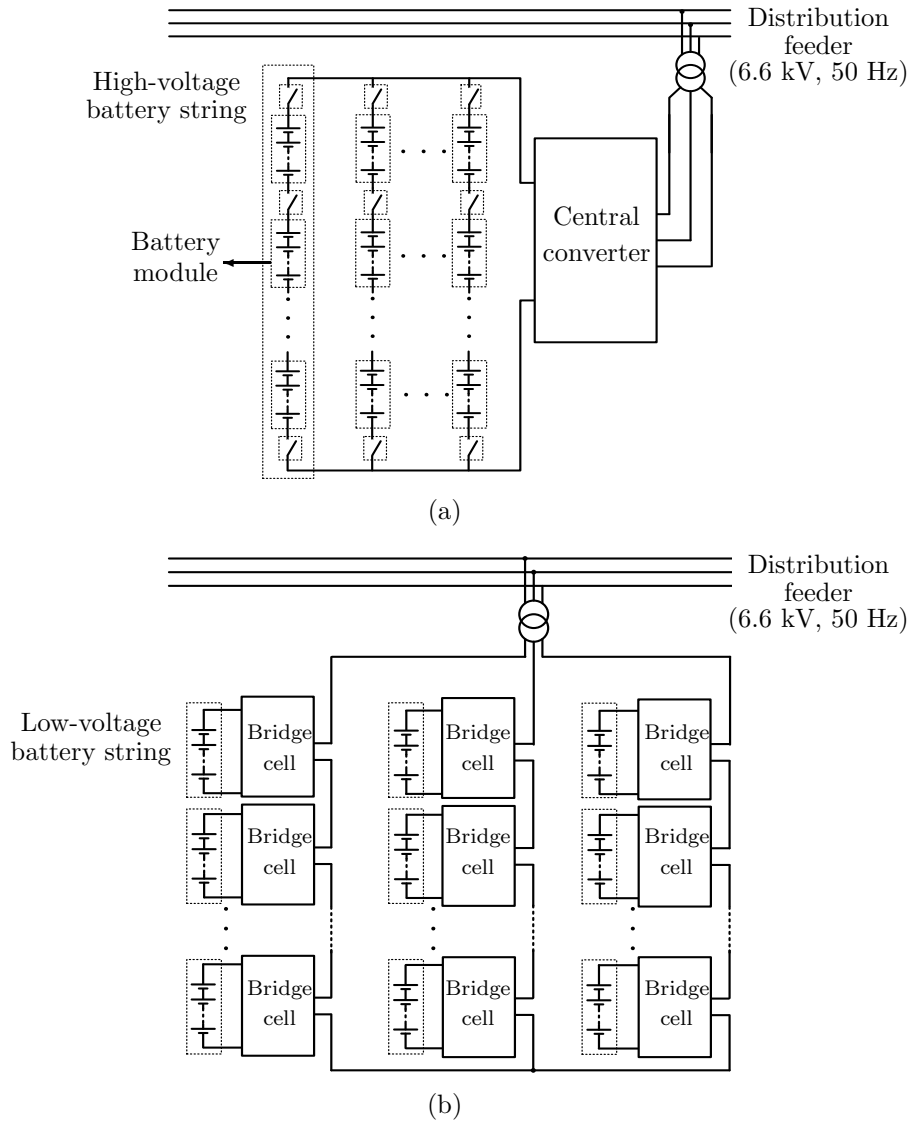


**Fig. 3.4:** Two possible BESS configurations. (a) The use of a single central converter with several parallel-connected high-voltage battery strings. (b) The use of an SSBC with multiple floating, isolated low-voltage battery strings.

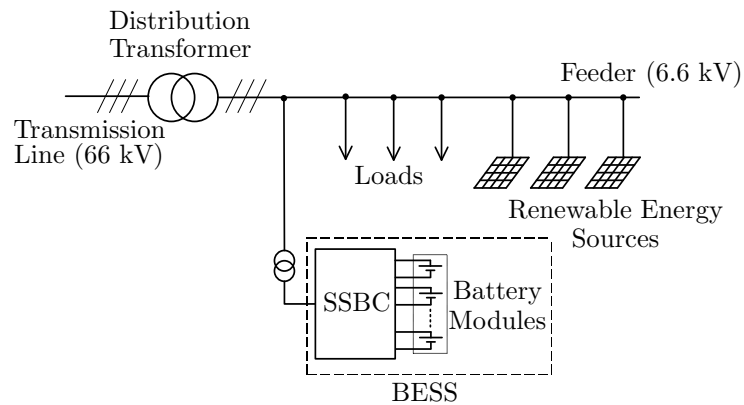


**Fig. 3.5:** An SSBC-based BESS within a 6.6-kV distribution feeder.

### 3.3 Experimental Downscaled Model of the Modular Multilevel SSBC Converter

Fig. 3.6 shows two photos of the downscaled model designed and constructed for experimental. Fig. 3.6(a) depicts the modular multilevel SSBC converter rated at 140 V and 10 kVA. Section 3.3.1 describes the experimental system of the SSBC-based D-STATCOM in details. Fig. 3.6(b) depicts the 18 Li-ion battery modules used to verify the SSBC-based BESS. Section 3.3.2 describes the BESS experimental setup in details.

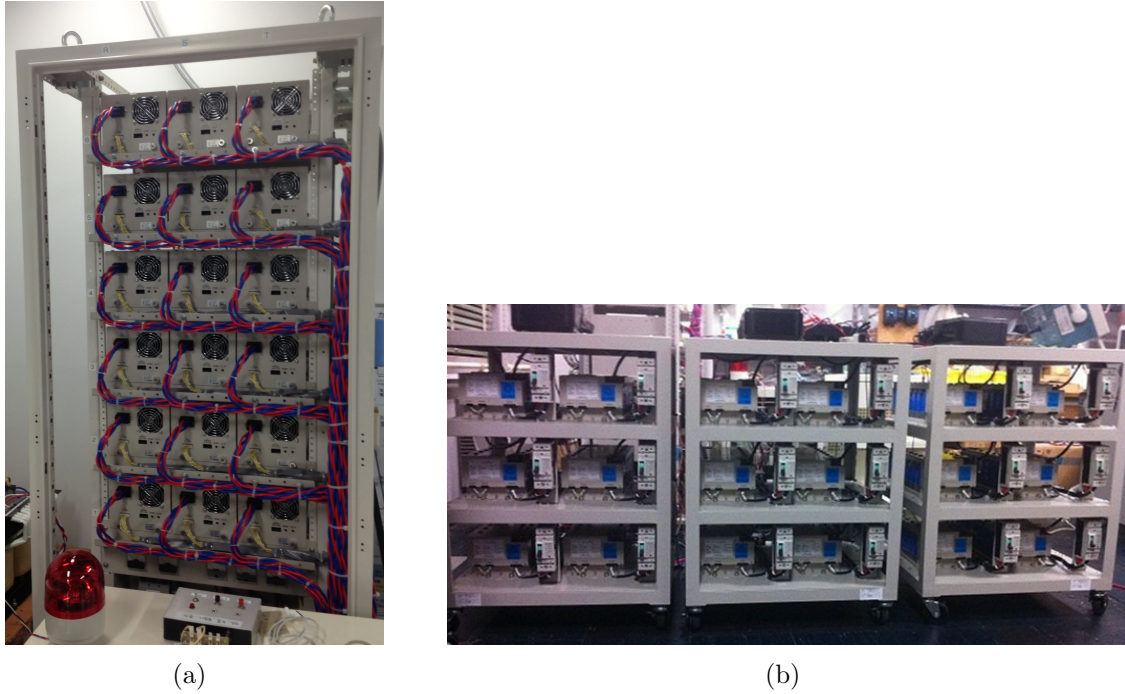


**Fig. 3.6:** Photos of the downscaled system used for experiments. (a) The three-phase 140-V, 10-kVA SSBC converter. (b) The 18 Li-ion battery modules rated at 21 kWh.

#### 3.3.1 The 140-V, 10-kVA SSBC-based D-STATCOM

##### Main Circuit Configuration

Fig. 3.7 shows the downscaled experimental circuit configuration of the three-phase phase-shifted-PWM D-STATCOM using the modular multilevel SSBC converter.

Table 3.1 summarizes the circuit parameters of the downscaled experimental system

rated at 140 V and 10 kVA. In this configuration, three clusters are star-connected through the common point M. Each cluster consists of a cascade connection of six full-bridge or H-bridge converter cell (bridge cell), and it is connected to each phase of the three-phase ac mains through an ac coupling inductor. Each bridge cell has a floating dc capacitor equipped only with a dc voltage sensor. A step-down transformer is used for voltage matching between the experimental systems and the ac mains, as well as to provide galvanic isolation for safety reasons. Parallel-connected 100-V, 80-A MOSFETs with a drain-to-source resistance as low as 10 m $\Omega$  are used as the switching devices.

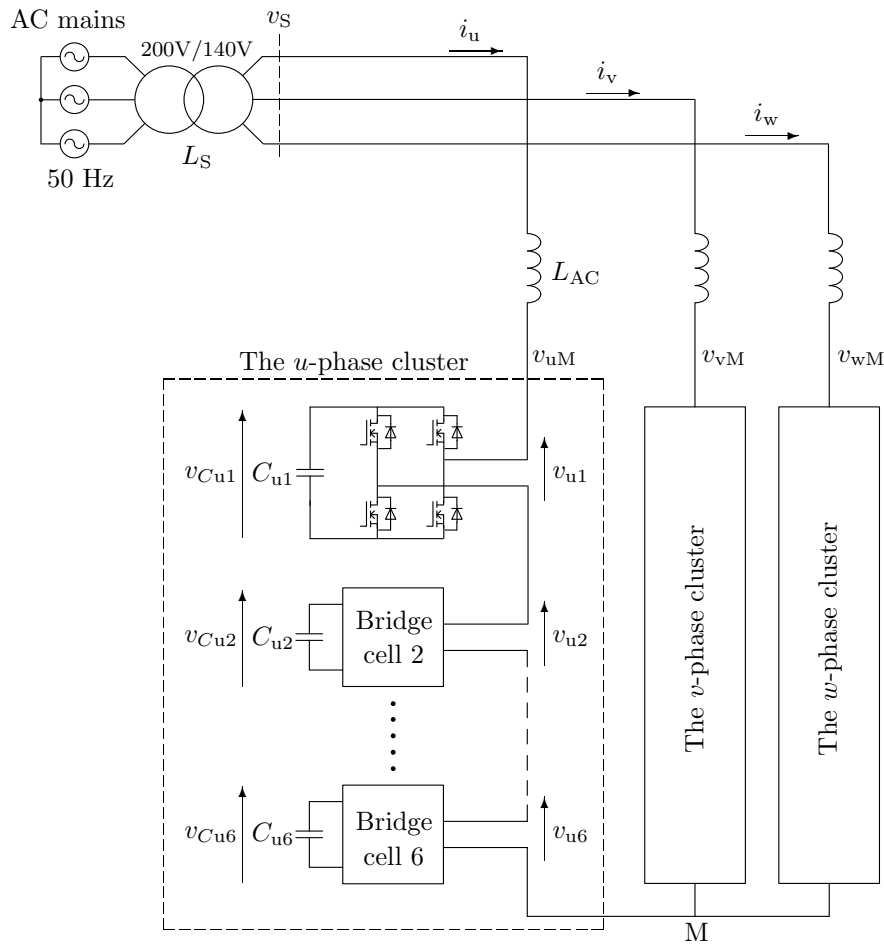


**Fig. 3.7:** Circuit configuration of the three-phase 140-V, 10-kVA SSBC-based D-STATCOM downscaled system with a cascade count of  $N = 6$ .

A 6.6-kV transformerless SSBC-based D-STATCOM using 3.3-kV IGBT modules available on the market would have a cascaded count of four cells per cluster ( $N = 4$ ), while an application with 1.7-kV IGBTs would have eight, nine, or ten cells per cluster

Tab. 3.1: Circuit constants and control parameters in Fig. 3.7.

|                                  |          |                                |
|----------------------------------|----------|--------------------------------|
| Nominal line-to-line rms voltage | $V_S$    | 140 V                          |
| Rated converter capacity         |          | 10 kVA                         |
| Cascade count per cluster        | $N$      | 6                              |
| Background system inductance     | $L_S$    | 0.10 mH (1.6%)                 |
| AC inductance                    | $L_{AC}$ | 0.33 mH (5.3%)                 |
| DC reference voltage             | $V_C^*$  | 24 V / 26 V                    |
| DC capacitance                   | $C$      | 47 mF                          |
| Unit capacitance constant [157]  | $H$      | 24 ms at 24 V<br>29 ms at 26 V |
| PWM carrier frequency            | $f_c$    | 1.75 kHz                       |
| Equivalent PWM carrier frequency |          | 21 kHz                         |
| Dead time                        |          | 4 $\mu$ s                      |

on a three-phase, 140-V, 10-kVA, 50-Hz base

( $N = 8, 9$  or  $10$ ). A D-STATCOM based on 1.7-kV IGBTs would have power ratings ranging from 500 kVA when 100-A devices are used, to 5 MVA when devices with current ratings higher than 600 A. Even if the D-STATCOM is installed on a higher-voltage distribution system (for example, 13.8-kV distribution systems in the USA), the cascaded count would be  $N = 9$  or  $10$  when 3.3-kV IGBTs are used. Thus, a cascade count of  $N = 6$  for the 140-V 10-kVA downscaled system is a good choice to demonstrate the functionality and operation of the 6.6-kV transformerless SSBC-based D-STATCOM.

### Control System

Fig. 3.8 shows the control system configuration. The three-phase ac mains line-to-line voltages  $v_S$  and line currents  $i$  are obtained through voltage (or potential) and current transformers, respectively, and acquired by A/D converter circuits. The dc capacitor voltages ( $v_{Cu1}, v_{Cu2}, \dots, v_{Cu6}$ ) of the 18 bridge-cells are detected through galvanic-isolated voltage sensors, and then acquired by multiplexers and A/D converter circuits. The three-phase reference currents for the D-STATCOM are calculated by a DSP board (Texas Instruments TMS320C6713), and the PWM gate signals for 18 bridge cells are generated by an FPGA board (Altera Cyclone II) and are sent to each bridge cell through copper flat cables. Photocoupler-based isolated gate circuits, located inside the bridge cell, activate the MOSFET devices.

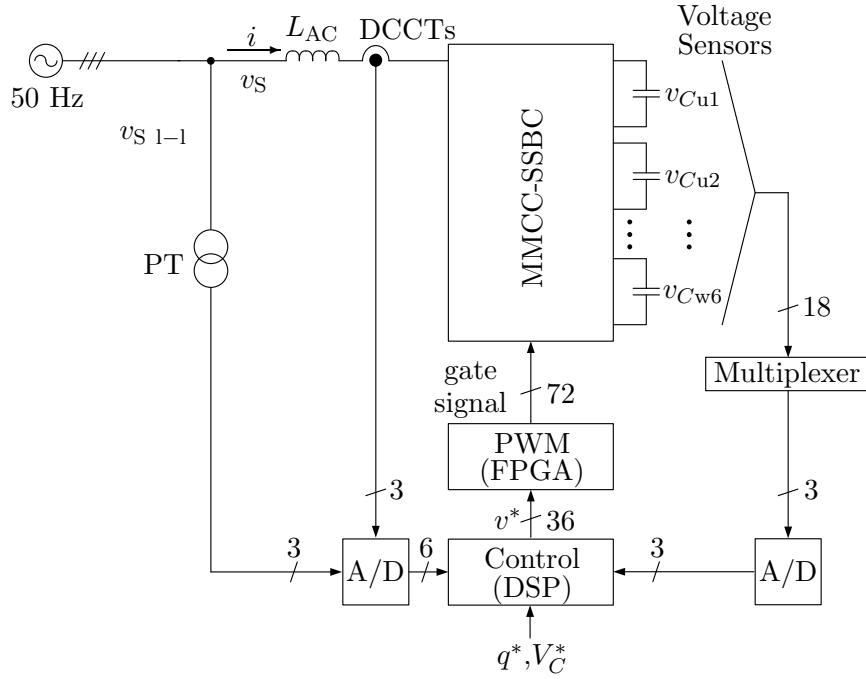


**Fig. 3.8:** Control and data-acquisition systems of the SSBC-based D-STATCOM.

The carrier frequency of a single bridge cell is set to 1.75 kHz in the downscaled experimental setup. An actual D-STATCOM based on IGBTs would have a lower carrier frequency when applying the unipolar phase-shifted-carrier pulse-width modulation (PWM). However, even for a reduction to below 1 kHz would still result in a high equivalent switching frequency if the cascade count is 8, 9, or 10. For example, for a carrier frequency of  $f_c = 800$  Hz and  $N = 10$ , the equivalent switching frequency would be  $2 \times 10 \times f_c = 16$  kHz.

### 3.3.2 The 140-V, 10-kW, 21-kWh SSBC-based BESS

#### Main Circuit Configuration

Fig. 3.9 shows the downscaled model of the SSBC-based BESS equipped with 18 lithium-ion (Li-ion) battery modules. Tables 3.2 and 3.3 summarize the circuit and control parameters of the BESS and the electric specifications of each Li-ion battery module respectively.

The SSBC-based BESS consists of three clusters with star configuration through the

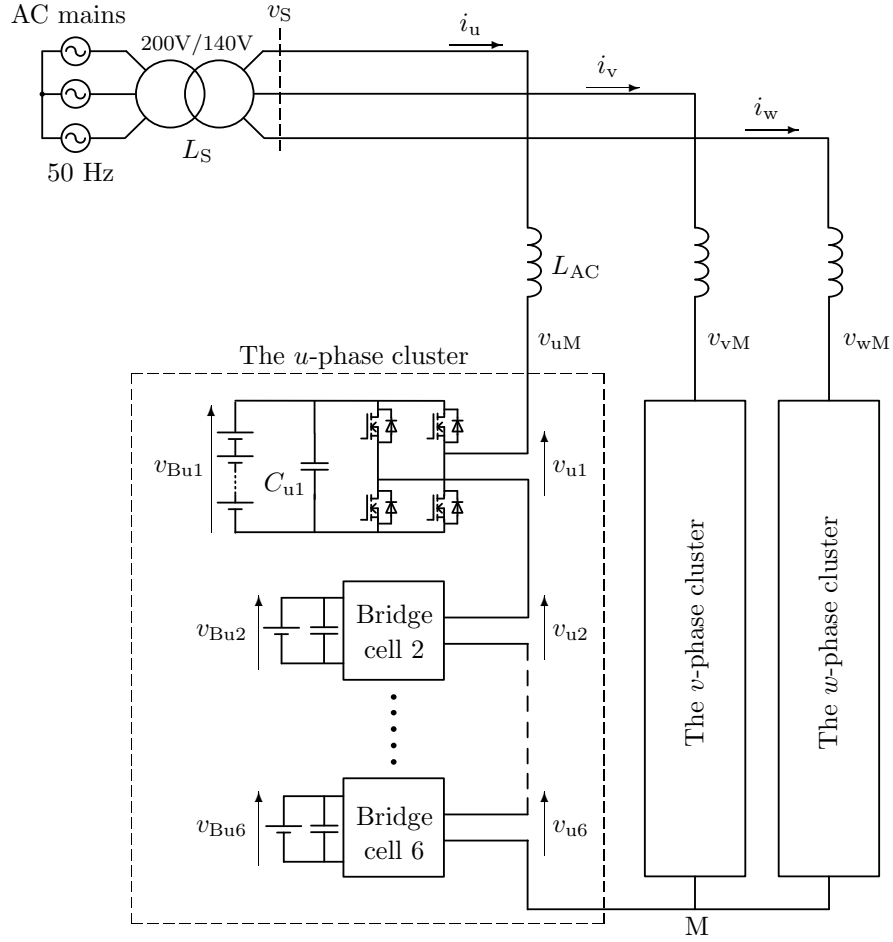


**Fig. 3.9:** Circuit configuration of the three-phase 140-V, 10-kW, 21-kWh SSBC-based BEES downscaled system with a cascade count of  $N = 6$ .

common point M. Each cluster consists of the cascade connection of six full-bridge or H-bridge cells, and the SSBC is connected to the ac mains through an ac inductor per phase. Parallel-connected 100-V, 80-A MOSFETs with a drain-to-source resistance as low as 10 m $\Omega$  are used as the switching devices. A three-phase transformer is used for voltage matching. Each bridge cell has a dc capacitor and a voltage sensor to detect the capacitor voltage. A battery module is connected directly to the dc terminals of each bridge cell via lead wires. Each battery module consists of seven series-connected lithium-ion (Li-ion) battery cells. The battery module has a nominal terminal voltage of 25.9 V, and a rated power capacity of 1.2 kWh [99, 158]. The total power capacity of the 18 battery modules is 21 kWh or 22 MJ. A battery management system (BMS) is integrated into each battery module. It manages to protect the battery module against

**Tab. 3.2: Circuit constants and control parameters in Fig. 3.9.**

|                                  |          |                 |
|----------------------------------|----------|-----------------|
| Nominal line-to-line rms voltage | $V_S$    | 140 V           |
| Rated converter capacity         |          | 10 kW           |
| Rated energy capacity            |          | 21 kWh (22 MJ)  |
| Cascade count per cluster        | $N$      | 6               |
| Background system inductance     | $L_S$    | 0.10 mH (1.6%)  |
| AC inductance                    | $L_{AC}$ | 0.33 mH (5.3%)  |
| Nominal battery voltage          | $V_B$    | 25.9 V          |
| DC capacitance                   | $C$      | 47 mF           |
| Unit capacitance constant [157]  | $H$      | 29 ms at 25.9 V |
| PWM carrier frequency            | $f_c$    | 1.75 kHz        |
| Equivalent PWM carrier frequency |          | 21 kHz          |
| Dead time                        |          | 4 $\mu$ s       |

on a three-phase, 140-V, 10-kVA, 50-Hz base

**Tab. 3.3: Specification of A Individual Battery Module.**

|                          |                                        |
|--------------------------|----------------------------------------|
| Nominal terminal voltage | 25.9 V (7 $\times$ 3.7 V/battery cell) |
| Operating voltage range  | 19.3–28.2 V                            |
| Rated power capacity     | 1.2 kWh (47.5 Ah)                      |

faults, short-circuit occurrences, and abnormal operation in temperature and battery-cell voltage.

Kawakami *et al.* [121] presented a grid-scale 500-kW SSBC-based BESS. A step-downs transformer with a voltage ratio of 6.6 kV:1.5 kV connects the BESS to a 6.6-kV distribution feeder. Although the use of a transformer is needed for isolation and safety reasons, it allows the application of low-voltage 600-V, 600-A IGBTs. The BESS uses lithium-ion battery modules with rated voltage of as low as 330 V. A 6.6-kV SSBC-based BESS using 1.7-kV, 1600-A IGBTs would be rated at 10 MVA and have an energy capacity of 10 MWh with lithium-ion battery modules having a nominal voltage as low as 700 V when using a cascade count of 10 [18].

Note that the battery current contains a dc component and a 100-Hz ac component. The 100-Hz component is intrinsic to the SSBC configuration. The presence of this component may shorten the lifetime of the internal battery cells of one battery module because the resulting rms battery current increases. Two possible solutions would be

applicable to mitigate or eliminate the bad effect of the 100-Hz component. One is to connect a simple bidirectional chopper between each battery module and each bridge cell [114, 119]. However, the use of this extra chopper makes the system complicated and costly. The other is to connect a dc inductor between each battery module and each bridge cell. This solution is simple and cost-effective because the dc inductor is much smaller in size or volume than one single battery module. The use of the dc inductor may bring voltage oscillations to each dc capacitor in dynamic or transient conditions. However, the voltage oscillation can be damped by means of a proper filtering technique, as is shown in chapter 4.

### Control System

Fig. 3.10 shows the control and data-acquisition systems of the SSBC-based BESS. The three-phase ac mains line-to-line voltages and line currents can be detected through voltage and current sensors, respectively, and are converted to digital signals by A/D converters. The terminal voltages  $v_{Bu1}$ ,  $v_{Bu2}$ ,  $\dots$ , and  $v_{Bw6}$  of the 18 battery modules are detected through galvanic-isolated voltage sensors installed on the dc capacitors of all the bridge cells. The detected capacitor voltages are converted through the combination of multiplexers and A/D converters. The three-phase current references for the BESS are calculated by a DSP board (Texas Instruments TMS320C6713), while 72 MOSFET gate signals to control the 18 bridge cells are generated by an FPGA board (Altera Cyclone II). Isolation of control system from the main power circuit is made by using photocoupler-based circuits, the potential transformer (PT), and the dc current transformers (DCCT). The methods used are enough for the verification of the downscaled model system.

As explained in section 3.3.2, an integrated BMS monitors the battery module operation. If any faulty condition or abnormal operation is detected, the BMS sends a digital signal to the FPGA board. Then, the FPGA immediately raises a flag to the DSP board, which interrupts the BESS operation. Differently from [56, 118], the control system does neither acquire any state-of-charge (SOC) information from each BMS nor detect any battery current from each module. Instead, the SOC value is monitored by detecting the terminal voltage of each Li-ion battery module.

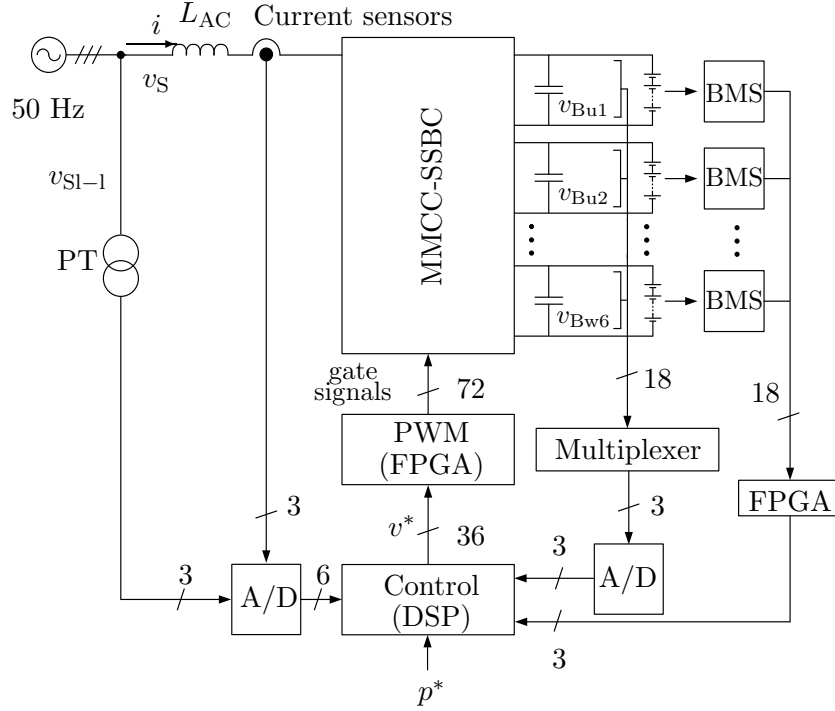


Fig. 3.10: Control and data-acquisition systems of the SSBC-based BESS.

Terminal voltage of battery modules are detected through a galvanic isolated dc voltage sensor equipped on the dc capacitor in the bridge cell. The detected signal is processed through an analog low-pass filter and sent to the multiplexer circuit. The BMS is powered by an external dc power supply. The FPGA board generates and send the gate signals to the bridge cells. Photocoupler-based isolated gate drive circuits, located within the bridge cells, activate the MOSFETs gates.

## 3.4 Current Control: Modeling, Design and Analysis

### 3.4.1 Phase-Shifted Carrier PWM on the SSBC

The stair-case modulation (SCM) was used by Peng *et.al.* in an SSBC-based STAT-COM [23, 24]. Switching angles for each cell are selected in order to generate an almost sinusoidal waveform. The main advantage is a low switching frequency that reduces total losses. Sirisukprasert *et al.* [159] implemented improved selective harmonic elimination (SHE) techniques and Rodriguez *et al.* [160] used a control strategy based on space vectors

to generate the staircase voltage waveforms.

Space vector pulse-width modulation (SVM or space-vector PWM) is a well-known technique to synthesize voltage waveforms in two-level inverters [161]. It can theoretically extend the utilization of dc voltage of inverters intrinsically, and its non-linear implementation makes it suitable to digital controllers. As for multilevel converters, Celanovic *et al.* [162] proposed a fast algorithm to SVM in three-phase multilevel converters confirmed through simulation results. Peng *et al.* [163] showed experimental results of a five-level NPC inverter using the SVM algorithm presented in [162].

The carrier-based pulse-width modulation (PWM) is one of the most used methods in industry for synthesizing voltage waveforms. Among its advantages are the simplicity and easy implementation. For an SSBC, a phase-shifted carrier PWM allows a high reduction of harmonic content, which eliminates the need of harmonic filters [55, 164, 165]. Moreover, the use of the PWM makes the actual switching frequency of a switching device equal to the carrier frequency. Therefore, the actual switching frequency is independent of modulation indexes and operation conditions, as well as circuit and control parameters. The constant switching frequency results in equal power losses on every bridge cell, thus leading to a simple design of heat sinks and cooling equipment.

The three methods are applicable to the SSBC. However, the SCM creates different voltage-pulse widths in each bridge cell, which causes an intrinsic power imbalance within the SSBC [58]. The space-vector PWM brings complexity in both implementation and computational time as the cascaded count increases [162, 166]. The phase-shifted PWM becomes much simpler in control system implementation than the space-vector PWM as the count of cascaded bridge-cells per cluster gets higher (e.g.,  $N = 10$ ). For both the SSBC-based D-STATCOM and BESS, hierarchical control techniques are implemented (later described in chapters 4 and 5). The hierarchy of control makes it possible to expand the SSBC to any cascaded count of bridge cells per cluster theoretically. Such reason motivates the author of this dissertation to adopt the phase-shifted PWM.

However, a non-negligible time delay caused by the phase-shifted PWM produces a harmful effect on current-control performance. A possible solution to overcome the bad effect resulting from the time delay is to perform multiple updates of each reference voltage signal during every half-cycle period of the individual phase-shifted triangular

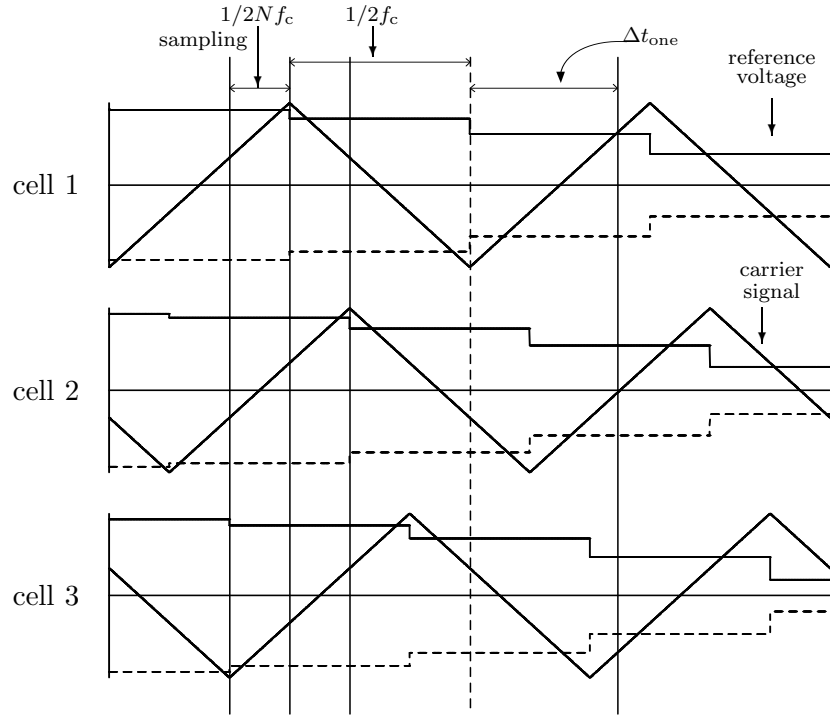


**Fig. 3.11: One-cell update method with  $N = 3$ .**

carrier signals. The author of this dissertation refer to it as the “all-cells” update method while the conventional method to perform a single update during that period as the “one-cell” update method. Walker [167], Odavic *et al.* [168], and Zhang and Spencer [169] had a theoretical and experimental discussion on the same solution as the all-cells update method.

This section discusses and analyzes two different types of update methods for the reference voltage, named the one-cell and the all-cells update methods. Both are applicable to phase-shifted PWM. For the sake of simplicity, this section assumes the bridge-cell count per cluster as  $N = 3$ . Three triangular carrier signals are shifted by  $\pi/3$ , and the frequency for each carrier is defined as  $f_c$ . Thus, the equivalent carrier frequency is  $f_{eq} = 6 \times f_c$ .

### Phase-Shifted-Carrier PWM: One-cell Update Method

Fig. 3.11 shows the triangular carrier signals and reference voltages of the three bridge cells when the one-cell update method is applied. Data sampling occurs for every carrier top and bottom, which yields a sampling period of  $T_s = 1/(2Nf_c)$ . To avoid multiple

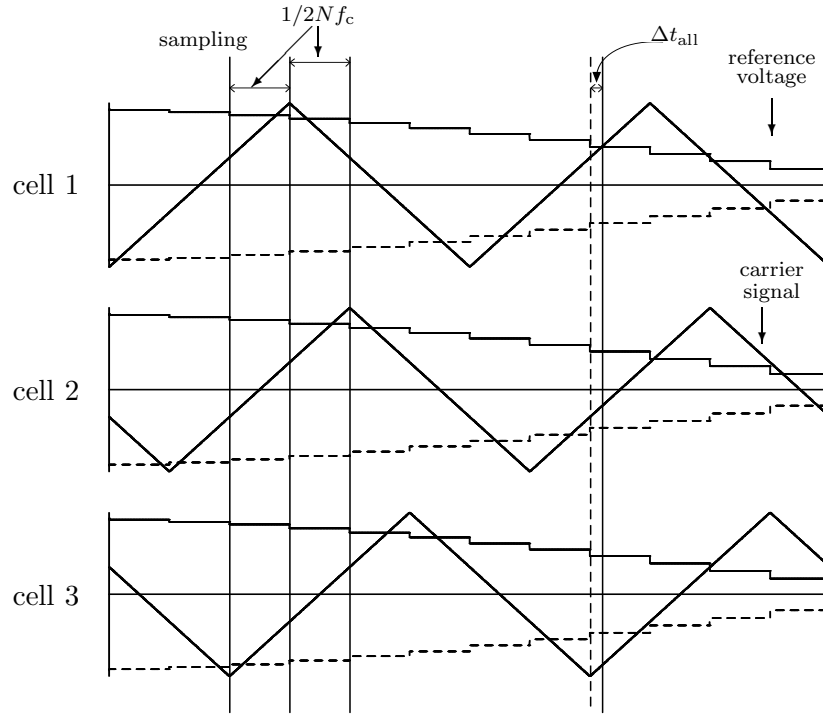


**Fig. 3.12: All-cells update method with  $N = 3$ .**

switching during the transition period between the carrier top and bottom, the reference voltage for each bridge cell is updated only at the respective carrier top and bottom. The updated reference voltage is held for a period of  $1/(2f_c)$ .

The time delay,  $\Delta t_{\text{one}}$ , between the reference voltage update and the actual switching can also be observed in Fig. 3.11. Although the time delay varies depending on the actual value of the reference voltage, the average time delay can be assumed to be a half of the reference voltage hold period ( $T_{\text{PWM}} = 1/(4f_c)$ ). Note that the time delay is not related to the cascade count of the SSBC.

The delay time of the once-cell update method could be reduced by increasing the PWM carrier frequency. However, this solution brings an engineering trade-off issue, because a limitation exists in the increased carrier frequency of an SSBC converter.

### Phase-Shifted-Carrier PWM: All-cells Update Method

Fig. 3.12 shows the triangular carrier signals and reference voltages of the three bridge cells when the all-cells update method is applied. In the same way as the one-cell update method, data sampling occurs at every carrier top and bottom. The only difference from

the one-cell update method is that the reference voltage update of each bridge cell occurs at the top and the bottom of all the carrier signals. The authors of [167] and [168] use a similar method to overcome the time delay caused by phase-shifted PWM, and refer to it as a “multisampled” reference voltage.

From Fig. 3.12, it is also possible to observe that the time delay between the reference update and the actual switching,  $\Delta t_{\text{all}}$  is shorter than the time delay  $\Delta t_{\text{one}}$  from the one-cell update method. The time delay of the all-cells update method can be assumed to be, in average,  $T_{\text{PWM}} = 1/(4Nf_c)$ . The time delay  $T_{\text{PWM}}$  and the cascade count  $N$  are inversely proportional. Therefore, an increase in the cascade count results in a shorter time delay, thus improving the system response and expanding the control frequency bandwidth.

The main drawback of the all-cells update method is that multiple switchings (also called as “multiswitching”) may occur during the transition period between the carriers top and bottom [167]. A simple software solution is integrated in the FPGA program to prevent the occurrence of multiswitchings.

As  $N$  is higher, a shorter calculation time requires a faster digital control system, because the reference voltage update period also becomes shorter [167]. Nevertheless, no problem happens when an SSBC is applied to a D-STATCOM and BESS. The reason is that the cascaded count of an SSBC converter would not be higher than  $N = 10$ , as pointed in section 3.3.1.

### 3.4.2 Modeling and Analysis of Current Control

This section analyzes the effect of the time delay  $T_{\text{PWM}}$  on current control performance. The analysis clarifies the time delay effect when the one-cell update method is used, and the attenuation of this effect when the all-cells update method is used.

#### When the One-cell Update Method is Used

Fig. 3.13(a) shows a PWM-pulse transfer block for the current control loop when the one-cell update method is used. The “Delay” block corresponds to the digital control time delay, and the “Hold & Inductor” block represents the hold time of the reference voltage

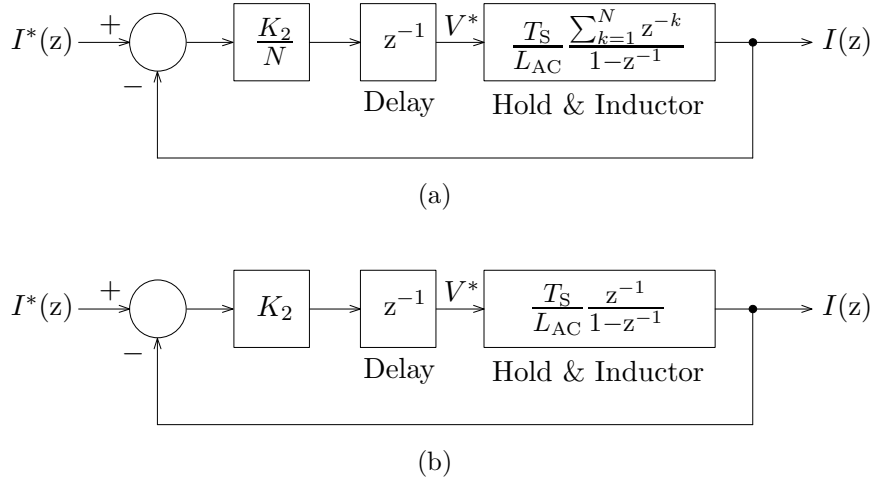


**Fig. 3.13: Diagram of the current control. (a) One-cell update method. (b) All-cells update method.**

and the voltage applied to the ac inductor. Here  $I^*(z)$  can be referred either to the current reference  $I_d^*(z)$  or  $I_q^*(z)$ , and the output current  $I(z)$ , respectively to  $I_d(z)$  or  $I_q(z)$ . The integral component of the PI control is discarded, because it has an insignificant effect on the control transient response. Since the reference voltage  $V^*$  is equally divided for each cell, the proportional gain is represented as  $K_2/N$ . Here, the modeling of the “Hold & Inductor” block of the current control is analyzed. The sampling period ( $T_S = 48 \mu s$ ) is different from the period during which the reference voltage  $V^*$  is held ( $1/(2f_c) = 286 \mu s$ ). Although the current output  $I(z)$  changes within one hold period, it may not occur within one sampling period after the update of the reference voltage. This makes it difficult to define a transfer function for the “Hold & Inductor” block.

To create an approximated model for the “Hold & Inductor” block, let each bridge cell be an ideal controllable voltage source with no restrictions in its output. This assumption makes it possible to calculate the value of  $I(z)$  at every data sampling instant. For a pulse response,  $I(z)$  can be approximated to a discrete integration. This approximation results in a value of  $NL_{AC}/T_S$  for  $I(z)$  by the end of the hold period. Therefore, the transfer

function for the “Hold & Inductor” block can be given by

$$\begin{aligned}\frac{I(z)}{V^*(z)} &= \frac{T_S}{L_{AC}} \left( \frac{z^{-1}}{1 - z^{-1}} + \frac{z^{-2}}{1 - z^{-1}} + \cdots + \frac{z^{-N}}{1 - z^{-1}} \right) \\ &= \frac{T_S}{L_{AC}} \frac{\sum_{k=1}^N z^{-k}}{1 - z^{-1}}.\end{aligned}\quad (3.1)$$

Fig. 3.13(a) includes this approximation. The closed-loop transfer function can be obtained by

$$\frac{I(z)}{I^*(z)} = \frac{\frac{K_2 T_S}{N L_{AC}} \sum_{k=1}^N z^{k-1}}{z^{N+1} - z^N + \frac{K_2 T_S}{N L_{AC}} \sum_{k=1}^N z^{k-1}}. \quad (3.2)$$

The gain  $K_2$  for the critical damping response can be obtained from (3.2). However, a numerical method was used because it is impossible to calculate the gain by a straightforward method. The analysis of the dynamic response of the 7th-order transfer function in (3.2) was approximated to that of a second-order transfer function taking into account only the dominant poles of the original 7th-order transfer function. This approximation is valid because the dominant poles in a multipolar transfer function are the ones with the slowest time constant, thus governing the overall system response.

Fig. 3.14 shows the location of the poles of (3.2) for different values of the current control gain  $K_2$ . For this calculation, the cascaded count was  $N = 6$ , the ac inductor was  $L_{AC} = 0.33$  mH, and the sampling period was set to  $T_S = 48$   $\mu$ s. The resulting poles plotted for different values of  $K_2$  show that the major changes on pole location occurs only for the dominant poles of (3.2). For large values of  $K_2$ , the dominant poles become complex conjugates. This leads to a under-damped response with overshoots, considering a second-order system. The complex conjugates for a gain value of  $K_2 = 0.6$  in Fig. 3.14 have a minimum imaginary part. This leads to a current response without oscillating components. Therefore, the gain value  $K_{2\text{one}} = 0.6$  V/A is obtained as the critical damping gain for the current control using the one-cell update method.

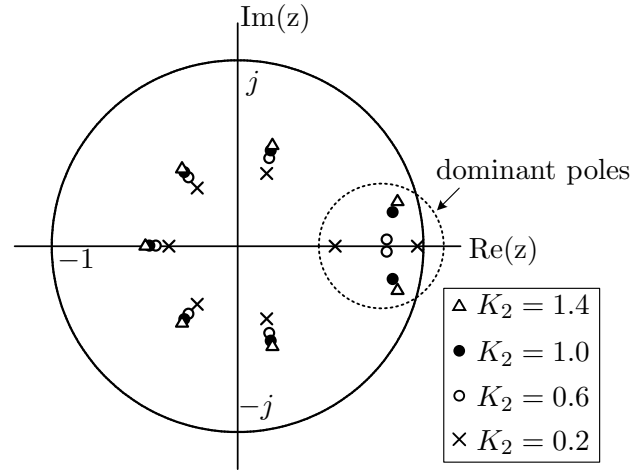


**Fig. 3.14:** Poles of the closed-loop transfer function given by (3.2) in the  $z$ -plane, when  $N = 6$ ,  $L_{AC} = 0.33$  mH, and  $T_S = 48$   $\mu$ s.

### When the All-cells Update Method is Used

Fig. 3.13(b) shows the control block diagram for the all-cells update method. The same considerations as those made for the one-cell update method are applicable to the all-cells update method. The current output can be directly obtained after a sampling period because the reference voltage update period and the sampling period are the same ( $T_S = 1/(2Nf_c) = 48$   $\mu$ s). Thus, the equivalent model for the SSBC converter can be obtained by

$$\frac{I(z)}{V^*(z)} = \frac{T_S}{L_{AC}} \frac{z^{-1}}{1 - z^{-1}}. \quad (3.3)$$

Equation (3.3) results in being equivalent to the transfer function of a conventional two-level converter.

Considering the closed-loop transfer function, the following equation can be obtained by

$$\frac{I(z)}{I^*(z)} = \frac{\frac{K_2 T_S}{L_{AC}}}{z(z-1) + \frac{K_2 T_S}{L_{AC}}}. \quad (3.4)$$

Equation (3.4) is a second-order transfer function. The poles of the transfer function are

defined as

$$z = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{K_2 T_S}{L_{AC}}}. \quad (3.5)$$

From (3.5), the critical damping gain can be easily obtained by

$$K_{2all} = \frac{L_{AC}}{4T_S} [\text{V/A}]. \quad (3.6)$$

Using the parameters  $L_{AC} = 0.33 \text{ mH}$  and  $T_S = 48 \mu\text{s}$ , the critical damping gain obtained from (3.6) is  $K_{2all} = 1.7 \text{ V/A}$ . This is almost three times higher than the critical damping gain value in the one-cell update method.

### Comparison Between One-Cell and All-Cells Update Methods

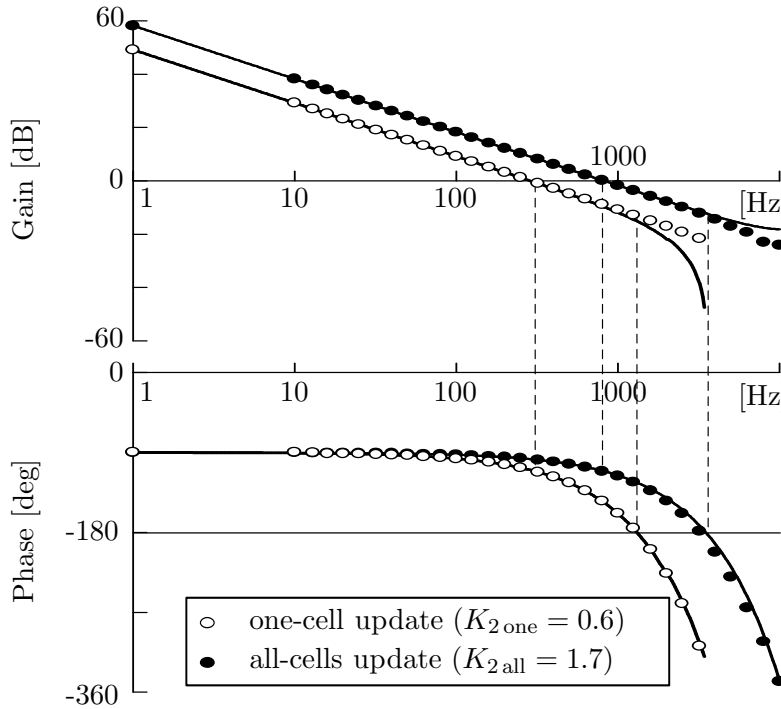


**Fig. 3.15:** Comparisons in closed-loop transfer function between the one-cell update method and the all-cells update method.

Fig. 3.15 shows the frequency response for the close-loop transfer function when either one-cell or all-cells update method is applied. The solid line corresponds to theoretical values obtained from (3.2) and (3.4), using the relationship given by  $z = e^{j2\pi f T_S}$ . The

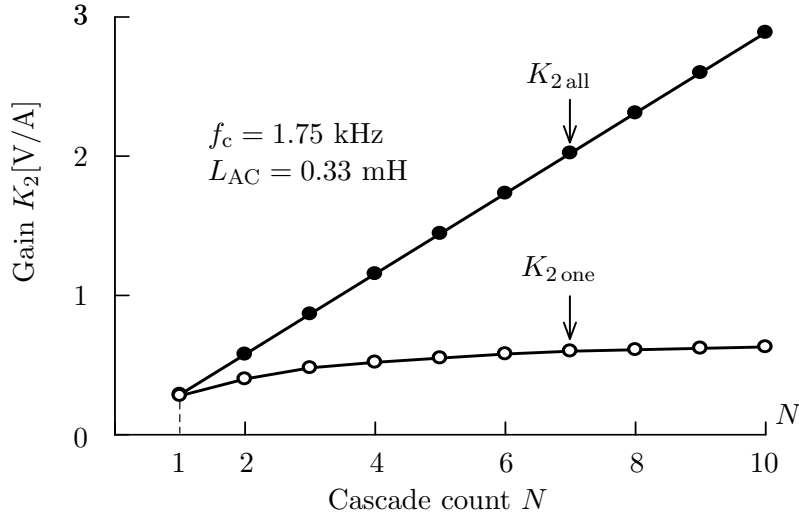


**Fig. 3.16:** Relation between the critical damping gains  $K_{2\text{one}}$ ,  $K_{2\text{all}}$  and the cascade count  $N$

black and white dots correspond to results obtained through simulation. Here, the critical damping gains  $K_{2\text{one}} = 0.6 \text{ V/A}$  and  $K_{2\text{all}} = 1.7 \text{ V/A}$  are used. As can be seen, the theoretical curves agree well with the simulated ones. The gain margin is 12 dB and the phase margin is 70 degrees for either one-cell or all-cells update method. These gain and phase margins are enough to guarantee stability.

Fig. 3.16 shows the relation between the critical damping gain and the cascade count  $N$  for either one-cell or all-cells update method, considering the same carrier frequency and ac inductor. For the one-cell update method, the critical damping gain was obtained by means of the numerical method presented in section 3.4.1. For the all-cells update method, it was directly obtained from (3.6). As the cascade count  $N$  increases, the critical damping gain increases slightly for the one-cell method, and then it saturates. However, it increases linearly for the all-cells update method.

### 3.4.3 Experimental and Simulated Results of Step Response

Experimental and simulated verification were done to verify the effectiveness of the all-cells update method on the current control response. Here, the SSBC converter was operated as a D-STATCOM. Section 3.3.1 describes the experimental setup, and chapter 4 details the control strategies adopted.

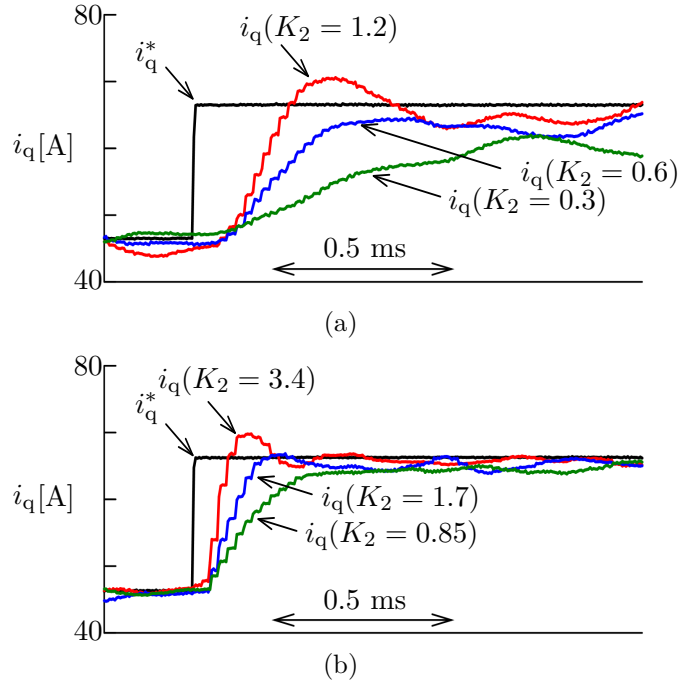


Fig. 3.17: Experimental comparison in step response of  $i_q$  between the one-cell update method and the all-cells update method as a parameter of current control gain  $K_2$ . (a) One-cell update method. (b) All-cells update method.

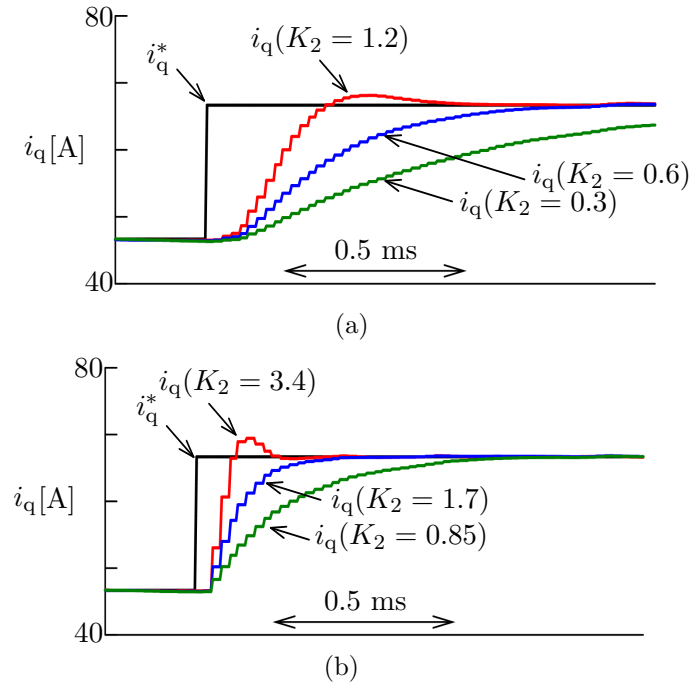


Fig. 3.18: Simulated comparison in step response of  $i_q$  between one-cell update method and all-cells update method as a parameter of current control gain  $K_2$ . (a) One-cell update method. (b) All-cells update method.

Figs. 3.17 and 3.18 show experimental and simulated waveforms for a step response of the current control when the reference reactive power was changed from 7 kVA to 10 kVA, respectively. The step response was obtained for different values of gain  $K_2$ , for both all-cells and one-cell update methods.

As can be observed, experimental waveforms agree well with the simulated ones. Figs. 3.17(a) and 3.18(a) shows the current control response when the one-cell update method was applied. Figs. 3.17(b) and 3.18(b) shows the current control response when the all-cells update method was applied. The control response was slower when using the one-cell update method than when using the all-cell update method. Note that a critical step response is obtained when  $K_2 = 0.6$  V/A for the one-cell update method, while for the all-cells update the critical step response is obtained when  $K_2 = 1.7$  V/A. As for the all-cells update method, a faster and stable current response is obtained by the use of a higher critical gain. For both methods, an overshoot occurs when a  $K_2$  higher than the critical value is applied, thus validating the analysis and modeling achieved in section 3.4.2 and showed in Fig. 3.16.

### 3.5 Summary

This chapter presented the experimental downscaled model of a D-STATCOM and a BESS based on an SSBC converter. The experimental downscaled system of an SSBC with per-cluster cascaded count of six allowed a proper evaluation to demonstrate the functionality of the D-STATCOM and the BESS.

The current control was modeled, design and analyzed with focus on how the phase-shifted-carrier PWM affects it. The critical gain saturates even for higher  $N$  when applying the one-cell update method. The all-cells update method reduces the effect of the intrinsic time delay, and improves the performance of the current control. Simulated and experimental results have confirmed the analysis and validated both the achieved model and design.

## Chapter 4

# Operation of the SSBC-based Distribution STATCOM

### 4.1 Introduction

The present chapter describes a distribution STATCOM (D-STATCOM) based on a modular multilevel SSBC converter intended for installation on 6.6-kV distribution power systems. An overview of the control strategy is presented, with attention to the modeling of the cluster-balancing control. Two methods to mitigate a 100-Hz component on the dc capacitor voltages are modeled and analyzed. This chapter presents experimental waveforms of steady-state operation of the D-STATCOM comparing the performance of one-cell and all-cells update methods presented in chapter 3. Transient operation is also verified. Finally, experimental results verifying the performance of the cluster-balancing control are presented.

### 4.2 Control of the SSBC-based D-STATCOM

Fig. 4.1 shows the diagram of the control block structure for the SSBC-based D-STATCOM. The control system can be divided in three main blocks: (1) reactive-power and overall balancing control, (2) cluster-balancing control, and (3) individual balancing control. Sections 4.2.1 and 4.2.2 make a detailed description of the control strategy used

for the SSBC-based D-STATCOM.

A three-phase digital PLL is used for obtaining the necessary phase information to synchronize the D-STATCOM with the ac mains. Chapter 6 presents a design of the adopted PLL. The mean dc values of the dc capacitor voltages  $v_{Cu1}, v_{Cu2}, \dots, v_{Cw6}$  are obtained through a moving average filter (MAF) with a moving window of 100 Hz. The MAF is superior to a low-pass-filter in enhancing the cluster-balancing control performance. The present chapter discusses the design of the cluster balancing control and compares the performance of the MAF and the LPF.

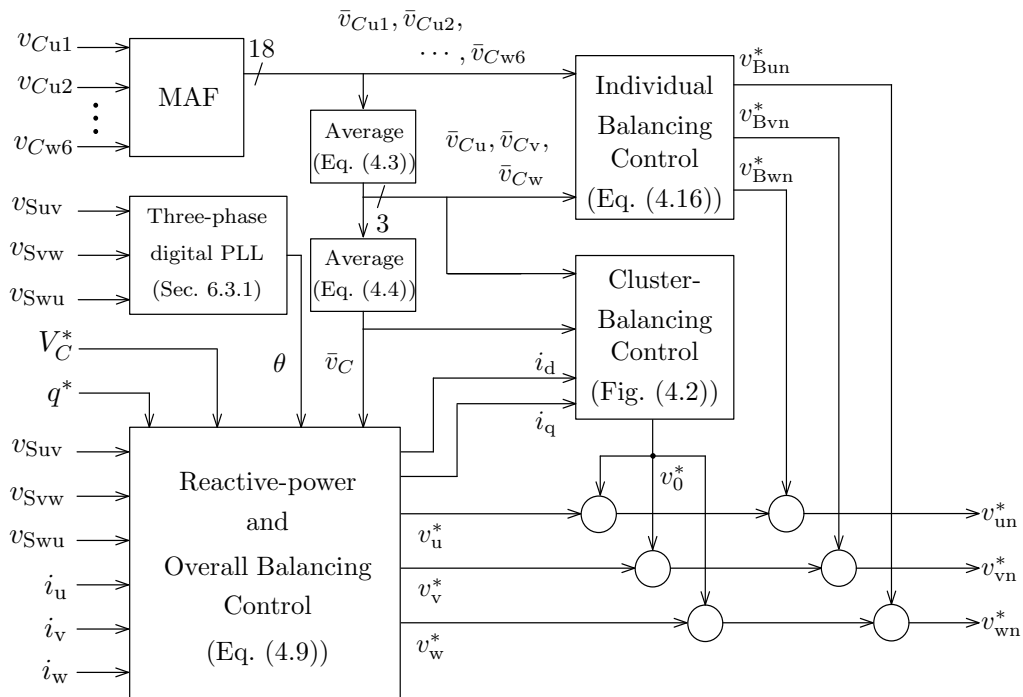


Fig. 4.1: Control block diagram.

### 4.2.1 Overall DC Capacitor Voltage Balancing Control and Reactive Power Control

The instantaneous active and reactive power flows [170] within the SSBC can be defined by

$$p = v_{sd} i_d + v_{sq} i_q \quad (4.1)$$

$$q = v_{sd} i_q - v_{sq} i_d. \quad (4.2)$$

Here,  $v_{sd}$  and  $v_{sq}$  refer to the ac mains voltages in the  $dq$ -frame, and  $i_d$  and  $i_q$  are currents drawn by the D-STATCOM in the  $dq$ -frame, as showed in Fig. 3.8. When the ac mains voltages are balanced,  $v_{sq}$  is always zero because  $\vec{v}_s$  is aligned with the  $d$ -axis [55].

From the six dc capacitor voltages of the u-phase cluster, the arithmetical average dc voltage can be calculated by

$$\bar{v}_{Cu} = \frac{1}{6} (\bar{v}_{Cu1} + \bar{v}_{Cu2} + \dots + \bar{v}_{Cu6}). \quad (4.3)$$

The voltages  $\bar{v}_{Cu1}, \bar{v}_{Cu2}, \dots, \bar{v}_{Cu6}$  refers to the mean dc values of the capacitor voltages, obtained through the MAF, as shown in Fig. 4.1.

With the average dc voltage of each cluster, the arithmetical average voltage of the 18 dc capacitors can be obtained by

$$\bar{v}_C = \frac{1}{3} (\bar{v}_{Cu} + \bar{v}_{Cv} + \bar{v}_{Cw}). \quad (4.4)$$

The references for the instantaneous active and reactive powers can be defined by

$$p^* = K_1 (V_C^* - \bar{v}_C) v_{sd} \quad (4.5)$$

$$q^* = v_{sd} i_q^*. \quad (4.6)$$

From (4.5) and (4.6), the reference currents for the D-STATCOM on the  $dq$  reference

frames can be defined as

$$i_d^* = K_1(V_C^* - \bar{v}_C) \quad (4.7)$$

$$i_q^* = \frac{q^*}{v_{Sd}}. \quad (4.8)$$

Here  $V_C^*$  corresponds to the dc reference voltage for the dc capacitors.

The ac-voltage commands for the SSBC-based D-STATCOM can be defined by

$$\begin{bmatrix} v_d^* \\ v_q^* \end{bmatrix} = \frac{1}{6} \left( \begin{bmatrix} v_{Sd} \\ v_{Sq} \end{bmatrix} - \begin{bmatrix} 0 & -\omega L_{AC} \\ \omega L_{AC} & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} - K_2 \begin{bmatrix} i_d^* - i_d \\ i_q^* - i_q \end{bmatrix} - \frac{K_2}{T_2} \int \begin{bmatrix} 0 \\ i_q^* - i_q \end{bmatrix} dt \right). \quad (4.9)$$

The combination of the first and second terms in the right-hand side of (4.9) corresponds to the feed-forward compensation of the ac mains voltages due to cross-coupling terms caused by the  $dq$  transformation. The third and fourth terms correspond to the feedback loops for the  $d$ -axis and  $q$ -axis currents in  $i_d$  and  $i_q$ .

Note that the  $d$ -axis current is regulated by a proportional (P) control loop with a gain  $K_2$ , while the  $q$ -axis current is regulated by a proportional-plus-integral (PI) control loop with a gain  $K_2$  and a time constant  $T_2$ . The P control loop is applied to the  $d$ -axis current loop since the use of a PI controller may bring overshoot and damped oscillations in the current response at the occurrence and restoration of line faults and voltage sags.

## 4.2.2 Cluster Balancing Control

Fig. 4.2 shows the block diagram for the cluster-balancing control. The cluster-balancing control is achieved by injecting a common zero-sequence voltage into the clusters of the STATCOM [171, 172].

The differences between the arithmetical average dc capacitor voltage of all the clusters,  $\bar{v}_C$  and the arithmetical mean dc capacitor voltage of each cluster is obtained as

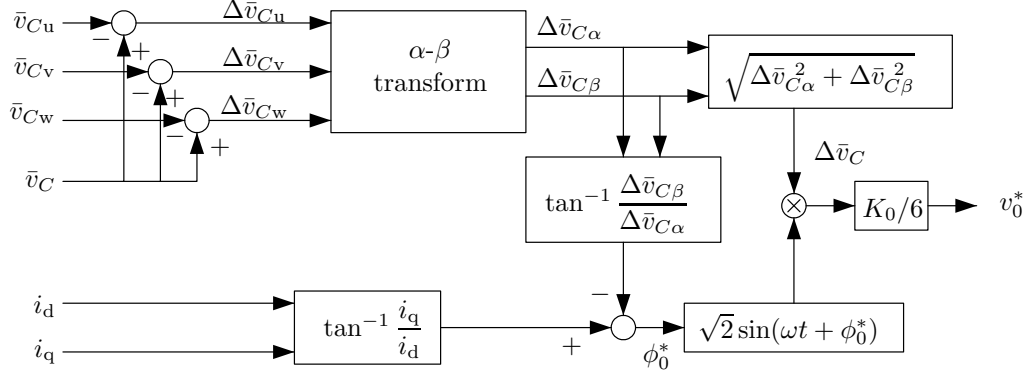


Fig. 4.2: Cluster-balancing control based on zero-sequence voltage injection.

follow:

$$\begin{bmatrix} \Delta \bar{v}_{Cu} \\ \Delta \bar{v}_{Cv} \\ \Delta \bar{v}_{Cw} \end{bmatrix} = \begin{bmatrix} \bar{v}_C - \bar{v}_{Cu} \\ \bar{v}_C - \bar{v}_{Cv} \\ \bar{v}_C - \bar{v}_{Cw} \end{bmatrix}. \quad (4.10)$$

Using the  $\alpha$ - $\beta$  transformation makes it possible to obtain the signals  $\Delta \bar{v}_{C\alpha}$  and  $\Delta \bar{v}_{C\beta}$  from the voltage differences  $\Delta \bar{v}_{Cu}$ ,  $\Delta \bar{v}_{Cv}$  and  $\Delta \bar{v}_{Cw}$ . The voltage differences on the uvw reference frames are transformed on the  $\alpha$ - $\beta$  reference frames as follows:

$$\begin{bmatrix} \Delta \bar{v}_{C\alpha} \\ \Delta \bar{v}_{C\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} \Delta \bar{v}_{Cu} \\ \Delta \bar{v}_{Cv} \\ \Delta \bar{v}_{Cw} \end{bmatrix}. \quad (4.11)$$

Thus, let  $\Delta \bar{v}_C$  and  $\phi_0^*$  be defined as

$$\Delta \bar{v}_C = \sqrt{\Delta \bar{v}_{C\alpha}^2 + \Delta \bar{v}_{C\beta}^2} = \sqrt{\Delta \bar{v}_{Cu}^2 + \Delta \bar{v}_{Cv}^2 + \Delta \bar{v}_{Cw}^2} \quad (4.12)$$

$$\phi_0^* = \tan^{-1} \frac{i_q}{i_d} - \tan^{-1} \frac{\Delta \bar{v}_{C\beta}}{\Delta \bar{v}_{C\alpha}}. \quad (4.13)$$

Here,  $\Delta \bar{v}_C$  is an rms value and  $\phi_0^*$  is a phase angle to represent a degree of the imbalance among dc capacitor voltages on the  $\alpha$ - $\beta$  reference frames.

The zero-sequence voltage to be injected into each cluster can be obtained through the results from (4.12) and (4.13):

$$v_0^* = \frac{\sqrt{2}K_0}{6}\Delta\bar{v}_C \sin(\omega t + \phi_0^*) \quad (4.14)$$

The signal  $v_0^*$  must be added to the reference ac voltage signal of each bridge cell, as showed in Fig. 4.1. Equation (4.14) suggests that the magnitude of the zero-sequence voltage to be injected is proportional to the imbalance among the mean dc capacitor voltages of the three clusters.

Section 4.3 presents a proper design of the proportional gain  $K_0$ , resulting in an accurate cluster-balancing response.

### 4.2.3 Individual Balancing Control

The aim of the individual balancing control is to keep each mean dc capacitor voltage equal to the arithmetical average dc voltage of the respective cluster. This is the same method presented by Akagi *et al.* [55]. Because the D-STATCOM draws only the reactive power from the grid, the current flowing in the u-phase can be represented by

$$i_u = \sqrt{\frac{2}{3}}I_q \cos(\omega t). \quad (4.15)$$

The following reference voltage can be defined:

$$v_{\text{Bun}}^* = \begin{cases} K_3 (\bar{v}_{C_u} - v_{C_{\text{un}}}) \cos(\omega t), & \text{if } q^* > 0 \\ -K_3 (\bar{v}_{C_u} - v_{C_{\text{un}}}) \cos(\omega t), & \text{if } q^* < 0. \end{cases} \quad (4.16)$$

Equation (4.16) shows that the voltage  $v_{\text{Bun}}^*$  is in phase with the correspondent cluster current. Thus, the reference voltage  $v_{\text{Bun}}^*$  produces an active power flow for the respective bridge cell to balance the mean dc capacitor voltages within a cluster. Consider the following relationship:

$$\sum_N v_{\text{Bun}}^* = \sum_N (\bar{v}_{C_u} - v_{C_{\text{un}}}) = 0. \quad (4.17)$$

Equation (4.17) indicates that the reference voltages of the individual balancing control produces no effect either on the overall current control or on the cluster-balancing control.

### 4.3 Analysis and Modeling of the Cluster-Balancing Control

The SSBC-based D-STATCOM makes the dc capacitor voltages of each bridge cell contain a 100-Hz component. This component may produce harmful effects on the performance of the cluster-balancing control. This section analyzes the following two filtering methods to remove the 100-Hz component:

1. a low-pass filter (LPF);
2. a moving-average filter (MAF).

The use of an LPF is the first approach to mitigate the ac component present on the dc capacitor voltages. Although it is known that an LPF does not totally cancel selected frequencies, its design is simple and straightforward.

The moving average filter (MAF) is a simple digital filter with a straightforward design. The frequency response of an MAF is composed of multiple notches. The gain on each notch is zero, making it possible to mitigate a selected frequency totally. Nevertheless, the filtering characteristic is poorer on the remaining frequency bands when compared to the LPF with an equivalent cutoff frequency.

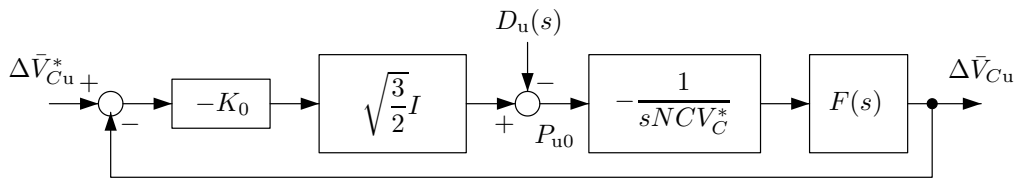


**Fig. 4.3: Block diagram of the cluster-balancing control (u-phase cluster).**

Fig. 4.3 shows the equivalent control block diagram for the cluster-balancing control, taking in account the u-phase. The input  $D_u(s)$  represents a power loss and a disturbance. The block defined by the transfer function  $F(s)$  represents the filter used to remove the 100-Hz component from the dc capacitor voltages of each bridge cell.

### 4.3.1 Low-Pass Filter

Akagi *et al.* [55] presented the use of a first-order low-pass filter (LPF) to extract the dc component from the dc capacitor voltage. The transfer function  $F(s)$  can be given by

$$F_{\text{LPF}}(s) = \frac{1}{1 + sT}. \quad (4.18)$$

The close-loop transfer function can be obtained from Fig. 4.3 as follows:

$$\frac{\Delta V_{Cu}}{\Delta V_{Cu}^*} = \frac{\sqrt{\frac{3}{2} \frac{K_0 I}{NCV_C^* T}}}{s^2 + \frac{1}{T}s + \sqrt{\frac{3}{2} \frac{K_0 I}{NCV_C^* T}}}. \quad (4.19)$$

Equation (4.19) is a second-order transfer function that yields a simple design for the gain. The damping factor  $\zeta$  and the natural frequency  $\omega_n$  are defined as follows:

$$\zeta = \sqrt{\frac{NCV_C^*}{2\sqrt{6}K_0 I T}} \quad (4.20)$$

$$\omega_n = \sqrt{\frac{\sqrt{3}K_0 I}{\sqrt{2}NCTV_C^*}}. \quad (4.21)$$

Equation (4.20) gives the gain for a critical damped response ( $\zeta = 1$ ) as follows:

$$K_0 = \frac{NCV_C^*}{2\sqrt{6}IT} [\text{V/V}], \quad (4.22)$$

and the frequency  $\omega_n$  as follows:

$$\omega_n = \frac{1}{2T}. \quad (4.23)$$

Therefore, the cutoff frequency of the LPF must be defined to obtain the critical damping gain  $K_0$ .

Considering the critical damping factor ( $\zeta = 1$ ), the response  $\Delta \bar{v}_{Cu}(t)$  for a given initial value  $\Delta \bar{v}_{Cu}(0)$  can be obtained from (4.19), as follows:

$$\Delta \bar{v}_{Cu}(t) = \Delta \bar{v}_{Cu}(0) \cdot (1 + \omega_n t) e^{-\omega_n t}. \quad (4.24)$$

Equation (4.24) corresponds to the response of  $\Delta\bar{v}_{Cu}$  when the cluster-balancing control is enabled. The value  $\Delta\bar{v}_{Cu}(0)$  corresponds to the initial difference between the arithmetical average dc voltage of all the clusters and the mean dc capacitor voltages of the u-phase cluster.

### 4.3.2 Moving-Average Filter

The moving-average filter (MAF) is designed to eliminate the 100-Hz component from the dc capacitor voltages of each bridge cell [28]. The transfer function  $F(s)$  when the MAF is applied can be given by

$$F_{\text{MAF}}(s) = \frac{1}{N_S} \frac{1 - e^{-sN_S/f_S}}{1 - e^{-s/f_S}}. \quad (4.25)$$

Here, the sampling frequency of the capacitor voltages is  $f_S = 3.5$  kHz. To eliminate the 100-Hz component, the number of samples taken by the filter is defined as  $N_S = 35$ , which yields to a moving window of  $T_{\text{MAF}} = 10$  ms. To simplify the analysis and design of the gain  $K_0$ , the open-loop transfer function in (4.25) is approximated to a first-order LPF with a cutoff frequency of 32 Hz ( $T = T_{\text{MAF}}/2 = 5$  ms).

Fig. 4.4 shows the frequency response of the MAF and the LPF with a 32-Hz cutoff frequency. Here, the similarity between the MAF and the LPF is clearly observed, mainly in a frequency range between 1 Hz and 10 Hz. Therefore, the critical damping gain  $K_0$  for the MAF can be calculated from (4.22). For a cutoff frequency of 32 Hz ( $T = 5$  ms), the value of the gain  $K_0$  is

$$K_{0\text{MAF}} = 7.3 \text{ V/V}. \quad (4.26)$$

The approximation of the MAF to an equivalent LPF is made on the basis that the MAF notches can be ignored on the desirable operating range of the filter. The same rationale justifies the use of an analog model to design  $K_0$  instead of a digital one.

Fig. 4.4 also presents the phase and gain margins of the closed-loop transfer function when the MAF is applied. The values of the gain and phase margins from the graphic

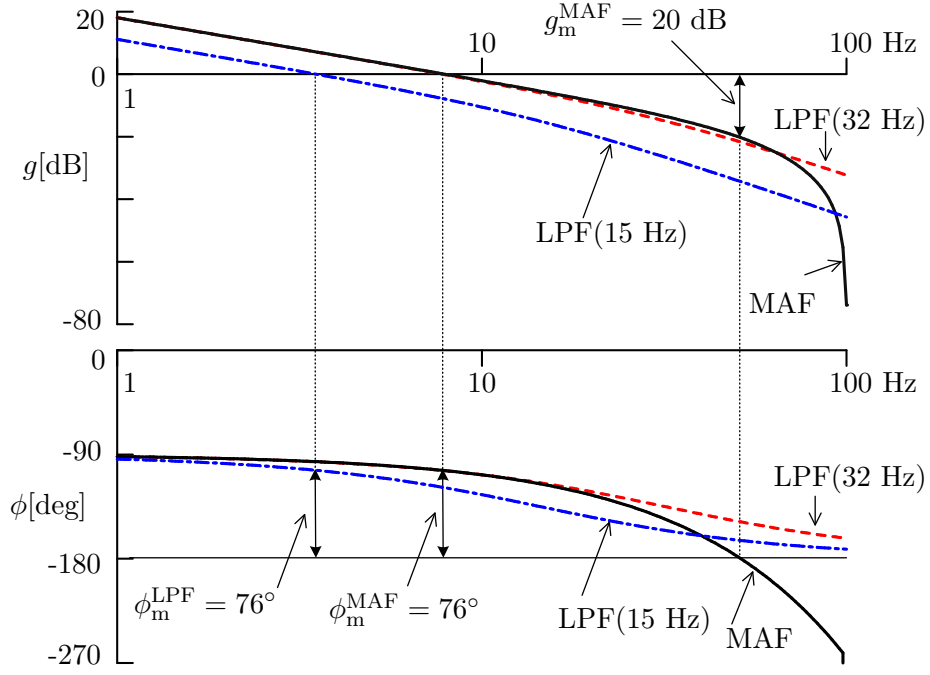


Fig. 4.4: Frequency response of the open-loop transfer function  $F(s)$ .

analysis yields

$$g_m^{\text{MAF}} = 20 \text{ dB} \quad (4.27)$$

$$\phi_m^{\text{MAF}} = 76^\circ, \quad (4.28)$$

which are within the limits for stable operation.

## 4.4 Experimental Results

### 4.4.1 Verification of the Cluster-Balancing Control Performance

#### Low-Pass Filter

A cutoff frequency of 15 Hz ( $T = 10$  ms) for the LPF was selected. The critical gain  $K_0$  in this case is

$$K_{0\text{LPF}} = 3.3 \text{ V/V}. \quad (4.29)$$

Fig. 4.5 shows experimental waveforms when the LPF is applied to the cluster-balancing control. The actual value of  $\Delta\bar{v}_C$  and the theoretical response obtained in (4.24) are compared. The dc capacitors voltages  $v_{Cu1}$ ,  $v_{Cv1}$ , and  $v_{Cw1}$  converged toward the dc voltage reference, and  $\Delta\bar{v}_C$  was reduced when the cluster-balancing control was enabled. However, the oscillation caused by the 100-Hz component in  $\Delta\bar{v}_C$  still remained. A higher cutoff frequency could be applied in the LPF to achieve a faster response. However, the remaining oscillation caused by the 100-Hz component would increase.

#### Moving-Average Filter

Fig. 4.6 shows the experimental results when the MAF is applied to the cluster-balancing control. Because the MAF can be approximated to a 32-Hz LPF, the theoretical response obtained in (4.24) can be still used to evaluate the cluster-balancing control performance. The mean dc voltages of the clusters were getting balanced after the cluster-balancing control was enabled. The response of the voltage difference  $\Delta\bar{v}_C$  agrees well with the theoretical one from (4.24), validating the approximation of the MAF to an equivalent LPF. Note that the MAF eliminates the 100-Hz component. Moreover, the response time of the cluster-balancing control is faster than the one applying the LPF. As a result, a significant improvement is achieved when applying the MAF to the cluster-balancing control for both steady-state and transient response.

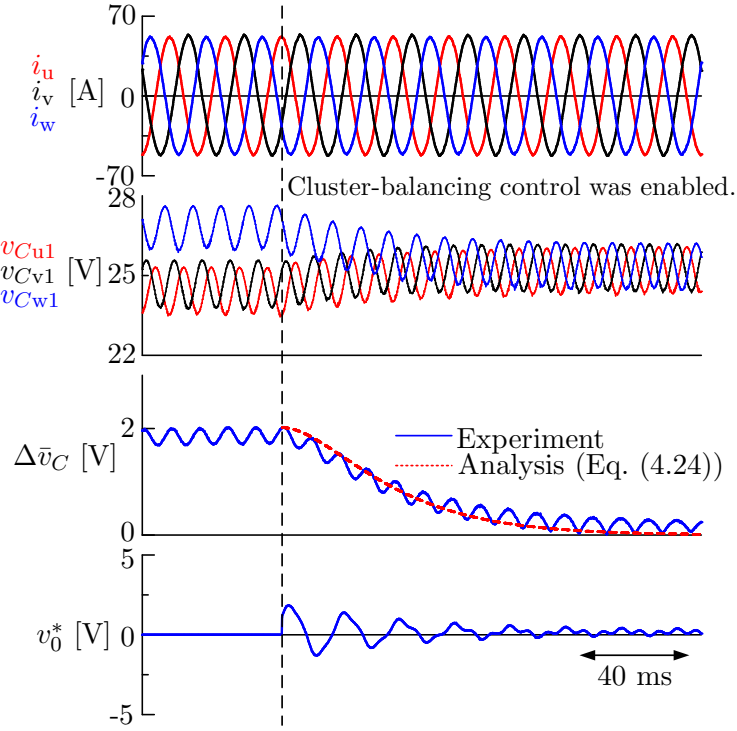


**Fig. 4.5:** Experimental waveforms for the rated capacitive operation when using the LPF.

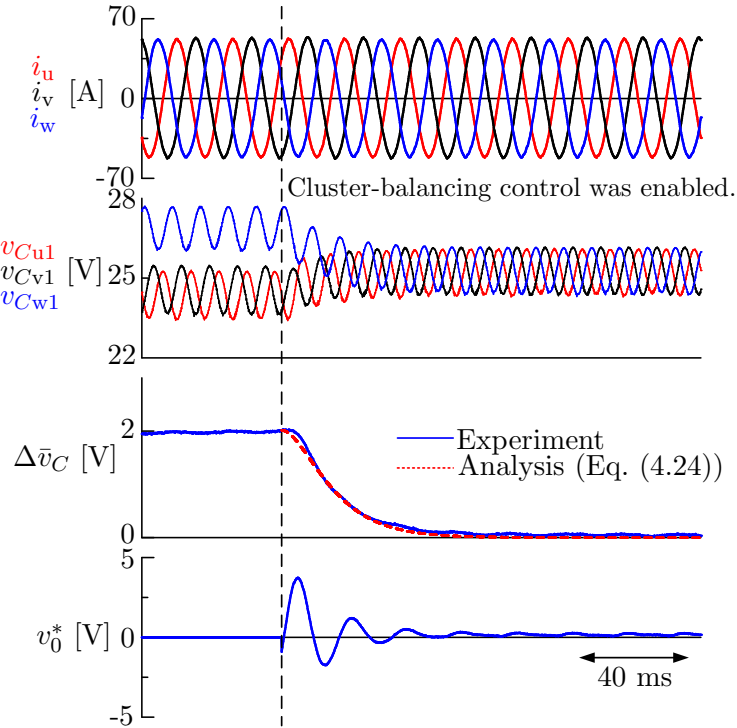


**Fig. 4.6:** Experimental waveforms for the rated capacitive operation when using the MAF.

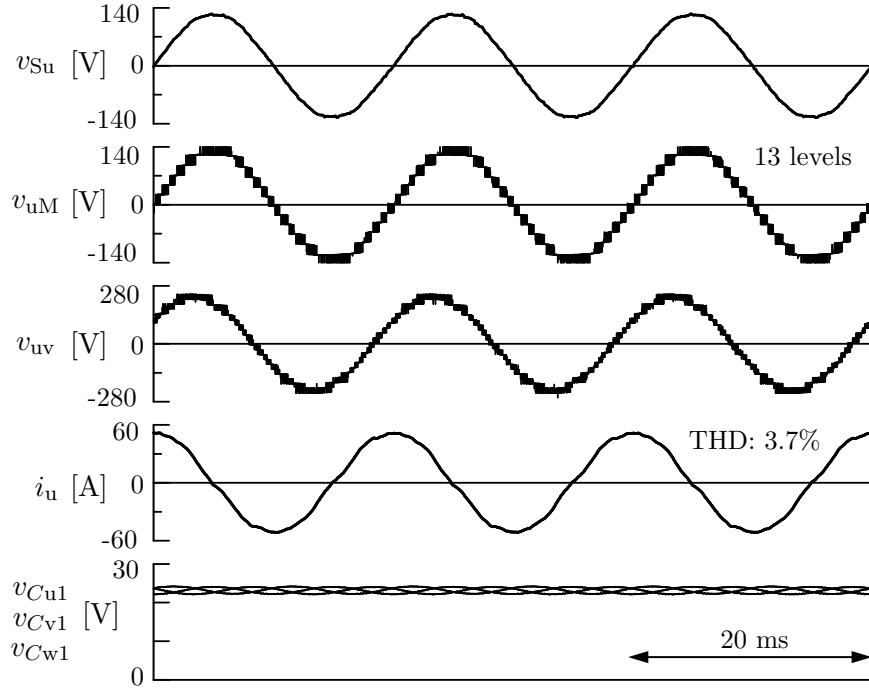
### 4.4.2 Steady-state Operation of the D-STATCOM

Figs. 4.7 and 4.8 show the experimental waveforms for the u-phase at the rated capacitive and inductive operation of D-STATCOM to compare the performance when either the one-cell or all-cells update methods described in chapter 3 are applied. Fig. 4.7 shows waveforms when the one-cell update method is applied, and Fig. 4.8 shows the ones when the all-cells update method is applied. The measured electrical quantities can be referred from Fig. 3.7. The line-to-neutral voltage produced by the u-phase cluster is represented by  $v_{uM}$ , which is measured from the u-phase terminal in respect to the common point M. In other words,  $v_{uM}$  corresponds to the sum of the bridge-cells ac voltages  $v_{u1}$ ,  $v_{u2}$ ,  $\dots$ , and  $v_{u6}$ . For the experimental verification, the dc capacitor voltages  $v_{Cu1}$ ,  $v_{Cv1}$ , and  $v_{Cw1}$  are measured only. Nevertheless, the voltages on the remaining bridge cells within a same cluster are similar [55]. Since the STATCOM has a cascaded count of  $N = 6$ , the line-to-neutral voltage at the ac side has 13 levels. The line-to-line voltage output presents a 25-level waveform, which can be considered as an almost sinusoidal voltage. The mean dc voltages are balanced and regulated to its reference of 24 V.

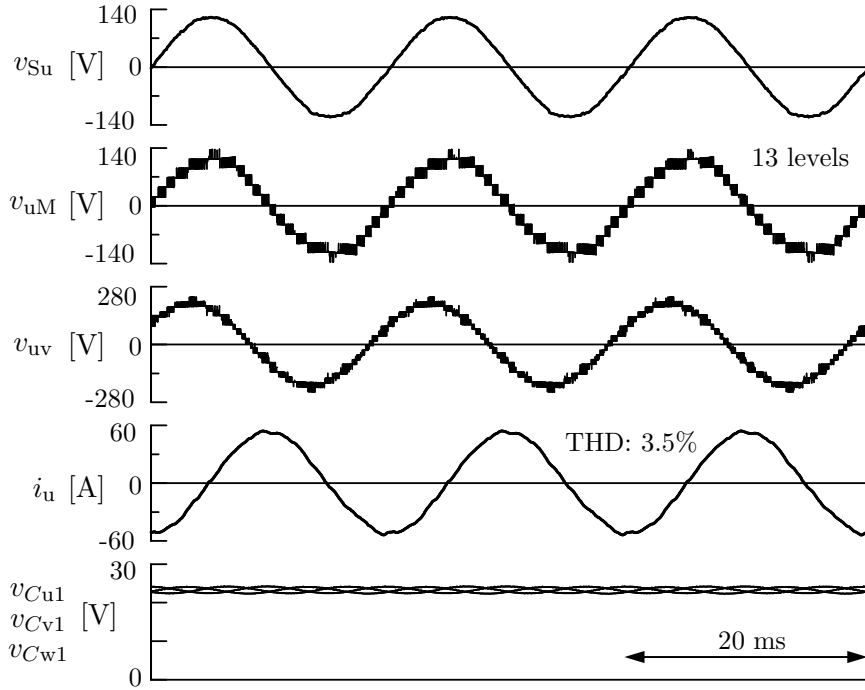
The u-phase current in Fig. 4.7 has a total harmonic distortion (THD) value of 3.7% during capacitive operation and 3.5% during inductive operation when using the one-cell update method. In Fig. 4.8, the u-phase current has a THD value of 1.5% during capacitive operation and 1.7% during inductive operation when using the all-cells update method. The experimental waveforms show a significant improvement in current control performance when the all-cells update method is applied.

### 4.4.3 Transient-state Operation of the D-STATCOM

Fig. 4.9 shows transient response waveforms from the rated inductive operation ( $q = -10$  kVA) to the rated capacitive operation ( $q = 10$  kVA), when the all-cells update method is applied. During the transient time of 20 ms, the actual reactive power shows no overshooting, and the mean dc capacitor voltages are kept balanced and regulated to its reference of 24 V.

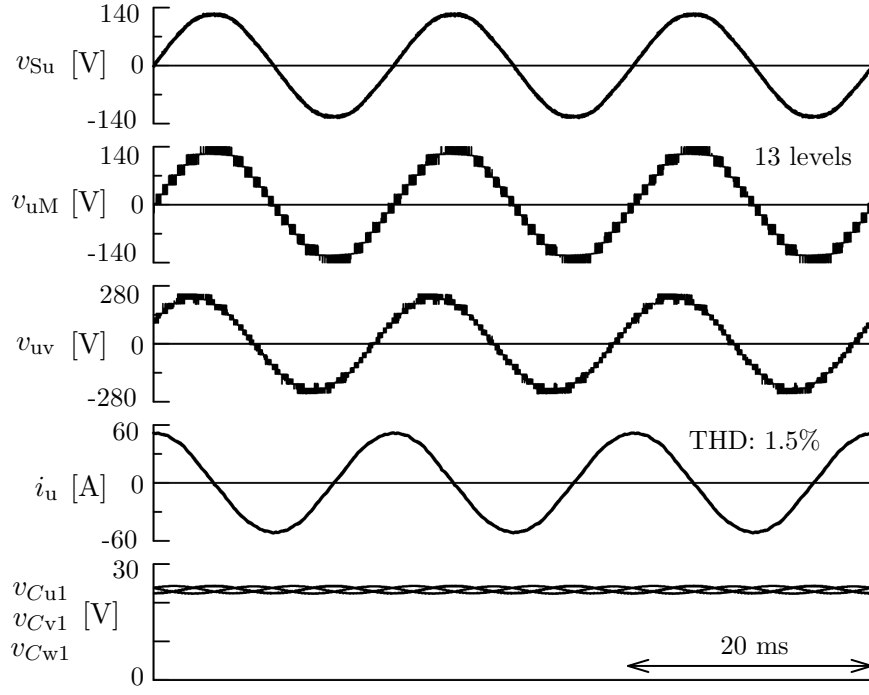


(a)

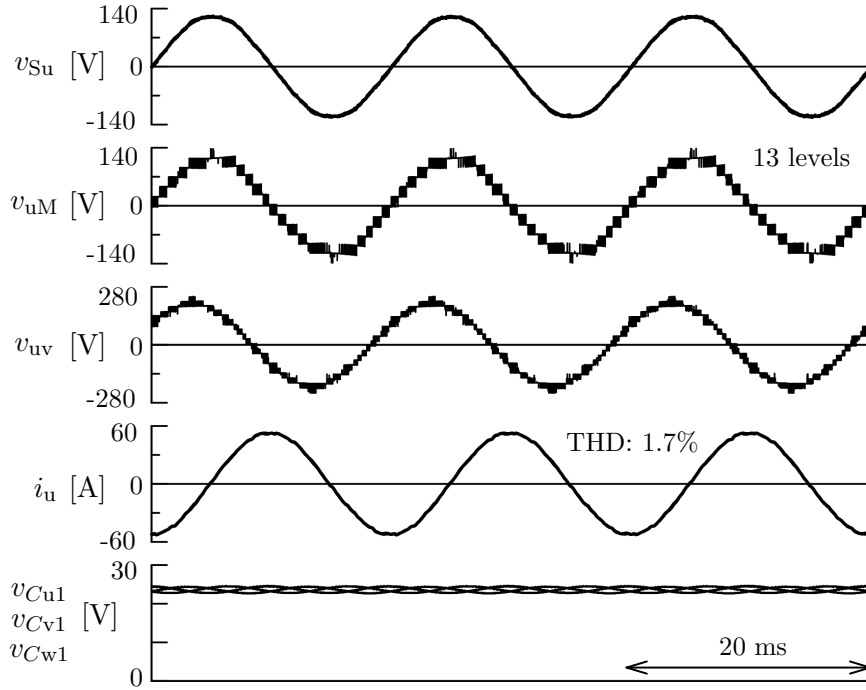


(b)

**Fig. 4.7:** Experimental waveforms by the one-cell update. (a) The rated capacitive operation ( $q^* = 10$  kVA). (b) The rated inductive operation ( $q^* = -10$  kVA).



(a)



(b)

**Fig. 4.8:** Experimental waveforms by the all-cells update. (a) The rated capacitive operation ( $q^* = 10$  kVA). (b) The rated inductive operation ( $q^* = -10$  kVA).

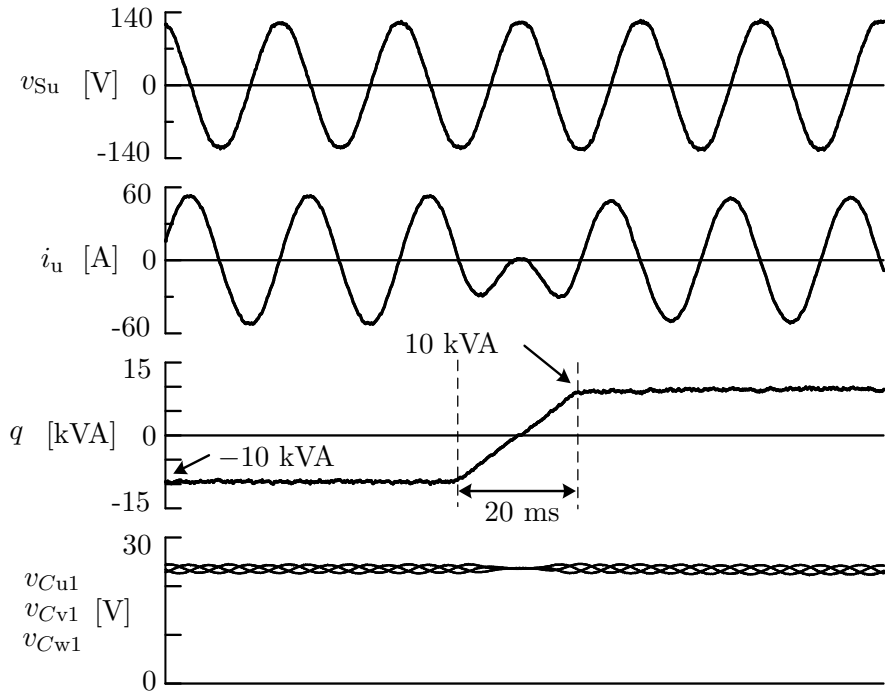


**Fig. 4.9: Experimental waveforms in a transient state from the rated inductive operation to the rated capacitive operation when the all-cells update method was applied.**

## 4.5 Summary

This chapter described the operation and the control strategy of a D-STATCOM based on an SSBC converter. Experimental waveforms confirm the operation of the D-STATCOM both for steady-state and transient operation.

The design of the cluster-balancing control gain is carried out, considering the use of either an LPF or an MAF to mitigate the 100-Hz oscillation component present on the dc capacitor voltages. An analysis based on analog models is made, and experimental results validates the methods and the approximation used. Moreover, the improved performance of the MAF over the LPF is confirmed.

## Chapter 5

# Operation of the SSBC-based Battery Energy Storage System

### 5.1 Introduction

The present chapter describes a battery energy storage system (BESS) based on a modular multilevel SSBC converter. The BESS is intended to support governor-free frequency regulation and load-peak shaving on a 6.6-kV distribution power system. Control strategies of the BESS are described. Special attention is given to the active-power control of individual bridge cells with power estimation. Experiments verify the effectiveness of the control strategy during steady-state and transient operation.

### 5.2 Control Strategies of the SSBC-based BESS

The control strategy for the SSBC-based BESS can be divided in two blocks. One block is the overall active-power control [56] defines the ac voltage commands to the bridge cells of the SSBC-based BESS. The BESS is controlled by a current feedback control strategy along with a phase-lock loop to follow the active-power reference  $p^*$  (see Fig.3.10). The second block consists of control strategies that performs the balancing either the power or the energy among the individual bridge cells. For this control, strategies such as the SOC-balancing control [56], the fault-tolerant control [117] and the individual-cell active-power

control [118] can be applied.

### 5.2.1 Overall Active-Power Control

The decoupled current control based on the instantaneous reactive power theory [170] makes it possible to control the active and reactive power in the SSBC independently [56]. From a practical point of view, a grid-scale SSBC-based BESS operates by drawing only active power from the distribution feeder. In other words, no reactive power is drawn by the BESS, which means that  $q^* = 0$ .

Similarly to the description made in section 4.2.1, the references for the instantaneous active and reactive powers in the BESS can be defined by

$$p^* = v_{\text{Sd}} i_{\text{d}}^* \quad (5.1)$$

$$q^* = v_{\text{Sd}} i_{\text{q}}^*. \quad (5.2)$$

From (5.1) and (5.2), the reference currents on the  $dq$  reference frames can be defined as

$$i_{\text{d}}^* = \frac{p^*}{v_{\text{Sd}}} \quad (5.3)$$

$$i_{\text{q}}^* = \frac{q^*}{v_{\text{Sd}}}. \quad (5.4)$$

Here  $V_{\text{C}}^*$  corresponds to the dc reference voltage for the dc capacitors.

The ac-voltage commands for the SSBC-based BESS can be defined by

$$\begin{bmatrix} v_{\text{d}}^* \\ v_{\text{q}}^* \end{bmatrix} = \frac{1}{6} \left( \begin{bmatrix} v_{\text{Sd}} \\ v_{\text{Sq}} \end{bmatrix} - \begin{bmatrix} 0 & -\omega L_{\text{AC}} \\ \omega L_{\text{AC}} & 0 \end{bmatrix} \begin{bmatrix} i_{\text{d}} \\ i_{\text{q}} \end{bmatrix} - K_2 \begin{bmatrix} i_{\text{d}}^* - i_{\text{d}} \\ i_{\text{q}}^* - i_{\text{q}} \end{bmatrix} - \frac{K_2}{T_2} \int \begin{bmatrix} i_{\text{d}}^* - i_{\text{d}} \\ i_{\text{q}}^* - i_{\text{q}} \end{bmatrix} dt \right). \quad (5.5)$$

The combination of the first and second terms in the right-hand side of (5.5) corresponds to the feedforward compensation of the ac mains voltages due to cross-coupling terms caused by the  $dq$  transformation. The third and fourth terms correspond to the

feedback loops for the  $d$ -axis and  $q$ -axis currents in  $i_d$  and  $i_q$ .

Here, note that both  $d$ - and  $q$ -axis currents are regulated by a proportional-plus-integral (PI) control loop with a gain  $K_2$  and a time constant  $T_2$ . The decoupled current control allows the BESS to absorb or inject instantaneous active and reactive power independently.

### 5.2.2 State-of-Charge-Balancing Control

The aim of the state-of-charge (SOC)-balancing control is to minimize the difference of SOC among all battery modules [172]. A balanced SOC operation of the battery modules can maximize their use along their life time span. Using the SOC-balancing control also reduces maintenance costs and improve the reliability of the SSBC-based BESS. When the replacement of a battery module occurs, the SOC difference among the new battery module and the already installed ones is balanced by the SOC-balancing control during the BESS standard operation [121]. The maintenance time between units replacement can be greatly reduced because a new unit can be connected directly without a previous SOC adjustment.

#### Direct SOC Balancing Control

Maharjan *et al.* [56] presented the SOC-balancing control as a strategy to balance the energy flow among the battery modules of the SSBC-based BESS. A balanced charge and discharge rate can be achieved for all battery modules when the SSBC-based BESS operates despite of small differences on the charging characteristics among the battery modules resulted from manufacturing processes. This strategy relies on the SOC information provided by the battery management system (BMS) of each battery module. Experimental results in [56] confirmed the effectiveness of the SOC-balancing control with NiMH-based battery modules. Experimental verification in [121] shows the effectiveness of the SOC balancing control when a Li-ion battery module replacement takes place.

### Monitoring the SOC by the Battery Module Terminal Voltage

The SOC of a Li-ion battery cell can be monitored by detecting its terminal voltages because the correlation of terminal voltage and SOC is practically linear in its operation range [173]. Generally, the BMS uses the terminal voltage to estimate the SOC of a battery module, along with algorithms that consider equivalent models of the battery cell and module [156].

The voltage-balancing control of an SSBC-based D-STATCOM presented in chapter 4 (sections 4.2.2 and 4.2.3) is used in the downscaled model. However, two important differences exist when the voltage-balancing control is applied to the SSBC-based BESS. The first is that the battery modules have an energy capacity much higher than stand-alone dc capacitors. Consequently, the time response of the voltage-balancing control in the BESS is much slower than the one observed in the D-STATCOM. The other is that terminal voltages of battery modules are not set to follow a given dc voltage reference for BESS applications. In other words, the terminal voltage of each battery module changes along with the BESS charging and discharging operation. Although monitoring the SOC through terminal voltages may not guarantee an accurate SOC-balancing control because of manufacturing differences, the small SOC deviation among the battery modules is acceptable for the downscaled model of the SSBC-based BESS.

### 5.2.3 Active-Power Control of Individual Bridge Cells

The continuous utilization of the BESS and the intrinsic manufacturing differences among the battery modules bring alterations on the operation conditions of the battery modules. The resulting deviations can reduce both energy and power capacity of the battery modules. In order to maximize the use of each battery module, a BESS capable to deal with this issue is highly desirable.

A suitable control strategy for this situation is the active-power control of individual bridge cells presented by Maharjan *et al.* [118]. The main idea is to control the power flow of every battery module with a respective and individual power command independently. As a consequence, the active-power control of individual bridge cells does not necessarily perform a balanced charging/discharging operation among the battery modules. This is

an important difference from the SOC-balancing control depicted in section 5.2.2.

Balanced three-phase currents can be drawn by the BESS even when the battery modules have different active-power commands by the means of the zero-sequence voltage injection method [118,171]. The basic principle of this control strategy was verified in [118] for a system with a cascade count  $N = 3$  and nickel metal hydride (NiMH) battery modules. The section 5.4 presents experimental results for the downscaled presented in section 3.3.2, which has more similarities to a practical system than that from previous research in [118]. Moreover, the active-power control of individuals bridge cells is achieved using a method for estimating the power of a battery module that is detailed section 5.3.2.

## 5.3 Active-power Control of Individual Cells Based on Power Estimation

### 5.3.1 Operating Principles

Active-power control of individual bridge cells is described by Maharjan *et al.* [118]. The main idea is to inject a zero-sequence voltage reference  $v_0^*$  into each cluster reference voltage.

The reference of the zero-sequence voltage is defined by

$$v_0^* = \sqrt{2}V_0 \sin(\omega t + \phi_0), \quad (5.6)$$

where the authors of [118] gave the amplitude  $V_0$  and the phase angle  $\phi_0$  as follows:

$$\phi_0 = \tan^{-1} \left( \frac{i_q}{i_d} \right) + \tan^{-1} \left( \frac{2}{\sqrt{3}} \left( \frac{1}{2} + \frac{\Delta p_v}{\Delta p_u} \right) \right) \quad (5.7)$$

$$V_0 = \frac{\Delta p_u}{I \cos(\phi_0)}. \quad (5.8)$$

Although  $v_0^*$  is added as a feedforward term, the active-power feedback loop is implemented to assure the power matching between the ac and the dc sides of each bridge

cell [118].

Fig. 5.1 shows the control block diagram for the active-power control of individual bridge cells [118]. The control strategy can be divided in two blocks, as explained in section 5.2. The overall active-power control block is described in section 5.2.1. After  $v_0^*$  is added, the active-power reference for each bridge cell is weighted accordingly to its contribution on the cluster total active power. Chapter 6 presents the design of three-phase digital PLL used to synchronize the BESS with the ac mains.

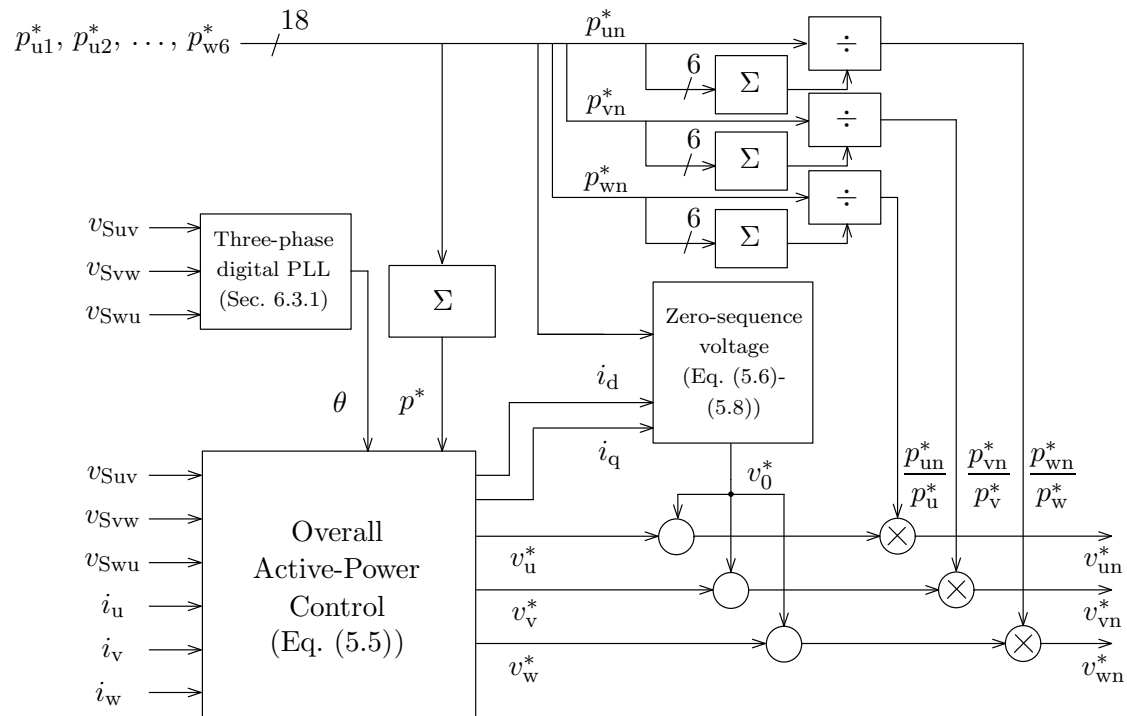


**Fig. 5.1:** Block diagram of the active-power control of individual bridge cells [118].

### 5.3.2 Battery-Current Estimation

As described in section 3.3.2, no battery current is detected although the experimental setup has a voltage sensor for monitoring the terminal voltage of each battery module. This dissertation proposes a simple method for estimating the battery current  $i_B$  of each battery module. It is characterized by combining the cluster current flowing at the ac side of the BESS (see Fig. 3.10) with PWM switching states.

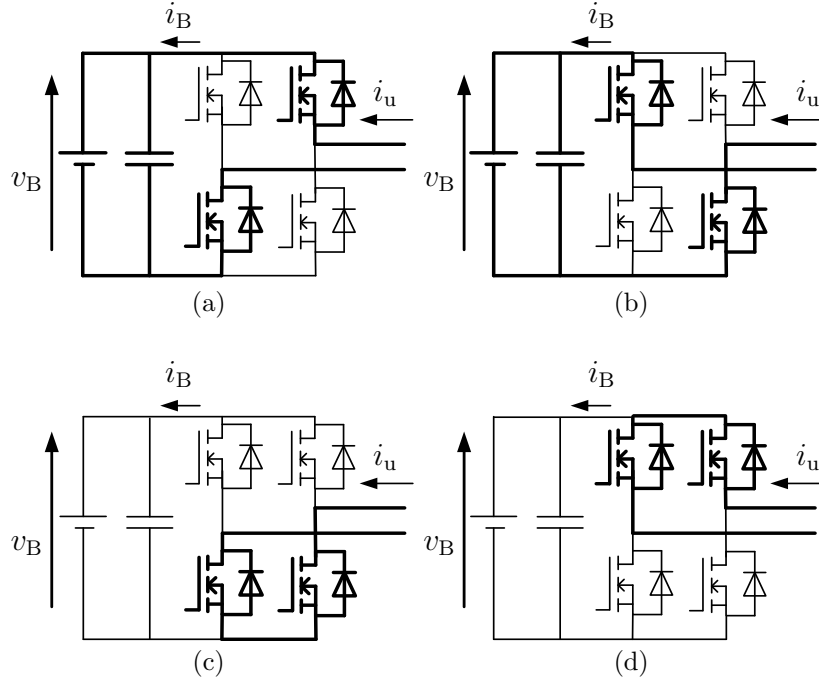


**Fig. 5.2:** Four possible switching patterns during the operation of a bridge cell. (a) When  $i_B = i_u$ . (b) When  $i_B = -i_u$ . (c) and (d) When  $i_B = 0$ .

Fig. 5.2 show four possible switching patterns for a bridge cell in the u-phase cluster. When the pattern shown in Fig. 5.2 (a) occurs,  $i_B$  and  $i_u$  are the same. When the pattern in (b) occurs,  $i_B$  has the inverse value of  $i_u$ . In case of either pattern shown in (c) or (d),  $i_B$  is zero. Considering the four switching patterns, the switching function  $SW(t)$  can be defined as follow:

$$SW(t) = \begin{cases} 1 & \text{for the pattern in (a);} \\ -1 & \text{for the pattern in (b);} \\ 0 & \text{for the patterns in (c) and (d).} \end{cases} \quad (5.9)$$

From the switching function  $SW(t)$  and the u-phase cluster current  $i_u$ , the battery current  $i_B$  can be obtained by

$$i_B = SW(t) \times i_u. \quad (5.10)$$

As an alternative to (5.10), the following equation exists.

$$i_B = m i_u, \quad (5.11)$$

where  $m$  is a modulation index of the bridge cell. The value of  $m$  is given as a ratio of the ac-voltage reference of the bridge cell with respect to the corresponding dc capacitor voltage. Note that the instantaneous currents estimated from (5.10) and (5.11) are not the same. However, when attention is paid to their dc components, they are the same.

The authors prefer (5.11) to (5.10) because the signal process for acquiring the switching patterns may cause a time delay in the digital controller. Hence, the power of each bridge cell in the u-phase cluster can be estimated by

$$\hat{p} = v_B m i_u. \quad (5.12)$$

Here,  $\hat{p}$  contains both a dc component and a 100-Hz ac component. To extract the dc component, a moving-average filter (MAF) is used, which is similar to the one described in section 4.3.2.

### 5.3.3 Limitations on the Bridge Cell Active Power Flow

The estimated power in (5.12) depends on the actual value of  $m$ , which changes with the ac-voltage reference of each bridge cell. Since no overmodulation is desirable for stable operation of the SSBC-based BESS, a theoretical limit should be imposed on the power output of each bridge cell. In other words, the modulation index is limited to

$$|m| \leq 1. \quad (5.13)$$

Applying (5.12) to (5.13) yields

$$|m| = \left| \frac{\sqrt{6} V_S \bar{p}}{V_B P} \right| \leq 1. \quad (5.14)$$

Here,  $\bar{p}$  corresponds to the dc component of the estimated power  $\hat{p}$ ,  $P$  to the BESS rated power of 10 kW,  $V_B$  to the nominal battery module terminal voltage of 25.9 V, and  $V_S$  to the ac mains line-to-line rms voltage of 140 V. For the downscaled system (see Tables 3.2 and 3.3), the maximum power of each bridge cell is 755 W.

## 5.4 Experimental Results

Figs. 5.3 and 5.4 show the waveforms during steady-state and transient operation when the active-power control of individual bridge cells was utilized. The measured electrical quantities can be referred from Fig.3.9. The ac mains line-to-line voltages  $v_{Suv}$ ,  $v_{Svw}$ , and  $v_{Swu}$  are obtained from the step-down transformer terminals. The line-to-neutral voltages produced by each cluster is represented by  $v_{uM}$ ,  $v_{vM}$ , and  $v_{wM}$ , which are measured from the terminal of each cluster in respect to the common point M. As for the terminal voltage of the battery modules, the voltages  $v_{Bu1}$ ,  $v_{Bv1}$ , and  $v_{Bw1}$  are detected only. Nevertheless, the voltages on the remaining battery modules within a same cluster are similar [118].

Fig. 5.3 shows those when the power reference of the u-phase bridge-cell numbered 1  $p_{u1}^*$  was changed from 500 W to 250 W in 20 ms. Initially, all bridge cells had the same active-power reference ( $p_{u1}^*$ ,  $p_{u2}^*$ , ..., and  $p_{w6}^*$ ) as 500 W, the overall power reference  $p^*$  was 9 kW, and the current THD on the u-phase cluster was 2.8%. After  $p_{u1}^*$  was changed, the current THD was 2.9%, and  $p^*$  was 8.75 kW. A small increase in the THD was observed due to the presence of a 3.5-kHz current ripple. Although  $p_{u1}^*$  was different from the remaining bridge-cells power references, the three-phase currents were still balanced. The terminal voltages of the three battery modules,  $v_{Bu1}$ ,  $v_{Bv1}$ , and  $v_{Bw1}$  were kept constant during the transient operation, except for a small ripple caused by a non-negligible battery internal resistance. The average value of  $v_B$  among the 18 battery modules was 26.5 V. The estimated active power of the u-phase bridge-cell numbered 1  $\hat{p}_{u1}$  was obtained by (5.12). A low-frequency oscillation was observed in  $\hat{p}_{u1}$  during the transient operation, which results from a dynamic behavior of the MAF. However,  $\hat{p}_{u1}$  settled down within 10 ms after the transient period of  $p_{u1}^*$  finished. This response agrees with the expected behavior of the MAF.

The actual zero-sequence voltage  $v_0$  was detected to confirm the effectiveness of zero-

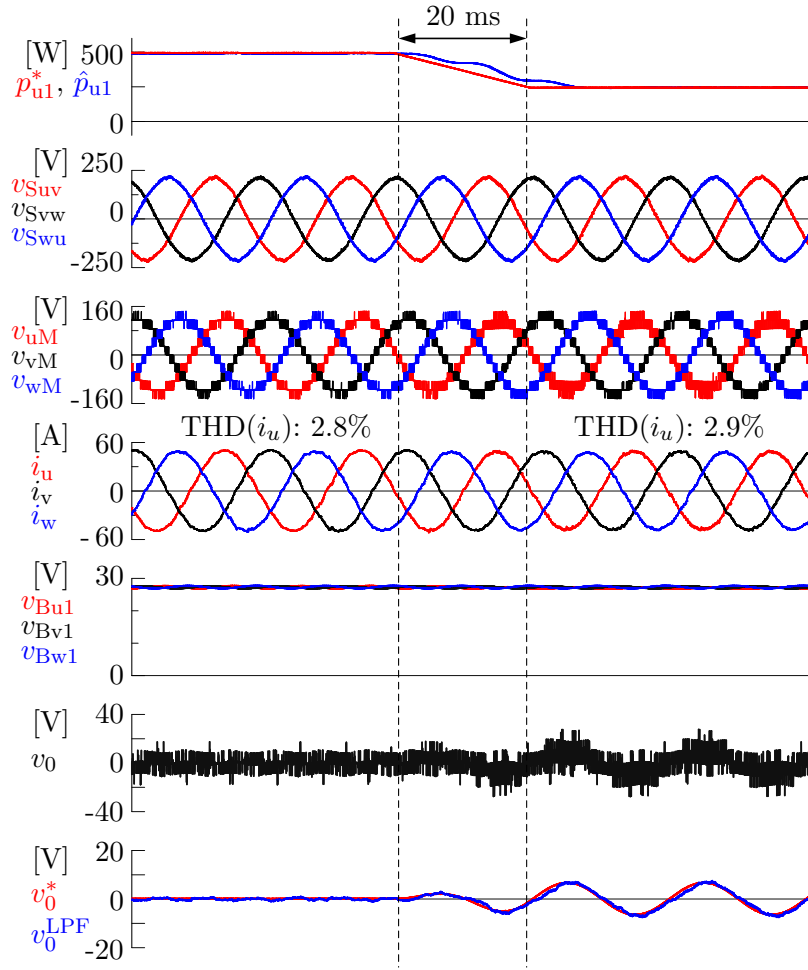


**Fig. 5.3:** Experimental waveforms for a transient response of the active-power reference of the u-phase battery module numbered 1 from 500 W to 250 W when the active-power control for individual bridge cells was applied during charging operation.

sequence-voltage injection. The zero-sequence voltage  $v_0$  was detected by:

$$v_0 = v_{uM} + v_{vM} + v_{wM}. \quad (5.15)$$

Eq. (5.15) is valid because the point M in Fig.3.9 is isolated from the ac mains ground. In other words, the potential of point M fluctuates. From Fig. 3.9,  $v_0$  can be measured from the point M to the ac mains ground. Nevertheless, because doing such measurement is clumsy, the author prefers to obtain it from the detected line-to-neutral ac voltages of the SSBC. A filtering on  $v_0$  was performed after experiments, because of the harmonic content. The waveform  $v_0^{\text{LPF}}$  was obtained by using a 300-Hz cutoff frequency low-pass filter (LPF), and it was compared to the waveform of the zero-sequence voltage reference,

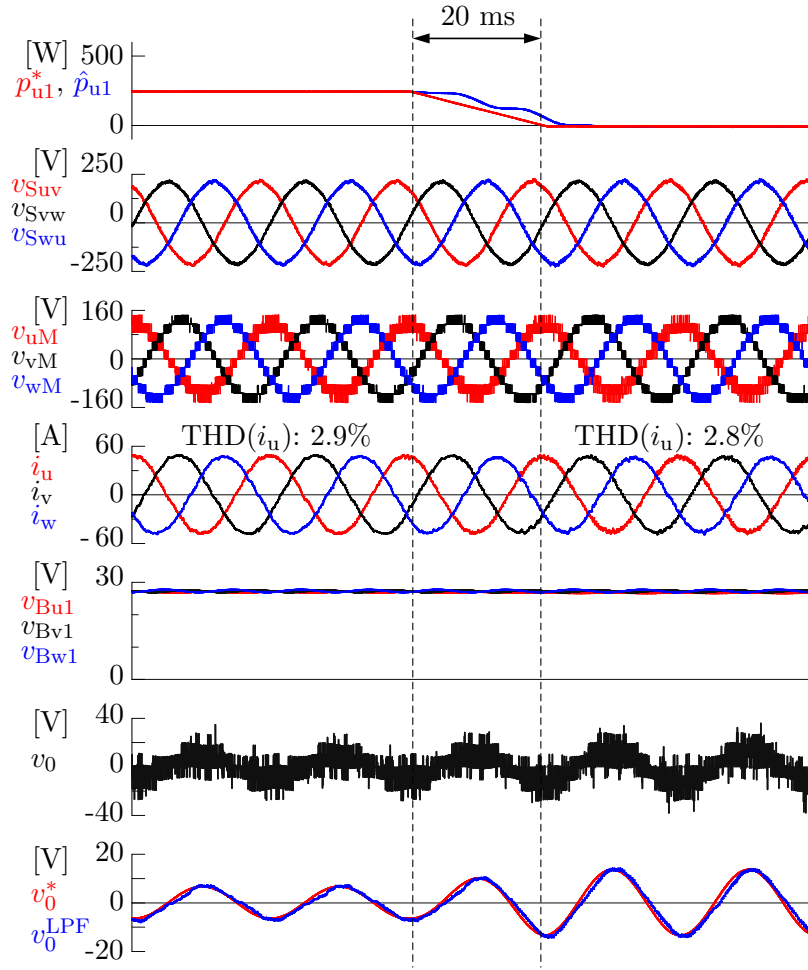


**Fig. 5.4:** Experimental waveforms for a transient response of the active-power reference of u-phase battery module numbered 1 from 250 W to 0 W when the active-power control for individual bridge cells was applied during charging operation.

$v_0^*$ . The voltage reference  $v_0^*$  is calculated by using (5.6)–(5.8), and it is detected internally from the DSP board.

Before  $p_{u1}^*$  was changed,  $v_0$  oscillated between  $-9$  V and  $9$  V, whereas  $v_0^*$  and  $v_0^{\text{LPF}}$  had an almost null value. After the transient operation,  $v_0$  oscillated between  $-18$  V and  $18$  V, while  $v_0^*$  and  $v_0^{\text{LPF}}$  had a sinusoidal waveform at the fundamental frequency of 50 Hz. The amplitude increased up to 6.9 V and the phase angle was  $-\pi$  rad with respect to the u-phase cluster current. The waveform of  $v_0^{\text{LPF}}$  agreed well with that of  $v_0^*$ .

Fig. 5.4 shows the waveforms when  $p_{u1}^*$  was changed from 250 W to 0 W in 20 ms. After the transient operation,  $p^*$  was reduced to 8.5 kW, and the three-phase currents were still balanced. The current THD on the u-phase cluster was 2.8%. This means that no major

change was observed on the THD value. The average value of  $v_B$  was 26.5 V. Similar to Fig. 5.3, a low-frequency oscillation occurred in  $\hat{p}_{u1}$  during the transient operation. This oscillation settled down within 10 ms. The voltage  $v_0$  oscillated between  $-27$  V and  $27$  V after  $p_{u1}^*$  became null. The amplitude of  $v_0^{\text{LPF}}$  increased up to 14.2 V, and the phase angle was  $-\pi$  rad with respect to the u-phase cluster current. The waveform  $v_0^{\text{LPF}}$  agreed well with that of  $v_0^*$ .

In both Figs. 5.3 and 5.4, the dc voltages  $v_{Bu1}$ ,  $v_{Bv1}$ , and  $v_{Bw1}$  of the BESS had almost no oscillation when compared to those of the D-STATCOM in Figs. 4.7, 4.8, and 4.9, because the battery modules have a much higher energy density than the dc capacitors.

## 5.5 Increased Reliability of the SSBC-based BESS

The tested BESS can produce three-phase balanced currents even when one battery module has a null power, as shown in Fig. 5.4. This seamless operation is similar to that when a battery module becomes unavailable. Although any zero-sequence voltage with no restriction could be injected by the active-power control of individual bridge cells theoretically [118, 171], a limitation exists practically.

Let  $r$  be defined as a ratio of the ac mains line-to-neutral peak voltage with respect to  $N$  times of the nominal battery-module voltage in a cluster:

$$r = \sqrt{\frac{2}{3}} \frac{V_S}{NV_B}. \quad (5.16)$$

As a grid-connected converter, the BESS has to produce an ac voltage higher than the ac mains voltage. The resulting voltage margin is used for zero-sequence voltage injection. Thus, the rms value  $V_{0 \text{ max}}$  can be given by

$$V_{0 \text{ max}} = \sqrt{\frac{3}{2}} NV_B - V_S \quad [\text{V}]. \quad (5.17)$$

The first term on the right-hand side of (5.17) refers to the maximum ac rms voltage

produced by the BESS. Substituting (5.16) into (5.17) yields

$$V_{0 \max} = \frac{1-r}{r} V_S \quad [\text{V}]. \quad (5.18)$$

Equation (5.18) implies that the BESS can produce three-phase currents with no distortion when the injected zero-sequence voltage has an amplitude lower than  $\sqrt{2}V_{0 \max}$ . Note that (5.18) excludes effects of the on-state saturation voltage occurring across each semiconductor switching device, the voltage appearing across each ac inductor, and so on from the derivation.

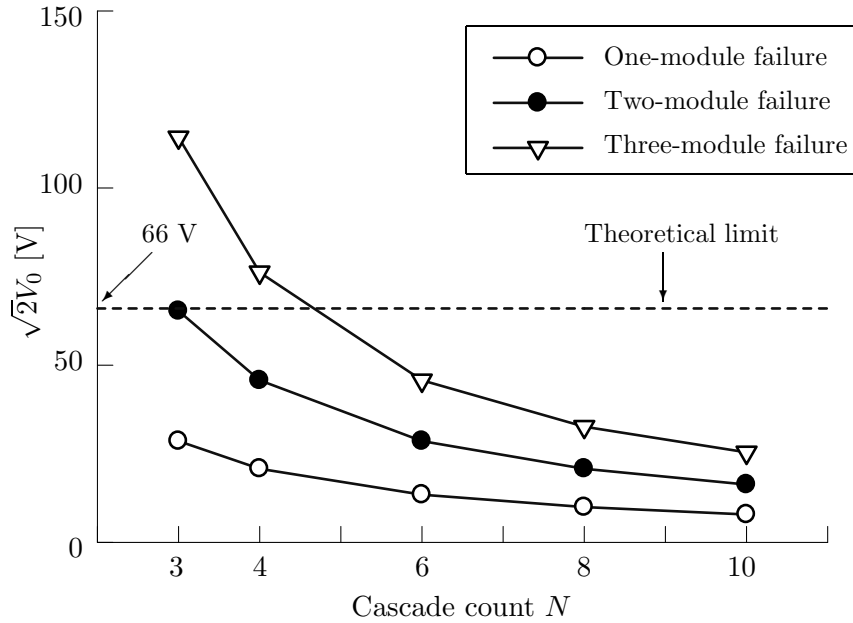


**Fig. 5.5: Relation between  $\sqrt{2}V_0$  and  $N$  when considering the failure of battery modules within a single cluster in the 140-V, 10-kW BESS.**

Fig. 5.5 shows the relationship between the amplitude  $\sqrt{2}V_0$  and the cascade count  $N$  when a failure of one, two, or three battery modules occurs within one cluster. The curves show that, the amplitude  $\sqrt{2}V_0$  decreases as  $N$  increases for a given number of faulty battery modules. The curves are compared with the theoretical limit of the zero-sequence-voltage injection method. Note that the theoretical limit is obtained by substituting  $r = 0.75$  and  $V_S = 140$  V into (5.18).

A first glance into Fig. 5.5 suggests that the BESS can withstand the failure of more battery modules as  $N$  increases. Generally, once a single battery module fails, the replacement of the faulty battery module should occur as soon as possible. Nevertheless,

**Tab. 5.1:** Comparison of Terminal Voltage of a Battery Module and Zero-Sequence Voltage for Different Cascaded Count  $N$ .

| $N$                      | 3    | 4    | 6                          | 8    | 10   |
|--------------------------|------|------|----------------------------|------|------|
| $V_B$ [V]                | 51.8 | 37   | 25.9                       | 18.5 | 14.8 |
| $V_0$ [V] <sup>(1)</sup> | 9.5  | 7.0  | 4.6<br>4.9 <sup>(3)</sup>  | 3.5  | 2.7  |
| $V_0$ [V] <sup>(2)</sup> | 20.2 | 14.7 | 9.5<br>10.3 <sup>(3)</sup> | 7.0  | 5.6  |

For the 140-V, 10-kW BESS

<sup>(1)</sup>when  $p_{u1}^*$  reduces to half.<sup>(2)</sup>when  $p_{u1}^*$  reduces to zero.<sup>(3)</sup>these two values obtained from experiment.

this analysis shows that the availability of the SSBC-based BESS improves with a higher  $N$ . Moreover, Fig. 5.5 can be extended to a design of the terminal voltage of battery modules, according to fault-tolerance requirements of the BESS.

Table 5.1 compares the nominal battery-module voltage  $V_B$  and the rms value  $V_0$  for different values of  $N$ . The values of  $V_0$  were calculated when  $p_{u1}^*$  is reduced to half of its original value and to zero, assuming that all of the bridge cells had the same power reference initially. The values of  $V_B$  were obtained by (5.16) for  $r = 0.75$ , and were approximated by considering a nominal Li-ion battery-cell voltage of 3.7 V [99, 158].

A lower  $V_B$  can be achieved for a higher count of  $N$ . Note that  $V_0$  also decreases for a higher count of  $N$ . For  $N = 6$ , the experimental results based on the power estimation agreed well with the theoretical ones. This confirms the validity of the active-power control for individual bridge cells. The use of multiple battery modules (or strings) with a reduced terminal voltage made it possible to enhance the overall reliability of the BESS as described in section 3.2.2.

## 5.6 Summary

This chapter has described the control strategies of the BESS based on an SSBC converter. Attention was given to the active-power control of individual bridge cells with power estimation of the bridge cells. The use of this control strategy allows the BESS

to keep its operation even when one battery module fails. Experimental results verified the effectiveness of this strategy. Analysis on the compensation limitation was carried out and concludes that the use of multiple low-voltage battery modules can improve the BESS availability.



# Chapter 7

## Conclusions

### 7.1 Summary and Contributions

The present dissertation has discussed the applications of a modular multilevel SSBC converter to a distribution STATCOM (D-STATCOM) and a battery energy storage system (BESS) to 6.6-kV distribution power systems. A downscaled model was design built and constructed to test the SSBC-based D-STATCOM and the SSBC-based BESS equipped with Li-ion low-voltage battery modules.

This dissertation has contributed to the improvement of an SSBC converter applied to a D-STATCOM and a BESS by the following ideas:

■ **Experimental verification of a downscaled SSBC converter for D-STATCOM and BESS applications with a per-cluster cascade count of six ( $N = 6$ ).**

Previous research of the SSBC-based PWM STATCOM [55] and BESS [56, 117, 118, 120] have presented verification of a downscaled experimental setup with a per-cluster cascade count of three ( $N = 3$ ). The downscaled model with a increased cascade count allows a better evaluation when it comes to an actual application intended to installation on 6.6-kV distribution power systems.

■ **Modeling, analysis, and design of the SSBC current control when using phase-shifted-carrier PWM.** When the one-cell update method is considered, the current control gain for the critical damping response exhibits saturation even for a higher cascaded count  $N$ . The theoretical analysis has confirmed that the

saturation comes from the inherent time delay in phase-shifted PWM. The phase-shifted PWM using the all-cells update method brings a shorter time delay than that when the one-cell update is used. Thus, an eventual increase in the cascade count  $N$  allows the use of a higher gain to result in an improvement of the current control response.

- **Modeling, analysis, and design of a moving average filter (MAF) to improve the cluster balancing control of the SSBC-based D-STATCOM.** Two different filtering methods to suppress a 100-Hz voltage oscillation on the dc capacitors were analyzed and compared. The use of a moving average filter brought an improved dynamic response of the cluster balancing control when compared to a low-pass filter.
- **Verification of enhanced availability and reliability of the BESS for a increased number of battery modules per cluster.** Experimental results have shown that the downscaled BESS can provide three-phase balanced currents with a THD value lower than 3.0% even when operating with a single faulty cell. A simple technique for estimating the active power of each bridge cell has been adopted, and the accuracy has been verified by experiments. Discussions on the limitation of zero-sequence-voltage injection and on the design of the BESS have highlighted the advantages of using multiple low-voltage battery modules.
- **Capability to ride through voltage sags, frequency deviations, and phase jumps.** Experimental verification of the ZVRT capability have shown that both D-STATCOM and BESS can endure the severest voltage sags. As for the D-STATCOM, no overshoot appears in the dc capacitor voltages during fast transient due to the sag occurrence and restoration. The voltage deviation on the dc capacitor is kept within an acceptable value for the safe operation of the D-STATCOM during the occurrence of the voltage sags. As for the BESS, no major changes were observed on the terminal voltages of the battery modules, suggesting that the voltage sags produces no effect on the SOC of battery modules.

Attention has been paid to the effects of phase-estimation errors on the SSBC, and a

PLL was design to reduce the disturbances resulting from a phase-estimation error. The phase-estimation error affects the instantaneous active and reactive powers of both D-STATCOM and BESS. As for the D-STATCOM, it results in inducing oscillations on the capacitor voltages, which would bring it to failure. As for the BESS, the power oscillation causes no effect in the battery modules, due to their high energy density. Experimental verification has confirmed the efficacy of a high-gain  $K_{PLL}$  for reducing the phase-estimation error coming from frequency deviations and phase jumps.

## 7.2 Limitations and Future Work

- **Verification of long-term reliability.** The present dissertation suggested in chapter 4 that the BESS can operate when one or more battery module fails. In other words, the overall system availability can be considered to be higher than that from a single high-voltage battery stack. However, no analysis or verification of the long-term operation was made, due to the limitations of the downscaled experimental system. Also, no strict analysis based on reliability engineering [129] is carried out.
- **Further analysis of SSBC converter efficiency.** The present dissertation does not deal with the efficiency of the SSBC converter. The SSBC-based D-STATCOM draws only a small amount of power to keep its dc capacitor charged. However, the BESS would constantly inject active power to, and absorb it from, the ac mains. Once that a BESS with a high round-trip efficiency is desirable, the efficiency of the SSBC converter becomes a important topic.
- **An SSBC-based BESS with reactive compensation function.** The present dissertation dealt with an SSBC applied to a BESS only injecting and absorbing active power from the ac mains. Nevertheless, it would be possible to operate it also with reactive power, resulting in a very flexible compensation system in a grid. Some researchers have envisioned the use of FACTS with energy storage as the ultimate solution to maintain the stability of a power system [15, 191].



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# List of Publications

## Journal Publications

1. 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 Transactions on Industry Applications*, vol. 51, no. 1, pp. 279–288, Jan. 2015.
2. 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 Transactions on Industry Applications*, vol. 51, no. 1, pp. 289–296, Jan. 2015.
3. J. I. Y. Ota, T. Sato, and H. Akagi, "Enhancement of performance, availability, and flexibility of a battery energy storage system based on a modular multilevel cascaded converter (MMCC-SSBC)," *IEEE Transactions on Power Electronics*, vol. 31, no. 4, pp. 2791–2799, Apr. 2016.

## Conference Publications

1. J. I. Y. Ota, Y. Shibano, N. Niimura, and H. Akagi, "Current control of a phase-shifted-PWM STATCOM using the modular multilevel cascade converter based on single-star bridge-cells (MMCC-SSBC)," in *2013 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2013, pp. 420–427.
2. J. I. Y. Ota, Y. Shibano, and H. Akagi, "Low-voltage-ride-through (LVRT) capa-

bility of a phase-shifted-PWM STATCOM using the modular multilevel cascade converter based on single-star bridge-cells (MMCC-SSBC),” in *2013 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2013, pp. 3062–3069.