A Review of Medium-Voltage Front-End Converters for Grid-connected Battery Energy Storage Systems

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***Abstract*— Medium-voltage power conditioning systems (MV-PCS) are used to interface battery energy storage systems (BESS) to medium-voltage ac distribution systems. MV-PCS usually include an ac-dc stage, also referred to as the front-end converter (FEC). In this paper, several FEC topologies are categorized according to the type of BESS connection and evaluated. The specific connections are centralized, distributed, and hybrid. The evaluation is performed in terms of power density, FEC efficiency, and construction complexity. Finally, this evaluation is used to provide design guidelines and highlight future research aspects.**

***Keywords*— Battery energy storage system, dc-ac power converter, medium-voltage distribution system, multilevel converters, power conditioning system**

I. Introduction

Grid-connected electrical energy storage systems (G-EESS) are one proven solution to face the current technical challenges of smoothing the intermittent nature of the power generated by variable renewable energy sources (VRES) [1], [2]. Therefore, governments are enacting regulations mandating targets for G-EESS with the primary goal of accelerating the integration of VRES into electric power grids; for example, several states in the USA have required energy storage percentages [3]. G-EESS have many value propositions besides alleviating the intermittence of VRES-generated power, such as offering time-varying energy management and improving power quality.

The G-EESS functions can be classified in terms of power and energy. For example, power-based functions include transient voltage stability and harmonic mitigation, while energy-based functions refer to congestion management and loss minimization [4], [5]. Moreover, there are power-energy-based functions such as VRES power swing mitigation, primary frequency control, and load smoothing. Grid-connected BESS (G-BESS) can be designed to meet the requirements of power-energy-based applications, such as fast response times, high energy density, high output power, and high efficiency [6]. Hence, G-BESS can be widely utilized in energy management, power quality, and ride-through power applications.

The main components of a G-BESS are battery packs and their battery management controller (forming a BESS), medium-voltage power conditioning systems (MV-PCS), and ancillary balance of plant equipment, as shown in Fig. 1. MV-PCS includes two stages: the ac-dc stage also referred to as the FEC, and the dc-dc stage, which can be referred to as isolated bidirectional dc-dc converters (IBDC) in case of requiring galvanic isolation. FEC enables connecting G-BESS to medium-voltage ac (MVAC) distribution systems, so it must comply with grid codes and standards at all operating conditions as well as regulate bidirectional power flows. Traditional FEC utilizes a set-up transformer to connect to MVAC systems, while modern FEC are based on transformerless connections [6], [7].

The advantages of high-voltage (HV) silicon carbide (SiC) power semiconductor devices over Si devices are well known, such as higher switching frequencies and operating temperature [8], [9]. SiC MOSFET power modules rated 1.7-kV are already commercialized, 3.3-kV modules will soon be available [10], [11] and 6.5-kV and 10-kV modules are only available as engineering samples [12], [13]. These HV SiC MOSFET modules are spurring significant R&D efforts in developing multilevel converters (MLCs) for directly connecting G-BESS to MVAC systems [14], [15].

G-BESS can generally be classified based on the type of BESS connection; centralized, distributed, and hybrid. In [6], transformer-based centralized-connected BESS was compared, while distributed-connected BESS was considered without much detail. In [16], only transformer-based distributed-connected BESS were investigated without considering centralized and hybrid types. The main contribution of this paper is an evaluation of the three connection types considering factors like power density, FEC efficiency, complexity/modularity.

The rest of the paper is structured as follows: transformerless FEC topologies are discussed in Section II. the evaluation of these topologies considering power density, fault tolerance, and efficiency is provided in Section III. Practical design guidelines and future research issues are investigated in Section IV. Finally, conclusions and future work are discussed in Section V.

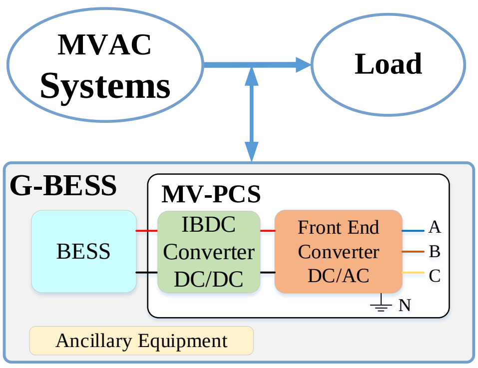

Fig. 1. Main components of a G-BESS.

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II. Transformerless FEC Topologies

FEC can be directly connected to MVAC systems without utilizing a line-frequency transformer by applying one of these two methods; using series-connected switching devices or employing series-connected cells [17]. The second method is based on connecting several cells (also called building blocks, sub-modules, or bridges) in series to build a string that can withstand the maximum applied voltage. These series-connected cells form MLC topologies. The main features of these MLC include decreased dv/dt's and common-mode voltages, reduced harmonic content by increasing the number of voltage levels, and scaling voltage and output power without requiring devices with higher ratings [18], [19].

The main MLC topologies are presented in Fig. 2, which include a cascaded H-bridge converter (CHBC), modular multilevel converter (MMC), diode-clamped converter (DCC), and flying capacitor converter (FCC) [20], [21]. These MLC can be categorized based on the connecting IBDC and BESS stages into two main categories: centralized and distributed. Another MLC type that received attention during the last decade is the hybrid topology proposed to combine the advantages of centralized and distributed BESS while improving other features such as converter reliability.

A. *Centralized-connected BESS*

Similar to two-level converters, MLC topologies such as MMC, DCC, and FCC have a common dc link that can be connected to a centralized BESS and IBDC. For example, a three-phase MMC, with cells composed of a half-bridge module and a dc-link capacitor connected to a centralized IBDC and BESS is illustrated in Fig. 3. In [22], an MMC-based G-BESS was used as a STATCOM integrating a hybrid EESS consisting of batteries and supercapacitors connected to the common dc-link capacitor using multiple IBDC units connected in series to generate the required voltage. The main objectives of this G-BESS included alleviating VRES output power variations, regulating the PCC voltage, and balancing grid currents.

The DCC topology can also be used to integrate a centralized IBDC and BESS with MV distribution systems. For example, a G-BESS composed of a three-phase three-level DCC, IBDC units, and a centralized BESS is shown in Fig. 4. The three-level DCC consists of four switching devices, clamping diodes, and common dc-link capacitors. The switching devices are subjected to only half of the dc-link voltage in this topology. Moreover, the applied voltage to the switching devices is reduced by increasing the number of voltage levels at the expense of increased complexity. The benefits of the DCC topology include simple control, using passive clamping elements, and low cost. However, its main disadvantages are unbalanced stress on the switching devices, low modularity, a high number of diodes, and more components than other MLC [23].

Another MLC for integrating centralized BESS is the FCC topology being similar to DCC by replacing the clamping diodes with clamping capacitors for each converter level, as shown in Fig. 5. The FCC topology can be considered a partially modular converter based on a building block made of two series-connected switching devices with a flying capacitor in parallel. These blocks are different because of charging the flying capacitors with different voltages, and thus the number of capacitors is higher as the number of levels increases [24]–[26]. In [27], a multi-source energy system including PV system, wind generators, and BESS is coupled via an FCC to an MVAC grid. A control algorithm focused on a backstepping control of the BESS was studied. The proposed approaches to regulate the active and reactive powers controlled the currents, battery voltage, and dc-bus voltage on the grid-side converter, and three selective control goals were achieved.

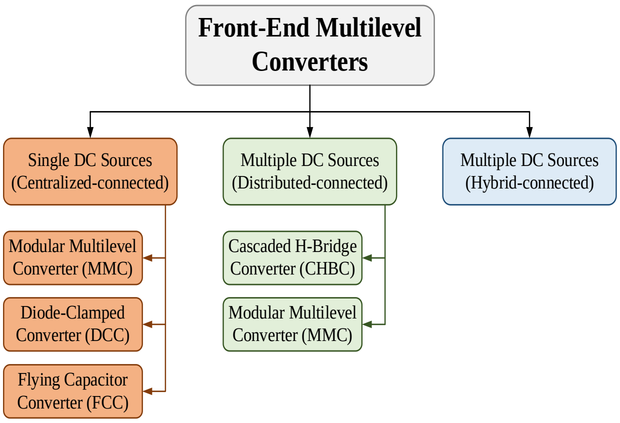

Fig. 2. Classification of MLC topologies according to BESS connection types.

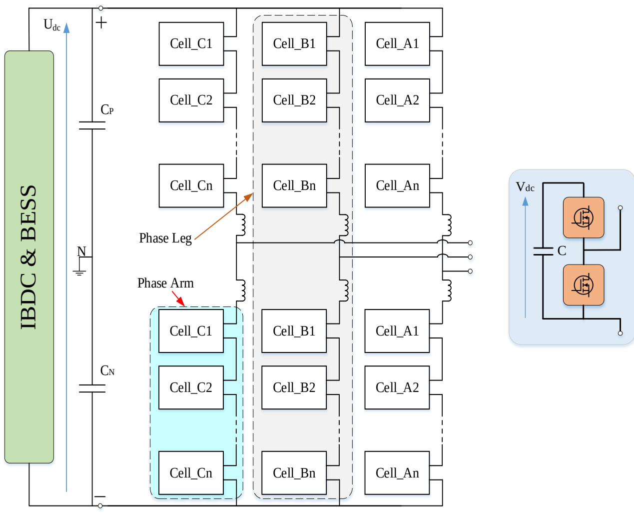

Fig. 3. Three-phase MMC topology using half-bridge cells for integrating centralized-connected IBDC and BESS.

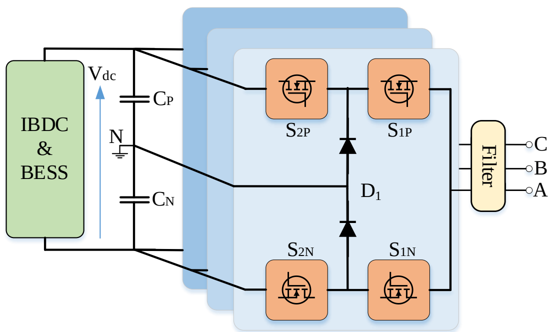

Fig. 4. Three-phase three-level NPC integrated with a centralized IBDC and BESS.

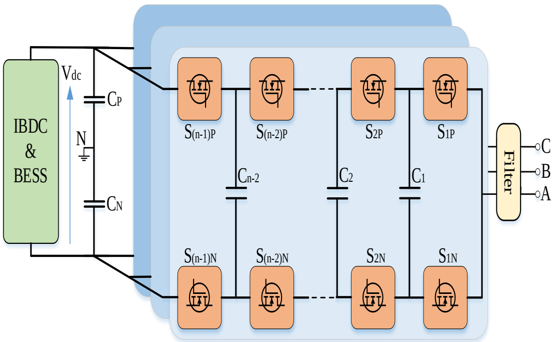

Fig. 5. Three-phase FCC integrated with centralized-connected

The main objectives were obtaining sinusoidal symmetrical currents, suppressing reactive power ripples, and canceling active power ripples in the event of grid imbalance. Moreover, the backstepping control strategy maximized energy extraction from VRES and improved BESS performance by using the surplus energy for BESS charging and optimizing the G-BESS operation.

B. Distributed-connected BESS

For integrating distributed BESS into MVAC grids, MLC topologies such as CHBC and MMC are suitable. These topologies enable controlling the power of each BESS independently, and reliability [16].

The well-known three-phase CHBC consists of three legs with multiple H-bridge cells connected in series [28]. Each cell has H-bridge modules and its dc-link capacitor. So, these separate dc buses can be connected to IBDC and BESS modules, as presented in Fig. 6. In this manner, each cell can control the power flow of the BESS connected to its dc bus individually. The advantages of CHBC include its modular structure (requiring fewer components than in other topologies) and simple control. The modularity feature of CHBC allows for design flexibility and easy maintenance even during its operation mode [29]. The three-leg CHBC can be connected in two ways: star connection (single-star bridge cells SSBC) and delta connection (single-delta bridge cells SDBC) [20], [30]. The disadvantages of CHBC include many separate dc-voltage sources and voltage imbalance between phases [21].

In [31], a three-phase star-connected 2-MW 10-kV CHBC-based G-BESS was investigated. This CHBC included 20 cascaded cells per phase and a battery pack connected in parallel to each cell. A fault-tolerant control algorithm maintained the G-BESS in operation when one cell was bypassed in case of failure. The control strategy was verified by decoupling power control, emergency shutdown, and step response tests. However, using low voltage switching devices increased the number of cells and system complexity, and reduced system reliability.

Another important topology for integrating distributed-connected G-BESS is the MMC topology, consisting of three parallel-connected phase legs. Each phase leg contains upper and lower arms, and each arm is established by several cells (also referred to as submodules SM) with a line-side filter, as shown in Fig. 7. Each cell has a half-bridge module and its dc-link capacitor (also called double-star chopper cell DSCC). Still, a cell type can be built using an H-bridge (also referred to as double-star bridge cell DSBC) as used for specific purposes such as wind/solar power conditioning [32], [33].

The required two-arm inductors, which can be coupled or uncoupled, are used to limit the current through cell capacitors during charging and discharging processes to support the voltage difference between the cells and the common dc link to control the circulating current in each leg. By connecting IBDC and BESS across these capacitors, distributed battery packs can be integrated with the grid. Because of its modularity nature, MMC can be maintained easily, provides design flexibility, simple and robust construction, and has low dc-link stray inductances. Nevertheless, MMC has disadvantages, such as its circulating current within the converter, which can increase both conduction losses and thermal stresses. Also, the circulating current produces high voltage ripples through the capacitors, increasing their sizes. Therefore, balancing cell capacitor voltages in the MMC becomes the main problem besides many isolated dc-voltage sources that are required [18], [21].

In [34], second-life batteries were evaluated for an MMC-based G-BESS. The power flows among all sources within this system were analyzed by proposing a three-level state-of-charge (SOC) equilibrium control strategy consisting of SOC balance of cells within each arm, SOC balance between the lower and upper arms of each phase, and SOC balance among the three-phase legs.

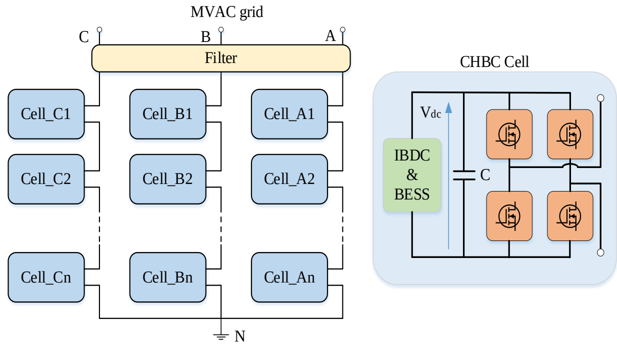

Fig. 6. CHBC and H-bridge cell integrated with IBDC and BESS.

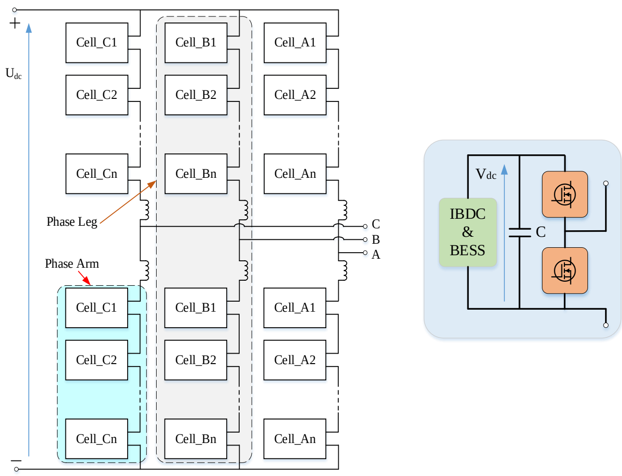

Fig. 7. Three-phase MMC composed of half-bridge cell integrated with distributed IBDC and BESS.

When only considering G-BESS applications, the comparison between CHBC and MMC shows that CHBC is preferable because the MMC is a more complex and expensive system. Other problems within the MMC include higher conduction and switching losses due to the circulating currents, the use of large cell capacitors because of the large fundamental-frequency voltage component existing in them, and the possibility of injecting dc currents into the grid as a result of unbalanced battery voltages [35]. However, MMC may represent a potential candidate for integrating G-BESS with motor drive systems, HVDC transmission, or second-life batteries [36].

C. *Hybrid-connected BESS*

BESS and other types of EESS can be connected to MLCs in different ways such as partially distributed. In [37], and MMC topology was used for integrating a hybrid EESS in a hybrid configuration. Supercapacitor units were connected to the common dc link through multiple series-connected IBDC converters, while distributed BESS were connected to each cell. This proposed configuration presented good transient performance and extended battery life span. The main functions of this G-BESS were mitigating voltage fluctuations at the point of common coupling (PCC) using STATCOM control and smoothing the active power generated by a wind farm by controlling the hybrid-connected EESS.

The hybrid multilevel converter proposed in [38] was based on the MMC topology that can be functionally expanded with partial interleaved ESS as a fraction of the total converter power rating. The topology contained a three-phase, three-level FCC for the upper and lower arms and some half-bridge SMs connected in series. The three-level FCC replaced two half-bridge SMs in each arm, demanding the same number of switching devices, one common capacitor for the outer stage, and a capacitor per phase as the flying capacitors. In addition, using three-phase FCC submodules removed the second-order harmonic oscillations, including a common ESS within the three-phase FCC-SM. So, the converter can supply multi-directional power flows between the ac, dc, and EESS sides.

III. Evaluation of Selected FEC Topologies

The main features of the above-mentioned FEC topologies, including an example of a hybrid one, are presented in Table I elaborated from [38]–[41]. Figures of merit such as the number of switching devices, main diodes, control complexity, and modularity are considered. While all the presented FEC topologies have the same number of switching devices and main diodes, the other features are different. The required dc-bus capacitors are higher in CHBC, MMC, and hybrid FEC, but the dc-bus voltage of their cells is much lower than those in the DCC and FCC for the same distribution system voltage. While the required components for CHBC and MMC are the least compared to other FEC, DCC requires the highest number of components. However, DCC requires the least complex control system.

CHBC and MMC have the highest modularity since each one has the same number of power blocks or cells for all levels. FCC has partial modularity because its power blocks are different between levels. Most of the presented FEC are redundant except DCC. Both CHBC and MMC can be operated in fault-tolerant control mode by adding more cells to keep the operation of the converter in case of a cell failure. In DCC and FCC, the converter will be out of service when one switching device fails. Finally, CHBC has the lowest cost because of its high modularity and the low number of required components.

TABLE I. Comparison Between Different FEC Topologies.

FEC Topology	**CHBC (SSBC)**	**MMC (DSCC)**	**DCC**	**FCC**	**Hybrid FEC [38]**
Switching devices	6(m-1)*				
Main diodes	6(m-1)*				
DC bus capacitors	(3/2) (m-1)*	3(m-1)*	(m-1)*	(m-1)*	3(m-5)*
Clamping diodes	0	0	3(m-1) (m-2)*	0	0
Clamping capacitors	0	0	0	(3/2) (m-1) (m-2)*	4
Arm inductor	0	6	0	0	6
No. of components	Low	Low	Very high	High	Medium
DC-link voltage balance	Isolated dc source	Possible	Difficult	Difficult	Difficult
Voltage quality	High	High	Medium	Medium	High
Control complexity	High	High	Low	High	High
Modularity	High	High	Low	Medium	Medium
Redundancy	Redundant	Redundant	Not redundant	Redundant	Redundant
Fault tolerance	Yes	Yes	No	No	No
Flexibility	Flexible	Not Flexible	Not Flexible	Not Flexible	Not Flexible
Cost	Medium	High	High	High	High
Control concern	Power-sharing	Circulating current	Voltage balancing and loss distribution	Voltage setup (pre-charge)	Circulating current
Modulation Technique	Phase-shifted PWM	Nearest-level	Space vector PWM	Phase-shifted PWM	Phase-shifted PWM
Type of IBDC & BESS	Distributed	Centralized or Distributed	Centralized	Centralized	Hybrid

* where m is the number of output phase voltage levels

While power-sharing and balancing SoC between all cells is the main control concern of CHBC, the circulating current issue between the phases presents the first control objective of MMC. Pre-charging all the capacitors of FCC up to the required voltage requires additional equipment. In the case of the DCC, voltage balancing and loss distribution issues represent the main control challenge [25].

The provided evaluation of FEC topologies showed that CHBC presents the best selection for integrating distributed-connected BESS. However, MMC may represent a potential candidate for merging MV BESS with motor drives systems, HVDC transmission, and working as a multi-port hub by connecting MVDC link, MVAC systems, and distributed-connected BESS [36].

IV. Design Guidelines and Future Research Aspects

The future designs of G-BESS would be based on considering these main features; performance, power density, total cost, efficiency, and power rating [42]. These features are affected by many factors such as the type of switching techniques, control techniques, improving MLC topology, and the switching devices.

A. Soft-switching methods

The drawbacks of utilizing hard-switching methods include high switching losses, more complicated thermal management, low power density, electromagnetic interference (EMI) emission, low system efficiency, etc. [43]. So, soft-switching schemes are investigated to mitigate these drawbacks. These schemes will allow higher switching frequencies which reduce the filtering requirements, decrease the size of bulky passive components, increase FEC efficiency, and minimize the thermal management.

B. Advanced control techniques

Another factor is the FEC controller which has a significant role since it has to improve the power quality, meet grid requirements during different operating conditions and grid faults, and provide a fast response. However, the FEC controller's main function is to regulate the grid current in the output filter to the reference current, which is given by the G-BESS main controller, by modulating the dc-link voltage [44]. Hence, employing advanced control techniques would be required which can be divided into two main categories; linear and non-linear controllers.

C. Hybrid MLC topologies

Improving the topology of MLC is also considered a one of the key factors. The shortcomings of the main MLC include a large number of passive components and complex control methods. So, hybrid MLC topologies have been proposed to reduce these shortcomings, provide better dynamic operation, reduce system cost, increase the power density, and allow scaling of FEC power ratings up.

D. Developing switching devices

New wide-bandgap switching devices are being developed to optimize their static and dynamic behaviors. These devices can be used to increase the FEC power rating by connecting them in parallel or in series to achieve the required current or voltage ratings, respectively. However, the first option requires additional protection circuits to maintain thermal and electrical switching time coefficients balanced. The second option necessitates alleviation of the common-mode current problems for power and control signals. Also, series-connected devices will have to be provided with compensation for deficient dynamic and static voltage sharing [45].

V. Conclusions and Future Work

This paper reviewed selected MLC-based FEC for integrating G-BESS considering three different types of connection: centralized, distributed, and hybrid with MVAC distribution systems. The provided analysis showed that both CHBC and MMC have the potential for integrating G-BESS more than other MLC topologies. However, hybrid MLC topologies have been proposed to overcome some drawbacks such as second-order harmonic oscillations. Many designs and future research aspects were highlighted like soft-switching techniques and control methods.

In the future, a detailed analysis may be presented to compare CHBC and other hybrid MLC topologies by considering FEC efficiency, cost, and power density as the main keys of the comparison. Other objectives of FEC would be taken into account like balancing grid currents and power factor correction.

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