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REVIEW

Bidirectional DC–DC converter based multilevel battery storage systems for electric vehicle and large-scale grid applications: A critical review considering different topologies, state-of-charge balancing and future trends

Fatih Eroğlu[1] | **Mehmet Kurtoğlu**[1,2] | **Ahmet Mete Vural**[1]

[1] Electrical and Electronics Engineering Department, Gaziantep University, Sehitkamil, Gaziantep, Turkey

[2] Electrical and Electronics Engineering Department, Iskenderun Technical University, Iskenderun, Hatay, Turkey

Correspondence
Fatih Eroğlu, Electrical and Electronics Engineering Department, Gaziantep University, 27310 Sehitkamil, Gaziantep, Turkey.
Email: feroglu@gantep.edu.tr

Abstract

The expanding share of renewable energy sources (RESs) in power generation and rise of electric vehicles (EVs) in transportation industry have increased the significance of energy storage systems (ESSs). Battery is considered as the most suitable energy storage technology for such systems due to its reliability, compact size and fast response. Power converters are vital for the integration of batteries into power grid and EVs as they play an active role in both power conversion and battery management. Multilevel converters (MLCs) are types of power converters and attract widespread interest due to their improved power quality, reliability and modularity. There are two main challenges in MLC based battery storage systems (BSSs) which are selecting a proper MLC topology and balancing state-of-charges (SOCs) of batteries. Although some research has been carried out on either MLCs or SOC balancing, no single study exists which presents a comprehensive review on MLC based BSSs for large-scale grid and EV applications. This paper begins by reviewing several major battery storage technologies that are utilised in MLC based BSSs. Later on, a systematical review of commonly used and recently proposed MLC topologies for BSSs are provided along with different control schemes for MLCs by specifically focusing on SOC balancing techniques. Finally, potential challenges and suggestions for future improvement of MLC based BSSs are addressed.

1 | INTRODUCTION

Energy is recognised as the essence of humanity as it directly affects the economy, wealth and prosperity of a society. Fossil fuels, coal, oil and natural gas can be considered as the major energy sources since almost 85% of the energy in use is supplied by these sources [1]. Increase in the energy demand due to industrial development and population growth during the past decades leads to a growth in carbon dioxide (CO_2) emissions and consequently environmental challenges such as climate change, global warming and air pollution [2]. According to the Fifth Assessment Report published in 2014 by Intergovernmental Panel on Climate Change (IPCC), electricity and heat production is responsible for 25% of the global CO_2 emissions while transportation sector takes part in 14% of it [3]. Renewable energy sources (RESs) like nuclear, biomass, wave, wind and solar play an important role in reducing the global CO_2 emissions. According to International Energy Agency (IEA), 215 megatonne (Mt) of CO_2 emissions are avoided in 2018 due to integration of renewables into the power industry [4]. Moreover, CO_2 emissions in transportation sector are reduced by the deployment of electric vehicles (EVs) since the amount of CO_2 emitted by EVs is 10 times lower than conventional internal combustion engine vehicles (ICEVs) [5, 6]. Although there are numerous environmental merits of integrating RESs into the power grid, there are some challenges to be faced in the process as well. RESs show intermittent and variable behaviour since their operating conditions highly depend on local climate

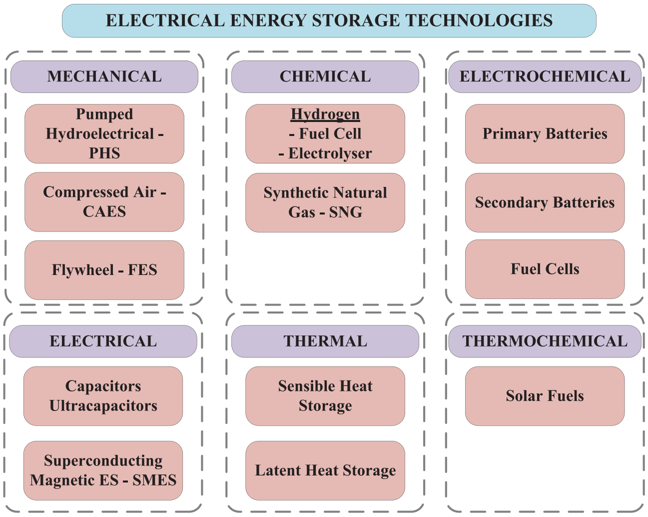


FIGURE 1 Classification of electrical energy storage technologies in terms of the form of stored energy

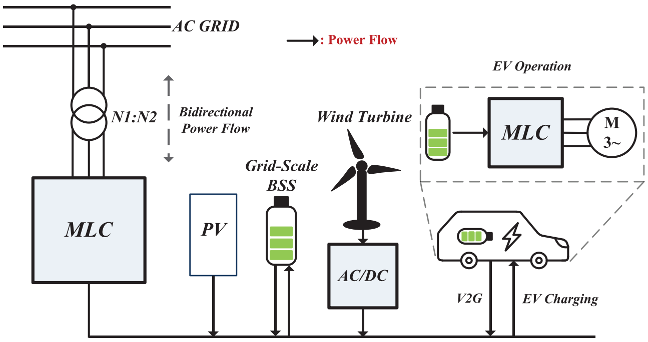


FIGURE 2 MLC based BSS applications

conditions [7, 8]. Furthermore, as the integration of RESs into power systems increase, it gets much harder for conventional power systems to adapt to oversupply conditions caused by RESs. Under these circumstances, a curtailment may be needed in renewable energy generation which is not preferable since environmental and economic merits of RESs are thrown away [9]. Therefore, adaptation of a power system to dynamic demand and supply conditions is very critical in terms of sustaining an efficient, reliable and flexible operation. That is where energy storage systems (ESSs) come into play. An ESS is able to draw energy from the system when overgeneration occurs and supply the stored energy to the system when overconsumption occurs. This provides flexibility to the power system in terms of balancing demand and supply efficiently [10, 11]. ESSs are also utilised in EVs since electrical energy needs to be stored to provide power for the electric motor of the vehicle [12–15].

An appropriate ESS should not only store large amounts of energy but also release it quickly according to load demands. Energy density, power density, lifetime, cycling time, response time, cycle efficiency, conversion rate, storage costs, environmental impacts and maintenance are the most important parameters to consider while designing an ESS [16, 17]. ESSs can be divided into six main categories in terms of the form of stored energy as seen in Figure 1 [17–20]: mechanical, chemical, electrochemical, electrical, thermal, thermochemical. Among these, battery storage systems (BSSs) are attracting a widespread interest in power industry due to their efficiency, ease of controllability, reliability, compact size, fast response and low maintenance cost [21, 22]. Batteries are mainly categorised into four major groups [23]: primary batteries (non-rechargeable), secondary batteries (rechargeable), fuel cells and electrochemical capacitors. Secondary batteries are very suitable for power system applications since they are extensively used in large-scale grids and EVs [24, 25]. Lead-acid (Pb-acid), lithium-ion (Li-ion), lithium-sulphur (Li-S), nickel-metal hydride (Ni-MH), nickel-cadmium (Ni-Cd) and nickel-zinc (Ni-Zn) are the most commonly used rechargeable batteries.

A BSS comprises a power conditioning system (PCS) along with a battery management system (BMS) [21]. Both functionalities of a BSS can be achieved by power converters. Power converters are key to interface batteries into AC grid or utilise batteries in EVs since they can be responsible for the conversion between DC and AC power [26]. Moreover, power converters play a significant role in controlling the power flow, operating the batteries in the most efficient manner and increase the lifetime of the batteries [27]. Voltage source converters (VSCs) and multilevel converters (MLCs) are among the most commonly used types of power converters. Among them, MLCs are generating considerable interest in BSSs due to their enhanced power quality, reliability and fault-ride through capability [28, 29]. Figure 2 indicates possible applications of MLC based BSSs. As seen MLCs not only utilised in renewable energy integrated large-scale grid applications but also used in EV applications for charging, vehicle-to-grid (V2G) and EV operation purposes.

A challenging area in this field is to select a proper MLC topology that is efficient and cost-effective. Another important problem to solve here is that state-of-charge (SOC) imbalances may occur between batteries due to differences in electrochemical characteristics of each battery in the MLC. Those imbalances between batteries cause degradation in the output voltage and current quality of the MLC.

A considerable amount of literature has been published on MLCs [30–35] and SOC balancing techniques [36–40] in BSSs. Despite this interest, no one to the best of our knowledge has presented a comprehensive overview of the MLC topologies for BSS applications. Moreover, no previous study has reviewed the SOC balancing techniques used in MLCs. In this context, the purpose of this paper is to make an up-to-date review on current state-of-the-art of MLC topologies used in BSS applications, and their control objectives by specifically focusing on SOC balancing techniques.

The overall structure of the study takes the form of six sections, including this introductory section. Section 2 begins by explaining the working principle of rechargeable batteries, and investigates five of the most important types of those batteries. In the third section, traditional and recent MLC topologies that are employed in BSSs are examined. Fourth section presents different types of control techniques that are utilised in MLC based

BSSs by putting emphasis on SOC balancing. In Section 5, discussion and future trends on MLC based BSSs are given. Finally, conclusions are drawn in Section 6.

2 | BATTERY STORAGE TECHNOLOGIES

Batteries are the most widespread types of ESSs due to their superiorities like reliability, efficiency and ruggedness. Chemical energy is converted to electrical energy in batteries by electrochemical reactions. A battery is made up of two electrodes (one positive and one negative), an electrolyte which is responsible for charge transfer and a separator which consists of an electrically insulating material [18]. In this section, a brief overview of several rechargeable battery storage technologies will be given.

2.1 | Lead-acid (Pb-acid) batteries

The oldest type of rechargeable battery is lead-acid battery and it compriseslead oxide (PbO_2) in positive electrode and sponge lead (Pb) in negative electrode. Two electrodes are electrically insulated by a separator and diluted sulfuric acid is used as electrolyte. Lead-acid batteries present several advantages in power applications such as fast response times, high cycle efficiency and low cost [41]. However, deep discharge states severely affect their lifetimes. Moreover, their share in power industry significantly decreased in the past decade due to its disadvantages like low energy density, low specific energy, high self-discharge rates and long charge times [42, 43].

2.2 | Lithium-ion (Li-ion) batteries

Li-ion batteries gained an extensive use in consumer electronics, EVs and grid storage applications during the past decade [44, 45]. In the positive electrode, lithium metal oxide (e.g. $LiCoO_2$, $LiNiO_2$, $LiMn_2O_4$) can be used, however, the most popular material is lithium iron phosphate ($LiFePO_4$). The most widely used material in the negative electrode is graphite. Lithium salt dissolved in non-aqueous solvents is used as electrolyte. A separator which is mostly made up of lithium hexafluorophosphate ($LiPF_6$) is used for electrical insulation. Li-ion batteries have high energy density, high specific energy, long lifetime, high cycle efficiency, fast response time and low self-discharge rates [21, 46]. Nevertheless, there are some properties of Li-ion batteries that limit its applications in power industry such as high costs and safety issues since they are prone to temperature increases and internal short circuits when they are overcharged [45].

2.3 | Nickel-cadmium (Ni-Cd) batteries

Ni-Cd batteries consist of a nickel hydroxide ($Ni(OH)_2$, NiOOH) based positive electrode and metallic cadmium based negative electrode. Aqueous alkali solvents are used as the electrolyte [47]. It is vital that Ni-Cd batteries can be fully discharged. Moreover, they have long lifetime and low maintenance requirements. However, since cadmium is a toxic metal, Ni-Cd batteries are not environmentally friendly. In addition, memory effect is seen such that their capacity decreases if they are repeatedly charged after not fully discharged [23]. Ni-Cd batteries are more suitable to applications where extreme operating temperatures are observed [22, 24].

2.4 | Nickel-metal hydride (Ni-MH) batteries

Similar to Ni-Cd batteries, Ni-MH batteries employ nickel hydroxide based positive electrode and aqueous alkali solvents as electrolyte. The difference lies in the utilisation of a hydrogen-absorbing metal alloy like vanadium or titanium as the negative electrode. Therefore, environmental hazards and memory effect of Ni-Cd batteries are not reflected to Ni-MH batteries [47]. They have higher energy density than Ni-Cd batteries. Similar to Ni-Cd, Ni-MH batteries have moderate lifetime and can be recycled. However, they have high self-discharge rates and their performance decreases after a couple hundreds of cycles [48]. Although these issues have negative impacts on their use in power applications, they are frequently utilised in portable products, EVs and utility-scale applications [49, 50].

2.5 | Sodium-sulfur (Na-S) batteries

Na-S batteries utilise molten sulfur and sodium as their positive and negative electrodes, respectively. Solid beta alumina ceramic is used as electrolyte and separator in Na-S batteries [23]. The characteristic property of Na-S batteries is their high operating temperatures (300–350°C) to keep the liquid states of the electrodes. Under these circumstances, it is likely that battery corrodes and integrity of the cell seal is broken [51]. Hence, thermal management of Na-S batteries is required. On the other hand, Na-S batteries have high energy density, long lifetime, low self discharge rates and low cost [23]. These properties make Na-S batteries a promising candidate on utility-scale storage applications [21, 24]. Yet, dependence on high temperatures is the problem to solve for Na-S batteries in the near future.

2.6 | Aluminum-ion (Al-ion) batteries

Al-ion batteries employ pure aluminum as their positive electrode. Graphite, V_2O_5, TiO_2 and Ni_3S_2 can be counted among different materials that are used in negative electrode [52]. Among them, graphite is the most popular one due its electrical conductivity and low cost [53]. Ionic liquid based electrolytes are utilised. Aluminum is the most abundant metal and the third most abundant element on the earth crust, hence cost is significantly reduced compared to Li based batteries [54]. It has a volumetric capacity of 8096 mAh/cm^3 which is four times of the Li-ion batteries (2062 mAh/cm^3). Gravimetric capacities of Al-ion and Li-ion batteries are comparable (2980 and 3860 mAh/g, respectively) [55]. Moreover, small electrochemical equivalence (0.336 g/Ah) of Al makes it an ideal candidate for rechargeable batteries [56]. High reactivity and corrosivity of ionic liquid based electrolytes, corrosions that occur in negative electrode and poor cyclic stability can be counted among the disadvantages of Al-ion batteries [55, 57]. Table 1 summarises different aspects of abovementioned rechargeable battery storage technologies.

3 | MULTILEVEL CONVERTER SCHEMES FOR BATTERY STORAGE SYSTEMS

MLCs are increasingly becoming a key component in BSSs due to improved power quality, fault-ride through capability and reliability. MLCs can be utilised in MLCSs as the sole representative of power conversion stage in BSSs. This configuration is called single-stage MLCS. However, they can also be combined with bidirectional DC–DC converters to create two-stage MLCSs in BSSs. MLCs that are used in MLCSs can be mainly realised in four different configurations: modular multilevel converters (MMCs), cascaded submodule multilevel converters (CSM-MLCs), diode-clamped multilevel converters (DC-MLCs) and flying-capacitor multilevel converters (FC-MLCs) [28, 29]. Similarly, bidirectional DC–DC converters that are utilised in MLCSs can be divided into four main categories: buck–boost (BB) converter, dual active bridge (DAB) converter, quasi-z-source (QZS) converter and interleaved converter [63–66]. In this section, traditional types of MLCSs which are employed in BSSs will be investigated. Furthermore, recently proposed configurations of these schemes will be introduced as well as some brand new MLCSs.

3.1 | Modular multilevel converters schemes

Circuit topology of a three-phase MMCS in a BSS is demonstrated in Figure 3. Each battery is connected to a submodule (SM) which is essentially a power converter structure. SMs can be classified in two categories depending on employing a DC–DC converter stage or not: single-stage SM and two-stage SM. While two-stage SMs utilise a DC–DC converter stage to connect the battery to DC–AC converter, the battery is directly connected to DC–AC converter in single-stage SMs. Two-stage SMs are advantageous compared to single-stage SMs since a degree of freedom is provided by the DC–DC converter for the control of the system, however, efficiency in power conversion is reduced in two-stage SM configurations [67]. SMs are series connected to create upper and lower arms in each phase (leg) of MMCS. Moreover, an inductor to filter currents is utilised in each arm. A multilevel output waveform is obtained at the output of MMCSs and number of levels depend on number and type of submodules and modulation technique.

Figure 4 shows different types of single-stage SM configurations that are used in MMCSs. The most commonly used single-stage SM is the half-bridge (HB) configuration [68–73]. It consist of two switches which work in an opposite manner to each other and SM becomes ON and OFF when S_1 and S_2 conducts respectively as seen in Figure 4a. In full-bridge (FB) configuration, there are four switches as seen in Figure 4b and fault-ride through capability is increased compared to HB configuration [74–76].

Reference [77] introduces a new single-stage SM configuration called reverse blocking SM as seen in Figure 4c. In this configuration, two anti-parallel insulated gate bipolar transistors with reverse blocking capability and an additional bypass circuit are employed. The proposed SM configuration blocks DC fault currents effectively.

Some researchers employ both FB and HB configurations in MMCS [78–80]. These types of topologies are called as hybrid MMCS as demonstrated in Figure 5. Reference [79] employs FB SMs along with HB SMs to enhance the DC fault-ride through capability of MMC. FB SMs with batteries and HB SMs with capacitors are used in [80] to provide additional system services by partially decoupling DC and AC grids. In [81], packed U-cell (PUC) configuration is used as a single-stage SM and higher number of levels are achieved by using less components.

Figure 6 shows different types of two-stage SM configurations that are used in MMCSs. The most commonly used among them is buck–boost half-bridge (BB-HB) configuration [63, 66, 78, 82] as seen in Figure 6a. Similarly, buck–boost full-bridge (BB-FB) configuration is given in Figure 6b [79]. The use of BB converter in these SM configurations is to regulate capacitor voltages [83].

Reference [84] proposes a new two-stage SM configuration called as quasi-full-bridge (QFB) SM with integrated battery as seen in Figure 6c. Although the name of the SM includes quasi in it, it operates as a BB-HB SM in normal operating mode and anti-parallel thyristors are only used in DC fault conditions. It possesses DC fault-ride through capability and battery current is smoothed out. Cost is somewhat increased due to utilisation of thyristors. A back-to-back BB-HB SM configuration is proposed in [85] as seen in Figure 6d. While boost part of the converter is responsible for maintaining a constant capacitor voltage, charging profile of the battery is controlled by the buck part.

Figure 7a and Figure 7b indicate dual-active bridge half-bridge (DAB-HB) SM [86] and dual-active bridge full-bridge (DAB-FB) SM [80] configurations, respectively. The use of DAB converter in these SM configurations is to regulate the power of the battery pack and provide galvanic isolation [86]. A two-stage SM that consist of DAB converter along with series and parallel configuration of four full-bridges is suggested in [87]. As a result, current capability of the overall topology is doubled and efficiency of the system is increased.

Figure 7c presents an interleaved boost converter based HB SM configuration [66]. In this two-stage SM configuration, current is distributed between two legs of the interleaved boost converter as well as power losses. Hence, it is very suitable for high power BSSs.

TABLE 1 Comparison of rechargeable battery storage technologies [18, 21, 23, 24, 48, 54, 58–62]

	Specific power (W/kg)	Specific energy (W h/kg)	Power density (W/L)	Energy density (W h/L)	Cell nominal voltage (V)	Daily self-discharge (%)	Lifetime (years)	Lifetime (cycles)	Advantages	Disadvantages
Pb-acid	75–200	25–50	10–400	50–90	~2.1	0.1–0.3	5–15	500–2000	Low cost Low self discharge rate Fast response time	Long charge times Not environmentally friendly Low specific energy Limited discharge depth
Li-ion	150–500	80–200	1000–10000	200–500	~3.6	0.1–0.3	5–15	1000–10,000	High cycle efficiency Low self-discharge rate Fast response time	High cost Requires management
Ni-Cd	150–300	45–80	90–600	15–105	~1.2	0.2–0.6	10–20	2000–2500	Long lifetime Can be recycled Can be fully discharged	Not environmentally friendly Has memory effect High cost
Ni-MH	~200	40–110	500–3000	170–420	~1.2	~0.67	~10	600–1200	High energy density Can be recycled Environmentally friendly	High self discharge rate Moderate lifetime
Na-S	150–230	100–220	140–160	150–300	~2.1	~0	15	~2500	Low cost High energy density Long lifetime	Requires thermal management Safety issues
Al-ion	—	40–45	3000	—	~1.8	—	—	7500–36000	Low cost High volumetric capacity	Poor cyclic stability Corrosion on electrolyte

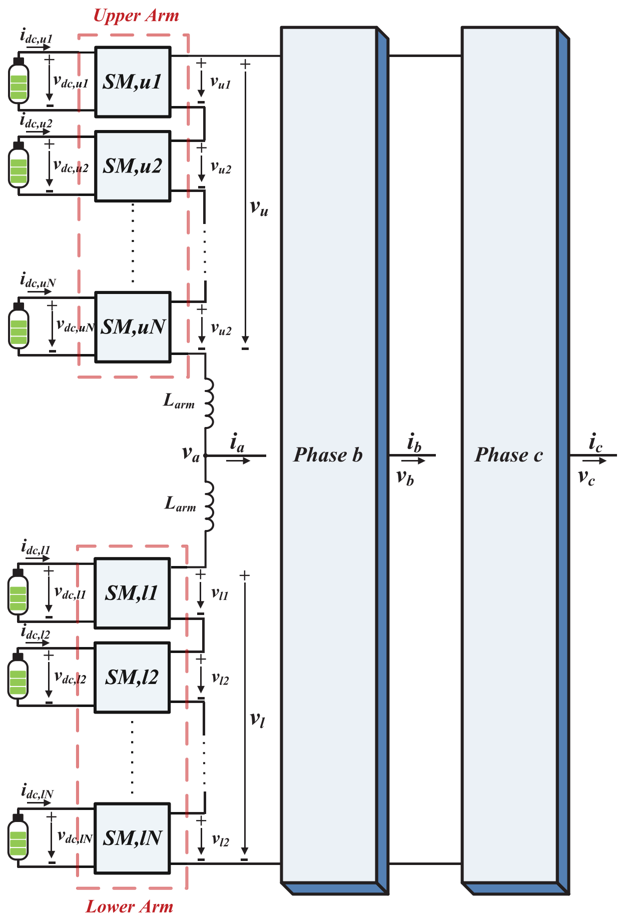


FIGURE 3 Circuit topology of modular multilevel converter scheme (MMCS) in a BSS

3.2 | Cascaded submodule multilevel converter schemes

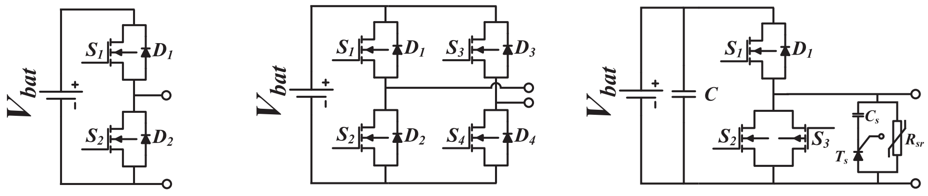
Circuit topology of a single-phase CSM-MLCS in a BSS is demonstrated in Figure 8. Similar to MMCSs, each battery is connected to a SM which could either be single-stage or two-stage and those SMs are series connected to generate CSM-MLCS. As the name suggests, a multilevel output waveform is obtained and the number of levels change with respect to type and number of SMs and modulation technique. Figure 9 shows different types of single-stage SM configurations that are used in CHB-MLCS based BSSs. Among all, the most commonly used configuration is the FB [88–103] as shown in Figure 9b. When the SMs of CSM-MLCSs consist of FBs, the topology is called cascaded H-bridge (CHB) MLCS.

A hybrid system that combines an ultra-capacitor (UC) along with a battery is proposed in [104] as seen in Figure 10a. The main reason to use UCs here is that UCs reduce the inefficiencies caused by slow dynamics of batteries since power and energy densities of UCs are much higher than batteries and UCs can deliver energy much faster than batteries. Hence, UCs enhance the efficiency of the system, especially in rapidly changing drive profiles. Another advantage is that fewer number of semiconductors become active to a certain voltage level compared to traditional FB based SM configuration.

An unorthodox SM configuration that has four terminals and nine switches is suggested in [105, 106] as shown in Figure 10b. This configuration enables SMs to be connected in series and/or parallel. Hence, each SM may be interconnected to its neighbouring SMs according to the needs of the system such as requirement of optimum source resistance, balanced aging of batteries and achieving lowest SOC cycling.

Some researchers combine the single-stage SM configurations given in Figure 9 and create more advanced types of CSM-MLCSs. References [107–109] propose a CSM-MLCS for DC–AC applications that utilises both HB SMs given in Figure 9a and a FB SMs as indicated in Figure 11a. Similarly, the same topology is used in [110], however, this time for a DC–DC application. Moreover, references [111, 112] produce a back-to-back configuration based on this topology for high frequency wireless EV chargers. In the proposed topology, the use of HB SMs and FB SMs are to generate multilevel waveform and provide polarity, respectively. The advantage of this topology is to achieve a certain number of levels at the output by using less number of switches. A few years later, a CSM-MLCS that employs three-level (TL) SMs given in Figure 9c and an FB SM as seen in Figure 11b are suggested by [113]. Compared to the topology given in Figure 11a, the proposed topology achieves higher number of levels at the output with the same number of SMs. Finally, references [114, 115] suggest a single-phase five-level topology as seen in Figure 11c. The proposed topology possesses voltage boosting capability and utilises fewer number of switches to generate an output waveform with the same number of levels compared to CHB-MLCs.

Figure 12 shows different types of two-stage SM configurations that are used in CSM-MLCSs. The most commonly used among them is BB-FB configuration [94, 99] as seen in Figure 6b. Similarly, BB-HB configuration is given in Figure 6a [110]. Unlike conventional use of BB-HB SMs, researchers in



(a) Half-Bridge SM (HBSM) (b) Full-Bridge SM (FBSM) (c) Reverse blocking SM

FIGURE 4 Traditional and recently proposed single-stage submodule configurations for MMCSs

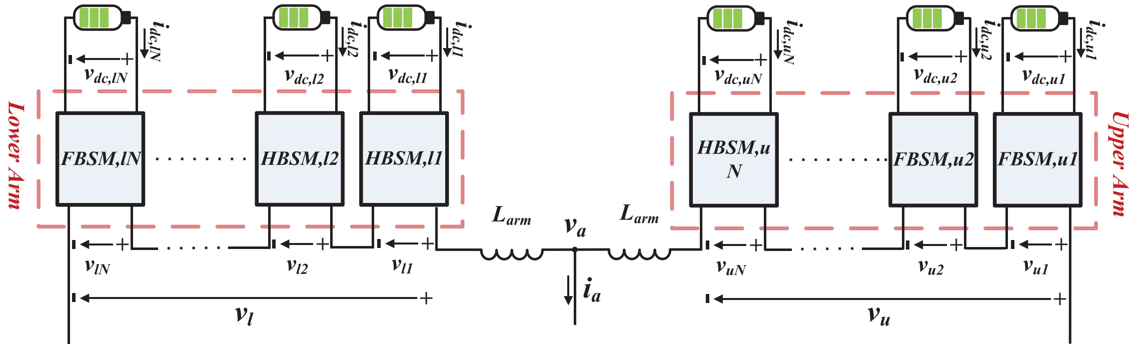
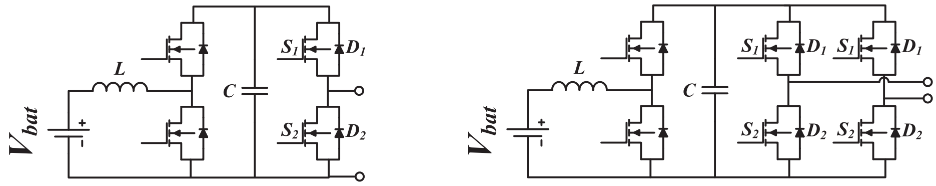
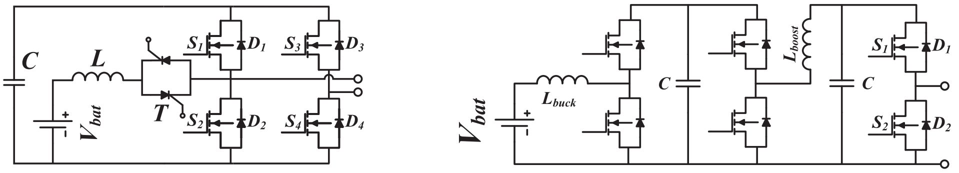


FIGURE 5 Circuit topology of a hybrid modular multilevel converter scheme (MMCS) in a BSS



(a) Buck Boost Half-Bridge (BB-HB) SM

(b) Buck Boost Full-Bridge (BB-FB) SM



(c) Quasi Full-Bridge (QFB) SM

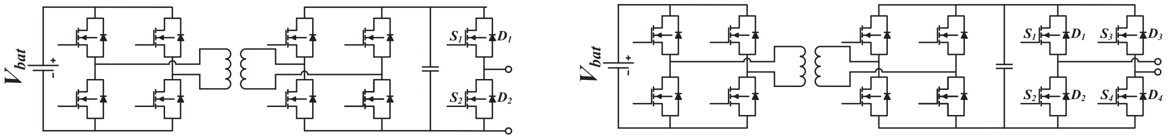
(d) Back-to-Back Buck Boost Half-Bridge (BB-HB) SM

FIGURE 6 Traditional and recently proposed two-stage submodule configurations for MMCSs

[116–118] employ BB-HB SMs in a modular DC–DC converter scheme.

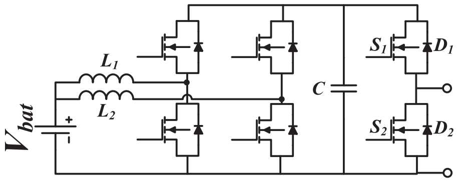
DAB-FB based two-stage SM configuration is demonstrated in Figure 6c [64, 119, 120]. The merits of using DAB based FB SMs are that obtaining galvanic isolation, ability to use soft-switching techniques and requiring a simple control structure [121].

References [65, 122] propose a QZS based two-stage SM configuration that utilises a DC source(e.g. photovoltaic (PV)) along with a battery as seen in Figure 13a. QZS SM configuration has



(a) Dual Active Bridge + Half-Bridge SM

(b) Dual Active Bridge + Full-Bridge SM



(c) Interleaved Boost Half-Bridge SM

FIGURE 7 Other recently proposed two-stage submodule configurations for MMCSs

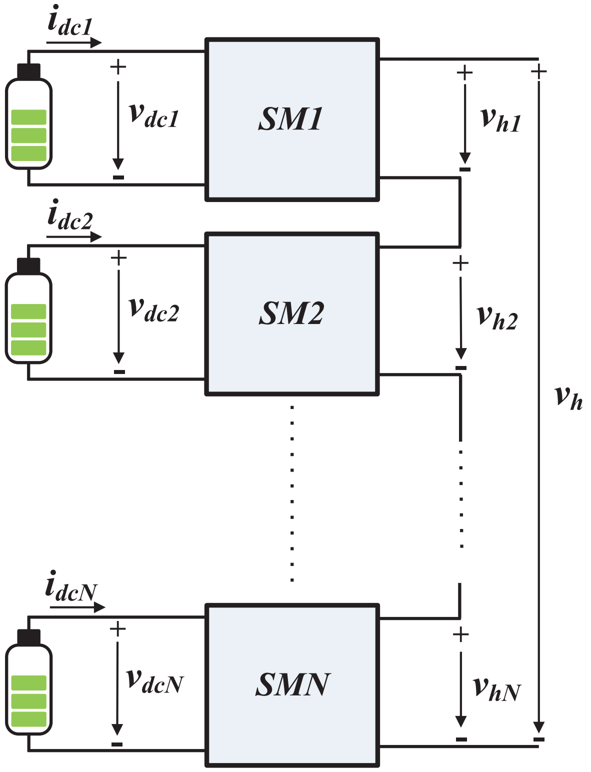


FIGURE 8 Circuit topology of cascaded submodule MLC in a BSS

the ability to balance and boost the DC-link voltage. A DBB-FB SM configuration is suggested in [123] as seen in Figure 13b. In this configuration, each leg consists of a semiconductor and a diode and buck–boost properties are observed along with conventional FB structure. Eliminating the shoot-through problem that occurs in traditional FB SM configuration and mitigating the reverse recovery power dissipation on semiconductors can be counted among the advantages of this two-stage SM configuration.

3.3 | Diode-clamped multilevel converter schemes

Circuit topology of a three-phase three-level DC-MLCS in a BSS is presented in Figure 14a. Three-level DC-MLCSs are the most popular DC-MLCS that are used in BSSs. Generally, batteries are connected to DC-MLCSs by DC–DC converter structures [124–127], however; direct connections are also possible [128]. Similar to MMCSs and CSM-MLCSs, a DC-MLCS is called a two-stage DC-MLCS if a DC–DC converter is utilised to connect the battery pack to the DC–AC converter. If battery back is directly connected to DC–AC converter, then it is called a single-stage DC-MLCSs.

In [129], a single-stage hybrid DC-MLCS that utilises PVs and two batteries instead of one is proposed as seen in Figure 14b. Cost of the system is reduced and efficiency is increased since no DC–DC converter stage is present. Similarly, reference [130] suggests a four-level single-stage DC-MLCS. In [131], two single-stage six-level DC-MLCSs are connected back to back for a possible BSS application.

In [124], a two-stage three-level BB based DC-MLCS is presented. A two-stage five-level DC-MLCS for a hybrid system that utilies both PVs and batteries is suggested in [132]. To track the maximum power point (MPP) of PVs, DC–DC converters are employed. Another use of those DC–DC converters are to store the excess energy generated by PVs into batteries. Figure 15a,b presents three-level DC–DC converter based DC-MLCSs [126, 127]. The advantages of using three-level DC–DC converter over two-level DC–DC converter in a DC-MLCS are as follows: ability to access both DC buses for power balancing, reduced voltage stress on semiconductors, improved efficiency and output current waveform. A two-stage five-level DC-MLCS is proposed in [133], and DAB DC–DC converters are employed. Although power quality is increased at the output, cost of the system increases as well.

3.4 | Flying-capacitor multilevel converter schemes

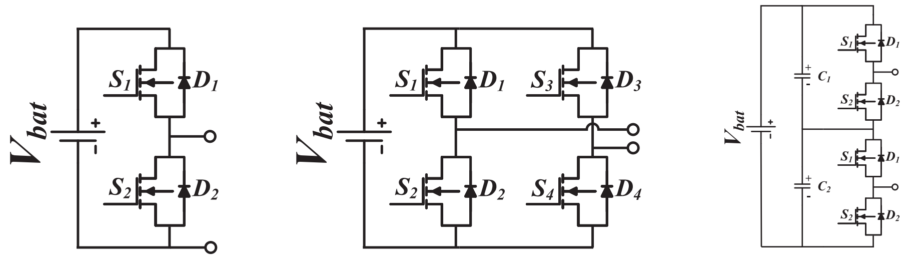
Circuit topology of a four-level FC-MLCS in a BSS is shown in Figure 16. In the literature, FC-MLCSs are mostly employed as single-stage multilevel DC–DC converters in BSSs because of a great reduction in inductance requirements, fast response and low voltage stresses on switching devices [134–136]. Reference [134] employs a four-level FC-MLCS to achieve three discrete DC voltage level at the output. In [135], a five-level FC-MLCS is suggested which has the abilities like operation in high frequencies, low ripples in input/output currents and low voltage drops on switching devices. Reference [136] utilises a six-level FC-MLCS as the DC–DC converter prior to an FB-based DC–AC converter for an EV charging system. A bidirectional FC based modular DC–DC converter structure is proposed in [137] and a five-level topology is created. In addition to low switching stresses, the proposed topology has modular structure and buck/boost capability.

3.5 | The most recent multilevel converter schemes

In the past decade, there has been a rapid rise in developing new MLCSs for BSSs. In this section, the most recent single-stage and two-stage MLCSs that are proposed for BSSs are investigated in detail along with recently proposed DC–DC converter structures that can be used in MLCSs.

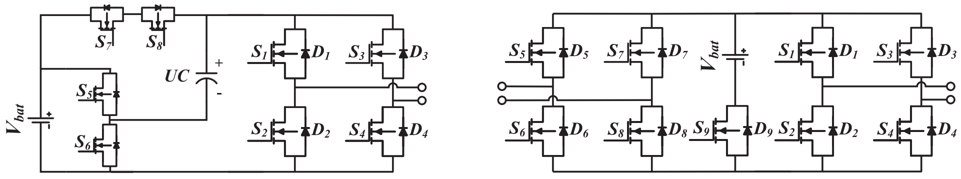
In [138], a two-stage switched-battery boost MLCS is proposed for a standalone application as seen in Figure 17a. The proposed topology consists of modular switched-battery cells and an FB. It has two modes of operations: charging mode and inverter mode. The most important superiorities of the proposed topology are requiring less switches compared to traditional MLC topologies, enhanced reliability and reduced cost.

A new two-stage MLCS that is based on an asymmetric HB converter and a front-end circuit is suggested in [139] for



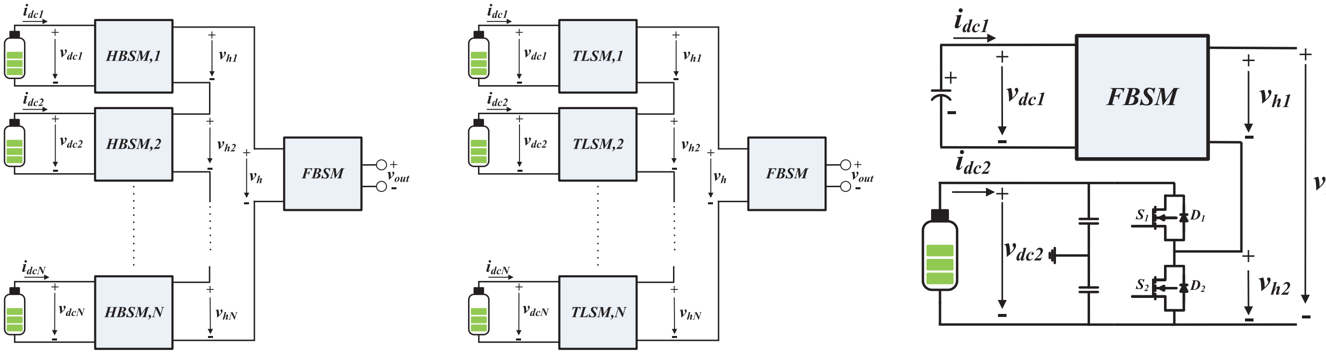
(a) Half-Bridge (HB) SM (b) Full-Bridge (FB) SM (c) Three-Level (TL) SM

FIGURE 9 Traditional single-stage submodule configurations for CSM-MLCSs



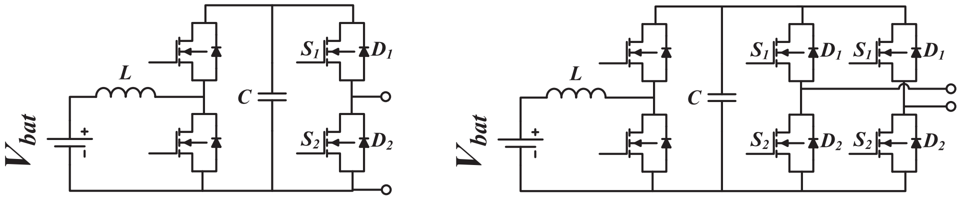
(a) Hybrid SM (b) Four Terminal SM

FIGURE 10 Recently proposed single-stage submodule configurations for CSM-MLCSs

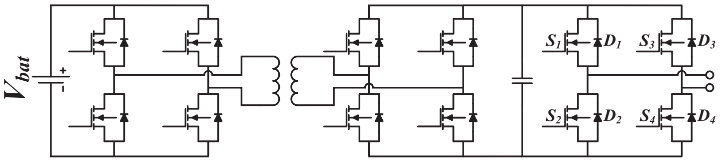


(a) Full-Bridge + Half-Bridge (b) Full-Bridge + Three-Level (c) CSM-Boost MLC

FIGURE 11 Recently proposed cascaded submodule multilevel converter schemes (CSM-MLCS) in a BSS

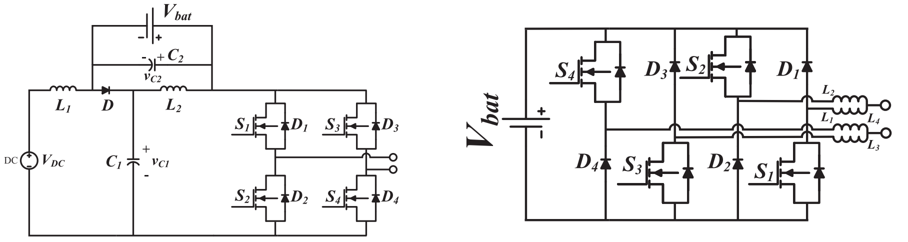


(a) Buck-Boost Half-Bridge (BB-HB) SM (b) Buck-Boost Full-Bridge (BB-FB) SM



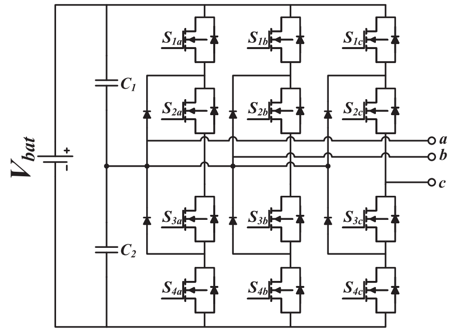
(c) Dual Active Bridge Full-Bridge (DAB-FB) SM

FIGURE 12 Traditional two-stage submodule configurations for CSM-MLCSs

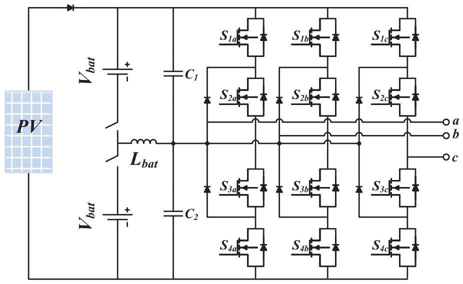


(a) Quasi Z-Source (QZS) SM (b) Dual Buck-Boost Full-Bridge (DBB-FB) SM

FIGURE 13 Recently proposed two-stage submodule configurations for CSM-MLCSs

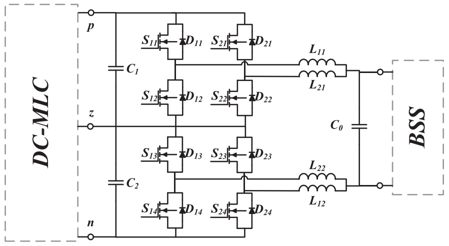


(a) Three-Level DC-MLCS

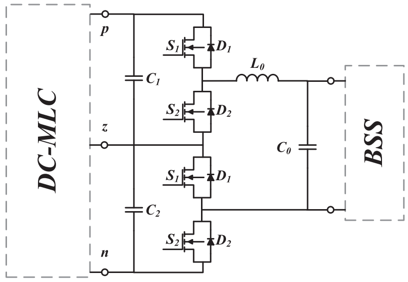


(b) Improved DC-MLCS

FIGURE 14 Traditional and recently proposed single-stage diode-clamped multilevel converter schemes (DC-MLCSs) in a BSS



(a) Three-Level DC-DC Converter Based DC-MLCSs



(b) Improved Three-Level DC-DC Converter Based DC-MLCSs

FIGURE 15 Recently proposed two-stage diode-clamped multilevel converter schemes (DC-MLCSs) in a BSS

plug-in hybrid EV applications as seen in Figure 17b. Front-end circuit provides the proposed topology with flexibility to change operating mode of the converter and generation of multilevel waveform. The proposed MLCS requires less switches and a simpler control algorithm.

A single DC source based two-stage seven-level MLCS is suggested in [140] for EV applications as seen in Figure 17c. It utilises a single-input dual-output boost DC–DC converter and the proposed seven-level MLCS employs less switches and DC sources to achieve same number of levels at the output compared to traditional MLCSs. Moreover, boost gains up to 2.1 can be achieved by the proposed scheme.

A 9-level and a 49-level single-stage MLCSs are proposed by the same researcher in [141] and [142], respectively. As seen in the nine-level MLCS in Figure 17d, the proposed topology consists of flying-capacitor and FB modules. Voltage ratings on switches are greatly reduced and hence, efficiency is increased in this MLCS. It is also possible to reach higher levels by increasing the flying-capacitor modules and decreasing the full-bridge modules. The proposed topology is suitable for EV applications.

In [143], a single-stage five-level MLCS that utilises one leg of a three-level DC-MLC and a HB converter is proposed. It has fault-tolerant capability and requires less active switches compared to single-stage DC-MLCSs and FC-MLCSs that generate an output with the same level.

A MMC based single-stage boost MLCS is proposed for high power wireless EV charging systems in [144]. The proposed scheme has boosting capability and improved efficiency compared to traditional MLCSs.

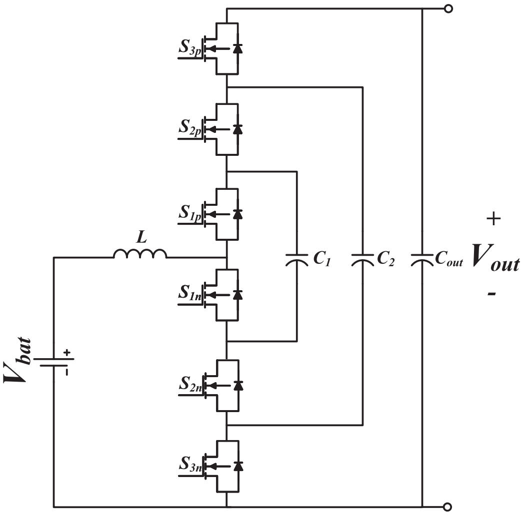


FIGURE 16 Circuit topology of flying-capacitor (FC) MLCS in a BSS

In [145], a single-phase 17-level MLCS is suggested for EV applications. The proposed scheme consists of two single-stage three-level FC-MLCSs with 3:1 DC voltage ratio and an FB converter. The most significant advantage of this scheme is that it requires less switching devices to achieve same number levels compared to CHB-MLCSs.

In [146], a single-stage modular DC–DC converter that employs bidirectional half-bridge DC–DC converter as power modules is suggested. The proposed topology makes use of used batteries instead of new batteries and reduces cost significantly.

A two-stage five-level T-type MLCS is proposed in [147]. It employs an interleaved boost converter based DC–DC converter for battery connection and successfully reduces voltage and current ripples at the output compared to traditional MLCSs. Similarly, references [148, 149] suggest a two-stage MLCS that is based on a boost DC–DC converter and five-level T-type converter. The proposed scheme utilises two extra switches and a capacitor to balance the voltages on the capacitors of T-type converter. The proposed topology reduces size and cost and provides fault tolerance.

Figure 18 shows recently proposed DC–DC converter structures that have not been utilised in MLCSs yet, however, these structures are worth mentioning in this paper as they could be a good candidate for a possible use in two-stage MLCSs. Figure 18a indicates a switched capacitor (SC) boost DC–DC converter [150]. SC circuit is employed to create multilevel DC voltage in front of conventional three-phase VSC. Inductor is eliminated compared to conventional boost converter in the proposed topology.

A three-phase interleaved BB converter is employed in [151] along with a conventional VSC for EV applications. The converter operates in buck mode while battery charging and regenerative breaking and in boost mode while vehicle propulsion.

Figure 18b demonstrates an interleaved flyback boost converter (IBFC) for an EV charger application [152]. The merits of IBFC are to have low number of switches and obtaining low current ripple if high number of phases are interleaved.

A two-phase interleaved boost converter is combined with a full-bridge LLC (FB-LLC) multiresonant converter in [153] for an EV charger application as seen in Figure 18c. While interleaved boost converter is responsible for power factor correction (PFC) and reducing total harmonic distortion (THD), the duty of FB-LLC converter is to provide galvanic isolation and apply DC–DC conversion.

Similar to previous DC–DC converter topology, a Cuk converter and half-bridge LLC (HB-LLC) resonant converter based DC–DC structure is proposed in [154] as given in Figure 18d. Here, HB-LLC converter is responsible for obtaining galvanic isolation and DC–DC conversion, PFC is held by Cuk converter.

4 | CONTROL STRATEGIES FOR MULTILEVEL CONVERTER BASED BATTERY STORAGE SYSTEMS

Since MLCSs are generally utilised as an interface between AC and DC grids in BSSs, the direction and amount of power that is interchanging between AC and DC grids as well as batteries should be controlled. Moreover, balancing the SOCs of the batteries in different SMs within the MLCS is very critical in terms of improving the energy utilisation ratio and avoiding overcharge and overdischarge problems. Pulse width modulation (PWM) techniques also play a critical role in BSSs since switches in MLCs are controlled by them. A BSS should be resilient to faults since faults can severely affect the power exchange between AC and DC grids. Hence, this section will investigate different control strategies for MLCS based BSSs in detail.

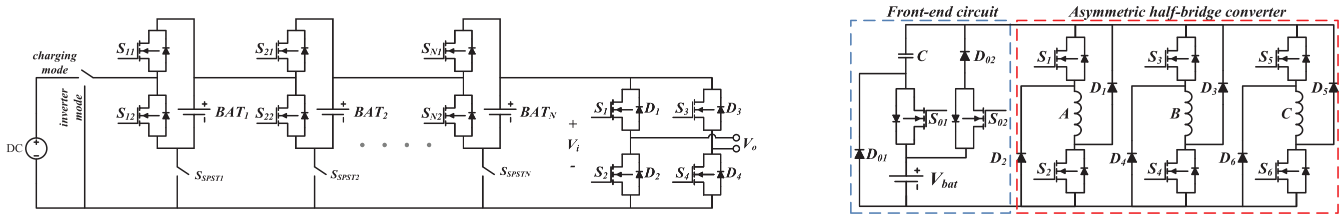
4.1 | Power flow control

MLCSs are responsible for the power exchange between batteries (P_{bat}), DC (P_{dc}) and AC (P_{ac}) grids in BSSs. This type of an exchange often occurs in MMCSs since they utilise a common DC link along with batteries in each SM [63, 79, 155]. All three powers in the system flow bidirectional as seen in Figure 19a. The relationship between those three powers are given as follows:

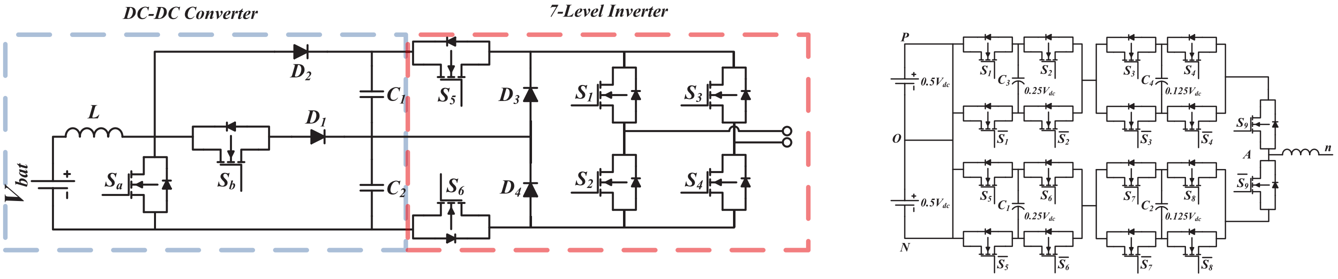
$$P_{\text{bat}} = P_{\text{dc}} - P_{\text{ac.}} \tag{1}$$

Eight different operating regions given in Figure 19b are obtained in a BSS depending on the direction and nominal powers (P_{nom}) of AC and DC grids as given below [63, 79]:

1. MLC as rectifier ($P_{\text{ac}} < 0$):
    I) $P_{\text{dc}} = P_{\text{ac}} \rightarrow P_{\text{bat}} = 0$: idle,
    II) $|P_{\text{ac}}| > |P_{\text{dc}}| \rightarrow P_{\text{nom}} \geq P_{\text{bat}} > 0$: charging,
    III) $|P_{\text{ac}}| < |P_{\text{dc}}| \rightarrow -P_{\text{nom}} \leq P_{\text{bat}} < 0$: discharging,
    IV) $P_{\text{ac}} < 0 < P_{\text{dc}} \rightarrow 2P_{\text{nom}} \geq P_{\text{bat}} > 0$: charging.

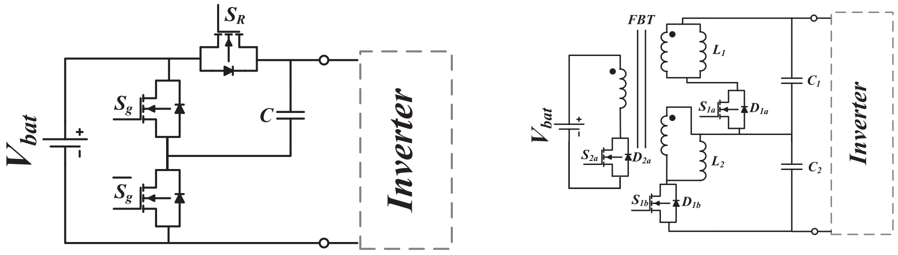


(a) Switched-Battery Boost Two-Stage MLCS (b) Two-Stage MLCS with Front-End Circuit

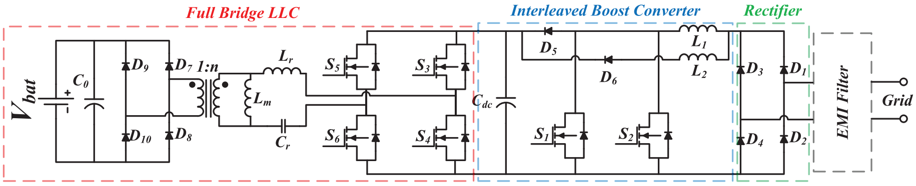


(c) Single DC Source Two-Stage MLC (d) Stacked Single-Stage MLCS

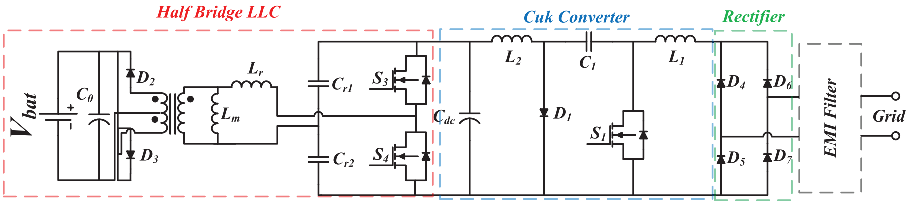
FIGURE 17 Recently proposed single- and two-stage multilevel converter schemes (MLCSs) in BSSs



(a) Switched-Capacitor (SC) Boost DC-DC Converter (b) Interleaved Bidirectional Flyback Converter (IBFC)

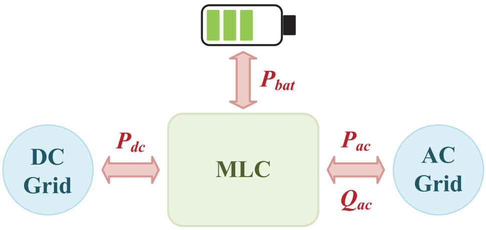


(c) Interleaved Boost and Full-Bridge LLC (FB-LLC) Based DC-DC Converter

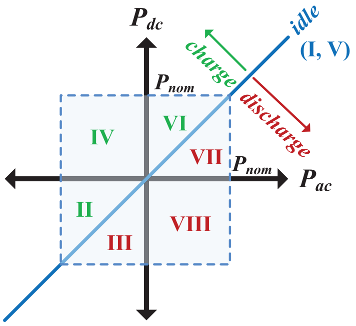


(d) Cuk and Half-Bridge LLC (HB-LLC) Based DC-DC Converter

FIGURE 18 Recently proposed DC–DC converter schemes that can be used in MLCSs in BSSs



(a) Power Flow Diagram



(b) Operating Regions

FIGURE 19 Power flow diagram and operating regions of the MLC based BSS

2. MLC as inverter ($P_{ac} > 0$):
   - V) $P_{dc} = P_{ac} \rightarrow P_{bat} = 0$: idle,
   - VI) $|P_{ac}| < |P_{dc}| \rightarrow P_{nom} \geq P_{bat} > 0$: charging,
   - VII) $|P_{ac}| > |P_{dc}| \rightarrow -P_{nom} \leq P_{bat} < 0$: discharging,
   - VIII) $P_{dc} < 0 < P_{ac} \rightarrow -2P_{nom} \leq P_{bat} < 0$: discharging.

Operating regions can be divided into three main groups which are batteries are charging (II, IV, VI), batteries are discharging (III, VII, VIII) and batteries are idle (I, V). In regions I and V, directions and magnitudes of P_{dc} and P_{ac} are the same, hence batteries become idle. The directions of P_{dc} and P_{ac} are the same in regions II, III, VI and VII but their magnitudes are different. Thus, batteries are charged or discharged with a power of P_{nom}. Finally, directions of P_{dc} and P_{ac} are opposite in regions IV and VIII, therefore, batteries are charged or discharged with a power of $2P_{nom}$.

Different ways of controlling the power flow in MMCSs are proposed by researchers in recent years. Circulating current is utilised in [80, 85, 156] to control active and reactive power flow between batteries and AC grid in MMCs. A method to eliminate active and reactive power oscillations in AC grid is proposed in [156]. In [80], batteries are employed as auxiliary power sources and an extra power injection to AC or DC grid up to 10 % is achieved by circulating current injection.

In order to control the active and reactive power in CSM-MLCSs, a $d-q$ coupled controller must be employed [119, 157–160]. By reflecting the grid components into two-dimensional plane, active power reference (I_{dref}) and reactive power reference (I_{qref}) are obtained. I_{dref} is used to control active power flow between batteries and AC grid, hence charging and discharging of the batteries are controlled by the sign of I_{dref}. Either it is a V2G application [119, 160] or large-scale grid application [157–159], reactive power compensation may be required to meet the reactive power demands of the local loads or support grid voltage. In these cases, I_{qref} are utilised as the main control parameter. It should be noted that the effect of I_{qref} on battery charging and discharging is negligible in MLCS based BSSs.

In DC-MLCSs, active and reactive power control are achieved by $d-q$ coupled controllers similar to CSM-MLCSs. Park's transform is utilised in [132] to convert three-phase grid components into two-dimensional dq components in a PV based BSS. Likewise, a decoupled control strategy is employed in [129] in a PV based BSS. In both systems, batteries are charged by the excess PV power and discharged to provide support to PVs when PVs fail to meet the power requirements of AC grid.

4.2 | State-of-charge balancing

Prior to investigating SOC balancing techniques in MLCS based BSSs, the term SOC should be properly defined. SOC of a battery is defined as its instantaneous capacity denoted as a rate of its nominal capacity as indicated below:

$$\mathrm{SOC} = \frac{Q_{\mathrm{ins}}}{Q_{\mathrm{bat}}} \times 100\%, \tag{2}$$

where Q_{ins} and Q_{bat} are instantaneous capacity and nominal capacity of the battery, respectively. A more mathematical representation of SOC for a single battery is given as follows:

$$\mathrm{SOC}_k(t) = \mathrm{SOC}_k(0) + \int_0^t \frac{i_{\mathrm{bat}}}{Q_{\mathrm{bat}}}\, dt, \tag{3}$$

where i_{bat} is denoted as battery current, $\mathrm{SOC}_k(t)$ and $\mathrm{SOC}_k(0)$ represent instantaneous and initial SOC of the corresponding battery.

Due to differences in electrochemical characteristics of the batteries that are utilised in MLCS based BSSs, SOCs of those batteries may vary. This phenomena causes an inhomogeneous distribution between individual battery voltages. In addition, the capacity of the whole system decreases rapidly and system failures may happen. That is why balancing of SOCs are crucial in MLCS based BSSs. SOC balancing techniques can be divided into two main groups: active and passive SOC balancing. In active SOC balancing, energy storage devices like capacitors and inductors or DC–DC converters are utilised. This increases the complexity and cost of the system even though it has high efficiency and fast balancing rate. On the other hand, the surplus energy in the batteries with higher SOCs are dissipated via resistors within the system in passive SOC balancing. This technique is less complex and more cost-effective compared to active SOC balancing techniques [161, 162]. In this section, SOC balancing techniques will be investigated for different MLCSs.

4.2.1 | SOC balancing in MMCSs

Different SOC balancing techniques are used in MMCSs, however, one of the most famous method is achieved by dividing SOC balancing into three categories: phase SOC balancing, arm SOC balancing and SM SOC balancing. In this technique, phase, arm and SM SOCs are balanced individually and it is very popular among researchers [63, 67, 79, 86, 162–170]. In SM SOC balancing, SOC of an individual SM within an arm is made equal to the mean SOC of all SMs in that arm. A part of the reference signal that is used to modulate the switches in the corresponding SM is obtained in SM SOC balancing. It should be noted that some researchers use simple sort and select algorithm for SM SOC balancing [171, 172]. In this technique, SOCs of all SMs are sorted and SMs with the higher SOCs are discharged more or charged less compared to SMs with lower SOCs and this is achieved by adjusting the reference signal or changing the carrier rotations in the PWM method. The formula to calculate mean SOCs of both arms in one phase of an MMCS is given below:

$$\mathrm{SOC}_{uj} = \frac{\sum \mathrm{SOC}_{ujk}}{N}, \qquad \mathrm{SOC}_{lj} = \frac{\sum \mathrm{SOC}_{ljk}}{N}, \tag{4}$$

where SOC_{uj} and SOC_{lj} represent mean SOCs of upper and lower arm, respectively. Moreover, SOC_{ujk} and SOC_{ljk} demonstrate the SOCs of individual SMs within upper and lower arms, respectively. It should be noted that k takes values between 1 and N where N is the number of SMs within an arm.

In arm SOC balancing, SOC of a branch as given in Equation (4) is kept equal to mean SOC of all branches in a phase. Arm SOC balancing yields the AC component of the circulating current. Mean SOC of all branches is calculated as follows:

$$\mathrm{SOC}_j = \frac{\mathrm{SOC}_{uj} + \mathrm{SOC}_{lj}}{2}, \tag{5}$$

where SOC_j is the SOC of the corresponding phase. Finally, SOC of each phase is aimed to be equal to the mean SOC of all phases in phase SOC balancing. As a result of phase SOC balancing, DC component of the circulating current is obtained. Mean SOC of all three phases is calculated as below:

$$\mathrm{SOC}_{\mathrm{BSS}} = \frac{\sum \mathrm{SOC}_j}{3} \tag{6}$$

where $\mathrm{SOC}_{\mathrm{BSS}}$ represents the average SOC of the whole MMCS.

Block diagrams for phase, arm and SM SOC balancing controls in MMCSs are presented in Figure 20. Block diagrams for lower arm SOC balancing and lower arm SM SOC balancing are very similar to the block diagrams of upper arm and upper arm SM SOC balancing controls respectively, hence those diagrams are not given in the context for the sake of simplicity.

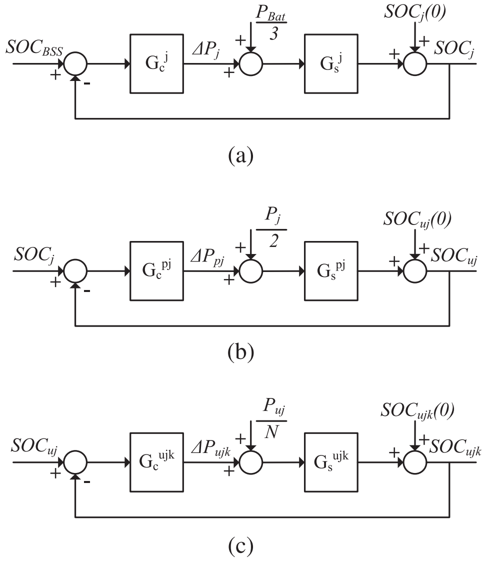


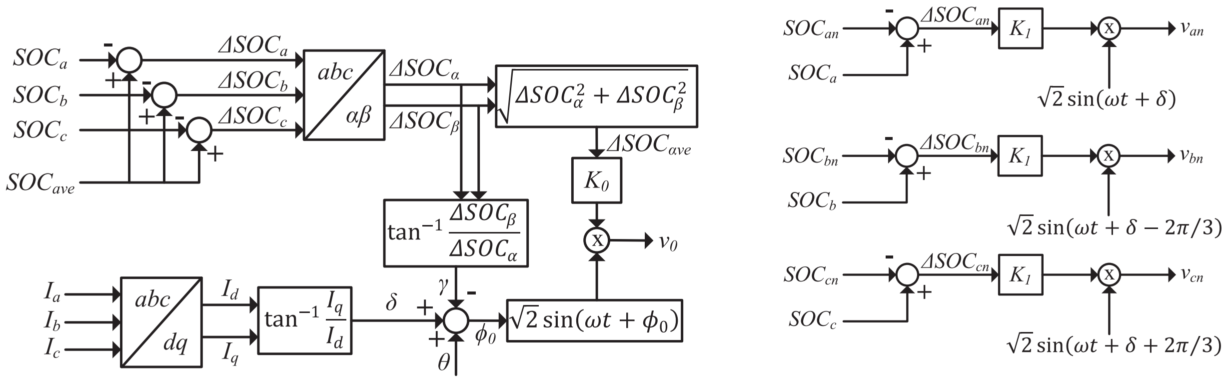
FIGURE 20 Block diagrams for submodule SOC balancing in MMCSs in (a) phase, (b) upper arm, (c) submodules in upper arm

As seen, SM SOC balancing controls are realised by controller parameter G_c. While some researchers use simple proportional (P) type controllers [63, 79, 162–164, 169, 170], others employ proportional-integral (PI) controllers [165–167, 172]. It should be noted that utilisation of proportional-integral-resonant (PIR) controller is also observed in the literature [67].

Besides traditional techniques, some researchers propose more advanced SOC balancing techniques in MMCSs. A SOC balancing method which is based on a virtual SOC (V-SOC) parameter for EV applications is suggested in [173]. This strategy is based on getting information from the user about the expected SOC and charge/discharge time. Adding initial SOC value into the equation yields V-SOC. As a result, a power ratio factor to share the power between EVs is determined using all V-SOCs within an arm. In [83], an individual SM SOC balancing method is proposed. In this technique, first, a battery power unbalance parameter is determined. This parameter indicates how the power provided by the battery in a SM varies from the average battery power in all SMs within the arm. Based on these parameters, two other parameters named DC and AC factors are calculated. Finally, DC and AC factors determine the reference signal that is fed to each SM.

4.2.2 | SOC balancing in CSM-MLCSs

In CSM-MLCSs, SOC balancing control techniques are mainly focused on CHB-MLCSs. In CHB-MLCSs, SOC balancing techniques are investigated depending on whether the system is three phase or single phase. If the system is three phase, SOC balancing is divided into two categories: phase SOC balancing and SM SOC balancing. If the system is single phase, only SM SOC balancing control is held. For three-phase CHB-MLCSs, phase SOC balancing aims to make the average SOC of each phase equal to the average SOC of all phases. It is achieved by



(a) Phase SOC balancing

(b) SM SOC balancing

FIGURE 21 Phase and SM SOC balancing control diagrams

zero-sequence voltage (v_0) injection to the voltage reference of each phase [38, 64, 121, 174–182]. The injected v_0 influences the power delivered by or extracted from each phase, hence changes phase voltages but does not affect line to line voltages. Figure 21a demonstrates phase SOC balancing in CHB-MLCCs by v_0 injection technique. The formula to calculate v_0 is given below:

$$v_0 = \sqrt{2}K_0 \Delta\mathrm{SOC} \sin(\omega t + \phi_0), \tag{7}$$

where K_0 is proportional gain and ΔSOC represents SOC imbalance degree among phases. Phase angle ϕ_0 in Equation 7 is formulated by:

$$\phi_0 = \theta + \delta - \gamma, \tag{8}$$

where θ is the output of phase locked loop (PLL), δ is the power factor angle and γ indicates SOC imbalance in terms of phase angle in $\alpha\beta$ axes.

SM SOC balancing in three-phase CHB-MLCSs is given in Figure 21b. Here, SOC of each SM is kept equal to average SOC of all SMs in the corresponding phase. Voltage reference of each SM is modified to control the active power transfer between SMs.

In single-phase CHB-MLCSs, SOC balancing among SMs is achieved by two main methods: sort and select (SS) [37, 65, 123, 183–188] and carrier orientation [107, 108, 113, 189, 190]. In SS technique, SOCs of all SMs are sorted and SMs with higher SOC values are discharged more or charged less. In carrier orientation, carrier signals in PWM technique are interchanged among SMs so that equal power sharing among SMs is achieved.

Besides traditional SM SOC balancing techniques, some unique solutions are presented by researchers as well. SM SOCs are balanced in [191] by selecting proper states in space-vector PWM. Power of each SM is set to a reference value in [122] to achieve SOC balancing. References [192, 193] employ some sort of a SS technique, however, the essence of SOC balancing control is to adjust phase angles of the high frequency part of the voltage reference of each SM. Redundant switching states are utilised for SOC balancing in [194]. An interesting approach is taken in [195] such that at every 3 s, one SM is removed from the system and its pseudo open circuit voltage (POCV) is measured. After measuring the POCVs of all SMs, they are sorted and these sorted values are fed to nearest voltage matching algorithm. SS technique is also used in [196] to achieve SOC balancing in a CSM-MLCS with the SM topology given in Figure 10b.

4.2.3 | SOC balancing in other MLCSs

In DC-MLCSs and FC-MLCSs, capacitor voltage balancing is the real issue to be solved instead of SOC balancing [124, 125, 129, 135]. The main reason for this is that these MLCSs do not have a modularised structure unlike MMCSs and CSM-MLCSs. Consequently, they mostly employ single battery pack and this battery pack is connected to the capacitors which provide the DC voltage to the MLCS [126, 134]. SOC balancing in DC-MLCSs is investigated in [130]. Here, a multiphase structure which utilises multiple battery packs in each phase is employed. PI compensators are used to serve SOC balancing purpose. Finally, redundant switching states are employed in [143] to achieve SOC balancing for the proposed MLCS.

4.3 | Pulse width modulation

Various PWM techniques are employed by researchers on MLC based BSSs. However, the most popular one is phase-shifted PWM (PS-PWM) method as it is extensively utilised in MMCs [67, 83, 164, 165, 167, 169, 170, 172, 173, 197–200] and CSM-MLCs [38, 65, 119, 122, 123, 159, 175, 177, 180, 186, 194, 201–205]. In PS-PWM, carriers of subsequent SMs are shifted in phase and phase-shift angle is determined by the number of SMs. Level-shifted PWM (LS-PWM) technique is also used in MMCs [162], DC-MLCs [133] and other topologies [133], however, it is mostly employed in CSM-MLCs [108, 158, 196, 206]. Carriers of subsequent SMs are shifted in magnitude in LS-PWM. Utilisation of space-vector PWM (SV-PWM) method is very popular in DC-MLCs [125, 128, 129, 132], nevertheless, it is also employed in CSM-MLCs [191]. Selective harmonic elimination PWM (SHE-PWM) is an effective technique to eliminate specific harmonics in CSM-MLCs [37, 187, 207–211], however, it is used in other topologies occasionally [138]. Fundamental frequency PWM method improves the efficiency of the system by reducing the effective switching frequency of the converter and it is mostly used in CSM-MLCs [115, 157, 160, 185, 190]. Nearest level modulation (NLM) is another technique to enhance the efficiency of the system and finds itself a use in CSM-MLCs [183, 195, 212].

Besides traditional PWM schemes, new PWM techniques are proposed by researchers in recent years. A multi-dimensional (MD-PWM) technique is proposed for MMC and CHB-MLC based EV applications in [176, 193] respectively. In MD-PWM, output of each SM is represented in coordinate axes and a control region is generated. Switching signals are produced based on the control region. An odd-harmonic hybrid modulation (OHHM) technique is suggested in [193] for CHB-MLC based hybrid BSS. In this technique, a harmonic frequency component is introduced to the system and active power that is delivered to the supercapacitors is controlled by this component. A hybrid PWM technique is proposed in [107] for the CSM-MLC topology given in Figure 11a for EV applications. In the proposed technique, carriers are arranged differently for terminal voltage balancing and SOC balancing.

A virtual space-vector PWM method is suggested in [130] for DC-MLCs. Average values of the inner DC-link currents can be controlled in this technique. References [126, 127] present a modulation method that is based on an improved version of SV-PWM. In this technique, carrier waveforms are adjusted depending on the amplitude of the modulation signal.

4.4 | Fault-tolerant control

Fault tolerance in a MLC based BSS is very critical since faults can directly affect the power exchange between AC and DC grids. Furthermore, reliability and availability of the vehicle are severely impacted by faults in EV applications. That is why different fault-tolerant control techniques are proposed by researchers for MLC based BSSs. A fault-tolerant SOC balancing control is suggested in [79] for DC and AC grid faults of MMCs. When DC grid faults occur, MMC becomes an AC–AC converter and when AC grid faults occur, MMC becomes a DC–DC converter. In either case, SOC balancing is achieved successfully.

In [176], a fault-tolerant control technique is proposed for CHB-MLCs. In the proposed technique, fault signal is utilised to adjust the reference voltage for each SM and load is equally distributed among other healthy SMs to produce a balanced three-phase output. It is noted that utilisation of this technique under low modulation indices are more preferable as the performance of the method degrades for higher modulation indices. In [180], a single SM fault-tolerant control method is proposed for CHB-MLCs. The essence of the proposed technique is zero-sequence voltage injection. Fault-tolerant control methods proposed for CHB-MLCs in [205] are divided into three categories: fundamental phase-shift compensation, third harmonic injection and hybrid compensation. In all three techniques, it is aimed to enhance the post-fault performance of the system by avoiding over-modulation.

Reference [128] proposes a technique in DC-MLCs for open- and short-circuit switch faults along with the failure of one battery supply which can be due to an external short circuit or an internal battery supply fault. Software-based detection and localisation of open-circuit faults are the main focus in the proposed method. Moreover, an open-circuit fault-detection method using a current estimator and two new fault localisation techniques are presented.

A transformer based fault-tolerant control scheme is suggested in [143] for a five-level MLC. In the proposed technique, open- and short-circuit faults occurring in switches and/or sources are detected and output voltage is maintained at the nominal value by a center tap transformer.

4.5 | Other control techniques

In this section, a review of different control techniques that are employed in MLC based BSSs will be given. Besides SOC balancing control, state-of-health (SOH) balancing control is implemented in MLC based BSSs. To start with, SOH of a battery is defined as the maximum releasable capacity as a rate of the rated capacity of the battery [197]. It is hard to estimate the SOH of a battery, however, it is closely related to depth of discharge (DOD) of the battery. Instantaneous SOH of a battery can be formulated as given below:

$$\mathrm{SOH}(t) = \mathrm{SOH}(0) - \frac{C_{\mathrm{acu}}}{a\,\mathrm{DOD}^{-b}} \tag{9}$$

where C_{acu} is the accumulated lifecycle and SOH(0) is the initial SOH value of the battery. Moreover, the parameters a and b are battery dependent. As inferred from Equation 9, DOD of a battery is inversely proportional to SOH of a battery.

Utilisation of recycled batteries along with new batteries in a system causes SOH imbalances. For this purpose, a SOH balancing technique is proposed in [197] for MMCs. In the proposed technique, a relative SOH variable that is calculated based on normalisation of SOC variation rate of a SM to the SM with the minimum SOC variation rate is determined. The relative SOH variable is calculated in every 150 life cycles, SOH values of all SMs become equal after 600 life cycles. Similarly, an SOH balancing method for MMCs is proposed in [213] as well. This time, SOH balancing is achieved by an active balancing circuit after a predetermined C_{acu} value.

Model predictive control (MPC) is also becoming popular among researchers in MLC based BSSs. A finite control set MPC (FCS-MPC) technique is proposed in [76] to track AC and DC side currents in MMC for EV charging applications. The developed control strategy minimises the computational burden, reduces DC ripples and grid harmonic components. A discrete-time disturbance observers (DOBs) based

TABLE 2 Comparison of multilevel converter based battery storage systems

Ref	MLC scheme	SM type	PWM technique	Battery type	Simulation plaftorm	Experimental Board	Battery voltage (V)	Rated power	SOC balancing	Application
[63]	MMCS	Half bridge	Not defined	Li ion	Not defined	FPGA	76.8	4 kVA	Yes	Grid
[64]	CSM-MLCS	Full bridge	Not defined	Li ion	Not defined	FPGA	25.6	Not defined	Yes	EV
[84]	MMCS	Half bridge and quasi -full bridge	PS-PWM	Lead acid	MATLAB/Simulink	TMS320F28377D DSP	12	3 kW	No	Wind
[129]	DC-MLCS	Three level Buck–oost	SV-PWM	Not defined	MATLAB/Simulink	TMS320F28335 DSP & FPGA	63.2	300 W	No	PV grid
[134]	FC-MLCS	FC-MLC	Proposed	Not defined	No	FPGA	230	55 kW	No	EV
[143]	Proposed	Half bridge TL cell	LS-PWM	Lead acid	MATLAB/Simulink	dSPACE 1104	96	Not defined	Yes	PV
[158]	CSM-MLCS	Full bridge	LS-PWM	Li ion	No	TMS320F2812 DSP & FPGA	256	1.25 MW	No	PV grid
[162]	MMCS	Half bridge	LS-PWM	Li ion	MATLAB/Simulink	FPGA	3.7	550 W	Yes	EV
[174]	CSM-MLCS	Full bridge	Not defined	Li ion	No	Not defined	27.6	6.9 kVA	Yes	Grid
[177]	CSM-MLCS	Full bridge	PS-PWM	Ni MH	No	DSP & FPGA	72	10 kW	Yes	Grid
[215]	MMCS	Half bridge	PS-PWM	Not defined	PSCAD/EMTDC	TMS320C6713 DSP	140	5 kVA	No	Grid
[216]	CSM-MLCS	Full bridge	Not defined	Not defined	MATLAB/Simulink	TMS320LF2407A DSP	50	1 kW	No	EV

MPC scheme to limit the disturbances caused by power quality problems and parameter mismatches is proposed in [214]. The proposed technique has low computation cost and anti-disturbance ability.

Equations to calculate optimum switching angles in SHE-PWM are highly non-linear, hence difficult to solve. That is why optimisation algorithms are utilised in MLC based BSSs. One of the most popular optimisation algorithm is genetic algorithm (GA). References [138, 208] propose GA based SHE-PWM technique for CHB-MLC and the topology given in Figure 17a, respectively. A comparison of selected works on MLC based BSSs is presented in Table 2 for different aspects.

5 | DISCUSSION AND FUTURE TRENDS

The growing utilisation of MLCSs in BSSs during the last decade has led to improvements on battery technologies, topologies and control techniques. Based on the conducted research, some evident and other more arguable trends can be inferred from this paper on MLCS based BSSs. Although MLCS is well-established in power systems, there are still some issues that need to be solved on its use in BSSs. Some of these trends and issues will be investigated in this section.

There is an increasing trend in using Li-ion based batteries in MLCS based BSSs due to its long lifetime and high power density. However, research on metal-air based battery technology yields that its high energy density and low cost make it a suitable candidate for EV applications [217]. Among metal-air batteries, aluminum air (Al-air) battery makes a case in terms of high specific energy, being light and non-toxic, and recyclability. Non-chargeable nature and self-corrosion in metal electrodes can be counted among disadvantages. Hence, research direction on metal-air batteries will mainly be on producing rechargeable battery cells in the future [218].

It is already known that MLCSs are superior compared to traditional two- or three-level converter schemes in terms of low harmonic content, small size and less dependency on magnetic circuits. That is why research focus on BSSs has shifted to MLCSs during the last decade. Nowadays, new MLCSs as well as novel SM configurations for MMCSs and CSM-MLCSs are being developed by researchers. Although switch and passive component count seems to be a straightforward approach to compare different MLCSs, voltage stress, power sharing of semiconductors and thermal distribution of the system are other significant parameters that need to be considered for the new MLCSs and SM configurations in the market.

A challenge that could be faced in MLCS based BSSs is voltage and SOC imbalances between battery packs. This could be because electrochemical differences between battery packs as well as utilisation of second-life batteries [116, 117]. Number of research has been published on SOC balancing mainly focusing on MMCSs and CSM-MLCSs in the recent years. As SOC imbalances affect the power quality and lifetime of the MLCS severely, SOC balancing on traditional MLCSs as well as new MLCSs that employ multiple battery packs will be a challenge in the near future. Achieving balanced SOC levels between battery packs does not guarantee balanced voltages in the MLCS since different series–parallel configurations may be held to create different battery packs. Even though the same series–parallel configuration with the same type of battery is utilised in each battery pack, differences on discharge curves and aging may generate different voltages. Using a two-stage SM configuration would be helpful in this case as output of the DC–DC converter can be adjusted so that each SM has the same DC voltage. Furthermore, modifying the applied PWM technique could be a solution in single-stage MLCSs. Here, solutions would be based on mitigating the effects unbalanced DC voltages on harmonic performance of output voltage and current and improving power quality at the output instead of having balanced DC voltages in each SM. Hence, this is a challenge that researchers will move towards in the future.

Reliability is a key feature in the future enhancement of MLCSs. Despite having a modular structure provides a degree of freedom to MMCSs and CSM-MLCSs depending on the utilised SM configuration, taking advantage of the modularity highly depends on fault-detection and fault-diagnosis ability of the MLCS. Hence, fault-tolerant actions can be limited by these constraints. Since battery and capacitor faults and short- and open-circuit faults on power switches tend to happen quickly, having a fully fault-tolerant MLCS does not seem possible in practice considering the current state-of-the-art. Therefore, there is definitely a room for improvement on fault-tolerant control strategies in MLCS based BSSs. To sum up, there may be promising research directions for future work in MLCS based BSSs including, but not limited to

1. Designing new types of MLCSs that have reduced component count.
2. Employing sliding-mode, fuzzy-logic and artificial neural network based controllers on various types of MLCSs.
3. Utilisation of other optimisation algorithms such as particle swarm optimisation (PSO), differential evolution (DE), art colony system (ACS), clonal search algorithm (CSA), bee algorithm (BE) and bacterial search algorithm (BSA) in SHE-PWM and real-time implementation of those algorithms on MLCSs to improve power quality of the system.
4. Minimising the adverse effects of voltage and SOC imbalances between battery packs with possible improvements on PWM method and/or SOC balancing control.
5. Integration of RESs, especially wind, into BSSs via MLCSs to mitigate the negative effects of the intermittent nature of RESs.
6. Novel SOH balancing techniques that improve the lifetime of the batteries as well as MLCS.

6 | CONCLUSION

This paper provides an up-to-date review on current state-of-the-art of MLCS based BSSs considering the most recent contributions on battery technologies, MLC topologies and control techniques. First, major rechargeable battery storage technologies are reviewed. Then, a systematic review of traditional and recently proposed MLCSs is provided. Later, various control schemes that are employed in MLCS based BSSs are investigated. Finally, future directives in MLCS based BSSs considering the gaps in research are incorporated. It is clear that MLCSs will take an active part in BSSs and extensive research will be held on several aspects like reducing the component count in MLCSs and finding effective solutions for imbalances in battery voltages and SOCs in the future.

ORCID

Fatih Eroğlu https://orcid.org/0000-0001-6341-5949

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