Whitepaper
04-2020

Benefits of multilevel topologies in power-efficient energy storage systems (ESS)

Abstract

In this paper, we discuss the adaption of ESS in residential solar and utility-scale applications. System requirements and possible topologies are looked into. For utility-scale, we introduce a multilevel converter topology concept.

By Peter B. Green, Principal Engineer, Infineon Technologies Americas

www.infineon.com/energy-storage-systems v1.0

Table of contents

1 What are energy storage systems?

Broadly speaking, energy storage is the gathering of energy produced at one time to be stored and used later. Battery based energy storage systems may be used to create utility independent solar-powered homes or businesses (termed residential or commercial ESS), which are referred to as ‘behind the meter’ in contrast to utility-scale ESS referred to as ‘before the meter’, used to supplement generated power during periods of high demand. In each case, the ESS consists of a bidirectional power converter, which employs various architectures and converter topologies as well as a range of power semiconductor technologies.

2 ESS in applications

2.1 Adoption of ESS in residential solar installations

Earlier generation residential solar energy systems are tied to the utility power grid via inverters, which convert power from solar panels to AC electrical power during hours of sunlight. Excess power could be sold back to the utility company but during hours of darkness, the end-user still has to rely on the utility to supply their electricity. Utility companies have been able to take advantage of these limitations by adjusting their pricing model and moving residential customers to ‘time-of-use’ rates thereby charging more when solar power is not available. Adding an ESS to the system enables users to combat this and protect themselves against high energy costs by so-called ‘peak-shaving’, storing electricity collected by their solar panels in batteries and using these batteries to supply their power demand at any time.

Developments in battery technology have led to the production of lithium-ion (Li-ion) battery packs with much higher charge storage per unit mass and unit volume than older technology lead-acid batteries. Combined with efficient bidirectional power conversion systems these can be used to create compact wall-mounted ESS units in the 3- to 12-kilowatt range able to supply a home for 24 hours or more. However, despite their energy density advantage Li-ion batteries have some disadvantages, particularly with regards to safety, including a tendency to overheat or become damaged at high voltages. This can potentially lead to thermal runaway and combustion, therefore safety mechanisms are required to limit voltage and internal pressures. Storage capacity also deteriorates due to aging leading to eventual failure after some years of operation. It is, therefore, necessary for each battery pack to include an electronic battery management system (BMS) to ensure safe and efficient operation.

Unlike solar inverters an ESS must operate in two different modes:

1. Charging mode, when the battery is being charged
2. Backup mode, when the battery is supplying power to connected loads

For this reason, ESS power conversion systems are always bidirectional. Residential ESS combined with solar panels is broadly categorized into DC- or AC-coupled systems. In DC-coupled systems, a single hybrid inverter combines the outputs of a bidirectional battery converter and a DC-DC solar MPPT (maximum power point tracking) stage at a common DC bus, which then supplies a grid-tied inverter stage. However, AC-coupled systems (sometimes called ‘AC batteries’) are becoming more popular since this type of ESS can be easily added to an already existing solar installation that did not originally include energy storage. This is because the AC-coupled ESS is directly tied to the grid. An additional advantage is that such systems can be easily paralleled to provide greater power capability and storage capacity.

Figure 1 **Example of residential ESS**

2.1.1 Residential ESS power converter architecture

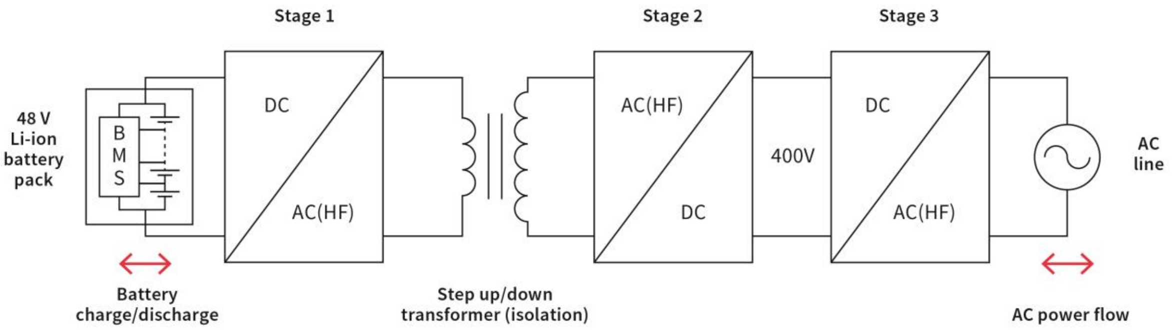

Figure 2 **Basic block diagram for a residential energy storage system**

The above figure outlines an AC-coupled system based on a 48 V Li-ion battery pack. The entire system is typically housed in a wall-mounted enclosure. The battery pack includes an integrated electronic battery management system (BMS) needed to manage the state of charge (SOC) of the individual cells, which are typically rated at a nominal 3.2 V. Cell deterioration is minimized by preventing operation in over- or undercharged states. The BMS contains specialized control ICs combined with low-voltage MOSFET switches based on trench technology such as Infineon’s OptiMOS™ or StrongIRFET™ families, typically in the 80 to 100 V range.

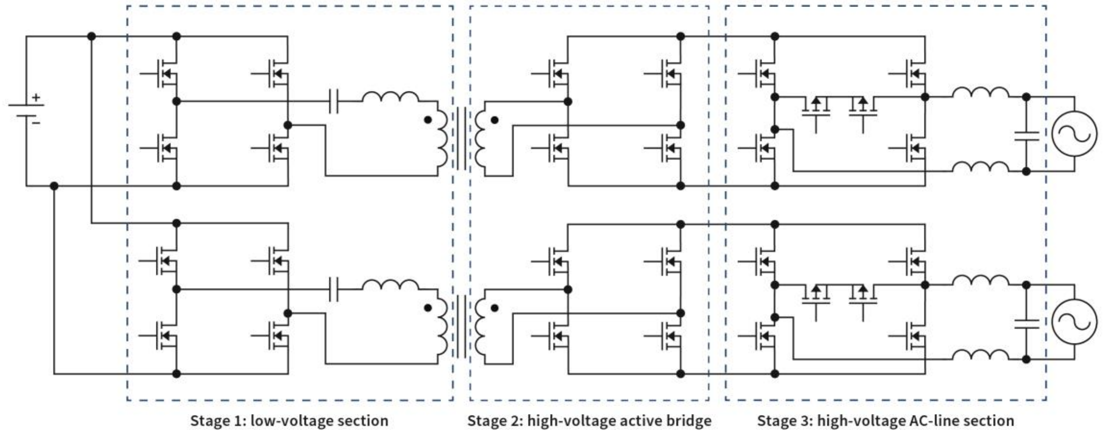

Figure 3 A possible converter topology for residential ESS

In this example, the bidirectional power conversion system is separated into three stages, each of which supports bidirectional power conversion and must, therefore, be based on active power switches and not diodes. Several possible topologies may be used, many of which are variations of the basic H-bridge. The following schematic shows a possible topology combining two parallel power conversion stages to share the power throughput:

- **Stage 1:**

The first stage converts battery voltage (typically 48 V) to high-frequency AC to be stepped up through the transformer. In this example, a resonant topology is chosen to operate with zero voltage switching during backup mode to maximize efficiency by avoiding switching losses as much as possible. In charging mode, this stage operates as a synchronous rectifier.

This stage switches at low voltage and high current for which 60 V trench MOSFET devices with very low $R_{DS(on)}$ such as Infineon's OptiMOS™ family are well suited. Such devices may be connected in parallel. Packages with excellent heat dissipation capabilities and very low parasitic package inductance such as the DirectFET™ are ideally suited.

- **Stage 2:**

The second stage operates at high voltage and relatively low current, performing the function of synchronous rectification when the ESS is supplying power in backup mode and converting high voltage DC to high-frequency AC during charging mode to be stepped down through the transformer.

Since the bus voltage is typically between 400 and 500 V this stage would require 600-650 V switches capable of switching at high frequency with the lowest possible switching and conduction losses. Wide bandgap silicon carbide (SiC) trench MOSFETs offer several advantages over silicon superjunction (SJ) devices, which make it possible to reach higher conversion efficiencies at power levels of several kilowatts and above. The higher critical breakdown field allows a given voltage rating to be maintained while reducing the thickness of the device enabling lower on-state resistance. The Infineon CoolSiC™ family of 650 V MOSFETs offers devices with $R_{DS(on)}$ as low as 27 mΩ. The higher thermal conductivity corresponds to higher current density and the wider bandgap leads to lower leakage current at high temperatures. The multiplication factor from 25°C to 100°C to the $R_{DS(on)}$ is 1.67 for CoolMOS™ and 1.13 for CoolSiC™. This means that to have the same conduction losses ($Pcond = I2 \cdot R(on)(TJ)$) of CoolMOS™ and CoolSiC™ it is possible to design-in a higher $R_{DS(on)}$ for CoolSiC™. In addition, the output charge (Q_{oss}) and reverse recovery charge (Q_{rr}) are significantly lower. Developments in CoolMOS™ have led to the reduction of the body diode Q_{rr}, now available as fast diode device families CFD and CFD7. Nevertheless, this charge is still too high to achieve the very high-efficiency results possible with CoolSiC™, which has a 10 times lower charge than the best fast diode SJ MOSFET available on the market.

- **Stage 3:**

The third stage in the example shown here is based on the High Efficient and Reliable Inverter Concept (HERIC). During backup mode, the high DC bus voltage is converted to a PWM modulated high-frequency AC waveform, which then passes through a low pass output filter to produce a sine wave output. The HERIC inverter employs additional back to back switches, which operate at low frequency to de-couple the output inductor current from the input during periods of the cycle when the four H-bridge switches are all off. This reduces common mode noise leakage current and EMI.

During charge mode, this stage operates as a synchronous totem pole PFC boost converter able to operate in positive and negative line half-cycles to generate the high voltage DC bus, which is then converted back through stages (2) and (1) to charge the battery.

600 - 650 V power switches are required for the H-bridge to avoid avalanche during any line surge event. Since this stage is hard switching in both operating modes fast body diode recovery is essential. Minimizing the switching losses in conjunction with reduced conduction losses due to low on-state resistance and improved temperature stability contribute to overall higher efficiency. The back to back switches also require a similar voltage rating and fast body diode recovery during backup mode operation.

2.1.1.1 Multilevel converter topologies

In the third stage, a multilevel (ML) inverter may be used as an alternative since it is also bidirectional. In such a topology rather than only two or three levels, multiple possible voltage levels can be produced at the output node of the power converter switching stage that feeds the output filter. These include the 0 V mid-point and various intermediate voltage levels between $+V_{DC}/2$ and $–V_{DC}/2$. Many voltage levels are combined to produce a smoother output waveform with less filtering required. There is a variety of multilevel topologies, which may be operated with 5, 7 or 9 levels depending on the DC bus and output voltage requirements. In such designs, MOSFETs can be connected in series-parallel combinations.

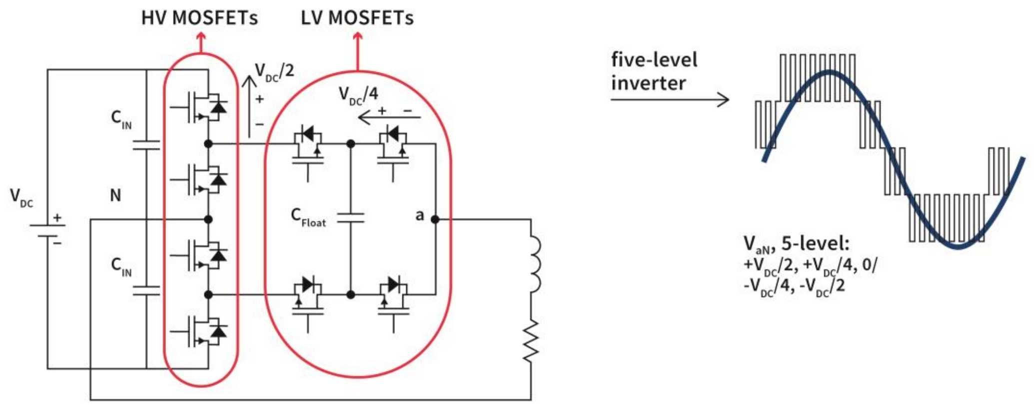

Figure 4 Five-level flying capacitor-based active neutral point clamp inverter basic schematic

Unlike traditional inverters, which use high-voltage switches, multilevel inverters can utilize low-voltage trench MOSFET devices that offer very low $R_{DS(on)}$ and body diode recovery charge (Q_{rr}). These factors greatly reduce conduction losses, which combined with reduced switching losses, make it possible to reach higher efficiency levels than are possible in traditional inverters. Multilevel inverter designs have become popular in medium- and high-power applications because of the reduced power dissipation of switching elements reducing heat sinking, lower harmonic content and significantly lower EMI. The drawback is the greater level of complexity necessary to realize a multilevel design compared to traditional topologies and the higher number of switches and isolated gate drivers needed. However, at a certain power level in the 3 to 5 kW range, the benefits of the multilevel design such as a reduction in size and weight as well as higher efficiency and power density, justify the added complexity.

2.2 Utility-scale ESS

Power levels in industrial ESS range from 10 to 100 kW and utility-scale ESS above 100 kW, which are connected to three-phase AC typically at 480 V_{RMS}. The system concept is similar to the residential ESS, however many Li-ion battery packs are connected in series with each battery pack including its own integrated BMS to produce a total battery voltage greater than 740 V.

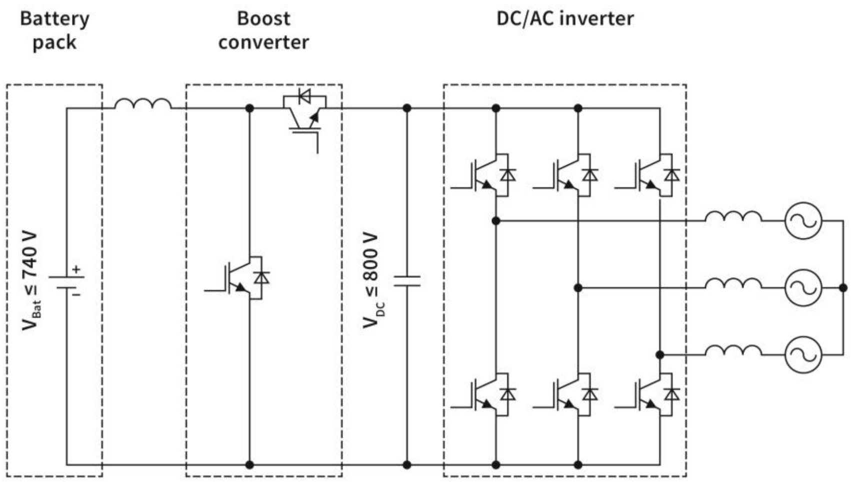

Figure 5 **A possible converter topology for industrial or utility-scale ESS**

Systems like the one shown here require switches rated at 1200 V for the power conversion stages connected to the 800 to 900 V DC bus, these switches are normally IGBT discrete devices and modules. This system architecture, however, is limited in battery utilization. This is because, with battery packs with different states of charge connected in series, the system is only able to operate until one pack reaches the minimum allowable charge level. At this point the whole system needs to shut down even though the other packs may still hold a lot of charge, therefore limiting battery utilization to the weakest battery pack.

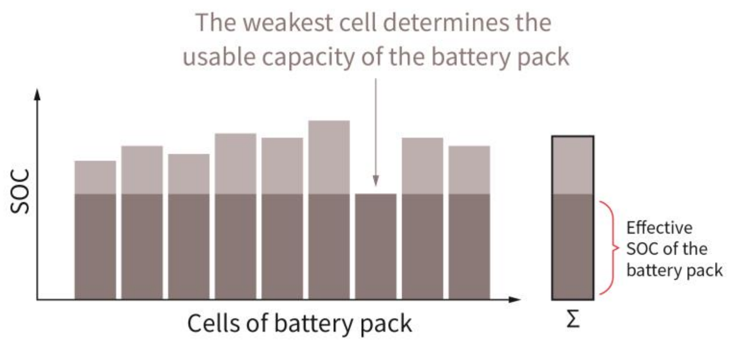

Figure 6 **Battery limitation of large scale ESS**

2.2.1 Multilevel converter topologies in utility-scale ESS

To overcome the above-mentioned limitation, modular cascaded multilevel architectures have been developed. In these systems, each battery pack is connected to its bidirectional power converter and the outputs of these converters are then connected in series to create the high voltage DC bus. The multilevel operation occurs at the system level as modules may be connected in different series and parallel configurations to produce different voltage levels, managed by a central controller. By stepping through voltage levels an approximate full-wave rectified sinusoidal voltage bus is constructed. This is then filtered to remove harmonic content and passed through a low-frequency unfolding stage to produce a clean sine wave voltage output to connect to the grid.

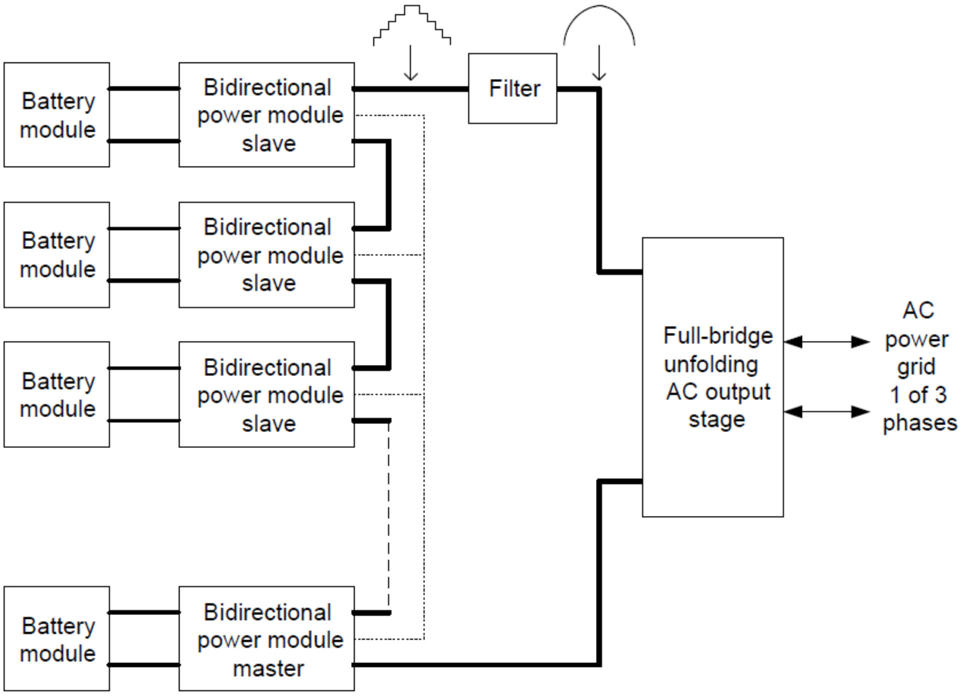

Figure 7 **Cascaded modular multilevel concept for large scale ESS**

With the added flexibility of being able to configure or bypass modules, it also becomes possible for advanced control schemes to balance the SOC of different batteries by placing a heavier load on those packs with higher SOC. In this way, the SOC can be balanced among all of the pack even if the battery condition varies among them.

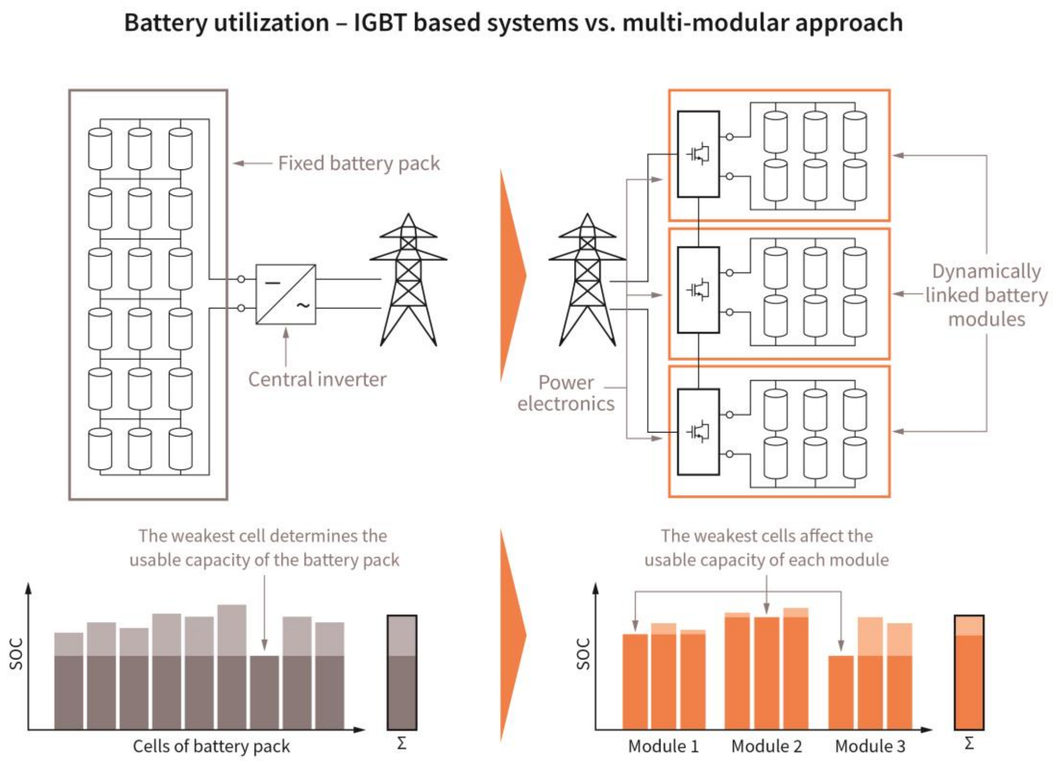

Figure 8 **Battery charge flexibility in cascaded modular multilevel ESS**

There are several variations of the topology for each module. One example is shown below based on an H-bridge. These modules typically require 80 or 100 V trench MOSFET devices with packages optimized for minimum possible parasitic resistance and inductance with high current carrying capability. Two or more MOSFETs may be used in parallel to share currents in the hundreds of Amps. In these systems, the switching frequency can be below 10 kHz because the effective output frequency in a multilevel system multiplies the module switching frequency by the number of levels or modules minus one. For this reason trench devices with low $R_{DS(on)}$ and wide safe operating area (SOA) in leadless packages such as the TOLL or DirectFET™ packages may be used, such as the Infineon StrongIRFET™ and OptiMOS™ families.

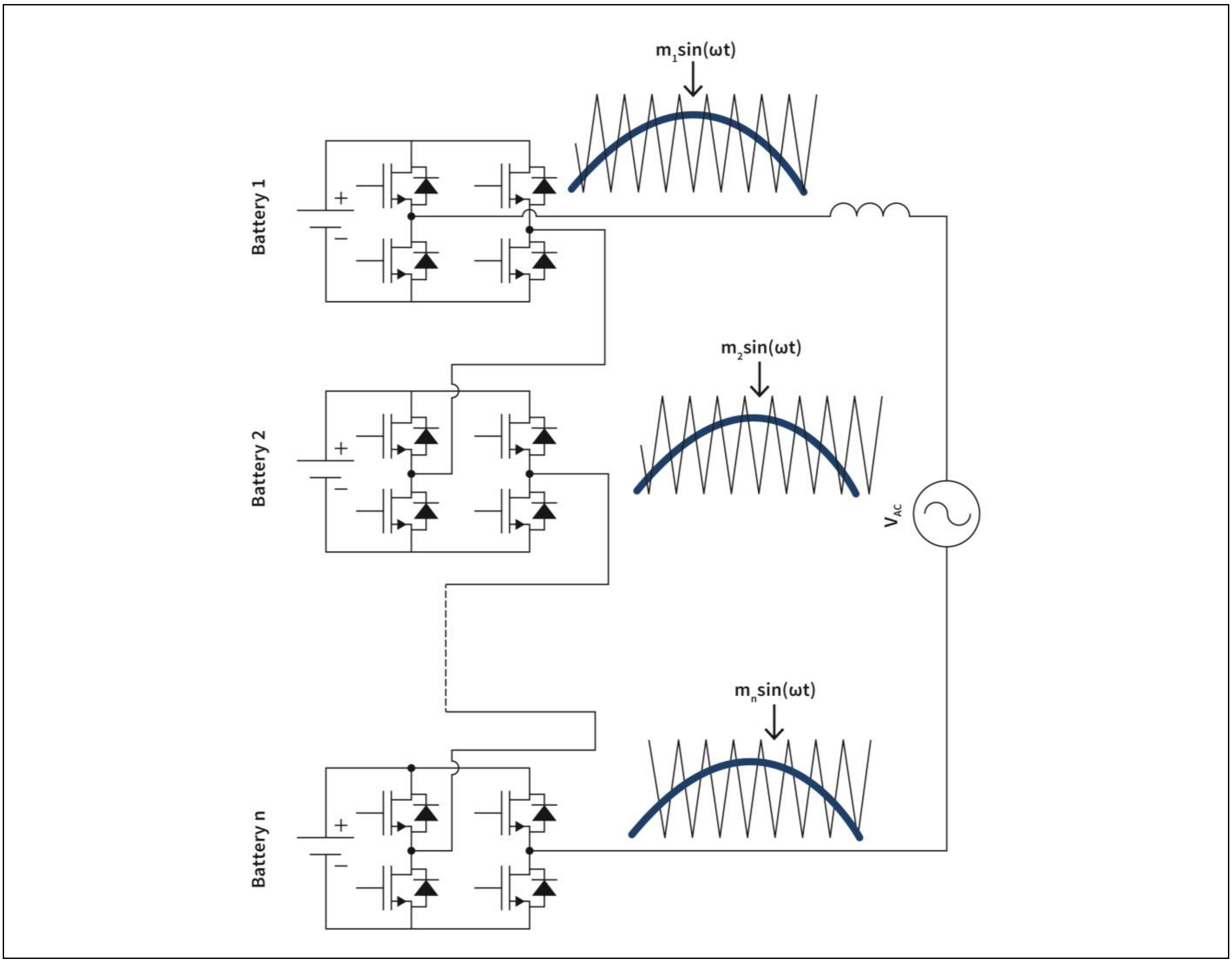

Figure 9 Cascaded modular multilevel basic schematic

3 Summary

In this paper, we gave a brief introduction to ESS. With the growing importance of renewable energy resources, their usage is expected to grow over the next decade at the residential, industrial and utility-scale areas. Several concepts had been developed but so far there has been no architecture that has become dominant.

References

[1] Infineon Technologies (www.infineon.com), DirectFET^{TM}, CoolSiC^{TM}, OptiMOS^{TM}

[2] Infineon Technologies, CoolSiC™ 650V M1 SiC trench power device (AN_1907_PL52_1911_144109)

[3] Essam Hendawi, “A comparative study between H5 and HERIC transformer-less inverters for PV standalone system”, Power Electronics and Energy Conversion Dept. Electronics Research Institute, Egypt

[4] Robert Keim, “Exploring the Pros and Cons of Silicon Carbide (SiC) FETs”, All About Circuits (www.allaboutcircuits.com)

Published by
Infineon Technologies AG
85579 Neubiberg, Germany

© 2020 Infineon Technologies AG.
All Rights Reserved.

Document number: B152-I1003-V1-7600-EU-EC
Date: 04/ 2020

Please note!
This Document is for information purposes only and any information given herein shall in no event be regarded as a warranty, guarantee or description of any functionality, conditions and/or quality of our products or any suitability for a particular purpose. With regard to the technical specifications of our products, we kindly ask you to refer to the relevant product data sheets provided by us. Our customers and their technical departments are required to evaluate the suitability of our products for the intended application.

We reserve the right to change this document and/or the information given herein at any time.

Additional information
For further information on technologies, our products, the application of our products, delivery terms and conditions and/or prices please contact your nearest Infineon Technologies office (www.infineon.com).

Warnings
Due to technical requirements, our products may contain dangerous substances. For information on the types in question please contact your nearest Infineon Technologies office.

Except as otherwise explicitly approved by us in a written document signed by authorized representatives of Infineon Technologies, our products may not be used in any life endangering applications, including but not limited to medical, nuclear, military, life critical or any other applications where a failure of the product or any consequences of the use thereof can result in personal injury.