POWER ELECTRONICS NEWS

APR 2020

Power-efficient energy storage systems

infineon

Benefits of multilevel topologies in power-efficient energy storage systems

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

WHAT ARE ENERGY STORAGE SYSTEMS?

Energy storage is the gathering of energy produced to be stored and used later. Battery energy storage systems are 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 utility-scale ESS are referred to as *"before the meter"*, used to supplement generated power during periods of high demand. Both cases utilize bidirectional power converters employing different architectures, topologies, and power semiconductor technologies.

ESS IN RESIDENTIAL SOLAR INSTALLATIONS

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 can be sold back to the utility company but during hours of darkness, the end-user must still rely on the utility to supply their electricity. Utility companies have been able to take advantage of these limitations by adjusting their pricing model moving residential customers to 'time-of-use' rates thereby charging more when no solar power is 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 to supply their power requirements 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. 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.

Excess power can be sold back to the utility company but during hours of darkness, the end-user must still rely on the utility to supply their electricity.

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

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

Residential ESS combined with solar panels is 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 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 retrofitted to an already existing solar installation not originally equipped with energy storage because the AC-coupled ESS is directly tied to the grid. An additional advantage is the ability to be easily paralleled to provide greater power capability and storage capacity.

RESIDENTIAL ESS POWER CONVERTER ARCHITECTURE

The figure 1 outlines an AC-coupled system based on a 48V Li-ion battery pack.

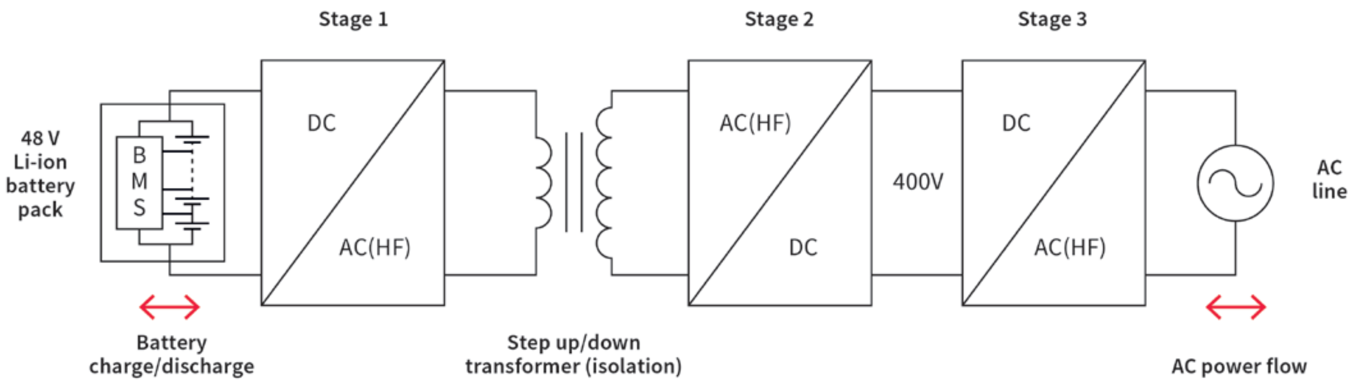

Figure 1: Basic block diagram for a residential energy storage system

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 100V range.

In this example, the power conversion system is separated into three stages, each of which supports bidirectional power conversion based on active power switches rather than diodes. There are several possible topologies, many of which are variations of the basic H-bridge. The following schematic shows a topology combining two parallel power conversion stages to share the power transfer:

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.

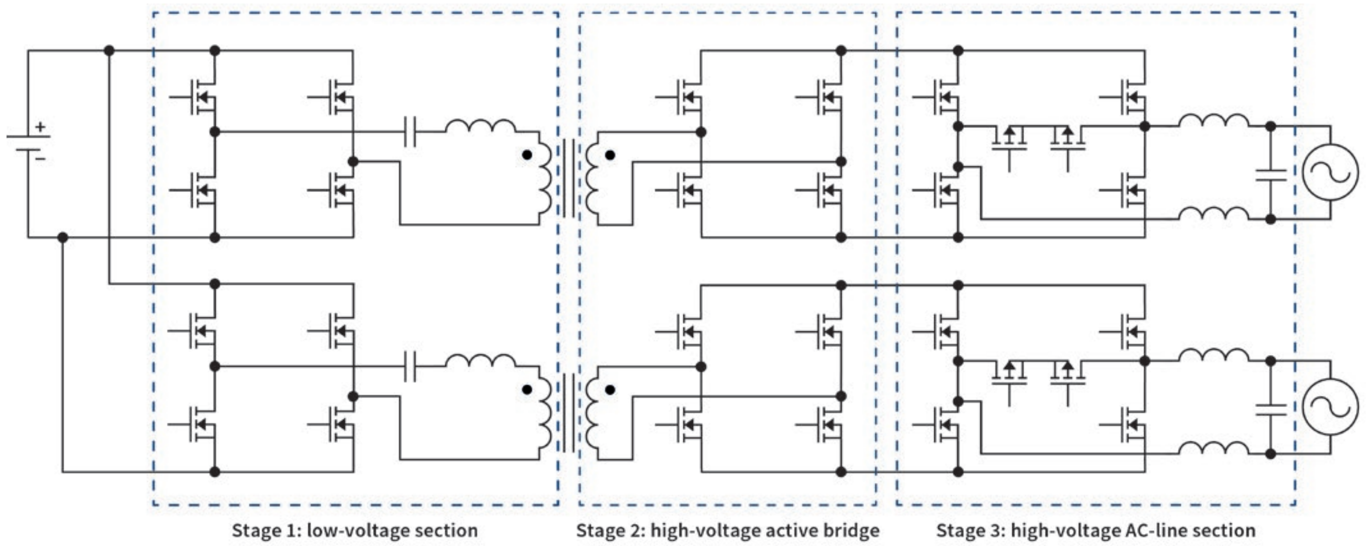

Figure 2: A possible converter topology for residential ESS

POWER ELECTRONICS NEWS
Benefits of multilevel topologies in power-efficient energy storage systems

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.

The higher critical breakdown field allows a given voltage rating to be maintained while reducing the thickness of the device enabling lower on-state resistanc

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 super-junction (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™ MOSFET 650 V product family 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 in order to have the same conduction losses ($P_{cond} = I^2 \cdot R_{(on)}(T_J)$) 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 10 times lower charge than the best fast-diode SJ MOSFET available on the market.

Stage 3: The third stage in the example 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.

MULTILEVEL CONVERTER TOPOLOGIES

The third stage could be replaced with a multilevel (ML) inverter, which is also bidirectional. Instead of only two levels, multiple possible voltage levels including the 0 V mid-point and intermediate voltage levels between $+V_{DC}/2$ and $-V_{DC}/2$ can be produced at the output node of the switching stage to feed the output filter. 5-, 7- or 9-level topologies are possible depending on the DC bus and output voltage requirements. MOSFETs can be connected in series-parallel combinations.

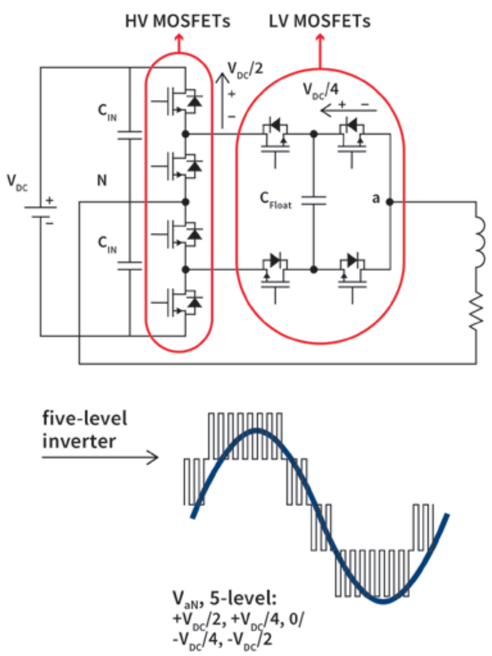

Figure 3: 5-level flying capacitor active neutral point clamp inverter basic schematic

Instead of high-voltage switches, multilevel inverters utilize low voltage trench MOSFET devices with very low $R_{DS(on)}$ and body-diode recovery charge Q_{rr}. These factors greatly reduce conduction and switching losses making it possible to reach higher efficiency levels than are possible in traditional inverters. Multievel 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 requiring less filtering and significantly lower EMI.

UTILITY-SCALE ESS

Utility-scale ESS operate above 100 kW to supply 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.

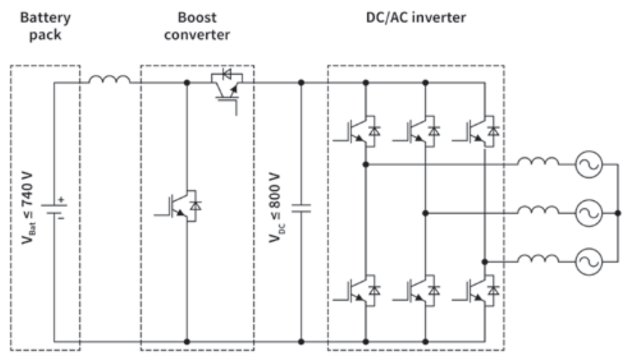

Figure 4: A typical converter topology for utility-scale ESS

IGBT modules rated at 1200 V are typically used in the power conversion stages connected to the 800 to 900V DC bus. This system architecture is limited in battery utilization because with series-connected battery packs having different states of charge, the system can only operate until one pack reaches the minimum allowable

Benefits of multilevel topologies in power-efficient energy storage systems

charge level. At this point, the entire system must shut down even though other packs may still hold substantial charge limiting battery utilization to the weakest pack.

MULTILEVEL CONCEPT IN UTILITY-SCALE ESS

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

With the added flexibility of being able to configure or bypass modules, it becomes possible for advanced control schemes to compensate for the different SOC of different batteries by drawing more power from packs holding more charge.

There are several variations of module topology typically requiring 80 or 100V trench MOSFET devices such as Infineon StrongIR-FET™ and OptiMOS™ families, with low $R_{DS(on)}$

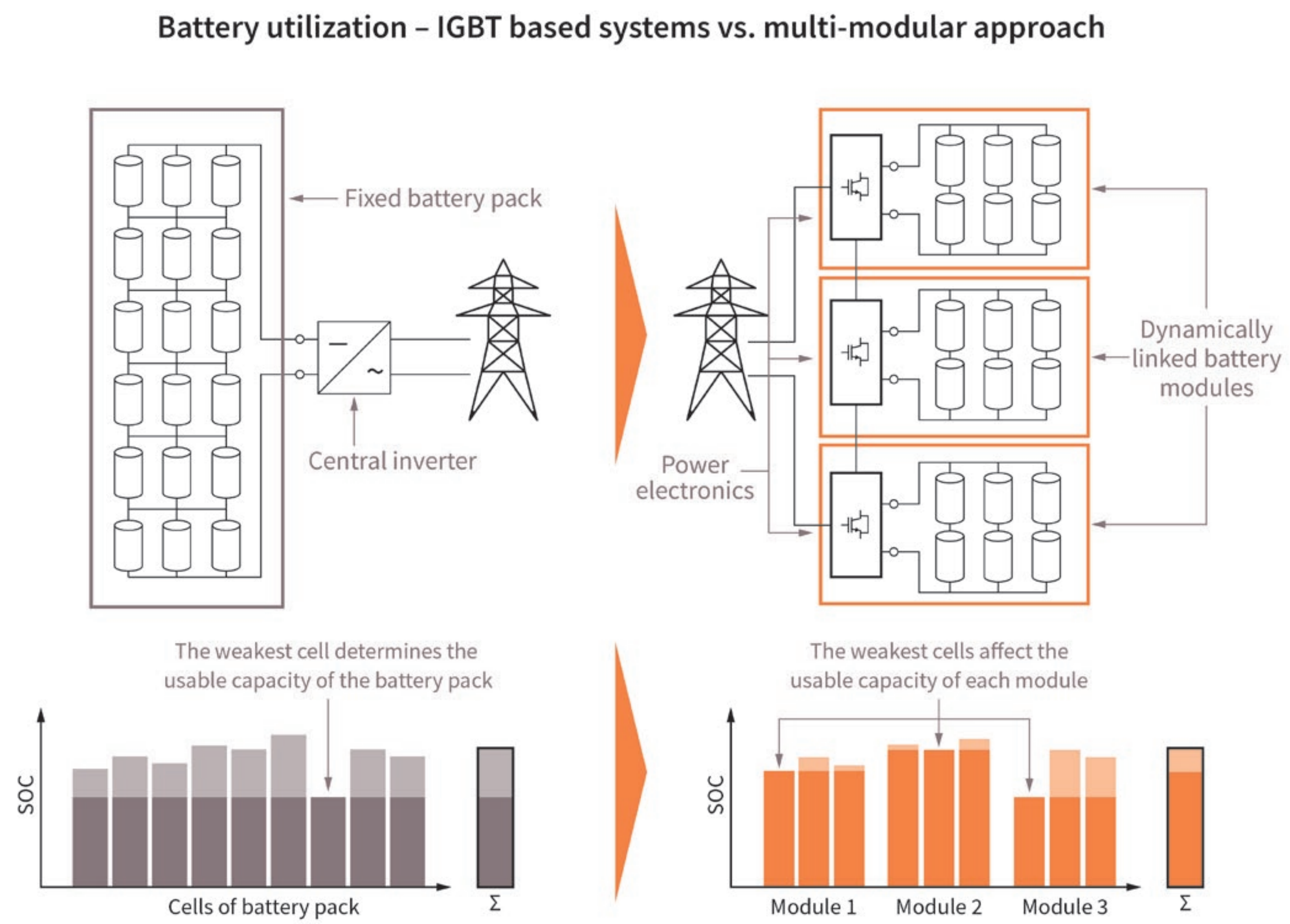

Figure 5: Battery-charge flexibility in cascaded modular multilevel ESS

and wide safe operating area (SOA) in leadless packages such as the TOLL or DirectFET™ with packages optimized for minimum possible resistance and inductance supporting high current. Two or more MOSFETs can be used in parallel to share currents in the hundreds of Amps. The switching frequency can be under 10 kHz since the effective output frequency in a multilevel system multiplies the module switching frequency by the number of levels (modules) minus one.

A brief introduction to ESS has been given here. Adoption is expected to grow over the next decade at the residential, industrial and utility scales. So far no single architecture has become dominant.

For more information, please visit ***www.infineon.com/energy-storage-systems*** or scan the QR code.

For More Information

- **Infineon Technologies, DirectFET™, CoolSiC™, OptiMOS™**
- **Infineon Technologies, 650 V M1 SiC trench power device (AN_1907_PL52_1911_144109)**
- **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.**
- **CoolSiC Infineon Technology**
- **CoolGaN Infineon Technology**
- **CoolGaN, the new power solution – Interview to Tim McDonald, Senior Director, GaN Marketing & Application @ Infineon during the Power Conference**