CHAPTER 13
POWER CONVERSION SYSTEMS

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Abstract

Power electronic conversion systems are used to interface most energy storage resources with utility grids. While specific power conversion requirements vary between energy storage technologies, most require some form of energy conversion and control. This chapter describes the basics of power electronic energy conversion and identifies the core components of a conventional power converter. Typical power conversion solutions for energy storage applications are presented, and each hardware architecture's various strengths and limitations are discussed. The chapter concludes with a brief look into emerging research trends in the area of power conversion systems for energy storage.

Key Terms

Energy storage, insulated gate bipolar transistor (IGBT), metal oxide semiconductor field effect transistor (MOSFET), power conversation systems (PCS), power electronics, state of charge (SOC), voltage source inverter (VSI), wide bandgap device

1. Introduction

Power electronics provide unprecedented control over, and flexibility in, how energy flows in an electric power system. Power electronic converters are a key enabling technology for modern energy storage systems. The behavior of power electronic converters can be flexibly adjusted via software. This functionality enables new capabilities that have not previously been available to power system designers and planners. This chapter explains these capabilities and their importance to energy storage systems by providing sufficient information to understand the basic principles of power converter operation and control, how these principles are put to use in conventional energy storage interface applications, and how power conversion technology may be expected to progress based on current R&D trends.

This chapter is intended to help engineers involved in storage system planning and deployment to understand the capabilities and limitations of conventional power conversion systems, and to anticipate future challenges and solutions as capabilities of power electronics evolve.

2. Power Conversion System Background

2.1. Overview: An Enabling Technology

Power electronics and power electronic conversion systems (PCSs) are often referred to as an enabling technology. To understand the importance of power electronic conversion—both in the limited case of energy storage applications and in the greater challenge of grid modernization—the mechanics by which power electronics act as an enabling force must be put in clear terms. Power electronics provide two key services:

1. Interconnection of otherwise incompatible forms of electricity, such as AC and DC sources, DC sources of different voltage magnitudes, AC sources with different frequencies, and all combinations thereof
2. Precise control over the flow of electrical energy in a system

The following sections describe these services in detail, and their importance to grid modernization.

2.1.1. Interconnection of Incompatible Forms of Electricity

As noted, power electronics facilitate the efficient and flexible interconnection of incompatible forms of electricity, such as AC and DC, DC at two different voltages, or AC at two different frequencies. In the past, such conversions had to be performed by complex and relatively inefficient systems of electromechanical devices, and the ability to interconnect DC at two different voltages was practically nonexistent (this is a key reason why AC is the dominant technology for power transmission and distribution—and has been for over a century). Today, power electronic converters provide much more flexible and efficient means for such conversions, and as a result they have become nearly ubiquitous. For example, a cell phone's internal electronics require tightly regulated DC voltages, without which they may malfunction or be damaged. The wall supply is AC, so the first conversion step is to convert AC at the typical household voltage to DC at a voltage compatible with the electronics. This step is handled by an AC-DC converter, or rectifier. The battery provides a DC voltage that varies with the battery's state of charge (SOC), so DC-DC converters are used to convert the variable DC voltage from the battery into constant DC voltage for the electronics.

Nearly all digital devices include similar power conversion stages; the information age was built on a foundation of power electronic energy conversion. However, power electronics are also routinely used with non-digital devices. For example, motors driven directly from the AC grid will have a rotational frequency determined by the grid electrical frequency and the construction of the motor, but it is often advantageous to decouple these two frequencies. This can be achieved by a converter that first converts the grid AC to DC (a rectifier), followed by a conversion of that DC to AC at any desired frequency using an inverter. This AC-DC-AC arrangement forms a variable-speed drive (VSD), and VSDs are utilized today in a wide range of applications.

2.1.2. Control Over Flow of Electrical Energy

It is tempting to view power converters as simple connectors that facilitate exchanges of energy between different sources in the same way that a transformer enables conversion between different AC voltages. However, this "black box" perspective provides limited insight into the value of power electronic conversion. The real transformative potential of power electronics, particularly with respect to power delivery infrastructure, lies in the second key function: the ability to exercise direct control over the flow of electrical energy. Power electronic converters can control the injection of small "packets" of power or current into a power system with high speed and precision, to achieve almost any function that can be programmed into software. As a result, they enable new functions not previously achievable, and create the possibility of entirely new modes of operation of power systems.

Energy storage is a prime beneficiary of this flexibility. The value of energy storage in power delivery systems is directly tied to control over electrical energy. A storage installation may be tasked with peak-shaving, frequency regulation, arbitrage, or any of a variety of grid services. How the installation delivers value depends on how the power conversion system leverages the storage reservoir to accomplish its given task. Similarly, the health, performance, and reliability of storage devices are dependent on how the storage system is managed, i.e. on voltage and current profiles applied to charge or discharge storage devices. While charge/discharge actions originate with higher level control decisions in battery management systems, energy management systems, or exogenous operator commands, it is the power electronic system that controls the real-time exchange of stored energy. For these reasons, it is critical that energy storage system owners and integrators understand the mechanics of power electronic conversion beyond the limited scope provided by a "black box" model.

2.2. Fundamentals of Power Electronic Energy Conversion

This section provides an overview of the basic principles of power electronic conversion and an explanation of the roles that key components play in the conversion process. A full description of all considerations involved in power converter design and implementation is beyond the scope of this chapter, but may be found in introductory power electronics textbooks, e.g. [1, 2]. This discussion provides summary-level information, relating high-level converter performance characteristics and limitations to developments in component technologies.

2.2.1. Switched-Mode Conversion

Consider an application in which an unregulated DC source (a battery, for instance) provides power to a DC load. The battery's voltage varies with its SOC and other factors, but the DC load requires a fixed voltage that is less than that of the battery. A simple, idealized conversion solution is shown in Figure 1. The battery is shown as an ideal voltage source, labeled V_b. The load is shown as a fixed resistance, R; the voltage across the load is V_o. The circuit includes an inductor L, a capacitor C, and two ideal switches, S_1 and S_2. The switches are active devices—they turn on and off according to an external signal. When a switch is on, it acts as a short circuit; when a switch is off it acts as an open circuit.

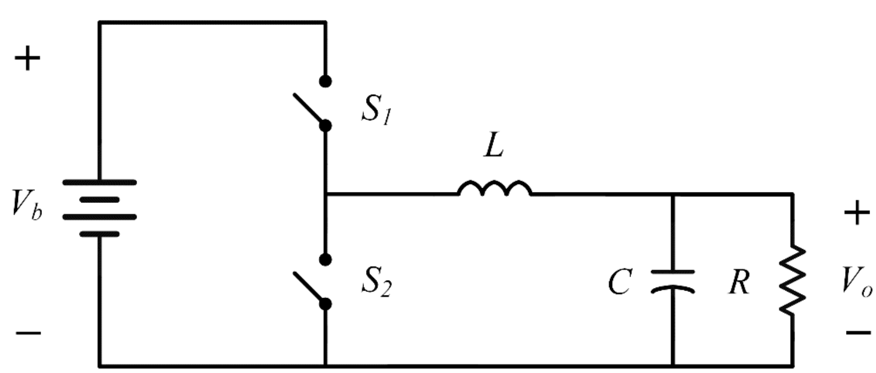

Figure 1. Ideal DC-DC step-down converter circuit

The conversion circuit in Figure 1 operates as follows. Switches S_1 and S_2 are complementary: S_1 is only on when S_2 is off, and vice versa. The switches alternate through two modes. In mode 1, S_1 is on and S_2 is off, forming an equivalent circuit shown in Figure 2a. In mode 2, S_2 is on and S_1 is off, forming the equivalent circuit shown as Figure 2b. The frequency at which the converter cycles between these two modes is referred to as the switching frequency, f_{sw}. The duration of single switching cycle is the switching period, T, where $T = 1/f_{sw}$. For the purposes of this example, f_{sw} is fixed. The switching period may be subdivided into two periods, T_1 and T_2, corresponding to the durations of modes 1 and 2, respectively.

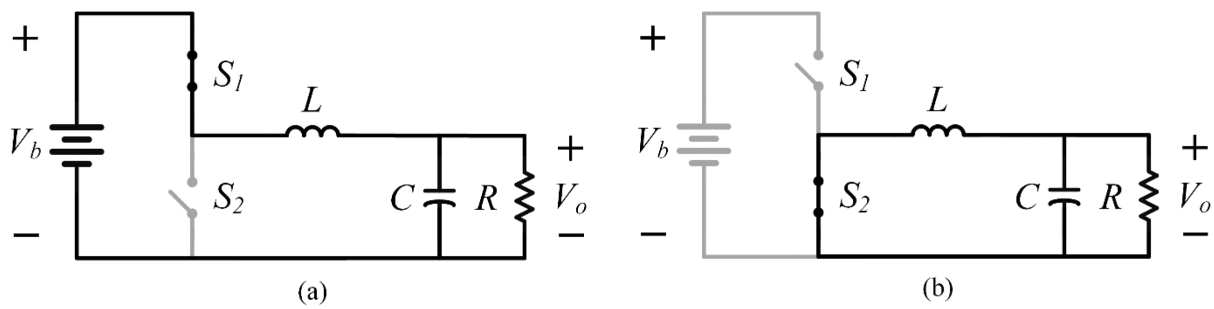

Figure 2. DC-DC converter equivalent circuits for modes1 (a) and mode 2 (b)

The converter is controlled by adjusting the durations of the two modes. Because there are only two modes, the sum of their durations is equal to the switching period, i.e. $T_1 + T_2 = T$. The duration of each mode may therefore be set by specifying the ratio T_1/T. This ratio is commonly referred to as the duty ratio, d, where $0 < d < 1$. The duty ratio is the control input for the converter shown in Figure 1. When d is set externally, the mode durations T_1 and T_2 may be expressed as dT and $(1 - d)T$, respectively. Figure 3 shows selected waveforms for the converter in steady-state operation.

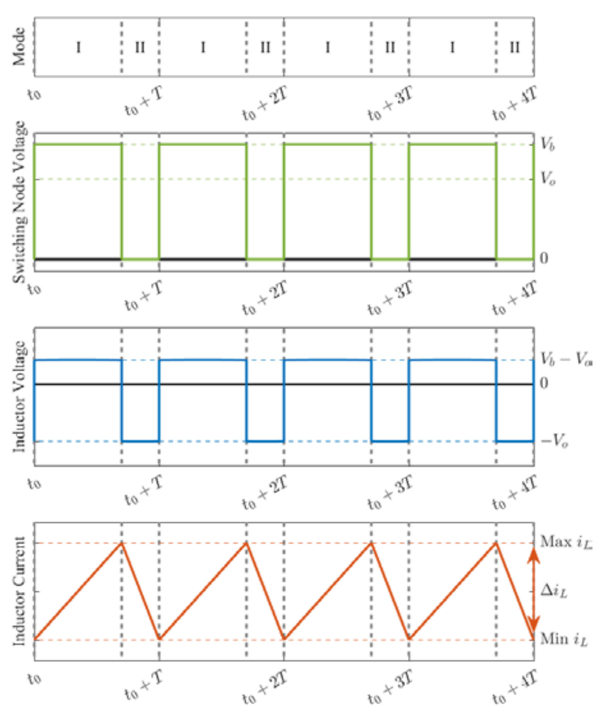

Figure 3. DC-DC converter current and voltage waveforms

To simplify the analysis, assume that the value of C is large enough to hold the output voltage approximately constant over a switching period. At the start of each switching period, the converter is in mode 1, and is equivalent to the circuit shown in Figure 2a. Applying Kirchhoff's voltage law (KVL) to this circuit, it is clear that the voltage across the inductor is $V_L = V_b - V_o$. Since, by design, the output voltage is less than the battery voltage, V_L is positive and constant throughout the duration of mode 1. As a result, the current in the inductor increases linearly as shown in the bottom plot in Figure 3. The change in inductor current during mode 1 is:

$$\Delta i_{L1} = \frac{V_b - V_o}{L} dT.$$

As inductor current increases in mode 1, energy is stored in the inductor's magnetic field. This energy is released in mode 2. By applying KVL to the equivalent circuit in Figure 2b, the inductor voltage during mode 2 is determined to be $V_L = -V_o$. Consequently, the inductor current ramps down as shown in the bottom plot in Figure 3, releasing stored energy to the load. The change in inductor current during mode 2 is:

$$\Delta i_{L2} = \frac{-V_o}{L}(1-d)T.$$

In steady-state operation, the energy stored is equal to the energy released. Because the inductor is the primary energy storage element, this relationship may be expressed in terms of the change in current over each mode duration. The energy stored in the inductor, W_L, is related to the inductor current as:

$$W_L = \frac{1}{2} L i_L^2$$

For the energy stored in the inductor to equal the energy released, the inductor current at the end of the switching period must equal the inductor current at the start of the switching period. In other words, the sum of the changes in inductor current for the two modes must be zero:

$$\Delta i_{L1} + \Delta i_{L2} = \frac{V_b - V_o}{L} dT + \frac{-V_o}{L}(1-d)T = 0$$

From here, the equation may be rearranged to provide an expression relating the input and output voltages to the control input, d:

$$(V_b - V_o)d = V_o(1-d)$$
$$V_o = dV_b$$

The store-and-release energy cycle described here is the basic premise of switched-mode power conversion. The duty ratio d is controlled such that the converter meets its specified objectives.

Although the converter analyzed above is simplified and consists entirely of ideal circuit elements, the analysis still offers useful insights into general converter design relationships. The performance of the converter is highly dependent on the characteristics of the active switching elements. When off, the switches must have high impedance and block the full input voltage without breaking down. When on, the switches must provide a low impedance path and conduct the full inductor current. During mode transition, the switches must change their configuration as rapidly as possible. In practice, switches are implemented using semiconductor devices, and these three characteristics (blocking voltage, current capacity, and switching frequency) are subject to physical limitations that are a dominant factor in nearly all metrics of converter performance. For this reason, the evolution of power conversion circuits and applications is inextricably tied to developments in semiconductor technology. Semiconductor devices are discussed in more detail in Section 2.3.1.

The converter's steady-state behavior may also be understood by thinking of it as chopping and filtering the DC voltage. The switching action produces a rectangular voltage waveform at the node between the two switches. The average value of this switching voltage waveform, calculated over a full switching period, is equal to the desired output voltage. The averaging function is applied by the inductor and capacitor, which act together as a second order low pass filter. This is a useful interpretation for understanding the relationship between switching parameters (namely f_{sw}) and passive component values. As switching frequencies increase, the required cut-off frequency to filter the switching waveform also increases and required inductance and capacitance values decrease. In general, higher switching frequencies make it possible to use smaller passive components and achieve higher power density. Additional information on passive components is given in Section 2.3.2.

In the example shown in Figure 1, a converter is intended to regulate a fixed voltage to serve a DC load. The output voltage is set by adjusting the duty ratio. If the converter's input voltage is known and fixed, one option is to set a constant duty ratio. However, this open-loop control has no feedback path, so if the input varies the output will drift from its target value.

Figure 4 shows the same converter with closed-loop control. Here, the output voltage is measured and compared to a target reference value. The error, or difference between the target and measured value, is fed to a controller, which generates the duty ratio. A proportional-integral controller is suitable for this task, but more sophisticated control strategies are certainly possible. This circuit controls output voltage but can also be used to control other operating parameters. For example, if the application required control of the output current, a similar feedback path could be included to sense and control the inductor current i_L.

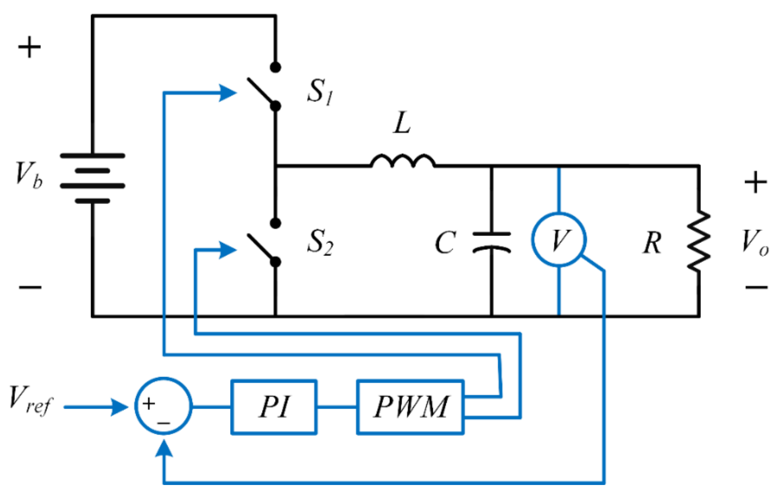

Figure 4. DC-DC converter with closed-loop voltage control

Introducing a feedback path and controller increases complexity and creates challenges for control design, stability, and noise immunity, etc. However, closed-loop control improves dynamic performance and radically expands the potential functionality of the converter. For all but the simplest applications, closed-loop control is a necessary component of the power conversion system.

2.2.2. Basic DC-AC Conversion and Control

This chapter is primarily concerned with power conversion systems for grid-connected energy storage. Electrochemical energy storage produces DC electricity, and electromechanical storage such as flywheels produces variable-frequency AC that is then rectified to DC. Thus, an essential function for connecting an energy storage system to the power system is the ability to convert between DC and AC. The converter that performs this function is called an inverter[1]. The same basic principles used in the DC-DC converter described above are used in the DC-AC inverter described here.

The circuit in Figure 5 is a single-phase voltage source inverter, named for the single-phase AC output and voltage source input. For obvious reasons, this circuit is also known as an “H-bridge.” The load is shown in the figure as a passive device. This could, for instance, represent a converter for an off-grid energy storage system powering a local AC load. Because this inverter directly controls output voltage it is said to be voltage-controlled, and it appears to the load as a controlled voltage source element. The voltage-controlled inverter does not require an external grid voltage and can operate completely on its own, essentially forming a local grid voltage at its AC terminals. An inverter operating in this way is sometimes referred to as a “grid-forming” inverter.

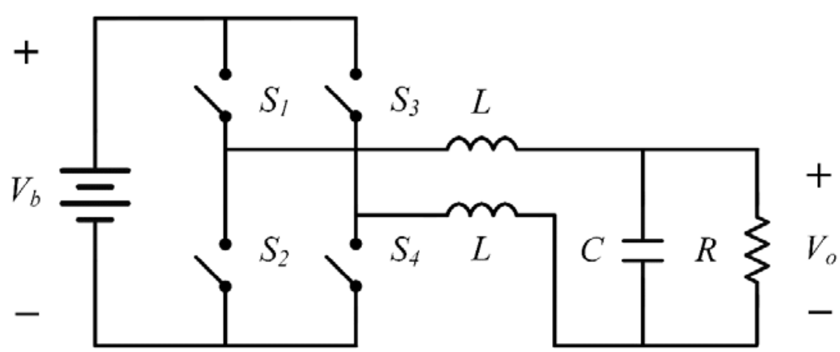

Figure 5. Single phase voltage source inverter topology

The basic principle of operation of a single-phase H-bridge inverter can be understood as follows. Assume that the L-C components at the output of the H-bridge constitute a low-pass filter that will pass 60 Hz but reject high frequencies. The switches in the H-bridge are switched in complementary pairs: when S_1 and S_4 are on (closed), S_2 and S_3 are off (open), and vice-versa. For the H-bridge, the duty ratio d is defined as the portion of the switch period during which S_1 and S_4 are closed. When S_1 and S_4 are closed, the voltage applied to the filter is $+V_b$. When S_2 and S_3 are closed, the voltage applied to the filter is $-V_b$. Alternating between the two pairs of switches at 60 Hz results in a 60-Hz square wave voltage at the filter. This can be a useful form of DC-AC conversion (in fact some low-cost “square- wave” inverters work in this way), but the power quality provided by this type of inverter is low.

[1]Traditional converter terminology is based on unidirectional power flow. For example, an AC-DC converter is traditionally understood as a converter designed to transfer power from an AC port to a DC port. Such a converter is also traditionally referred to as a “rectifier.” On the other hand, a DC-AC converter is typically referred to as an “inverter.” These labels become arbitrary for converters that support bidirectional power flow. To prevent confusion, the term inverter is used exclusively in this chapter, and should be understood to mean any converter capable of exchanging power bidirectionally between AC and DC ports.

To achieve a more sinusoidal voltage, instead of switching at 60 Hz, the switching frequency is made to be much higher, usually in the kHz or low tens of kHz range. Then, the duty ratio of the switches is modulated in a sinusoidal fashion. This is done by comparing a sine wave at the desired AC output frequency (i.e., 60 Hz) to a triangle or sawtooth wave at the desired switching frequency f_{sw}. The latter is referred to as the "carrier" signal. The carrier signal and the sinusoidal modulation waveform are shown in Figure 6.

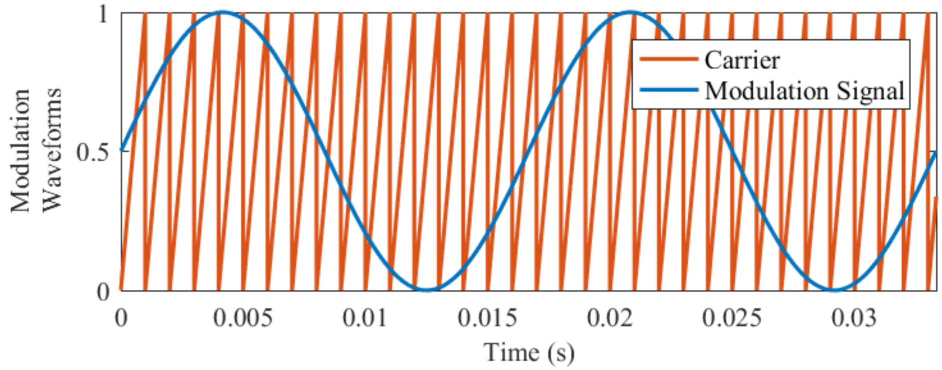

Figure 6. PWM carrier signal and sinusoidal modulation waveform

A comparator generates a digital on/off signal by comparing the carrier and sinusoidal waveform. When the sinusoid is greater than the carrier, the output is on; when the sinusoid is less than the carrier the output is off. The output of the comparator is the waveform shown in Figure 7, which is a pulse wave with the frequency of the carrier signal (f_{sw}) and with a duty ratio varying at the frequency of the sine wave. This waveform has a sinusoidal frequency component at the desired line frequency, along with higher-frequency components. The process of generating the pulses shown in Figure 7 is referred to as pulse width modulation (PWM).

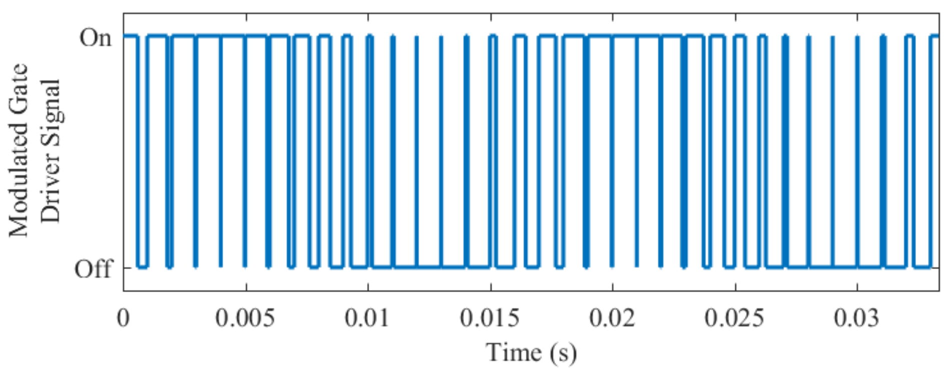

Figure 7. Pulse width modulated gate driver signal

The voltage applied to the filter at the output of the H-bridge will have the same wave shape; it will alternate between $+V_b$ and $-V_b$ at the carrier frequency, but with the same modulation at the frequency of the sine wave, as shown in Figure 8. The L-C filter at the output of the inverter then removes the higher-frequency components of the waveform, leaving only the desired low-frequency sine wave. The H-bridge is now being controlled as a DC-AC inverter creating a sinusoidal AC voltage output.

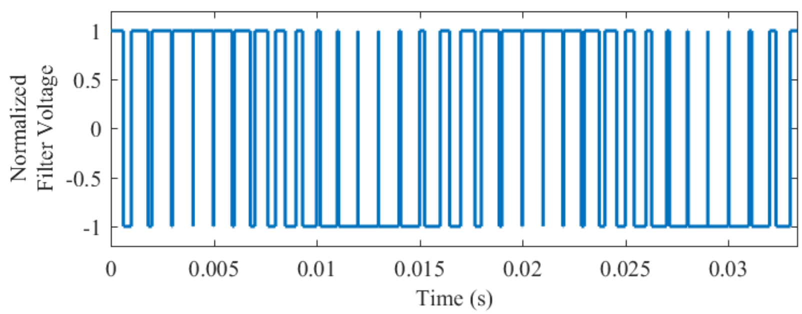

Figure 8. Normalized voltage applied to H-bridge output filter

The H-bridge can also be used as a "grid-following" inverter. The hardware is essentially the same; only the control of the converter changes. The grid-following inverter tracks the phase, frequency, and magnitude of the external grid voltage and controls power injected into the grid according to external power commands. These commands may originate from a battery management system, a maximum power point tracker for a PV array, or any number of other application-specific sources. Because the grid-following inverter cannot directly control the voltage at the point of connection, it regulates power injections by controlling output current. Consequently, this inverter is said to be current-controlled and appears to the rest of the system as a controlled current source element.

Distributed generation sources most commonly interface with the grid through grid-following inverters. However, large quantities of distributed resources in grid-following operation cause undesirable effects at the system level. Scalable control strategies that overcome limitations of grid-following behavior are an active area of research. Proposed solutions include coordinating interconnected systems of grid-forming inverters.

The difference between grid-forming and grid-feeding inverter behavior illustrates why a black box perspective on power conversion systems is insufficient. Both types of inverter share the same power stage and high-level functionality (i.e., conversion between AC and DC sources). However, their behavior and impact on the grid is entirely different. This difference, which is purely due to internal control algorithms, is as fundamental as the difference between voltage and current source elements. Inside the black box, a power conversion system is a general-purpose tool with high-speed sensing and actuation capabilities cast into a specific application by its control system.

There is no physical reason why the same power stage cannot be used for several different control functions over its life cycle, provided that hardware-dependent voltage, current, and frequency ratings are respected. This flexibility, if leveraged effectively, could be a valuable resource in the rapidly changing grid environment. For a utility-scale power conversion system, the ability to adapt control functionality in response to emergent stability and power quality issues holds great value potential—particularly in energy storage interface applications.

2.3. Implementation

Idealized circuits are useful tools for understanding the principles of converter operation, but when it comes to real-world capabilities, the devil is in the details. The most challenging aspects of converter design and analysis pertain to non-ideal behaviors of physical devices used to realize the functionality of ideal circuit elements.

This section provides a brief overview of the component and subsystem technologies used to implement conventional power electronic systems. The intended takeaway is a general understanding of how power converter capabilities are linked to—and limited by—material, component, and subsystem technologies. Again, this discussion is not intended as a comprehensive reference, but rather as a condensed primer.

2.3.1. Semiconductors

Active switching elements are the heart of a power conversion system. Each switch is realized as a semiconductor device (or combination of multiple semiconductor devices). Semiconductors provide the unique ability to operate both as a conductor and as an insulator depending on external circuit conditions.

The simplest semiconductor device is the diode. The schematic symbol and operating characteristic of a diode is shown in Figure 9. The operating characteristic shown in Figure 9b shows device voltage and current on the x and y axes, respectively, with polarity/direction corresponding to those shown in Figure 9a. This diagram is referred to as the device's IV characteristic.

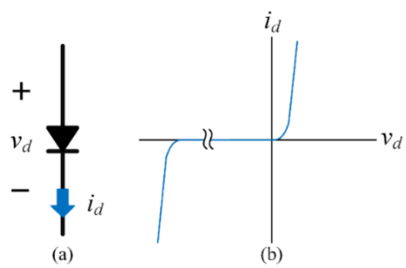

Figure 9. Diode symbol (a) and IV characteristic (b)

The diode is a two-terminal passive device, meaning its behavior is governed by the polarity of voltages and currents applied to it. When a forward voltage is applied to a diode (i.e., a voltage with positive polarity), current flows in the positive direction. In this condition the voltage drop across the diode is very small. When a reverse voltage is applied, no current flows in the diode until a terminal breakdown voltage is reached. In this reverse bias configuration, the diode can block large voltages without conducting current. However, voltage magnitudes above the rated blocking voltage will cause the device to break down.

While the passive operation of the diode is useful for many applications, power conversion circuits more commonly require an active device, or transistor, which can change operational characteristics through the application of a control signal. There are a variety of power transistor devices. The two most common are the power metal oxide semiconductor field effect transistor (MOSFET) and the insulated gate bipolar transistor (IGBT). Schematic symbols for these devices are shown in Figure 10.

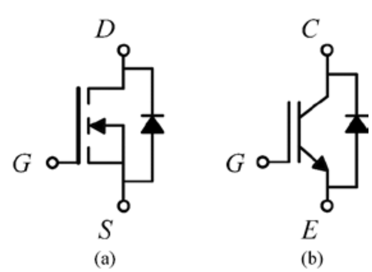

Figure 10. Symbols for MOSFET (a) and IGBT (b)

The principles of operation and underlying physics behind MOSFET and IGBT behavior are beyond the scope of this document. The two are (crudely) grouped together here, based on similar high-level functionality. Both are three-terminal devices, and both are controlled through the application of voltages at the gate terminal. In the MOSFET, the remaining two terminals are the drain and source terminals. The remaining terminals of the IGBT are the collector and emitter terminals. This variation in nomenclature is due to differences in internal device construction and physical basis of operation. For the limited purposes of this discussion, the collector and emitter terminals of an IGBT may be understood to be functionally equivalent to the drain and source terminals of a MOSFET.

The basic limiting factors for power semiconductor devices are maximum blocking voltage, maximum on-state current (primarily a function of thermal properties), and time durations of on/off state transitions. These attributes are interrelated and depend on the physical construction of the device. In general, devices with larger blocking voltages have greater on-state resistance, meaning more heat is generated internally due to power loss during conduction. This places restrictions on maximum allowable current. Likewise, devices with larger blocking voltages tend to take longer to transition between on and off states. For the MOSFET, applying a voltage to the gate terminal that causes the voltage difference between the gate and source terminals to be greater than some device-specific threshold value will force the transistor into a conductive on state—i.e., the MOSFET acts like a closed switch. While in this state, a positive voltage applied from drain to source will cause current to flow through the device. When the gate to source voltage is below the threshold value, the device will return to an off state—i.e., it acts like an open switch. In this state, a positive drain-source voltage will result in negligible current through the device and the voltage drop from drain to source will be equal to the applied voltage.

MOSFETs are the dominant transistor technology for applications lower than 600 V. MOSFETs switch faster than IGBTs. Above 600 V, IGBTs are more competitive. IGBTs have longer switching times but much larger voltage ratings, and they tend to have lower on-state resistance than comparable MOSFETs. Half-bridge and 6-pack IGBT modules rated for 600 V to about 1.7 kV are the dominant solution for inverters in distributed generation and motor drive applications. IGBT modules are commercially available up to 6.5 kV.

Since the introduction of power semiconductor devices, silicon (Si) has been the dominant material. Recently, however, wide bandgap (WBG) materials such as silicon carbide (SiC) and gallium nitride (GaN) have been used to push beyond the limitations of traditional Si devices. WBG devices achieve higher blocking voltages, lower on-state losses, and higher switching frequencies than traditional Si alternatives. While WBG devices are still at relatively early stages of commercialization and industry adoption, their impact is certain to disrupt the traditional dominance of Si devices. SiC MOSFETs are already commercially available at voltages up to 1.7 kV, putting them in direct competition with Si IGBTs. Additional detail on power semiconductor devices may be found in [3]. Reviews of state-of-the-art devices and the impacts of WBG materials may be found in [4-6].

2.3.2. Passives

Passive components are elements that have current-voltage characteristics that do not change with a control signal. Examples include inductors, capacitors, transformers, and resistors. Passive components play an essential role in the operation of power electronics. As described earlier, power electronic converters operate by rapidly storing and releasing energy to facilitate transfer between source and load. Semiconductor switches reconfigure circuits to control the energy transfer, but the energy storage and release occurs in passive components (usually inductors and capacitors). Thus, the properties of passive components are as critical to power converter performance as those of the semiconductors.

A single converter involves a diverse range of passive component technologies, each tailored for a specific function. For instance, polarized DC bus capacitors, which store and release charge to an inverter's switching bridge, have fundamentally different compositions than AC filter capacitors, which eliminate switching ripple at the AC interface. Likewise, high-frequency transformers used in isolated DC-DC converters use different core materials than the Si steel 60 Hz transformers at an inverter's point of connection to the grid.

Materials used in passive devices have different relationships with switching frequency and temperature range. As WBG semiconductor technologies mature, selection of appropriate passive materials and components becomes more important and more difficult. One of the most important advantages of WBG devices is the ability to operate with higher switching frequencies. Passive components are typically the bulkiest elements of a power converter, but higher switching frequencies reduce passive component weight and volume requirements and facilitate the production of power converters with higher power densities. Because of these trends and advantages, materials and designs for—and electromagnetic compatibility of—high-frequency passive elements for power electronics are active areas of research.

2.3.3. Control Electronics

Most power electronic converters require a closed-loop control system to allow the converter to meet its performance objectives. For very simple power converters, such as the DC-DC converter in Figure 4, it is possible to implement an analog control system with basic signal-level electronics. This is an appropriate solution for low-power applications, because power loss in the analog control circuitry is very small and components are inexpensive. As power capacity and system complexity increase, control systems are more commonly implemented digitally in a microcontroller, digital signal processor (DSP), or field-programmable gate array (FPGA). At the scale of a grid-tied converter, digital control is generally considered mandatory.

There are many advantages to a digital control platform. Digital controls provide an enormous level of flexibility, enabling power converters to realize a wide variety of functions not possible with an analog controller. They also allow the same power converter hardware to perform many different functions simply by changing the programming. Digital controllers are less susceptible to undesirable environmental influences, such as thermal parameter drift and electromagnetic noise, and have become increasingly powerful and affordable. Several manufacturers offer product lines specifically tailored to power conversion applications.

Basic tasks of a power converter control system include measurement, computation, actuation, and communication. The control system must receive external commands, sample local measurements from voltage and current sensors, compute appropriate actions, and generate gate drive signals for the power semiconductors. Low voltage communication and control electronics are typically grounded but must connect to floating nodes in power stage hardware. Connections between control devices and power hardware must therefore cross some voltage isolation barrier. Isolation is most commonly provided in the components or subsystems involved in measurement and actuation tasks, where the control system and power stage meet.

In addition to isolation, signals must be scaled in both directions. Dedicated gate driver components amplify the switching signals generated by the control device to reliably operate the power semiconductors. At the measurement side, sensor data must be scaled and converted to a digital signal. Depending on device selection, analog-to-digital conversion may be done in the sensor, in a dedicated component, or in the controller itself. The sensor data are generally filtered to remove noise or other unwanted components. There is usually a small amount of analog filtering, followed by more extensive digital filtering. These filters can have a significant impact on the dynamic response of a power converter, and thus filter design (which itself is a major electrical engineering subdiscipline) is crucial to converter performance. In general, practical challenges at the interface of the control system and power hardware scale with converter operating voltages.

2.3.4. Thermal Management

Losses in a power conversion circuit must be dissipated as heat. Nearly all components in a power converter generate heat—and nearly all are susceptible to thermally induced failures. Unless heat is removed from the components at an acceptable rate, converter reliability and time-to-failure will be reduced. Thus, thermal management is an essential aspect of converter implementation and is critical to system reliability.

Semiconductor devices present the most significant thermal management challenges. Thermal stress is the primary cause of failure in semiconductor devices. Heat is generated in a semiconductor in two ways – conduction loss and switching loss. Conduction loss occurs when the device is in the on-state because the semiconductor material never acts as an ideal conductor. Switching loss occurs during the transitions between states. Heat generated through these loss processes must be dissipated away from the semiconductors. The efficacy of heat transfer away from the devices is heavily dependent on thermal interfaces between the device and cooling elements, so device packaging plays a key role in determining thermal management performance. Device design is also important because heat is not generated uniformly throughout the device and tends to be concentrated in certain parts of the device structure.

To some extent, thermal issues may be mitigated by reducing losses. For a fixed power value, conduction loss and I^2R loss is reduced by operating at higher voltage. This relationship provides strong motivation for increasing the operating voltages of power converters.

2.3.5. Resonant Converter Structures

Another approach to reducing power conversion losses is to use advanced resonant converter topologies. When a switch in an inverter transitions between its on and off states, there is a short time interval during which current and voltage are both nonzero, meaning power is dissipated in the device. If not managed properly, this switching loss may have a significant impact on converter efficiency and heat generation in semiconductor devices. Furthermore, during the switch transition both current and voltage experience high rates of change. These rapid current and voltage changes can lead to electromagnetic interference issues which degrade performance and reliability. Resonant converter topologies address these switching issues by switching states only when device voltage or current is zero. This “soft-switching” behavior reduces switching loss and mitigates electromagnetic interference.

Detailed operation of resonant converters can be quite complex and is beyond the scope of this chapter. In general, however, resonant converters operate by matching active switch transitions with resonant dynamics of passive elements such that the switch current or voltage is forced to zero either before or simultaneous to the switch transition. This requires both careful hardware design and precise control. The level of complexity involved in design, analysis, and operation of these converters is a barrier to widespread commercial adoption. Nonetheless, resonant converter topologies and soft-switching techniques are active areas of research.

3. PCS in Energy Storage Systems

3.1. Introduction to PCS Hardware Architectures

Electrochemical energy storage devices, such as batteries and electrochemical capacitors[2], store and release energy through electrochemical reactions that generate static DC voltages and currents. These technologies require DC-to-AC conversion to be used in with AC power systems. Consequently, the PCS architectures that interface these storage resources with the grid are similar in form to the inverter described in Section 2.2.2.

Storage technologies based on thermal, kinetic, or gravitational potential energy involve an additional conversion step in which stored energy is converted to electricity. This is most commonly done by driving electric machines that generate AC voltages and currents. Some of these storage technologies, such as flywheels, produce variable-frequency AC power and require AC-AC conversion to interface with constant-frequency power systems. The PCSs typically used in this case involve converting the variable frequency AC-to-DC, then converting that DC-to-AC using an inverter. The converter architectures that do this are often called “back-to-back” converters because of the two conversion steps.

For purposes of organization in this section, storage technologies are categorized as either electrochemical or electromechanical depending on whether their electrical output is DC or AC. PCS architectures for electrochemical storage systems are described in Section 3.2; PCS architectures for electromechanical storage are described in Section 3.3. This classification scheme simplifies the introduction of PCS architectures, but it is not absolute.

3.1.1. Grid Interface

Regardless of the architecture used, energy storage systems that interface with the larger AC power system must meet specified performance requirements to avoid causing adverse impacts to grid performance or to other customers. Basic capabilities that must be provided by grid-following energy storage plants are:

- Synchronization to the grid’s AC voltage
- The ability to provide certain reactive power functions and grid support functions such as volt-var and frequency-watt droops
- Various over/undervoltage and over/underfrequency ride-throughs
- Specific levels of power quality
- Transient response parameters and ramp rates
- The ability to detect the formation of unintentional islands

[2] Electrochemical capacitors are sometimes referred to as supercapacitors, ultracapacitors, electric double layer capacitors, and a variety of different trade names.

To ensure that the performance standards are met, requirements are also commonly imposed on the types and accuracies of measurements used by inverters.

The standard that sets the grid interface requirements for a particular energy storage system depends on the point in the system at which the energy storage system is connected. Systems connected at the distribution level are subject to IEEE Standard 1547-2018 and its companion testing standard IEEE 1547.1-2020. There is also an application guide currently being written, IEEE P1547.9, which is dedicated to the application of IEEE 1547 to energy storage systems[3].

Power converters for connection to distribution systems are generally certified under the UL-1741 certification standard or an equivalent. UL-1741 includes the testing requirements laid out in 1547.1 and includes additional requirements[4]. For grid-following energy storage systems interfaced with transmission-level circuits through power electronics, the standard that will set the grid interface requirements is IEEE P2800, and its companion testing standard IEEE P2800.1. IEEE P2800 is currently being drafted, and the requirements it will impose are still subject to change as of this writing. The transmission-level requirements in P2800 will include significant differences from the distribution-level requirements in 1547-2018, in part because of its close connection with North American Electric Reliability Corporation (NERC) system performance requirements.

Another key performance metric for grid interface power electronics is efficiency. Improvements in converter efficiency translate to additional active power that can be sold into the grid. Energy storage plants can see monetary benefits with even modest improvements in efficiency. Converter efficiency also plays a significant role in thermal management: the losses are converted to heat that must be removed from the device, so higher efficiency reduces the heat-removal requirements. To minimize I^2R losses, operation at higher AC and DC voltages is desired to reduce the current required to transmit the same power, and it is beneficial to minimize the series resistances of all components in the converter (see Sections 2.3.1, 2.3.2, and 2.3.4).

3.1.2. Storage Interface

While grid interface requirements are fixed by the grid environment and apply equally to storage installations, requirements pertaining to the storage device interface are heavily dependent on storage technology. In electrochemical storage systems, different chemistries require different methods for charge and discharge operations. Failure to comply with these requirements may degrade system performance, shorten lifetime, or create unsafe conditions in the storage system. Therefore, most requirements that affect the storage side of the PCS are covered in standards primarily concerned with system safety. Information on these safety standards may be found in Chapter 20: Safety of Electrochemical Energy Storage Devices.

Several IEEE standards provide general guidance on PCS design and operation. For instance, IEEE Standard 2030.2.1-2019 describes design, operation, and maintenance of battery storage systems in both stationary and mobile applications and includes recommendations that apply specifically to PCS for energy storage, such as DC voltage ranges requirements for the storage interface. IEEE Standard 1662-2016 provides recommendations on design and operation of power converters in electrical power systems and applies more generally to the PCS as a power electronic system.

[3] IEEE 1547.9 is expected to be approved by the end of Q2 of 2021.
[4] IEEE 1547 and IEEE 1547.1 are not certification standards; UL-1741 is.

3.2. PCS Hardware Architectures for Electrochemical Storage

Electrochemical cells are the irreducible units of storage used in the construction of a storage system. Cells are low voltage DC devices. The voltage of a cell is typically between 1 V and 5 V depending on chemistry. Moreover, cell voltage is variable and depends on a variety of operating factors, most notably SOC. While the total energy capacity of a cell may be scaled upwards using larger form factors and geometric arrangements, the voltage is set by the chemical reaction. Because of this, system-level voltage requirements are typically met by connecting multiple cells in series. A utility-scale battery system may involve complex arrangements of series and parallel cell connections to meet target voltage and energy capacity specifications.

Although electrochemical energy storage systems consist of many individual cells, they are typically operated as a single unit. That is, charge and discharge procedures are applied at the system level. For example, all cells in a series-connected string share the same charge/discharge current. The problem with this arrangement is that cells are not identical. Due to normal manufacturing tolerances, even cells constructed in the same batch will be slightly different. When a series-connected string is charged, the weakest (lowest capacity) cell will reach maximum SOC first. At this point, continued charging will overcharge the cell and, depending on chemistry, could result in catastrophic failure. To avoid this, the battery management system (BMS) must track and equalize charge imbalances.

The central challenge for PCS in electrochemical storage systems is that low voltage electrochemical cells must somehow interface with AC systems that invariably prefer higher voltages. In conventional PCS architectures, the storage system must consist of multiple series-connected cells to meet voltage DC voltage specifications. In the series-connected configuration, each cell acts as a single point of failure and system-level performance is limited by the weakest cell. A BMS may counteract these deficiencies, at the cost of additional losses (for passive balancing) or circuit cost/complexity (for active balancing). The challenges described here become more problematic as the system DC voltage (and number of series-connected cells) increases. This has important implications for the PCS, which drives storage system voltage requirements While trends in power converter development favor higher working voltages, there is a practical limit on the DC voltage which can be attained through series-connected battery cells. The relationship between PCS and storage system voltage requirements is explained further in Section 3.2.1

3.2.1. Single-Stage Architecture

In the single-stage PCS architecture, a single converter is used to accomplish tasks pertaining to both the grid and storage system interfaces. In a single-stage architecture, the energy storage system sets the DC bus voltage. This voltage varies significantly with SOC of the storage devices, and the voltage ratings of the PCS must be appropriately matched to the range of this variation. At minimum allowable SOC, the storage system voltage must exceed the peak voltage on the AC side of the PCS. At maximum SOC, semiconductor voltage ratings must still provide enough overhead to ensure safe operation. This relationship limits scalability—as the nominal DC link voltage increases, the cost of necessary overdesign in semiconductor voltage ratings grows. As a result, most utility-scale storage installations are connected to low-voltage grids despite the availability of multilevel inverters capable of operating at much higher voltage ranges.

At present, most electrochemical energy storage systems in the grid use a single-stage PCS with nominal DC-link voltage less than 1,000 V. At this scale, charge imbalances and reliability issues in the storage system are manageable, and simple voltage source inverter (VSI) topologies offer satisfactory performance. When an application requires power beyond the capabilities of a single VSI, multiple storage systems are paralleled at the AC interface. However, without some way of addressing scalability issues in the energy storage system, the single-stage architecture is limited to low working voltages.

The simplest and most common realization of this architecture is the three-phase voltage source inverter shown in Figure 11. The key advantage of this topology is its simplicity. Due to its low parts count, it has high reliability and low comparative cost. Its low complexity also means that it is simple to control.

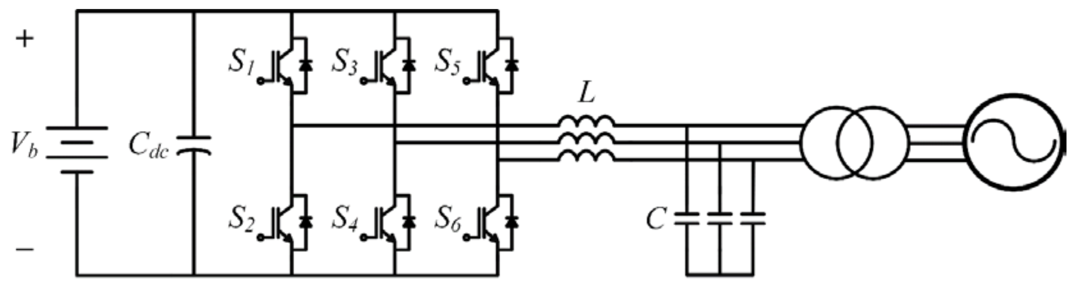

Figure 11. Three-phase voltage source inverter topology

Because of these attributes, it has become a popular conversion solution in distributed generation and industrial motor drive applications. The three-phase inverter in Figure 11 is similar in form and function to the H-bridge inverter described in Section 2.2.2. The circuit consists of a switching bridge, L-C filter, and grid connection. The figure also shows a 60 Hz transformer at the point of connection to the grid. The transformer is not a technical requirement for circuit operation, but it is almost always included as part of the PCS. The transformer provides galvanic isolation between the grid and inverter and can be used to interface the low-voltage AC output of the inverters with the higher-voltage AC system. When included, the transformer contributes to overall system losses and often is the largest single element of the PCS in terms of physical size.

The main limitation of the basic VSI topology in Figure 11 is the DC voltage scalability. The semiconductors must block the full DC-link voltage, so the ratings of these components must be greater than the maximum possible voltage provided by the DC source. Exceeding semiconductor voltage ratings will quickly destroy the device, so inverter design typically includes a substantial safety margin. In the case of electrochemical energy storage, variations in the storage system voltage with SOC require further overdesign.

A more advanced inverter topology is the multilevel inverter. Multilevel inverter topologies enable higher working voltages by splitting voltage stress between multiple semiconductors. There are a variety of multilevel inverter topologies, but the most common is the three-level neutral point clamped inverter (NPC) shown in Figure 12. Whereas the basic VSI can only provide two voltage levels (the DC link voltage with positive and negative polarity), multilevel inverters subdivide the DC link voltage into multiple levels, allowing the AC output synthesized by the switching action to better approximate a sinusoidal waveform. This improved voltage output reduces passive filter requirements and minimizes harmonic distortion. Disadvantages of multilevel topologies are increased cost and complexity, which increase rapidly with number of discrete voltage levels. While three-level inverters have found widespread acceptance in high-power industrial applications, inverters with greater than three levels are uncommon.

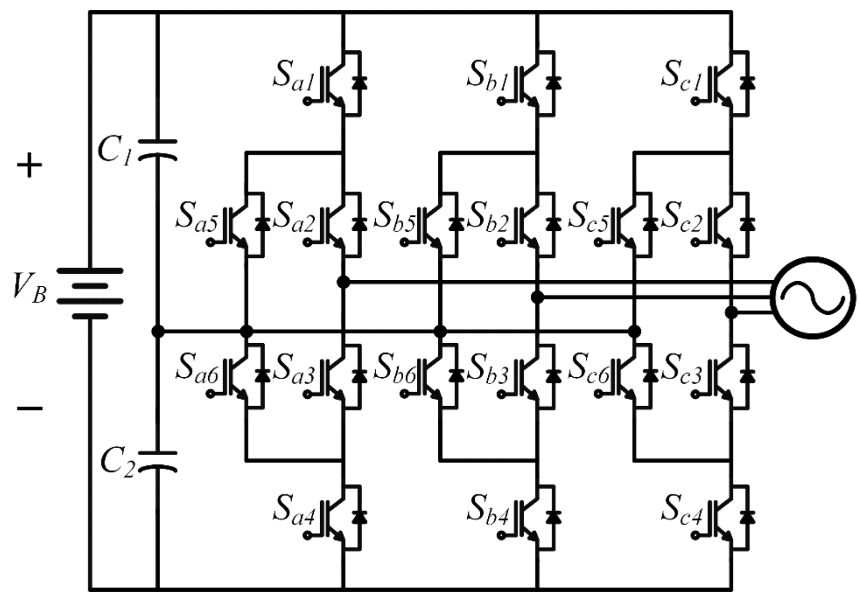

Figure 12. Three-Level Active Neutral Point Clamped Inverter [7, 8]

3.2.2. Multi-Stage Architecture

In a multi-stage architecture, grid and energy storage interface tasks are divided among multiple power converters. In the simplest multi-stage PCS arrangement, shown in Figure 13, a DC-DC converter is placed between the energy storage system and inverter. There are several advantages to this configuration. The DC-DC converter may boost the voltage of the energy storage system, effectively decoupling the storage system voltage from the minimum DC-link voltage requirement. This also eliminates variability from the DC-link voltage and improves inverter semiconductor utilization. Depending on topology, the DC-DC converter may also provide galvanic isolation.

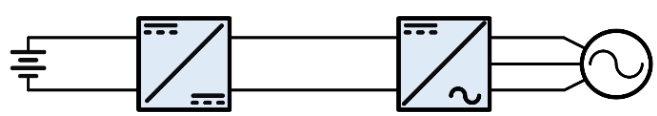

Figure 13. Single-Input Multi-Stage PCS Architecture

Using a DC-DC converter to boost voltage allows the energy storage system to be designed with lower nominal voltage. Because lower voltage configurations require fewer series-connected cells, balancing loss and reliability are improved. However, introducing a second power converter also increases cost, complexity, and power conversion losses. Since the DC-DC converter processes the full rated system power, these losses may be significant. In a point-to-point comparison with single-stage architectures, these disadvantages typically outweigh the potential benefits, so the arrangement shown in Figure 13 is uncommon in the grid space.

The real benefit of multi-stage conversion is flexibility. Because the inverter DC-link is not tied to a storage system voltage, it can be used as a common point of connection for multiple DC-DC converters in series or parallel arrangements. Using multiple converters it is possible to construct system architectures that mitigate the disadvantages associated with the single-input case shown in Figure 13. A few possible configurations are shown in Figure 14 and Figure 15. In the former, the outputs of DC-DC converters serving separate storage systems are connected in series at the inverter DC link. Because voltage stresses are distributed between the converters, much higher DC link voltages are possible without sacrificing reliability in the storage system [9-11]. At the AC side of the configurations in Figure 14 and Figure 15, a multilevel inverter connects directly to a medium voltage (MV) point of connection. Moreover, if DC-DC converters provide isolation, voltages at storage device terminals are limited to the storage system potential, mitigating the severity of floating voltage hazards.

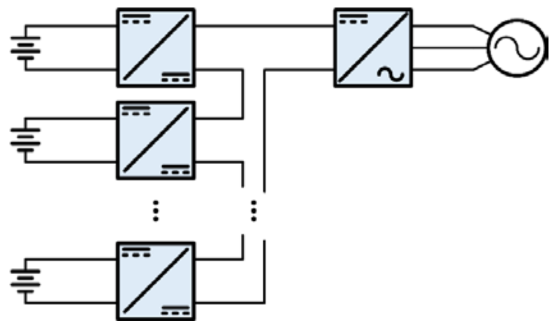

Figure 14. Series-Connected Multi-Stage PCS

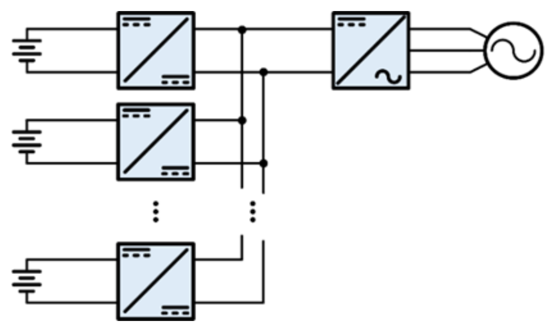

Figure 15. Parallel-Connected Multi-Stage PCS

The main disadvantages of a multi-stage PCS are that a) there are more series points of failure, making overall converter reliability somewhat more challenging; and b) the series conversion steps each incur losses, making achieving high efficiency more challenging.

In Figure 15, DC-DC converters are arranged in parallel. The DC link voltage is lower, but each DC-DC converter operates independently. That is, if a DC-DC converter or storage system must be taken offline, the rest of the system may continue to operate normally [12, 13]. Maximum power capacity will be reduced, but the system may continue operating at reduced capacity without disruption of service, thereby increasing overall reliability.

In both configurations the total storage capacity is broken into multiple storage systems, each with its own DC-DC converter interface. The control flexibility provided by the DC-DC converter interfaces makes it possible to support storage systems with different ratings, different states of health, or even different chemistries within the same multi-stage structure. While each storage system shares a fraction of total output power at a given instant, the specific distribution of power sharing can easily be configured according to the systems' operating characteristics. This capability could support more flexibility in storage device sourcing and enable hybrid storage installations in which complementary storage technologies are paired to improve overall performance. These topics are addressed in more detail in Section 3.4.2.

3.3. PCS Hardware Architectures for Electromechanical Storage

Section 3.2 discussed grid-connected PCS architectures energy storage resources that produce DC electricity. That section mentions that the DC voltage of electrochemical cells depends on the cells' SOC. However, consider that flywheels are usually coupled to a DC or AC machine that acts as a motor when charging the flywheel and a generator when discharging it. A flywheel's stored energy W is given by

$$W = \frac{1}{2} I \omega^2$$

where I is the moment of inertia and ω is the rate of rotation, so the rotation rate of the flywheel is directly related to its SOC. Because the voltage produced by DC or permanent-magnet machine depends on its rotational speed, a flywheel coupled to a DC machine will also produce a voltage dependent on SOC, and the PCS designed for this system will face some of the same DC-link voltage constraint challenges explained in the previous section. If the flywheel is coupled to an AC machine, then both the magnitude and the frequency of the AC output will depend on the SOC. To interface a variable-frequency AC machine to the grid, the variable-frequency AC must first be converted to DC, which can then be re-inverted to fixed-frequency AC. The PCS architecture that achieves this is sometimes called a "back-to-back" converter and is shown in block diagram form in Figure 16.

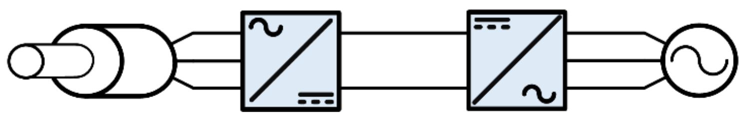

Figure 16. Back-to-Back Inverters for AC-DC-AC Conversion

This architecture is very similar to the two-stage architecture shown in Figure 13, with the primary difference being that the first stage at the left is AC to DC instead of DC to DC. The second stage at the right does not change between the two applications, and the grid interface performance requirements dictated by standards like IEEE 1547 are the same for both architectures. Note that the block diagram in Figure 16 is only a general structure. The back-to-back inverters may be simple two-level VSIs, three-level NPCs, or any other AC-DC conversion circuit depending on the needs of the application.

Pumped hydro and compressed air energy storage (CAES) also use AC machines as bidirectional energy converters, just as the flywheel does. Although these systems could be interfaced to the grid using PCSs, they typically are not because of their very large sizes. Pumped hydro and CAES typically use standard synchronous machines directly connected to the grid, with the power flow controlled via control of the mechanical torque on the machine.

3.4. Trends and Future Directions

PCS R&D is driven by the emerging needs of future energy storage systems. The role of storage in the grid is expanding, and future installations are expected to achieve higher power capacity, lower loss, and better reliability. As power ratings increase, it will eventually become necessary to move storage from the edges of the grid into distribution systems at MV and beyond. It is easy to envision a future in which energy storage systems are trusted utility assets tasked with grid support functions that directly affect system stability. In this case, PCS must be treated as critical infrastructure. Future PCS should be robust against internal and external disturbance. When possible, the PCS should be fault-tolerant and serviceable. When failure cannot be avoided, damage should be restricted to an isolated and replaceable subsystem, such that full-service restoration does not require full system replacement.

The landscape of energy storage technologies is constantly changing. A PCS should provide some level of invariance to these changes, particularly for electrochemical storage systems. If the storage devices are to be replaced at some point during the service life of the storage installation, the replacement should not be restricted to products and manufacturers available at the original time of deployment. In general, the PCS should support flexibility in storage device sourcing.

Like all power electronics applications, PCS research occurs in parallel with semiconductor developments. In some cases, the impact of component improvements is directly aligned with the needs of next generation storage. In others, more work is needed to match disparities between needs and capabilities. The following subsections describe current research trends and prospects for future systems.

3.4.1. Scalability and Modularity

When increasing the power ratings of electrical equipment, higher working voltages are invariably preferred. The quadratic relationship between current and Ohmic loss is a compelling reason to pursue higher voltage and lower current operating regimes whenever possible. In semiconductor development, IGBTs and WBG devices represent ongoing efforts to enable power electronic conversion at higher voltage levels. Devices with higher voltage ratings make it possible to use simple topologies (e.g., two-level VSIs) for higher power conversion. Likewise, multilevel inverters enable working voltage levels well beyond the limitations of a single semiconductor device.

As described in the previous section, high voltage AC-DC conversion only addresses half of the energy storage scalability problem, particularly for electrochemical storage devices. Multi-stage conversion architectures provide additional options at the energy storage interface and address key limitations of the single-stage approach. However, both strategies use a “centralized” approach to AC-DC conversion, in which the various DC sources are aggregated as a single DC input. Some of the advantages of multi-stage architectures are solutions to limitations of a centralized inverter.

Alternate conversion structures, in which the centralized inverter is eliminated entirely, may better suit the needs of high-power energy storage systems. One example is the cascaded H-bridge (CHB) topology. The CHB, shown in Figure 17, is a multilevel inverter with multiple DC inputs and fundamentally modular structure. The converter consists of multiple single-phase AC-DC conversion modules connected in series at their respective AC terminals. When the CHB was originally proposed for motor drive applications, its dependence on multiple isolated DC input sources was viewed as a significant disadvantage. However, the multiple input requirement is actually an advantage to energy storage applications because it allows low voltage storage systems to interface directly with MV grids [14-16].

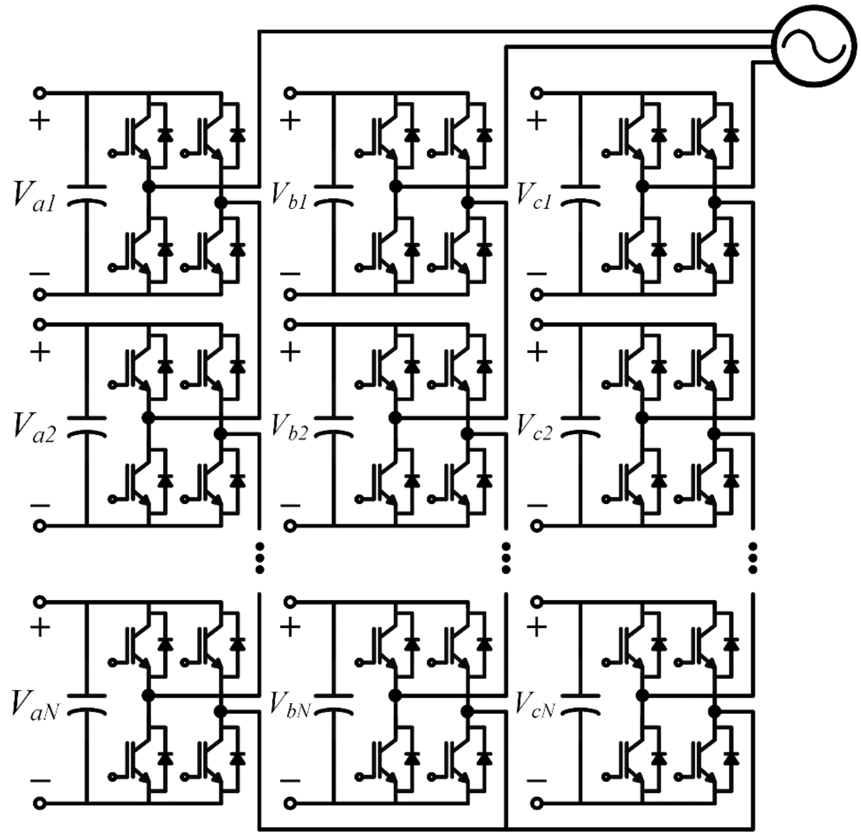

Figure 17. Cascaded H-Bridge (CHB) Topology

The CHB topology is closely related to the modular multilevel converter (MMC) topology. In a CHB, phase legs are connected in a "wye" configuration. The phase legs of an MMC are broken into upper and lower sections that connect to positive and negative terminals of a high voltage DC bus. The resulting structure is massively scalable and, as a result, has become the standard for modern high-voltage DC (HVDC) converter products [17, 18]. In an HVDC application, the module-level DC terminals are connected to capacitors but may also be used as a point of connection for energy storage devices. This strategy could allow storage to be embedded in new or existing infrastructure at a fraction of the cost of a dedicated storage installation [19-21].

Modular converters like the CHB and MMC also offer the possibility of fault-tolerance and serviceability. In a failure event, modules containing failed components may be bypassed without disruption of system-level functionality [22, 23]. If redundant modules are included in the system design, the converter may ride through module failures without reduction of capacity. Even if the failure requires the system to operate at a reduced capacity, the modular structure streamlines the process of service restoration, allowing damaged modules to simply be replaced.

The possibilities of modular and fault-tolerant conversion structures are promising, but additional work is needed to mature these concepts, demonstrate their performance, and assess commercial viability. Full-scale demonstration, while costly and challenging, is needed to gain a full picture of the practical considerations involved in deployment and operation of such a system.

3.4.2. Storage Device Flexibility

Lithium ion battery storage is the most rapidly growing energy storage technology in the grid. The installed power capacity of large-scale (>1 MW) battery storage systems in the U.S. power grid has risen substantially over the last decade. According to U.S. Energy Information Administration electric generator inventory data, large-scale battery storage capacity grew from less than 100 MW operational in 2009 to over 1,000 MW in 2019 [24]. At the end of 2018, over 90% of large-scale battery installations used some form of lithium ion chemistry [25]. Lithium ion batteries are also the technology of choice for plug-in electric vehicles and have enjoyed similarly rapid growth in the automotive industry.

In general, automotive applications require more strenuous battery utilization patterns than grid services, and EV manufacturers typically recommend replacing batteries at 80% capacity. Motivated by the relatively high cost of lithium ion cells, researchers have suggested repurposing EV batteries for utility applications. Studies have shown that this "second life" concept could provide a low-cost source of batteries [26-28]. However, there are still technical issues to address, including logistics of repurposing, safety and reliability challenges of aged cells, and design requirements for the PCS.

As battery cells age, the variations between them grow. This means that in an aged batch of cells the difference between average batch capacity and the capacity of the weakest outlier cell is greater than in a fresh set. Since the weakest cell limits the capacity of a series-connected string, aging exacerbates scalability issues described in the previous section. Multi-scale PCS architectures relax voltage requirements and break storage systems into smaller independent units, providing more control over cell operating conditions. This flexibility provides much better support for second life storage than the single-stage approach. However, the additional cost of the second conversion stage is one of many aspects to the economic viability of second life batteries.

For some storage applications, it is difficult to meet both power and energy requirements using a single type of storage device. For instance, in situations that require both high power (to provide fast response) and high energy (to provide long duration support), it may not be feasible to satisfy all requirements with a single storage technology. One solution is to use a hybrid mix of storage technologies, each adapted to a specific response characteristic [29]. The PCS in a hybrid system would coordinate the response to ensure optimal utilization of each storage technology and would therefore control each type of storage independently.

From a PCS design perspective, hybrid storage and second life batteries are two instances of a larger problem involving support for mixed storage device configurations. Generally, a power electronic interface should support interconnection of—and extract the optimal performance from—any storage system regardless of chemistry, manufacturer, or state of health. Systems with different power ratings will require differently rated power converters. However, when storage devices must be replaced, whether due to damage or normal life-cycle conclusion, the process of replacement should involve as little hardware modification as possible and should not be subject to strict compatibility constraints. To achieve this functionality, a fundamental shift is needed in PCS design. In the conventional single-stage architecture, the storage system is designed around the limitations of the power electronics (e.g., the minimum necessary DC voltage constraint). However, due to the rapid development of power electronics technologies, constraints of storage devices now present the most significant limitations. In conceiving new power conversion solutions for energy storage, it is perhaps better reverse the traditional approach and design power conversion system capabilities around the limitations of energy storage.

4. Summary

Energy storage allows us to decouple power generation from consumption. This is a fundamental break from the operating principles of traditional power delivery systems and provides many new options for improving energy efficiency, reliability, and sustainability. If energy storage reaches its full potential, electric *power* delivery systems will be transformed into electric *energy* delivery systems, with primary sources—including non-dispatchable resources like solar and wind generation—providing energy when available and immediate power demands being met by the storage.

These benefits are enabled by power electronics, which provide the necessary power conditioning and control functionality to interface energy storage resources with the grid. This chapter has provided a basic description of the principles of power electronic conversion, implementation in real hardware, and typical application to utility-scale storage. Developments in the PCS are driven by new component technologies, such as WBG devices, and by increasing demand for storage systems of larger size and scale. Advancements in materials technology for both active and passive devices are key drivers of advancements in power electronics.

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