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Solid State Power Substation Roadmap

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1 Introduction

The nation's electric power system is comprised of more than 19,000 generators, 642,000 miles of high voltage transmission lines, and 6.3 million miles of distribution lines, serving 145 million customers.[1] Within this expansive system, there are over 55,000 transmission substations and thousands more of other types that serve as the critical interconnection points between generation, transmission, distribution, and customers (Figure 1). Given the ubiquitous nature and importance of substations, development of advanced substation technologies presents a tremendous opportunity to improve the electric grid's reliability, resiliency, efficiency, flexibility, and security, through new functionality, new topologies, and enhanced control of power flow and voltage.

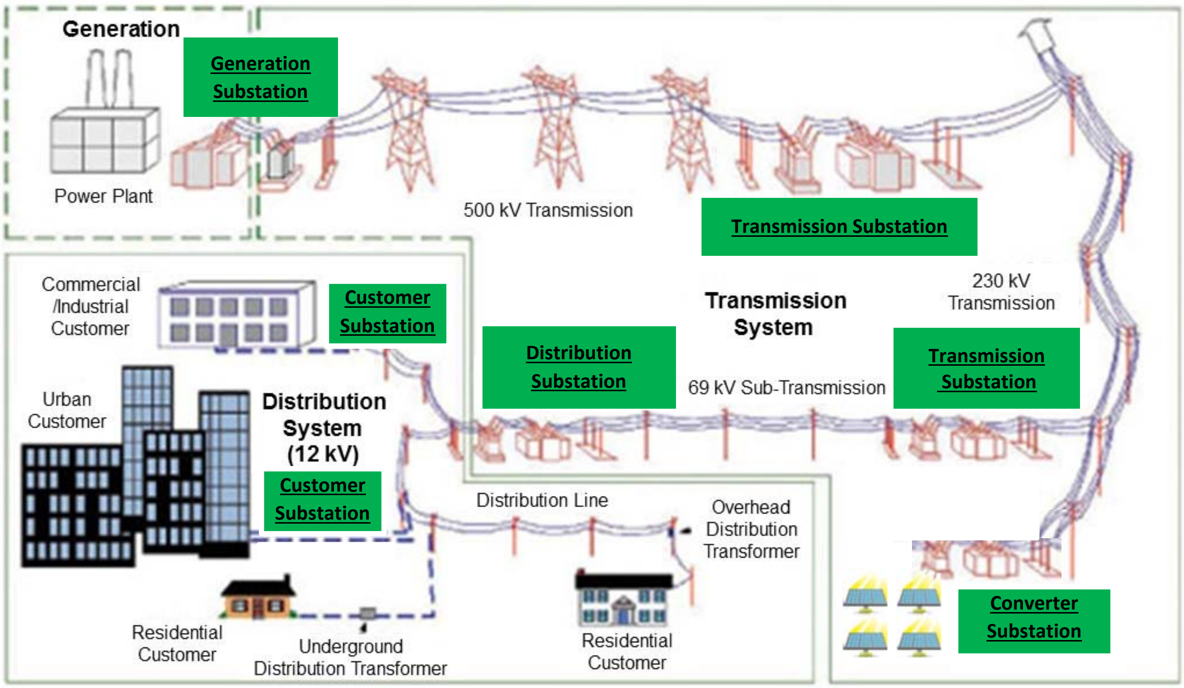

Figure 1: Electric Power System with Substation Types

1.1 Power System Trends

The electric power system is currently undergoing significant changes in the sources we rely on to generate electricity, the means by which we receive electricity, and even in the ways we consume electricity. Recent grid modernization efforts to address these changes mainly focus on integrating advanced data analytics, communication systems, and real-time monitoring and controls to improve the functionality and performance of the electric power system. However, these technologies do not address the full spectrum of advances needed without upgrades to the fundamental hardware components and systems that make up the electric delivery infrastructure.

As the system evolves, with greater deployment of variable and distributed energy resources (DERs), the potential for mass-market adoption of electric vehicles (EVs), and broader customer engagement in the generation and use of energy, physical limitations within substations will present challenges to the modernization of the grid. Additionally, increasing use of information and communication technology (ICT), aging infrastructure, and growing risks from a range of threats pose additional requirements for the next-generation of substations.

Substations with the strategic integration of high voltage power electronic converters, discussed from here on as Solid State Power Substations (SSPS), can provide advance capabilities and facilitate evolution of the electric power system. SSPS technology can overcome some of current limitations within substations by enabling control of real and reactive power flows, management of voltage transients and harmonic content, and the ability to increase the flexibility, resiliency, and security of the electric power system.

1.2 Roadmap Overview

This roadmap is structured to provide the context, rationale, and potential benefits of utilizing SSPS technology, and articulates a research and development pathway to accelerate maturation of SSPS. It aims to capture the state-of-the-art in critical enabling technologies, highlight research gaps and opportunities, and align disparate activities across the stakeholder communities to realize the SSPS vision.

Chapter 2 introduces the various types of substations considered in this roadmap, presents the various components that make up a substation, and discusses the current challenges they face and utility concerns. Chapter 3 discusses current grid-scale power electronic systems, defines SSPS technology more clearly, and explains their benefits. Chapter 4 highlights the envisioned technology development pathway and potential applications of SSPS technology while Chapter 5 frames the research needs and documents specific actions needed to move the technology forward. Chapter 6 summarizes the roadmap findings and articulates roles and responsibilities for various stakeholders.

2 Conventional Substations

Substations are essentially the on-ramps, off-ramps, and interchanges for electricity in the electric power "highway" that we call the grid. While a single term is used for these critical interconnection points, they are complex systems composed of many different devices and components such as transformers, circuit breakers, and control equipment.[2] Each substation is unique, balancing costs and components, to meet local electrical, power, control, and protection requirements such as system impedances and short circuit ratings. Their customized nature and integration complexities result in high engineering, planning, acquisition, construction, repair, and modification costs. In 2013, U.S. spending on turn-key substations alone was estimated to be $4.5 – $5 billion.[3]

While each substation is unique, there are several categories that can be identified based on their location and intended purpose as summarized in Table 1. Generally, they serve to connect different voltage levels and current types (i.e., alternating current (AC), direct current (DC)) within the grid to ensure seamless transfer of electric power. They all usually include some form of equipment and switchgear for electrical isolation and protection to deal with abnormal conditions, faults, and failures. However, the monitoring, control, and operation of a substation varies in sophistication, transparency, and accessibility depending on the application and the owner of the assets. For example, transmission and distribution substations are often heavily instrumented and operated by utilities in coordination with system operators, while customer and converter substations don't necessarily have the same requirements.

Table 1: Different Categories of Conventional Substations

Substation Category	Substation Types	Input	Output	General Purpose
Generation	• Generator Step-Up • Non-Inverter Based Renewables	Generation Facility	Transmission System	Connecting generator electric power output
Transmission	• Networked • Switching	Transmission System	Transmission or Sub-Transmission Systems	Ensuring reliability of electric power delivery
Distribution	• Step-Down	Transmission or Sub-Transmission Systems	Distribution System	Ensuring reliability of electric power delivery and regulating feeder voltage
Customer	• Industrial • Commercial • Campus • Building	Sub-Transmission or Distribution Systems	Customer Facility	Ensuring customer/ local power quality requirements and needs are met
Converter	• Inverter Based Renewables • HVDC/MVDC	Generation Facility or Transmission System	Transmission or Distribution Systems	Connecting generator electric power output or improving the efficiency of electric power delivery

2.1 Substation Components and Functions

In addition to the basic function of physically connecting different parts of the electric power system, substations also provide other important functions critical to the safe, reliable, and cost-effective delivery of electricity. As the electric power system changed over time with different generation technologies, different loads, and different system requirements, substations and their components have also evolved to provide advanced functions and features including:

- Stability control in steady state and transient conditions
- Power flow control to minimize system congestion
- More efficient delivery of power over long distances
- Sharing of power between asynchronous systems
- Monitoring to improve control, protection, and maintenance
- Voltage control for energy conservation and managing violations
- Increased reliability through surge protection and limiting fault currents

Due to the unique system characteristics, operating range, and functions desired in a particular substation, a variety of components, devices, and equipment have been developed by vendors with various ratings, styles, and capabilities to meet specific cost and performance requirements. This customized approach to substation design and the limited availability of standardized components lead to added complexity and increased costs. Table 2 provides a general list of substation equipment types, their basic function, and the category of substations that they would be used in.

Table 2: Substation Equipment and Functions

Equipment Type	Function	Substation Category
Arrestors	Limits the magnitude of voltage transients that can damage equipment by providing a path to ground once a voltage threshold is reached	All
Air-break Switches	Switching device used to reconfigure or isolate parts of the substation to allow for maintenance work	All
Capacitor Banks	Used to increase the voltage at a specific point in the grid and provide power factor correction through reactive power compensation	Transmission, Distribution, Customer
Circuit Breakers	Mechanical switches that automatically isolate circuits in emergency situations to prevent damage caused by excess currents	All
Control House	Provides weather protection and security for control equipment	All
FACTS Devices	Flexible alternating current transmission system (FACTS) alters system parameters to control power flows	Transmission
Fault Current Limiters	Limits excessive fault currents in the grid through injection of a large impedance to absorb the energy	Transmission, Distribution
Fuses	One-time safety devices which provide over-current protection by quickly isolating the system during emergency situations	Distribution, Converter, Customer
Power Electronic Converters	Converts AC power to DC power or vice versa	Converter
Instrument Transformers	Measures voltage and current at different points within a substation	All
Reclosers	Device used to detect, interrupt, and clear momentary faults	Distribution
Sectionalizers	Automatically isolates faulted sections of the distribution system	Distribution
Transformers	Step-up or step-down AC voltage levels	All

Equipment Type	Function	Substation Category
Protective Relay	Trips a circuit breaker when a fault is detected	All
Voltage Regulators	Maintains feeder voltage levels as loads change throughout the day	Distribution

2.2 Challenges in a Modernizing Grid

As the electric power system continues to change in response to the trends discussed in Section 1.1, the utility industry will face challenges and growing concerns. Several interrelated challenges that have direct implications for substations include accommodating high penetration of distributed generation, enhancing security and resilience to a number of hazards, ensuring reliable operations with rapid system changes, and making prudent investments in an environment of greater uncertainty.

2.2.1 Accommodating Distributed Generation

With greater adoption of solar photovoltaics (PV), combined heat and power (CHP) system, fuel cells, and other distributed generation technologies at residential, commercial, and industrial facilities, there are physical effects that impact the operation and maintenance of distribution substations and potentially customer substations. One of the biggest concerns is the back feeding of energy onto the distribution system, and potentially back into the transmission system. As shown in Figure 2, distribution substations are designed for the unidirectional flow of power from the transmission system to the distribution system. Reverse power flows or reduced power flows will impact relay operations and protection coordination (due to static settings), potentially leading to equipment damage or unsafe conditions during faults. Another issue is the potential for phase imbalances that can impact equipment performance.

The intermittency of PV presents another unique challenge since they can cause rapid voltage fluctuations along feeders. Load tap changers or voltage regulators located within distribution substation automatically respond to compensate for these fluctuations, leading to more frequent operation and higher maintenance costs. Additionally, solar PV inverters can introduce harmonics into the system that can potentially couple with substation equipment, such as capacitor banks, and result in unexpected behavior or early failure. Local power quality and power factor can also be impacted, requiring substation upgrades.

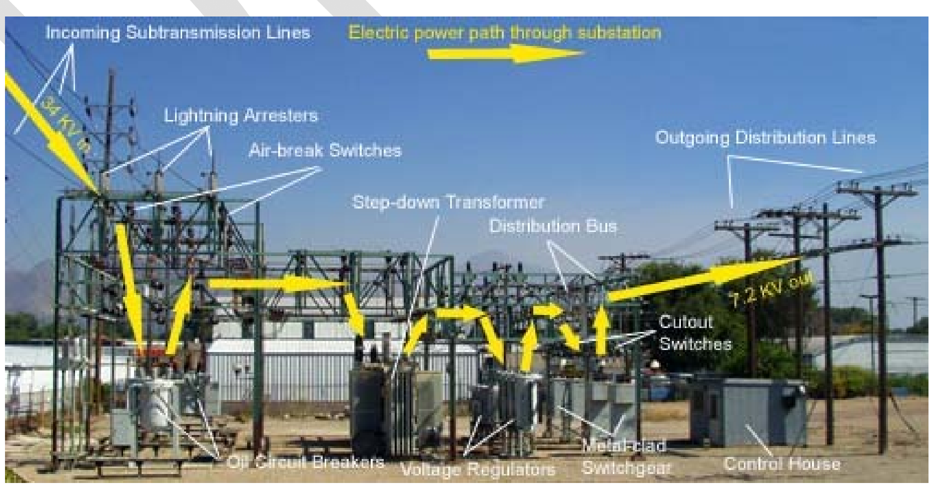

Figure 2: Power Flow and Equipment in a Distribution Substation[4]

2.2.2 Enhancing Security and Resilience

The greater utilization of advanced ICT in the electric power system has enabled improved monitoring, more efficient operations, and increase reliability. Broad deployment of phasor measurement units (PMUs) in transmission and generation substations has improved wide-area situational awareness and enabled a range of new applications such as detecting and preventing cascading outages. However, adoption of these technologies introduces new vulnerabilities to cyber-attacks and cybersecurity requirements will need to be included in substation designs. Physical security has also been a growing concern after the 2013 Metcalf substation attack where 17 transformers were severely damaged from sniper rifles. This incident resulted in demand for hardening technologies and increased security that will add to substation costs.

Additionally, as electricity becomes more vital to our digital economy and well-being, increased resilience to a range of natural and man-made threats has become a focal point. More frequent and extreme weather events can damage equipment within substations through flooding or debris. High-Impact, Low-Frequency events such as electromagnetic pulses (EMP) and geomagnetic disturbances (GMD) can permanently damage large power transformers (LPTs) in critical substations leading to wide-scale outages. The need to mitigate damage and rapidly recover from these incidents requires new considerations, designs, and technologies for substations as well as their components.

2.2.3 Ensuring Reliable Operations

Greater deployment of variable renewable resources, such as wind and solar, are introducing large and fast swings in power injection and voltages on the transmission system. The location of some of these facilities are often remote and connected to weak systems (i.e., low short circuit ratios) that require additional substation equipment or improved controls to ensure voltage stability and reliable system operations. Other changes in the location and type of generation, such as coal plant retirements and growth in natural gas combustion turbines, will alter system power flows and require new or upgraded transmissions lines and associated substations.

The changing generation mix is also resulting in the loss of system inertia (i.e., the kinetic energy associated with synchronized spinning machines), which means contingencies (e.g., generator or transmission line tripping off-line) will cause frequency disturbances that are much larger and faster. These deviations can trigger other protection actions within substations that could lead to outages. Greater customer adoption of loads with power electronic interfaces, such as variable speed motors, electric vehicles, and consumer electronics, is also reducing system inertia. They also tend to operate in a manner (i.e., constant power mode) that decreases the ability of the system to withstand disturbances. Substation upgrades may be needed to improve protection coordination and maintain system reliability during contingencies.

2.2.4 Making Prudent Investments

A majority of substation equipment, such as transformers and circuit breakers, will soon be past their design life and need to be replaced. As the power system changes, from potential load growth with EV charging to negative load growth with customer adoption of DERs and microgrids, and the potential need for substations upgrades for system reliability, utilities are facing a very difficult challenge with making prudent investments amidst the uncertainty. This challenge is exacerbated by the fact that changes to substations are not incrementally scalable; capacity upgrades generally require the wholesale replacement of many pieces of equipment. Customized components, interoperability, and backwards compatibility with legacy devices add to the integration challenge and increases costs. These large expenses must be carefully planned to ensure that the benefits outweigh the costs, and utility commission approval is received.

3 Solid State Power Substations

Solid state electronics, electrical switches based primarily on semiconductor materials, is responsible for launching the digital revolution and continues to transform numerous industries. In addition to enabling computers to perform a variety of tasks rapidly, solid state technology can also be used to control the flow of electric power. Technologies used for the control and conversion of electric power (i.e., from AC to DC, DC to AC, DC to DC, or AC to AC) is called power electronics and are critical for a range of applications. These power electronic converters are quite ubiquitous in consumer electronics, which operate at low voltages (< 240 V) and low power levels (< 500 W), while medium to high voltage applications have been much more limited due to technical challenges and high costs.

In light of the challenges facing the utility industry discussed in Section 2.2., this section examines the current state of power electronic technologies used in grid-scale applications and explores the opportunity space for SSPS, or the strategic integration of high voltage power electronic converters within substations. In addition to converting between AC and DC, power electronic converters can be designed and operated with advanced functions and features by leveraging the speed and controllability of the underlying solid state devices. Deployment of power electronic systems within substations can facilitate evolution of the grid by enabling better asset utilization, increasing system efficiency, enhancing security and resilience, and easing the integration of DERs and microgrids.

3.1 Grid-Scale Power Electronic Systems

Power electronic systems have been used in grid-scale applications since the 1920's, with mercury arc valves serving as the high-power switches, and have incrementally improved over time with the transition to solid state devices (e.g., thyristors, insulated gate bipolar transistors (IGBT)) in the 1970's. There are currently two main types of power electronic systems used in the transmission system, FACTS devices and HVDC. More recently, with the greater deployment of solar PV and battery energy storage, there has also been an increase in the number of inverters in the distribution system. While there has been significant interest in the concept of a Solid State Transformer (SST) for utility applications, they have largely remained in the research and development phase. Greater adoption of these power electronic systems face unique design and integration challenges, but one common barrier is the high costs.

3.1.1 Flexible AC Transmission System

FACTS devices are a collection of technologies defined as "a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability."[5] These power electronic systems are connected in series or shunt (parallel) with the power system to alter line impedances or inject reactive currents respectively to control AC power flows, provide voltage stability, transient stability, and damp power system oscillations. Depending on their configuration (e.g., shunt vs. series) and the technology used in the power electronic converters (e.g., thyristors vs. IGBT), their costs and capabilities can vary quite dramatically (see Table 3). Despite their benefits, deployment of FACTS devices has been limited due to their higher costs compared to more traditional reactive power compensation methods such as electro-mechanical switching capacitor banks. As the electric power system continues to change, there will be a growing demand for FACTS devices.

Table 3: List of FACTS Devices and Their Costs

FACTS Devices	Function	Costs
Static VAR Compensator (SVC)	Shunt based capacitor and reactor bank switching device	20 – 200 $/kVAr
Static Synchronous Compensator (STATCOM)	Shunt based device using voltage source converters (i.e., IGBT based topology) to emulate SVCs	200 – 500 $/kVAr
Thyristor Controlled Series Compensator (TCSC)	Series based device that controls the ratio of impedance of series capacitor and reactor banks	150 $/kVAr
Static Synchronous Series Compensator (SSSC)	Series based device using voltage source converters (i.e., IGBT based topology) to emulate TCSCs	Greater than STATCOM
Unified Power Flow Controller (UPFC)	Most versatile as a shunt and series based device; essentially a combination of STATCOM and SSSC	Combination of STATCOM and SSSC

3.1.2 High Voltage Direct Current

In general, HVDC systems are used in the grid for delivery of large amounts of power (e.g., greater than 500 MW) over long distances (e.g., greater than 300 miles). These power electronic systems consist of very large power electronic converters (see Figure 3) within substations that connect HVDC transmission lines. Due to the reactive power losses in AC transmission lines (overhead as well as underground), HVDC systems tend to be more economic despite higher losses in the converter substation and the higher capital costs compared to a standard AC transmission substation. Other applications of HVDC converters include back-to-back connections that enable sharing of power between two asynchronous systems, improving reliability and stability, and the creation of HVDC networks for improved system efficiencies, such as with off-shore wind farms.

There are currently two commercial HVDC converter technologies: line commutated converters (LCCs) based on thyristors and voltage source converters (VSCs) based on IGBTs. LCCs are more mature and have losses of about 0.7% per substation, while VSCs are newer and have losses of about 1.4%–1.6% per substation. While losses are higher for VSCs and their maximum rated power is smaller than LCCs, they enable simpler configurations that can reduce total system costs. VSCs require little to no filtering and no reactive power compensation, making them more compact which provide a value stream. Additionally, VSCs have black start capabilities, enable multi-terminal configurations, and are easier to deploy without complex studies and system reinforcements, unlike LCCs. These capabilities may become more important as the grid continues to evolve.

Figure 3: HVDC Converter Hall for 320 kV 2 GW VSC Transmission Link Between France and Spain

3.1.3 Grid-Tied Inverters

Inverters are the general term for power electronic converters that change DC power to AC power. These power electronic systems are critical to the function of PV systems and battery energy storage since they enable the electricity generated or stored to be injected back into the grid. Due to the greater demand for DERs, there has been cost-reductions and advancements for inverters used at customer facilities (e.g., rooftop PV). However, grid-tied applications such as utility-scale batteries, solar farms, and wind farms still require the use of a step-up transformer within the converter substation to connect to the distribution system or transmission system.

Currently, the majority of installed PV inverters operates at unity power factor and do not provide any support functions to the grid. While these converters are capable of sourcing reactive power, there is no incentive to do so since only real power is monetized at generation facilities. Enabling reactive power support requires having excess capacity on the inverter, adding to costs, or limiting real power generation, reducing economic returns. Additionally, existing standards require PV inverters to disconnect from the grid during a fault which can exacerbate power system instability during a contingency. Recent revisions to IEEE 1547 will enable these technologies to become more "grid-friendly" but there is an opportunity to more greatly expand their functionality to support evolution of the grid.

Development of smart inverters, converter systems with two-way communication capabilities and local intelligence, can mitigate problems associated with high penetration of DERs and be used to improve the operation of the distribution system through enhanced coordination and control. Smart inverter functions, such as power factor correction, can help regulate voltage at the point of interconnection as shown in Figure 4. More advanced functions such as the injection or absorption of reactive power will allow smart inverters to serve as small FACTS devices in the distribution system, helping to stabilize the grid and control power flows on networked feeders. The maturation of wide band gap semiconductor devices is also enabling inverters to directly connect to the distribution system without a step-up transformer.

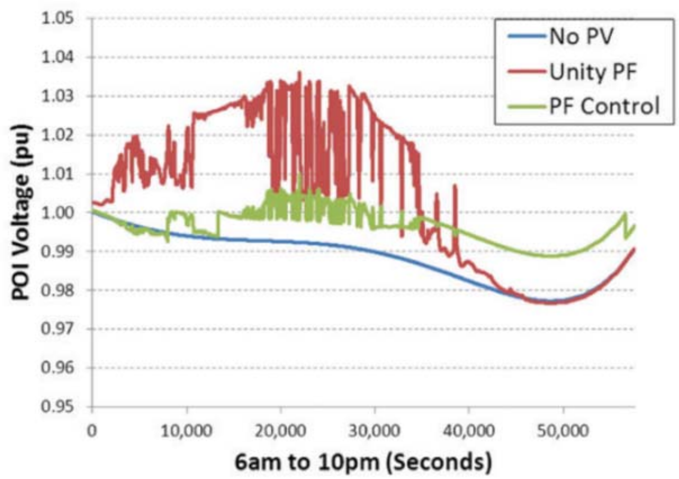

Figure 4: Power Factor Control with a Smart Inverter[6]

3.1.4 Solid State Transformers

Conceptually, a solid state transformer is a combination of power electronic converters coupled through a high frequency (HF) transformer to connect two different AC voltages (see Figure 5). The primary benefit of utilizing these technologies compared to a conventional line frequency (e.g., 60 Hz) transformer is that the HF link enables significant size and weight reductions at the same power rating. In addition to the increased power density, these power electronic systems can provide a range of capabilities depending on their design and configuration. Advanced functions and features include allowing bi-directional power flow, input or output of AC or DC power, active control of frequency and voltage, and improving power quality. These capabilities have implications for the adoption of microgrids, enabling seamless islanding and reconnections, and other advance system topologies such as hybrid grids (i.e., combination of AC and DC circuits).

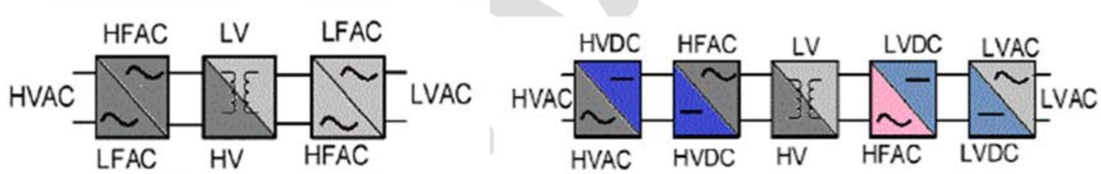

Figure 5: Different Block Diagrams for SSTs[7]

Despite their flexibility and potential benefit to grid-scale applications, SSTs developed to-date (Table 4) suffer from higher costs, lower efficiency, and lower reliability compared to a conventional transformer. In general, these power electronic systems cannot compete as a one-to-one replacement for utility transformers, especially within transmission substations. SSTs will need to be valued for the additional services and capabilities they can provide. Currently, the SST market is focused on traction applications due to benefits achieved from their high power density. However, technological advancements made for the transportation sector can be potentially leveraged for utility applications.

Table 4: Current SST Research Projects and Their Capabilities

Category Capability	NC State[8]	MEGAlink[9]	UNIFLEX[10]	EPRI[11] IUT	CREE[12]
Voltage	7.2kV/280V	10kV/400V	3.3kV/415V	2.4kV/480V	13.8kV/465V
Power Rating	20kVA	1MVA	300kVA	45kVA	1MVA
Mobility- Assembled in a Trailer	LARGE	LARGE	LARGE	LARGE	LARGE
Main Dielectric	AIR + MODULE	AIR + MODULE	AIR + MODULE	OIL	AIR + MODULE
Mobility- Modular Free Standing Outside	NO	NO	NO	NO	NO
Power Flow Unidirectional	YES	YES	YES	YES	YES
Power Flow Bidirectional	YES	YES	YES	NO	YES
Power Flow Control	NO	DC only	YES	NO	NO
Size > transformer	YES	SAME	?	Yes	YES
Cost ≈ STATCOM (>$100/kVA)	YES	?	?	YES	YES
Future Cost Trend	FLAT	Lower Cost	FLAT	FLAT	FLAT
Scalable/Flexible Power and Voltage	NO	NO	NO	NO	NO
Expandable Power	YES	YES	YES	YES	YES
Overload	YES	YES	YES	YES	YES
AC/DC	NO	NO	NO	NO	NO
Frequency Compensator	NO	NO	NO	NO	NO
Voltage Compensator	YES	NO	YES	YES	YES
VAR Compensator	NO	NO	YES	YES	NO
Power Quality Compensator	NO	NO	NO	NO	NO
Harmonics Compensator	NO	NO	YES	YES	NO
Efficiency	97%	97%	92%	96%	97%
Trip Free	high trip probability	high trip probability	high trip probability	high trip probability	high trip probability
MVDC or HVDC	NO	YES	NO	NO	MAYBE

3.2 SSPS Converters

Across the various power electronic systems used for grid-scale applications, the common technology is the power electronic converter. This critical component is responsible for enabling advanced functionality but is also the primary driver of high system costs. Design and development of a flexible, standardized power electronic converter that can be applied across the full range of grid applications can enable the economy of scale needed to drive down costs and increase reliability.

Ultimately envisioned as a modular, scalable, flexible, and adaptable power block that can be used within all substations, SSPS converters will serve as power routers or hubs that have the capability to electrically isolate system components and provide bidirectional AC or DC power flow control from one or more sources to one or more loads - indifferent to magnitude and frequency. SSPS converters will also include functional control, communications, protection, regulation, and other features necessary for safe, reliable, resilient, and cost-effective operation of the future grid.

Due to the range of challenges associated with the development and adoption of new grid hardware technologies, achieving the vision articulated for SSPS will require a staged approach that incrementally broadens the application space of SSPS converters. For each potential application, the enhanced functions enabled by SSPS converters must provide benefits that outweigh their costs. As such, three classifications of SSPS have been identified, designated as SSPS 1.0, SSPS 2.0, and SSPS 3.0, which mark milestones in the technology maturity. Each classification is based on the voltage and power ratings of the SSPS converter, as well as on defining feature and functions along its development pathway. The progressive advancement of SSPS sophistication is outlined in Table 5.

Table 5: SSPS Classification and Defining Functions and Features

	Defining Functions and Features
SSPS 1.0 25 kVA – 1 MVA Up to 34.5 kV	• Provides reactive power compensation • Provides voltage and frequency control • Capable of bi-directional power flow • Allows for multi-frequency systems (i.e., AC and DC) • Capable of riding through faults and disruptions (e.g., HVRT, LVRT)
SSPS 2.0 25 kVA – 100 MVA Up to 230 kV	+ Capable of serving as a communications hub + Enables system coordination of fault current and protection + Provides bidirectional power flow control between transmission and distribution + Enables distribution feeder islanding and resynchronization
SSPS 3.0 All Power Levels All Voltage Levels	+ Distributed control of multiple SSPS for global optimization + Autonomous control for plug-and-play features + Provides black start support and recovery coordination + Enables fully decoupled, asynchronous systems

SSPS 1.0 is expected to involve applications at distinct, locally controlled substations, such as industrial customers or community distributed generation facilities at the edges of the grid. Applications at lower voltage levels (up to 34.5 kV) and power ratings (up to 1 MVA) presents less of a concern to broader system reliability, and enables the foundational functions and features of SSPS converters to be developed. Improved controls, increased power density, and multi-frequency capabilities of SSPS 1.0 are critical to establishing initial value for this technology.

SSPS 2.0 is envisioned to expand on the capabilities of SSPS 1.0, increasing the voltage level (up to 230 kV) and power ratings (up to 100 MVA) of the converter. This classification includes the integration of enhanced communication capabilities, extending applications to distribution substations and utility-scale generation facilities. As SSPS applications broaden and move towards the transmission system (i.e., away from the edges of the grid), the communication capabilities is critical for coordination with downstream protection and control actions to ensure reliable system operations.

SSPS 3.0 is the final classification and denotes when SSPS converters can be scaled to any voltage level and power rating, spanning all possible applications. The key features of SSPS 3.0 are the autonomous, distributed controls, which enable system-wide coordination of SSPS converters across transmission and distribution for enhanced benefits, and black start capabilities. The availability of SSPS 3.0 will enable a fundamental paradigm shift in how the grid is designed and operated, with the potential for grid segments that are fully asynchronous, autonomous, and fractal.

3.3 SSPS Benefits

SSPS converters provide a means to reach the goals of a modernized grid: increased resiliency, reliability, and flexibility. There are a range of benefits associated with the use of SSPS technology, as envisioned, that can address many of the challenges identified in Section 2.2. Utilization of SSPS converters within substations can:

- Increase energy efficiency by optimizing between AC and DC topologies to minimize losses and reducing the no-load losses associated with conventional transformers
- Improve power quality and system operations through the ability to inject and absorb reactive power and fast, dynamic control of frequency and voltage
- Increase asset utilization and system optimization through power flow control, managing system peaks, and through enhanced monitoring capabilities
- Enhance protection and system reliability through fault current mitigation, the ability to rapidly isolate and stabilize faulted parts of the system, and the provision of essential reliability services
- Simplify and reduce the costs of capacity expansion and upgrades due to the modular, scalable, flexible, and adaptable nature of the converters, higher energy densities, and integrated functions
- Increase security and resilience due to the modular, standardized designs that reduces criticality, built-in cyber-physical security, and black start capabilities
- Enable new grid paradigms such as greater use of DC topologies, operating substations like an energy router, and novel business models including differentiated quality of service

Despite the benefits listed, potential deployments of SSPS converters must have advantages that outweigh their costs. The adoption of SSPS should evolve by progressively upgrading substations as opportunity affords; through replacement of outdated or failed components, as a means to upgrade functionality and capacity to meet new requirements, and through new substation installations. Deployment opportunities for the three SSPS classifications are discussed in the next chapter, highlighting the potential "market-pull" that can support advancement of SSPS technology.

4 SSPS Technology Development Pathway

With the growth in DER penetration, increased demand for energy storage technologies, and the need for greater flexibility to accommodate variable renewable generation, these power system changes serve as opportunities to advance SSPS technology. These demands, in addition to load growth around the world, are driving advancement in power electronic systems for transmission (e.g., HVDC and FACTS devices), including new converter topologies, advanced controls, and higher voltages. Simultaneously, advances are being made with smart inverters at the distribution level through adding enhanced functionality and enabling connections to higher voltages. Aligning these development efforts and charting a path where progressive deployment of SSPS converters across the range of substation applications can help mature the technology as illustrated in Figure 6.

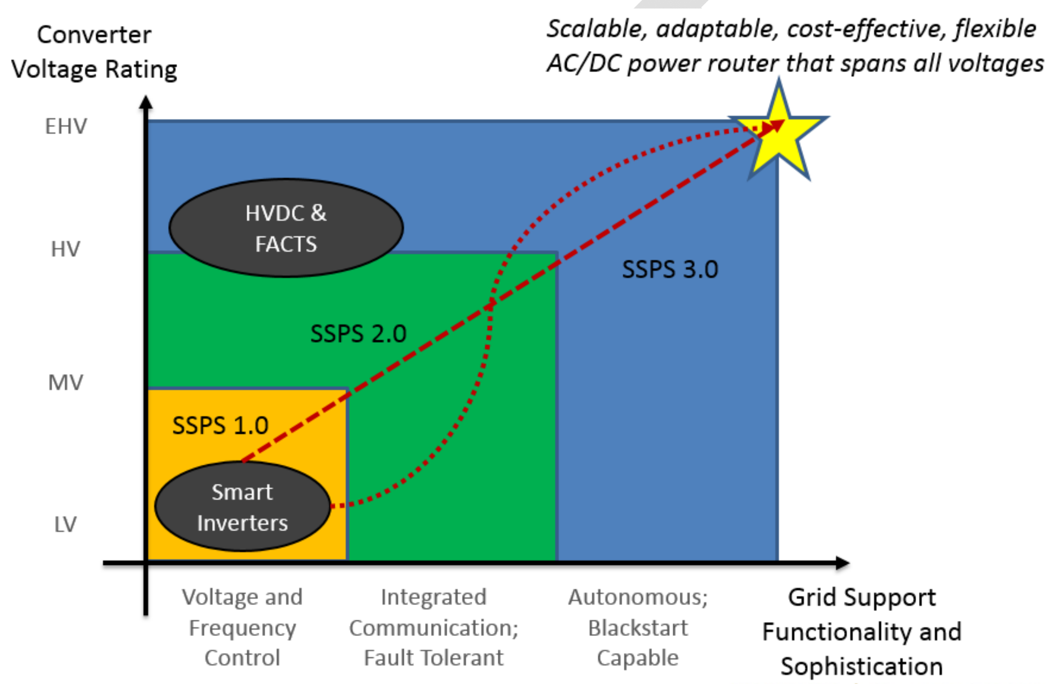

Figure 6: SSPS Technology Development Pathway

4.1 Potential Applications of SSPS 1.0

Opportunities to deploy SSPS 1.0 involve the use of power electronic converters for local or grid edge applications, including adding new functionality and supporting greater penetration of DERs. These lower voltage and lower power applications can be more easily deployed since they present less of a challenge to grid stability if they fail. These applications, primarily within customer or converter substations in the distribution system, are where enhanced control and flexibility from SSPS technology can provide benefits. Examples include the provision of grid support services, regulation of power quality (e.g., sags, swells, and harmonics), balancing loads across phases on 3-phase feeders, active power factor correction, voltage and frequency regulation, and the isolation of faults.

The growing demand for energy efficiency and increased resilience for data centers, buildings, campuses, manufacturing facilities, and homes also present a large opportunity for SSPS 1.0. The multi-frequency capability can more efficiently integrate disparate sources and loads, enabling more optimal designs and configurations such as a DC data center and Net-Zero homes. Other applications include simplifying the integration of DERs, such as solar PV, batteries, and responsive load, to maximize efficiency and provide enhanced controls to meet customer or local power needs.

Enhanced local control capabilities can also be extended to nanogrid or microgrid applications since SSPS converters can serve as the point of common coupling to the electric grid. Other than enabling two-way power flow control, it can rapidly isolate faults on the customer side of the meter to mitigate impacts on medium voltage feeders or the distribution system. SSPS 1.0 can also be used to form remote microgrids for military applications (i.e., forward operating based), in developing countries, or in rural communities that can eventually be scaled depending on power needs or load growth.

4.2 Potential Applications of SSPS 2.0

A majority of opportunities to deploy SSPS 2.0 are the same as SSPS 1.0 but at higher voltage levels and power ratings, such as microgrids and the integration of battery energy storage with variable renewable resources at the utility scale to make them more dispatchable. However, there are a few new applications for SSPS 2.0 associated with the extension of capabilities that help with managing system complexity and ensuring existing assets continue to provide value as the system evolves. The integrated communication capability is one of the highlights of SSPS 2.0 since it enables regional control and coordination of fault protection, which is critical with broader deployment of SSPS technology across the grid.

One of the new value propositions of SSPS 2.0 is that it can serve as an integrated smart node within the transmission and distribution systems. The localized communication and intelligence can help to address concerns around scaling challenges, particularly with the coordination of an increasing numbers of DERs and active consumers throughout the distribution system. This capability can also be leveraged to analyze distributed sensor data, manage system topology changes, and facilitate restoration and recovery after man-made or natural events. An additional application includes the ability to provide asset monitoring services to extend equipment lifetimes.

Another set of applications are associated with the higher voltages and power ratings that enable SSPS converter deployment within transmission and distribution substations. These applications help increase the reliability and flexibility of the grid, mainly through FACTS-like functions to improve controllability in responses to disturbances and power flow control capabilities to improve asset utilization. SSPS 2.0 can also help manage reverse power flows into the transmission system from the distribution system due to higher DER penetration, limit fault currents at this interface, and potentially remove the need for down-stream circuit breakers in distribution substations.

SSPS 2.0 can also enable some new paradigms for the grid such as MVDC in the distribution or sub-transmission systems. MVDC systems can be used to create links between distribution substations to route power in emergency situations and provide a better-balanced system, or in enabling DC distribution feeders to reduce power losses and increase power delivery. The integrated communications can also be used to coordinate the control of networked microgrids and enabling the islanding and resynchronization of these systems up to the distribution substation. Another potential application is for mobile substations, augmenting current designs or enabling advanced designs due to the high power density, functionality, and communication capabilities of SSPS 2.0.

4.3 Potential Applications of SSPS 3.0

Since SSPS 3.0 expands on the capabilities of SSPS 2.0, a majority of opportunities to deploy SSPS 3.0 are the same as the prior classifications but now at any voltage level or power rating. Key new features include autonomous controls, black start capabilities, and coordination of multiple SSPS converters across the entire electric power system. At this point, SSPS converter development should reach the envisioned end-state, a scalable, flexible, and adaptable energy router or hub, and the technology should be cost-effective, proven, and trusted to enable several new applications and grid paradigms.

The autonomous and distributed control capabilities of SSPS 3.0 can make the electric power system behave more like modern communication systems, enhancing reliability and resilience. New functions and features enabled include dynamic routing of power flows, graceful degradation and rapid isolation during disruptions or failures, automated recovery and blackstart coordination after outages, and true plug-and-play functionality that adjust settings when new generators, loads, or components are connected. These capabilities can enable a new grid paradigm based on an asynchronous and fractal topology, new business models such as differentiated quality of service, and other concepts that have yet to be identified.

More discrete applications of SSPS 3.0 include replacement of valve halls in existing HVDC systems or the creation of multi-terminal MVDC and HVDC networks that can augment the HVAC backbone we have today. It is also possible to replace LPTs in critical substations with more modular designs that can reduce their criticality, increasing resilience. The high power density of SSPS 3.0 can also be used to create substations with smaller footprints, indoor substations, or underground substations to increase their physical security.

5 SSPS Technology Challenges, Gaps, and Goals

In addition to the deployment opportunities identified in Chapter 4, there are also many R&D challenges that must be addressed to advance SSPS technology. These challenges are grouped into three categories, Substation Application, Converter Building Block, and Grid Integration, and their associated goals are summarized in Table 6. The goals reflect functions, features, or targets that must be achieved to realize each classification of SSPS technology and are color coded to provide an indication of the resources or level-of-effort needed to close the gaps.

Green reflects that current R&D activities are sufficient to achieve goals and that modest efforts will be needed to integrate advances into SSPS technology. Yellow reflects that current R&D activities are making progress towards goals but could benefit from additional resources and intentional focus towards SSPS applications. Red reflects that current R&D activities are insufficient to achieve goals and will require substantial effort and dedicated resources. These determinations were made from assessing the state-of-the-art and the gaps identified in the following sections.

Table 6: Technology Challenges and Goals for SSPS

		SSPS 1.0	SSPS 2.0	SSPS 3.0
Category	**R&D Challenges**	**Goals**		
Substation Application	Power Converter Architecture	Modular, flexible, and scalable for various applications with high reliability		
	Converter Controller and Communications	Local Controls; Basic Plug-and-Play	Grid Forming & Synchronization; Wide Area Connectivity	Autonomous/AI & Distributed Controls; Peer-to-Peer
	Converter Protection and Reliability	Fault and Over-Voltage Tolerant; Withstand EMI and meets BIL; Manages Inrush/Fault Currents		Adaptive/Dynamic; Self-Healing
	System Costs and Performance	< \$150/kVA > 96% 5 MW/m^3 10 Year MTTF	< \$125/kVA > 96.5% 10 MW/m^3 20 Year MTTF	< \$100/kVA > 97% 20 MW/m^3 40 Year MTTF
Converter Building Block	Module Costs and Performance	< \$20/kVA > 97% 2.5 W/cm^3 2 Year MTTF	< \$15/kVA > 98% 5 W/cm^3 4 Year MTTF	< \$10/kVA > 99% 10 W/cm^3 8 Year MTTF
	Drivers and Power Semiconductors	1.7 kV \$0.1/kW	3.3 kV \$0.1/kW	10 kV \$0.1/kW
	Dielectric, Magnetic, and Passive Components	160 kV/mm 0.1 H/m 6.0x10^7 S/m	600 kV/mm 1.0 H/m 1x10^8 S/m	2000 kV/mm 2.0 H/m 1.5x10^8 S/m
	Packaging and Thermal Management	> 500 W/(m^2°C)	> 1000 W/(m^2°C)	> 10,000 W/(m^2°C)
Grid Integration	Grid Architecture	Distribution Platform Paradigm	Asynchronous, Fractal, and Multi-frequency Paradigm	
	Grid Control and Protection Systems	Coordinates with Existing Protection	Dynamic Fault Detection and Adaptive Protection	Graceful Degradation & Blackstart
	System Modeling and Simulation	Tools and models capable of analyzing advanced controls, power flows, short circuit, faults, power quality, dynamics, and transient stability		

5.1 Substation Application

Deployment and integration of SSPS converters within substations is where the value and benefits of SSPS technology can be realized. As envisioned, these converters should be designed and configured to perform multiple functions, and have the flexibility and adaptability to be utilized in a range of substation applications. Aspects to consider and balance include physical and cyber connectivity, interoperability with legacy equipment, capital and operating and maintenance costs, and system reliability in the field. Several R&D challenges associated with substation application include power converter architectures, converter controllers and communication platforms, converter protection and reliability, and overall cost and performance. These challenges are inter-related and will need to be addressed holistically. Actions needed to close the gaps in the near-term (within 5 years), mid-term (within 10 years), and long-term (within 20 years) are identified at the end of this section.

5.1.1 Power Converter Architecture

Since power converters are at the core of SSPS technology, it is very important to ensure their designs are able to meet operating requirements across a range of applications. Architectures for SSPS converters will need to be capable of expanding functionality, scale-up in power and voltage ratings as needed, and be compatible with new and legacy components. Other features that need to be considered include multi-frequency inputs and outputs, bi-directional power flows, galvanic isolation, self-protection and system reliability under non-ideal and faulted conditions, reconfigurability of components, and integration with controls and communications. Envisioned as consisting of modular building blocks, module voltage and power ratings, module subcomponents, and the replacement and upgrade of modules will also need to be considered within the converter architecture.

5.1.1.1 State of the Art

The modular converter concept has been around since the late 1990's, driven primarily by R&D funded through the Office of Naval Research. Since then, the Power Electronic Building Block (PEBB) concept has continually advanced to meet various electric ship applications. Extension of this concept to electric grid applications was explored by the IEEE in 2004, with a generic architecture shown in Figure 7, but only limited progress has been made to unify across applications.

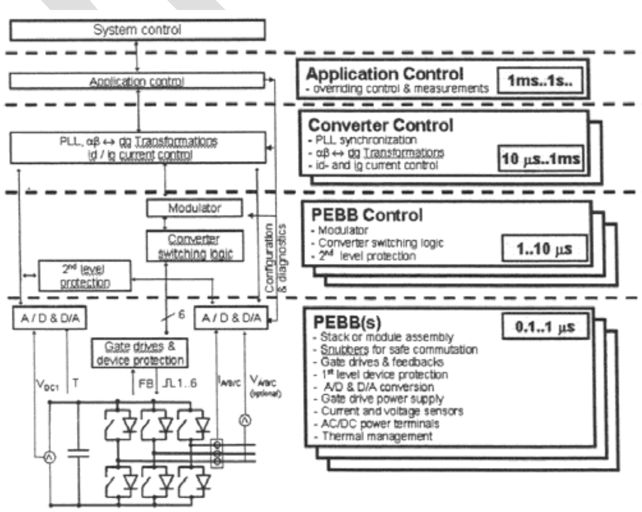

Figure 7: Generic Control Architecture with Power Electronic Building Blocks[13]

On the other hand, multi-level converter topologies have been making advances in grid applications since they enable lower common-mode voltages, reduced harmonic content, smaller input and output filters, increased efficiency, and can be fault tolerant. Table 7 lists several popular multi-level topologies used in applications today, but not all support the desired modularity of SSPS converters. Modern HVDC systems have leveraged modular multi-level topologies to enable scalability and greater flexibility, and vendors have been exploring applications to FACTS devices. Recently, there has been research in adopting this topology to solar inverter and battery converter applications as well.

Table 7: Multi-level Converter Topology Overview[14]

Multi-level Topology	Control	Voltage Balance Control	Modular	Major Disadvantage
Neutral Point Clamped	Simple	Unattainable	No	Systems with more than 3 levels have voltage balance problems
Flying Capacitor	Complex	Complex	Yes	Require large # of capacitors for high voltage outputs
Cascade H-Bridge	Simple	Simple	Yes	Number of components reduces efficiency
H-Bridge NPC	Complex	Complex	Limited	Complex control and modulation
3-Level Active NPC	Complex	Complex	No	# of clamping diodes increases with output level squared
5-Level Active NPC	Complex	Complex	Yes	Complex Circuit
Transistor-Clamped	Simple	Complex	Yes	Large # of transistors
Modular Multi-level	Complex	Complex	Yes	Complex Control

5.1.1.2 Research Gaps

Critical research is needed in the development of a flexible, adaptable, and scalable converter architecture that can span multiple grid applications, promote standardization, and meet the defining features for SSPS technology across all three classifications. The architecture established should promote innovation in the different subcomponents, especially with the power electronic building blocks, and enable backwards compatibility so modules of different generations are interoperable as technology improves. Other desirable characteristics include the ability to "hot-swap" modules, some degree of redundancy for high reliability, and direct connection to all voltages (i.e., 60 Hz transformer unnecessary). Research in novel converter topologies that leverage advances in semiconductor devices, controls, and new materials can also lead to improvements in overall converter performance.

5.1.2 Converter Controller and Communications

The converter controller serves as the "brains" of the converter system, managing the functions of and interactions between subcomponents, especially the modular building blocks. It also translates higher-level control signals into individual actions to meet application objectives, including balancing between local and global needs. Communication technologies are also vital to SSPS functionality since they enable connectivity and coordination with other substation equipment and the broader electric power system. As such, interoperability and cybersecurity must be included in this facet of SSPS technology development.

SSPS controllers should be programmable, in a secure manner, to allow for upgrades and customization for different applications. At a minimum, these controllers and communications (local and wide area) should enable plug-and-play features, such as auto-discovery and auto-configuration in response to other technologies and equipment connected to the same system. Localized intelligence coupled with sensing and measurement of local and internal parameters can enable more complex interactions and features such as diagnostics and self-protection. Additional capabilities include dynamically switching between grid support and grid forming modes as needed, under both normal and abnormal conditions, being able to operate in both grid-connected and islanded environments, and facilitating resynchronization of different parts of the grid.

5.1.2.1 State of the Art

Controllers for FACTS devices and HVDC systems are fairly mature, using well established techniques and algorithms, for basic functionalities such as reactive power compensation and setting the direction of power flows. However, new controllers are being developed for HVDC systems that enable grid support functions in addition to managing power transfers, including frequency response and voltage support. There have also been advances with rooftop PV inverters with plug-and-play functionality to help lower installation costs and research into smart functionally to enable grid support. Research in vehicle and grid-scale batteries has also led to controllers that monitor the health and state of individual cells to optimize charging and discharging operations.

Microgrid research has led to the development of several controllers with differing levels of sophistication to coordinate the operation of a variety of resources (e.g., PV, batteries, CHP) in order to meet objectives, such as ensuring local system reliability and safety. For example, the CERTS[15] microgrid controller leverages plug-and-play and peer-to-peer concepts to avoid the need for a master controller, operating autonomously to maintain frequency and voltage. Meanwhile, the CSEISMIC[16] microgrid controller has more advanced functions and can facilitate interactions with the broader electric power system, enabling multi-objective optimization. There has also been research to advance technologies that support creation of nanogrids within buildings. VOLTTRON[17] is an open-source software platform that was developed to facilitate coordination and control of various loads and energy resources within a building.

Grid-related communication technologies have continued to develop incrementally, leveraging advances made in the broader ICT industry. While the protocols for these technologies are fairly well-defined for both wired (e.g., Modbus, DNP3, and IEC 61850) and wireless (e.g., Bluetooth, ZigBee, LTE, RFID, and INGENU) networking, their application to grid technologies has been less consistent. This diversity allows for innovation but also brings challenges with interoperability and system integration. Additionally, the costs associated with these communication technologies still present challenges to broader adoption. On-going research focuses on developing low-cost communication platforms that can be used in a variety of utility and non-utility applications.

5.1.2.2 Research Gaps

Close coordination between converter architecture development and the controller and communications capabilities is critical to ensure that SSPS can allow for expandability and growth as technology evolves, especially in the ICT industry. Additionally, development of new control algorithms will need to consider the impact of communication delays and be flexible to the range of technology choices and protocols. The need for cybersecurity, possibly down to the chip-level (e.g., FPGA, ASIC, microcontroller), and the ability to withstand electromagnetic interference (EMI) and electromagnetic pulses (EMP) will need to span both converter architecture as well as the controllers and communications.

Development of SSPS controllers that can be coordinated solely through peer-to-peer communications and distributed intelligence will require substantial investigation. This is especially critical to enable the control and coordination of system recovery, including blackstart conditions, with limited communications or the loss of system wide control. Advanced autonomous control should be able to prioritize loads, fragment the system, and form microgrids during a contingency or emergency to sustain operations. Research in artificial intelligence, distributed intelligence, and self-learning can be used to improve SSPS performance and response for enhanced reliability and resilience. It is important that advances in controller algorithms and embedded intelligence are made in concert with the broader system architecture, especially in new grid paradigms such as multiple micro-grids connected asynchronously.

Advance controller functions will depend on SSPS having situational awareness of internal and external conditions independent of information from other systems (e.g., SCADA). Development of sensors that can measure the local parameters of interest, at the required bandwidth and within the SSPS operating environment, will be needed for this feature. Additionally, low-cost, secure, and robust communication platforms that can be integrated and upgraded with SSPS converters in a modular fashion is also needed. These technologies should be able to operate in emergency situations, and handle a range of data and timing needs depending on the application as SSPS technology evolves.

5.1.3 Converter Protection and Reliability

For SSPS technologies to be deployed in substations, they will need to offer the same degree of reliability and robustness as conventional substation components. SSPS converters will be exposed to high voltage transients, fault currents, inrush currents, lightning strikes, power surges, and a range of other abnormal conditions that can damage or negatively impact power electronic systems. Additionally, grid protection technologies (e.g., fuses, relays, circuit breakers) have been designed around high fault currents for proper operation. SSPS converter protection will need to withstand these conditions and be able to operate in a manner that is compatible with existing protection schemes.

In addition to operating through the full range of non-ideal electrical phenomena, SSPS converter should be able to fail gracefully (i.e., operate with degraded performance instead of failing catastrophically) and maintain basic functionality during catastrophic failures (i.e., fail-normal). They will also need to manage or supply very large currents, orders of magnitude higher than steady-state operations, for short durations to meet system demands from faults and inrush currents. Ideally SSPS converters should be self-healing, possessing the ability to detect degraded or damaged states autonomously and initiate actions to return to a normal state or adapt dynamically.

5.1.3.1 State of the Art

Protection of grid-tied converters currently revolves around managing over-currents and over-voltages beyond their designed operating rating. Generally, these converters disconnect or isolate the sensitive power electronic devices from the power source (e.g., grid, energy storage, generator) when adverse conditions are detected. Industry standards are also used to inform the operation of these systems under abnormal conditions to ensure safety, which are incorporated into controller algorithms. Recently, issues encountered with PV inverters tripping-off during system faults have led to updates requiring low-voltage and high-voltage ride-through capabilities. Other technologies that help protect converters from damage include surge arresters, metal oxide varistors, and spark gaps in over-voltage conditions, and fuses, relays, and contactors to detect and isolate components in over-current conditions.

Increasing converter reliability has focused around design principles and standards, such as basic impulse level (BIL) ratings, to ensure the system can withstand surge voltages, transients, and statistical failures.

Physical shielding and component layout can also be used to mitigate the impact of undesirable effects such as EMI. Power electronic systems also include filters or snubber circuits to minimize the impact of abnormal conditions. Finally, introducing redundancy in the converter architecture, utilizing de-rated power electronic devices, and having internal monitoring are other practices that improve reliability.

Advances in handling inrush currents have been more limited. This functionality is usually accomplished by intelligent controls on the load side, such as soft starting, or having capacitors to provide the necessary energy on the grid side, especially during fault recovery conditions. Advances in this area are primarily driven by electronic motor drive and HVDC system applications.

5.1.3.2 Research Gaps

SSPS technology cannot operate like a traditional converter; it must ensure that grid needs are met before it protects itself. Research is needed to holistically examine the design, control, and protection of SSPS converters to manage fault currents of 5 kA to 65 kA at high voltages, as well as the inrush currents needed to charge transformers and other inductive loads. Simply increasing the power rating of the converter is not a pragmatic solution as it will be prohibitively expensive. Some degree of programmable fault control is also desirable. Advances in converter protection and reliability will need to be made in concert with the overall converter architecture.

Research is also needed in a range of topics to enable self-healing capabilities. For example, innovation in dielectrics, conductors, and other materials that can repair itself when exposed to stresses can extend the lifetimes of SSPS components. Development of advanced converter controls that could intelligently and dynamically reallocate operational stress across SSPS modules and enable hot-swapping of modules (e.g., replacement without shutting the system down) will also enhance reliability. Assessing and understanding the range of failure mechanisms in SSPS technologies is also a fundamental need in advancing converter protection and reliability.

5.1.4 System Costs and Performance

In addition to the SSPS converter building blocks envisioned, there are other components and auxiliary system that make up the final converter to be used in a particular substation application. These additional pieces of equipment, such as filters, protection devices, structural encasements, communications, and thermal management systems, impact the overall cost and performance of SSPS technologies. As such, it is important to consider them in the design and implementation of the SSPS application, including integration into new and existing substations. To gain industry acceptance, SSPS converter will have to be competitive with current solutions based on capital, installation, operating, and maintenance costs.

5.1.4.1 State of the Art

Increasing deployment of renewable resources and DERs has generated the demand to help decrease the cost of inverters through economy of scale. However, these converters do not connect directly to grid voltages and rely on a conventional transformer. Recent advances have looked at utilizing wide band gap (WBG) semiconductor devices to increase system efficiency, removing the need for a step-up transformer, and enabling a smaller footprint to justify the price increase. Other inverter advances such as plug-and-play functionality and ensuring interoperability helps to lower installation and integration costs.

However, large grid-scale power electronic systems (e.g., FACTS devices and HVDC system) remain fairly customized and detailed engineering and design studies are needed to assess trade-offs between cost and performance. Current industry trends towards more modular components, standardized specifications, and parts that are commercially off-the-shelf help to drive down the cost of ownership. In addition to lowering capital costs, these trends help to reduce down-time during maintenance, leading to savings.

5.1.4.2 Research Gaps

Research is needed in understanding and defining the design space for SSPS converters. Establishing a framework to assess the cost, performance, and complexity trade-offs of different converter architectures is critical to optimizing the design for the broadest set of application. Development of design tools, multi-physics models, and more accurate models that can be used to evaluate different combinations of modular building blocks, auxiliary components, layouts, and operational modes will be important to move SSPS technology forward.

Consideration of externalities, such as price reductions from manufacturing at scale, and statistical failure of components can improve the capabilities of SSPS design tools. Meanwhile, prototyping, reliability testing, component characterization, hardware-in-the- loop testing, and field validations will be needed to improve the fidelity of the models.

5.1.5 Near, Medium, and Long-Term Actions for Substation Applications

Advances in substation application will require heavy involvement from utilities to ensure that the target applications are valuable to the industry. However, the value of these applications will vary by region because of the multi-faceted diversity in the U.S. electric power system. SSPS converters should have the flexibility and adaptability to span the range of regional differences.

In the near-term, research needs to focus on developing a power converter architecture that balances cost and performance that would allow for widespread applications. Advances in local controls and plug-and-play functionality developed in DER and microgrid applications should be integrated with SSPS. Design work will also be needed to ensure SSPS converters can to handle fault currents, over voltage conditions, and other abnormalities typically experience by traditional equipment. Finally, prototyping and power hardware-in-the-loop testing is required before SSPS operation can be validated in the field.

In the mid-term, new SSPS applications will require more advanced converter controllers that allow these systems to switch between grid-forming and grid-supporting modes. Additionally, these systems will need a higher degree of reliability and robustness to be deployed in distribution substations. Low-cost communication capabilities will also need to be developed and integrated into SSPS for more advanced features. As before, upgraded SSPS converters will require prototyping, power hardware-in-the-loop testing, and controller hardware-in-the-loop testing to build confidence in the new capabilities.

In the long-term, advances will be needed in artificial intelligence to enable autonomous distributed control between multiple SSPS converters for system wide application. Additionally, advances in self-healing materials and localized intelligence will be needed to increase SSPS converter reliability beyond simple n+1 redundancy. At this point, there should be a sufficient track record for SSPS technology development to expand applications to the highest voltage and power levels.

5.2 Converter Building Block

SSPS technology is based on power converter building blocks that are flexible, adaptable, and scalable to allow for different configurations and multiple applications. These modules are critical to the success of

SSPS converters so their design, performance, and costs must be coordinated with the broader converter architecture development. Aspects to consider include identifying which requirements at the substation application level will need to cascade down into the building block level, and which do not. This demarcation would enable innovation, allowing converter building blocks designs with different internal components and layouts to be compatible and interoperable as long as high-level cost, performance, and design requirements are met. Several R&D challenges associated with converter building blocks include module costs and performance, drivers and power semiconductors, dielectric, magnetic, and passive components, and packaging and thermal management. Actions needed to close the gaps in the near-term (within 5 years), mid-term (within 10 years), and long-term (within 20 years) are identified at the end of this section.

5.2.1 Module Costs and Performance

Overall module cost and performance is driven by design considerations of a range of interrelated factors, but primarily focus around the semiconductor devices used. The performance and ratings of these devices determine the number needed in the design, the physical size of passive components, the efficiency of the module, and the degree of thermal management needed. For example, utilizing better performing semiconductor devices that are more expensive can improve efficiency, reducing thermal management concerns which save costs. Therefore, multi-objective optimization is required to balance between cost and performance to meet SSPS converter requirements.

5.2.1.1 State of the Art

As with other industries, greater standardization can help reduce costs and improve performance through economy of scale. Leveraging parts and materials that are readily available will also help to drive down costs. On-going research and deployment experience with HVDC systems and electric ship applications for the Navy have been advancing modular building block designs and concepts to meet cost and performance objectives. Meanwhile, other applications such as solar PV, energy storage, and EVs have been making parallel advances in component designs utilizing wide band gap (WBG) semiconductor devices. However, these applications all have different design, cost, and performance requirements. Other recent advances include utilizing embedded intelligence, sensors, and protections to improve performance and reliability.

5.2.1.2 Research Gaps

Establishing the high-level requirements for SSPS converter building blocks is an important pre-requisite to addressing module cost and performance. These requirements should be consistent with the broader converter architecture, and allow for design innovation and integration of technological advances. Test protocols that simulate a realistic operating environment will also need to be developed to properly assess, characterize, evaluate and compare different converter building blocks designs.

Additionally, advanced design tools and improved models with multi-physics capabilities will be needed to help understand the interactions and trade-offs between different materials, components, and power electronic devices, especially WBG devices that can operate at higher switching frequencies. New design methodologies such as genetic algorithms to support optimization, new manufacturing techniques, and different modes of operation should all be considered in the development of SSPS modules.

5.2.2 Drivers and Power Semiconductors

Power semiconductors are the fundamental enabling technology of converter building blocks, driving the overall cost and performance of SSPS modules. Various power electronic devices exist today that are suitable for grid-scale application, with the most popular being thyristors, IGBTs, MOSFETs, and diodes. These power semiconductors have a range of operating parameters that must be factored into the design of modules such as blocking voltages, current ratings, on-resistance, switching frequency, slew rates, parasitic parameters, and leakage currents. Gate drivers are also an important technology needed for the reliable and consistent operation of power semiconductors. They control the switching of the devices and should be designed and co-optimized with the power semiconductors used. Drivers can also possess a degree of intelligence to monitor and protect the sensitive power electronic devices.

5.2.2.1 State of the Art

Silicon (Si) thyristors and IGBTs are the dominant power semiconductors today since they can handle high voltages, high power, and are affordable (e.g., a 300A dual 1700V IGBT costs $0.17/kW.)[18] While advances continue to be made in these technologies, they will hit a fundamental performance limit based on the underlying Si material. Significant on-going research is exploring the development of next-generation devices using WBG semiconductor materials, such as Silicon Carbide (SiC) and Gallium Nitride (GaN), which have superior properties compared to Si (see Figure 8).

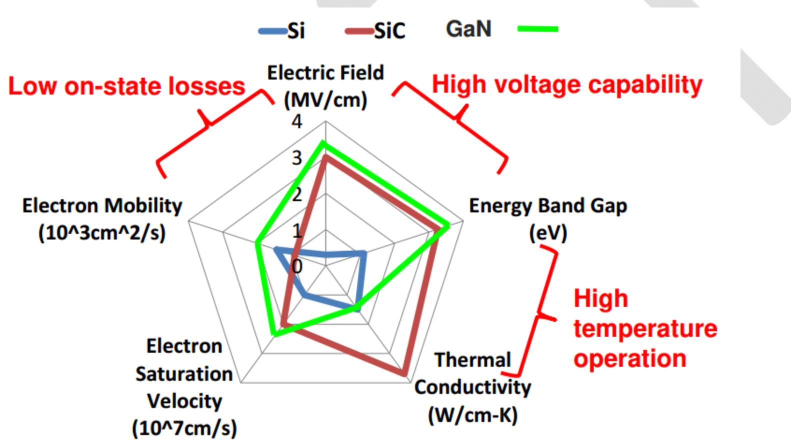

Figure 8: Performance Comparison of Semiconductors[19]

SiC MOSFETs are now commercially available, with lower conduction and switching losses than Si IGBTs, but they come at a significant cost premium (e.g., a 444 A dual 1200 V device costs $1.3/kW.)[20] Other innovations include hybrid power modules that integrate Si transistors with WBG diodes, leading to solutions with improved performance but at a modest cost increase. Recent efforts have also focused on advancing WBG semiconductor manufacturing and processing techniques to reduce the cost and improve the performance of these next-generation power devices.

5.2.2.2 Research Gaps

Research is needed to continue improving the cost and performance of WBG semiconductor devices, especially at higher voltages (e.g., 10 kV) and power ratings. New topologies, new gate dielectrics, better metal contacts, better substrates, and advanced manufacturing can help increase the reliability, efficiency, and consistency of devices. Research is also needed to develop appropriate gate drivers that can switch at the frequencies of interest while being able to withstand EMI generated by the devices. Additionally, the electrical coupling that occurs due to device parasitics (e.g., ringing) must be managed. Localized sensors that can monitor the state of power semiconductors at the high voltage and power levels, and at high switching frequencies may also be needed.

5.2.3 Dielectric, Magnetic, and Passive Components

In addition to drivers and power semiconductors, there are a range of other components that are important to the functionality of converter building blocks. Electrical insulation, capacitors, resistors, transformers, traces, connectors, and cabling are some of the dielectric, magnetic, and passive components that impact the final cost and performance of SSPS modules. As voltages, currents, and frequencies increase with power semiconductors, especially with WBG devices, the physical properties of these components result in losses that limit the maximum module efficiency and power densities achievable. Their robustness to a range of physical stresses will also impact the reliability of the converter building block.

5.2.3.1 State of the Art

For substation equipment, air, paper, and mineral oil are the dominant electrical insulators primarily due to their low costs and high reliability. More advanced materials such as sulfur hexafluoride (SF6), cross-linked polyethylene (XLPE), Nomex, and 3M Novec have been used in special applications where their increased dielectric strength, temperature rating, and mechanical properties justify their higher costs. In addition to insulation, dielectric materials are used in capacitors which play a critical role in the function of power electronic system. Electrolytic capacitors are commonly used since they are low-cost and can be based on both solid and non-solid electrolytes.

Magnetic components in power electronics systems include transformers and inductors that are based on silicon steel or ferrites due to low costs. While most of these components perform well at low frequencies, their losses become more significant at higher frequencies. More advanced materials such as METGLAS and nanocomposites have been applied to these components to reduce losses and increase power densities, especially when combined with WBG semiconductor devices. Copper and aluminum are still the primary metals used as electrical conductors due to their low cost and high conductivity to reduce losses. Research in more advanced conductor materials, such as covetics and graphene, are on-going but have yet to make it into components that can be readily used.

5.2.3.2 Research Gaps

Critical research is needed in dielectrics for insulators and capacitors, especially if SSPS converters are to be used in transmission system applications. High dielectric strength and high reliability will be needed, including self-healing capabilities and the ability to withstand high-frequency transients. Research is also needed to continue advancements in soft magnetics to drive down costs and to improve high frequency performance. Application of advanced manufacturing technique to dielectric, magnetic, and passive components can also help improve their physical properties and prices points.

5.2.4 Packaging and Thermal Management

Packaging and thermal management are critical to the reliable and safe operation of converter building blocks, and they will play an important part in the maximum power density achievable. As with all power converters, switching losses, conduction losses, and parasitic losses all result in heating that must be managed. Without effective cooling, component temperatures will rise that lead to accelerated aging and potentially damage. Packaging is intimately tied to thermal management and must be developed hand-in-hand to effectively extract heat. For example, SSPS modules with high power densities will most likely require liquid cooling and the packaging must be designed to accommodate the coolant flows. Another important design consideration for packaging and thermal management of converter building blocks is their ability to be modular and scalable.

5.2.4.1 State of the Art

Thermal management systems for grid applications include air cooled systems (passive or forced), liquid cooling (e.g., water or dielectric), or some combination of both. In some cases, the coolant also serves as an electrical insulator such as in large power transformers. Advances in thermal management systems that are more modular in nature have been driven by data centers and include forced water flow and 2-phase cooling, with some applications using refrigerants. Figure 9 shows current cooling options for different application power levels and the range of heat transfer provided.

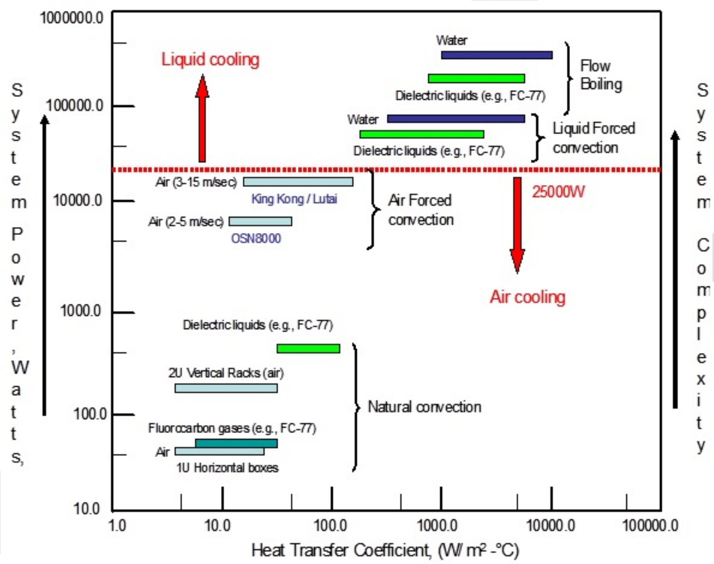

Figure 9: Heat Transfer Properties of Cooling Technologies[21]

At the power semiconductor level, there are numerous efforts underway to improve packaging and thermal management such as enabling higher temperature operations through the use of high temperature materials. [22,23,24] While some of these efforts have been successful, they are not sufficiently cost-effective. An increased temperature rating at the power module provides an increased margin for overload and fault conditions that help increase device reliability. The automobile and defense sectors have been leading the way in development of high temperature modules, but only custom packages have been manufactured which is more costly. Recent research has also investigated using additive manufacturing to improve the heat sinks for on-board electric vehicle applications.

5.2.4.2 Research Gaps

Research is needed in the application of available thermal management solutions to converter building blocks. One of the biggest challenges is to develop packaging that minimizes complexity and enables modularity and scalability while meeting cooling requirements. Ensuring interoperability and seamless connectivity with the broader converter architecture will also be necessary to achieve plug-and-play functionality and hot-swapping. Continued research in better heat sinks, high temperature materials, and packaging concepts will support the use of high power WBG devices in converter building blocks.

5.2.5 Near, Medium, and Long-Term Actions for Converter Building Blocks

Advances in converter building blocks will require close coordination with the broader SSPS converter architecture to ensure alignment of functional requirements and interoperability. Since these modules are the most "basic" part of SSPS technology, many of the advances needed deal with fundamental physical properties of the underlying devices and components.

In the near-term, research is needed in developing SSPS modules that utilize commercially available power semiconductors devices, such as Si IGBT, to ensure cost targets can be met. Developing design tools and integrating recent advances in thermal systems, dielectrics, and magnetics can help balance cost and performance. Research efforts should leverage lessons learned and capabilities in other sectors such as data centers, electric vehicles, and electric ships to achieve SSPS modules.

In the mid-term, reduction in the cost of WBG devices will be needed to enable higher voltage and higher power SSPS modules. Simultaneously, advances in drivers will be needed that are coordinated with the WBG devices used. Cost-effective high frequency magnetics, high voltage capacitors, and insulators will also be important components to advanced SSPS modules. Improved thermal management solutions to extract heat from high power density modules will also need to be addressed.

In the long-term, availability of the next-generation of dielectric, magnetic, and passive components, as well as cost-effective WBG semiconductors, will be needed to make converter building blocks even more affordable. The integration of advanced thermal management systems and self-healing capabilities can improve module reliability and increased power density for a range of new applications.

5.3 Grid Integration

The application of SSPS converters in substations and their integration into the electric grid is more complex than simply connecting the technology and letting it operate. The electric power system we have today evolved over time based on a control and protection paradigm that relies on synchronized machines and the behavior of electro-mechanical devices. As SSPS technology is introduced into the grid, the control and protection paradigm must change to accommodate the new capabilities and features of SSPS converters. More specifically, the multi-frequency and asynchronous nature of SSPS technology presents fundamentally new ways that the grid can be designed and operated. Several R&D challenges associated with grid integration of SSPS converters include grid architecture, control and protection systems, and modeling and simulation. Actions needed to close the gaps in the near-term (within 5 years), mid-term (within 10 years), and long-term (within 20 years) are identified at the end of this section.

5.3.1 Grid Architecture

Grid architecture is a relatively new term that encompasses the multiple facets of an electric power system. Aspects include topologies, technologies, communications, controls, protection, markets, institutions, and other systems (e.g., water, natural gas), and extends to the relationships and interactions between them. Grid architecture establishes an organizing principle that allows the design of the electric power system to be analyzed methodically and holistically, and can be used to assess the impacts of SSPS technology integration and help identify system changes needed. An important issue to examine is the coordination and interaction of SSPS converters with each other and with legacy technologies, especially in a system that is not synchronously coupled to ensure that system stability can be maintained.

5.3.1.1 State of the Art

The current grid architecture is still primarily based on power flowing from large, centralized generation connected to a transmission network that feed distribution systems to meet loads. The introduction of advanced ICT to improve situational awareness and enhance grid operations has added an additional layer of complexity as well as vulnerabilities. More recently, the growth in DERs and the ability for customers to interact with the grid (i.e., prosumers) has led to control and coordination challenges.

Research has been exploring new grid operating concepts such as transactive controls,[25] distribution system as a platform,[26] networked microgrids, DC microgrids, and energy routers.[27] Figure 10 illustrates a potential evolution from the grid architecture we have today to one with significantly more power electronic interfaces. Additionally, there have been efforts to advance the discipline of grid architecture,[28] developing tools and refining definitions to improve understanding of system relationships.

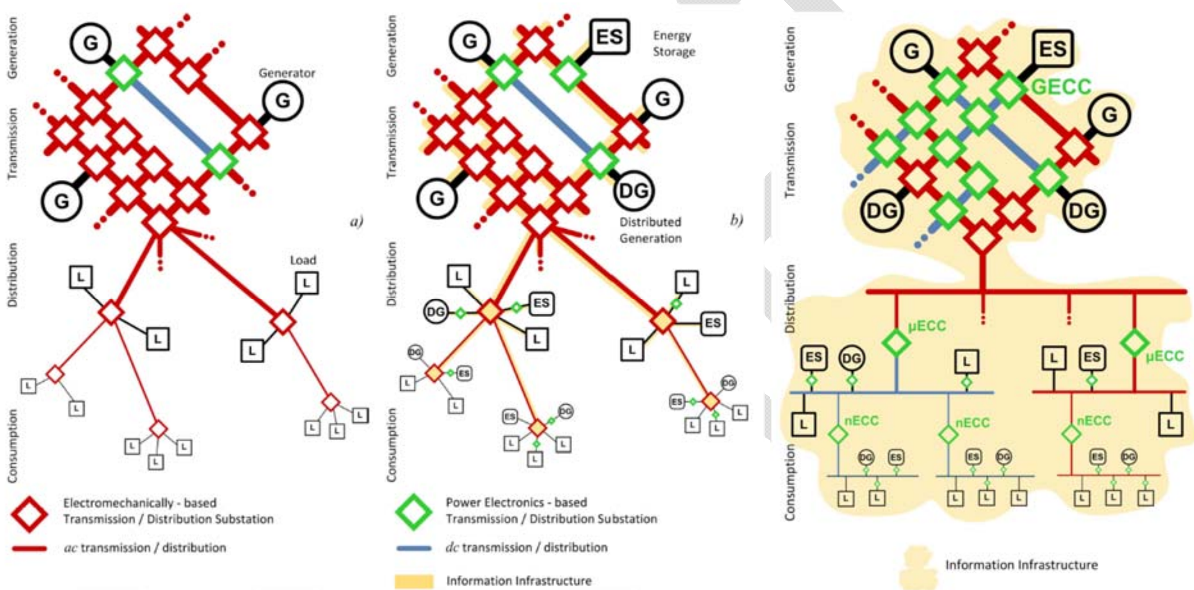

Figure 10: Evolution of Grid Topologies and Architectures[29]

5.3.1.2 Research Gaps

Broader deployment of SSPS technologies will decouple parts of the electric power system spanning generation, transmission, distribution, and loads. Research is needed to develop a broad range of control theory, network engineering, system architecture, and topologies to support this fundamental shift away from an operating paradigm based on rotating machines to one that is coordinated through active power electronic systems. Advances in distributed controls and protection is needed to allow for microgrids, DERs, and other SSPS applications to provide a range of functions (e.g., grid-supporting, grid-forming, flow control), in coordination with existing protections, to ensure stability, safety, and reliability.

Ultimately, a complete decoupling of the electric power system, with multiple microgrids that can operate at multiple frequencies, will require new management and operating concepts, including redefining roles and responsibilities of entities and institutions. Additional considerations for this asynchronous and fractal paradigm include changes to communication requirements, market operations, and autonomous controls which impact the overall complexity and fragility of the system. The new grid architecture will also need to consider how the system can break apart during a contingency, and seamlessly reconstitute itself and recover to normal operations, including in black start conditions.

5.3.2 Grid Control and Protection Systems

Control and protection systems have been developed to support operation of the electric power system as well as to protect equipment from damage during abnormal conditions. These ancillary technologies, spanning software and hardware solutions with varying degrees of sophistication, have been engineered to ensure the grid runs safely, reliably, and cost-effectively during predictable and unpredictable conditions. While control systems operate on time-scales that enable wide-area coordination to balance generation and load, protection systems operate rapidly and automatically without the need for central coordination. These devices allow for the electric power system to disconnect and isolate troubled areas while keeping the rest of the system operational until issues can be resolved. Since SSPS technologies will necessitate a new grid architecture, grid control and protection systems will also need to evolve to accommodate the new functions and features.

5.3.2.1 State of the Art

Energy management systems (EMS) have developed over time, in conjunction with SCADA systems, to coordinate the operation of centralized generation and the transmission system, including substations. These systems rely on computer aided tools to perform several important functions including state estimation, unit commitment and economic dispatch, forecasting weather and loads, and optimal power flow. Distribution management systems (DMS) have generally been less sophisticated since distribution feeders are often radial and have limited functionality. Broader deployment of distribution automation technologies has required advances to DMS to enable functions such as conservation voltage reduction (CVR), fault location, isolation, and restoration (FLISR), and outage management. There are numerous R&D efforts underway to improve these software tools and systems through integration of ICT, improved analytics, and leveraging new data sources from advanced sensors such as PMUs. A more recent focus has been on advanced distribution management systems (ADMS) to help coordinate DERs and enable the provision of grid services.

Protection systems in the transmission system focus on preventing faults from cascading throughout the system. This is achieved through a range of electromechanical relays set to open a circuit breaker in response to conditions measured through functions such as time-overcurrent, instantaneous current-voltage, directional-sensing, and distance-impedance. Recently, microprocessor based relays have been developed that integrate these various functions for improved coordination and faster response. Advances in programmable logic controllers have also been used to increase the sophistication of substation automation. Meanwhile, protection in the distribution system is more basic with the use of fuses, reclosers, and sectionalizers to isolate faults. Recent advances with the integration of ICT into the distribution system have enabled more complex protection.

5.3.2.2 Research Gaps

Critical research is needed to ensure that SSPS converters and the operating paradigms they enable, such as microgrids and multi-frequency systems, will be interoperable and coordinated with existing protection and control systems as the technology is deployed. Dynamic and adaptive relays and protection schemes will be needed to ensure the grid is properly protected during conditions where the anticipated fault current magnitude or power flow direction changes, especially in distribution systems with a large amount of DERs and microgrids. Other research needs include new protection algorithms that leverage the full capabilities of SSPS technology such as solid-state fault current limiting or electrical isolation. Additionally, fault protection in a fully fractal and asynchronous system may require new technologies and approaches.

Grid control systems will also need to be updated to reflect the capabilities of SSPS technology, while ensuring alignment with the new architectures developed. A combination of centralized coordinated control, distributed autonomous control, and advanced protection schemes will need to be integrated across both EMS and DMS. Research will also be needed for these systems to enable advanced functions such as graceful degradation during a contingency, dynamic power routing, multi-objective optimization, and system recovery from blackstart conditions.

5.3.3 System Modeling and Simulation

System modeling and simulation comprises of a suite of tools and capabilities that help engineers and designers understand how changes to the electric power system, from new technologies to new market operations, will affect the overall grid without experimenting on a real system. The electric grid is very complicated with numerous interdependencies; modeling and simulation capabilities allow for specific questions to be asked and results to be analyzed methodically. Some of the analyses needed for SSPS integration include engineering analysis, transient stability, short circuit, load flow, controls, and dynamics. These tools can also be used to inform decision making and build confidence in SSPS technology without full-scale development which can be very expensive. System modeling and simulations can help design new markets, refine controllers and algorithms, and evaluate new grid paradigms without risking blackouts.

5.3.3.1 State of the Art

A variety of modeling and simulations tools exist today to answer specific questions about the grid. They have continued to advance, leveraging faster and faster computational capabilities and innovations in mathematics and algorithms. However, a majority of these tools developed around the current architecture and may not be suitable for a grid with significant amount of power electronic systems. Recently, there have been research efforts aimed at integrating multiple tools to better evaluate interdependencies, such as between transmission, distribution, and communications, to better reflect reality.

The development of real-time digital simulators (RTDS) has allowed for power hardware-in-the-loop testing as well as controller-in-the loop testing. This capability enables actual pieces of hardware (e.g., converters, controller) to be hooked up to a software simulator while interacting through a real physical interface with power flows and information exchange. RTDS provides a mechanism to refine and validate models of specific pieces of hardware to ensure their behavior and operation are accurate throughout a range of conditions.

Accurate modeling and simulation results depends on accurate data and high fidelity models as inputs, especially ones that can replicate dynamic and transient behaviors in addition to steady state behavior. A process for traditional model development is shown in Figure 11, highlight different tiers of models that are needed for a new device. Recent research has been advancing component models as well as system models to ensure more sophisticated and accurate analysis can be conducted as modeling and simulation capabilities advance.

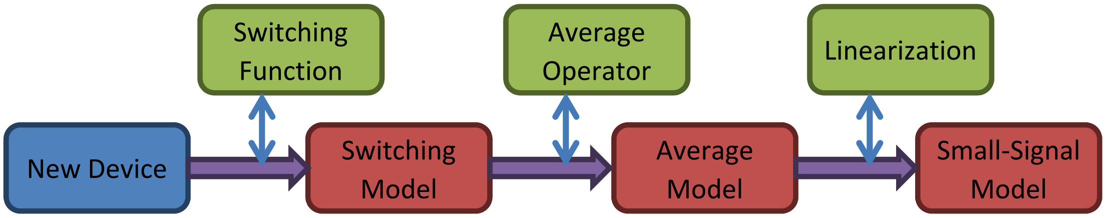

Figure 11: Traditional Model Development

5.3.3.2 Research Gaps

Research is needed to continue advancing modeling and simulation capabilities, including methodologies to assess and analyze a future grid paradigm that is fully distributed and asynchronous. Improvements are needed in the full spectrum of capabilities spanning engineering analysis, transient stability, short circuit, load flow, controls, and dynamics, from the full system level down to the converter level. As SSPS converters advance, high fidelity data and models will also be needed.

In addition to tool development, several analyses are needed to answer fundamental questions of SSPS integration in the grid. In a decoupled system, with ubiquitous SSPS converters, phase angle and voltage stability limits no longer apply and a new metric for controls will need to be identified. Additionally, new definitions for normal operation and contingencies will be needed for system security assessments and evaluation of resilience. Analysis is also needed to assess advanced converters function, markets designs, and new control and protection paradigms.

5.3.4 Near, Medium, and Long-Term Actions for Grid Integration

Advances in grid integration of SSPS converters will require a much broader perspective than a focus on converter development. The fundamental asynchronous nature of SSPS technologies will challenge the existing paradigm that ensures the safe and reliable operation of the electric power system. Improved understanding of the potential consequences of using SSPS converters and identifying the changes required are critical to ensure the technology is successful and adopted more broadly.

In the near-term, research is needed to develop and refine a grid architecture that is compatible with the envisioned SSPS capabilities. This is a critical effort that spans multiple facets of the electric power system, especially control and protection to ensure SSPS technologies won't decrease safety or reliability. Improved models, data, and modeling and simulation tools will also be needed to properly assess the behavior and benefits of SSPS converters. Power hardware-in-the-loop testing can be used to validate the new models developed.

In the mid-term, integration of SSPS capabilities into EMS and advanced DMS is needed to realize the new functionalities and benefits. Special attention is needed to refine the grid architecture, especially with the hierarchy of power flow control and operational override to keep multiple SSPS converters from working against each other and destabilizing the grid. Finally, adaptive, dynamic protection will need to be developed to ensure reliable operation with more microgrids and reverse power flows enabled by SSPS technology.

In the long-term, fundamental advances are needed to establish a grid architecture that is fractal, fully asynchronous, autonomous, and supports multiple frequencies. Advances in modeling and simulation tools, as well as methodologies, will be needed to evaluate and assess this new paradigm. Analysis is needed to improve understanding and establish new criteria for maintaining a stable grid when all grid components are no longer synchronized. Finally, advances in EMS and DMS will need to accommodate graceful degradation of the system and coordination of system recovery in blackstart conditions.

5.4 Industry Acceptance

Fostering industry acceptance of SSPS technologies will require actions to address issues beyond R&D. Topics such as cost benefit analysis, industry standards, markets and regulations, and testing, education and workforce are all issues that may limit the acceptance of SSPS technology. A range of non-technical activities will be needed to address these issues, especially considering the range of stakeholders impacted by the new grid paradigm and functions enabled by SSPS converters. However, it is important to note that these issues are not entirely decoupled from the technical challenges and must be tackled in a coordinated manner.

5.4.1 Cost Benefit Analysis

In the end, the benefits associated with adopting SSPS technologies must outweigh their costs for there to be any traction with industry. Developing principles that can help establish a robust and convincing cost benefit analysis is needed to help justify how the new defining functions and features of SSPS converters outweigh the cost premium over traditional solutions. For example, the application of SSPS technologies to replace a LPT in a distribution substation can increase system flexibility and resilience, reducing operational costs, installation costs, and outage costs, that can help justify their higher capital costs. Development of credible use cases that are broadly applicable can help inform utilities and investors of the value of using SSPS technologies. Accurate cost benefit analyses will depend on advancement made in grid modeling and simulation capabilities.

5.4.2 Industry Standards

As SSPS technologies penetrate into the grid, they will require the development or update of industry standards to ensure safe, reliable, and secure operations. For example, inverter-based DERs are currently grid following and disconnect under faulted conditions. Due to the advanced functions enabled with the next-generation of inverters, revisions now dictate ride-through capabilities and eventually will include grid support functionalities. While updates to IEEE 1547 are applicable to SSPS converters, there are additional capabilities that must be reflected in future revisions. Active participation in standards development organizations will be needed to ensure SSPS converter functions and features can be institutionalized. Table 8 provides a range of other standards that are relevant to SSPS technologies and will require active involvement.

Table 8: Standards Associated with SSPS Integration

Interconnection Standards		
SSPS 1.0	IEEE 1547-2003	Standard for Interconnecting Distributed Resources with Electric Power Systems
SSPS 2.0	IEEE P1032	Guide for protecting Transmission static VAR compensators
SSPS 3.0	IEEE 1378-1997	Commissioning HVDC Converter Stations and Associated Transmission Systems
Controls Standards		
SSPS 1.0	IEEE 2030-2011	Standard provides guidelines in understanding and defining smart grid interoperability of the electric power system with end-use applications and loads.

SSPS 2.0	IEEE 1676-2010	Guide for control architecture for high power electronics >1MW used in transmission and distribution systems
SSPS 3.0	IEEE C37.1	Provides the basis for the definition, specification, performance analysis, and application of SCADA and automated systems in electric substation, including generation stations, power utilization a, and conversion facilities
Communications Standards		
SSPS 1.0	IEC 61850-6	Configuration language for communication in electrical substations related to IEDs
SSPS 2.0	IEC 61850-90-1	Communication between substations
	IEEE 1815.1-2015	Standard for exchanging information between networks implementing IEC 61850 & DNP3
SSPS 3.0	IEC 61850-90-2	Communication between substations and control centers
Cyber & Physical Security Standards		
SSPS 1.0	IEEE 1686-2013	Defines Functions and features to be provided in substation IEDs to accommodate critical infrastructure protection programs
SSPS 2.0	IEEE 1402-2000	Guide for Power substation physical security
SSPS 3.0	IEEE C37.240-2014	Cybersecurity Requirements for Substation Automation, Protection, and Control Systems

5.4.3 Markets and Regulations

Markets rules, regulations, and other institutional entities have evolved over time to ensure reliable, safe, and cost-effectiveness operations. With the broader deployment of SSPS technology, these issues will also need to be addressed and modernized. As with other new technologies, such as energy storage and demand response, understanding and educating the relevant stakeholders of the value of the technology is important to refine market rules and product changes. For example, having real-time pricing can help address some of the value proposition of SSPS technology by managing peaks and power flows. Enabling monetization of the SSPS benefits and ensuring fair and equitable allocation of cost is very important for industry acceptance.

Another issue to consider is how stability limits and penalties will need to be redefined. For example, in a completely asynchronous system, frequency regulation and limits on area control error will need to be changed since they may no longer be relevant. During SSPS autonomous operations, determining which entities are liable for outages is another challenge that needs to be addressed. New business models enable by advanced SSPS functions, such as differentiated quality of service, will also need proper oversight.

5.4.4 Testing, Education, and Workforce

Open access to testing facilities and establishing test protocols to benchmark SSPS performance is important for broader adoption. The ability to test SSPS converters under a controlled environment helps reduce risks for industry, especially with more advanced control concepts and high voltage operations. Standardized testing protocols will help spur innovation since different SSPS modules, controllers, and converters can be evaluated side by side. Data, refined models, and experimental results from this testing will need to be shared broadly to ensure transparency. However, there is a need to respect business sensitive information.

Furthermore, advances in education and workforce training will be needed to develop the skill-sets needed to design, build, and maintain SSPS converters in a future grid paradigm. Current line crews and engineers are mostly familiar with passive components and the existing grid architecture. Developing the research capacity, curricula, and capabilities for the next-generation workforce will support continued advancement and adoption of SSPS technologies.

6 Conclusions

As the electric power system evolves and the threat environment changes, there are new and pressing challenges that face the electricity delivery network, especially for substations. On the path towards grid modernization, there are opportunities to improve the performance of substation components and to rethink the design of these critical nodes of the system. SSPS, a substation with the strategic integration of high voltage power electronic converters, can provide system benefits and support evolution of the grid.

SSPS technologies have the potential to disrupt the current market – spanning every aspect of electrical power generation, transmission, distribution, and consumption, including infrastructure support services and opportunities for upgrades. SSPS converters represents a new technology group that has potential to tap into a multi- billion-dollar industry, creating new U.S. businesses and jobs. Achieving this capability within the U.S. before other countries would be a tremendous economic advantage and can bolster domestic energy security.

This roadmap has identified several R&D challenges and critical gaps, documents a technology adoption trajectory that minimizes risks and costs, and highlights the potential benefits of broader utilization of these technologies in order to accelerate the realization of the SSPS vision presented. Actions needed to address the gaps identified are both technical and institutional in nature, and are summarized below:

	Challenges	Actions
Near-Term		
Mid-Term		
Long-Term		

While the challenges are numerous, stakeholders across government, industry, and academia have on-going efforts that support advancements needed for SSPS technologies. Each group of stakeholders play a specific role in development of SSPS. Academia contributes through addressing fundamental challenges in theory, modeling, simulation, and prototype research. National laboratories help to address fundamental challenges as well but also can provide neutral validation platforms for models and prototypes through their scientific user facilities. The utility industry supplies insights and expertise into the operating conditions and business justification for the technology as well as contributing to data and pilot testing. Manufacturers will be vital to taking outcomes of research pilots and prototypes and advancing them through product development and commercialization. Finally, the federal government can contribute resources and facilitate collaboration across the entire stakeholder community.

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