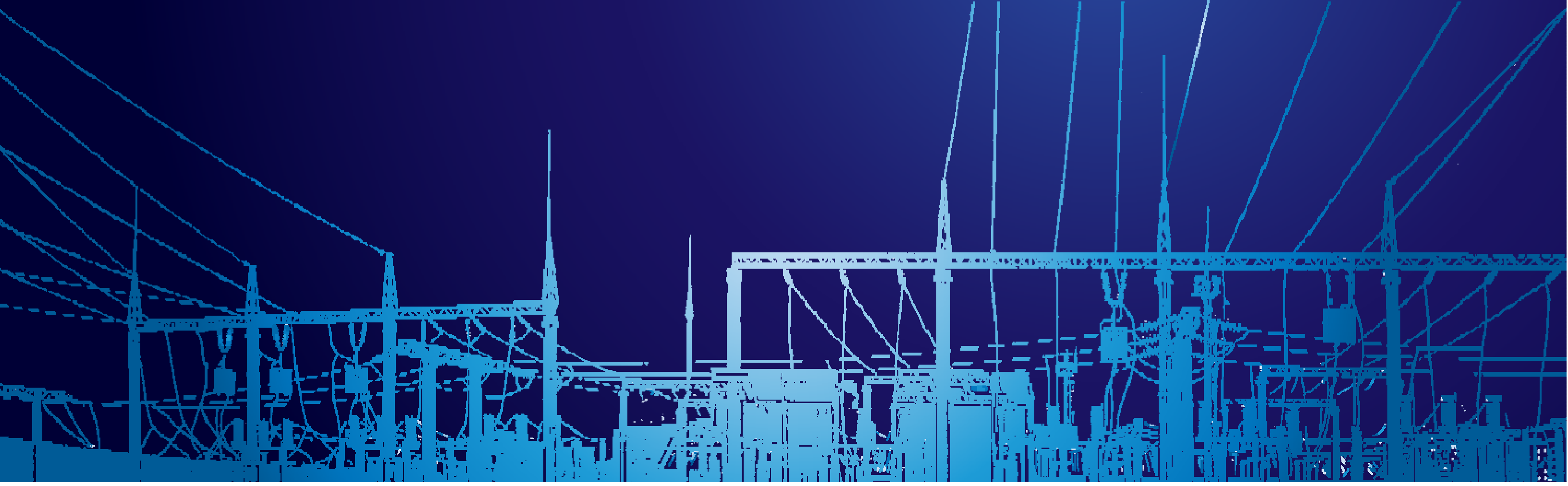

Solid State Power Substation Technology Roadmap

U.S. DOE Office of Electricity
Transformer Resilience and Advanced Components (TRAC) Program
June 2020

Advanced Grid Research
OFFICE OF ELECTRICITY
US DEPARTMENT OF ENERGY

Acknowledgments

The Office of Electricity (OE) Transformer Resilience and Advanced Components (TRAC) program[1] would like to acknowledge Klaehn Burkes and Joe Cordaro from Savannah River National Laboratory, Tom Keister from Resilient Power Systems, and Emmanuel Taylor from Energetics Incorporated for their early efforts in framing and developing the draft Solid State Power Substation Technology Roadmap. The draft roadmap also benefited substantially from the information gathered during the Solid State Power Substation Roadmap Workshop held June 27–28, 2017.[2] The TRAC program would like to thank the participants who were in attendance and the various organizations that were represented, including:

- ABB Group
- Arkansas Electric Cooperative Corporation
- Clemson University
- Delta Star, Inc.
- Eaton Corporation
- Electric Power Research Institute (EPRI)
- Energetics Incorporated
- Florida State University
- Georgia Tech
- Google
- Infineon Technologies Americas Corp.
- KCI Technologies, Inc.
- Los Alamos National Laboratory
- National Energy Technology Laboratory
- National Institute of Standards and Technology
- National Renewable Energy Laboratory
- NextWatt, LLC
- North Carolina State University
- Oak Ridge National Laboratory
- Phoenix Electric Corporation
- Resilient Power Systems, LLC
- S&C Electric Company
- Sandia National Laboratories
- Savannah River National Laboratory
- SNC-Lavalin
- Southern California Edison
- Southern States, LLC
- TECO-Westinghouse Motor Company
- U.S. Department of Energy
- University of Arkansas
- University of Central Florida
- University of North Carolina at Charlotte
- University of Pittsburgh
- University of Wisconsin–Madison
- Virginia Tech
- ZAPTEC

Finally, the detailed comments received through the Request for Information[3] that ran March 23–May 7, 2018, helped refine and enhance the quality of this document. The TRAC program is extremely grateful for the contributions from:

- ABB Group
- AEP Transmission
- Burns & McDonnell
- Carnegie Mellon University
- Eaton Corporation
- Electranix Corporation
- GE Global Research
- GridBridge, Inc.
- Illinois Institute of Technology
- National Energy Technology Laboratory
- North Carolina State University
- Oak Ridge National Laboratory
- Ohio State University
- Pacific Northwest National Laboratory
- S&C Electric
- SmartSenseCom
- Texas A&M University
- Virginia Tech

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Executive Summary

As the electric power system evolves to accommodate new generation sources, new loads, and a changing threat environment, there are new and pressing challenges that face the electricity delivery network, especially for substations. Given the ubiquitous nature and importance of these critical nodes, advanced substations present a tremendous opportunity to improve performance of the grid. Development of advanced substation technologies that enable new functionalities, new topologies, and enhanced control of power flow and voltage can increase the grids reliability, resiliency, efficiency, flexibility, and security.

A solid state power substation (SSPS), defined as a substation or "grid node" with the strategic integration of high-voltage power electronic converters, can provide system benefits and support evolution of the grid. Design and development of a flexible, standardized power electronic converter that can be applied across the full range of grid applications and configurations can enable the economy of scale needed to help accelerate cost reductions and improve reliability.

Ultimately envisioned as a system consisting of modular, scalable, flexible, and adaptable power blocks that can be used within all substation applications (Figure ES-1), SSPS converters will serve as power routers or hubs that have the capability to electrically isolate system components and provide bidirectional alternating current (AC) or direct current (DC) power flow control from one or more sources to one or more loads—regardless of voltage or frequency.

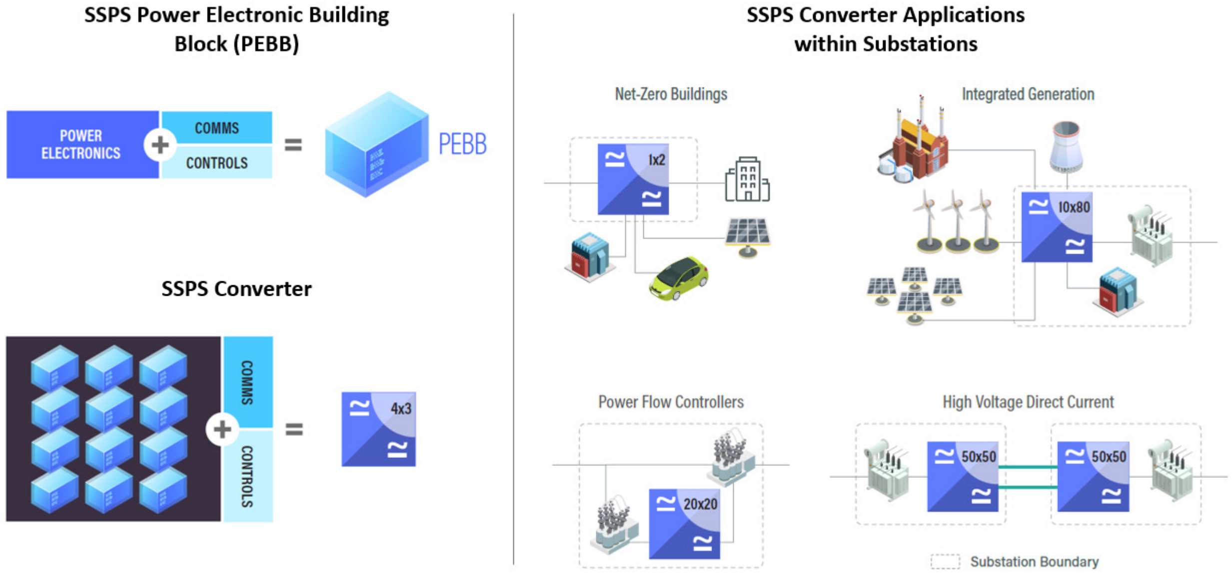

Figure ES-1: Vision for SSPS Converters

For each potential application, the enhanced functions enabled by SSPS converters must provide benefits that outweigh their costs. As such, three classifications of SSPS converters have been identified—designated as SSPS 1.0, SSPS 2.0, and SSPS 3.0—which mark milestones in their developmental pathway and integration in the electric grid. Each classification is based on the voltage and power ratings of the SSPS converter application, as well as on defining functions and features they enable. Their progressive advancement is outlined in Table ES-1, indicating the capabilities for each generation that expand upon those of the previous generations (denoted by the "+").

Table ES-1: SSPS Converter Classification and Defining Functions and Features

CONVERTER CLASSIFICATION	**DEFINING FUNCTIONS AND FEATURES**
SSPS 1.0 UP TO 34.5 KV 25 KVA–10 MVA	• Provides active and reactive power control • Provides voltage, phase, and frequency control including harmonics • Capable of bidirectional power flow with isolation • Allows for hybrid (i.e., AC and DC) and multi-frequency systems (e.g., 50 Hz, 60 Hz, 120 Hz) with multiple ports • Capable of riding through system faults and disruptions (e.g., HVRT, LVRT) • Self-aware, secure, and internal fault tolerance with local intelligence and built-in cyber-physical security
SSPS 2.0 UP TO 138 KV 25 KVA–100 MVA	+ Capable of serving as a communications hub/node with cybersecurity + Enables dynamic coordination of fault current and protection for both AC and DC distribution systems and networks + Provides bidirectional power flow control between transmission and distribution systems while buffering interactions between the two + Enables distribution feeder islanding and resynchronization without perturbation
SSPS 3.0 ALL VOLTAGE LEVELS ALL POWER LEVELS	+ Distributed control and coordination of multiple SSPS for global optimization + Autonomous control for plug-and-play features across the system (i.e., automatic reconfiguration with integration/removal of an asset/resource from the grid) + Enables automated recovery and restoration in blackout conditions + Enables fully decoupled, asynchronous, fractal systems

The envisioned evolution of SSPS technology and its integration into the grid is depicted in Figure ES-2. SSPS 1.0 is expected to involve applications at distinct substations or "grid nodes" and local impact, such as those associated with industrial and commercial customers, residential buildings, or community distributed generation/storage facilities at the edges of the grid. SSPS 2.0 is envisioned to expand on the capabilities of SSPS 1.0, increasing the voltage level and power ratings of the converter application. This classification also integrates enhanced and secure communication capabilities, extending applications to include those at distribution substations, such as integration of advanced generation technologies (e.g., small, modular reactors, flexible combined heat and power), and utility-scale generation facilities. 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 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.

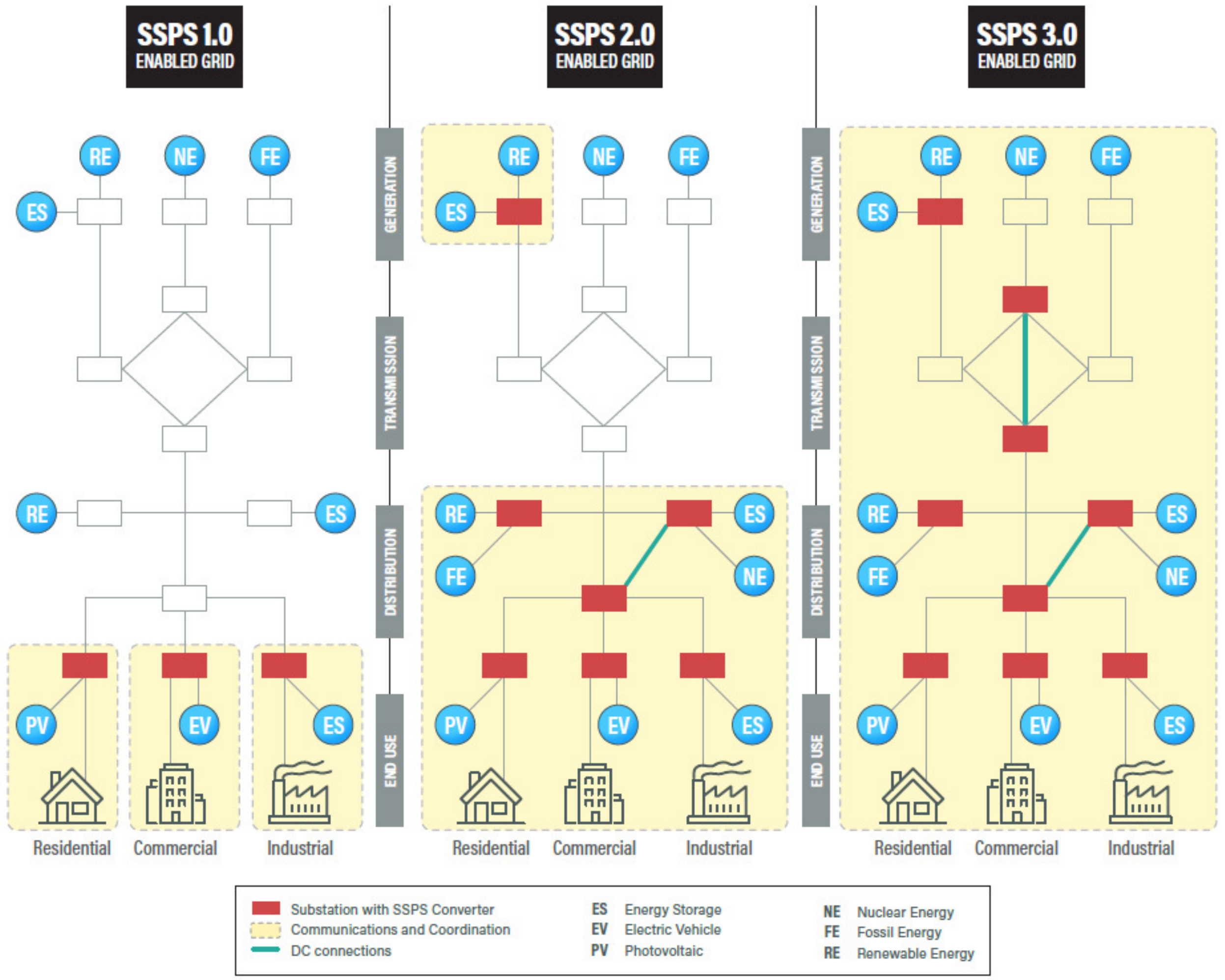

Figure ES-2: SSPS Enabled Grids Through Its Evolution

In addition to the staged deployment opportunities, there are many research and development (R&D) challenges that must be addressed to advance SSPS technology. Both technical and institutional activities needed to address the gaps identified over the near term, midterm, and long term are summarized in Table ES-2.

Table ES-2: Summary of Roadmap Activities

TIMING	ACTIVITIES
NEAR TERM (WITHIN 5 YEARS)	• Establish a community to support multidisciplinary research spanning controls, power electronics, and power systems to advance fundamental understanding of SSPS • Develop secure SSPS converter architectures suitable for multiple applications and enhance associated design tools • Support research in core technologies such as gate drivers, material innovations, sensors, and analytics needed for advanced SSPS functions and features

	• Develop, characterize, and demonstrate SSPS modules and converters utilizing commercially available technologies and state-of-the-art controls • Establish characterization methodologies and testing capabilities to create baseline performance benchmarks for SSPS modules and converters • Explore new grid architectures, develop protection and control paradigms compatible with SSPS converters, and establish a valuation framework • Improve data, models, and methods necessary for modeling and simulating system dynamics, including developing generic models for SSPS modules and converters • Engage and educate standards development organizations, regulatory commissions, and other institutional stakeholders, especially utilities
MIDTERM (WITHIN 10 YEARS)	• Advance hardware-in-the-loop (HIL) testing and co-simulation capabilities to enable accurate steady-state and dynamic modeling from a converter up to the full power system • Refine grid architectures and develop advanced control and optimization algorithms for converter and system operations to enable and leverage SSPS capabilities • Develop new components and technologies from near-term core research, including high-temperature packaging and advanced thermal management solutions • Establish wide band gap (WBG) devices as a commercially available technology along with suitable gate drivers that possess monitoring and analytics capabilities • Develop dynamic, adaptive protection schemes and relays and ensure their integration, along with SSPS functions and features, into existing energy management systems (EMS)/distribution management systems (DMS) • Develop, characterize, and demonstrate robust SSPS modules and converters using WBG devices and new drivers, and with modular, low-cost communications capabilities • Develop design practices for SSPS converter integration into substations and conduct analyses based on data, experience, and performance of SSPS converter deployments, including through HIL testing • Continue engaging and educating standards development organizations, regulatory commissions, and other institutional stakeholders, especially equipment vendors
LONG TERM (WITHIN 20 YEARS)	• Explore a fractal, asynchronous grid architecture with autonomous, distributed controls that leverages research in artificial intelligence and machine learning • Conduct modeling, simulation, and analysis to explore the paradigm with many SSPS converters interacting, helping to establish new criteria for grid stability • Establish next-generation components that utilize new materials and high-voltage, high-power WBG modules as commercially available technologies

	- Support research in new semiconductor devices beyond 10–15 kV blocking capability and other material innovations for self-healing components - Develop, characterize, and demonstrate SSPS modules and converters with advanced components, communications, and enhanced reliability beyond n+1 redundancy - Integrate advanced control and optimization algorithms developed in the midterm into EMS/DMS, supporting graceful degradation and blackout recovery - Generate and document sufficient design and operational experience with SSPS converters to make it extendable to all substation applications of interest - Continue engaging and educating standards development organizations, regulatory commissions, and other institutional stakeholders, especially market operators

Addressing the full range of activities listed will require participation from industry, academia, and government laboratories on topics spanning hardware design and development, real-time simulation, control algorithms, power electronics, thermal management, magnetics and passive components, network architecture, communications, cyber-physical security, and computation. Expertise in analysis, markets, regulations, standards, testing, and education will also be needed.

While there are numerous challenges, there also are numerous stakeholders. Each stakeholder group plays a key role in moving toward the SSPS vision, where SSPS technology will be mature, reliable, secure, cost-effective; broadly used across the grid in a variety of substation applications; and an integral part of the future electric power system.

SSPS technology has 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 represent a new technology group that has the potential to tap into a multibillion dollar industry, creating new U.S. businesses and jobs. Achieving this capability within the United States before other countries would be a tremendous economic advantage and can bolster domestic energy security.

1. Introduction

The Nation's electric power system is composed of more than 20,000 generators, 642,000 miles of high-voltage transmission lines, and 6.3 million miles of distribution lines, serving 150 million customers.[4] Within this expansive system, there are over 55,000 transmission substations and thousands more of other types that serve as the critical interconnection points or "grid nodes" between generation, transmission, distribution, and customers (Figure 1). Given the ubiquitous nature and importance of these critical nodes, advanced substations present a tremendous opportunity to improve performance of the grid. Development of advanced substation technologies that enable new functionalities, new topologies, and enhanced control of power flow and voltage can increase the grids reliability, resiliency, efficiency, flexibility, and security.

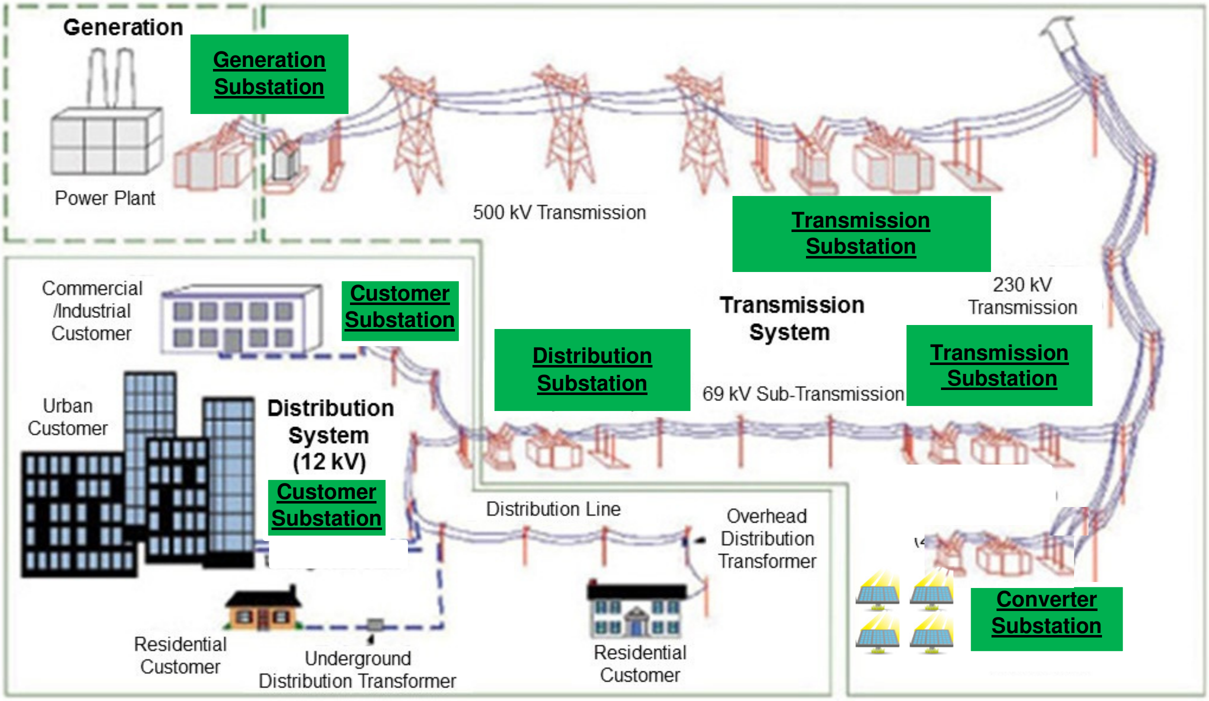

Figure 1: Electric Power System with Substation Categories

1.1 Power System Trends

The electric power system is currently undergoing significant changes in the sources for generating electricity, the means by which we receive electricity, and even the ways we consume electricity. Major trends that are driving grid modernization include:

- **Changing demand** driven by population growth, adoption of energy-efficient technologies, dynamic economic conditions, broader electrification, and the potential mass market availability of electric vehicles.
- **Changing generation mix,** including resource type (e.g., renewable, nuclear, oil and natural gas, and coal) and location (e.g., centralized, distributed, and off-shore), of the Nation's generation portfolio driven by technology, market, and policy developments.

- **Increasing variability of generation and load patterns,** including the integration of variable renewable energy sources, more active consumer participation, and the accommodation of new technologies and techniques.
- **Increasing risks to electric infrastructure,** such as more frequent and intense extreme weather events, increases in cyber vulnerabilities and threats, physical attacks, and growing interdependencies with natural gas and water infrastructure.
- **Aging electricity infrastructure** that is rapidly becoming outdated in light of the other changes happening system-wide, introducing greater vulnerabilities.

Recent efforts to address these changes have mainly focused on integrating sensors, communication systems, real-time monitoring and controls, advanced data analytics, and cybersecurity solutions to improve situational awareness, operating performance, and cybersecurity of the electric power system. Adoption of these technologies has improved system visibility and controllability, leading to increased flexibility, reliability, security, and resilience. However, these technologies do not address the full spectrum of advances and functionalities needed without upgrades to the fundamental hardware components and systems that make up the electric delivery infrastructure.

As the electric power system evolves, the changing landscape of generation and load-side technologies is fundamentally altering the electric power flows and physical phenomena that the grid was designed to accommodate. For example, increased distributed energy resource (DER) penetration is requiring conventional, large-scale generation systems such as coal-fired power plants to operate more flexibly than how they were initially designed (i.e., purely base-load). These physical limitations can potentially lead to reduced grid reliability and will present challenges to grid modernization efforts if unaddressed. Additionally, the growing risks from a range of threats (both cyber and physical) and the pace of system changes are demanding next-generation hardware solutions, including substations, which are more flexible, adaptable, secure, and resilient.

1.2 Solid State Power Substation Vision

Substations or “grid nodes” with the strategic integration of high-voltage power electronic converters, discussed from here on as solid state power substations (SSPS), can provide advanced capabilities and facilitate evolution of the electric power system.

In light of the power system trends discussed in section 1.1, an electric grid with greater penetration of SSPS can overcome some of the constraints that the electric infrastructure will soon face, such as the limited ability to handle reverse power flows, rapidly control voltage levels, and ensure system protection in rapidly changing conditions. SSPS technology can overcome these issues and offer new value streams by managing voltage transients and harmonic content, providing dynamic control of real and reactive power (particularly with integrated energy storage), enabling new grid architectures (e.g., hybrid networks), and facilitating energy dispatch and black starts. Research and development (R&D) of SSPS technology will yield a critical tool for increasing the flexibility, adaptability, security, and resiliency of the future electric grid.

SSPS Vision: SSPS technology will be mature, reliable, secure, and cost-effective; broadly used across the grid in a variety of substation applications; and an integral part of the future electric power system.

1.3 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 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 as well as 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.[5] 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 turnkey substations alone was estimated to be $4.5 billion to $5 billion.[6]

While each substation is unique, several categories can be identified based on the substation's 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, accessibility, and security 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 and with strict cybersecurity requirements, while customer and converter substations do not 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	• Network • 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 High-Voltage Direct Current Medium-Voltage Direct Current	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 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 generator 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
- Adoption of cyber and physical security measures to meet evolving standards

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, performance, and security 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
ARRESTERS	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, Distribution
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 that 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	Devices used to detect, interrupt, and clear momentary faults	Distribution
SECTIONALIZERS	Automatically isolates faulted sections of the distribution system	Distribution
TRANSFORMERS	Steps up or steps down AC voltage levels	All
PROTECTIVE RELAYS	Trip 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. While numerous issues are associated with grid modernization, several interrelated challenges have direct implications for substations. These challenges include accommodating high penetration of distributed generation, enhancing security and resilience to a number of threats and hazards, ensuring reliable operations with rapid system changes, and making prudent investments in an environment of greater uncertainty. The immediacy of these challenges is prompting the exploration of various solutions spanning new technologies, improved standards, proper designs, and better planning and modeling tools.

2.2.1 Accommodating Distributed Generation

With greater adoption of solar photovoltaics (PV), combined heat and power (CHP) systems, 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. The integration of DERs into microgrids will also result in asynchronous systems with low short-circuit currents during islanded conditions, presenting challenges to system protection.

One of the biggest concerns is the back-feeding of energy into the distribution system, and potentially back into the transmission system, particularly in the absence of distributed energy storage. 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 affect 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 affect equipment performance, especially in situations where energy from distributed generation exceeds local consumption.

The intermittency of PV presents another unique challenge because it can cause rapid voltage fluctuations along feeders. Load tap changers or voltage regulators located within the 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 couple with substation equipment, such as capacitor banks, and cause 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

2.2.2 Enhancing Security and Resilience

The greater utilization of advanced information and communication technology (ICT) in the electric power system has enabled improved monitoring, more efficient operations, and increased 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; cybersecurity requirements will need to be included in substation designs and retrofits. Ensuring the scalability, upgradability, and interoperability of cybersecurity solutions across various substation locations and categories will be critical, especially as cyber-attacks grow in frequency and sophistication. Physical security has also been a growing concern after the 2013 Metcalf substation attack in which 17 transformers were severely damaged from sniper rifles. This incident resulted in a demand for hardening technologies and increased security that will add to substation costs.

Additionally, as electricity becomes more vital to our digital economy and societal well-being, increased resilience to a range of natural and manmade 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 and geomagnetic disturbances can permanently damage large power transformers 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 energy generation, are introducing large and fast swings in power injection and voltages on the transmission system. The locations 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 transmission lines and associated substations.

New loads and applications such as batteries, electric heating, and megawatt (MW)-level fast charging and wireless charging of electric vehicles can lead to large and quick swings in power consumption that can also jeopardize system stability if not properly coordinated. The rapid fluctuation of these loads can have adverse effects on voltage stability and inject harmonics into the system, potentially requiring substation upgrades to manage these dynamics and ensure power quality and reliability. Changes in demand due to greater electrification (e.g., transportation, heating), changing demographic and economic conditions, and new industries (e.g., urban farming, bitcoin mining) will also alter system power flows and may require new or upgraded substations, especially near dense urban centers.

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. These loads 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—with load growth from electric vehicle charging, negative load growth from customer adoption of DERs and microgrids, and substation upgrades to meet reliability and cybersecurity requirements—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 and the cyber threat landscape is ever-changing. Customized components, interoperability, and backwards compatibility with legacy devices add to the integration challenge and increase costs. These large expenses must be carefully planned to ensure that the benefits outweigh the costs and utility commission approval is received.

Additionally, the development of more advanced applications, such as offshore wind farms and DC networks, will be impacted by the cost, performance, maintenance, ease of installation, and serviceability of associated substations. Stringent interconnection requirements, different operating environments, and timing of approvals can all introduce uncertainty and risks that jeopardize the successful implementation of a project. The customized nature of substation equipment for a range of new and existing applications, along with evolving standards and requirements, makes it more difficult to efficiently and effectively invest in grid modernization.

3. Solid State Power Substations

“Solid state electronics” refers to electrical switches based primarily on semiconductor materials and is responsible for launching the digital revolution, which 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. “Power electronics” refers to technologies that are 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) and is 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 (< 1,500 W), while medium- to high-voltage applications have been much more limited due to technical challenges and high costs.

This chapter examines the current state of power electronic technologies used in grid-scale applications. This chapter also explores the opportunities 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 or “grid nodes” can facilitate evolution of the grid by enabling new grid architectures; improving asset utilization; increasing system efficiency; controlling power flow with unprecedented speed and flexibility; enhancing reliability; 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 1920s, with mercury arc valves serving as the high-power switches. The systems incrementally improved with the transition to solid-state devices (e.g., thyristors, insulated gate bipolar transistors [IGBT]) in the 1970s. There are currently two main types of power electronic systems used in the transmission system: flexible AC transmission system devices and high-voltage direct current. More recently, with the greater deployment of solar PV and battery energy storage, the number of inverters and converters in the grid has increased, especially in distribution systems. While there has been significant interest in the concept of a solid state transformer (SST) for utility applications, SSTs have largely remained in the R&D phase. There are unique design and integration challenges related to greater adoption of these power electronic systems, but one common barrier is high cost. Emerging concepts that can be considered hybrid transformers are being developed and deployed on distribution systems that begin to address the issue of high costs.

3.1.1 Flexible AC Transmission System

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.” 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 and transient stability, and damp power system oscillations. Depending on their configuration (e.g., shunt versus series) and the technology used in the power electronic converters (e.g., thyristors versus 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 growing demand for FACTS devices. Recent innovations include utilizing multiple fractionally rated devices along transmission lines that can be coordinated to provide power flow control capabilities.[7] This modular and distributed approach begins to help address the issue with cost. In addition to transmission applications, the need for power flow control capabilities in distribution systems, especially in meshed networks with large amounts of DERs, is prompting the development and deployment of solutions such as custom power devices and hybrid transformers, discussed in more detail below.

Table 3: List of FACTS Devices and Their Costs

FACTS DEVICES	FUNCTION	COST
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, high-voltage direct current (HVDC) systems are used in the grid for the 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 interconnection of offshore 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 percent per substation, while VSCs are newer and have losses of about 1.4 percent–1.6 percent per substation. While losses are higher for VSCs—and their maximum rated power is smaller than for LCCs—VSCs 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 provides a value stream. Additionally, VSCs can provide black start capabilities, enable multi-terminal configurations, and are easier to deploy without complex studies and system reinforcements, unlike LCCs.

The capabilities and benefits of HVDC systems may become more important as the grid evolves. For example, as we connect more remote wind and utility-scale PV facilities and the degree of electrification increases, the need to increase transmission capacity will also likely grow.[8,9] Converting HVAC lines to

HVDC is an option that holds considerable promise for moving more power through an existing transmission corridor.[10,11,12,13] Installation of HVDC systems has also been growing in Europe, India, China, and other countries for a variety of applications, including the provision of ancillary services. More recently, the development of HVDC converters for medium voltage (MV) and distribution system applications (i.e., medium-voltage direct current [MVDC]) is being explored and considered. There has also been research on new ways to utilize these technologies, such as in multi-terminal and multi-frequency connections.[14,15]

Figure 3: HVDC Converter Hall for 320 kV 2 GW VSC Transmission Link

3.1.3 Grid-Tied Inverters and Converters

“Inverters” is the general term for power electronic converters that change DC power to AC power. These power electronic systems are critical to the integration of variable renewable resources and battery energy storage because they enable the electricity generated or stored to be injected back into the grid. Recently, the increased demand for DERs (e.g., rooftop PV, distributed batteries) has led to a significant number of inverters and converters being deployed within customer premises (i.e., behind-the-meter). These low voltage, low power systems can be directly connected to the local grid of the facility, easing integration. However, inverters and converters for grid-tied applications (i.e., those connected upstream of a utility meter), such as MW-scale batteries, solar farms, and wind farms, generally require a step-up transformer to interconnect with the distribution system or transmission system, adding to costs.

Currently, most installed PV inverters (both grid-tied and behind-the-meter) operate at unity power factor and do not provide any support functions to the grid. 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 the Institute of Electrical and Electronics Engineers (IEEE) standard 1547 and the development of smart inverters will enable these power electronic systems to become more “grid-friendly.” However, there is an opportunity to expand their capabilities to further support the grid, such as through power factor correction, as shown in Figure 4. The injection or absorption of reactive power allows smart inverters to regulate voltage, help stabilize the grid, and control power flows on networked feeders. The maturation of wide band gap (WBG) semiconductor devices is also enabling inverters and converters to directly connect to the distribution system without a step-up transformer.

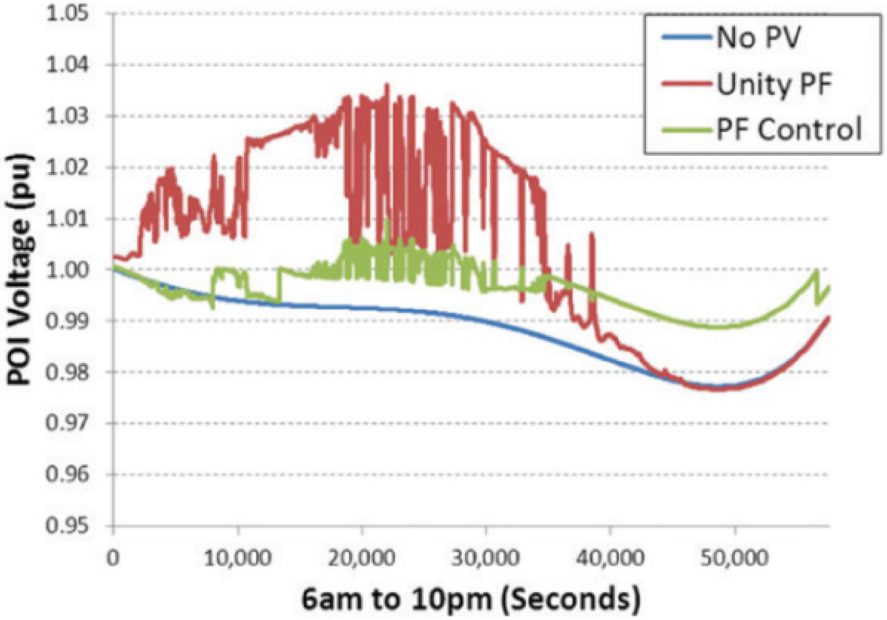

Figure 4: Power Factor Control With a Smart Inverter[16]

3.1.4 Solid State Transformers

Traditionally, an SST is composed of front-end and back-end power electronic converters, coupled through an isolation transformer that can connect two different AC voltages (see Figure 5). The primary benefit of this design, compared to a conventional line frequency (e.g., 60 Hz) transformer, is the ability to use a high frequency (HF) link that 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. It is important to note that the HF transformer is not mandatory in an SST design, and other device architectures are possible. Advanced functions and features of these systems include allowing bidirectional power flow, input or output of AC or DC power, and active control of frequency and voltage, which can be used to improve power quality. These capabilities have implications for the adoption of microgrids, enabling seamless islanding and reconnections, and advance system topologies such as hybrid grids (i.e., combination of AC and DC circuits).

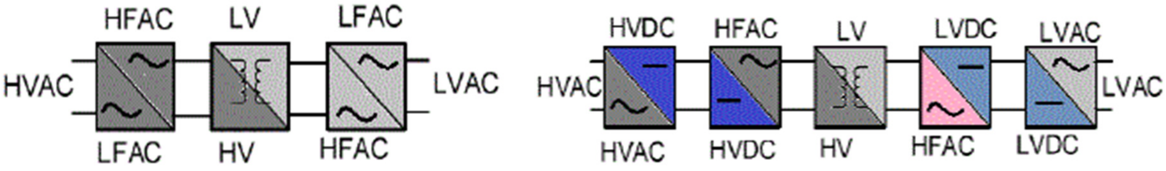

Figure 5: Different Block Diagrams for SSTs[17]

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 than conventional transformers. In general, these power electronic systems cannot compete as a one-to-one replacement for utility transformers, especially within transmission substations that demand very high efficiencies. Moreover, the typical lifetime of a line frequency transformer is approximately three times higher than that of a power electronics converter. SSTs will need to be valued for the additional services and capabilities they can provide to justify the added complexity and costs. For example, transformers whose electrical properties can be tuned to meet the needs of specific locations within the grid could provide substantial value for national security in the event of large natural disasters or terrorist attacks.[18,19] 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[20]	MEGALINK[21]	UNIFLEX[22]	EPRI IUT[23]	CREE[24]
VOLTAGE	7.2 kV / 280 V	10 kV / 400 V	3.3 kV / 415 V	2.4 kV / 480 V	13.8 kV / 465 V
POWER RATING	20 kVA	1 MVA	300 kVA	45 kVA	1 MVA
MOBILITY—ASSEMBLED INTO A TRAILER	Large	Large	Large	Large	Large
MAIN DIELECTRIC	Air + Module	Air + Module	Air + Module	Oil	Air + Module
MOBILITY—AS MODULAR, FREE-STANDING UNITS	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

3.1.5 Hybrid Transformers

Hybrid transformers are a relatively new concept; they involve the integration of conventional line frequency transformers with power electronic converters to achieve advanced functionalities. While similar in principle to SSTs, the key difference is that hybrid transformers do not require converters to be rated at the full power of the system or the voltage levels they are connecting. Utilizing fractionally rated converters or converters only on the low voltage end of the system enables mature power electronic technologies to be combined with legacy component designs. This simplifies the system and helps address concerns of the high costs and typically lower reliability of traditional SSTs.

Currently, low-power systems (e.g., 50 kVA) are commercially available[25] and can be integrated on the low voltage end of a distribution transformer, upstream of a customer meter. These systems can provide multiple grid support functions, including autonomous power factor correction, voltage regulation, and integrated control and monitoring through a secure SCADA (supervisory control and data acquisition) interface. Other designs have shown the capability to provide a voltage control range of ±10 percent and reactive power up to 10 percent while maintaining efficiency as high as 99 percent.[26,27,28] Higher power systems (e.g., 66 MVA) are being explored based on a modular design that connects a converter to the neutral of a power transformer. This concept is capable of controlling apparent impedance, voltage, and phase and can be deployed in a centralized or distributed manner. Additionally, it builds off industry standard designs for the transformer and converter, lowering development risks and eventual system costs.

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 numerous advanced functionalities 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 and configurations, including those discussed above, can enable the economy of scale needed to help accelerate cost reductions and improve reliability. Availability of this core SSPS technology will be critical to realizing the SSPS vision.

Ultimately envisioned as a system consisting of modular, scalable, flexible, and adaptable power blocks that can be used within all substation applications, as depicted in Figure 6, SSPS converters will serve as power routers or hubs that have the capability to electrically isolate system components and provide bi-directional AC or DC power flow control from one or more sources to one or more loads—regardless of voltage or frequency. SSPS converters will also include functional control, communications, protection, regulation, and other features necessary for the safe, reliable, resilient, secure, and cost-effective operation of the future grid.

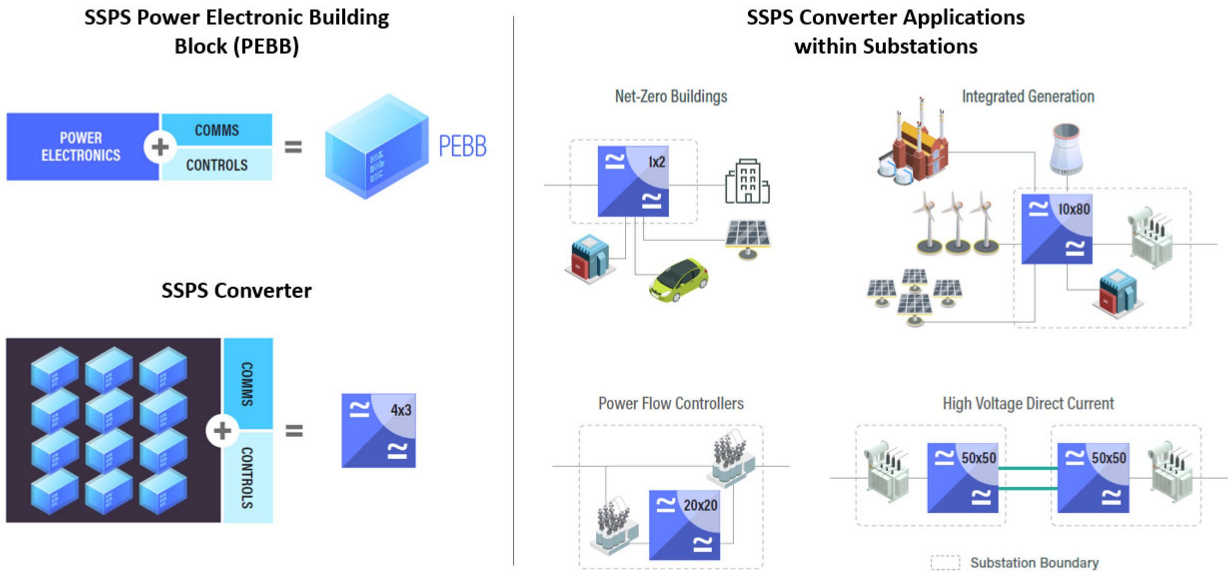

Figure 6: Vision for SSPS Converters

There are a range of challenges associated with the development and adoption of new grid hardware technologies, including integration and understanding their impact on operations, maintenance, and existing practices. Achieving the vision articulated for SSPS (i.e., SSPS technology will be mature, reliable, secure, cost-effective; broadly used across the grid in a variety of substation applications; and an integral part of the future electric power system) will require a staged approach that incrementally broadens the application space, integration experience, and technical sophistication 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 converters and associated applications have been identified—designated as SSPS 1.0, SSPS 2.0, and SSPS 3.0—which mark milestones in their developmental pathway and integration in the electric grid. Each classification is based on the voltage and power ratings of the SSPS converter application, as well as on defining functions and features they enable. Their progressive advancement is outlined in Table 5, indicating the capabilities for each generation that expands upon those of the previous generations (denoted by the "+"). The order of the list does not mean the capability is to be developed sequentially or that it does not exist today; it is meant to indicate when the SSPS converter function and feature is thought to provide the most value along its maturation.

Table 5: SSPS Converter Classification and Defining Functions and Features

CONVERTER CLASSIFICATION	**DEFINING FUNCTIONS AND FEATURES**
SSPS 1.0 UP TO 34.5 KV 25 KVA–10 MVA	• Provides active and reactive power control • Provides voltage, phase, and frequency control including harmonics • Capable of bidirectional power flow with isolation • Allows for hybrid (i.e., AC and DC) and multi-frequency systems (e.g., 50 Hz, 60 Hz, 120 Hz) with multiple ports • Capable of riding through system faults and disruptions (e.g., high-voltage ride through, low-voltage ride through) • Self-aware, secure, and internal fault tolerance with local intelligence and built-in cyber-physical security
SSPS 2.0 UP TO 138 KV 25 KVA–100 MVA	+ Capable of serving as a communications hub/node with cybersecurity + Enables dynamic coordination of fault current and protection for both AC and DC distribution systems and networks + Provides bidirectional power flow control between transmission and distribution systems while buffering interactions between the two + Enables distribution feeder islanding and resynchronization without perturbation
SSPS 3.0 ALL VOLTAGE LEVELS ALL POWER LEVELS	+ Distributed control and coordination of multiple SSPS for global optimization + Autonomous control for plug-and-play features across the system (i.e., automatic reconfiguration with integration/removal of an asset/resource from the grid) + Enables automated recovery and restoration in blackout conditions + Enables fully decoupled, asynchronous, fractal systems

The envisioned evolution of SSPS technology and integration into the grid is depicted in Figure 7. Converter power and voltage ratings limit where SSPS can be used (e.g., distribution, transmission), and the defining functions and features limit the breadth of coordination and controls that can be enabled.

SSPS 1.0 is expected to involve applications at distinct substations or "grid nodes" and local impact, such as those associated with industrial and commercial customers, residential buildings, or community distributed generation/storage facilities at the edges of the grid. Applications at lower voltage levels (up to 34.5 kV) and power ratings (up to 10 MVA) present less of a concern to broader system reliability and enable the foundational functions and features of SSPS converters to be developed. Improved controls, increased power density, and hybrid (i.e., AC and DC), multi-frequency, multi-port capabilities of SSPS 1.0 are critical to establishing initial value for this technology. Integrating advanced computational capabilities (e.g., field-programmable gate array [FPGA], parallel computing), embedded cyber-physical security, and sensors for local intelligence will also be foundational to SSPS evolution.

SSPS 2.0 is envisioned to expand on the capabilities of SSPS 1.0, increasing the voltage level (up to 138 kV) and power ratings (up to 100 MVA) of the converter application. This classification also integrates enhanced and secure communication capabilities, extending applications to include those at distribution substations, such as integration of advanced generation technologies (e.g., small, modular reactors, flexible combined heat and power), and utility-scale generation facilities. As SSPS applications broaden and move toward the transmission system (i.e., away from the edges of the grid), the communication capabilities are critical for coordination with downstream protection and control actions to ensure safe and 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, seamless integration of new assets and resources, and automated recovery and restoration in blackout conditions. 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.

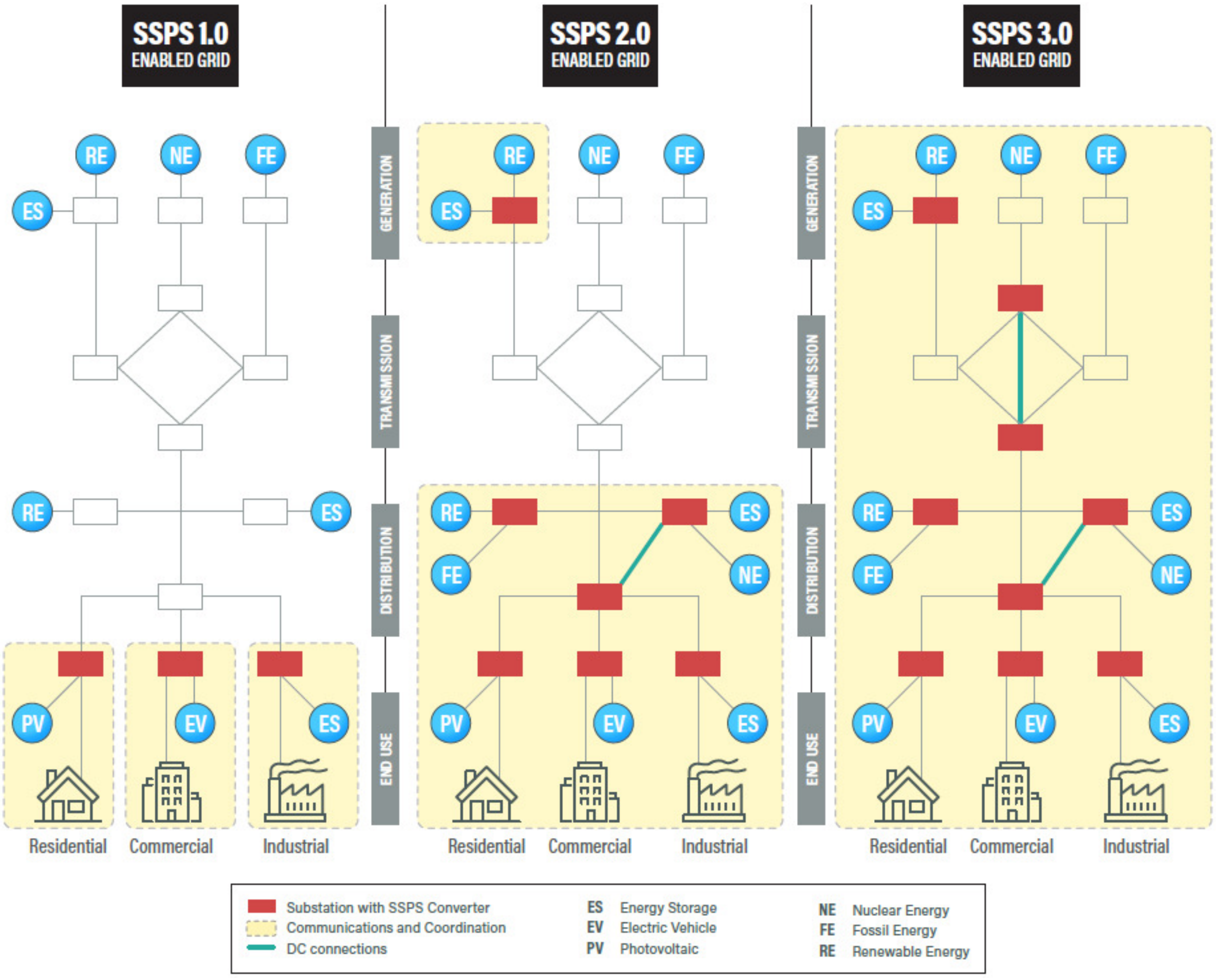

Figure 7: SSPS Enabled Grids Through Its Evolution

3.3 SSPS Benefits

SSPS technology provides a means to achieving the goals of a modernized grid: increased resiliency, reliability, security, and flexibility. There are a range of benefits associated with the use of SSPS converters, as envisioned, that can address many of the challenges identified in section 2.2. Greater integration of SSPS converters within substations can:

- Increase energy efficiency by optimizing between the use of AC and DC topologies/networks to minimize total system losses and facilitate the integration of multiple types of distributed energy resources, including battery energy storage[29] and eventually micro nuclear reactors.
- Improve power quality, system stability, and system operations through the ability to inject and absorb real and reactive power, fast and dynamic control of frequency and voltage, and buffering different parts of the grid as needed.
- Increase asset utilization, substation and transmission line capacity, and distribution system performance through power flow control, managing peaks, interphase balancing, and load sharing between circuits.

- Enhance protection and system reliability through fault current limiting capabilities, fast fault clearing, the ability to rapidly isolate and stabilize faulted parts of the system, and the provision of essential reliability services.
- Increase performance and lifetimes of existing equipment and systems connected to substations and within substations (e.g., conventional generators, transformers) by augmenting assets with greater flexibility, controllability, and monitoring capabilities.
- Simplify and reduce the costs of capacity expansion, upgrades, and new installations due to the modular, scalable, flexible, and adaptable nature of the converters (e.g., AC/DC universality, plug-and-play, use in weak/strong grids), higher power densities, and integrated functions.
- Accelerate installation and commissioning of new substations due to smaller footprints from integrating traditional component functions (i.e., eliminating circuit breaker, capacitor banks) and alleviating community concerns (e.g., lower audible noise, undergrounding).
- Increase security and resilience due to modular, standardized converter designs that reduce criticality of substation components, ease of transport and sharing in emergency and recovery situations, built-in cyber-physical security, and availability of black start support capabilities.
- Enable new grid paradigms and architectures such as greater use of DC topologies (e.g., DC distribution), operating substations like an energy router, new control concepts (e.g., transactive, dynamic pricing), and novel business models, including differentiated quality of service.

Despite the numerous benefits, deployment of SSPS technology must provide advantages that outweigh its costs and therefore requires analysis of the application, the needs at the specific substation, and possible alternative solutions. However, it is important to consider how the modular and scalable nature of SSPS converters can be used to progressively upgrade substations when opportunities arise: by replacement of outdated or failed components as a means to upgrade functionality and capacity to meet new requirements or by new substation installations. Various deployment opportunities for the three SSPS converter classifications are discussed in chapter 4, 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 need for greater flexibility to accommodate variable renewable generation, these power system changes are opportunities to advance SSPS technology. These demands, in addition to load growth around the world, are driving advancement in power electronic systems for transmission systems (e.g., HVDC and FACTS devices), including new converter topologies, advanced controls, and higher voltages and power levels. Simultaneously, advances are being made in solar inverters, storage converters, and microgrid controllers at the distribution level through adding enhanced functionality and enabling connections to higher voltages. Underlying research is also ongoing in materials, components, subsystems, autonomous controls, and modeling associated with these developments.

Alignment of the various R&D efforts discussed above, and identifying deployment opportunities for SSPS converters across the range of substation applications as the technology advances, will help chart a pathway to maturing SSPS technology (see Figure 8). This chapter identifies some of the potential applications for SSPS converters that can help drive deployment, while chapter 5 focuses on R&D gaps and opportunities. This roadmap does not set timelines or targets for SSPS converter deployment, as market conditions, technology costs, and value proposition in specific applications will ultimately drive adoption rates. However, this roadmap does identify time frames for research activities that will help achieve the functional requirements and performance objectives of SSPS technology.

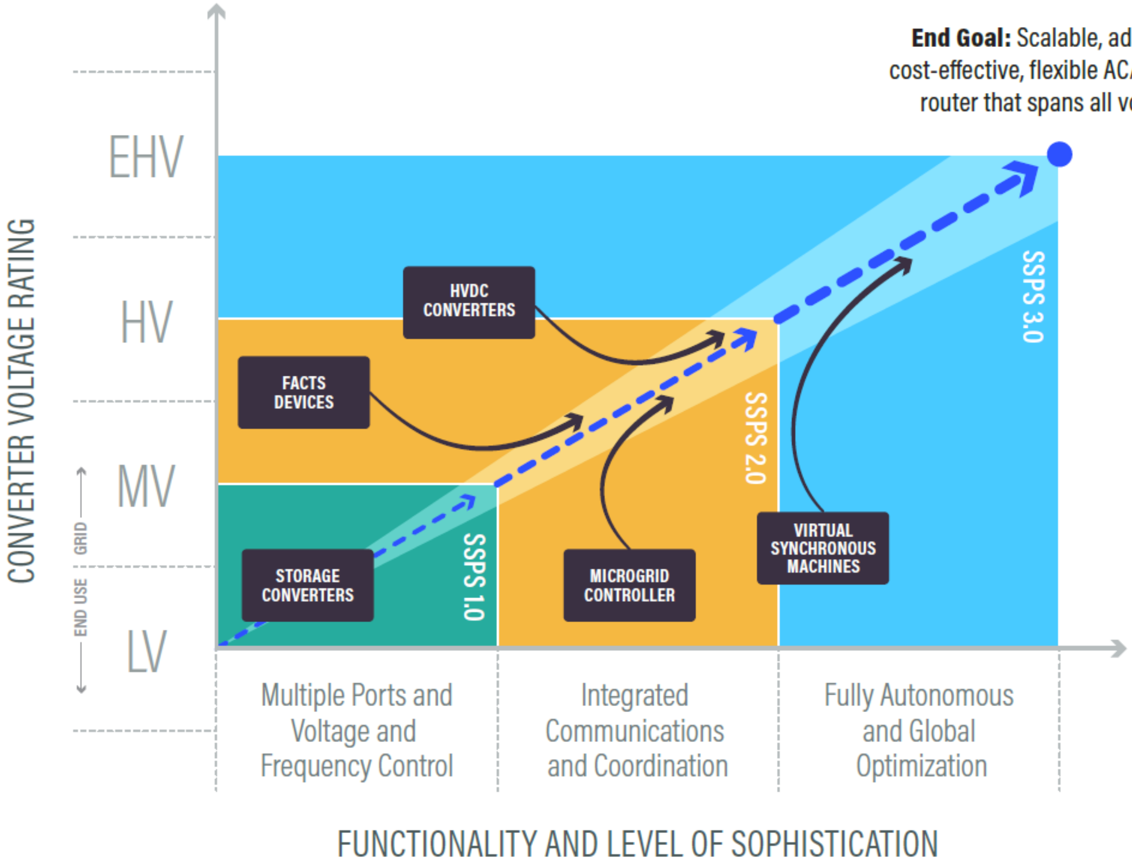

Figure 8: SSPS Technology Development Pathway

4.1 Potential Applications of SSPS 1.0

Opportunities for SSPS 1.0 involve the use of SSPS converters in local or grid-edge applications, focusing on adding new functionality, easing DER integration, and increasing hosting capacity in distribution systems. These lower voltage and lower power applications can be more easily deployed because 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 the 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, active power factor correction, voltage and frequency regulation, and the isolation of faults.

Discrete applications for SSPS 1.0 could include strategically connecting radial feeders to form meshed networks while providing power flow control, thereby increasing line redundancy and resilience; and serving as a static transfer switch to provide high availability of power to critical industrial or commercial loads by rapidly switching between a preferred feeder and an alternate. SSPS 1.0 can also be used to facilitate the integration of electric vehicle charging infrastructure by making them more grid-friendly, especially considering the potential impacts of extreme fast charging or wireless charging.

The growing demand for energy efficiency and increased resilience for data centers, buildings, campuses, manufacturing facilities, and homes also presents a large opportunity for SSPS 1.0. The hybrid, multi-frequency, and multi-port capability can more efficiently integrate disparate sources and loads, enabling more optimal designs and configurations such as a DC data center, DC buildings, and net-zero homes. Other applications include simplifying the integration of DERs with one another (e.g., through a DC tap), such as combining solar PV, batteries, and responsive load, to maximize efficiency and provide enhanced controls to meet customer or local power needs. This flexibility helps future-proof the initial investment, enabling new generation and new loads to be seamlessly integrated as needed.

Enhanced local control capabilities can also be extended to nanogrid or microgrid applications because SSPS converters can serve as the point of common coupling to the electric grid. For example, several houses tied to the same distribution transformer can be interconnected to share resources, such as energy storage and distributed generation, forming a community microgrid. Other than enabling multi-directional power flow control, SSPS 1.0 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 bases), 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

Opportunities for SSPS 2.0 are mostly the same as for SSPS 1.0 but at higher voltage levels and power ratings. SSPS 2.0 can be used to form microgrids on large campuses or military bases, integrate battery energy storage[30] with variable renewable resources (e.g., wind, solar PV) at the utility-scale to make them more dispatchable, and enable DC feeders and distribution systems for improved efficiency. SSPS 2.0 can also be used to facilitate the integration of advanced generation technologies such as small, modular reactors and flexible combined heat and power systems. However, there are a few new applications for SSPS 2.0 associated with the extension of SSPS converter capabilities that include integrated communications, computation, and analytics. These enhanced capabilities enable regional control and coordination of assets, resources, and fault protection, which are critical for broader deployment of SSPS technology across the grid.

SSPS 2.0 can serve as an integrated smart node within the transmission and distribution systems, helping to manage complexity and handle scaling challenges as the system evolves, especially with increasing numbers of DERs and active consumers throughout distribution systems. For example, an SSPS converter deployed at a distribution substation can coordinate with various downstream SSPS converters (e.g., those deployed in 1.0 applications) to improve management of the distribution system through volt-VAR optimization and power flow control in meshed networks. Another application is smart charge management, with large fleets of EVs to mitigate impacts on the distribution system and delay infrastructure upgrades. This expanded 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 is associated with the higher voltages and power ratings that enable SSPS converter deployment within transmission and distribution substations. These applications help enhance grid reliability and flexibility, such as by serving as dynamic load-tap changers to regulate voltages on distribution feeders or as FACTS devices (e.g., unified power flow controllers) to improve stability in response to disturbances (e.g., damping oscillations). They can also provide power flow control to improve asset utilization and manage system congestion (e.g., moving power between lines). 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 remove the need for downstream circuit breakers in distribution substations. Another possibility is taking an entire distribution network temporarily off the bulk grid to relieve congestion.

SSPS 2.0 can enable new grid paradigms such as MVDC in sub-transmission and distribution systems, including offshore wind and sub-sea applications. MVDC systems that use SSPS converters with integrated breaker functionality can create links between distribution substations, routing power in emergency situations and supporting power-balancing between distribution systems in normal situations. The integrated communications capabilities can also be used to coordinate the control of networked microgrids, enabling islanding and resynchronization of these various systems without perturbing the transmission system.

Other potential applications include mobile substations and next-generation transformers that are more flexible and adaptable for increased resilience. SSPS converters can augment current designs or enable advanced designs with higher power densities, new functionalities, and communication capabilities. These new features can reduce size and weight to facilitate transport, enhance interchangeability to accelerate recovery and restoration, and enable undergrounding for increased security.

4.3 Potential Applications of SSPS 3.0

Because SSPS 3.0 builds on the SSPS converter capabilities used in SSPS 2.0, a majority of opportunities for SSPS 3.0 are the same as for SSPS 1.0 and 2.0. However, they are now expanded to any voltage level or power rating. Key new functions and features of SSPS 3.0 include autonomous controls, blackout recovery capabilities, and coordination and optimization of multiple SSPS converters across the entire electric power system. At this point, SSPS converter development should reach the envisioned end-state of a scalable, flexible, and adaptable energy router or hub. The technology should also be cost-effective, proven, and trusted to enable several new applications and grid paradigms.

The distributed, autonomous control capabilities associated with SSPS 3.0 can make the electric power system behave more like modern communication systems, which would enhance reliability and resilience. New applications include dynamic, real-time routing of power flows; graceful degradation and rapid isolation during disruptions or failures; automated recovery and black start coordination after outages; and true plug-and-play functionality that adjust system-wide 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 with 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 large power transformers (i.e., capacity greater than 100 MVA) in critical substations with more modular designs that can reduce their criticality, increasing resilience. The high-power density of SSPS converters and the full suite of functions and features can be used to create entire substations with smaller footprints, enabling indoor or underground applications and increasing system capacity in dense urban centers.

5. SSPS Technology Challenges, Gaps, and Goals

In addition to the deployment opportunities identified in chapter 4, there are 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; their associated goals are summarized in Table 6. “Substation application” refers to challenges associated with developing the full SSPS converter system that can be used in multiple substation applications. “Converter building block” refers to challenges associated with developing the fully functional, standalone “modules” that can be put in series or parallel to form the SSPS converter. “Grid integration” refers to challenges associated with integrating multiple SSPS converters into electric power system design, operations, and planning.

The goals listed in Table 6 reflect functions, features, or targets that should be achieved (at a minimum) to realize each classification of SSPS technology. They are color-coded to indicate the resources or level of effort needed to close the gaps. Green indicates that current R&D activities are sufficient to achieve goals and that modest efforts will be needed to integrate advances into SSPS technology. Yellow indicates that current R&D activities are making progress toward goals but could benefit from additional resources and intentional focus. Red indicates 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.

As discussed in chapter 4, this roadmap does not set timelines or targets for SSPS converter deployment. However, it does identify time frames (e.g., near-term, midterm, and long-term) for research activities needed to achieve the goals outlined for each classification of SSPS. It is important to note that the goals serve as important milestones in the progressive advancement of SSPS technology but may not be comprehensive of needs. Additionally, the goals associated with the various challenges expand and build upon the success of previous generations. However, activities to reach the goals across the three classifications do not need to be sequential; some may require pursuit parallel with each other. For example, research in dielectric materials needed for SSPS 3.0 may be completely different from those needed for SSPS 2.0.

Table 6: R&D Challenges and Goals for SSPS Technology

		SSPS 1.0 UP TO 34.5 KV UP TO 10 MVA	SSPS 2.0 UP TO 138 KV UP TO 100 MVA	SSPS 3.0 ALL VOLTAGES ALL POWER LEVELS
GOALS	**R&D Challenges**	**Goals**		
SUBSTATION APPLICATION	Power Converter Architecture	Modular, flexible, and scalable for multiple applications with high reliability and built-in cyber-physical security		
	Converter Controller and Communications	Local Intelligence; Self-Aware and Auto-Configuration	Grid Forming and Synchronization; Wide Area Connectivity	Autonomous/AI and Distributed Controls; Peer-to-Peer
	Converter Protection and Reliability	Fault and Over-Voltage Tolerant; Withstand Electromagnetic Interference and meets Basic Impulse Level; Manages Inrush/Fault Currents		Adaptive/Dynamic; Self-Healing
	Converter System Cost and Performance	< \$150/kVA > 96% 2 MW/m^3 10-Year Mean-Time-to-Failure (MTTF)	< \$125/kVA > 96.5% 5 MW/m^3 20-Year MTTF	< \$100/kVA > 97% 10 MW/m^3 40-Year MTTF
CONVERTER BUILDING BLOCK	Block/Module Cost and Performance	< \$20/kVA > 97% 5 W/cm^3 2-Year MTTF	< \$15/kVA > 98% 10 W/cm^3 4-Year MTTF	< \$10/kVA > 99% 20 W/cm^3 8-Year MTTF
	Drivers and Power Semiconductors	≥ 1.7 kV \$0.10/kW	≥ 3.3 kV \$0.10/kW	≥ 10 kV \$0.10/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, Hybrid, and Multi-Frequency Paradigm	
	Grid Control and Protection Systems	Coordinates with Existing Protection	Dynamic Fault Detection and Adaptive Protection	Graceful Degradation and Automatic Black Start
	System Modeling and Simulation	Tools and models capable of analyzing advanced controls, power flows, short circuits, faults, power quality, dynamics, and transient stability		

5.1 Substation Application

Deployment and integration of SSPS converters within substations or "grid nodes" 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, have the flexibility and adaptability to be utilized in a range of substation applications, and possess optionality for subsequent upgrades and capacity expansion. Aspects to consider and balance between 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 converter system 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), midterm (within 10 years), and long term (within 20 years) are identified at the end of this section.

5.1.1 Power Converter Architecture

Because power electronic converters are at the core of SSPS technology, it is very important to ensure that their design and circuit topologies can meet operating and security requirements across a range of applications. Architectures for SSPS converters will need to be capable of expanding functionality, to scale up in power and voltage ratings as needed, and to be compatible with new and legacy components. Other features that need to be considered are hybrid, multi-frequency inputs and outputs with multiple ports, multi-directional power flows, galvanic isolation, self-protection and system reliability under non-ideal and faulted conditions, reconfigurability of components, integration with controls and communications, and built-in cyber-physical security. Ultimately envisioned as a system of modular building blocks, the power converter architecture will also need to consider the voltage and power ratings of modules, module subcomponents, and process of replacing and upgrading modules.

5.1.1.1 State of the Art

The modular converter concept has been around since the late 1990s, driven primarily by R&D funded through the Office of Naval Research.[31] Since then, the Power Electronics Building Block (PEBB) concept has continually advanced to meet various electric ship applications, such as increasing energy efficiency and power density of the entire system and for active power management of onboard loads. IEEE explored the extension of this concept to electric power system applications in 2004, with a generic system architecture (see Figure 9). A modular MV substation for electric vehicle charging infrastructure was recently made available. The system design includes MV switchgear, a step-down transformer, and an integrated high-power inverter that complies with local utility standards.[32] However, development is much more limited of converter architectures that are suitable across multiple substation applications, various substation designs, and the range of conversions desired (i.e., AC/DC, DC/DC, DC/AC, AC/AC). Converter architecture designs with built-in cyber-physical security for grid applications are also very limited.

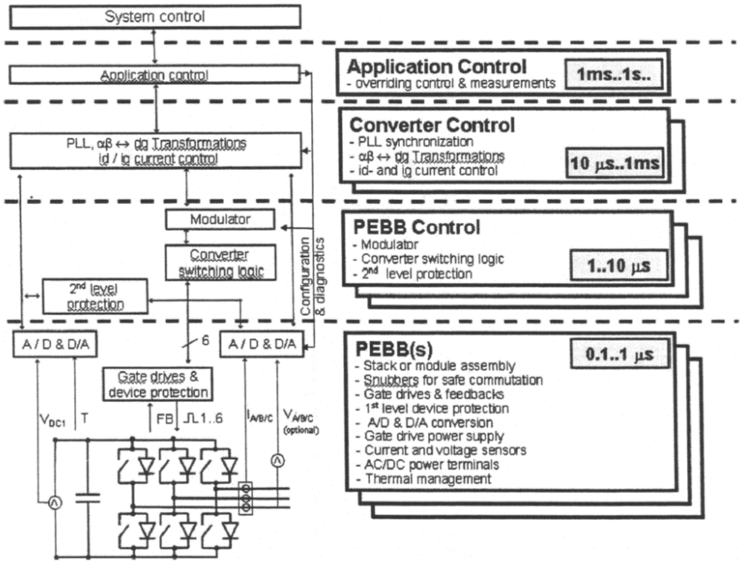

Figure 9: Generic Control Architecture With Power Electronics Building Block[33]

On the other hand, multi-level topologies for various converter stages are making advances in grid applications. These topologies offer lower common-mode voltages, reduced harmonic content, smaller input and output filters, increased efficiency, and improved fault tolerance. Table 7 lists several popular multi-level topologies for AC/DC converters used in applications today, but not all support the desired modularity envisioned of SSPS converters. The high frequency dual-active bridge topology is also a popular choice for modular DC/DC converters and will become more important in DC-based grid architectures.

Table 7: Multi-Level Converter Topology Overview[34]

MULTI-LEVEL TOPOLOGY	CONTROL	VOLTAGE BALANCE CONTROL	MODULAR	MAJOR DISADVANTAGE
NEUTRAL POINT CLAMPED	Simple	Unattainable	No	Systems with more than three levels have voltage balance problems
FLYING CAPACITOR	Complex	Complex	Yes	Require large number of capacitors for high-voltage outputs
CASCADE H-BRIDGE	Simple	Simple	Yes	Number of components reduces efficiency
H-BRIDGE NEUTRAL POINT CLAMPED (NPC)	Complex	Complex	Limited	Complex control and modulation
3-LEVEL ACTIVE NPC	Complex	Complex	No	Number of clamping diodes increases with output level squared
5-LEVEL ACTIVE NPC	Complex	Complex	Yes	Complex circuit
TRANSISTOR-CLAMPED	Simple	Complex	Yes	Large number of transistors
MODULAR MULTI-LEVEL	Complex	Complex	Yes	Complex control

Modern HVDC system architectures have leveraged modular multi-level converter (MMC) topologies to enable scalability and greater flexibility, and equipment vendors have been exploring their application in FACTS devices. Recently, there have been research efforts in adopting MMC topology in solar inverter and battery converter systems to enable direct connection to distribution system voltages. However, technical challenges such as control stability and cost-effectiveness remain. Other efforts have been investigating the impact of various converter module configurations that have direct implications for SSPS converter performance. These configurations include input series output parallel, input parallel output series, and input series output series.[35]

5.1.1.2 Research Gaps

Critical research is needed to develop a flexible, adaptable, and scalable converter architecture that can span multiple grid applications, promote standardization, and meet the defining functions and features for SSPS technology across all three classifications. Research will need to consider the ease of upgrades; hybrid, multi-frequency, multi-port capabilities; multi-directional power flows; and cyber-physical security. The architecture established should promote innovation in the different subcomponents, especially within the power electronics building blocks. Other desirable characteristics include the ability to "hot-swap" modules, some degree of redundancy for high reliability, and direct connection to transmission and distribution system voltages (i.e., 60 Hz transformer unnecessary).

Efforts should emphasize determining suitable module topologies and configurations through multi-objective optimization. This method can be used to develop standardized voltages, power ratings, topologies, and other architecture requirements to ensure interoperability of modules. This design approach will enable backwards compatibility so modules of different generations will be interchangeable as technology improves, especially with the use of WBG semiconductor devices. Standardized isolation requirements for gate drivers, transformers, building blocks, and other components and subsystems will also be critical to a viable design.[36]

Dedicated research is also needed to understand how to coordinate the isolation requirements for high-voltage and high-power converter architectures, especially in grid-scale applications. Use of high-voltage design procedures can help advance the understanding of failure modes and potential mitigation solutions. Multi-objective design optimization should incorporate the impact of electric fields or the partial discharge inception voltages. Additionally, solutions will be required to ensure proper isolation of power stages for communications and controls.

Research in novel converter topologies that leverage advances in semiconductor devices, control methodologies, and new components can also lead to improvements in overall converter performance. For example, an alternative to high frequency magnet-based converter topologies are ones based on capacitor banks. This new topology has the potential for significantly higher power densities and efficiency; research is needed to assess the full potential of this approach. Modular topologies capable of single-phase operation with built-in redundancy will also be needed.

5.1.2 Converter Controller and Communications

The converter controller serves as the brains of the converter system. It manages 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 because they enable connectivity and coordination with other substation equipment and the broader electric power system. Interoperability and cybersecurity, therefore, 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-supporting 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. They use well-established techniques and algorithms for basic functionalities, such as reactive power compensation and setting the direction of power flows. However, new controllers and methods are being developed for HVDC systems that enable grid support functions and management of power transfers, such as providing frequency response and voltage support. Recently, there have been many advances in rooftop PV inverter controllers with plug-and-play functionality to help lower installation costs and research into smart functionality to provide grid support. Research on electric vehicle and grid-scale batteries has also led to intelligent controllers that monitor the health and state of individual cells to optimize battery charging and discharging operations for greater reliability and improved safety. Cybersecurity for these various controllers and applications is also an active research area.

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[37] microgrid controller leverages plug-and-play and peer-to-peer concepts to avoid the need for a master controller and operates autonomously to maintain frequency and voltage. Meanwhile, the CSEISMIC[38] 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[39] is an open-source software platform that was developed to facilitate coordination and control of various loads and energy resources within a building.

As the electric power system becomes more dependent on power electronic devices, with the potential deployment of millions of converters, a fundamental challenge is enabling these large numbers of devices to work together to maintain system stability. Currently, the basic control method for converters requires synchronization with a relatively strong AC signal, which will not be available in a system with a high penetration of inverter-based generators. Ongoing research is exploring new control algorithms to enable these converters to behave like conventional synchronous machines. This virtual synchronous machine concept allows power electronic-based loads and generators to interact reliably without needing a dedicated communications network.[40]

Sensors also play an important role in converter controllers. Good control is not achievable without high quality information such as voltage, current, and phase. As semiconductor devices move to higher switching frequencies, the signals to be measured introduce phenomena that can reduce sensor accuracy. Optical sensors have been developed to measure voltage and current that demonstrate enhanced performance over conventional sensors (e.g., ones based on magnetics) in terms of linearity across a wide dynamic range, minimal and stable phase delay, and bandwidth from several hertz to several kilohertz.

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 International Electrotechnical Commission [IEC] 61850) and wireless (e.g., Bluetooth, ZigBee, LTE, RFID, and INGENU) networking, their application to grid technologies has been less consistent. This diversity brings innovation but also challenges with interoperability and system integration. Development of the Open Field Message Bus framework and architecture has helped solve some of these challenges, enabling enhanced connectivity with field devices and integration of devices at the grid edge.

The costs associated with the various communication technologies and systems still present challenges to broader adoption. Various research efforts focus on developing low-cost communication platforms that can be used in a variety of utility and non-utility applications. There has also been interest in the use of power line carrier (PLC) (e.g., broadband over power lines) as an alternate means of communication to conventional radio/wireless technologies or dedicated fiber that are popular today. Additionally, PLC logic can provide many of the functions desired for advanced controls.

5.1.2.2 Research Gaps

Close coordination between developing SSPS converter architecture and identifying converter controller and communication requirements is critical to ensuring that SSPS converters can allow for expandability and growth as technologies evolve, especially in the fast-changing ICT industry. Development of new control algorithms (e.g., modulation control for efficiency optimization) will need to consider the impact of communication delays. New control algorithms should also be flexible and adaptable to the range of technologies, configurations, and protocols available now and in the future. The need for cybersecurity solutions, possibly down to the chip level (e.g., FPGA, ASIC, microcontroller), and the ability to withstand electromagnetic interference (EMI) and electromagnetic pulses are other areas of investigation that will need to span the entire converter architecture, including the controllers and communication subsystems.

Development of SSPS controllers that can be coordinated solely through peer-to-peer communications and distributed intelligence will require substantial R&D effort. This is especially critical to enable the control and coordination of system recovery in situations where there is limited communications capability or a loss of wide-area system control, including during blackout conditions. The future grid should be able to provide basic electric service without relying on communication networks. This would mitigate risks posed by natural disasters and unforeseen situations when communication devices or networks are damaged, compromised, or fail to respond.

To sustain operations during a contingency or emergency, advanced autonomous control should be able to prioritize loads, fragment the system, and form microgrids. Research in artificial intelligence, distributed intelligence, and self-learning can be used to improve SSPS converter performance and response for enhanced security, reliability, and resilience. These algorithms should be able to learn and adapt to normal and abnormal grid conditions, including to detect islanded conditions. 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 microgrids that are connected asynchronously.

Certain advance controller functions, such as self-protection and fault tolerance, will depend on having situational awareness of internal and external conditions independent of information from external communication systems (e.g., SCADA) that may be too slow or potentially compromised. Also needed are sensors and analytics that can measure the local parameters of interest and accurately assess conditions within the converter and the surrounding environment (e.g., system impedances). Challenges remain with costs, performance (e.g., resolution, linearity, stability, bandwidth), immunity to EMI, timing accuracy, and data fusion.

Low-cost, secure, and robust communication platforms that can be integrated and upgraded with SSPS converters in a modular fashion will also be needed. As SSPS technologies evolve, they should be able to operate in emergency situations and handle a range of data and timing needs depending on the application.

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 converters 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 in order to meet system demands from faults and inrush currents. Ideally, SSPS converters should be self-healing, possessing the ability to detect compromised, 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; these standards 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 are surge arresters, metal oxide varistors, and spark gaps in over-voltage conditions. Fuses, relays, and contactors detect and isolate components in over-current conditions.

Increasing converter reliability has focused on design principles and standards, such as basic impulse level ratings, to ensure that 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. Some other systems use a hybrid design with an analog transformer alongside the solid-state devices to respond to overload situations. Finally, other practices that improve reliability are introducing redundancy in the converter architecture, utilizing de-rated power electronic devices, and having internal monitoring.

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 or other energy storage technologies 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.

Sensors also play a critical role in the protection and reliability of converters because they are used to determine normal and abnormal operating conditions. These sensors need to tolerate the extreme environments associated with grid operations and faults. Optical instrument transformers for voltage and current measurements have been developed that do not contain explosive materials (e.g., oil) for increased safety and have 100 percent immunity to external electromagnetic effects including EMI. They can operate at 65 kV and 1,000 amps nominally, and have been tested to 550 kV impulses and 265 kV without any damage or loss in performance.

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. Existing equipment within substations must survive short-circuit currents of up to 40 times nominal current for 1.5 seconds. For example, line frequency transformers are designed to deliver 25 times their rated current for at least 2 seconds. These requirements are not possible with power electronic systems without significantly overrating the semiconductor devices because they have thermal time constants on the order of milliseconds. Simply increasing the power rating of the converter is not a pragmatic solution, as it will be prohibitively expensive. 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.

In general, advances in converter protection and reliability will need to be made in concert with the converter architecture and consideration of the overall grid's protection and control schemes (i.e., grid architecture). For example, SSPS converters should actively contribute to fault mitigation schemes, such as by limiting fault currents, withholding any energy stored within their structure under faults, and avoiding fault propagation. This will have implications for the converter, such as enabling a degree of programmable fault control. Integrating circuit protection and fault-tolerance capability for the converter itself (e.g., quickly bypassing a faulted module without affecting operation) is also desirable and can help lower total system costs.

Equipment health monitoring of the converter system, as well as at the subsystem and component levels, and machine learning techniques such as predictive maintenance and prognostics should also be explored. Converter protection and reliability must take into consideration the impact of mechanical vibrations, acoustics, and thermal parameters that can play an important role in understanding the converter's state of health. In the case of insulation materials and dielectrics, chemical parameters (e.g., specific vapors, dissolved gases) can be key indicators of acute or longer-term degradation. Operational performance parameters such as the status of cooling systems also should be included. Integrated sensing and measurements of key electrical parameters that indicate overall system power flows, stability, and faults are also important, as discussed in section 5.1.2.2.

Assessing and understanding the full range of failure mechanisms in SSPS technologies, including their integration into substations, is a fundamental need in advancing converter protection and reliability. The reliability of a system is determined by the reliability of its weakest component. For example, converters have auxiliary equipment such as power supplies for gate drivers and thermal management systems (e.g., cooling fans, pumps). These subsystems must be powered at all times and can lead to system failure if power is lost. Research toward reliability-oriented designs that take into consideration application-specific profiles, abnormal or compromised conditions, and their impacts on various components and subsystems will be needed. Establishing reliability data from field-relevant experience for emerging components such as WBG devices and DC link capacitors where data is scarce will also be needed.

Research should also be explored into better materials, manufacturing processes, and system designs to increase component lifetimes and converter robustness and enable self-healing capabilities. For example, innovation in dielectrics, conductors, and other materials that can repair themselves 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.

5.1.4 Converter System Cost and Performance

In addition to the SSPS converter building blocks envisioned, other components and auxiliary subsystems are needed in the converter for a particular substation application. These additional pieces of equipment—such as bus bars, filters, protection devices, structural encasements, communications, and thermal management systems—affect the overall cost and performance of SSPS technology. It is therefore 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 converters will have to be competitive with current solutions based on capital, installation, operating, and maintenance costs. They will also need to manage unintended consequences and prevent negative impact on legacy or surrounding equipment within the substation.

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 and storage converters through economy of scale. Larger converters (e.g., 360 MVA and higher) using silicon devices are now available that can connect to voltages up to 69 kV. However, connections to higher voltages for the full range of grid applications still rely on using a conventional transformer. Recent advances have looked at utilizing WBG semiconductor devices to increase conversion efficiency, raise voltage capabilities to remove the need for a step-up transformer, and enable a smaller footprint to justify the price increase. Other inverter advances include plug-and-play functionality to help lower integration costs and grid support functionality (e.g., providing reactive power) for increased value. There has also been research in integrating battery converters with solar inverters to lower total system costs and improve overall system efficiency.

Other large grid-scale power electronic systems (e.g., FACTS devices and HVDC systems) remain fairly customized due to the more limited number of deployments. Detailed engineering and design studies are needed to assess the tradeoffs between cost and performance. The design tools and methods used for optimizing cost and performance for these applications are fairly well established, building on data and experience with past installations. However, current industry trends to help drive down the cost of ownership are moving towards more modular components (e.g., MMC topologies); standardized specifications and subcomponents; and using parts that are commercially available off-the-shelf. In addition to lowering capital costs, these trends help reduce downtime during maintenance, leading to savings over the lifetime of the equipment.

5.1.4.2 Research Gaps

Research is needed to understand and define the design space for SSPS converters. Developing a systems framework to analyze the cost, performance, and complexity tradeoffs of different converter architectures is critical to optimizing the design for the broadest set of grid applications. The system cost, performance, and mean-time-to-failure metrics are a multi-objective problem that requires detailed information and analysis.[41] Establishing benchmarks for comparisons, including lifetimes of various solutions, will also be important. Even though SSPS technology can provide multiple functionalities, it may not be required in all situations. There might be alternative approaches or technologies that can achieve similar results at reduced costs, higher efficiency, and with fewer integration challenges.

Improved understanding of the impacts and implications of SSPS converter integration on substation design (e.g., switchyard layout, wiring, auxiliary power, ground, safety), on secondary equipment (e.g., relaying, monitoring and control, energy management systems [EMS], distribution management systems, communications, protection), and on costs and procedures (e.g., installation, operations, maintenance, repairs) will also be important for substation applications. For example, harmonics from power electronic converters can lead to unwanted resonances that can influence the operation and lifetimes of other substation equipment. EMI impacts, noise, and overall substation footprint are other facets that need to be considered.

Enhancement in design tools, multi-physics models, and more accurate models that can be used to evaluate different combinations of modular building blocks, auxiliary components, configurations, 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 these tools. Meanwhile, prototyping, reliability testing, component characterization, hardware-in-the-loop testing, and field validations will be needed to improve the fidelity of models and data.

5.1.5 Near-Term, Midterm, and Long-Term Actions for Substation Application

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 multifaceted 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 secure power converter architectures that are suitable for multiple applications and establishing an evaluation framework that can help balance costs, performance, functions, and features. Advances in local controls and plug-and-play functionality developed in DER and microgrid applications should be integrated with SSPS converters. Research in sensor technologies and analytic methods for advanced converter functions should also be a focus. Design work and tool enhancements will be needed to ensure that SSPS technology can be integrated into substations, including handling of fault currents, over-voltage conditions, and other abnormalities typically experienced by traditional equipment. Finally, prototyping and power hardware-in-the-loop testing are required before SSPS converter operation can be validated in the field. Standardized PEBB characterization methods and procedures will also need to be developed.

In the midterm, new SSPS applications will require more advanced converter controllers and algorithms that allow these systems to switch between grid-forming, grid-supporting, and islanded modes. Additionally, these systems will need a higher degree of reliability and robustness to be deployed in distribution substations. Collecting data on SSPS converter performance and developing an understanding of failure mechanisms will be critical to expanding capabilities. Modular, secure, 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 and machine learning. This capability can help compensate for the lack of real-time data and speed up computation 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 in the design. 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 (i.e., PEBBs) 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 cost 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 to the building block level, and which do not. This demarcation would enable innovation, allowing converter building block 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 the block/module cost 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), midterm (within 10 years), and long term (within 20 years) are identified at the end of this section.

5.2.1 Block/Module Cost and Performance

Overall module cost and performance is driven by design considerations of a range of interrelated factors but primarily focus on 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 module efficiency and reduce thermal management requirements, which ultimately can save costs. Therefore, multi-objective optimization will be 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 drive down costs. Ongoing research and deployment experience with HVDC systems and electric ship applications for the U.S. Navy has been advancing modular building block designs and concepts to meet cost and performance objectives. Meanwhile, other applications such as solar PV, energy storage, and electric vehicles have been making parallel advances in component designs and new topologies utilizing WBG semiconductor devices. However, these applications all have different design, cost, and performance requirements that may limit opportunities to share advances. Other recent developments include utilizing embedded intelligence, advanced sensors, and novel protection methodologies to improve performance and reliability.

5.2.1.2 Research Gaps

Establishing the high-level requirements for SSPS converter building blocks is an important prerequisite to addressing module cost and performance. These requirements and specifications should be consistent with the broader converter architecture and allow for design innovation and integration of future technological advances. Standardized test protocols that simulate a realistic operating environment will also need to be developed to properly assess, characterize, evaluate, and compare different converter building block designs. Additionally, design and development of a platform for prototyping can help accelerate research efforts. A generic building block module that allows for new components to be swapped in and out and easily connected to testing capabilities will facilitate performance evaluation.

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 when considering the use of WBG devices that can operate at higher switching frequencies and temperatures. For example, advanced electromagnetic modeling coupled with thermal modeling techniques will be required to evaluate new building block architectures and designs. New design methodologies such as genetic algorithms to support optimization, new manufacturing techniques, and different modes of operation are fundamental areas for research that should be advanced to support 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 (metal-oxide-semiconductor field-effect transistors), 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 and should be coordinated with the overall converter control architecture, especially cyber-physical security considerations.

5.2.2.1 State of the Art

Silicon (Si) thyristors and IGBTs are the dominant power semiconductors used today in grid-scale applications because they can handle high voltages and high power, and are affordable (e.g., a 300 A, 1700 V half-bridge module costs $0.16/W).[42] While advances continue to be made in these technologies with new device designs and alterations, they will hit a fundamental performance limit based on the underlying Si material. Significant ongoing 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 (Figure 10). However, most of the focus has been on commercial applications in the low-voltage space (e.g., 650 V–1,200 V), with some efforts in commercializing 3.3 kV, 6.5 kV, and 10 kV SiC chips and modules. Devices using higher performance semiconductors, such as beta-gallium oxide and diamond, are at the early stages of research.

SiC MOSFETs are now commercially available and demonstrate lower conduction and switching losses than Si IGBTs. However, they come at a cost premium (e.g., a 444 A, 1,200 V half-bridge module costs $0.46/W) due to lower yields and more expensive substrates.[43] Recent research has focused on advancing

WBG semiconductor manufacturing and processing techniques to reduce the cost and improve the performance of these next-generation power devices.[44] Other recent innovations include hybrid modules that integrate Si transistors with WBG diodes, leading to solutions with improved performance but at a modest cost increase. Research efforts in developing gate drivers that can withstand the high EMI generated by these WBG devices have also been a focus.[45,46]

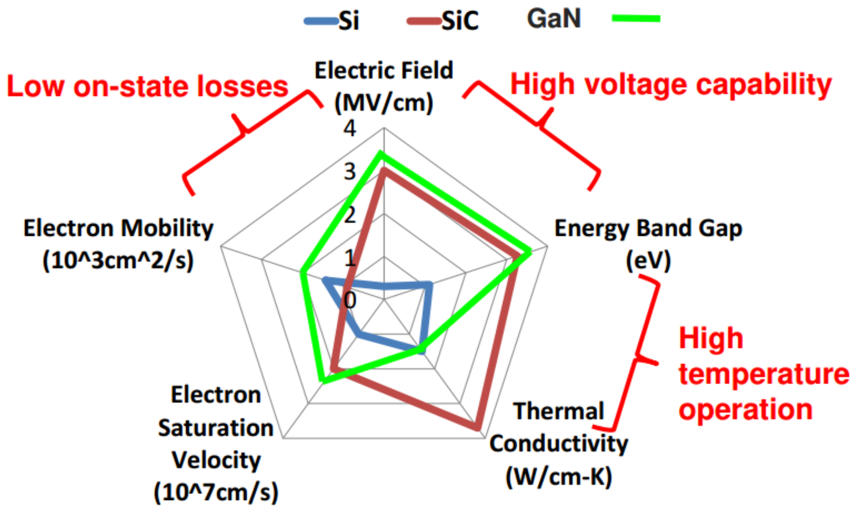

Figure 10: Performance Comparison of Semiconductors[47]

5.2.2.2 Research Gaps

Research is needed to continue improving the availability, cost, and performance of WBG semiconductor devices, especially those at higher voltages (e.g., 10 kV and up) and power ratings. For example, medium voltage WBG devices above 1.7 kV are only available as engineering samples. Additionally, these devices have only been used in limited field applications, so reliability data is scarce. Investigation is needed into their reliability, lifetimes, and short-circuit ruggedness. Development is needed of high-voltage, high-current modules that address challenges with paralleling devices at high frequencies. Research into advanced hybrid device concepts may also provide opportunities. For more aggressive substation applications, the current state-of-the-art 10 kV and 15 kV devices may not suffice, and completely new devices based on other WBG semiconductor materials will be needed. New device topologies, new gate dielectrics, better metal contacts, better substrates, and advanced manufacturing can also help increase the reliability, performance, efficiency, and consistency of power semiconductors.

Development is also needed of gate drivers that can switch at the frequencies of interest while being able to withstand EMI from high dv/dt and manage ringing from electrical coupling to device parasitics. Establishing isolation requirements and standards for these gate drivers and associated power supplies for high-voltage applications is a research gap.[48] New solutions and methods will be needed because gate drivers are required for each device and isolation from system-operating voltages can be prohibitively expensive, especially at grid voltages of hundreds of kV. Also needed are enhanced gate drivers that can monitor the state of the semiconductors (e.g., current, voltage, temperature), predict lifetimes, and enhance protection.[49] Further investigation into gate driver design for parallel operation of WBG devices to ensure high-performance and dynamic current sharing will also be important.

5.2.3 Dielectric, Magnetic, and Passive Components

In addition to drivers and power semiconductors, a range of other electrical components are important to the functionality and design 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 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 used, primarily due to their low costs and high reliability. More advanced insulation made from cross-linked polyethylene (XLPE), Nomex, and 3M Novec has 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 the power electronic system. Electrolytic capacitors are commonly used because they are low cost and can be based on both solid and non-solid electrolytes. Ceramic capacitors are another popular option that can be used in high temperature applications.

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. Components made from more advanced materials such as Metglas and nanocomposites can reduce losses at these higher frequencies and help increase power densities, especially when combined with WBG semiconductor devices. Additionally, recent work illustrated the importance of transformer and winding geometry as a dominant mechanism for losses in addition to the intrinsic material properties.

Electrical conductors are primarily made from copper and aluminum due to their low losses, low costs, and manufacturability. Research is ongoing into more advanced conductor materials with higher conductivities, such as covetics and graphene, but these materials have yet to make it into components that can be readily used cost-effectively.

5.2.3.2 Research Gaps

Critical research is needed on dielectric materials for insulators and capacitors, especially if SSPS converters are to be used in transmission system applications. High dielectric strength and high reliability are desired properties, including self-healing capabilities and the ability to withstand high-frequency transients. New dielectric materials will need to be developed and characterized for dielectric strength, dielectric losses, and thermal properties to ensure suitability. Modeling and investigation will be important to understanding the effect of electric field stress—including mixed frequency electric fields—on the dielectric properties of insulator and capacitors in high-voltage, high-power environments.[50]

Design and development of high-voltage, high-frequency, and high-power isolation transformers and filters that meet cost, efficiency, thermal, and power density requirements for SSPS modules will be needed. Establishing design practices such as reducing parasitic capacitances and increasing the physical distances between surfaces with different voltages will help reduce stress on insulators and minimize leakage currents, increasing component reliability. Advancing multi-physics modeling and simulation capabilities that can be used to assess voltage isolation requirements, efficient thermal management, low inter-winding capacitances, and accurate losses will also be important.

Continued research in soft magnetic materials to drive down costs and improve high frequency performance is critical. It is likely that high saturation magnetic alloys with low losses over a wide range of frequencies will be required. Developing research capabilities and characterization of these new magnetics materials will also be important.[51] Investigation of new transformer designs and geometries that leverage the enhanced properties of emerging soft magnetic materials is also an opportunity.

Exploration of advanced manufacturing techniques for the creation of dielectric, magnetic, and passive components can potentially improve performance and lower price points. Additive manufacturing can reduce material waste and fine-tune the material properties of a component. For example, changing the microstructure orientation and grain size of a magnet will alter its electromagnetic and thermal properties. However, nanometer scale control of soft, magnetic alloys and management of eddy current losses will be very challenging.

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 determining 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 potential damage. Packaging is intimately tied to thermal management and must be developed hand-in-hand to effectively extract heat from the sources. For example, SSPS modules with high power densities will most likely require liquid cooling; the packaging must be designed to accommodate the coolant flows. Another important design consideration for packaging and thermal management of SSPS 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 have been driven by data centers. These advances include forced water flow and two-phase cooling, with some applications using refrigerants. Figure 11 shows current cooling options for different application power levels and the range of heat transfer capability provided. Recently, a self-contained, closed-loop cooling system based on phase transition materials and thermosiphon technology was developed for a 2 MW centralized inverter application.[52] Because this system has no fillable liquids, pumps, valves, inhibitors, or leaks, it is low maintenance, which is a highly desirable design characteristic.

For power semiconductor modules, numerous efforts are underway to improve packaging and thermal management through the use of high-temperature materials.[53,54,55] This approach takes advantage of the higher operating temperature tolerances associated with WBG devices to reduce the cooling load. While some of these efforts have been successful, they are not sufficiently cost-effective for broad adoption. Instead of constant operation at a higher temperature, increasing the temperature rating of a power module also increases its reliability because it provides a higher margin for overload and fault conditions. The automobile and defense sectors have been leading the way in development of high-temperature modules, but only custom packages have been manufactured to date, which is costly. Recent research has also investigated the use of additive manufacturing techniques to improve the effectiveness and density of heat sinks for on-board electric vehicle applications.

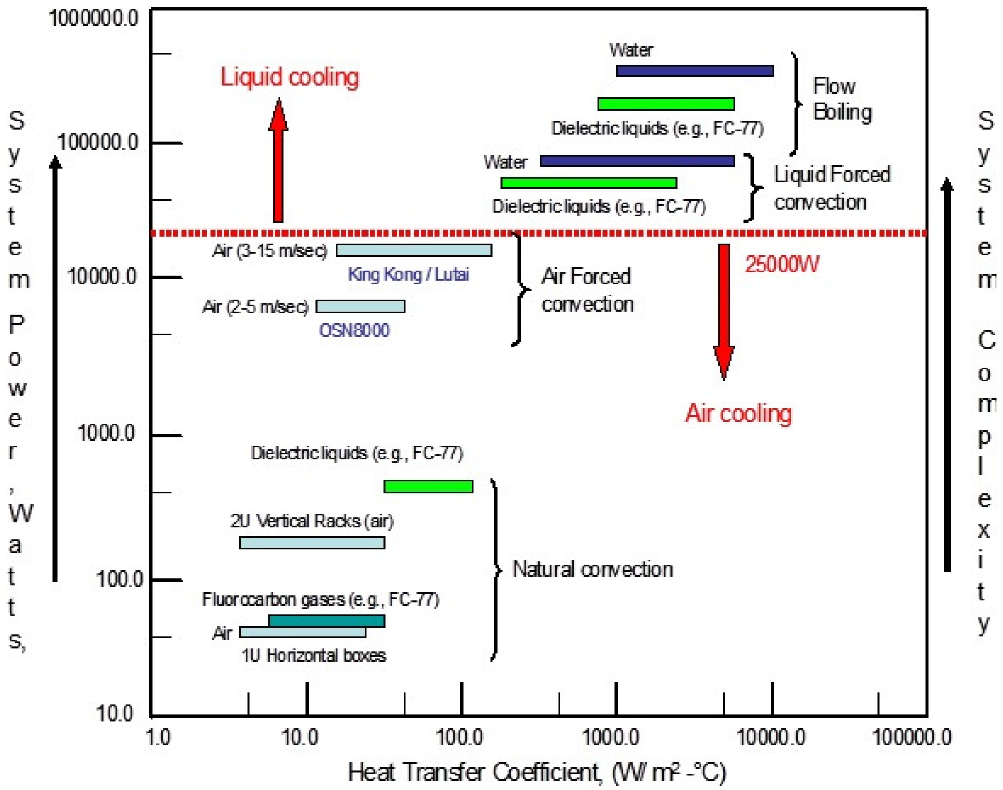

Figure 11: Heat Transfer Properties of Cooling Technologies[56]

5.2.4.2 Research Gaps

Research is needed in the application of available thermal management solutions to SSPS converter building blocks. One of the biggest challenges is the development of packaging that minimizes complexity and enables modularity and scalability while meeting cooling requirements. Ensuring interoperability and seamless connectivity with the broader converter architecture and associated cooling infrastructure will also be necessary to achieve plug-and-play functionality and hot-swapping. Continued research into better heat sinks, high-temperature materials, and packaging concepts will support the use of high power WBG devices in SSPS modules. Additionally, there is an opportunity to leverage packaging and thermal management innovations from other technologies, such as graphic processing units used in gaming and other computing applications.

Developing a systems understanding of failure mechanisms associated with packaging and thermal management for the entire SSPS module is critically important. While temperature is a key concern to building block reliability, electrical issues are intimately connected because electricity is the source of heat. Electric field stresses can lead to shorts in transformer insulation, generating heat, and EMI can couple with parasitic capacitances in heat-sinks and the metallic cases used for packaging. Advances in packaging should consider an integrated EMI containment strategy along with the insulation strategy, as both semiconductor power modules and the converter building block will be subject to them. Tools and design rules to simplify the multidisciplinary, multicomponent task of handling heat, managing electric fields, and providing a controlled and directed path for EMI will be needed.

It is also important to balance the power density of the converter building block and the thermal management capabilities to ensure adequate and reliable system performance. Investigation of high-temperature SSPS module designs using WBG semiconductors will need to consider the thermal limits of other components in the system package. Additionally, closed-loop control may be used to improve cooling system efficiency, and a series of thermal de-rating controls can be used to ensure reliable operation.

There are also opportunities for advanced design of dielectric, magnetic, and passive components to improve packaging and thermal management of the converter building blocks. By leveraging advanced manufacturing techniques, it is possible to tailor the thermal properties of components to alleviate the requirements for active cooling and thermal management. Similarly, research into new materials such as high thermal conductivity dielectrics could help maintain electrical isolation while minimizing thermal management requirements. Overall, enabling systems to operate at higher temperatures is another method for increasing reliability, and high temperature SSPS module designs and associated technologies should be explored.

As an extension, the thermal performance of the semiconductor device packaging will need to consider the interplay between electrical and thermal issues. Research efforts are needed in the design and development of packaging for WBG power modules based on multiple chips. Considerations include identifying suitable substrate materials and optimizing direct bonded copper layouts to reduce parasitic capacitances to mitigate impacts from EMI. There is an opportunity to advance high-temperature packaging and interconnection technologies to take full advantage of WBG material properties. Efforts are also needed in the qualification of power module packaging for high-power, high-voltage, and high-frequency applications.

5.2.5 Near-Term, Midterm, and Long-Term Actions for Converter Building Block

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

In the near term, research is needed in developing SSPS modules that utilize commercially available power semiconductor devices and components, such as Si IGBT, to ensure that cost and performance targets can be met. Establishing PEBB characterization capabilities, system understanding, design experience, and performance benchmarks will be critical to advance SSPS technologies. Enhancing design tools that can incorporate innovations in thermal systems, dielectrics, and magnetics will help assess performance and reliability. Research efforts should leverage lessons learned and capabilities in other sectors, such as data centers, graphic processing units, electric vehicles, and electric ships. Additionally, research will need to begin in core technologies such as isolated gate drivers, semiconductor device packaging, and new materials for semiconductors, dielectrics, magnetics, and passives.

In the midterm, improvements in commercially available WBG devices (e.g., cost, performance) will be needed to enable advanced SSPS modules. Simultaneously, improved gate drivers suitable for these devices (e.g., high voltage, high frequency, high temperature) will also be needed. Additionally, the integration of enhanced monitoring and analytics capabilities into gate drivers is desired. Design and development of high-frequency transformers, high-voltage capacitors, and improved insulators that build off near-term research in materials and manufacturing will be critically important. Improved packaging and thermal management for converter building blocks with high power densities, including high-temperature solutions, should be explored. Finally, research is needed in developing SSPS modules that utilize WBG power semiconductors and advanced components to assess reliability and performance.

In the long term, commercial availability of the next generation of dielectric, magnetic, and passive components, as well as of high-voltage, high-power WBG power semiconductor modules, will be important. Research into self-healing capabilities, both in materials and system design, to increase performance and reliability will be needed. Additionally, development of semiconductor devices beyond 10–15 kV and research into other material innovations may be a critical gap for SSPS modules that can meet the full range of substation applications envisioned. Finally, testing and demonstration of converter building blocks that integrate these various technological advances will be needed to evaluate improvements in performance and costs.

5.3 Grid Integration

The application of SSPS converters in substations and their integration into the electric grid at large 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 electromechanical devices. As SSPS technology is introduced into the grid, the control and protection paradigm will need to evolve to accommodate all the new capabilities and features of SSPS converters. More specifically, the hybrid, multi-frequency, multidirectional power flows and asynchronous nature of SSPS technology present 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), midterm (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 extend 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. It 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 AC power flowing from large, centralized generation connected to a transmission network that feeds 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. For example, ensuring cybersecurity and interoperability between disparate systems has created new challenges that are actively being investigated. More recently, the growth in DERs (e.g., PV, energy storage, microgrid, EV) and the ability of customers to interact with the grid (i.e., prosumers) have also led to control and coordination challenges. Various studies, tests, and pilots have been conducted to evaluate the impact of these changes on the electric power system.

Research has been exploring new grid operating concepts, such as transactive controls,[57,58] distribution system as a platform,[59] networked microgrids, DC microgrids, and energy routers.[60] These efforts are investigating methodologies for the control and coordination of resources with different grid paradigms. Figure 12 illustrates a potential evolution from the grid architecture we have today to one with significantly more power electronic interfaces. In this future, the conventional power electronic grid-following control algorithm requiring a strong AC signal may not be valid. Research in lateral control architectures and virtual asynchronous machines is addressing some of these concerns.[61] Additionally, there have been efforts to advance the discipline of grid architecture,[62] developing tools and refining definitions to improve understanding of system relationships. Analysis frameworks are being developed to better explore interdependencies, cybersecurity, and system resilience.

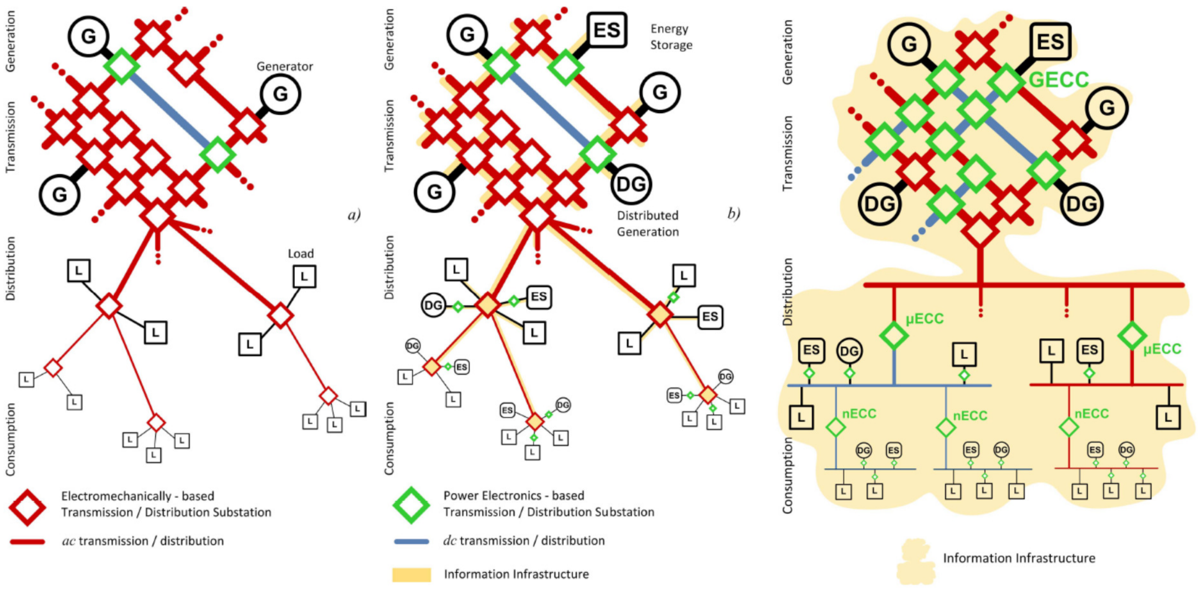

Figure 12: Potential Evolution of Grid Topologies and Architectures[63]

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, protection engineering, system architecture, cyber-physical security, 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. This is truly a paradigm shift in the way electrical energy is processed, transmitted, and distributed. Understanding the static and dynamic aspects of such operations will be crucial, given that power electronic systems can respond easily in the microsecond range, as opposed to seconds in current electromechanical actuators and systems.

Multidisciplinary research spanning control and system theory, power electronics, and power systems is crucial to establishing the fundamental understanding of SSPS-enabled grids. The dynamic interactions between SSPS converters in a network structure, as well as the SSPS modules with its own subsystems, must be fully understood and studied to avoid the onset of instabilities. Research into system-of-systems behavior, from semiconductor devices up to the entire electric grid, is critical to ensuring the stability of future power systems that have millions of power electronic converters. Additionally, SSPS converters regulating frequency, voltage, and power flows will feature negative incremental impedances that will need to be investigated. This behavior has been shown in constant power loads and other grid-scale power electronic systems, which can easily render the system unstable if neglected.

Because the electric grid cannot be "upgraded" overnight, it is important to develop tools and capabilities that can support the smooth transition of electric grid paradigms with SSPS technology advancements. Research is needed into grid architecture evolution with special considerations of the characteristics and capabilities of SSPS converters. For example, identification and evaluation of opportunities to utilize DC topologies will require planning studies that consider related topics such as DC circuit protection. Focused efforts on addressing challenges with interoperability, security, and integration will also be needed, including standards-related activities. Additionally, incremental advances in control and protection concepts are needed to allow for microgrids, DERs, and other SSPS technologies to increasingly provide a range of functions (e.g., grid-supporting, grid-forming, flow control) in coordination with existing protections to ensure stability, safety, security, and reliability.

Ultimately, moving toward a future scenario where the electric power system is completely decoupled, consisting of multiple microgrids that operate at multiple frequencies, will require the development of new management and operating concepts.[64] Redefining roles and responsibilities of various entities and institutions will also be needed. Additional research required for this asynchronous and fractal paradigm includes investigating changes to communication and security requirements, market operations, and autonomous controls, which impact the overall complexity and fragility of the system. This new grid architecture will also need to explore how the system can break apart gracefully during contingencies, and seamlessly reconstitute itself and recover to normal operations or a degraded state, even in blackout 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 timescales 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. Because SSPS technologies will enable new grid architectures, 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

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 because 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, fault location, isolation, restoration, and outage management. There are numerous R&D efforts underway to improve these software tools and systems through integration of ICT, improved analytics, and new data sources from advanced sensors such as PMUs. Cybersecurity of these new software tools and systems is also an active area of research. A more recent focus has been on advanced distribution management systems 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 integrating ICT into the distribution system have enabled more complex protection.

In addition to relays, there has also been research to advance the protection devices themselves. For example, circuit breakers for use in DC networks and electric ship applications have been investigated. These solutions range from designs based entirely on solid state devices as well as hybrid solutions that combine semiconductor devices with traditional electromechanical components. Meanwhile, advances in AC breakers focus primarily on new designs and insulation materials to make the systems more intelligent and compact. Research into fault current limiters using semiconductors and high temperature superconductors has been pursued as well.

5.3.2.2 Research Gaps

System protection and control is an intimate part of grid architecture, so design and development of advanced control and protection systems must also be aligned. Critical research is needed to ensure that SSPS converters and the operating paradigms they enable—such as microgrids and hybrid, multi-frequency systems—will be interoperable and coordinated with protection and control systems as the technology is deployed. Ensuring the system is secure and resilient to cyber threats and attacks will also be critical. Because power electronic systems have limited capability to supply large fault currents, research is needed to investigate existing protection schemes that are compatible with SSPS technologies.[65] For example, static relay settings remain a challenge to protection coordination in dynamic, reconfigurable networks and will need to be addressed. Additionally, some relay settings are built into the controllers of existing grid equipment, making them difficult to update or change.

Dynamic and adaptive protection schemes that can rapidly detect and respond to a variety of situations and adapt to changing grid conditions (e.g., topologies, weak versus strong) are required for SSPS converters. For example, protection schemes will be needed that ensure proper protection when the anticipated fault current magnitude or power flow direction changes, especially in distribution systems with a large amount of DERs or in islanded microgrids that have substantially smaller fault currents than grid-connected operations. Research will be needed to evaluate these protection schemes and associated relays with SSPS technology deployed in the grid. Demonstrating sufficient selectivity, sensitivity, speed, safety, and reliability will be critical to gaining acceptance by networks operators.

Generally, the equipment within a substation has a significant impact on the architecture and design of protection systems. For example, HVDC converter substation designs need to consider the ability to withstand sufficient voltages, contribute to short circuits, clear faults, address EMI and harmonics, and prepare for contingencies through redundancy. Extending these design concepts and best practices for SSPS applications will be needed as well, such as considering the impact on collocated power lines. Other research needs include developing new protection paradigms and algorithms that leverage the full capabilities of SSPS technology, such as integrated fault current limiting, dynamic impedance, and very fast electrical isolation. For example, the multi-port, multi-direction power flow capabilities of SSPS converters can manage the impact of faults across adjacent lines by adapting impedances. Additionally, fault protection in a fully fractal and asynchronous system may require the development of 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 grid architectures developed. Combinations of centralized coordinated control, distributed autonomous control, and advanced protection schemes will need to be integrated across EMS, DMS, and other control software platforms. For example, research is needed to understand how new power flow control capabilities of SSPS converters can be used to improve system operations and must consider interactions with other control technologies (e.g., FACTS devices, topological switching). Additionally, existing substation monitoring technologies (e.g., PMUs, SCADA) and control coordination strategies cannot respond at timescales consistent with power electronics systems (e.g., milliseconds, microseconds). Development of faster communication technologies, methods, and protocols can enable higher bandwidths to realize advanced control concepts utilizing SSPS technology. Research will also be needed on control methods and algorithms to enable advanced functions, such as graceful degradation during a contingency or cyber-attack, dynamic power routing, multi-objective optimization, and system recovery from blackout conditions.

5.3.3 System Modeling and Simulation

System modeling and simulation consist 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 requiring experimentation 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 converter integration are 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 simulation 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 are developed around the current architecture (e.g., AC power flows, system frequency set by rotating electric machines) and may not be suitable for a grid with a 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 realities like data transport delays and the impact of cyber-attacks. There has also been some progress in the co-simulation of converters and power systems (e.g., power systems computer-aided design, Power System Simulator for Engineering) to better understand HVDC system impacts and operations.

The development of advanced simulation capabilities, such as real-time digital simulators (RTDS), has led to new experimental paradigms. These include power hardware-in-the-loop testing and controller-in-the loop testing that help accelerate R&D of power electronic systems. These tests involve connecting actual hardware components or subsystems (e.g., converters, controllers) to a programmable software simulator platform (i.e., RTDS) that emulates the rest of the system. The physical interfaces enable power flows and data exchanges in real-time to better understand hardware interactions and to assess control and protection code, and can be used to validate component performance. This capability provides a mechanism to refine hardware designs and software code to ensure that their behavior is accurate and consistent throughout a range of operating conditions.

The accuracy of modeling and simulation results depends heavily on having accurate, high-quality, high-fidelity data and models as inputs. While significant progress has been made in collecting data sets and refining device and system models to replicate steady-state behavior, the development of models to analyze dynamic and transient behavior is becoming critically more important. A process for traditional model development is shown in Figure 13, highlighting different model tiers that need to be coordinated and validated for a new device. Research efforts have been advancing the fidelity of component models, controller models, and system models to ensure more sophisticated and accurate analysis, as well as improving the underlying speed and capabilities of modeling and simulation tools.

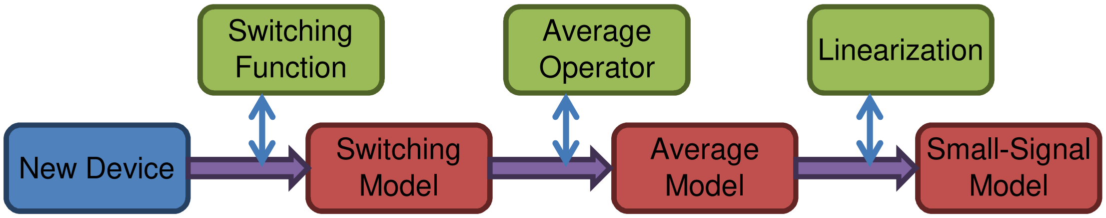

Figure 13: Traditional Model Development

5.3.3.2 Research Gaps

Overall, improvements are needed in the full spectrum of modeling and simulation tools and capabilities for engineering analysis spanning transient stability, short circuit, load flow, controls, and dynamics, from the full power system down to the converter and device levels. Accurate, rapid, dynamic modeling and large-scale simulations are essential for understanding the operations and planning of a grid with high levels of SSPS converter deployments. Additionally, a unified system modeling integration framework and methodology can help connect the capabilities of these various modeling and simulation tools.

Traditional power system simulators perform electromechanical transient simulations that are insufficient for large-scale power electronics. Electromagnetic transient simulations will be required, and potential co-simulation tools will also be needed to understand the interaction with existing electromechanical generators. Other co-simulation tools that will be needed for high-fidelity modeling include those that can bridge component-level power electronics to system-level applications. Additionally, simulating one SSPS converter by itself will be challenging due to its complexity; understanding interactions in a grid with a large number of SSPS converters will be a significantly bigger challenge.

Advanced mathematical algorithms and computational capabilities will be required to support simulation of grids with large-scale deployment of SSPS converters that include very small time-constants and stiff nonlinear interactions. Potential issues with modeling time-steps, as well as the scalability of real-time platforms, will need to be resolved. Moreover, new methods are required to assess the dynamics of SSPS converters and the grid paradigms they enable, such as real-time variations in power transfers and fully distributed asynchronous grids. Additionally, new modeling methodologies beyond frequency and time-domain simulations are needed for studying the operation of large systems; parametric and model-form uncertainty quantification can move away from deterministic simulations and basic view-graph comparisons usually relied on in power electronics analysis and design.

Generic models for SSPS converters that can be used in conventional engineering, integration, and valuation studies will need to be developed. These models should be based on SSPS functional requirements for power flow, short circuit, and transient stability studies. Characterization of SSPS modules with hardware-in-the-loop testing will be extremely important to validate the performance and fidelity of generic models. Research is also needed to improve existing RTDS systems because they cannot model the fast dynamics of power electronics due to underlying computational limitations. Additionally, SSPS converter models will need to be capable of interacting with grid control and protection systems. Next-generation RTDS systems will require extremely low latencies with high computational capabilities to be able to evaluate control and protection systems and perform large system studies of multiple SSPS converter interactions.

In addition to tool and capability development, analysis through modeling and simulation is needed to answer fundamental questions of SSPS technology integration in the grid. For example, 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 through analysis. Additionally, new definitions for normal operation and contingencies will be needed for system security assessments and evaluation of resilience. More importantly, a value model for SSPS technology is needed to explore future grid scenarios with sufficient detail to understand requirements. This will help guide technology development by defining the need for SSPS converters along with its economic justification. Large-scale deployment of SSPS technology will require significant changes to the existing grid infrastructure, which makes it important to justify the need for such investments as well as to avoid creating new problems. Advanced converter functions, market designs, and new control and protection paradigms will all need to be considered as well.

5.3.4 Near-Term, Midterm, 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 ensuring that the technology is successful and adopted more broadly. Many of the advances needed thus deal with improving foundational understanding, establishing tools and capabilities to accommodate a very different future, and conducting analyses to answer questions.

In the near term, research is needed to develop and refine a grid architecture that is compatible with the SSPS vision. This is a critical effort that spans multiple facets of the electric power system, especially control and protection to ensure SSPS converters are compatible with existing technologies and will not decrease grid safety, security, or reliability. Establishing a multidisciplinary research focus that spans control theory, power electronics, and power systems to guide modeling and simulation needs will be equally important. Additionally, continued improvements in models, data, methodologies, and modeling and simulation capabilities will be needed to properly assess the behavior and benefits of SSPS converters, especially system dynamics. Research into grid evolution and establishing a value framework for SSPS converter integration is also foundational to future progress.

In the midterm, development of design practices for SSPS converter integration into substations and analysis of their value proposition is needed. Additionally, new capabilities enabled by SSPS technologies will need to be incorporated into EMS and advanced DMS to realize new functionalities and benefits. Dynamic, adaptive protection schemes and relays will also need to be developed to ensure reliable operation with more microgrids and reverse power flows enabled by SSPS technology. Improvements in hardware-in-the-loop testing capabilities and expansion of co-simulation capabilities will be needed to model and analyze more complex system dynamics, including interactions between multiple converters and from devices up to the system. 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. Research into new control methods and multi-objective optimization algorithms to support advanced SSPS functions and features will also be needed.

In the long term, fundamental advances are needed to establish a grid architecture that is fractal, fully asynchronous, autonomous, and supportive of 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 that integrate new control algorithms and concepts developed in the midterm will be needed to accommodate graceful degradation of the system and coordination of system recovery in blackout conditions.

5.4 Industry Acceptance

Fostering industry acceptance of SSPS technology will require actions to address issues beyond R&D. Generally, utilities are reluctant to adopt new technologies because their long-term reliability is uncertain and they want to avoid customer outages that may result from equipment failures. Additionally, regulatory hurdles and the ability of electric utilities to absorb the cost of new technologies into the rate base may pose more of a challenge than the necessary technological advances. The high cost of power electronic systems, their limited market size, unknown business models, and lack of government incentives are also issues that can impede progress toward industry acceptance.

A portfolio of activities will be needed to address these various issues, especially considering the range of stakeholders impacted by new grid paradigms and functions enabled by SSPS converters. These complex issues and concerns should be carefully evaluated and all of the key risks mitigated to ensure industry acceptance of SSPS technology in the future grid. However, it is important to note that these issues are not entirely decoupled from the technical challenges outlined and must be addressed in a coordinated manner. Required activities will involve cost-benefit analysis; industry standards; markets and regulations; and testing, education, and workforce.

5.4.1 Cost-Benefit Analysis

At the end of the day, the benefits associated with adopting SSPS technologies must outweigh their costs for there to be any traction with industry. Developing a value framework that can help establish a robust and convincing cost-benefit analysis for SSPS converters is needed to help justify their utilization over traditional solutions. The costs and losses of SSPS converters are expected to be higher than typical substation equipment, at least initially, so it is important to consider the additional functions and features they enable for a favorable techno-economic analysis. For example, the application of SSPS technology to replace a large power transformer in a distribution substation can increase system flexibility and resilience, reducing operational costs, installation costs, and outage costs, which can help justify their higher capital costs. Development of credible use cases that are broadly applicable, possibly through a survey of utilities, can help inform industry and investors of the value of using SSPS technologies. For these use cases and scenarios, the credibility of cost-benefit analyses will depend on the assumptions made and advancements in grid modeling and simulation capabilities. In addition to individual use cases, cost-benefit analyses for the entire grid should be considered. As more SSPS converters are deployed and interconnected, their cost will decrease from economies of scale and their benefits and value can be significantly larger due to network effects.

5.4.2 Industry Standards

As SSPS technologies penetrate the grid, they will require updated or newly developed 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, other functions and features must be reflected in future revisions. In addition to interconnection, users of the technology will be concerned about the integration and operation of the SSPS converter, so the control interfaces and communication standards will also be important. Ensuring interoperability with legacy systems and across SSPS classifications will be critical to gaining industry acceptance.

Active participation in standards development processes and organizations will be needed to ensure that SSPS converter functions and features can be institutionalized and will conform to industry practices. Table 8 identifies standards that are relevant to SSPS integration across the three envisioned classifications (SSPS 1.0, 2.0, and 3.0) and will require consideration as the technology matures. Additionally, compatibility analysis with existing substation design, communication, security, and application standards will be needed, especially to understand the implications or requirements of changes.

Table 8: Identified Standards Associated with SSPS Integration

INTERCONNECTION STANDARDS		
SSPS 1.0	IEEE 1547	Standard for interconnecting distributed resources with electric power systems
	IEEE 519	Recommended practices and requirements for harmonic control in electrical power systems
SSPS 2.0	IEEE P1032	Guide for protecting transmission static VAR compensators
SSPS 3.0	IEEE 1378	Commissioning HVDC converter stations and associated transmission systems
CONTROLS STANDARDS		
SSPS 1.0	IEEE 2030	Guidelines for understanding and defining smart grid interoperability of the electric power system with end-use applications and loads
SSPS 2.0	IEEE 1676	Guide for control architecture for high-power electronics >1 MW used in transmission and distribution systems
SSPS 3.0	IEEE C37.1	The basis for the definition, specification, performance analysis, and application of SCADA and automated systems in electric substation
	IEEE C37.118.1	Definition of synchrophasors, frequency, and rate of change of frequency measurement under all operating conditions
COMMUNICATIONS STANDARDS		
SSPS 1.0	IEC 62541	Unified architecture for machine-to-machine communications
SSPS 2.0	IEC 61850-90-1	Communication between substations
	IEEE 1815.1	Standard for exchanging information between networks implementing IEC 61850 and distributed network protocol (DNP3)
SSPS 3.0	IEC 61850-90-2	Communication between substations and control centers

	IEC 60870-6	Data exchange over wide area networks between utility control centers, utilities, power pools, regional control centers, and non-utility generators
CYBER AND PHYSICAL SECURITY STANDARDS		
SSPS 1.0	IEEE 1686	Definition of functions and features to be provided in substation intelligent electronic devices to accommodate critical infrastructure protection programs
SSPS 2.0	IEEE 1402	Guide for power substation physical security
SSPS 3.0	IEEE C37.240	Cybersecurity requirements for substation automation, protection, and control systems

Beyond the IEEE and IEC standards listed, there has been a rise in requests from North American utilities for UL/CSA certification for power electronic systems (e.g., UL 1741, UL 1973, UL 1998, and UL 9540). However, these standards tend to lag behind the technology, and in some cases overlook some fundamental protection requirements. Standards that consider dynamic aspects should also be developed to safely integrate a large number of SSPS converters. For example, this has been done for aerospace systems by specifying the terminal impedances of equipment. Additional standards that would be relevant to SSPS technology include isolation requirements, guidelines for physical implementation, standards for EMI considering high-frequency emissions with WBG devices, and protection scheme and control protocols. Overall, there are lessons learned and best practices from other industries and countries that should be explored and leveraged.

5.4.3 Markets and Regulations

Market rules, regulations, and other institutional entities have evolved to ensure reliable, safe, and cost-effective operations of the electric power system. With the broader deployment of SSPS technology, these various aspects of the grid will need to be addressed and modernized for broader industry acceptance. Federal and state regulatory commissions, market designers and operators, and other relevant entities and institutions will need to be educated and informed of the range of issues and opportunities associated with SSPS technology.

As with other new technologies introduced into the grid, such as energy storage and demand response, educating relevant stakeholders of the value of the technology is an important first step to refining market rules and changing market products. For example, SSPS converters can provide near real-time or real-time variations in power exchanges. Allowing SSPS technology to respond to real-time pricing can provide value by managing peaks and power flows more efficiently. Enabling monetization of these benefits (e.g., ancillary services) and ensuring fair and equitable allocation of cost to stakeholders are also very important for industry acceptance.

In today's regulatory environment, utilities can earn a regulated rate of return for investing in assets such as transmission lines, centralized power plants, or traditional substation equipment. However, there is little incentive for meeting the same system needs with distributed generation, demand-side management, or alternatives such as SSPS converters. Updates to utility regulations are needed to ensure that SSPS technology and the benefits they provide are considered and evaluated on a level playing field with all other available options. New business models will also need to be developed that can leverage the opportunities afforded by SSPS technology in a new regulatory environment.

Another important 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 because they may no longer be relevant. During SSPS autonomous operations, determining which entities are liable for outages is another challenge that will need to be addressed. Finally, new business models enabled by advanced SSPS converter functions, such as differentiated quality of service, will require proper oversight.

5.4.4 Testing, Education, and Workforce

Access to testing facilities, such as large-scale testbeds, development of testing protocols to benchmark SSPS technology performance, and establishment of detailed qualification procedures for their integration into substations is critical for broader industry acceptance. The ability to test SSPS converters in a realistic, controlled environment helps to reduce adoption risks for industry, especially with using more advanced control concepts and under high-voltage conditions. To advance SSPS technology, it will be important to assess the range of test capabilities needed spanning devices, components, subsystems, and systems; make existing capabilities available to researchers; and support the development of unavailable capabilities.

Developing standardized testing protocols will help spur innovation by enabling SSPS modules, controllers, and converters designed and manufactured by different vendors to be evaluated side by side. Characterizing these systems and subsystems with a benchmark ensures that they meet SSPS converter design requirements and industry standards, and will be interoperable with each other, supporting broader industry acceptance. Additionally, relevant data, refined generic models, and experimental results from these various tests should be broadly shared to ensure transparency and repeatability. However, confidentiality of business-sensitive information must be considered and respected in these practices.

Advances in educational programs and workforce training will be needed to develop the skill sets needed to design, build, and maintain SSPS converters in the future grid. This multidisciplinary technology area will rely on expertise that spans controls, power systems, and power electronics, in addition to material science, computer science, and cyber-physical security. Additionally, current line crews and engineers are mostly familiar with passive components and the existing grid architecture. A large, trained, and dedicated pool of subject matter experts in the areas of planning, construction, testing, commissioning, and operation and maintenance associated with SSPS converters will also be required to support industry acceptance. Supporting and developing the research capacity, curricula, and capabilities for the next-generation workforce is vital to the maturation and adoption of SSPS technology.

6. Conclusions

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

SSPS technology has 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 represent a new technology group that has the potential to tap into a multibillion dollar industry, creating new U.S. businesses and jobs. Achieving this capability within the United States before other countries would be a tremendous economic advantage and can bolster domestic energy security.

This technology roadmap highlights the potential benefits of broader utilization of SSPS converters, documents a technology adoption trajectory that minimizes risks and costs, and identifies several R&D challenges and critical gaps that must be addressed to realize the SSPS vision presented. The timing is ripe to advance SSPS technology, especially because enabling technologies such as WBG semiconductors, converter controllers, autonomous systems, and communications have sufficiently matured. Dedicated research into SSPS technology can leverage progress made to date and help push existing technologies to the next level. Activities needed to address the gaps identified are summarized in Table 9 and span both technical and institutional issues.

Table 9: Summary of Roadmap Activities

TIMING	ACTIVITIES
NEAR TERM (WITHIN 5 YEARS)	• Establish a community to support multidisciplinary research spanning controls, power electronics, and power systems to advance fundamental understanding of SSPS • Develop secure SSPS converter architectures suitable for multiple applications and enhance associated design tools • Support research in core technologies, such as gate drivers, material innovations, sensors, and analytics needed for advanced SSPS functions and features • Develop, characterize, and demonstrate SSPS modules and converters utilizing commercially available technologies and state-of-the-art controls • Establish characterization methodologies and testing capabilities to create baseline performance benchmarks for SSPS modules and converters • Explore new grid architectures, develop protection and control paradigms compatible with SSPS converters, and establish a valuation framework • Improve data, models, and methods necessary for modeling and simulating system dynamics, including developing generic models for SSPS modules and converters • Engage and educate standards development organizations, regulatory commissions, and other institutional stakeholders, especially utilities

MIDTERM (WITHIN 10 YEARS)	• Advance hardware-in-the-loop (HIL) testing and co-simulation capabilities to enable accurate steady-state and dynamic modeling from a converter up to the full power system • Refine grid architectures and develop advanced control and optimization algorithms for converter and system operations to enable and leverage SSPS capabilities • Develop new components and technologies from near-term core research, including high-temperature packaging and advanced thermal management solutions • Establish WBG devices as a commercially available technology, along with suitable gate drivers that possess monitoring and analytics capabilities • Develop dynamic, adaptive protection schemes and relays and ensure their integration, along with SSPS functions and features, into existing EMS/DMS • Develop, characterize, and demonstrate robust SSPS modules and converters using WBG devices and new drivers, and modular, low-cost communications capabilities • Develop design practices for SSPS converter integration into substations and conduct analyses based on data, experience, and performance of SSPS converter deployments, including through HIL testing • Continue engaging and educating standards development organizations, regulatory commissions, and other institutional stakeholders, especially equipment vendors
LONG TERM (WITHIN 20 YEARS)	• Explore a fractal, asynchronous grid architecture with autonomous, distributed controls that leverages research in artificial intelligence and machine learning • Conduct modeling, simulation, and analysis to explore the paradigm with many SSPS converters interacting, helping to establish new criteria for grid stability • Establish next-generation components that utilize new materials and high-voltage, high-power WBG modules as commercially available technologies • Support research in new semiconductor devices beyond 10–15 kV blocking capability and other material innovations for self-healing components • Develop, characterize, and demonstrate SSPS modules and converters with advanced components, communications, and enhanced reliability beyond n+1 redundancy • Integrate advanced control and optimization algorithms developed in the midterm into EMS/DMS, supporting graceful degradation and blackout recovery • Generate and document sufficient design and operational experience with SSPS converters to make it extendable to all substation applications of interest • Continue engaging and educating standards development organizations, regulatory commissions, and other institutional stakeholders, especially market operators

Addressing the full range of activities listed will require participation from industry, academia, and government laboratories on topics spanning hardware design and development, real-time simulation, control algorithms, power electronics, thermal management, magnetics and passive components, network architecture, communications, cyber-physical security, and computation. Additionally, expertise in analysis, markets, regulations, standards, testing, and education will also be needed. While there are numerous challenges, there also are numerous stakeholders. Each stakeholder group plays a key role in developing SSPS technology and moving toward the SSPS vision in the following ways:

- Academia contributes by addressing fundamental research challenges in theory, controls, modeling, simulation, and materials, and by developing bench-scale prototypes.
- National laboratories help to address fundamental research challenges. They provide neutral validation platforms and testbeds for models and lab-scale prototypes through their scientific user facilities and testing capabilities.
- Utilities provide insights and expertise into real-world operating conditions, help establish the business justification for new technologies, contribute data for modeling and analysis, and support pilot testing.
- International professional organizations, such as IEEE and CIGRE, provide platforms for technical exchange among subject matter experts, facilitate community-building, and lead standards development.
- Manufacturers are vital to leveraging outcomes of research, prototypes, and pilots for devices, components, subsystems, and other systems and advancing them through product development and eventual commercialization.
- Finally, the Federal Government can contribute resources to support and accelerate research, analysis, and field validations for the public benefit, facilitate collaboration and partnerships across diverse stakeholders, disseminate best practices and research results, and help overcome regulatory barriers.

7. Abbreviations

AC	alternating current
CHP	combined heat and power
DC	direct current
DER	distributed energy resource
DMS	distribution management systems
EMI	electromagnetic interference
EMS	energy management system
EV	electric vehicle
FACTS	flexible AC transmission system
FPGA	field-programmable gate array
HF	high frequency
HIL	hardware-in-the-loop
HVDC	high-voltage direct current
ICT	information and communication technology
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated gate bipolar transistors
LCC	line commutated converter
MMC	modular multi-level converter
MOSFET	metal-oxide-semiconductor field-effect transistor
MTTF	mean-time-to-failure
MV	medium voltage
MVDC	medium-voltage direct current
NPC	neutral point clamped
OE	Office of Electricity
PEBB	Power Electronics Building Block
PLC	power line carrier
PMU	phasor measurement units
PV	photovoltaics
RTDS	real-time digital simulators
SCADA	supervisory control and data acquisition
SSPS	solid state power substation
SST	solid state transformer
TRAC	Transformer Resilience and Advanced Components
VSCs	voltage source converters
WBG	wide band gap

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