Solid State Power Substation Roadmapping Workshop: Summary Report

Emmanuel Taylor,
Energetics Incorporated

Klaehn Burkes, Savannah River National Laboratory

Kerry Cheung, U.S. Department of Energy

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Emmanuel Taylor– Energetics Incorporated

Klaehn Burkes – Savannah River National Laboratory

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Prepared by

ENERGETICS INCORPORATED

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PREFACE

The *Solid State Power Substation Roadmapping Workshop* was organized by the U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE) and held on June 27 – 28, 2017, hosted at the Clemson University Zucker Family Graduate Education Center, in Charleston, South Carolina. The workshop was planned and executed under the direction of workshop chair Dr. Kerry Cheung (DOE-OE). The information contained herein is based on the results of the workshop, which was attended by nearly 50 experts from government, industry, and academia. The technology gaps and deployment challenges described in this report reflect the expert opinions of workshop participants, but are not intended to be comprehensive or representative of the views from the entire electric power community.

ACKNOWLEDGMENTS

Many thanks to everyone who participated in the *Solid State Power Substation Roadmapping Workshop*, held on June 27 – 28, 2017 at Clemson University in Charleston, South Carolina for making it a success (a complete list is provided in Appendix A). Special thanks are extended to the plenary speakers (listed below) who helped to frame the workshop. The plenary presentations and the outputs of the discussions that took place provided the foundation for this report.

Plenary Speakers:

Sandeep Bala (ABB)

Robert Yanniello (Eaton Corporation)

Alejandro Montenegro (S&C Electric Company)

Wensong Yu (FREEDM Center, North Carolina State University)

Giri Venkataramanan (University of Wisconsin)

Dushan Boroyevich (Virginia Tech)

Thanks are also extended to the representatives from Clemson University, who hosted and supported the execution of the workshop, and to the planning team, which helped organize the workshop, develop the draft Solid State Power Substation Roadmap, and facilitate the discussions.

Workshop Planning and Execution:

Dr. E.R. "Randy" Collins (Clemson University)

Klaehn Burkes (Savannah River National Laboratory)

Joe Cordaro (Savannah River National Laboratory)

Tom Keister (Resilient Power Systems)

Frederick Hansen (Energetics Incorporated)

Scott Morgan (Energetics Incorporated)

Emmanuel Taylor (Energetics Incorporated)

Support was provided to the Savannah River National Laboratory by the U.S. Department of Energy – Office of Electricity Delivery and Energy Reliability, Transformer Resilience and Advanced Components (TRAC) Research and Development Program. Work by Energetics Incorporated was performed under contract number DE-DT0010677. Photo credit for the report cover: Photo © David Neale (cc-by-sa/2.0).

EXECUTIVE SUMMARY

Substations are critical points within the vast U.S. power grid, serving a number of functions important to the safe, reliable, and cost-effective delivery of electricity. Substations serve as the entry point to the grid for electric power generators as well as the exit point for large industrial customers. Substations also form the boundaries between the high voltage transmission network and the distribution system, enabling the network to reconfigure to ensure stability and reliability, and to regulate power quality for down-stream electricity customers. As the electric power system continues to evolve, with stakeholders integrating higher amounts of variable renewable generation, deploying electric vehicles and associated charging infrastructure, and connecting more dynamic end-use devices and subsystems, substations will need to evolve as well. These critical nodes will need to continue providing their traditional functions as well as new functions and capabilities required in a future grid.

The Solid State Power Substation (SSPS) Roadmap currently in development will present a path for the strategic integration of high voltage power electronics technologies in substations to provide enhanced capabilities and support the evolution of the grid. Ultimately envisioned as a flexible and adaptable power router or hub within the transmission and distribution systems, the SSPS will be able to electrically isolate system components and provide bidirectional AC or DC power flow control from one or more sources to one or more loads - indifferent to magnitude and frequency. Applications may include upgrades for better asset utilization, increased efficiency, enhanced security and resilience, and improved integration of distributed energy resources and microgrids.

A draft roadmap was developed by Savannah River National Laboratory (SRNL) with support from the Office of Electricity Delivery and Energy Reliability (OE) Transformer Resilience and Advanced Components (TRAC) program. The draft roadmap communicated an envisioned pathway for bringing SSPS technology to market and identified three levels at which SSPS could be realized, with each embodiment adding an additional layer of functionality and complexity. These levels are referred to as SSPS Level 1.0, SSPS Level 2.0, and SSPS Level 3.0 as illustrated in Figure ES-1. The SRNL team made a preliminary determination of gaps and challenges that would need to be filled and overcome, in order to make SSPS technology a practical reality.

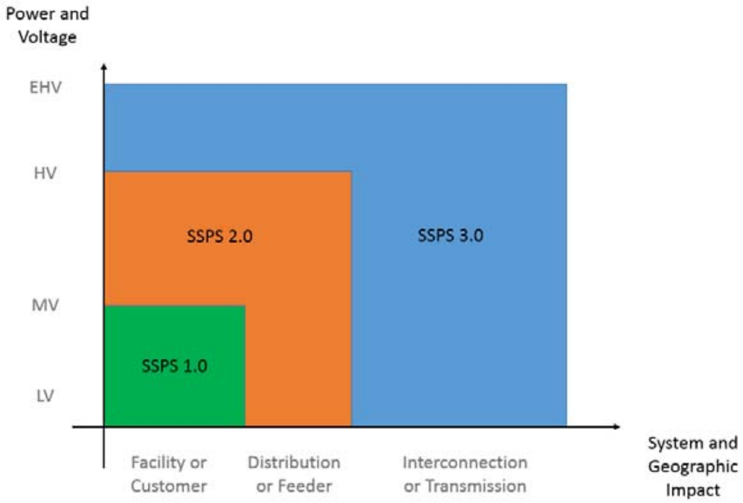

Figure ES-1: Three Embodiments of the SSPS

However, industry and the broader stakeholder community play an important role in achieving the SSPS vision and obtaining buy-in will be critical to success. Additional input concerning the benefits offered by SSPS technology, the application areas where SSPS technology can provide a value proposition, and the gaps which are most critical to fill must be collected and vetted. The SSPS Roadmapping Workshop was developed and structured to acquire this specific information. This document outlines the process undertaken, organizes the data collected, and presents preliminary conclusions drawn from the data.

During facilitated breakout sessions, workshop participants addressed specific focus questions, while their contributions were captured and documented. Workshop participants identified a number of areas where SSPS technology could provide distinct value, addressing current or anticipated issues associated with substations or the power grid. Table ES-1lists a few of the near-term, mid-term, and long-term value propositions that were identified:

Table ES-1: Summary of SSPS Value Propositions

Time Horizon	Value Proposition
Near-Term	• Add new functionality to distribution, customer, and converter substations to improve power quality, provide voltage and frequency regulation, and support the integration of distributed energy resources. • Enhance generation, transmission, and distribution substations with power flow control, dynamic stability response, address reverse power flows, and facilitate energy storage integration to improve reliability.
Mid-Term	• Serve as an integrated smart node within transmission and distribution substations to facilitate coordination of DERs, managing dynamic system topology changes, and facilitating restoration and recovery from man-made or natural events. • Enable new grid designs, manage complexity, and facilitate infrastructure upgrades through the use of modular, integrated, and adaptable SSPS technology that have advanced functions and are simpler, flexible, and more secure.
Long-Term	• SSPS technology will be applicable in all substations categories to increase security and resilience and support energy router functionality with a range of integrated control and coordination capabilities including blackstart.

In addition, workshop participants identified gaps that currently prevent SSPS technology from achieving the functions and features for each of the three SSPS levels defined. These gaps were discussed by participants, organized into clusters, and then ranked using a voting process. Of the gaps identified and synthesized across the breakout groups, Table ES-2 shows the themes that were deemed the most critical:

Table ES-2: Summary of Significant SSPS Gaps

Level	Theme	Summary of Gaps
SSPS 1.0	Converters	Focused around the technical capabilities and the performance of these power electronics systems, especially design, construction, and operating requirements.
	Controls	Focused around the fundamental theory, functional definitions, algorithms, and architecture needed to integrate and operate SSPS technology for advanced applications.
	Costs	Focused on SSPS converters costs and the associated analysis to help justify the expense of adopting SSPS technology, ensuring performance and benefits outweigh costs.

	Standards	Focused around test protocols, test beds, and criteria to demonstrate the capability and functionality of SSPS technology to address issues with interoperability and identify technology requirements.
SSPS 2.0	Protection	Focused on protection of the SSPS technology itself and the broader grid with an emphasis on distribution systems to ensure coordination of faults under various operating modes for different applications.
	Controls	Focused on controls that involve broader system considerations, such as coordination of advance applications, available resources, and system protection. Supporting technologies such as communications, algorithms, and wide are control platforms are also emphasized.
	Costs	Focused on the SSPS converter and the underlying technology needed for transmission voltage applications, including system designs that are optimally configured.
SSPS 3.0	Grid Architecture	Focused on development of topologies, communications, controls, and tools to better understand and realize a fundamentally new paradigm where there is SSPS technology ubiquitously deployed in the grid.
	Autonomous Controls	Focused on blackstart capabilities and other SSPS features that increase grid resilience, ensure reliability, and support system recovery with ubiquitous SSPS technology.
	Modeling and Simulation	Focused on the tools, models, and methodologies needed to simulate power systems with SSPS technology and other power electronics from the full system level down to the converter level.
	Converter	Focused on the understanding and advances needed in the underlying materials for SSPS converters to be deployed at the highest voltage levels on the transmission system.

NEXT STEPS

This workshop served as the initial step in an on-going effort to investigate the opportunity space for the strategic integration of high voltage power electronics technologies in substations to provide enhanced capabilities and support the evolution of the grid. This document presents an organized version of the data collected and an attempt at deriving significance from the data. However, a more thorough analysis is still needed to inform future research directions as well as refinement of the SSPS roadmap itself, which is still in development. DOE will continue to convene and engage the broader electric power community and other stakeholders to further explore this critical technology topic area.

1. INTRODUCTION

1.1 PURPOSE

A Solid State Power Substation (SSPS) is defined as a substation with strategic integration of high voltage power electronics for enhanced capabilities that can provide system benefits and support evolution of the electric power system. Applications may include upgrades for better asset utilization, increased efficiency, enhanced security and resilience, and improved integration of distributed energy resources and microgrids. Ultimately envisioned as a flexible and adaptable power router or hub within the transmission and distribution systems, the SSPS will have the capability to electrically isolate system components and provide bidirectional AC or DC power flow control from one or more sources to one or more loads - indifferent to magnitude and frequency. SSPS will also include functional control, protection, regulation, and other features.

The SSPS Roadmapping Workshop sought to inform and refine the development of a SSPS Roadmap under development by the U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE), by engaging the broader power systems community, including specialists in power electronics systems, substation design, and utility applications to weigh in on the challenges facing the future of substations, and the potential value propositions offered by SSPS technology.

This SSPS Roadmapping Workshop summary document presents the major findings from the workshop drawn from the discussions and inputs provided by participants. This document describes the perceived benefits of SSPS technology, the most pressing issues identified which impact substation design or operation, and the gaps that need to be filled to enable SSPS technology to be realized at each of the three levels defined.

1.2 WORKSHOP SCOPE AND DEFINITIONS

The workshop scope was bounded by two factors: (1) the types of substations under the consideration, and (2) a timeline up to the year 2040 where potential SSPS technology could be realized

While there are many types of substations in use on the electric grid with varying definitions, five categories were identified and considered. These substation categories are defined below, with a brief description of the primary functions that they provide.

Generation – Generator Step-Up and Collector Non-Inverter Based Renewables
- Connecting large generation to the transmission system
- Focused on maximizing output

Transmission – Networked and Switching
- Interconnect different transmission and sub-transmission voltage systems
- Focused on reliability and delivery

Distribution – Step-Down
- Connecting the transmission or sub-transmission systems to distribution systems
- Focused on reliability, voltage regulation, and delivery

Customer – Industrial, Commercial, Campus, Buildings, and Microgrids
- Non-utility owned connection to distribution or sub-transmission systems
- Focused on meeting customer and local requirements

Converter – Inverter Based Renewable and LVDC/MVDC/HVDC

- Used to integrate renewable generation and improve efficiency of delivery
- Focused on maximizing output and power transfers

The workshop focused on identifying opportunities where high voltage power electronics could be applied to the five substation categories listed above. Three levels envisioned for these applications and technological capabilities are referred to as SSPS 1.0, SSPS 2.0, and SSPS 3.0, with each embodiment adding an additional layer of functionality and complexity as illustrated in Figure 1.

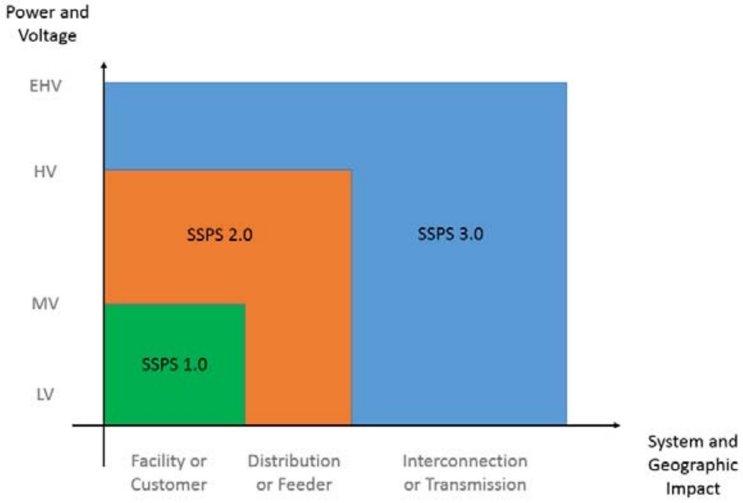

Figure 1: Three Embodiments of the SSPS

Level 1.0 focuses on applications at distinct, locally controlled substations, such as industrial customers or distributed generation facilities, with voltage levels up to 34.5 kV and therefore referred to as "SSPS 1.0 Low/Medium Voltage Local Applications." Level 2.0 expands on applications of Level 1.0 but includes higher power levels and voltages (up to 230 kV), such as distribution substations, and therefore referred to as "SSPS 2.0 Low/Medium/High Voltage Local Applications." While Level 1.0 and 2.0 limit applications to distinct substations, Level 3.0 extends the voltage and power levels beyond Level 2.0 and involves the coordination of multiple SSPS across transmission and distribution for system-wide benefits and therefore referred to as "SSPS 3.0 System Applications and Multiple Substations."

1.3 WORKSHOP PROCESS

The SSPS workshop sought to answer a number of focused questions pertaining to the value proposition offered by SSPS technology, and the gaps that impede their technical maturity. Workshop participants were organized into three parallel groups of no more than 20 while ensuring a diverse set of perspectives. Each group participated in four facilitated breakout sessions which answered the same list of focus questions. While discussions around similar concepts and ideas were encouraged within each group, arriving at consensus was not. The focus questions are listed below:

Focus question # 1: What issues and concerns most deeply impact the ability of substations to meet the demands of an evolving grid?

Focus question # 2A: What are the potential benefits (new or enhanced capabilities, functionalities, performance improvements, etc.) that solid state technologies in substations can be expected to provide from now through 2040?

Focus question # 2B: Do any of the anticipated benefits of using SSPS technology overcome a substation challenge that has been identified?

Focus question # 3: What technical gaps need to be overcome, to enable/actualize the defining functions that characterize each level of SSPS technology?

Focus question # 4: For the critical gaps identified, what metrics can we use to measure the gap? How do we track progress towards filling the gap?

The question numbers correspond to the breakout session in which the question was asked. Questions 1, 2A, and 2B were used to identify value propositions for using SSPS technology. Questions 3 and 4 helped to analyze the gaps that currently impede their technical maturity.

1.4 STRUCTURE OF THE REPORT

This report captures, organizes, and summarizes the remarks made by participants in every breakout session. The subsequent chapters present an analysis and synthesis of the results. The report appendices provide additional, relevant information pertaining to the workshop, including the workshop agenda, a list of participants, and the full listing of participant contributions as spreadsheets.

Chapter 2 summarizes the challenges that currently affect substations and the anticipated challenges as the grid continues to evolve. The intent is to identify potential areas where SSPS technology, as envisioned, can meet real demands of the industry. Examples of participant contributions are provided, along with overarching categories and themes that were most prominent.

Chapter 3 summarizes the perceived benefits of utilizing SSPS technology, highlighting themes and categories which were discussed along with specific examples. Additionally, pairings of identified needs to potential benefits of SSPS technology is also included. These matches are considered to be value propositions for applying SSPS technology and are analyzed across the three time horizons of interest.

Chapter 4 summarizes the gaps which should be overcome to enable the realization and maturation of each level of SSPS. In each group, participants grouped gaps and used a voting process to prioritize the clusters that were most critical to the development of SSPS technology. Discussion of the aggregated results and specific gaps is included.

Chapter 5 presents more detailed information on the high priority gaps that were identified. The tables presented capture the content of worksheets that were filled out during the parallel breakout sessions. These worksheets sought to more fully characterize the gaps, providing clear definitions for each and identifying pathways for closing the gap through focused R&D.

2. TECHNICAL CHALLENGES OF SUBSTATIONS

2.1 OVERVIEW OF BREAKOUT SESSION ONE

Breakout session one focused on the following topic area and focus question:

- *Topic area:* Key technical challenges limiting the performance of substations, as identified by the electric power community.

- *Focus question:* What issues and concerns most deeply impact the ability of substations to meet the demands of an evolving grid?

During the breakout session, each group identified technical challenges that currently affect the performance of substations, or have the potential to in the near future, given the growing demands placed on the grid. Each participant was encouraged to note the type of substation affected by the challenge identified. Participants were limited to the five substation categories listed in the workshop scope.

The following sections present an analysis and synthesis of the data collected by workshop participants during breakout session one.

2.2 SYNTHESIS OF RESULTS

Between the three breakout groups, workshop participants described 120 issues/concerns that impact substations. Each issue was assigned a categorical label, based on the subject matter addressed. The categorical labels used are described in Table 1. These same labels are used throughout the report to describe SSPS benefits and technical gaps.

Table 1: Categorical Labels and Descriptions

Label	Description
Communications	Pertains to communication requirements or the supporting infrastructure
Control	Describes new control strategies or objectives
Data	Relates to the way in which information is acquired, organized, processed, or utilized
Education	Pertains to workforce development
Functionality	Describes new capabilities or design features
Load	Load dynamics, growth, modeling, or related topics
Monetary	Describes monetary significance or implications
Protection	Relates to protection coordination or protection and control strategies
Regulation	Impacts or is impacted by regulation
Reliability	Impacts the ability to maintain acceptable levels of operation
Security	Addresses threats of all kinds
Standards	Impacts, or is impacted by, standards development, standards bodies, or existing standards

Table 2 summarizes the number of contributions belonging to each category. As shown, participants found the most pressing issues to be related to a lack of substation controls and limited functionality. A criterion was applied to determine the significance of the categories. All categories receiving a count equal or greater than half of the highest count are described herein. A listing of all the identified issues is included in the dataset that accompanies this report.

Table 2: Categorical Summary of Indentified Substation Issues and Challenges

Label	Count	Percentage
Control	20	17%
Functionality	19	16%
Security	14	12%
Monetary	13	11%
Reliability	13	11%
Protection	11	9%
Standards	9	8%
Data	6	5%
Education	6	5%
Load	4	3%
Regulation	4	3%
Communications	1	1%

The specific issues and challenges in the most significant categories (i.e., count of 10 or greater) were further analyzed. Duplicates were removed and similar items were grouped and synthesized into Table 3.

Table 3: Most Significant Issues and Challenges Identified

Label	Summary of Issue/Challenge
control	Bidirectional power flow as a consequence of renewables/DER; it's impact on protection/coordination
control	More distributed controls are needed, but control interactions may emerge as a result
control	With increase of DER and prosumer devices, complexity of securely monitoring and controlling them increases (e.g., coordination and bandwidth issue)
control	Enabling power flow control using high voltage, high frequency power electronics
control	Implementing volt/VAr control and frequency regulation to enhance operational flexibility
functionality	Lack of modularity and scalability; inability to provide emergency services as a result
functionality	Inability to provide dynamic reactive power or inertia to enhance system stability
functionality	Non-wires alternatives (e.g., batteries for solar to defer upgrades) versus traditional T&D reinforcement
functionality	Unmanned inspection capabilities for cybersecurity and for maintenance
functionality	Customized components (i.e., everything is unique)
functionality	"Static" substation operation cannot keep up with future -- dynamics (LTC and capacitor banks are only options)
functionality	Converter topologies and components are not optimized for efficiency
functionality	Limited grid hosting capacity, supply intermittency, ride through, islanding, and reconnection, all prevent the seamless integration of DER and microgrids
functionality	Power quality: imbalance, sag / swell; harmonics from grid or generated by customer including lack of high speed sensing
security	Cyber systems: big data, attacks, control; increase vulnerability with automation

Label	Summary of Issue/Challenge
security	Cyber attacks: can be carried out remotely; no major infrastructure required; can have significant local or national impact
security	Exposure to adverse conditions (e.g., natural and man-made; cyber and physical), including physical attack; EMP; GMD; tornado; hurricane
monetary	Required to buy power from independents but no infrastructure investment by independent
monetary	Upgrade capacity with limited real estate
monetary	Asset utilization (cost of adding stuff: who pays when renewables need more stuff?)
monetary	Pricing and market mechanisms for absorbing large percentage of renewables and DER
monetary	AC losses, reactive compensation is adding extra cost
monetary	Lack of quantified cost and benefits prevents value forecasting and value investing
monetary	Cost, performance, and commercial availability of dielectrics, insulators, and high voltage/power semiconductors
monetary	Weight and size drive transformer costs
reliability	Aging assets; downtime for maintenance and repairs
reliability	Maintaining grid stability with large penetration of renewables, DER, and their controllers
reliability	Self-contained operation under different scenarios -- a reliability concern
reliability	Prediction of components failure -- lacks good tools/techniques
reliability	Rapid restoration after equipment failure (radial feeds); emergency control and repairs after man-made or natural disasters
reliability	Increased operations and stress on mechanical tap changers from DERs results in wear out of components
reliability	Transformer sparing and redundancy; ease of transportation, repair, and installation (time, cost, availability)
protection	Detecting faults - problematic on inverter based systems due to low fault current
protection	Increasing fault currents requires equipment upgrades
protection	Detect islanding and take action economically
protection	Bi-directional flow and traditional over current protection scheme (i.e., over current scheme on radial circuits)
protection	Cascading system failures and protection complexity (e.g., Northeast blackout)
protection	Protection coordination today; protection adaptation tomorrow (e.g., adaptable coordinated protection schemes)
protection	Robustness of system integration, including fault isolation; DER can back-feed sub-transmission faults; ride-through vs. protection
protection	Safety: fault duty and arc flash

From Table 3, we see that the issues associated with reliability, monetary, and security is primarily due to greater deployment of variable renewable resources, concerns over cost allocation, and a changing threat environment. These trends and drivers are presenting challenges to the entire electric power industry and are expected to appear within the discussion of substations.

However, the issues associated with controls and protection is more interesting. While current substations lack the ability to control a number of operating parameters, it is recognized that increasing the number of control points in the system can lead to excessive complexity, such as controller interactions that could impact system reliability, and introduction of cyber vulnerability. Additionally, the dynamic range of the protection required in the future grid, detecting smaller fault currents from inverter based system and handling larger fault currents from growing loads, presents a unique challenge.

With regard to functionality, substations currently lack a wide array of beneficial capabilities and design features that should be considered in a future grid, including:

- Modularity and scalability
- Dynamic power flow control
- Power quality control
- Ride through, islanding, and reconnection

2.3 ISSUES BY SUBSTATION CATEGORY

Each participant was asked to indicate whether the issue they identified applies to a particular category of substation (or multiple categories). Using this information, each substation category was evaluated for its relative significance in the potential application of SSPS technology. Of the 120 issues/concerns identified, Table 4 shows the number that was deemed relevant to each substation category. Note that many issues were relevant to more than one substation category, so the percentages do not sum to 100.

Table 4: Issue Count by Substation Category

Category	Count	Percentage
Generation	33	28%
Transmission	57	48%
Distribution	77	64%
Customer	39	33%
Converter	57	48%

As shown in Table 4, participants believe that the overwhelming majority of issues are relevant to distribution substations with transmission and converter substations forming a second tier. These results are indicative of the significant challenges posed by a rapidly changing distribution system, concerns with reliability on the transmission system, and the greater deployment of power electronic interfaced devices (e.g., energy storage, PV inverters). Issues related to generation and customer substations appear to be of lesser significance. However, there may have been a bias toward grid-related issues as independent power producers and customer views were not adequately represented at the workshop.

A further discussion of the specific issues relevant to each substation category is not included in this report but the organized information can be accessed in the accompanying dataset.

3. POTENTIAL BENEFITS OF UTILIZING SSPS TECHNOLOGY

3.1 OVERVIEW OF BREAKOUT SESSION TWO

Breakout session two was divided into two segments (A and B). Segment A focused on the following topic area and focus question:

- *Topic area:* New capabilities or improved performance expected as a result of deploying power electronics technologies within substations.

- *Focus question:* What are the potential benefits (new or enhanced capabilities, functionalities, performance improvements, etc.) that solid state technologies in substations can be expected to provide from now through 2040?

Segment B combined the results of Breakout Session One with those from Segment A (from Breakout Session Two). Segment B focused on the following topic area and focus question.

- *Topic area:* The identification of near-term, mid-term, and long-term value propositions for the development of Solid State Power Substations.

- *Focus question:* Do any of the anticipated benefits of using SSPS technology overcome a substation challenge that has been identified?

During the breakout session, each group identified ways in which SSPS technology is expected to improve substations. For each benefit identified, participants were asked to note whether it could be realized in the near-, mid-, or long-term. These timeframes corresponded to a deployment window of five years, 10 years, and 20 years, respectively. After potential benefits were documented, participants identified matches between benefits identified, and the challenges that had been previously documented during the first breakout session.

3.2 SYNTHESIS OF RESULTS

Between the three breakout groups, workshop participants described 130 potential benefits associated with the use of Solid State Power Substations. Each proposed benefit was assigned a categorical label and the number of contributions belonging to each category is summarized in Table 5.

Table 5: Categorical Summary of Identified SSPS Benefits

Label	Count	Percentage
Functionality	61	47%
Control	23	18%
Monetary	12	9%
Reliability	12	9%
Protection	9	7%
Data	4	3%
Security	3	2%
Education	2	2%
Standards	2	2%

Label	Count	Percentage
Load	1	1%
Regulation	1	1%
Communications	0	0%

As shown, participants found the most compelling benefits to involve the provision of advanced functions and features associated with SSPS technology. A distant second involves improving controls and a third tier involves monetary and reliability benefits which are persistent issues with the industry. A listing of all the identified benefits is included in the dataset that accompanies this report.

The same criterion used in Chapter 2 was applied to prioritize these benefit categories (i.e., count of 30 or greater). The specific benefits in the most significant categories were further analyzed. Duplicates were removed and similar items were grouped and synthesized into Table 6.

Table 6: Most Significant Benefits Identified

Label	Summary of Benefit
functionality	Scalable HVDC features: No cascading faults; asynchronous systems; grid buffer
functionality	Enable grid reconfiguration based on demand/faults
functionality	Completely decoupled (asynchronous) grid will provide: local voltage and frequency control on feeders; islanding without instability; dynamic power routing;
functionality	Increased efficiency
functionality	Scalability, flexibility, modularity; simplifies upgrades and replacements; reduces overall substation size/footprint; increases power density;
functionality	Improve power quality: phase imbalance; line dip; harmonic mitigation; reactive power
functionality	Modularity and scalability: availability of spares; mobility
functionality	Seamless integration of AC and DC sources; can lead to enhanced renewable integration, higher hosting capacity, customer choice
functionality	Integration of active filtering stages for advanced dynamic grid connectivity
functionality	Coordination of energy sources: batteries and variable generation; enhance flexibility and dispatchability; UPS-like operation
functionality	Advanced MVDC topologies for generation and distribution, or power router links between feeders, that can help reduce overloads and give better balance
functionality	Grid forming power electronics: helpful for black start and provides ability to replace missing inertia
functionality	Enable prioritized Quality-of-Service through power flow like data networks
functionality	Power electronics building blocks: modular functionality; enhanced revenue opportunity with needs-based deployment; scaling with inherent interoperability
functionality	Synchronization between substations fed from different transmission lines
functionality	Power electronics could manage the average power over time and keep peaks low
functionality	Combination of electricity and data services (e.g., power line communication); more value/services over the same infrastructure
functionality	Grid support services: enhanced flexibility and power quality; islanding and reconnection, synthetic inertia, black start capability

From Table 6, we see that most of the advanced functionality involve the ability to control power flows including power quality, the provision of grid services that enhance reliability and resiliency, designs and capabilities that increase the economics of operating and expanding the grid, and features that leverage the asynchronous nature of DC power. Maturation of SSPS technology with these advanced functions will introduce a new component with valuable capabilities needed in the future grid.

3.3 BENEFITS BY EXPECTED TIME HORIZON

Each participant was asked to indicate whether the benefit they identified was likely to be realized in the near-term (5-year time horizon), mid-term (10-year time horizon), or long-term (20-year time horizon). Using this information, each time-horizon was evaluated for its relative significance in the potential application of SSPS technology. Of the 130 benefits identified, Table 7 shows the number that was attributed to each time period. Note that some benefits were deemed applicable to multiple time periods, so the percentages do not sum to 100.

Table 7: Benefits Count by Time Horizon

Time Horizon	Count	Percentage
Near-term	40	31%
Mid-term	60	46%
Long-term	44	34%

As shown in Table 7, participants believe that a majority of SSPS benefits can be realized in the mid-term. However, the potential for benefits to be realized is fairly evenly distributed across the three time horizons of interest. This provides an indicator that there is a reasonable trajectory for the maturation of SSPS technology. If a majority of benefits were in the near-term, the maturation of SSPS may miss the window of opportunity for the development of a cohesive strategy. If a majority of benefits were in the long-term, the urgency to advance the technology may not materialize.

An exhaustive discussion of the specific benefits associated with each time horizon is not included in this report but the organized information can be accessed in the accompanying dataset. However, a matching of issues and SSPS benefits identified by participants across these times horizons is included in the next section.

3.4 MATCHES BETWEEN SUBSTATION ISSUES AND SSPS BENEFITS

The SSPS workshop sought to identify application areas where utilization of SSPS technology provides a clear value proposition. This was done by identifying matches between an existing industry need and a benefit that derives from the use of SSPS technology. As noted in earlier sections, participants provided additional information with each issue (i.e., substation category impacted) and benefit (i.e., time horizon to realization) identified. Therefore, each match serves as a potential value proposition with an indicator of the substation types where SSPS technology can be applied and the relative timing of impact. An analysis sequentially across the time horizons provides an indicator of the high-value opportunities that can be leveraged to drive maturation of SSPS technology.

Each group took a slightly different approach to the exercise and as a result, there was not an explicit one-to-one matching of individual issues and benefits. Additionally, not all participants provided the additional information requested in their contributions. To simplify the analysis, benefits without time horizons were assumed to be realized across all horizons. Issues without designations of substation category impacted were removed since this exercise is meant to identify value propositions (i.e., addressing specific issues). In Tables 8-10, substation categories are denoted by the following letters: G = generation, T = transmission, D = distribution, C = customer, X = converter.

3.4.1 Near-Term Opportunities

The majority of near-term opportunities relate to distribution substations and involve the use of SSPS technology to add new functionality that support greater penetration of distributed energy resources (DERs) and provide enhanced control and flexibility. Examples include the regulation of power quality (e.g., sags, swells, and harmonics), balancing loads on 3-phase feeders, aggregation of DERs, the ability to regulate reactive power, and the management of faults. Many of these advanced features and functions are opportunities for customer and converter substations as well.

Another set of opportunities are focused on the bulk power system (i.e., generations, transmission, and distribution substations) to ensure the reliability of grid operations. Examples include facilitating the integration of energy storage to make variable energy resources more dispatchable, the ability to control power flows to address dynamic stability concerns, and accommodating reverse power flows with higher penetration of DERs on distribution systems.

Generally, the modularity and scalability of SSPS technology can address concerns with security and resilience across all substation categories. A building block concept can address issues associated with time, cost, and availability of critical equipment and allows for embedded cybersecurity and EMP protection. Additionally, the flexibility and adaptability of the technology (e.g., multiple frequency, AC and DC ports) can help manage complexity, simplifying upgrades, and enable microgrids.

Table 8: Near-Term Issue-Benefit Matches

Issue/Concern	G	T	D	C	X	SSPS Benefit
• Lack of modularity/scalability		x	x	x		• Modularity and scalability - available spares - mobile
• Aging assets	x	x	x	x	x	
• Ability to provide emergency services		x	x			
• Emergency control and repairs after man-made or natural disasters	x	x	x	x	x	
• Ability to provide dynamic reactive power for stability		x	x	x		• Dynamic (enhanced) power flow control • Improved asset utilization (power flow control) • Volt-VAR control (quality, PV hosting, voltage control)
• Inertia reduction and impacts on system dynamics ($\Delta MW/\Delta f$ = "bias" β)		x	x			
• Redirecting energy for better asset utilization	x	x	x			
• Current substations have no control - unable to handle dynamics from DER and prosumers - but addition of PE/control conflicts with need for high reliability, resiliency and cyber-physical security (and cost)		x	x			
• Evolving grid needs more dynamics distributed control, but no one has understanding of such distribution control system will behave or if it will be stable		x	x	x		
• Interaction of "many" active control devices, i.e., SVC, FACTs, PV, …		x	x			
• Inability to respond to V going outside ANSI C84.1. (i.e., taps and PE)			x			
• Sensing and situational awareness costs too much, complex and generates too much data.		x	x			• Real-time solutions to coupled

Issue/Concern	G	T	D	C	X	SSPS Benefit
How do you manage complex system?						operation not needed with SSPS
• Cyber Attack: - Cyber attacks can be carried out remotely without major infrastructure required for delivery - can have significant local or national impact.	x	x	x	x	x	
• Solutions based on PE are too complex; education is needed			x			
• "If it ain't broke don't replace it." Makes adoption of new technology challenging. PUC approval for funding.		x	x			
• Reverse power flow from DER/DG			x	x		• Completely decoupled (asynchronous) grid will provide ability to accommodate 100% renewables • Better renewable integration • Active participants with grid support functionalities • DC system integration into distribution system
• Backward compatibility (between different versions of technology progressions)		x	x	x	x	
• Situation awareness visibility (smart sensors) - Assets assessment - Predict fault conditions		x	x			• Make variable resources dispatchable and stable with minimal local storage and control (e.g., impedance control)
• Modernization of the metering at all levels. Need to implement smart grid.	x	x	x	x	x	
• Reliable communications and metering equipment for market operations/bidding	x	x				
• With substation automation, cyber threats?	x	x	x	x	x	• Multistage EMP-cyber-physical early embedded design for future generation substations
• Physical/cyber security	x	x	x	x		
• One concern is aggregating all the DER controllers. With increase of DERs, complexity of controlling them increases. (Coordination and bandwidth issue)	x	x	x			• Synchronization between subs fed from different transmission lines
• Maintains system stability with renewable controllers			x		x	
• Unbalanced loading on 3-phase feeders			x	x		• Specialized controllers such as POD, frequency, SSR and provide reactive support
• Reverse flow due to DER and its impact to protection/coordination			x	x		• Fault isolation implemented at a substation
• Cascading system failures. Protection complexity (e.g., Northeast blackout)			x	x		
• Protection coordination today; protection adaptation tomorrow (e.g., adaptable coordinated protection schemes)			x			
• How do we meet NERC requirements for sag events?	x	x	x	x	x	• Sag mitigation
• Redundancy; reliability			x	x	x	• Enhanced reliability; less number of outages
• Reliability as loads change	x		x			• Enhanced reliability; less number of outages

Issue/Concern	G	T	D	C	X	SSPS Benefit
• Ease of transportation, repair, and installation (time, cost, availability)		x	x			• Scalability: modularity and flexibility
• Volt/VAR and frequency regulation				x		• Controllability; volt/VAR regulation (completely dynamic, not discretized; faster response than traditional voltage regulators)
• Power quality: imbalance, sag / swell; harmonics from grid or generated by customer (lack of high speed sensing)			x	x	x	• Power quality improvement
• Transformer sparing	x	x				• Lower bill paid by customer
• Weight and size; cost	x	x	x	x	x	• Power density
• Increase penetration of renewables; large swings due to solar/wind penetration causing grid instability		x	x			• Choice of AC/DC supported for all end users (individual choice)
• Renewable integration; islanding; microgrids			x			• Enabling various frequencies, in addition to various voltages
• Increased fault currents		x	x			• Fault current limiting

3.4.2 **Mid-Term Opportunities**

A majority of the mid-term opportunities are the same as the near-term opportunities, indicating that the advanced featured and functions associated with SSPS technology will continue to be valuable as the grid evolves. However, there are a few new opportunities that are associated with the extension of capabilities to help manage the transition from the current electricity delivery infrastructure (i.e., transmission and distribution systems) to the grid of the future and a bigger emphasis on managing complexity.

One new capability highlighted is for SSPS technology to serves as an integrated smart node within transmission and distribution substations. Localized communication and intelligence can address concerns around scaling challenges, particularly with the coordination of an increasing numbers of DERs, making sense of distributed sensor data, managing dynamic system topology changes, and facilitating restoration and recovery from man-made or natural events. Additional benefits include the ability to provide asset monitoring services to extend equipment lifetimes and improve asset utilization.

The modular, integrated, and adaptable nature of SSPS technology appears to provide greater value in the mid-term. The increased flexibility and simplicity addresses concerns with a smaller workforce and the potential loss of power system expertise. SSPS technology provides freedom for exploring new grid designs and enable less experienced power system engineers to upgrade the grid. Integration of multiple substation components into one technology can also increase system security by minimizing the attack surface.

Finally, expanded applications such as multi-terminal MVDC and HVDC can provide system benefits within the transmission and distribution systems by managing congestion and providing frequency response. These advanced controls and topologies can facilitate integration of variable renewable resources, serve as a stabilizing force, and help manage operational complexity. Additional features include blackstart capabilities and islanding/reconnection to improve resilience to natural disasters.

Table 9: Mid-Term Issue-Benefit Matches

Issue/Concern	G	T	D	C	X	SSPS Benefit
• Lack of modularity/scalability		x	x	x		• Modularity and scalability - available spares - mobile
• Aging assets	x	x	x	x	x	
• Ability to provide emergency services		x	x			
• Emergency control and repairs after man-made or natural disasters	x	x	x	x	x	
• Ability to provide dynamic reactive power for stability		x	x	x		• Dynamic (enhanced) power flow control • Improved asset utilization (power flow control) • Volt-VAR control (quality, PV hosting, voltage control)
• Inertia reduction and impacts on system dynamics ($\Delta MW/\Delta f$ = "bias" β)		x	x			
• Redirecting energy for better asset utilization.	x	x	x			
• Current substations have no control - unable to handle dynamics from DER and prosumers - but addition of PE/control conflicts with need for high reliability, resiliency and cyber-physical security (and cost)		x	x			
• Evolving grid needs more dynamics distributed control, but no one has understanding of such distribution control system will behave or if it will be stable		x	x	x		
• Interaction of "many" active control devices, i.e., SVC, FACTs, PV, …		x	x			
• Inability to respond to V going outside ANSI C84.1. (i.e., taps and PE)			x			
• Sensing and situational awareness costs too much, complex and generates too much data. How do you manage complex system?		x	x			• Large complex distributed systems that do not require detailed system knowledge -- robust with local intelligence • Real-time solutions to coupled operation not needed with SSPS
• Cyber Attack: - Cyber attacks can be carried out remotely without major infrastructure required for delivery - can have significant local or national impact.	x	x	x	x	x	
• Solutions based on PE are too complex; education is needed			x			
• "If it ain't broke don't replace it." Makes adoption of new technology challenging. PUC approval for funding.		x	x			
• Reverse power flow from DER/DG			x	x		• Completely decoupled (asynchronous) grid will provide ability to accommodate 100% renewables • Better renewable integration • Seamless integration of AC and DC sources • Active participants with grid support functionalities • DC system integration into distribution system
• Backward compatibility (between different versions of technology progressions)		x	x	x	x	
• Situation awareness visibility (smart sensors) - Assets assessment - Predict fault conditions		x	x			• Data collection center from distributed sensors.

Issue/Concern	G	T	D	C	X	SSPS Benefit
• Modernization of the metering at all levels. Need to implement smart grid.	x	x	x	x	x	• Increased equipment sensor technology and equipment monitoring -- even "smart" (i.e. predictive) monitoring
• Reliable communications and metering equipment for market operations/bidding	x	x				• Key smart grid enabler, will significantly improve flexibility of the grid, but would need to be combined with energy storage to achieve full benefits
• With substation automation, cyber threats?	x	x	x	x	x	• Reduced attack surface area by replacing legacy components with single integrated device
• Physical/cyber security	x	x	x	x		
• One concern is aggregating all the DER controllers. With increase of DERs, complexity of controlling them increases. (Coordination and bandwidth issue)	x	x	x			• Synchronization between subs fed from different transmission lines • Multi-terminal MVDC/HVDC with advanced converter designs for economic benefits thru congestion and frequency response
• Maintains system stability with renewable controllers			x		x	• Be a stabilizing force to accommodate dynamic power delivery with uncertain and varying conditions in both generation, distribution, routing
• Legacy design/upgrade approaches as grid modernization takes place		x	x	x		• Likely increase in creativity with engineers (more degree of freedom)
• Impact of aging infrastructure to be upgraded and not enough engineering manpower to design and replace systematically while workforce is small	x	x	x	x	x	
• Workforce: Younger generation gathering interest in designing		x	x	x		
• Rapid restoration after equipment failure (radial feeds)			x			• Increased options for restoration (dynamic) - Faster/modular - Configurable
• Increased operations and stress on mechanical tap changers for DERs results in wear out of components	x	x	x			• PE could manage the average over time and keep peak
• Redundancy; reliability			x	x	x	• Enhanced reliability; less number of outages
• Reliability as loads change	x		x			• Enhanced reliability; less number of outages
• Ease of transportation, repair, and installation (time, cost, availability)		x	x			• Scalability: modularity and flexibility
• Power quality: imbalance, sag / swell; harmonics from grid or generated by customer (lack of high speed sensing)			x	x	x	• Power quality improvement
• Substation restoration and resiliency, from natural or man-made events		x				• Intelligent control and communication: quick power rerouting
• Scalability; lack of flexibility (legacy			x	x		• Modularity, scalability,

Issue/Concern	G	T	D	C	X	SSPS Benefit
protection and control)						multifunctional
• Resilience to natural disasters	x	x	x	x	x	• Improve black start capability, ease of islanding and re-connection to the grid
• Increase penetration of renewables; large swings due to solar/wind penetration causing grid instability		x	x			• Choice of AC/DC supported for all end users (individual choice)
• Increased fault currents		x	x			• Fault current limiting

3.4.3 **Long-Term Opportunities**

In the long-term, the opportunities for SSPS technology is more evenly distributed across all substation categories giving an indication that applications would span the full power system. While some of the new opportunities identified for the mid-term are extended into the long-term, the advanced control features to support distributed energy resources identified in the near-term is no longer relevant. This gives an indication that these capabilities are assumed to be ubiquitous and standard in the utilization of SSPS technology.

A new opportunity identified within this time horizon is aligned with the ultimate vision for SSPS technology - a flexible, scalable, and adaptable energy router or hub. Having this capability at every substation will enable a range of integrated control and coordination across the entire electric power system. The modular nature of SSPS technology is inherently more resilient which address security concerns. Additionally, this feature can facilitate system upgrades and capacity increased to accommodate demographic shifts.

Table 10: Long-Term Issue-Benefit Matches

Issue/Concern	G	T	D	C	X	SSPS Benefit
• Lack of modularity/scalability		x	x	x		• Modularity and scalability - available spares - mobile
• Aging assets	x	x	x	x	x	
• Ability to provide emergency services		x	x			
• Emergency control and repairs after man-made or natural disasters	x	x	x	x	x	
• Sensing and situational awareness costs too much, complex and generates too much data. How do you manage complex system?		x	x			• Large complex distributed systems that do not require detailed system knowledge -- robust with local intelligence • Real-time solutions to coupled operation not needed with SSPS
• Cyber Attack: - Cyber attacks can be carried out remotely without major infrastructure required for delivery - can have significant local or national impact.	x	x	x	x	x	
• Solutions based on PE are too complex; education is needed			x			
• "If it ain't broke don't replace it." Makes adoption of new technology challenging. PUC approval for funding.		x	x			
• Reverse power flow from DER/DG			x	x		• Completely decoupled

Issue/Concern	G	T	D	C	X	SSPS Benefit
• Backward compatibility (between different versions of technology progressions)		x	x	x	x	(asynchronous) grid will provide ability to accommodate 100% renewables • Better renewable integration • Active participants with grid support functionalities • DC system integration into distribution system
• Situation awareness visibility (smart sensors) - Assets assessment - Predict fault conditions		x	x			• Key smart grid enabler, will significantly improve flexibility of the grid, but would need to be combined with energy storage to achieve full benefits
• Modernization of the metering at all levels. Need to implement smart grid.	x	x	x	x	x	
• Reliable communications and metering equipment for market operations/bidding	x	x				
• With substation automation, cyber threats?	x	x	x	x	x	• Reduced attack surface area by replacing legacy components with single integrated device
• Physical/cyber security	x	x	x	x		
• One concern is aggregating all the DER controllers. With increase of DERs, complexity of controlling them increases. (Coordination and bandwidth issue)	x	x	x			• Controllability - Response to disturbances - Coordinated set points - FACTS in (every) substation
• Maintains system stability with renewable controllers			x		x	• Compatibility of load shedding/load transfer. Micro grid/islanding techniques.
• "Static" substation operation cannot keep up with future -- dynamics (LTC and capacitor banks are only options)	x	x	x	x	x	• Make existing substation infrastructure redundant in functionality and add capability beyond what we know today. E-gateway (two-way power flow)
• Redundancy; reliability			x	x	x	• Enhanced reliability; less number of outages
• Reliability as loads change	x		x			• Enhanced reliability; less number of outages
• Ease of transportation, repair, and installation (time, cost, availability)		x	x			• Scalability: modularity and flexibility
• Power quality: imbalance, sag / swell; harmonics from grid or generated by customer (lack of high speed sensing)			x	x	x	• Power quality improvement
• Weight and size; cost	x	x	x	x	x	• Power density
• Resilience to natural disasters	x	x	x	x	x	• Improve black start capability, ease of islanding and re-connection to the grid
• Population redistribution leads to converting / upgrading substations		x	x	x	x	• Improved capacity

4. IDENTIFICATION OF TECHNOLOGY GAPS

4.1 OVERVIEW OF BREAKOUT SESSION THREE

Breakout session three focused on the following topic area and focus question:

- *Topic area:* Gaps that hinder technology maturation.
- *Focus question:* What technical gaps need to be overcome, to enable/actualize the defining functions that characterize each level of SSPS technology?

During the third breakout session, each group was asked to identify the gaps that prevent each level of SSPS technology, with their defining functions and features listed in Table 11, from being realized. SSPS Level 1.0, 2.0, and 3.0 were discussed sequentially and in each discussion, participants identified gaps and similar ideas were clustered together. After the clustering, participants ranked the relative criticality using a voting process. Votes were placed on the cluster, not on individual participant contributions.

Table 11: SSPS Level with Functions and Features

	Defining Functions and Features
SSPS 1.0	• Provide reactive power compensation • Provide voltage and frequency regulation • Maintain appropriate power quality at its location • Perform bidirectional power routing on low voltage ports • Allow for multi-frequency systems • Enable nanogrids of single buildings
SSPS 2.0	+ Low voltage ride through + System coordination of fault current + Provides bidirectional power flow control between transmission and distribution + Enables distribution feeder islanding and microgrids
SSPS 3.0	+ Distributed control of multiple SSPS systems + Enhanced power routing for optimizing operational efficiency and increased resilience + System decoupling for improved stability + Provides black start support on a regional network

For each level of SSPS, the gaps clusters identified in each parallel breakout group was aggregated. The same “Half Max” criterion used in Chapter 2 and 3 was applied to determine the high priority clusters presented and analyzed below. Tables 12-14 shows the high priority clusters, vote counts, and the individual gaps and associated impacts or significance within those cluster. A discussion of the other gaps identified is not included in this report but the information can be accessed in the accompanying dataset.

4.2 SSPS LEVEL 1.0 RESULTS

For SSPS 1.0, seven gap clusters were identified associated with four themes: Converters (total count of 18), Controls (total count of 18), Costs (total count of 17), and Standards (total count of 8). From the combined votes, we see that gaps associated with Converters, Controls, and Costs are critically important to the realization of SSPS 1.0 while Standards play an important secondary role. More details on these themes are provided in the following sections.

4.2.1 **Converters**

Gaps associated with converters focused around the technical capabilities and the performance of these power electronics systems. Since converters are the core building block of SSPS technology, it is very important to ensure their design, construction, and operating requirements are well established. Aspects to consider include converter topologies that are fault tolerant and reconfigurable, voltage and power ratings, subcomponents such as drivers, passives, and power electronic devices, and insulation materials to handle high voltage connections (i.e., distribution level voltages). Additionally, SSPS converters will need to accommodate their expected operating environment to ensure reliability, such as handling over-voltages, managing fault conditions, and dealing with inrush currents from motors or other loads.

4.2.2 **Controls**

Gaps associated with controls focused around the fundamental theory, functional definitions, algorithms, and architecture needed to integrate and operate SSPS technology. These advances are needed to enable applications such as grid-edge control, microgrids, and voltage and frequency regulation to support more efficient and optimized grid operations. An important consideration for controls is the coordination and interactions with other converters and technologies on the grid, including establishing standards and responsibilities, to ensure system stability. Additional considerations include communication latencies, market operations, and the timing and geographic scale of control hierarchies which impact the overall complexity and fragility of the system.

4.2.3 **Costs**

Gaps associated with costs had two facets, the cost of SSPS converters and the associated analysis to help justify the expense of adopting SSPS technology. Ultimately, SSPS technology will only be accepted if their performance and benefits outweigh their costs. Demonstrated use-cases with the actual technology deployed is desired but hypothetical analysis would also be beneficial. Since semiconductor devices are the main cost element in SSPS converters, it is important to reduce their costs, especially at higher voltage and power levels. Development and commercialization of medium voltage wide band gap semiconductor devices (e.g., SiC) can help address cost issues.

4.2.4 **Standards**

Gaps associated with standards focused around test protocols, test beds, and criteria to demonstrate the capability and functionality of SSPS technology. Standardized and open procedures can address issues with interoperability and identify requirements for additional technology development. A common test bed can also help show successful use-cases and facilitate utility acceptance of SSPS technology.

Table 12: SSPS 1.0 Technology Gaps and Their Impact

Theme	Count	Gap	Impact
Converters	12	Power converters directly connected to the grid	Removes auxiliary transformers
		State of art power converters: Creative topologies [still emphasis on 80s/90s designs]	Device rating to continuously think about developing higher ratings (and allow multilevel and seriesing of devices)
		Power electronics integration of 10-15 kV SiC MOSFETs: gate drive isolation, bus, passives	Supply chain support for manufacturing of systems MV direct converter
		Fault tolerant/reconfigurable, redundant converter topologies and control to realize	Reach 5-nines type of availability

Theme	Count	Gap	Impact
		high availability	
Controls	11	Control theory for SSPS-based grid is non-existent	Excessive operational costs and non-optimized performance.
		Stability of system with ubiquitous power conversion to have limits and conditions	Have robust operation in the presence of high variability.
		Grid edge control functionality for second-to-second control for multiple DER and multiple grid constraints	Autonomous, real-time control
		Microgrid and ADMS control interoperability. - Demonstrations and practices not developed (standards exist)	Multiple level control able to consider SSPS functions
		Control standards need to be developed to define how SSPS 1.0 will function.	Open-architecture, standardized controls must be created.
Costs	10	Solid State Substation acceptance based on cost and performance	Cost Benefit Analysis will increase the penetration of new technologies
Standards	8	Standardized, open, field testing test (bed/lab) criteria for utility acceptance	Less competition and interoperability. Longer time to show successful cases
		Testing methods and standards specific to SSPS	Allows for identification of devices and component technology development
Costs	7	Full conversion SSPS is expensive; cost increases too fast with power rating	Cannot ride out brownout or do frequency conversion inexpensively
		System costs (mainly SiC devices) too high	All SSPS 1.0
		Don't have direct connect MV inverter; needs MV devices, as in ARPA-E ADEPT (Cree); commercialization gap, it exists, but it's not available	MV connection costs (inverter + system), controls, modular / expandable
		Quantified cost/benefit (even hypothetical, wishful) analysis of SSPS 1.0 does not exist	Without serious multidisciplinary analysis, it is impossible (and undesirable) to convince investors and policy makers to fund new technology development and deployment
Controls	7	Distribution system control architecture(s) must be defined. Should produce standards and responsibilities.	If different SSPSs are to be allowed to regulate frequency (including DC) & voltage mechanisms (protocols, algorithms, etc.) for arbitrage and system energy efficiency optimization with prescribed power quality bounds must be defined
		Controls hierarchy; local/fast to global/slow	Everything interacts, overall controls need to be (too) slow
		Adequate control standards need to be developed	Without them, no interoperability
		Use of security constrained OPF and state estimation requires detailed system knowledge and introducing latencies in control and market operation	Makes high DER and dynamic scenarios very challenging at high penetration
		Intelligent distributed systems getting too complex. This introduces fragility and single point of failure (communications, cloud, etc.)	System susceptible to large scale outages with slow restoration
		Local / wide area control systems. Need efficient control algorithms / schemes. (voltage and frequency regulation)	Allows local / wide area controllability

Theme	Count	Gap	Impact
Converters	6	High and low side standards	Need to start somewhere
		Fragility under faults	Cost, size
		Over-voltage handling (and EMP handling)	Size, reliability, cost
		Materials for insulation to achieve higher power and voltage	Allow for stacking modules
		Faults - standards for the way SSPS behave during fault conditions and then technology to accomplish	
		SSPS must deal with inrush, motor starting, etc.	

4.3 SSPS LEVEL 2.0 RESULTS

For SSPS 2.0, eight gap clusters were identified associated with three themes: Protection (total count of 31), Controls (total count of 23), and Costs (total count of 13). From the combined votes, we see that Protection dominates the gaps associated with the realization of SSPS 2.0 followed by Controls and then Costs. It is important to note that the exercise assumed the gaps for SSPS 1.0 will be addressed before the additional features and functions of SSPS 2.0 are implemented. Both Controls and Costs are persistent themes that extend from SSPS 1.0 giving an indication that the associated gaps will need to be considered holistically across SSPS levels. More details on these themes are provided in the following sections.

4.3.1 Protection

Gaps associated with protection has two focal points, one pertaining to the SSPS technology itself and the other pertaining to the broader grid with an emphasis on distribution systems. As SSPS technology advances to the next level, coordination of faults across the entire electric power system under various operating modes for different applications (e.g., microgrids, integrating DER) will be very important for safe, stable, and reliable grid operations. Dynamic fault detection, fast and adaptive protection, and solid state fault isolation are capabilities and features that will need to be developed. For SSPS converters, they will need to have high voltage and fault ride-through capabilities, sufficient BIL withstand capabilities, and other embedded protection functions that can be programmable.

4.3.2 Controls

Gaps associated with controls involved broader system considerations, especially coordination of advance applications (e.g., microgrids, virtual inertia, CVR) and resources (e.g., energy storage, DER) with system protection. Again, an established control architecture and hierarchy, along with roles and rules of the various interacting agents (i.e., grid-supporting vs. grid-forming), is critical to the continued advancement of SSPS technology. Additionally, supporting technologies such as communications, wide area control platforms that span transmission and distribution, algorithms, and energy storage will be needed to for the success of SSPS technology.

4.3.3 Costs

Gaps associated with costs are primarily focused on the SSPS converter and the underlying technology needed for transmission voltage applications. System designs that are optimally configured can help drive SSPS technology cost reductions in the long run. Additionally, reliable high voltage semiconductors that are cost-effective, such as 3.3 kV SiC MOSFETs, can help address overall SSPS converter costs.

Table 13: SSPS 2.0 Technology Gaps and Their Impact

Theme	Count	Gap	Impact
Protection	12	Faster protection for distribution system	Allows for SSPS to react and limit fault current
		How do we have adaptive dynamic protection paradigm to make conventional and power converters for synergy?	Long life and system reliability improvement for electrical service
		HVRT; fault ride-through	More stringent requirements on converters
		Ride through current and BIL withstand capability	Coordination / dependence / leveraging of legacy systems
Protection	10	Dynamic fault detection	Enables adaptable over current protection
		Self-adaptive protection	System coordination of fault current retained when going from 1.0 to 2.0
		Solid state fault isolation capability	
		Power electronics control that deals with nominal as well as mode-changing issues (e.g., fault setting, inrush)	Higher stability, stabilization, reliability
		Embedded protection functions (electrical and CS)	Security; reliability
		Programmable fault controls	
Protection	9	Dynamic fault detection; self-adaptive protection; solid-state fault isolation capability;	Adaptable over current protection; system coordination of fault current retained when going from 1.0 to 2.0;
Controls	8	Interconnecting feeders to improve loading and utilization creates challenges for protection coordination	Requires grid build - expensive, leads to poor asset utilization
		Grid stabilization using virtual resources not enabled (CVR, VAR support, spare PV)	Makes grid operation challenging, especially in high DER environment
		All grid elements need to operate to rules that are grid-supporting and grid-forming. Today, they operate for local benefit only	Fragile grid w/ possibility of cascading outages
		Control and architecture to allow proliferation of DER and microgrids without detailed utility studies	Slows down adoption of DER, makes it too expensive
		Distribution feeders do not provide dynamic support and power flow control for transmission	Significant duplication of resources, asset utilization poor
		Integrated communications to ensure coordination with other devices / legacy components	Needed for integration of technology at a distribution system
Controls	8	Distributed control algorithms to work with microgrids	Centralized solution maybe too slow
		Wide area control platform to securely group distribution devices into transmission services	Distributed control at lower cost
		Setting a control philosophy and hierarchy	Which controller has precedence and defining specific roles to each
Costs	7	Identify optimum system configuration first, then try to reduce cost	Reduced total cost of ownership; more environmental friendly; improved overall system performance

Theme	Count	Gap	Impact
Controls	7	Energy storage modularity, scalability, and integration	Enables low voltage ride through and microgrids
		Define / divide system into multiple microgrids which can operate independently	Minimum load loss
		Low-cost solution to enable islanding and microgrid	
		Understand SSPS role in microgrid	Cost and design
		Cost-effective energy storage integration	Default grid-forming source for microgrid; easy low voltage ride through
Costs	6	Reliable 3.3 kV SiC MOSFETs that meet cost goals	High
		Reliable high voltage for semiconductors	Allows for the research in getting grid connected PE at DL to TL

4.4 SSPS LEVEL 3.0 RESULTS

For SSPS 3.0, nine gap clusters were identified associated with four themes: Grid Architecture (total count of 27), Autonomous Controls (total count of 22), Modeling and Simulation (total count of 19), and Converters (total count of 8). From the combined votes, we see that Grid Architecture dominates the gaps associated with the realization of SSPS 3.0, with Autonomous Controls and Modeling and Simulation as a second tier, followed by Converters. As with SSPS 2.0, the exercise assumed that gaps associated with the prior level will be addressed before the additional features and functions are implemented with the current level. More details on these themes are provided in the following sections.

4.4.1 Grid Architecture

Gaps associated with grid architecture span the development of topologies, communications, controls, and tools to better understand and realize a fundamentally new paradigm where there is SSPS technology ubiquitously deployed in the grid. The complete decoupling of the electric power system through SSPS converters will require new approaches to manage system operations, such as redefining stability limits and requirements, and tools and methods to conduct security assessments during normal and contingency conditions, to ensure reliability. Additionally, the control and coordination strategies associated with a “fractal grid” will need to be developed that allow for optimization, control, and protection. The enabling technologies for this new SSPS paradigm will also need to be developed including autonomous controls, distributed intelligence platforms, and peer-to-peer communications.

4.4.2 Autonomous Controls

Gaps associated with autonomous controls centered on blackstart capabilities and other SSPS features that increase grid resilience. In a new operating paradigm with ubiquitous SSPS technology, the control and coordination of blackstart between SSPS converters and the various resources available (e.g., generators, storage) is important to ensure reliability and support system recovery. Autonomous controls should also be able to prioritize emergency loads, fragment the system, and form community microgrids during a contingency and sustain operations with limited communication and the loss of system wide control. This feature will require SSPS technology to be “situation aware” and event driven distributed intelligence to island and reconnect seamlessly and on the fly across multiple microgrids.

4.4.3 Modeling and Simulation

Gaps associated with modeling and simulation focuses on the tools, models, and methodologies needed to simulate power systems with SSPS technology and other power electronic converter operations. These gaps span the full spectrum of capabilities needed to conduct engineering analyses, including transient stability, short circuit, load flow, controls, and dynamics, from the full system level down to the converter level. Development of these capabilities will improve understanding of system behavior and interactions with ubiquitous deployment of SSPS technology and facilitate the design and testing of new converters, markets, and controls.

4.4.4 Converters

Gaps associated with converters at this level of SSPS focus on the improved understanding and advances needed in the underlying materials (e.g., semiconductors, magnetics, dielectrics, and insulators) for SSPS converters to be deployed at the highest voltage levels on the transmission system. Use of wide band gap power electronic devices will be a necessity and development of high frequency magnetics, high voltage insulation, and converter designs that minimize parasitic will help increase power density.

Table 14: SSPS 3.0 Technology Gaps and Their Impact

Theme	Count	Gap	Impact
Modeling and Simulation	12	Lack of methodology to simulate power systems and power electronics operation	Power system stability
		Simulation and modeling tools to understand behavior of large systems w/ SSPS and smart power electronic converters that have fast dynamic response	Do not know how system will behave and devices interact
		Standard 'market node' for all prosumers in new grid with real time pricing access	Sub optimal operation
		High DER penetration and variability at scale requires real-time pricing which can impact real time behavior of prosumers - simulation	Poor understanding of how systems will behave
		Simulation tools / models; load flow, short circuit, transient stability	Engineering analysis / study tool
Grid Architecture	11	Power electronics (SSPS) Grid approach versus transformer and rotating machine approach	PE capability determined grid approach and requirements. I.e. variable frequency, DC, etc.
		Need tools for system security assessment based on "angle stability" "voltage" stability during normal and contingency with routers	Improved levels of security margin, that is realistic
		Need in fast communications, wide area control, state estimation	Stability, reliability
		Synchronous generator stability analysis	Keeps the system stable and decouples through SSPS.
Grid Architecture	10	Autonomous controls / distributed artificial intelligence platform, for all protection, control, and optimization	Limit needs for real time communications and cyber security
		Distributed control architecture; distributed control needed for multiple SSPS	Increases reliability; each SSPS coordinates to enhance system performance
		Large scale distributed control algorithms	System control and optimization
		Control system integration among SSPS', protection, loads, etc.	

Theme	Count	Gap	Impact
		Peer to peer control / communication	Allow multiple SSPS and centralized control-stability
Autonomous Controls	8	Control and coordination of blackstart	Substation dependence.
		Black start coordination	Allows for system restoration
		Seamless multi-microgrid - grid transitions (automation)	System reliability and event recovery
Converters	8	Magnetic material, core, and transformer design to minimize parasitics for high frequency magnetics	Increased flexibility of SSPS design and increased power density
		Dielectric materials and improved understanding of dielectric breakdown	Increased flexibility of SSPS design and increased power density
		HV power devices needed to directly connect to the transmission grid	
		Insulation for HV	Switching and magnetic devices capable for high BIL
Autonomous Controls	7	SSPS needs to be autonomous yet "situation-aware" of its surroundings	Interconnected to assist, but not dependent
		Capable of completely autonomous operation, on loss of T&D	Emergency loads; community microgrid; decoupling; black start;
Modeling and Simulation	7	Modeling and simulation of new PE-dominated systems; testing of controls on surrogate platforms.	Pre-field deployment testing; accelerated deployment cycle.
		High fidelity modelling of converters and integration into system studies.	Will provide insights into economic benefits.
Autonomous Controls	7	How to realize blackstart for multiple SSPS?	Multiple SSPS availability
		Self-islanding a reconnection schemes on the fly	Blackstart, resilience
		Event-driven, secure, distributed control with limited communication and asynchronous power transfer	High scalability; high robustness; high system utilization; efficient dynamic power management
		Programmable black start at arbitrary node and time	High stability to intermittency; resilience; decentralized operation
		Blackstart behavior; ability to operate autonomously (default)	
		Coordination of blackstart; generators and substations with storage	Improved reliability
Grid Architecture	6	New "grid" architecture needs to be defined	Every node in new transmission system is SSPS 3.0
		Control and coordination strategies must be developed	Without which there is a risk of cascaded faults and domino effect
		Full system architecture concepts with ubiquitous SSPS (fractal grid)	Value proposition and many SSPS across T&D can be realized

5. DETAILED DESCRIPTIONS OF HIGH PRIORITY GAPS

5.1 OVERVIEW OF BREAKOUT SESSION FOUR

Breakout session four focused on the following topic area and focus question:

- *Topic area:* Developing R&D pathways and metrics

- *Focus question:* For the critical gaps identified, what metrics can we use to measure the gap? How do we track progress towards filling the gap?

During the final breakout session, each group was broken into smaller groups of 2-4 individuals. Each subgroup was asked to provide more detailed information associated with a high priority gap cluster identified through the voting process. The subgroups responded to prompts from a preprinted worksheet aimed at refining R&D pathways, defining associated metrics, and identifying relevant stakeholders.

5.2 GROUP A WORKSHEETS

The resulting worksheets for Group A can be found below.

Technology Gap Title: Definition of SSPS Architectures & SSPS-enabled Grid Architectures

Technology Gap Description:

Description: *Describe the technology need that exists.*

SSPS Architecture: Modularity; scalability -> voltage/current (power) (expandability); configurable (DC, AC, single phase, three phase, single and multiple input/output, variable frequency compatible. Grid Architecture: active and passive nodes in a mesh; AC/DC, high frequency lines; (fault) protection coordination. Assume all interconnects are bidirectional

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

Energy efficiency; fault restoration time; Technology Readiness Level (TRL); reliability; Scalability factor (ratio)

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?*	**Impact:** *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?*
SSPS Power Targets: (1) <1MW, (2) 1MW < target <100MW, (3) >100MW Grid architectures: Nanogrid, microgrid, grid	• Improvement in cost, security, efficiency, reliability, availability, resilience

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1 **(3 different projects)**	Extended study including literature search, modeling, simulation, and preliminary design for nano-, micro-, and full grid	• Three different reports • Open source models	• All the metrics mentioned above except cost
2	Cost/benefit analysis of the down-selected systems from step 1	• Cost/benefit report with recommendations	• Cost
3	Design and build SSPS prototypes to evaluate performance metrics	• Hardware and evaluation reports showing the validation. • Report with validated models	• All the metrics…
4	Design and build SSPS architectures (scaled down) for performance, protection, and security validation.	• Open access evaluation platform (software and hardware)	All the metrics… + stays operational user facility

Stake-holders and Roles: *List the **stakeholder(s)** (government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the **nature of their role** (e.g. collect or provide data, develop instrumentation, design models) and potential **needs/concerns***

Stakeholder	Role	Stakeholder Needs/Concerns
Academic Institutions	Modeling, simulation, and prototyping, workforce development	Advisory board
National Labs	Big data, user facilities (open access), workforce development	Industry/Academic collaboration
Industry (Utilities)	Customer behavior information, data, infrastructure cost/development information	Research outcomes, workforce
Industry (Vendors)	Cost, design and build prototypes, commercialization	Research outcomes, workforce

Technology Gap Title: Modeling and simulation tools for SSPS

Technology Gap Description:

Description: *Describe the technology need that exists.*

Component level multi-physics models don’t exist. Simulators are outdated unable to look at a future with more power electronics; problem formulation methodology (system of equations) may not be sufficient.

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

Validation and verification models/tools/architecture; simulations that can handle high frequency; latency.

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?* Simulation faster than decisions of interest 15 minutes to run 5000,000 nodes (offline)	**Impact:** *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?* Better decision making: need to convince stakeholders of value and impact of technology

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1	Efficient model formulation for SSPS	Reduced time to conduct analysis	Analysis less than 3 years (all)
2	Validate SSPS component/system (load flow; short circuit; dynamics/stability/EMTP)	Accurate models	Within 3-5% of observed data. (near-term)
3	Inclusion of communications network in system models	Understand delays/latency and information flows	Within 3-5% of observed data. (mid-term)
4	Market and control conveyance modeling-unknown impacts	Better understanding	?

Stake-holders and Roles: *List the **stakeholder(s)** (government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the **nature of their role** (e.g. collect or provide data, develop instrumentation, design models) and potential **needs/concerns**.*

Stakeholder	Role	Stakeholder Needs/Concerns
Labs/Academics	Develop tech	Resources//data
Utilities	Provide inputs: advice, data, pilots	Practicality, accuracy

Technology Gap Title: Control for SSPS and Power System with SSPS

Technology Gap Description:

Description: *Describe the technology need that exists.*

In the grid of the future, with high complexity to manage power flow and supply regulated power to loads while actively managing the grid.

Assumes:

- BIL, fault sourcing
- Efficient
- Cost effective
- Long life
- Reliable/resilient

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

(1) Ability to integrate physical and transactive grid elements in real time. (2) Demonstrate in island grid to prove concept. (3) Supporting analytic tools, models, simulation, validated or able. (4) Full scale simulation → deployment in area power system

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?*

Roadmap to higher penetration of DER and SSPS or move to G or F. Target SSPS with clearly developed rules that govern correction of smart devices to meet grid support and operational requirements and emerging local needs.

Impact: *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?*

Permits gradual migration from Grid to Future Grid with higher penetration, lower cost, higher availability and better asset utilization than an unplanned path with similar levels of DER (speed feeder) and transactive energy.

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1	Ability to integrate physical and transactive grid elements in real time	Viable/flexible model(s) that is basis for system simulation. Real time pricing with millisecond scale controls, with guaranteed stability.	• Validated models with instrumentation, rules, simulation. Investigate regulatory initiatives to support (3 years) • Models of distributed transactive and physical system with simulations (3 years)
2	Supporting analytic tools; models, simulation, validated as able.	Grid elements operate to rules that are grid supporting and grid forming and do not require detailed centralized system knowledge	• Application of rules in realistic system using validated models and tools (2 years) • Grid forming and support validation on multiple time-scales. (transient → daily) (2 years)
3	Demonstrated in island grid to prove concepts and extend to interconnected islanded grid. Demonstrate resiliency, cyber-hardening, autonomous operation	Tiling (break apart) and reassembly are key features allow autonomous black start	• Hardware demonstration; construction, instrumentation, stress test, validation (2 years)
4	Full scale simulations → deployment in area power system of SSPS technology.	Validated interconnection, control, stability, of network including legacy grid network.	• Scale up, integrate more complexity, study issues (5 years)

Stake-holders and Roles: *List the* ***stakeholder(s)*** *(government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the* ***nature of their role*** *(e.g. collect or provide data, develop instrumentation, design models) and potential* ***needs/concerns****.*

Stakeholder	Role	Stakeholder Needs/Concerns

Utilities/ISO/ Muni	Owners of legacy systems	Show how legacy preserved and new value is added
National lab	Government agent to review and validate and add to concept	Early involvement critical
EPRI, Edison Electric Institute	Evangelization within power industry	Early involvement critical
Vendors	Adapt to new paradigm, support productization	Need clear timeline for adoption at scale and R&D support for demonstration
Academia, research	Flesh out system and solve challenges	Need to get things right to support product with system level validation.

Technology Gap Title: High System (SSPS) Cost

Technology Gap Description:

Description: *Describe the technology need that exists.*

Demand for high performance components that can support applications that require high voltage, high power, high efficiency, high reliability SS systems.

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

\$/kVA, kVA/m^2, kW losses / kVA capacity

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?*	**Impact:** *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?*
Cost: within 10% of equivalent legacy system. Power density: 30-50% improvement Losses/capacity: equal to or better than existing system	Enable adoption System wide impact Accelerate retirement of legacy systems Enable black start

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1	Incentive credit scheme to foster early adoption	Early adoption	% of incentive. Match 20% premium over legacy systems
2	Plan out subsidies	Device demand	5 year sun down clause
3		•	•
4		•	•

Stake-holders and Roles: *List the **stakeholder(s)** (government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the **nature of their role** (e.g. collect or provide data, develop instrumentation, design models) and potential **needs/concerns**.*

Stakeholder	Role	Stakeholder Needs/Concerns
Government agencies	Provide incentives	Where is the money – need budget
Utility companies	Early adopters, business case justification	How to get the money – qualification schedule
OEM	Build equipment	Low cost components
Component manufacturers	Make devices/components	Need demand

5.3 GROUP B WORKSHEETS

The resulting worksheets for Group B can be found below.

Technology Gap Title: Medium voltage direct grid connect power converter

Technology Gap Description:

Description: *Describe the technology need that exists.*

(1) Power electronics integration of 10-15 KV SiC MOSFETS; gate drive isolation / bus / passives (2) reliable, fault tolerant, reconfigurable, converter (flexible architecture) (3) Smart grid functionality

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

(1) Service life of converter. (2) BIL rating improvement. (3) higher bandwidth (4) Density (5) Cost (6) Efficiency

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?*

(1) System cost around $0.10/W
(2) 13.8 kV, three-phase (system design) / 13.8 kV, single phase option
(3) Scalable to 10MW range
(4) 20 year life cycle @ minimal cost
(5) Efficiency better than if not comparable to transformers.

Impact: *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?*

(1) Value proposition for deployment is not prohibitive in many applications
(2) Supply chain exists and is scalable to high penetration.
(3) Captures value proposition of multiple power electronics needs for grid applications

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1	Establish reliable, cost effective, SiC module supply chain	Confidence in reliability and service life	3.3 kV, available from multiple vendors @ $0.01/W 10 kV, available from multiple vendors @ $0.01/W
2	10-15 kV SiC MOSFET circuit integration issues addressed: gate drive isolation, power bus assembly, passives.	Reliable system design / predictable design approaches	Supply chain in place for each item listed in research objective.
3	Laboratory and field demonstrations / testing	Regulatory and procurement functions are robust.	Test standards and labs established.

Stake-holders and Roles: *List the **stakeholder(s)** (government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the **nature of their role** (e.g. collect or provide data, develop instrumentation, design models) and potential **needs/concerns**.*

Stakeholder	Role	Stakeholder Needs/Concerns
Government: AMO, OE, Sunshot, VTO, ONR…		
Supply chain: SiC device and materials, passives		
Standards and regulatory: IEEE 1547, 2030, VL		
Academic: Research organizations, national labs		

Technology Gap Title: Control theory for SSPS 1.0

Technology Gap Description:

Description: *Describe the technology need that exists.*

There is not work done on grid friendly / system coordination for power converter system.

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

System metrics have to be defined. Controller saturation, voltage limits, power quality, component sizing, balance between centralized and local control

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?* • Reliability operations and combined with economics • Mitigating high PV peaks from forecasting • Minimize curtailment	**Impact:** *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?* • Affects the life cycle of components on the grid • Scaling the impacts of the control theory

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1	Reliability and economic operation	Mitigates the fluctuation of load with PV	Power quality Controller saturation
2	Control boundaries	Hardware and areas need to be defined for control	Dispatchable location and can be four quadrant.
3	Demand response and minimize curtailment	Allow for EV and ESS	
4			

Stake-holders and Roles: *List the **stakeholder(s)** (government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the **nature of their role** (e.g. collect or provide data, develop instrumentation, design models) and potential **needs/concerns**.*

Stakeholder	Role	Stakeholder Needs/Concerns
Regulatory system	Come together to come up with metrics	
Vendors		

Technology Gap Title: SSPS 2.0 Transient control theory

Technology Gap Description:

Description: *Describe the technology need that exists.*

Grid and controller transient control theory for ride through and fault protection

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

- Technical papers that show successful simulations and experimental results
- Generation of appropriate standard

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?*

Full scale SSPS 2.0 validation by 2027

Impact: *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?*

- Stability
- Resilience
- No restoration needed (faster restoration is an ancillary benefit)

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1	Generate control theory	Positive peer review	Technical papers
2	Simulations	Successful simulations	Second party validation
3	Experimental data	Favorable results consistent with simulation results	Second party validation
4	Initiate standard process	Approve standard	Adoption

Stake-holders and Roles: *List the* ***stakeholder(s)*** *(government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the* ***nature of their role*** *(e.g. collect or provide data, develop instrumentation, design models) and potential* ***needs/concerns****.*

Stakeholder	Role	Stakeholder Needs/Concerns
Academic institutions	#1 and #2	Limited resources (cost and people)
Industry/National labs	#3	Limited resources
Government agencies/standards organizations	#4	Limited resources (identify real applications)

Technology Gap Title: Control tools to improve stability, security, and reliability (SSPS 3.0)

Technology Gap Description:

Description: *Describe the technology need that exists.*

State of the art control tools are based on classical synchronous generator systems and do not permit the degrees of freedom available with power electronic converters in SSPS.

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

Development of dynamic models that are verified from physical systems.

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?*

Qualitative: usefulness and complexity of models and large scale adaptation of microgrids.

Quantitative: (1) Error between model and real systems. (2) Penetration % of renewable resources

Impact: *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?*

Primary benefits: Grid that is robust, stable, and secure.

Most impact: Large penetration of renewable resources.

Ancillary benefit: faster interconnection process

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1	How do we perform load flow, small signal stability, transient stability and contingency assessment with SSPS?	Updated system modeling tools for power system analysis (power flow, EMTDC, RTS)	Number of commercial tools that provide the capability for SSPS
2	How do we do testing and validate the models in laboratory and field?	Standardized testing validation protocols.	Number of standard protocols for testing SSPS.
3	How do model cyber physical control with power converters and power systems?	Standardized model blocks for simulation and system analysis.	Number of simulation tools and platforms for cyber physical analysis
4	How do we develop financial resources for bridging the gap?	Availability of funds	Amount of research/development dollars. Number of utilities adopting SSPS.

Stake-holders and Roles: *List the **stakeholder(s)** (government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the **nature of their role** (e.g. collect or provide data, develop instrumentation, design models) and potential **needs/concerns**.*

Stakeholder	Role	Stakeholder Needs/Concerns
Universities	Research advancement for scaling up and teaching	Funding, students, faculty and facilities.
Vendors/consultants	Product development and innovation	New business opportunities.
Utilities	Friendly hosts for adoption of new technologies	Uncertainty due to changing scenario
Government/national labs	Program incentives ($), neutral validation, testing	Maintain secure and resilient energy future.

5.4 GROUP C WORKSHEETS

The resulting worksheets for Group C can be found below.

Technology Gap Title: Identifying optimum system configuration

Technology Gap Description:

Description: *Describe the technology need that exists.*

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

Losses, response time, downtime, power density (for select markets), EMI/EMC and susceptibility, audible noise, environmental impact, intelligent quotient

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?*

Qualitatively better than existing substations.

Impact: *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?*

- Reduced total cost of ownership,
- More environmentally friendly,
- Improved overall system performance.

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1	How do we realize the SSPS losses comparable to existing substation (or better)?	• Loss < 120% of existing substation	• Loss, efficiency
2	How can we make SSPS more environmentally friendly?	• Zero-spills (SF_6, oil-free components) • Recyclable	• Green power standard • >% of recyclability (>90% e.g.)
3	How to minimize unwanted interactions with SSPS surroundings?	• Lower EMI/EM, • Reduced audible noise, • Improved cyber-physical security.	• Standards • Probability of intrusion
4	What is “IQ” for a SSPS?	• Standardized performance/health data.	IQ, response time, downtime.

Stake-holders and Roles: *List the* ***stakeholder(s)*** *(government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the* ***nature of their role*** *(e.g. collect or provide data, develop instrumentation, design models) and potential* ***needs/concerns****.*

Stakeholder	Role	Stakeholder Needs/Concerns
Utilities	Provide service to end user	How to deal with this new tech, costs
Govt.	National security, social good	National security
Manufacturers	Build equipment, offer services	Cost / Profitability
Standards organizations	Define the rules	Scientific details and info

Technology Gap Title: Secure Autonomous Distributed Control

Technology Gap Description:

Description: *Describe the technology need that exists.*

System needs to be cyber-physical resistant, real-time aware (health, etc.), enable distributed optimization.

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

Device/electronics technology, standards development and hardware/software development to meet,

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?*	**Impact:** *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?*
System scalability (5-15 years) Heterogeneous operability (10-20 years) Validation (off & online – simulations and hardware) (5-15 years)	Create a system that is resilient, optimal, self-aware, coordinated. T&D levels will be impacted Flexible and adaptable and robust grid

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1	How do you partition the network? How to define a module?	Ability to plug and play modules to scale.	Need to determine the limits of scalability. How many nodes? 100? Targets depend on location and cost/benefit tradeoffs.
2	How do we model and access in real-time preparedness of technology in the system.	Algorithms, new tools, meeting specifications and requirements. Feeding results into improvements (HIL)	Development of modular, real-time, scalable systems Platform independent
3			
4			

Stake-holders and Roles: *List the **stakeholder(s)** (government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the **nature of their role** (e.g. collect or provide data, develop instrumentation, design models) and potential **needs/concerns**.*

Stakeholder	Role	Stakeholder Needs/Concerns
Utilities	Obvious	System-level needs, costs, reliability
Industry	Obvious	Equipment needs, costs/benefit tradeoff
Regulatory agencies	Obvious	Standards, what is governing all of this?

Technology Gap Title: Fault Detection

Technology Gap Description:

Description: *Describe the technology need that exists.*

- Discrimination between load and fault conditions
- Continuous monitoring of system constraints
- Dynamic setting points adequate for the application and power electronics limitations
- Self-protection and coordination at converter level.

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

1. Number of false trips // Less than 1/1000
2. Number of missed trips // Less than 1/1000

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?*

1. Less than 1/1000 → mid-term (5-10 years)
2. Less than 1/1000 → mid-term (5-10 years)

Impact: *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?*

- Personnel, equipment safety
- Reliable operation
- Longer life-cycle
- Lower O&M
- DC microgrid and DER integration

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1	Baseline: Scope, requirements and specifications	• Specifications, standards, clear and agreed	• Completed and approved reviews of specification
2	Develop Solution: Architecture, Sensing, monitoring, communications, algorithms	• System architecture, defined subsystems controls	• System performance metrics o Set points; Comm protocols; TCC
3	Modeling: Simulation, iterative improvement	• Models, simulation results, proven solution (set points, algorithms)	• Virtual and HIL model
4	Testing: Commercialization/implementation, Time to market	• Testing for compliance, manufacturing and commercial readiness	• Performance validation • Market planning • Manufacturing plan and requirements

Stake-holders and Roles: *List the **stakeholder(s)** (government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the **nature of their role** (e.g. collect or provide data, develop instrumentation, design models) and potential **needs/concerns**.*

Stakeholder	Role	Stakeholder Needs/Concerns
Government (DOE,	Direction, funding, sponsorship.	Compliance, homeland security, public safety
Utilities	Current state, voice of customer, problem definition.	Complete solutions, suppliers, service
Academia	Research resources and develop labs. Tech development	Funding, partners
Industry	Manufacturing and marketing, product development.	Funding, cost feasibility, market opportunity

Technology Gap Title: Solid State Substation Acceptance Based On Cost and Performance

Technology Gap Description:

Description: *Describe the technology need that exists.*
Better Understanding of the Solid State Substation- What it can do, cost of each of the components and the overall performance of the SSPS.

Metric(s): *What parameter(s) can be used to track progress in closing this gap?*

1) Increase SSPS penetration of Existing Substations.
2) Reduce the Reactive Power Flow.
3) Increase the integration of renewables
4) Increase energy storage at substations
5) Cost Reduction of SSPS

Solution Specifications:

Targets: *What are the quantitative and qualitative targets that indicate that the gap has been filled? By when do these targets need to be met?*

1) 10% SSPS penetration of existing substations by 2035
2) Reduce the Reactive Power Flow by 30% on the US Grid
3) Increase the integration of renewables by 120% of the Feeder Capacity.
4) Of the SSPS's deployed by 2035, 50% will incorporate energy storage
5) Reduce the cost of a SSPS substations to $1000 per KVA by 2035

Impact: *What are the primary benefits to addressing the gap? Where will it have the most impact? What may be ancillary benefits?*

- Increase US Electrical Grid
  1) Resiliency – More capability for islanding and microgriding, reconnection, ease of black start
  2) Modularity – Ease of quick repair and maintenance of components and systems as needed.
  3) Flexibility – Allow incorporation of AC/DC in substation, variable frequency outputs, enable transactive control.
  4) Operability – Easier to operate
  5) Adaptability,
  6) Controllability.

Key Steps to Implement Solution:

Step:	Objective or Research Question:	Desired Outcome:	Associated Metrics and Targets:
1	Engage Stakeholders from the beginning to determine the value of SSPS features.	Buy in from Stakeholders of SSPS Features.	10% Acceptance by key stakeholders.
2	Define Optimum Topologies based on specific installation	Development of a suite of economical Topologies based on installation specifics	50% Acceptance of developed Topologies by key stakeholders.
3	Develop plan to gain acceptance by proving the performance metrics with full scale testing under grid conditions	Develop/build a National Testing Capability for Component and full Transmission Scale Substation to validate designs.	Operational capability for full scale and component testing.
4	Develop a Roadmap to Reduce Cost	Prioritized list of component and path to reduce cost of fabrication.	Validation by stakeholders and suppliers that cost targets is feasible.

Stake-holders and Roles: *List the **stakeholder(s)** (government agencies, industry, standards organizations, academic institutions, national labs, etc.) who could address this gap; describe the **nature of their role** (e.g. collect or provide data, develop instrumentation, design models) and potential **needs/concerns**.*

Stakeholder	Role	Stakeholder Needs/Concerns
Utilities	Acceptance, Guidance	
Regulators	Approval	
Suppliers/Manufacturer's	Develop Components and Systems	
Researchers	R&D, Prototyping, Pilot Demonstrations, Controls Development, Cyber	
Government (DOE, DHS)	Funding, Acceptance and Guidance.	

APPENDIX A. LIST OF PARTICIPANTS AND WORKSHOP AGENDA

LIST OF PARTICIPANTS

First Name	Last Name	Affiliation
Ram	Adapa	EPRI
Paulo	Guedes-Pinto	TECO-Westinghouse Motor Company
Madhav	Manjrekar	University of North Carolina - Charlotte
Madhu	Chinthavali	Oak Ridge National Laboratory
Vahan	Gevorgian	NREL
Joshua	Park	Southern California Edison
Bob	Yanniello	Eaton Corp.
Jeremiah	Miller	DOE - Solar Energy Technologies Office
Wensong	Yu	NC State University
Burak	Ozpineci	ORNL
Kerry	Cheung	USDOE
Emmanuel	Taylor	Energetics Incorporated
Timothy	Frank	Infineon Technologies Americas Corp.
Joe	Rostron	Southern States LLC
Keith	Dodrill	US DOE/NETL
Dushan	Boroyevich	Virginia Tech - CPES
Klaehn	Burkes	Savannah River National Laboratory
Karl	Schoder	Florida State University
Deepakraj	Divan	Georgia Tech
Josh	Keister	Resilient Power Systems
Brandon	Grainger	University of Pittsburgh
Earl	MacDonald	KCI Technologies Inc.
Thomas	Salem	Clemson University
Sandeep	Bala	ABB Inc.
Giri	Venkataramanan	University of Wisconsin-Madison
Andrew	Kling	Duke Energy
Juan Carlos	Balda	University of Arkansas

Sudip	Mazumder	NextWatt LLC
Leo	Casey	Google, Inc
Tavis	Clemmer	Arkansas Electric Cooperatives Corp.
Antonio	Trujillo	Eaton Corporate Research and Technology
Curtiss	Fox	Clemson University
Kjetil	Naesje	ZAPTEC
Joe	Cordaro	SRNL
Alejandro	Montenegro	S&C Electric
Aleksandar	Dimitrovski	University of Central Florida
Allen	Hefner	NIST
Scott	Morgan	Energetics Incorporated
Frederick	Hansen	Energetics Incoporated
Sam	Roach	Clemson
Dean	Millare	Clemson
Kevin	Tye	Clemson
Mohamed	El Chehaly	SNC-Lavalin
Tom	Keister	Resilient Power Systems
Arthur	Barnes	Los Alamos National Laboratory
M A	Moonem	Sandia National Laboratories
Randy	Collins	Clemson University
Ramtin	Hadidi	Clemson University
Rick	Poland	SRNL
Paul	Ohodnicki	DOE/NETL
Eric	Frost	Phoenix

WORKSHOP AGENDA

Day 1: Tuesday, June, 27th, 2017

Time	Activity	Location
7:00 am	**Registration and Networking**, Coffee/Refreshments	Zucker Family Graduate Education Center Lobby
8:00 am	**Welcome**, **Overview of the Clemson University Restoration Institute** *Dr. E. R. "Randy" Collins Jr., Executive Director of Academic Initiatives, Clemson University*	Main Plenary Room
8:20 am	**Overview of Workshop** *Kerry Cheung, Program Manager, U.S. Department of Energy (DOE)*	
8:45 am	**Plenary Presentation 1: Current Applications of Solid State Technology on the Grid** • *Le Tang, Vice President and Head of US Corporate Research Center, ABB (Sandeep Bala substituted)* • *Robert Yanniello, Vice President of Engineering, Electrical Systems & Services Business, Eaton* • *Alejandro Montenegro, System Architect, S&C Electric*	
9:45 am	**Break**	
10:00 am	**Plenary Presentation 2: Future Capabilities and Advances in Solid State Technologies for the Grid** • *Wensong Yu, Associate Research Professor, FREEDM Center, North Carolina State University* • *Giri Venkataramanan, Professor, Electrical and Computer Engineering, University of Wisconsin* • *Dushan Boroyevich, American Electric Power Professor, Center for Power Electronics Systems, Virginia Tech*	
11:00 am	**Plenary Presentation 3: Solid State Power Substation Vision** • *SSPS Vision – Klaehn Burkes, Savannah River National Laboratory* • *Benefits, Challenges, and Gaps – Tom Keister, Resilient Power Systems* • *Instructions for Breakout Sessions /Lunch/Tours – Emmanuel Taylor, Energetics*	
12:00 pm	**Lunch**	Zucker Family Graduate Education Center Lobby
1:00 pm	**Tour of Clemson University's SCE&G Energy Innovation Center**	SCE&G Energy Innovation Center
2:00 pm	**Parallel Breakout Session 1: Challenges Facing Substations/Grid** ***Focus question # 1:*** *What issues and concerns most deeply impact the ability of substations to meet the demands of an evolving grid?*	Breakout rooms
3:15 pm	**Break**	

3:30 pm	**Parallel Breakout Session 2: Benefits of Utilizing SSPS Technology** ***Focus question # 2A:*** *What are the potential benefits (new or enhanced capabilities, functionalities, performance improvements, etc.) that solid state technologies in substations can be expected to provide from now through 2040?* ***Focus question # 2B:*** *Do any of the anticipated benefits of using SSPS technology overcome a substation challenge that has been identified?*	
4:45 pm	**Break and return to Plenary Room**	
5:00 pm	**Report Outs (***5-10 min debrief from each group, with Q&A***)**	Main Plenary Room
5:30 pm	**Adjourn and instructions for next day**	
6:00 pm	**Optional No-Host Dinner**	Mellow Mushroom 4855 Tanger Outlet Blvd North Charleston, SC

Day 2: Wednesday, June, 28th, 2017

Time	Activity	Location
8:00 am	**Coffee/Refreshments**	Breakout rooms
8:30 am	**Parallel Breakout Session 3: Identifying and Prioritizing R&D Challenges and Gaps** ***Focus question # 3:*** *What technical gaps need to be overcome, to enable/actualize the defining functions that characterize each level of SSPS technology?*	
11:00 am	**Break**	
11:15 am	**Parallel Breakout Session 4: R&D Pathways Worksheets** ***Focus question # 4:*** *For the critical gaps identified, what metrics can we use to measure the gap? How do we track progress towards filling the gap?*	
12:15 pm	**Lunch**	Zucker Family Graduate Education Center Lobby
1:15 pm	**Report Outs (***5-10 min debrief from each group, with Q&A***)**	Main Plenary Room
1:45 pm	**Crosscutting Discussion**	
2:15 pm	**Next Steps** – *Kerry Cheung, Program Manager, U.S. DOE*	
2:30 pm	**Adjourn**	