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# Solid State Power Substation Vision, Benefits, Challenges, and Gaps


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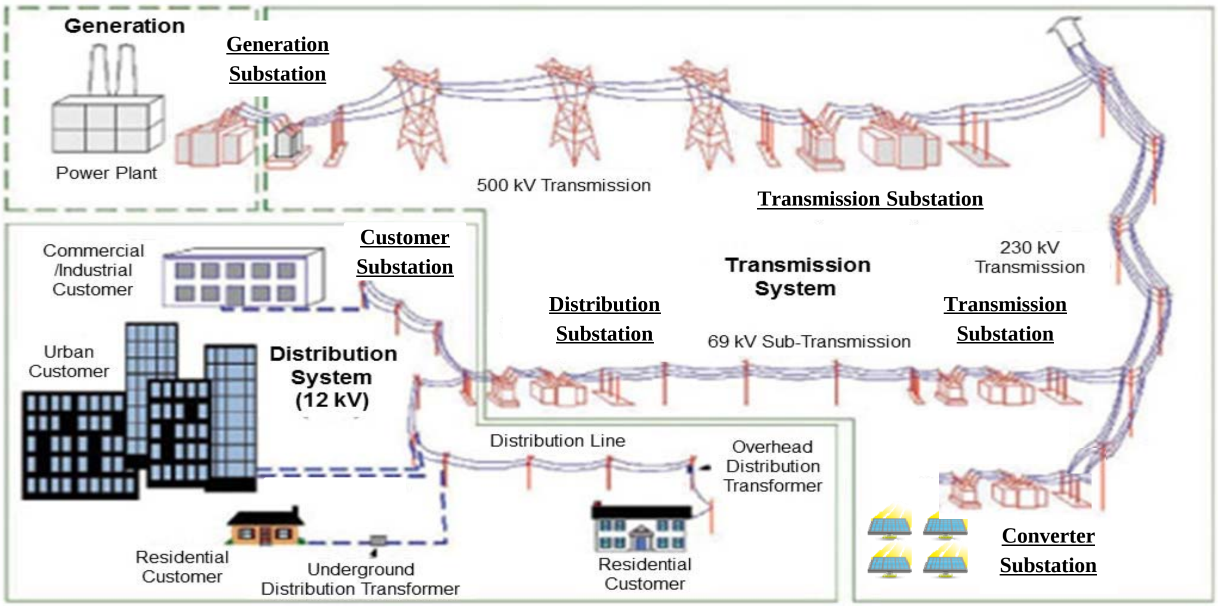
# Substation Classifications

| Types of Substation | Input | Output | Functionality |
|---|---|---|---|
| **Generation** | Generation Facility | Transmission System | Connecting large generation to the transmission system |
| **Transmission** | Transmission System | Transmission System | Interconnect different transmission and sub-transmission voltage systems |
| **Distribution** | Transmission System | Distribution System | Located near the end-user changes voltage level from transmission to distribution |
| **Customer** | Distribution System | Customer Facility | Non-utility owned connection to distribution or sub-transmission systems |
| **Converter** | Inverter Based Renewable and LVDC/MVDC/HVDC | Transmission/Distribution Systems | Used to integrate renewable generation and improve efficiency of delivery |



# Substation Classifications

Generation Substation

Transmission Substation

Distribution Substation

# Substation Classifications

Converter Substation


Customer Substation

# Existing Electrical Network

**We have the need …**

**and the technology and know-how to build a more efficient, flexible, and resilient electrical grid.**

# Evolution of Substations

# A wide variety of different features supported by a specific component that collectively form a system…

- Transformers
- Bus infrastructure
- Circuit breakers
- Fuses
- Disconnect Switches
- Reclosers
- Arrestors
- Reactors
- Grounding schemes
- Control Houses

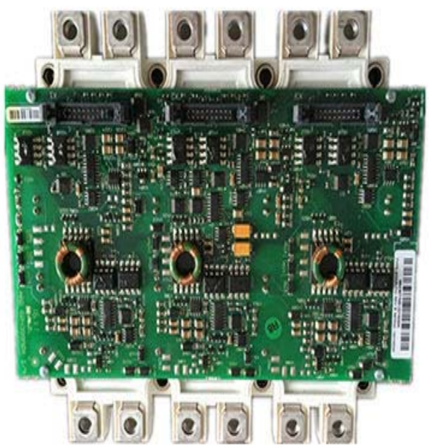
- Protective relays
- Battery Power Supplies
- Communication Networks
- Monitoring systems
- Voltage regulator
- Frequency regulators
- Current and voltage sensors
- Filters
- Reactive power compensation (FACTS)
- AC/DC and DC/AC converters (HVDC)

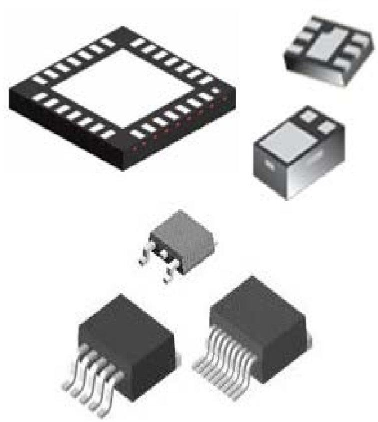
# The list keeps growing….

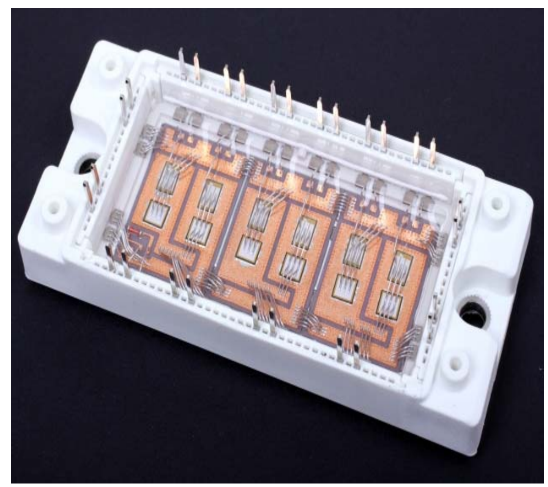
- Wireless Sensors and monitoring
- Frequency stabilizers
- Distance Fault detectors
- Fault current limiters
- Phasor analyzers
- Protective walls
- Mobile versions of all above including transformers

# Is there opportunity?


# Power Electronics







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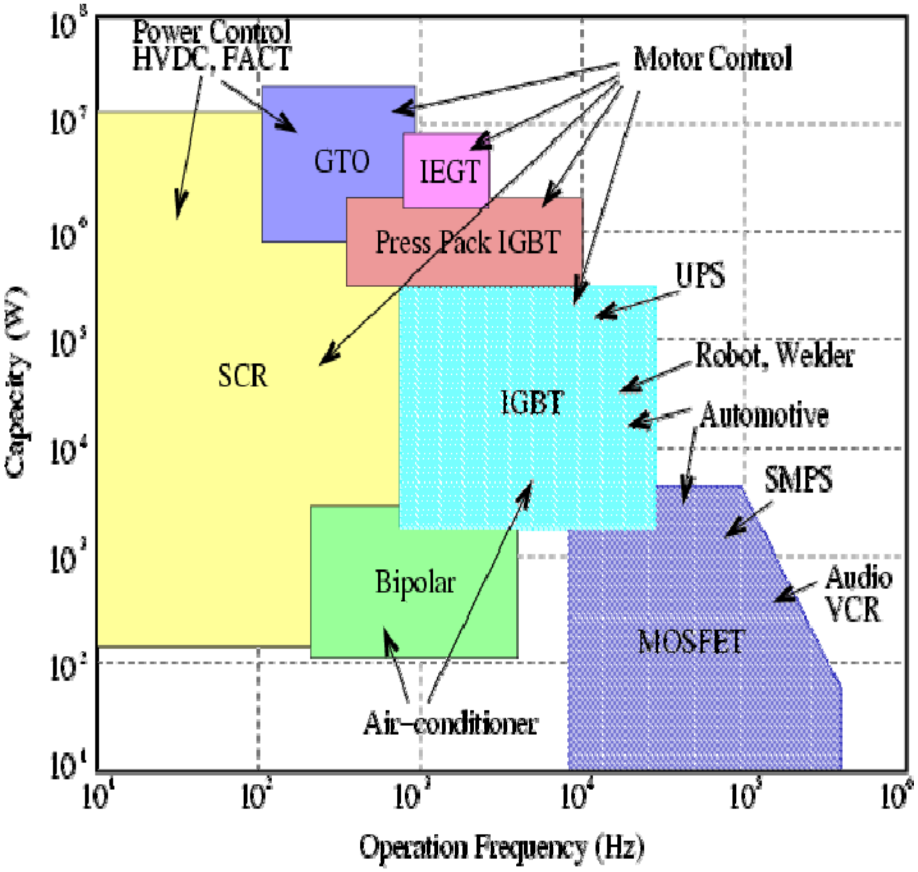
# Power Electronic Milestones

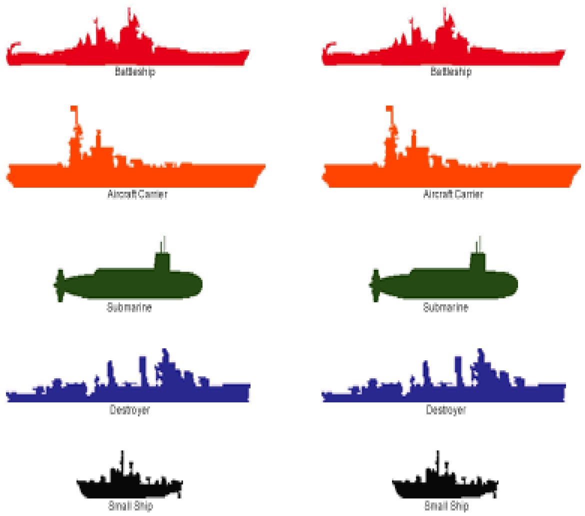
- Modern power electronics era began in 1957, the first commercial Silicon Controlled Rectifier (SCR), was introduced by General Electric Company.
- In the early years, DC converters superseded AC …
- Not until 1980’s with the invention of PWM microprocessor control – did AC converters become much more popular than DC.



# Power Electronics development has also been customer application driven

- **Product development in low, medium, and high voltages**
- **Examples**
  - AC Drives
    - *Wide range of application specific products and ratings*
  - High Voltage DC Systems (HVDC)
    - *Developed specifically for controlling power between large power networks*
    - *Designed to be cost effective at very high power and voltage*
    - *Large size with expensive complicated external systems*
    - *A marvelous technology developed for a task wherein money and size were not a high priority*

# In power electronics…
# Low Voltage/High Volume Reigns King!




Power Supplies

Automobile

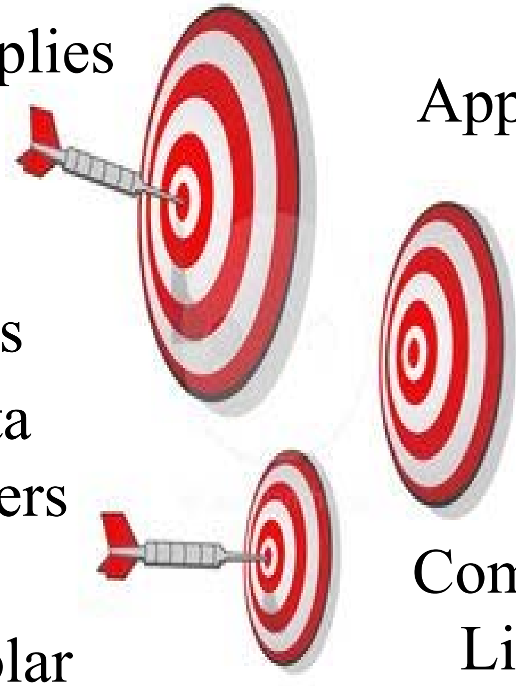
Appliances

AC Drives

UPS

Data Centers

Telecom



Commercial Lighting

Solar

Wind

Little focus on high volume medium and high voltage applications

# Why Power Electronics Now?

- **Semiconductors Silicon and Silicon Carbide**
  - More efficient operation at higher power conversion frequencies
  - Better packages and thermal designs
  - Higher voltage
- **Power Converters**
  - Embedded controllers advancements
  - Power components such as capacitors, gate drivers, interface, and sensors
  - High power density packaging with new thermal and dielectric systems
- **Power Conversion**
  - Continued advancement of topologies such as modular multilevel and matrix inverters

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# Unique Opportunity to Re-Imagine the Utility Workhorse " the Substation"

**Instead of the existing "component" based customized system solution…**

# Use medium and high voltage power electronics with multiple configurable features

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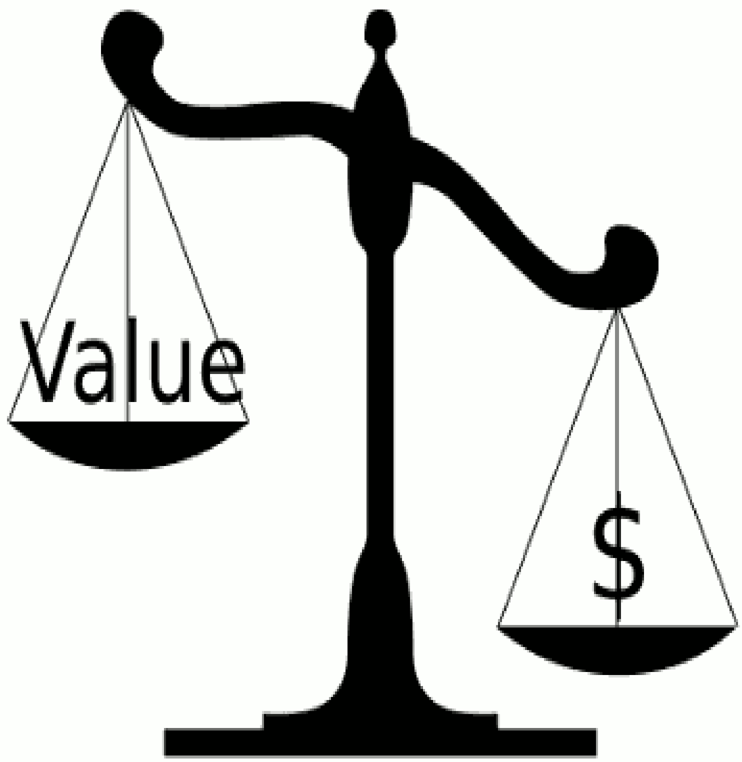
# How about….

**Imagining a substation built with power electronics that includes features from existing substations plus others such as:**

- **Proactive instead of reactive control**
- **Distributed rather than centralized control**
- **AC/DC Power Router**
- **Receives poor power quality and sends good**
- **Fault tolerant**
- **Multi-purpose scalable converters**

# How can we make this happen?



**This roadmap does not *hopefully* rely on**

**"perceived higher value from new SSPS features"**

**to**

**"convince the customer"**

**to pay more**

# The Roadmap seeks to reduce cost and increase value/benefits

- **Both are interdependent**
- **To realize the most benefits – it requires the widest use of SSPS**
- **To use the most SSPS – requires the lowest cost**

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# It’s goal is to develop lower SSPS Converter cost ….

The higher the cost differential between SSPS and existing technology, the lower the acceptance of extra value.

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# Reduce cost in many ways:

- **SSPS Converter Cost**
  - Semiconductor
  - Increasing efficiency
  - Reducing converter/system size
  - Same hardware for multiple applications
- **SSPS Power Conversion and System Cost**
  - Scalable power conversion products
  - Eliminate or minimize auxiliary or supporting components
  - Multiple flexible features to sell more products
- **SSPS Brownfield and greenfield applications**

# Increase value or benefits

**The greater the extra value, the higher the acceptable price for the product.**

# Develop extra value through research and analysis as well as Beta site development to improve :

- Asset utilization
- Network efficiency
- Network resiliency
- Black-start capability
- Capacity
- Power quality
- Flexibility

# SSPS Value Propositions

- Total impact of SSPS on network efficiency through better asset utilization (rather than just its inherent efficiency) is vital to achieve reasonable SSPS cost.
- Operation over a wide voltage span?
- Value of AC/DC choices?
- Fault tolerance?
- Improved power quality?

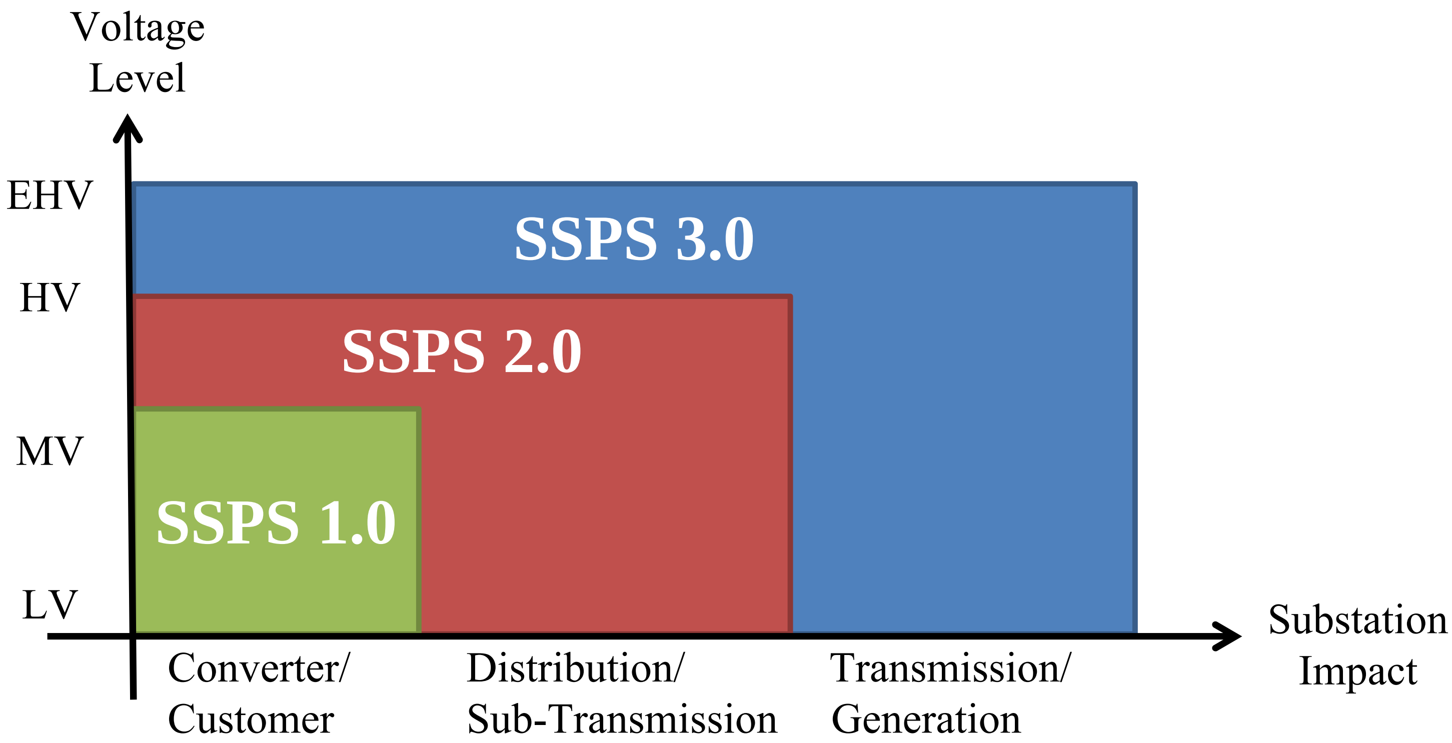
# Ultimate SSPS Vision

**Scalable, adaptable, flexible AC/DC Power routers that span all voltages**

A ***Solid State Power Substation*** 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.

# Envisioned SSPS Adoption/Deployment Pathway

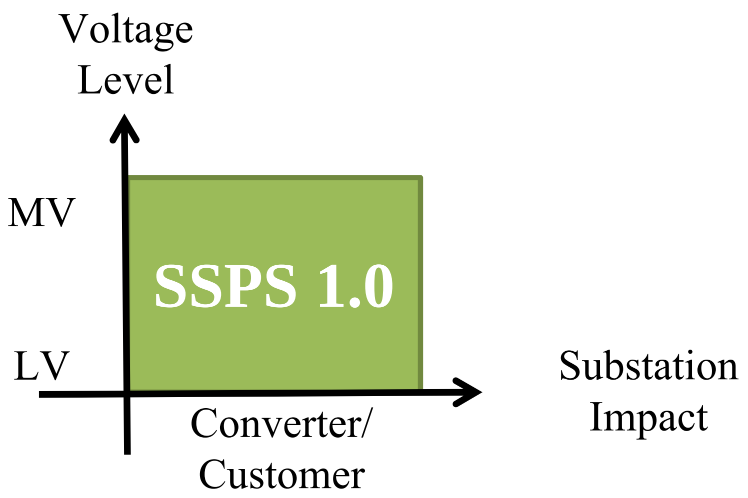
- **SSPS 1.0 – "Low/Medium Voltage Local Applications"**
- **SSPS 2.0 – "Low/Medium/High Voltage Local Applications"**
- **SSPS 3.0 – "System Applications and Multiple Substations"**



# Solid State Power Substation 1.0

**SSPS 1.0 – "Low/Medium Voltage Local Applications"** is a substation that can perform the following functions at voltage levels between 1kV ~ 35kV with primary applications at Customer and Converter Substations:

- 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 the connection of multi-frequency systems
- Enable nanogrids of single buildings



# Solid State Power Substation 1.0 Use Cases

## SSPS 1.0 – "Low/Medium Voltage Local Applications"

### Customer Substations

- **Data Centers**
  - DC power distribution
  - Improve power quality
- **Industrial Facilities**
  - Remote oil, gas, and mining operations
    - Improved power quality
  - High frequency bus for manufacturing facilities
    - Reduces converter losses for high frequency and efficiency motors
    - High frequency welding
  - Power flow control on low voltage ports for increased capacity, stability, and resiliency
- **Buildings**
  - DC power distribution
  - Nanogrid for single or multiple buildings utilizing combined sources and storage

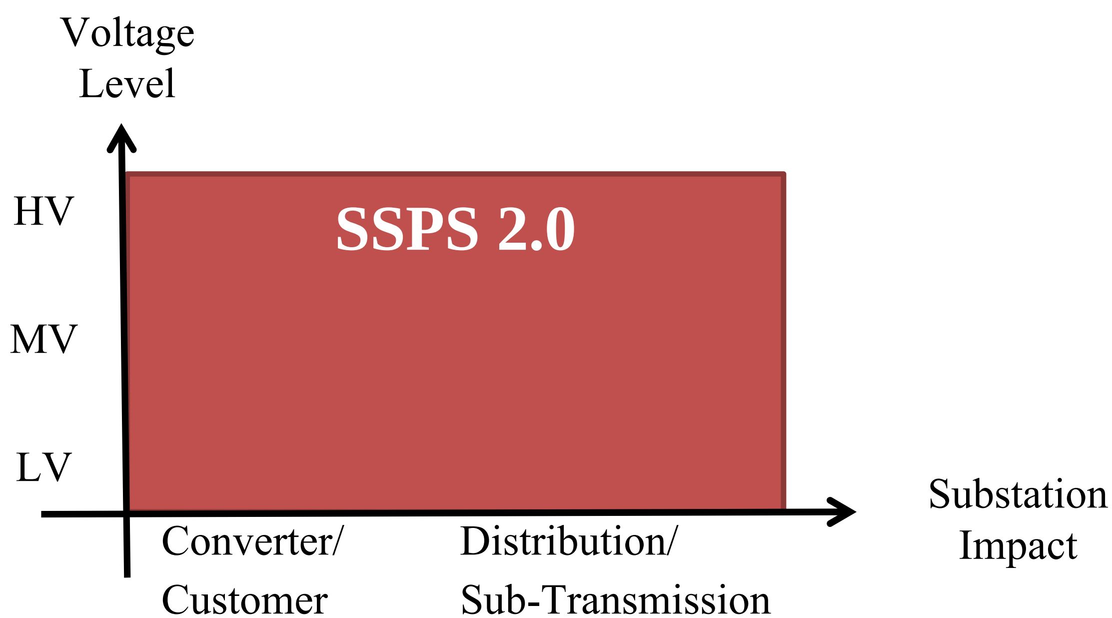
### Converter Substation

- Reducing cost for remote installation line capacity upgrades
- Provide better power quality management, minimize islanding concerns, and provide power flow control with DER and BES

# Solid State Power Substation 2.0

**SSPS 2.0 – "Low/Medium/High Voltage Local Applications"** builds on all of the capabilities and applications of SSPS 1.0 but can also provide the following functions and features at voltage levels up to 230kV, expanding applications to Distribution and Sub-Transmission Substations:

+ Low voltage ride through
+ System coordination of fault current
+ Provides bidirectional power flow control between transmission and distribution
+ Enables distribution feeder islanding and microgrids



# Solid State Power Substation 2.0 Use Cases

**SSPS 2.0 – "Low/Medium/High Voltage Local Applications"**

**Distribution Substations**

- **Power Quality**
  - Allows for VAR support and frequency regulation
  - Upgrade power line capacity
  - Agnostic to frequency (AC or DC)
- **Microgrids**
  - Enables integration of utility scale BES and DER
  - Improves resiliency with distribution feeder islanding/microgrids
  - Dynamic bidirectional power flow between loads and sources
- **Reduced substation footprint**

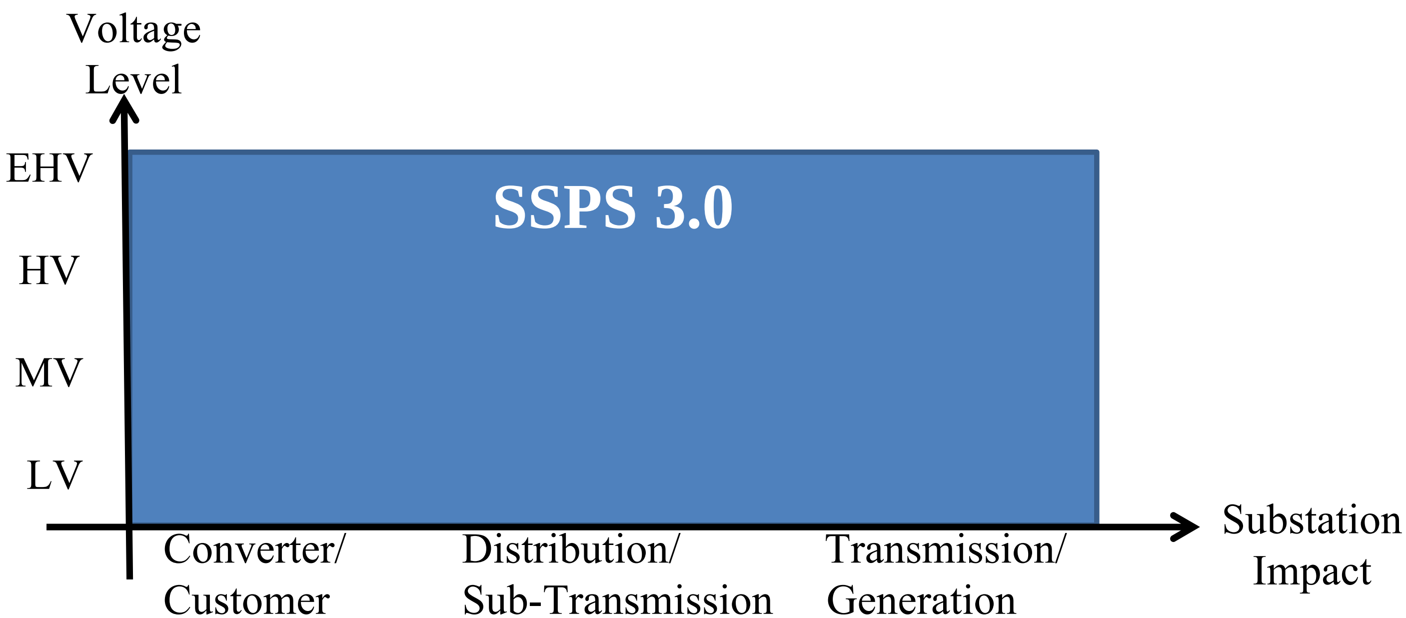
**Sub-Transmission Substations**

- **Power Quality and Flow Controller**
- **Mobile Substations**
  - Response to national disasters from man-made or natural soures
  - Modular, smaller, lighter and improved black-start capabilities
  - Deployment to critical loads

# Solid State Power Substation 3.0

**SSPS 3.0 – "System Applications and Multiple Substations"** possesses all of the capabilities of SSPS 2.0 but can also provide the following functions and features at any voltage level, enabling coordination of multiple SSPS across the entire electric power system and expanding applications to Transmission and Generation Substations:

+ 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



# Solid State Power Substation 3.0 Use Cases

**SSPS 3.0 – "System Applications and Multiple Substations"**

**Transmission Substations**

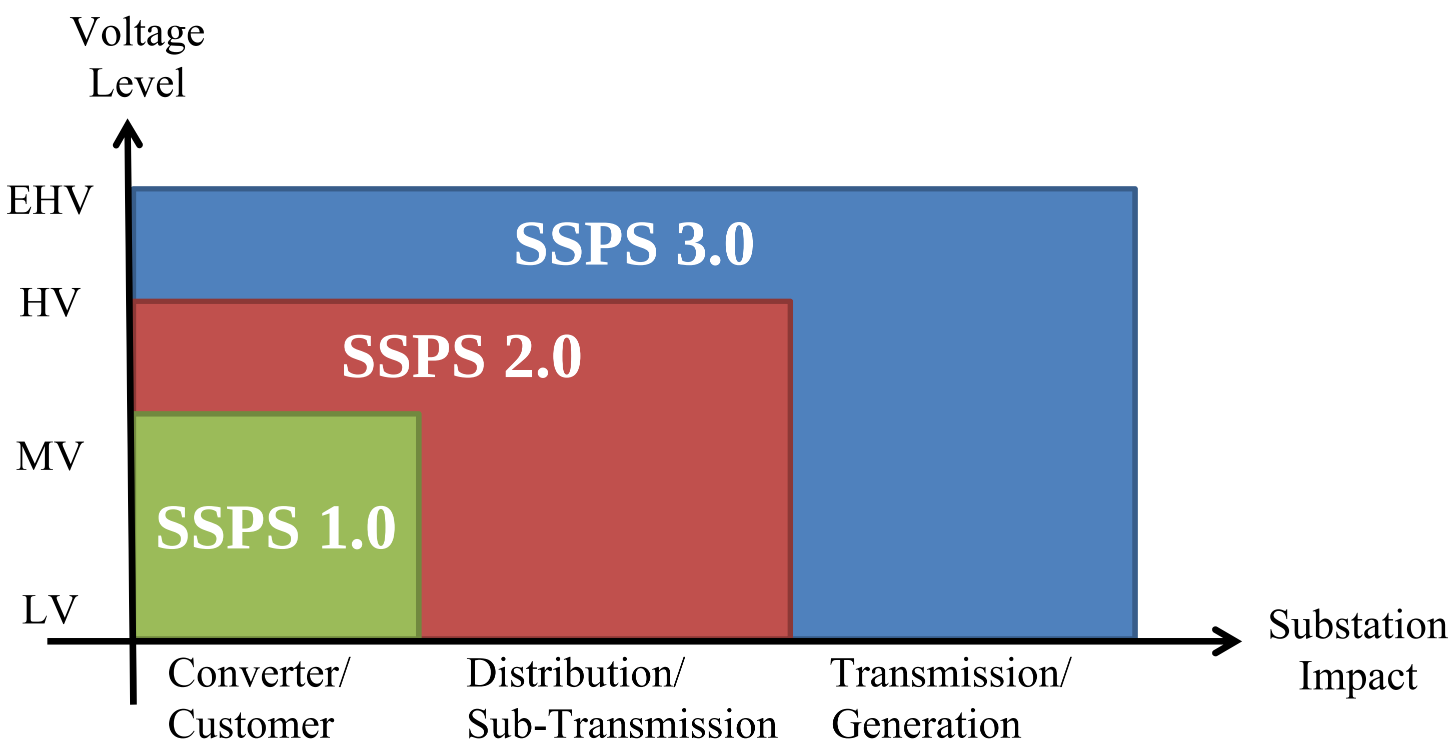
- **Energy Markets**
  - Enhanced control for buying and selling power in regions through distributed power flow control
- **Emergency and Black-start support**
  - Routing power through available transmission network to critical loads
  - Utilizing BES and other resources on the grid and slowly connecting load as sources become available
  - Mobile substations for deploying rapidly in critical locations
- **Asset Utilization**
  - Increasing capacity factor because of better power flow control
  - Modularity allows for easy increase in power capacity reducing over rating designs for population growth.

**Generation Substations**

- **Decoupling of Generator Synchronization**

# Envisioned SSPS Adoption/Deployment Pathway

- **SSPS 1.0 – "Low/Medium Voltage Local Applications"**
- **SSPS 2.0 – "Low/Medium/High Voltage Local Applications"**
- **SSPS 3.0 – "System Applications and Multiple Substations"**



# Technical Challenges of Implementing SSPS

Attempting to increase value proposition as we decrease cost. Therefore the Critical Technology Categories for SSPS are:

- Semiconductor Devices and Modules
- Power Electronic Converters and Systems
- Grid Integration and Application
- Industry Standards

# Semiconductor Device and Module Challenges

- SSPS requires cost effective and efficient semiconductor devices and modules for high frequency, high voltage, and high power operation attainable through:

| | | Near-Term (5 years) | Mid-Term (10 years) | Long-Term (20 years) |
|---|---|---|---|---|
| Technology Categories | R&D Challenges | Goals | | |
| Semiconductor Devices and Modules | Lower Conduction and Switching Losses | ↓20% | ↓40% | ↓80% |
| | Higher Blocking Voltage | 1.7kV | 3.3kV | 10kV |
| | Lower Device and Module Costs | ↓20% | ↓40% | ↓80% |
| | Module Packaging Temperature, Architecture, layout and Component Integration | ↑20% | ↑40% | ↑80% |

# Power Converter and System Challenges

- Providing scalable voltage and power solutions based on standard power electronic building blocks may reduce cost in many ways:

| | | Near-Term (5 years) | Mid-Term (10 years) | Long-Term (20 years) |
|---|---|---|---|---|
| **Technology Categories** | R&D Challenges | Goals | | |
| **Power Electronic Converters and Systems** | Modular and Scalable Architectures that are Resistant to Failure | N+1 Failures | Multiple Failures | Self-Healing |
| | Flexible System Design | <35kV | <230kV | EHV |
| | Intelligent System of SSPS Controllers | Hot Swappable | Full Substation | Network |
| | Enhanced Thermal Management Systems | Dielectric | Forced Dielectric | Flow Boiling Dielectric |
| | Lower System Costs | $120/kVA | $100/kVA | $60/kVA |

# Grid Integration and Application Challenges

- SSPS enhanced functionalities must provide benefits that outweigh their integration costs while maintaining or increasing grid reliability and safety through:

| | | Near-Term (5 years) | Mid-Term (10 years) | Long-Term (20 years) |
|---|---|---|---|---|
| Technology Categories | R&D Challenges | Goals | | |
| Grid Integration and Application | Control and Optimization Algorithms | Low Voltage Power Routing | Islanding and Microgrids | Distributed Power Flow Control |
| | System Modeling and Simulation | Single Substation | Multiple Sources/Loads | Network |
| | Analysis to understand optimal locations to quantify benefits | Customer & Converter | Distribution & Sub-Transmission | Generation & Transmission |
| | Tools and techniques to ensure coordination with existing protection schemes | Single Substation | Multiple Substations | Network |

# Industry Standard Development Challenges

- Standards are developed to ensure safety, compatibility, and interoperability between different technologies, and SSPS requires a fresh look at existing industry standards:

| | | Near-Term (5 years) | Mid-Term (10 years) | Long-Term (20 years) |
|---|---|---|---|---|
| Technology Categories | R&D Challenges | Goals | | |
| Industry Standards | Interconnection | IEEE 1547-2003 | IEEE P1032 | IEEE 1378-1997 |
| | Controls | IEEE 2030-2011 | IEEE 1676-2010 | IEEE C37.1 |
| | Communications | IEC 61850-6 | IEC TR 61850-90-1 & IEEE 1815.1-2015 | IEC TR 61850-90-2 |
| | Cyber & Physical Security | IEEE 1686-2013 | IEEE 1402-2000 | IEEE C37.240-2014 |
| | Mechanical Construction | IEEE 1127-2013, 979-2012, 1268-2016 | | |
| | Electrical Disturbances | IEEE 1585-2002 | IEEE WGI5-Voltage Sourced Converters | |

# SSPS 1.0 Functions and Technology Gaps

| | Defining Functions and Features | Technology Gaps |
|---|---|---|
| **SSPS 1.0** | • Provide reactive power compensation<br>• Provide voltage and frequency regulation<br>• Maintain appropriate power quality at its location<br>• Perform bidirectional power routing on low voltage ports<br>• Allow for multi-frequency systems<br>• Enable nanogrids of single buildings | - Converters able to directly connect to distribution level voltages<br>- Controls for secondary power routing<br>- Modular architectures<br>- Lower system costs<br>- Nanogrid controllers<br>- Interconnection standards<br>- Control standards<br>- Cyber & Physical Security standards |

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# SSPS 2.0 Functions and Technology Gaps

| | Defining Functions and Features | Technology Gaps |
|---|---|---|
| SSPS 2.0 | + Low voltage ride through<br>+ System coordination of fault current<br>+ Provides bidirectional power flow control between transmission and distribution<br>+ Enables distribution feeder islanding and microgrids | - Converters able to directly connect to transmission level voltages<br>- Controls for microgrid/islanding of distribution feeders<br>- Controls to optimize system power flow<br>- Communication standards<br>- Electrical disturbances standards |

# SSPS 3.0 Functions and Technology Gaps

| | Defining Functions and Features | Technology Gaps |
|---|---|---|
| SSPS 3.0 | + Distributed control of multiple SSPS systems<br>+ Enhanced power routing for optimizing operational efficiency and increased resilience<br>+ System decoupling for improved stability<br>+ Provides black start support on a regional network | - Converters able to directly connect to extra higher voltage systems<br>- Distributed power flow control<br>- Power system stability control<br>- Black start coordination<br>- Distributed control operation standards |

# Ultimate SSPS Vision

**Scalable, adaptable, cost effective, flexible AC/DC Power routers that span all voltages**