Next Generation Capacitor Solutions

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Advanced Conversion

Agenda

- Introduction and Corporate Overview
- Power Ring Film Capacitor
- Optimized DC Link Topology
- Cap/bus test kits
- New: Prototype Bus Capabilities
- Summary/Questions

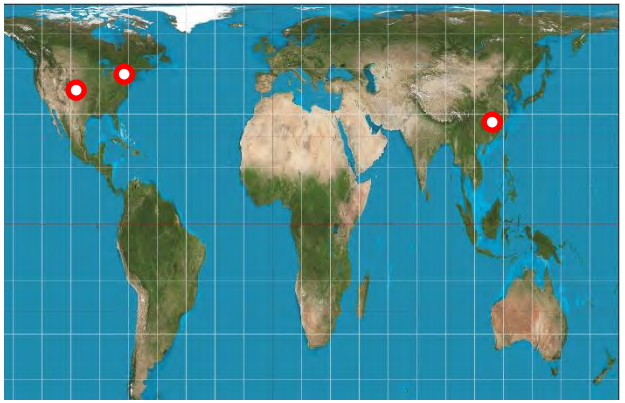
Advanced Conversion Overview

Established: 1945 as **Sprague Electric**; **SBE** formed in 1985, **Advanced Conversion** started December 2019

Locations: Headquarters, Manufacturing and R&D Center: Barre, Vermont
Application Engineering and Sales: Loveland, Colorado and Xiamen, China

Facilities: Vermont: main plant and corporate headquarters – 20,000 square feet
Colorado: engineering and assembly – 2,000 square feet
Xiamen: engineering and assembly – 5,000 square feet

Distributors: Richwood–China and Hong-Kong
Flux Interconnect – Korea
Jin Zon Enterprise- Taiwan
Pulse Power & Measurement – UK/EU
NAC Group - Americas



Ownership: Privately Held Corporation

Markets: EV, Traction, Aviation, Alternative Energy,
Medical, Military, HVDC, Statcom

Vermont Facility

Advanced Conversion Roadmap

DOE SBIR and Recover Act Funding plus investment

Next generation polypropylene film capacitors for 105C coolant automotive applications

Power Ring Capacitor with optimized form factor = best performance for ANY film

High performance capacitor design, simulation, and testing

Unique Proprietary winding technology

Advanced packaging

New Product: Integrated capacitor/bus

The Power Ring Advantage

- Film is film to all capacitor vendors - everyone has access to the same film suppliers
- We have targeted the annular form factor to provide the best possible performance
  - Significant investment in proprietary winding technology
  - Patent coverage for key technology aspects
    - Integration of polymer winding with copper terminals
  - Advanced design and simulation capabilities
  - Understand performance at the system integration level

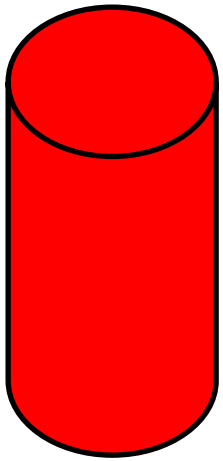
Key Technology Factors

- Large monolithic winding for lower cost
  - Better performance than a bank of smaller parts
- Short current path provides very low ESR
  - Low losses
- Large thermal cross section area provides efficient heat removal
  - Minimal hot spot temperature rise
  - Highest possible current rating for given capacitance
  - Best performance for ANY film

Key Technology Factors

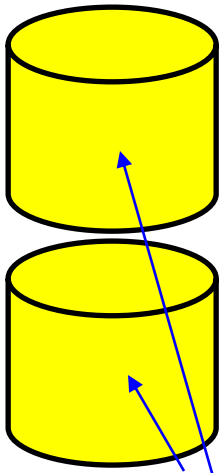
- Maximize A/μF so μF/kW is defined by control limit <u>not</u> capacitor current rating

Typical "Can"



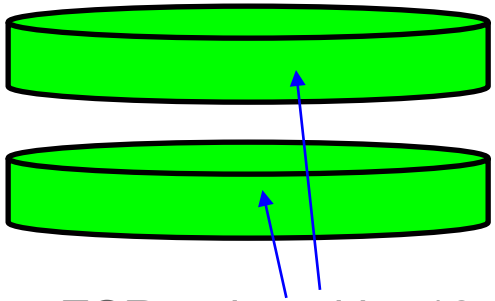
$\Delta T = I^2 \times ESR \times R_T$

Cut in Half



ESR reduced by 2x
R_T reduced by 2x

Narrow film wound into into a "Platter"



ESR reduced by 10x
R_T reduced by 10x

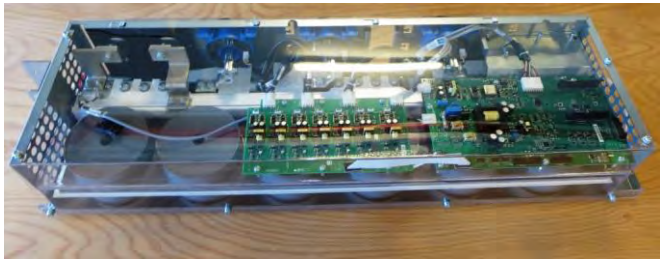
Next Generation Film Capacitor Solutions

Power Ring Film Capacitor is a Building Block for Enabling Technology at the SYSTEM Level

Pulse caps with excellent reliability and peak current rating

AC Filter – Oil free patented segmentation eliminates catastrophic failures

DC Link – Integrated cap/bus for high performance traction drive



DC Link – integrated cap/bus for increased power density in alternative energy and network power

Introduction to DC Link

- Traditional inverter design takes the approach of adding μF until the capacitor bank can handle current to achieve the required life
  - This is not effective in terms of power density, cost, or volume
- Working voltage and switching speed (efficiency) limited by the ESL of the DC link
  - Interconnection between DC link capacitor and switch module is limiting factor

DC Link Technology

- Objective: Provide an optimized DC link such that customer can extract maximum value from investment in switch modules
- This is achieved as follows:
  - Provide highest possible Ampere/μF rating such that capacitance is defined by control limit rather than capacitor life (minimize μF/kW)
  - Integrated cap/bus to provide the lowest possible inductance at switch module inputs

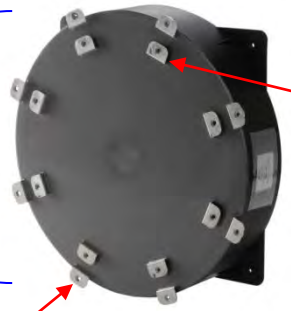
DC Link Technology

- Packaging and integration of the capacitors is critical for best performance
  - Optimize terminal configuration for capacitor to improve magnetic flux cancellation
  - Integrate capacitor(s) directly onto the bus structure as “surface mount” devices
    - Eliminate redundant conductor layers
  - Improve connection geometry from cap/bus to switch module(s) = optimal **TOPOLOGY**

DC Link Topology

Example: 777A104 Test Kit (3000uF at 1100V)

Start with 700D590 discrete capacitor



Keep top “crown” terminal for low ESL

Remove bottom terminal from “discrete” capacitor and let bus conductor be the terminal (reduce copper and path length)

Coaxial “through-hole” connections to half-bridge

Locate DC input tabs to optimize current distribution

Enabling the Ecosystem

- Next generation inverters must improve power density and efficiency
  - This requires an enabling “ecosystem” to support the semiconductor switches
    - Gate driver
    - Bus bar
    - DC link capacitor
    - Cooling

Advanced Conversion integrated cap/bus topology forms the foundation

Enabling the Ecosystem

- Advanced Silicon
  - Higher operating voltage
  - Faster switching
  - Massive paralleling of switch modules to achieve very high current
- Silicon Carbide
  - Higher operating voltage
  - Higher operating temperature
  - Very fast switching
  - Parallel modules needed to get to medium current

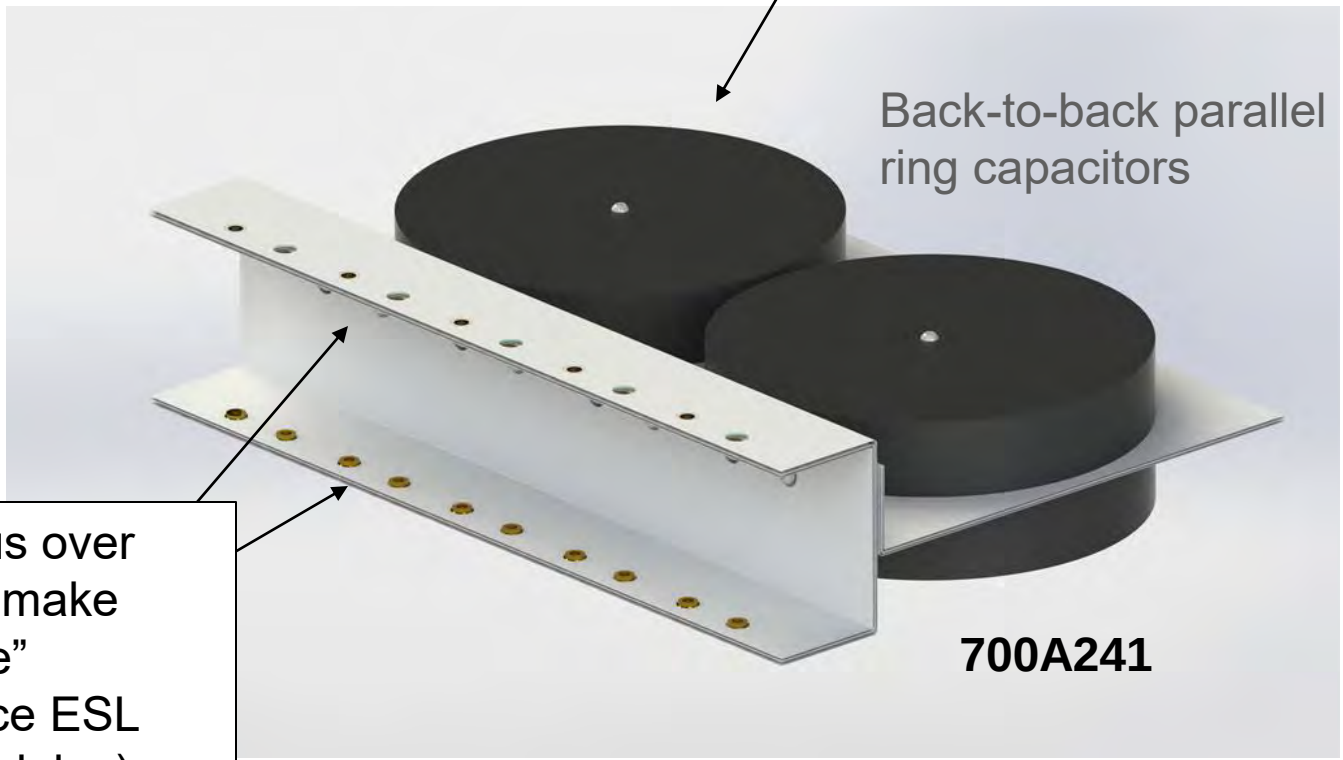
Enabling the Ecosystem

- The enabling DC link requires the following ingredients
  - Optimized topology and bus structure
    - Very low commutation inductance
    - Paralleling of switch modules (balancing)
  - Very low capacitor losses
  - Higher capacitor working voltages
  - Increasing capacitor temperatures

Paralleling Modules

DC Link for Paralleling Infineon XHP™ Modules

Add additional rows of 4x windings as needed for system mF value (e.g. weak grid)



Extend laminated bus over switch modules and make coaxial “through hole” connections to reduce ESL (< 10nH seen by modules)

Paralleling Modules

As displayed by Infineon at PCIM

Paralleling Modules

- Infineon double pulse testing demonstrates current balancing is better than 5% with 10x modules in parallel
- The use of two-sided cooling plate for modules complicates topology => multiple bus components needed
  - "C" bus connected to main cap/bus with multiple parallel coaxial contacts

Higher Working Voltage

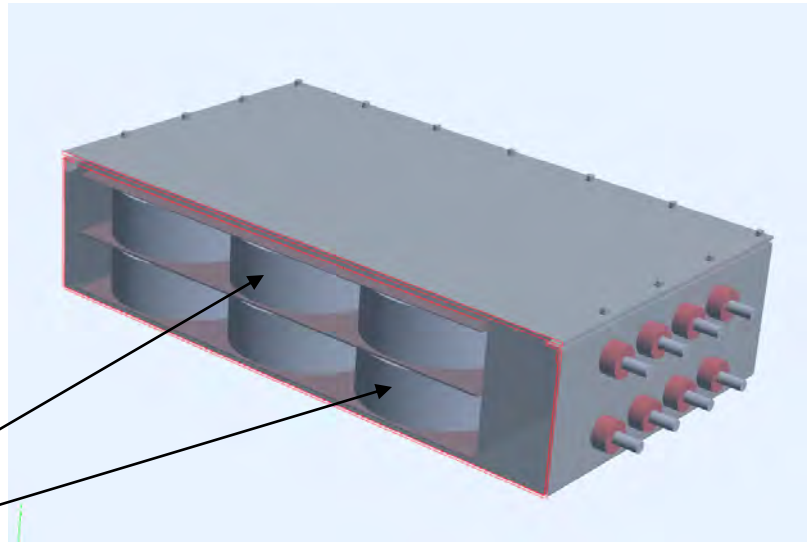
- Example: HVDC and SVC applications
  - 2.8kV and up
  - Customers are now looking to reduce all component losses
- Power density = capacitance density
  - Thinner film to manage capacitor volume
  - Lighter metallization to support higher operating stresses
    - Our form factor can actually reduce the ESR while taking this approach

Higher Working Voltage

The traditional “box cap”

Improved “box cap” with lower losses using Advanced Conversion rings

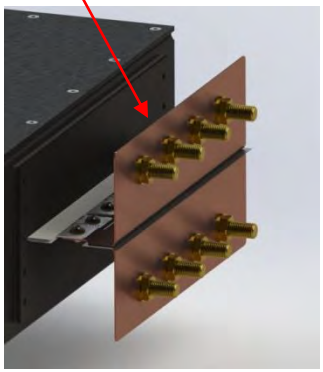
- Dissipation losses are the same
- Electrode losses are reduced by up to 3x



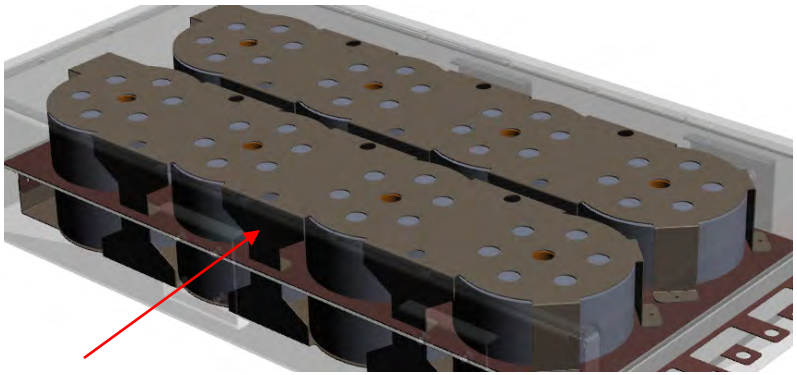
Array of ring capacitors connected to bus plates with patented technology

Topology

Universal bus with adapters allows immediate use with existing hardware with later upgrade



Support ESL migration roadmap



Low ESL “crown terminal”

Optimized: Mount capacitors “back to back” on low-inductance bus and transition bus out to of case to the switch modules

Higher Temperature

- Collaboration with DuPont Teijin Films launched in May 2017
- Excellent quality achieved with our unique winding equipment
- Enables operation beyond 125C
  - Dielectric strength and self-healing comparable to polypropylene
  - PEN HV windings can readily be utilized for existing DC link designs
  - Multiple customers utilizing this film for high performance applications

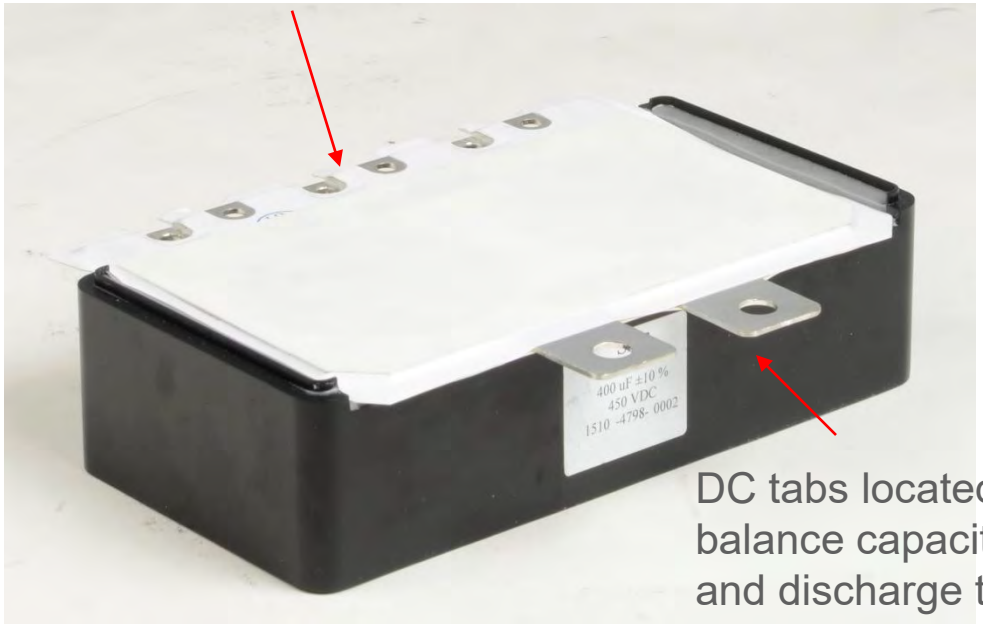
Capacitor/Bus Test Kits

- We provide capacitor/bus “test kits” for high performance switch modules
  - Low ESL
  - High current capability
- Allow customers to see what the semiconductor package can really do…
- Infineon HybridPACK™ Drive
- On Semiconductor VE-Trac™

DC Link for Infineon HybridPACK™ Drive

- Horizontal configuration 700A186

Optimized cap/bus gives 8nH at module inputs



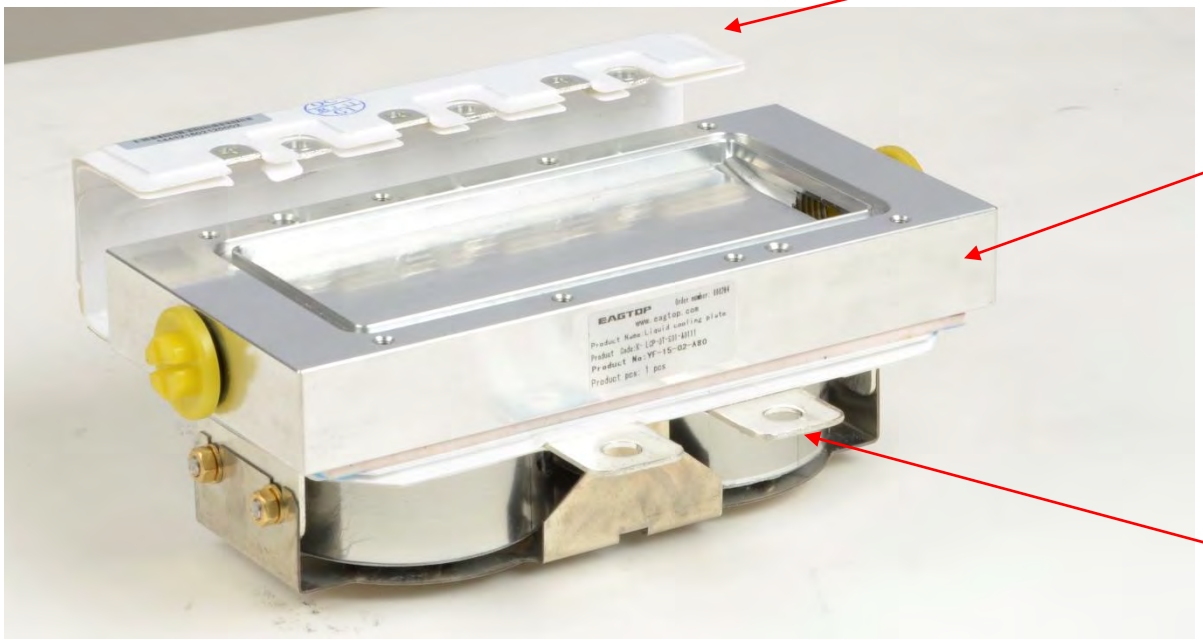
DC tabs located to balance capacitor charge and discharge to avoid current hogging

Combined with cooling plate and Infineon HybridPACK™ Drive for testing

DC Link for Infineon HybridPACK™ Drive

- Vertical configuration 700A205

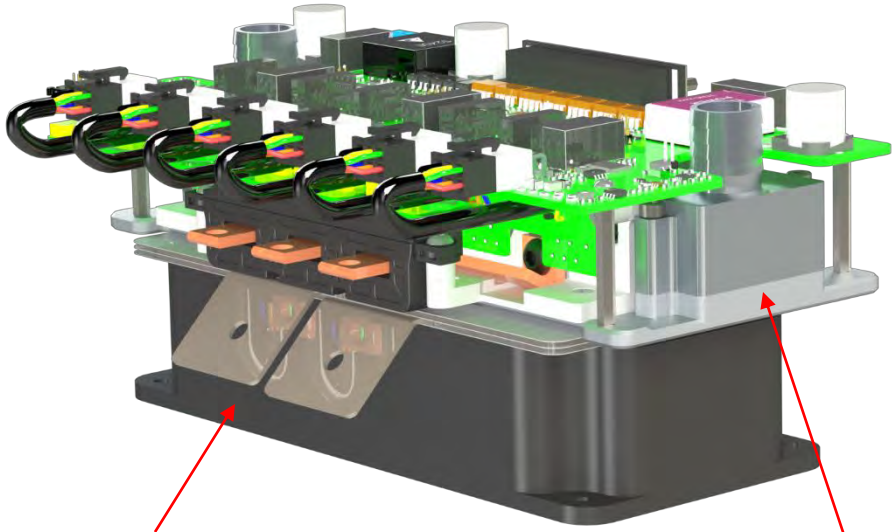
Optimized cap/bus 12nH at power module inputs

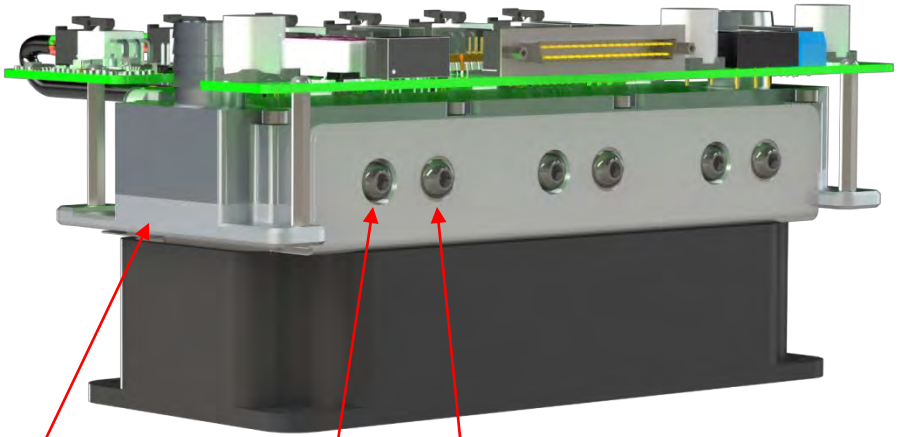


Cooling plate extracts heat from power module and bus = higher rating

DC tabs located to balance capacitor charge and discharge to avoid current hogging

DC Link for ON Semiconductor VE-Trac™





DC Inputs Opposite Switch Module Connections

2x 250uF MPP Windings Rated at $500V_{dc}$ Surface Mounted to Bus with Proprietary Technology

Switch Module Cooling Plate Thermally Coupled to Cap/Bus to Maximize Current Rating

Coaxial “Through-Hole” Connections from Laminated Bus to Module DC Inputs Minimize ESL (< 10nH)

New: Prototype Bus Capabilities

- The bus industry currently has prototype lead times ranging from 12 to 25 weeks
  - This does not support rapid customer validation of Advanced Conversion cap/bus technology
- Advanced Conversion has implemented in-house prototype bus design and fabrication for critical customer partners
  - Laminated: **4 - 6 weeks lead time**
  - Powder coat: **4 - 6 weeks lead time**

Summary

- We offer the lowest μF/kW rating
  - Smallest size and lowest cost
- Advanced Conversion DC link is a key component of the enabling “ecosystem” for advanced Si and SiC applications
  - Critical for paralleling of modules
- We provide integrated cap/bus solutions for low ESL
  - Allows for much greater switch utilization
- We have in-house bus fabrication capabilities