Superconducting and Solid-State Electronic Fault Current Limiter Technologies

The shift from demonstration projects to Business-as-Usual solutions

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Impedance on Demand

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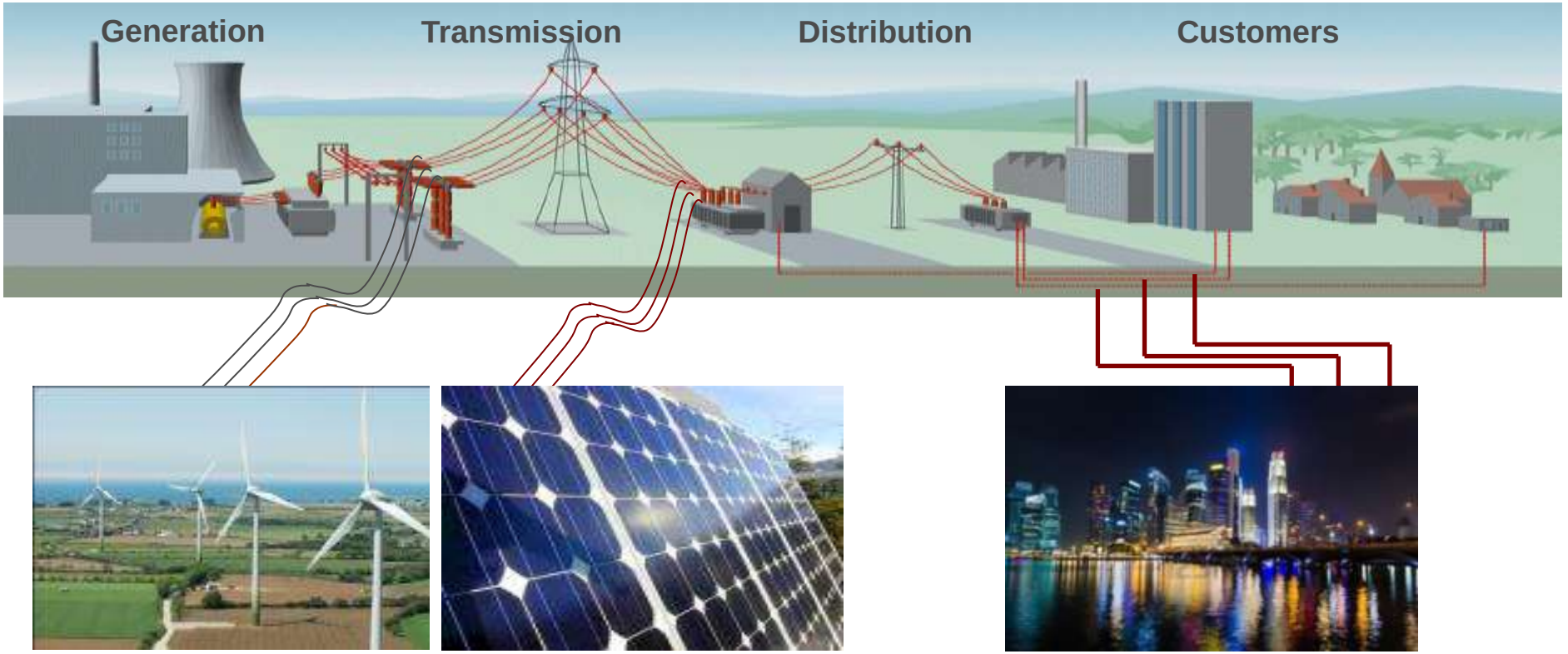
- The Fault Current Challenge
- Fault Current Limiters
- Applied Materials
- Projects

The Fault Current Challenge



New Energy Sources

- Renewable Power – Wind, Solar, Biomass
- Increased Grid Meshing for Reliability and Power Quality
- Distributed Generation

More Demanding Operations

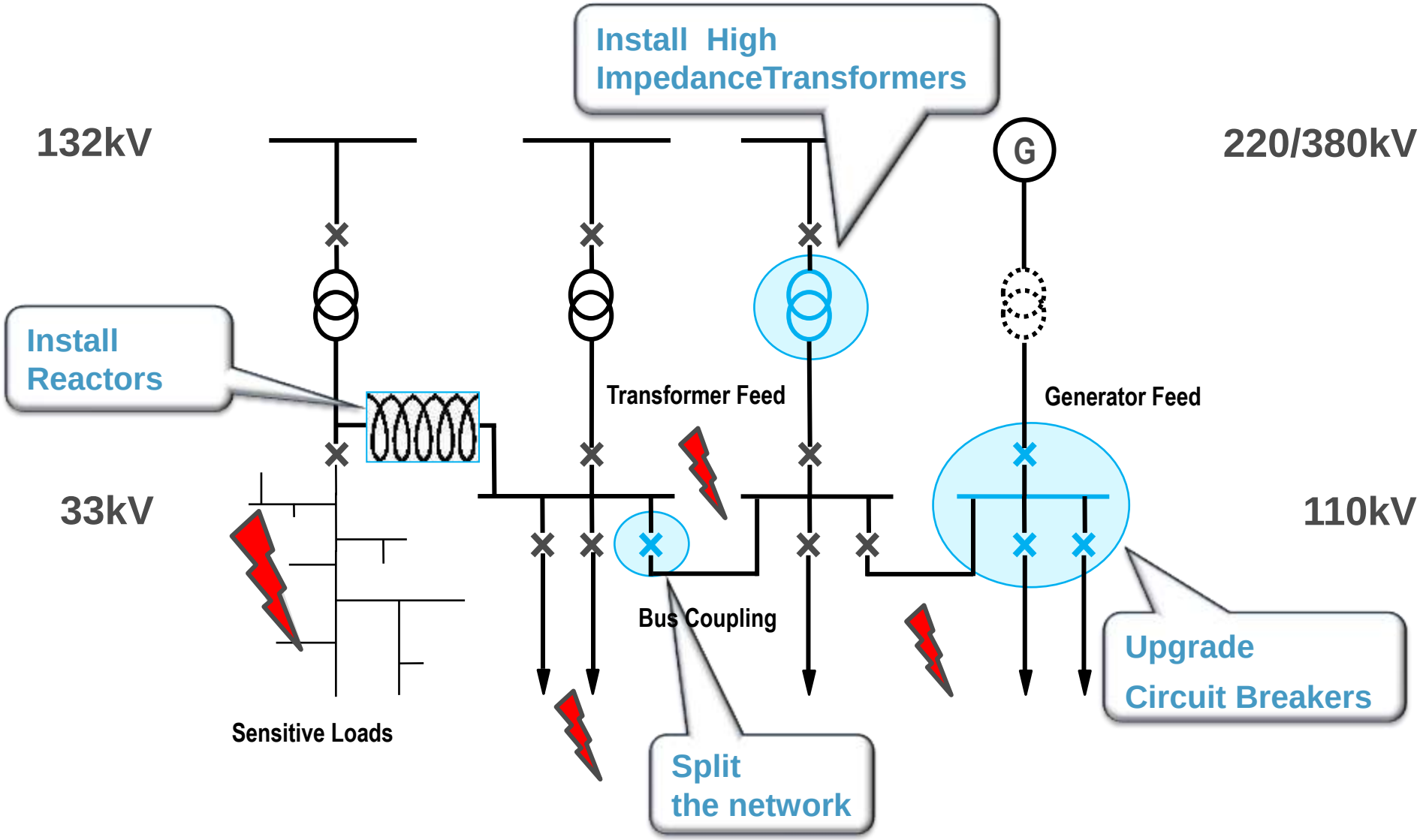
- Increased Duty Cycles
- Disappearing Off-Peak Periods
- Aging Infrastructure

Increased Load

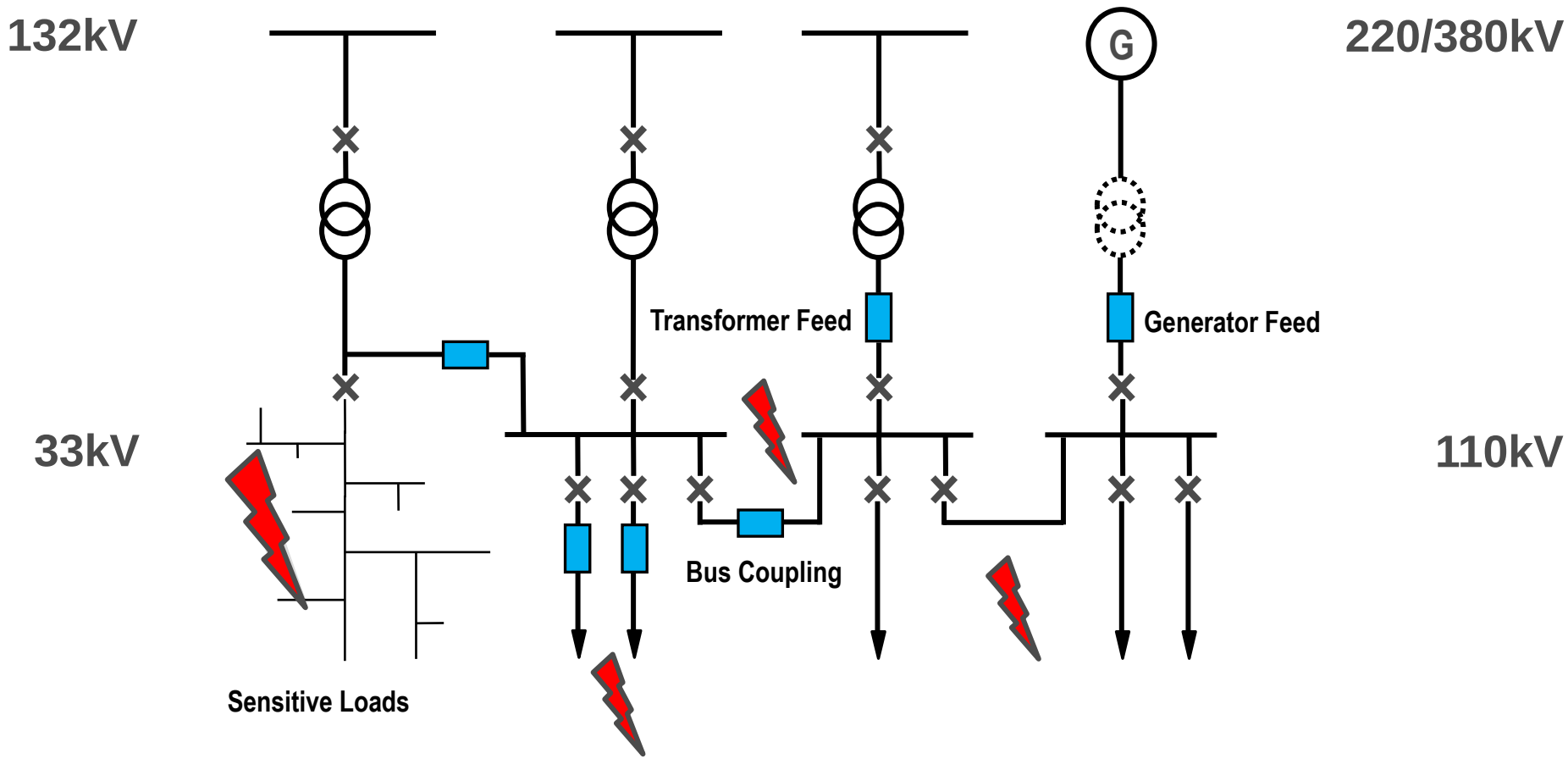
- Transportation - Electric Cars, Trains
- Urbanization - Population Growth
- Modern Conveniences

Trends in Electricity networks increase Fault Current Levels

Conventional Fault Current Mitigation



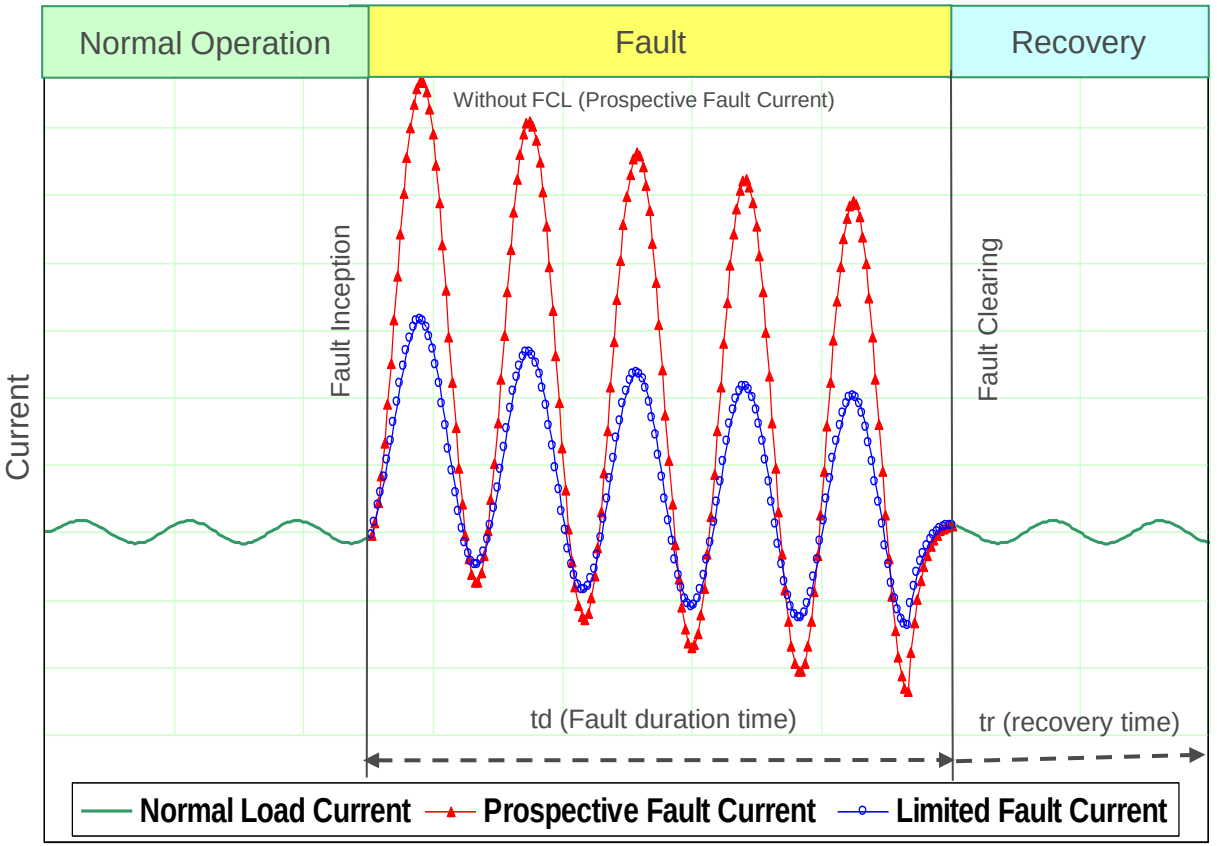
Use of Fault Current Limiters



Desired Characteristics of an Ideal FCL

- Increase the impedance on the line well before the first fault peak (when the most damage occurs)
- In normal operation, it is virtually "transparent“ (no power or voltage loss) to the network
- Diminish the fault current by at least a factor of 2 for its duration
- Return the source impedance to its original value when fault is cleared

Typical current waveforms due to fault



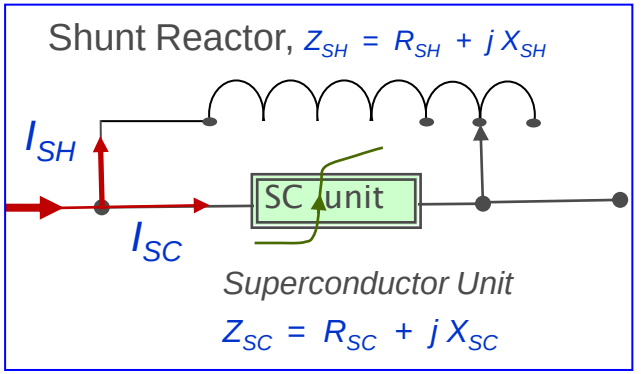
Fault Current Limiters Reduce Fault Currents Without the Need for Mitigation

Fault Current Limiter Solution Platform

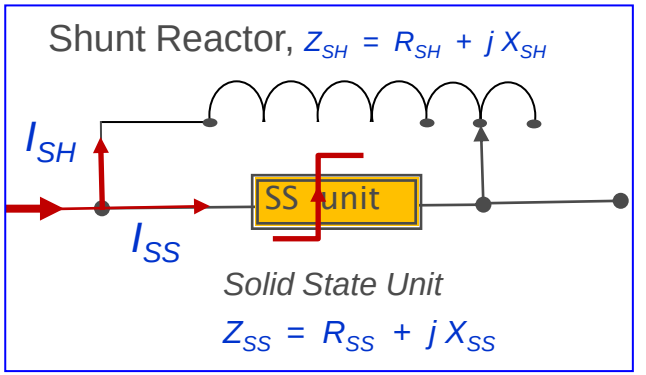
- **Transmission System FCL**
  - Superconducting Fault Current Limiter **(SCFCL)**
  - 66 kV to 230 kV transmission voltage levels

- **Distribution System FCL**
  - Solid State Fault Current Limiter **(SSFCL)**
  - Up to 66 kV distribution voltage levels

- **Proprietary Design Features**
  - FCL units can withstand long duration faults and remain in parallel with shunt for extended periods.
  - Solid-State Devices are protected against known failure modes including cascading failures due to aging and timing differences.
  - Modular design allows FCL components (shunt, FCL unit, instruments, cryogenics) to be separated to accommodate site conditions.
  - Modular design allows easy spares provisioning of field replaceable units.
  - SC and SS elements can be upgraded or repurposed as requirements change.

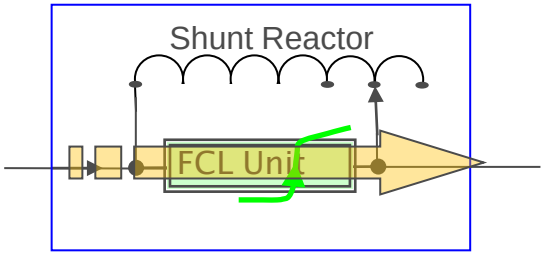


SCFCL

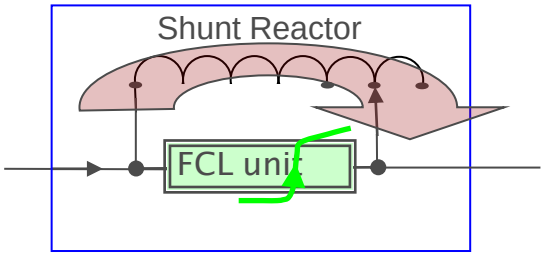


SSFCL

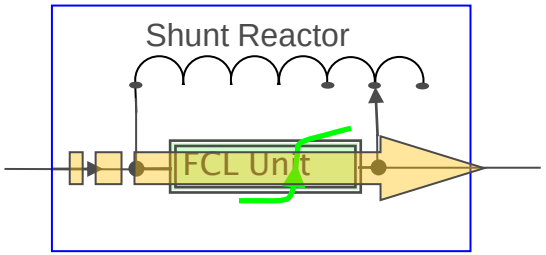
Common Operating Principles



- **Normal Operation**
  - Load current flows through FCL unit.
  - FCL introduces nearly zero impedance and voltage drop.
  - System (FCL unit, shunt, remaining components) is designed to handle the maximum load current at all times – even under contingencies.



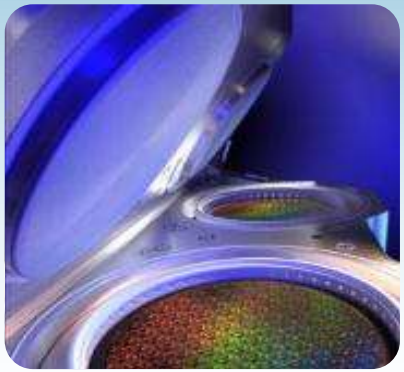
- **Fault Condition**
  - FCL unit responds to fault current. – Superconducting material quenches or solid-state path switches; both insert high resistance in ≈ 0.001second.
  - Load transfers to high-impedance shunt path that limits fault current.



- **Post-Fault**
  - Recovery is fast and automatic after fault clears.
  - SCFCL transitions (recovers) under load in about 3 seconds.
  - SSFCL switches in milliseconds (Programmable delay can be incorporated)

Leveraging HV and High Power Expertise

Semiconductor



Display

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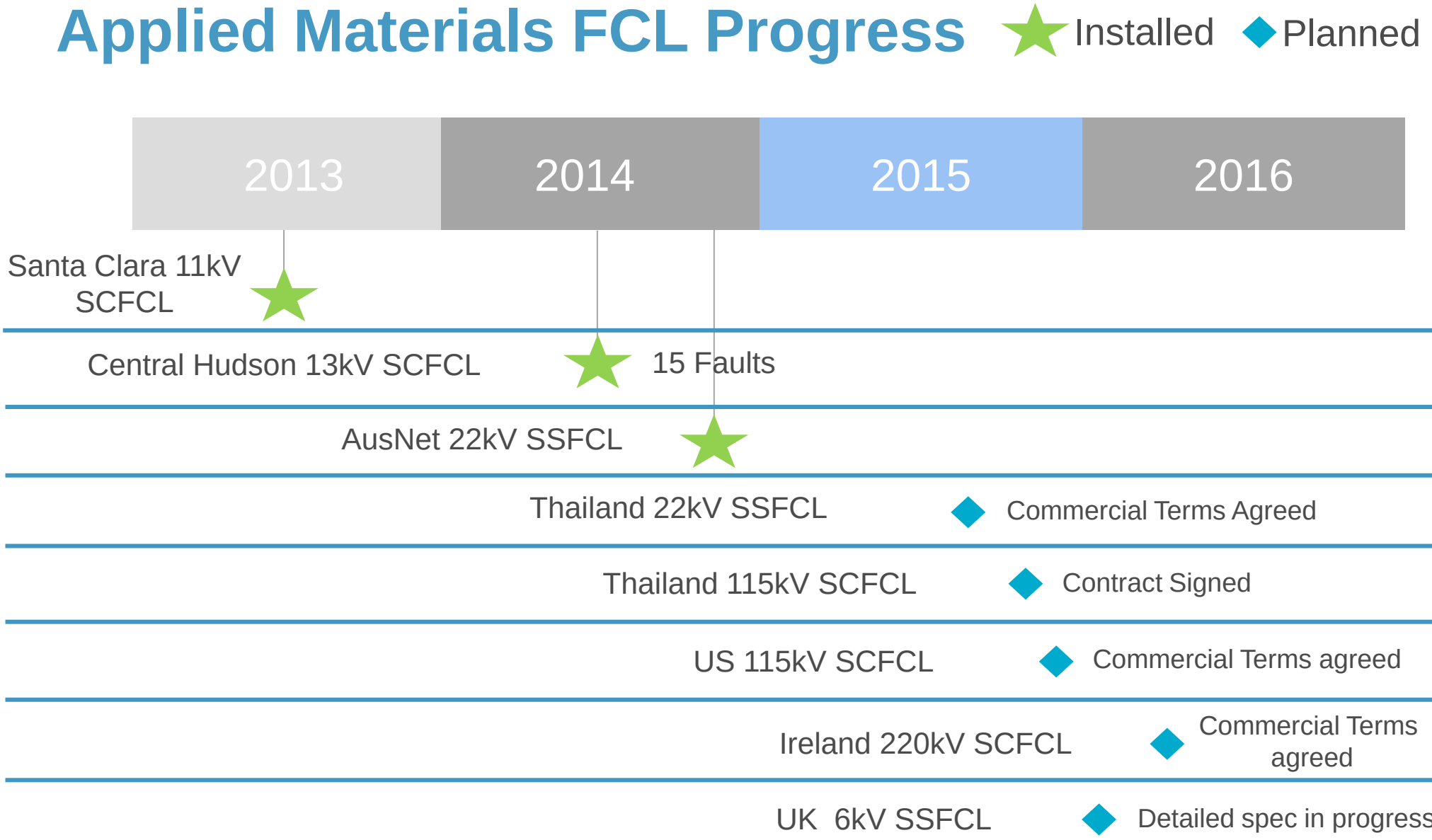
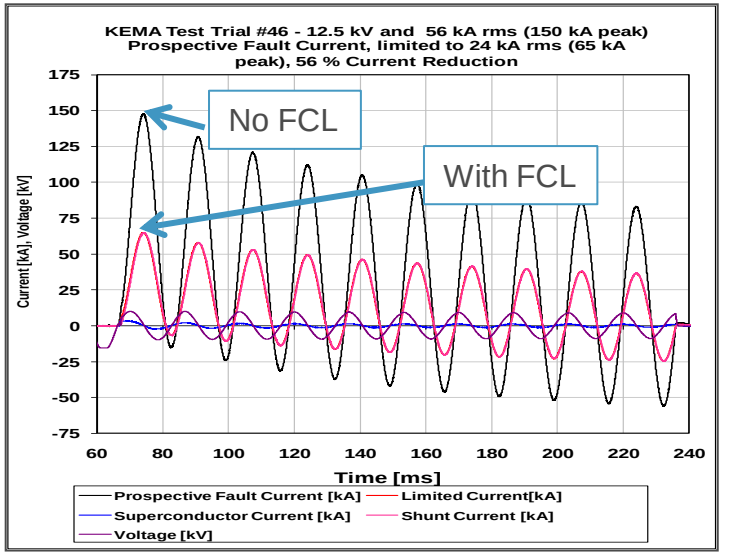
Stock Ticker:	**Nasdaq: AMAT**
Market Cap:	**$29.6 billion**
Fiscal 2014 Revenue:	**$9.1 billion**
Fiscal 2014 R&D:	**$1.4 billion**
Founded:	**November 10, 1967**
Headquarters:	**Santa Clara, California**
Global Presence:	**81 locations in 18 countries**
Fortune 500 Ranking:	**302**
RD&E and/or Manufacturing Centers:	**China, Germany, Israel, Italy, Singapore, Taiwan, United States**
Employees*:	**~14,000 worldwide**
Patents:	**~10,500 issued**

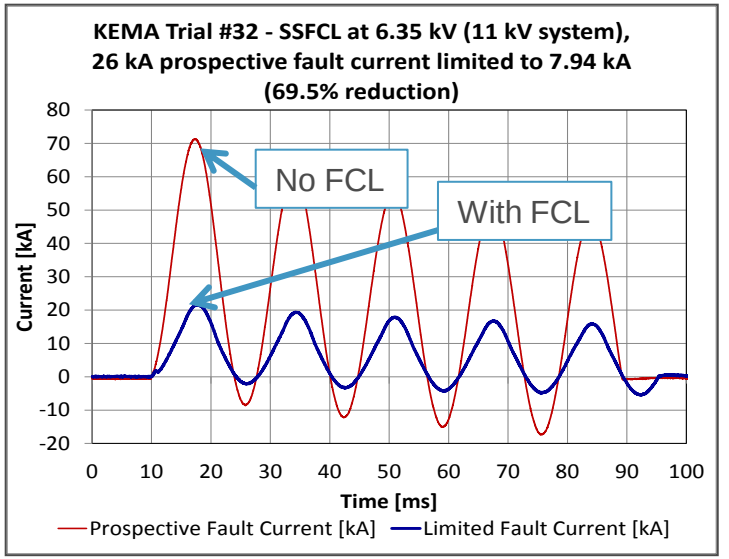
Applied Materials FCL Progress



SCFCL and SSFCL Extensively Tested

- Tested for many weeks at full-power at KEMA, Chalfont, Pennsylvania, USA
- "Lifetime" tested for hundreds of bus faults
- SCFCL fully qualified against relevant IEEE Standards for 230kV employment – Demonstrated at over 400kV
- SSFCL fully qualified for 45 kV employment – Demonstrated at over 66 kV
- Tested to failure to verify reliability and DFMEA Data
  → Failures are predictable and benign –
  → Grid remains protected with no cascading or induced secondary failures
- Automatic Recovery under load validated
- High-Level DFMEA performed by Core Engineering Team
  → 66 unique failure modes Identified
  → 11 mitigated through design changes
  → 55 mitigated through redundancy





Under all scenarios power flows and the Grid remains protected

SCFCL - 15kV for Silicon Valley Power, CA, US

- **Normal Operation**
  - Voltage = 15 kV class
  - Load current = 1000A
- **Fault Current limitation**
  - 23 kA to 11.5 kA (at 50% reduction)
  - Or 5 kA to 3.5 kA (at 30% reduction)
- Recovery Under Load (RUL)
  - 1 to 3.5 seconds depending on the fault current level
- **Installation**
  - At Applied Materials industrial substation supplied by Silicon Valley Power (SVP) – Santa Clara
  - Commissioned in July 2013

Reactors, Instrumentation and other devices under test

Cryostat – Superconductor Unit

Cryogenics – Cooling system

SCFCL - 15kV for Central Hudson, NY, US

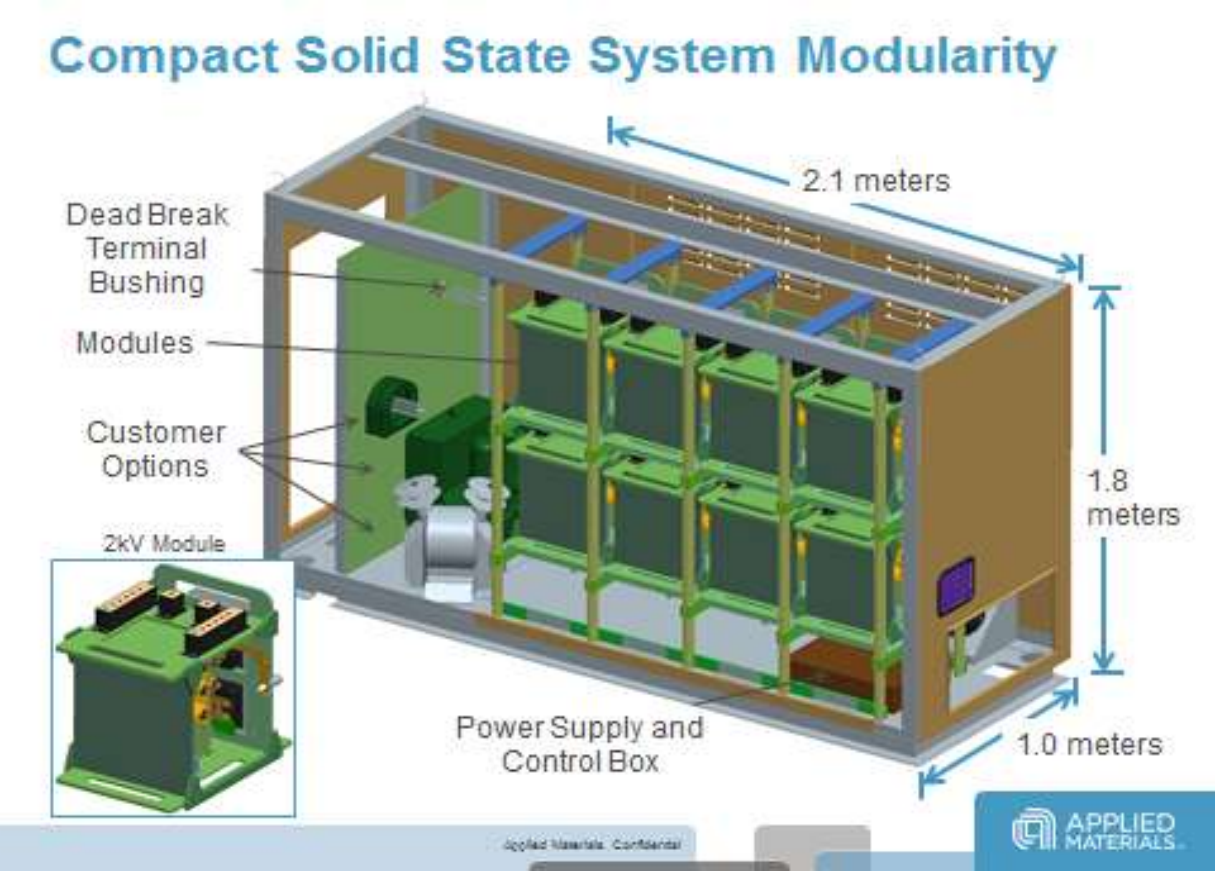
- **Normal Operation**
  - Voltage = 15 kV class
  - Load current = 400A
- **Installation**
  - Central Hudson's Knapps Corner Substation; Poughkeepsie NY
- **Performance**
  - Limited 15 faults since commissioned June 2014

Refrigeration Units (2)
- N+1 Redundant
- Environmental enclosure

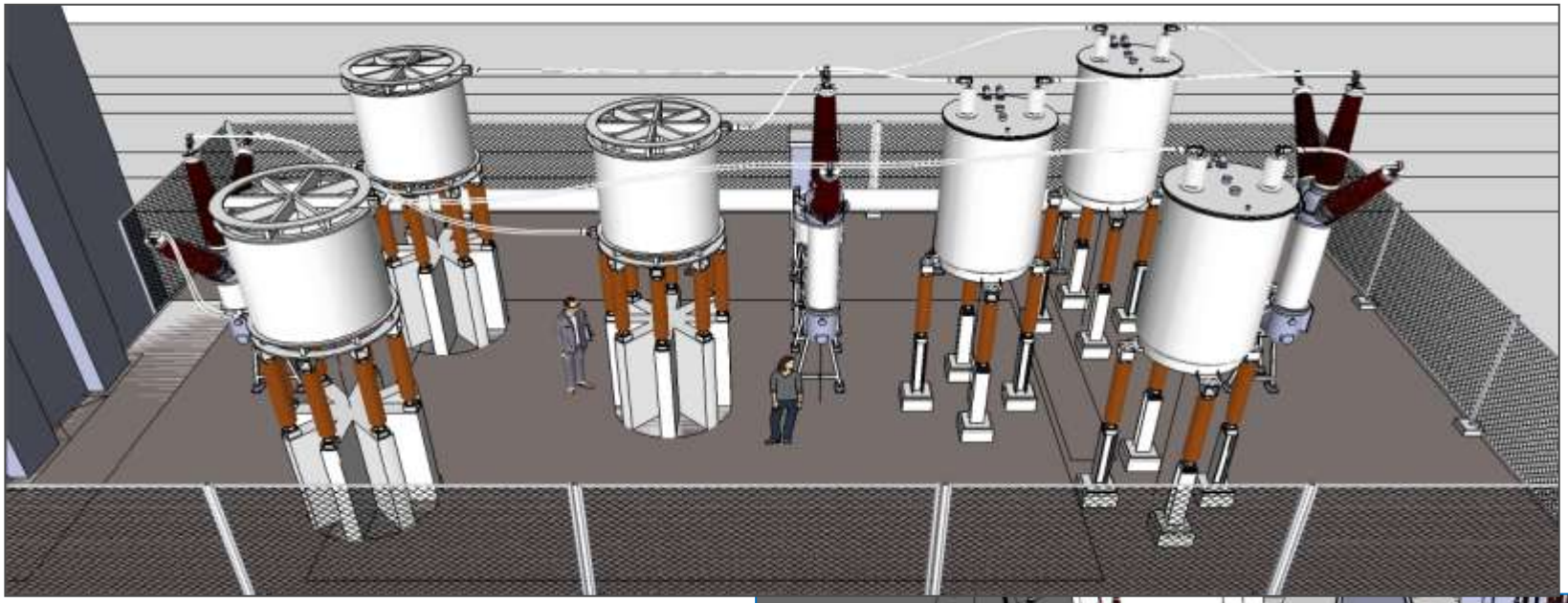
Superconducting Unit
- Neutral to Ground Configuration
- Redundant safety features

SSFCL - 22kV Solution for AusNet, AU

- Mitigates Brushfires caused by short-circuited lines
- Connected Neutral-to-Ground
- Limits 3-8 kA faults to 6, 40, or 70 A Peak (within <1ms)
- Fast subsequent reduction to < 2 A

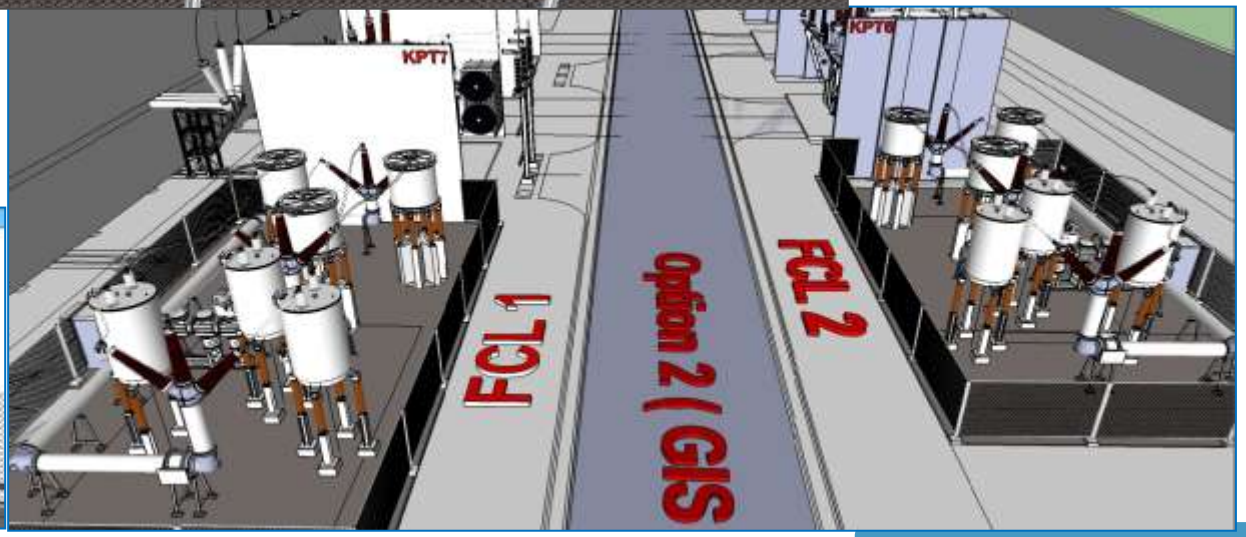


SCFCL - 115kV solution for Thailand



- 2 x 115kV/50%
- 800A
- Gas Insulated Switchgear
- Compact Design
- LN_2 tank outside accessible

Interconnects 8th Power Block at generating site without exceeding fault current duty



Summary

- **Platform of Fault Current Limiting Solutions ranging from 6kV to 230kV**

- Modular concept with independent designs for
  - Power switching functionality (=superconductors or solid state power electronics)
  - Current limiting properties (=shunt reactor)

- Fast deployment – less outage time
  - redeployable

- **FCLs increase network safety and reliability.**
- **FCLs facilitate meshed network operation and connection of generation.**
- **FCLs sustain network stability and prevent network losses.**
- **FCLs provide impedance when it is needed!**

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