Solid-State Circuit Breakers

Infineon Technologies AG
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Public

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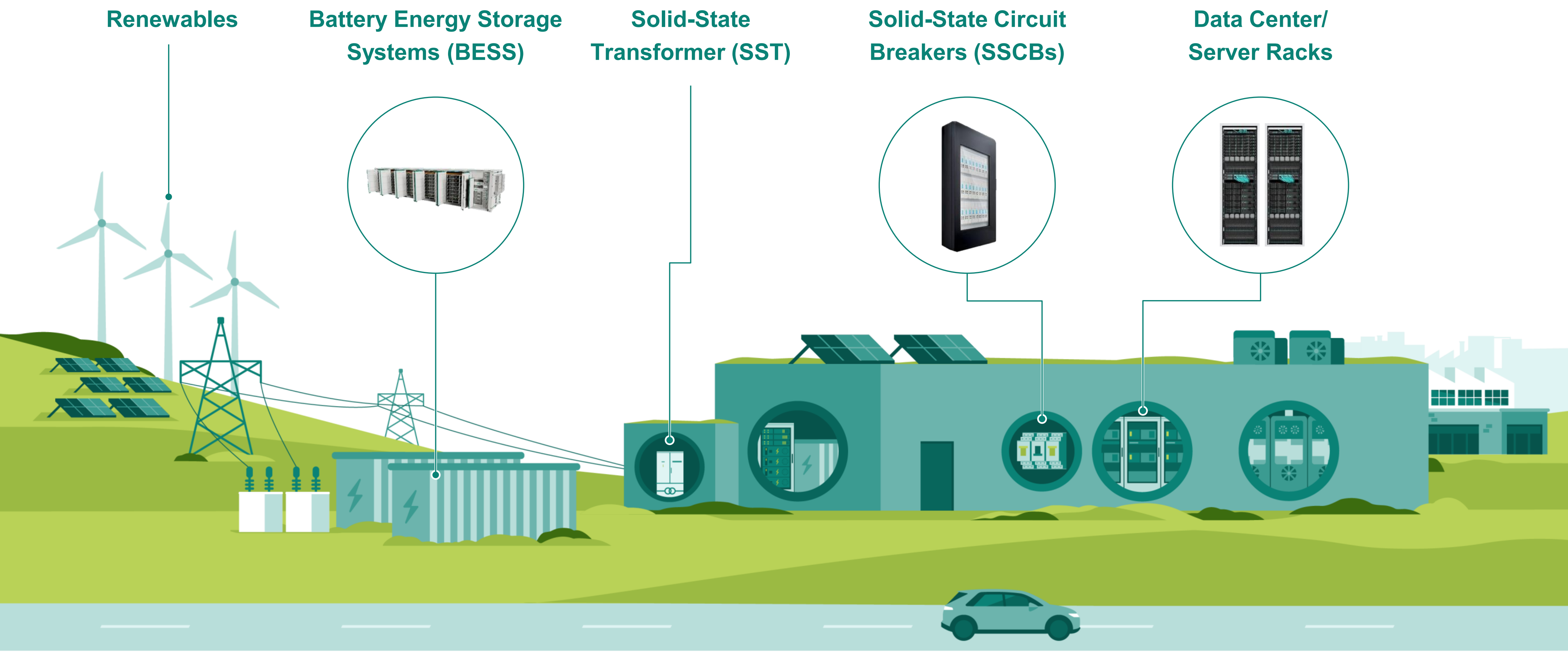
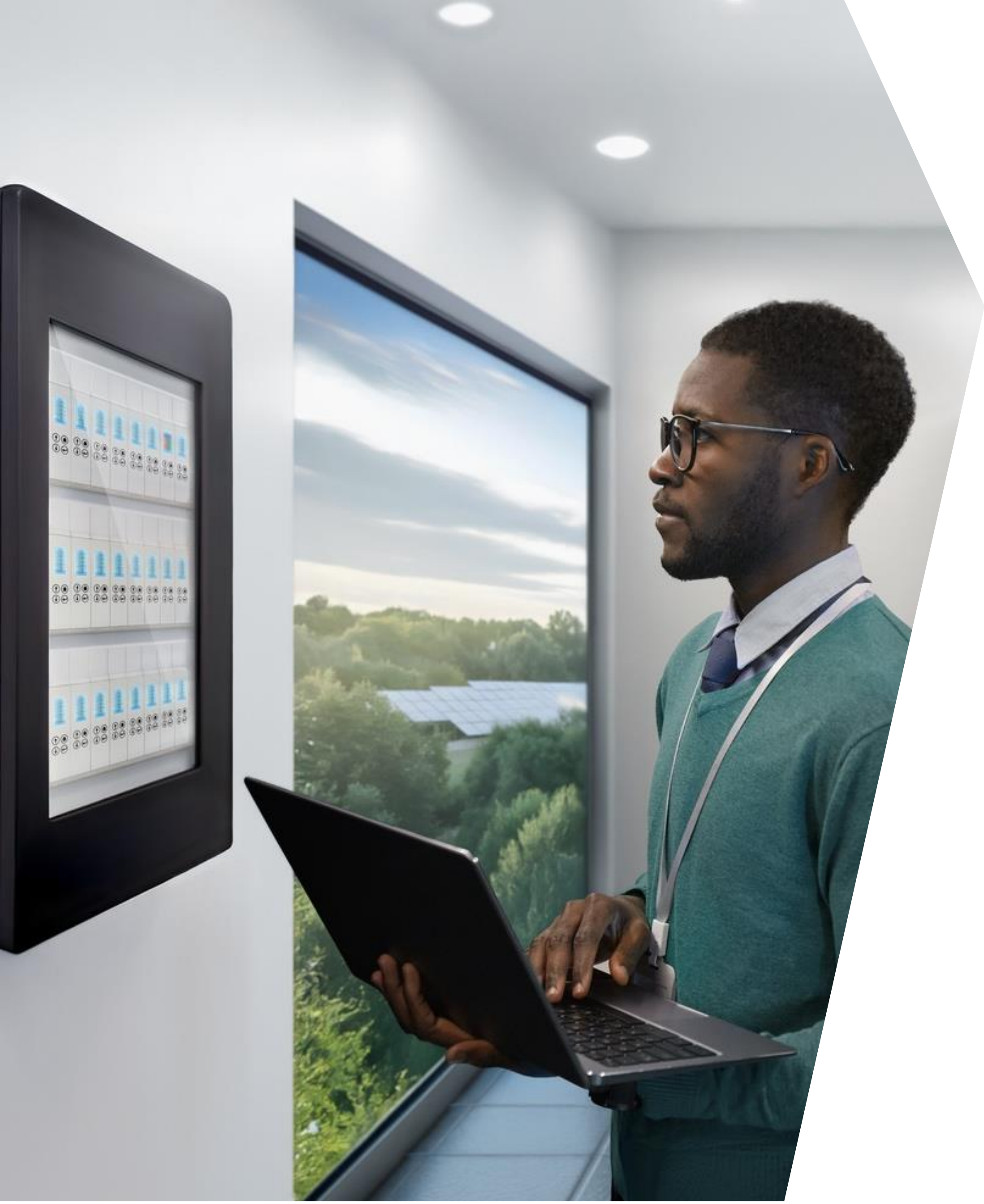
Introduction

Energy transition requires significant improvements in power distribution systems

- Renewables are variable and less predictable than conventional generation, requiring smart grid control down to individual sub-branches.
- The general trend towards electrification is driving sharp increases in electrical power demand resulting in high utilization of distribution systems.
- Industrial and public sites are moving to microgrids with distributed energy resources, blending grid supply with PV, batteries, and local generators.
- Modern factories orchestrate power and downtime with tight tolerances and intelligent protection.

The evolution of power distribution. Distributed Energy Resource (DER) grids require advanced protection, monitoring and control



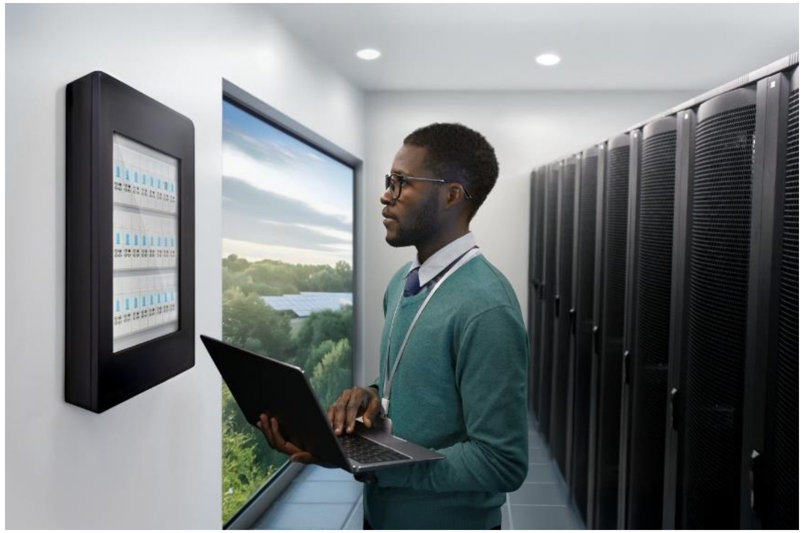


The Future of Power Distribution Systems — Enabled by Smart, Fast-Acting Power Distribution Devices

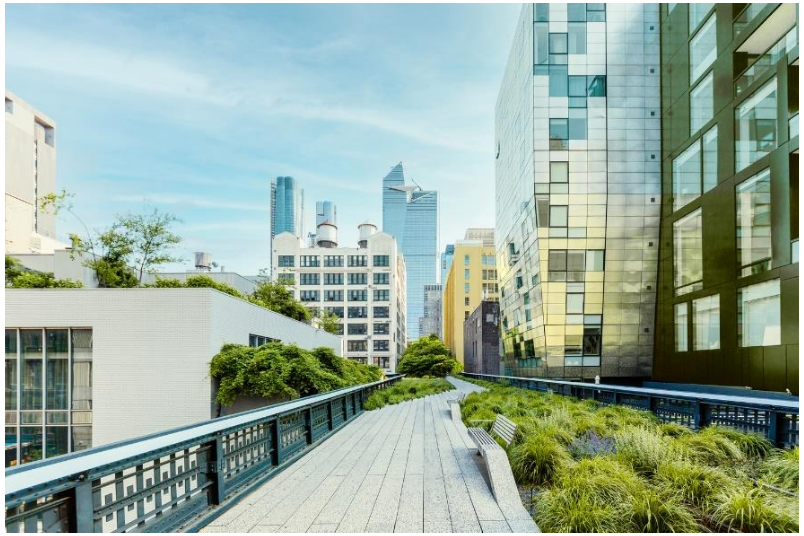
- Maximize availability through precise power and uptime control
- Intelligent load balancing and peak demand limiting
- Greater overall system efficiency
- Global data center growth is reshaping power distribution
- Shift to DC-based distribution
- µ-grids with distributed energy resources (DER)

Smart power distribution

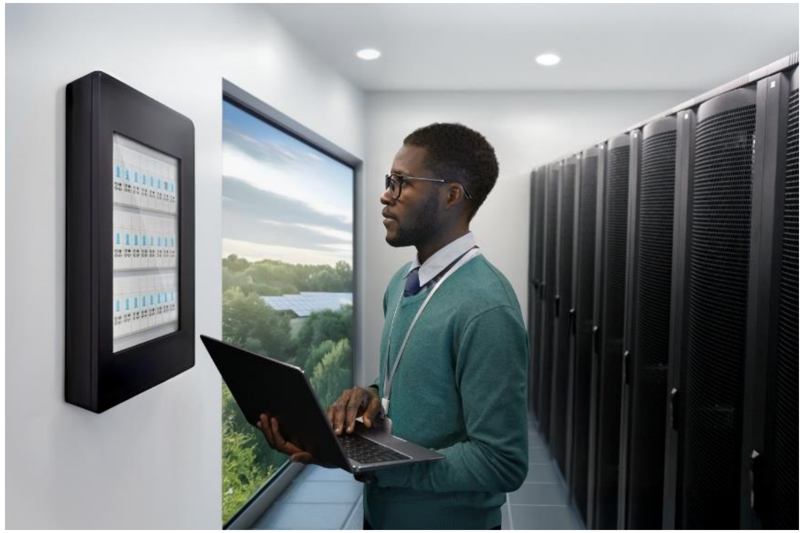
These segments primarily require smart power distribution: Efficiency, reliability and availability as key technology drivers

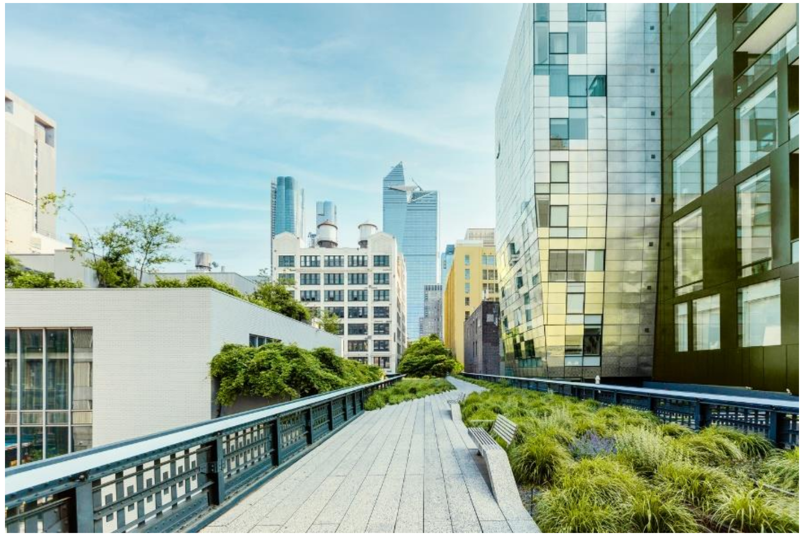







These segments primarily require smart power distribution: Efficiency, reliability and availability as key technology drivers





Megatrends and market drivers

- Decarbonization
- Digitalization
- Electrification
- Sustainability
- Cost of energy
- Grid availability and stability

Smart power distribution

- Maximize system availability
- Leverage power consumption (Peak power control)
- Improve efficiency
- Enable µGrids with distributed energy resources (DERs)
- DC-Distribution

Key enabler

- Smart power distribution device

Power distribution going smart: Smart circuit breakers integrate multiple functions into a single device

Monitoring and connectivity

- Real-time monitoring of load/supply condition
- Connectivity to Power Domain Controller
- Advanced smart billing concepts
- System optimization using AI
- State-of-health diagnostics of connected loads
- Embedded security solution

Protection

- Overcurrent and overload protection
- Programmable, accurate tripping characteristics
- AC and DC switching capability
- Arc-fault detection and interruption (AFDD, AFCI)
- Residual current/ground fault protection (RCD, GFCI)

Actuation

- Safe, reliable and wear-free actuation of branches
- Real-time, remote controllability
- AC and DC switching capability
- Zero-voltage and zero-current switching capability
- Smart power balancing, peak power control

Compatibility

- Compliance to applicable IEC60947 (-10) standard
- Backward compatibility to existing infrastructures (AC) and loads
- Enablement of new distribution systems (DC)
- Compatible form factor to legacy installations

Solid-State Power Distribution: Feature enhancements vs. traditional electromechanical implementations

Improved tripping characteristics	– Low-tolerance trip band to reduce tolerance stack up (wiring, selectivity) – High accuracy tripping for DER systems. (Inverter shutdown) – Digital power: software defined trip characteristic/ampacity – Faster tripping for grids with high PSCC and low residual reactance
Arc-free operation	– Operation in critical areas (e.g. IT-space) – Wear-free switching. – Increased MTBF, high system availability.
Accurate switch control	– Smart switching features (ZCS, ZVS, phase control) – Inrush current management – Grid/phase synchronization, pre-charging
Smartness and connectivity	– Load monitoring – Grid forming/power balancing features – SOH monitoring – Remote control and diagnostics, auto-recovery

Solid-State Power Distribution application examples: Industrial, AI data center, automotive

Industrial
Solid-State Circuit Breaker (SSCB)

- Programmable trip characteristic
- AFDD/GFCD (optional)
- Actuator/VS/ZCS
- Monitoring functions (V/I/THD/SOH)
- Communication

Industrial
Motor Soft Starter

- Circuit breaker and disconnector
- Startup controller
- Motor protection
- Load SOH monitoring
- Communication

Industrial
DC Circuit Breaker

- Programmable trip characteristic
- AFDD/isolation monitor
- Actuator w/ pre-charge function
- Monitoring functions (V/I)
- Droop control
- Communication

Industrial
µGrid Sync Device

- Circuit breaker and disconnector
- Synchronization monitor
- Fast connection unit
- Communication

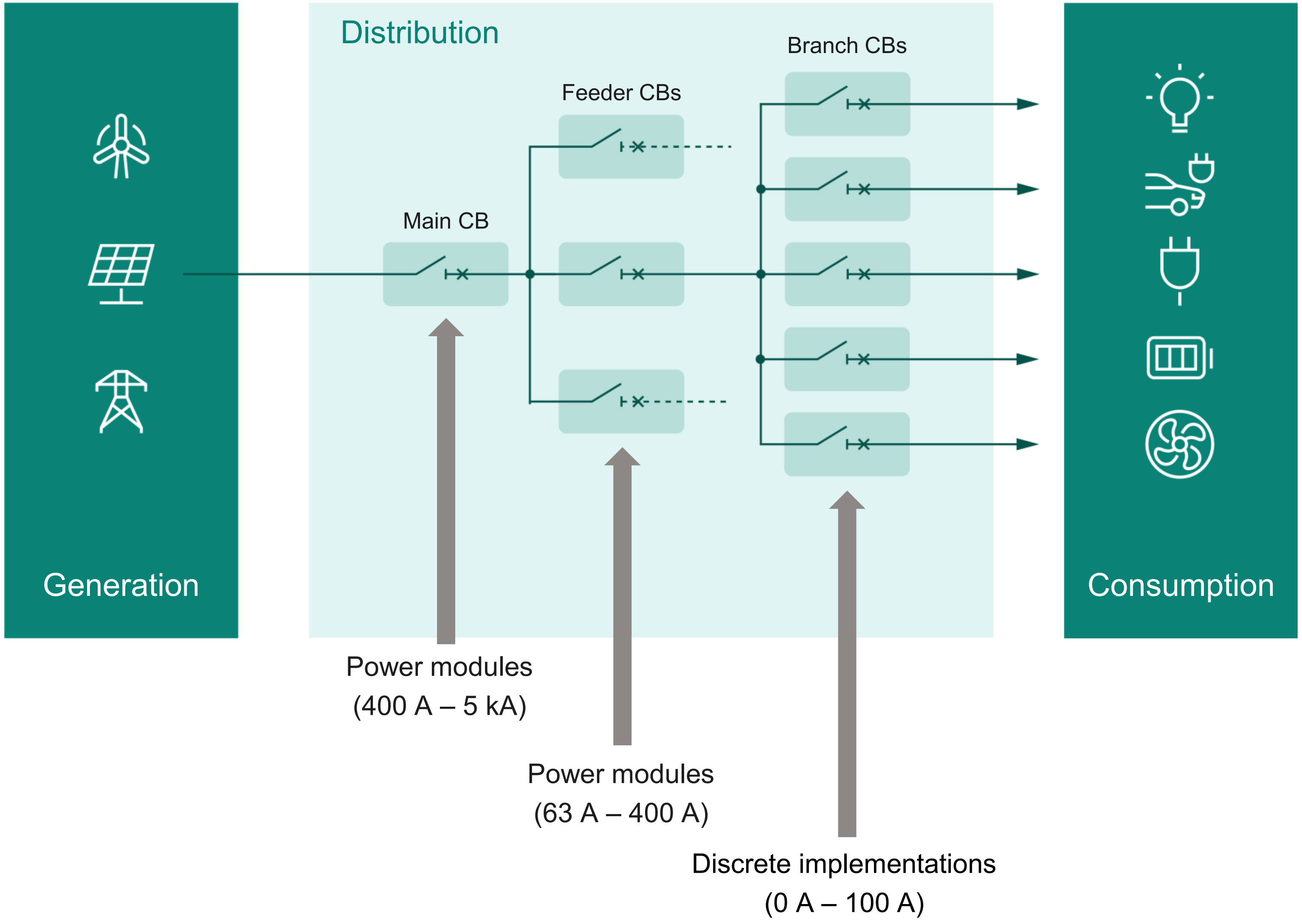
Data center
Power Distribution Unit (AC/DC)

- Programmable trip characteristic
- AC/DC compatibility
- Monitoring functions (SOH, i^2t)
- Communication

ATV/IND
eFuse (ATV/IND) + Battery Main Switch

- Programmable trip characteristic
- Pre-charge unit w/ re-closing function
- Monitoring functions (SOH, i^2t, FuSa)
- Communication

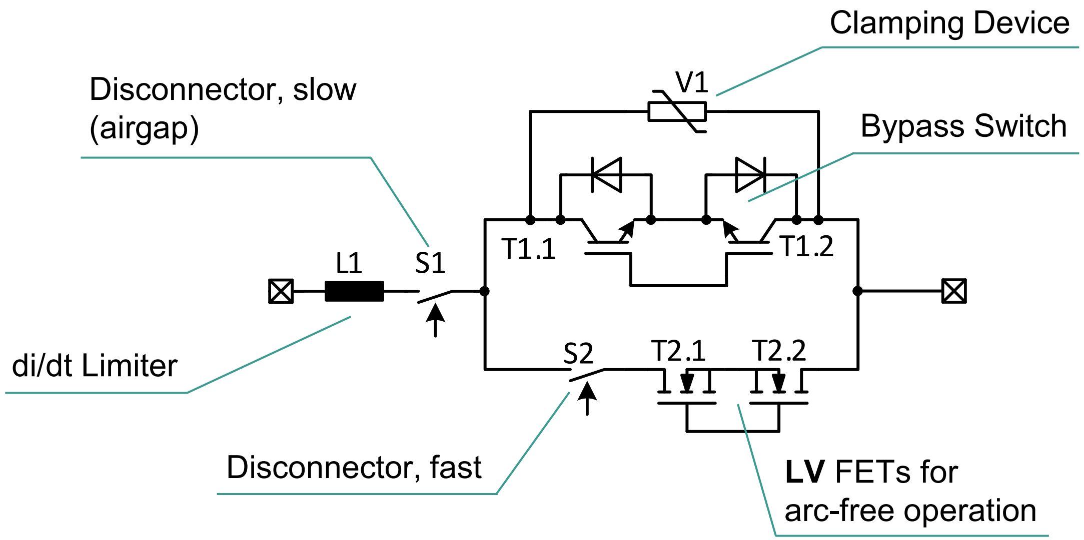
Power distribution topology:
SSCBs combine all required functions into one single device



- Industrial power distribution systems typically feature 2 to 3 stacked layers with increasing current levels.
- While branch CBs can be implemented using discrete devices, feeder and main CBs will be based on power modules.
- The rollout of SSCB solutions starts from branch level.

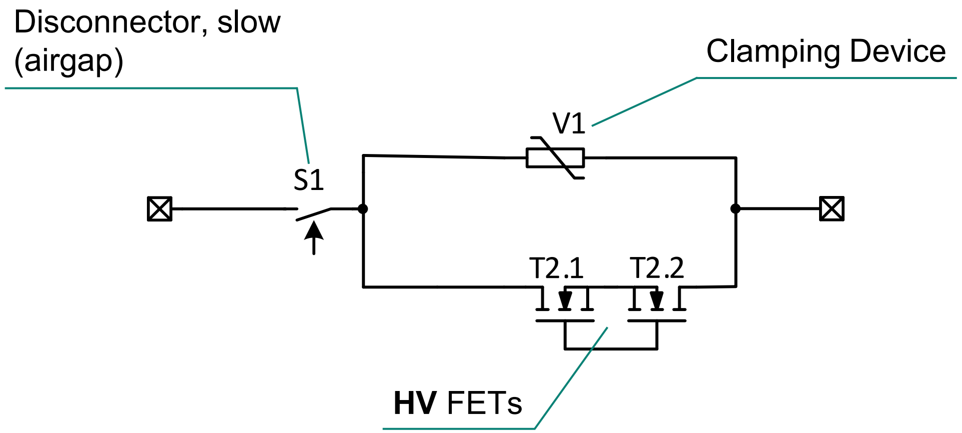
Power Stage: Hybrid implementations as complementary technology to full solid-state solutions

Hybrid Circuit Breaker



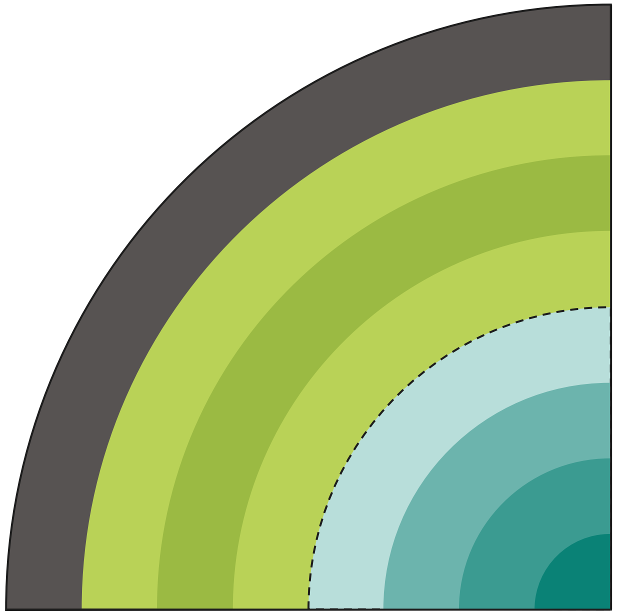
- Mechanical bypass enables high current (> 200 A)
- High complexity setup
- Typical actuation time < 1 ms → d_i/d_t limitation required
- Power opportunities for
  - High current LV FETs (30 V, > 500 A)
  - High current IGBTs (750 V, 1.2 kV … 3.3 kV)

Solid-State Circuit Breaker



- Continuous current flow thru solid state switch
- Low complexity setup
- Typical actuation time < 2 µs
- Power opportunities for
  - Very low $R_{DS(on)}$, highly robust HV switches

Solid-State Relay vs. Solid-State Circuit Breaker: Different levels of function integration



SCADA Functions (Control, Monitoring)

End User Protection (RCD)

Advanced Circuit Protection (e.g., AFDD)

Basic Circuit Protection (OCD, Thermal)

Output Fault Isolation & Reporting

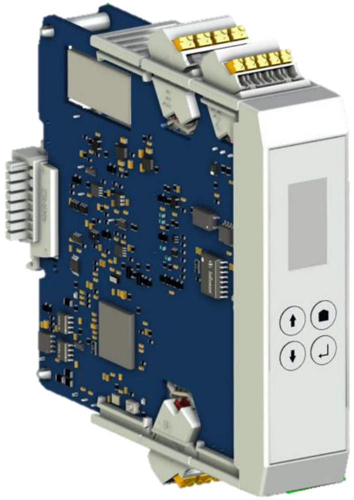
Self Protection

Advanced Actuation (Phase Control)

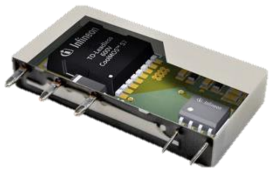
Basic Actuation

Solid-State Relay (SSR)

Solid-State Circuit Breaker (SSCB)

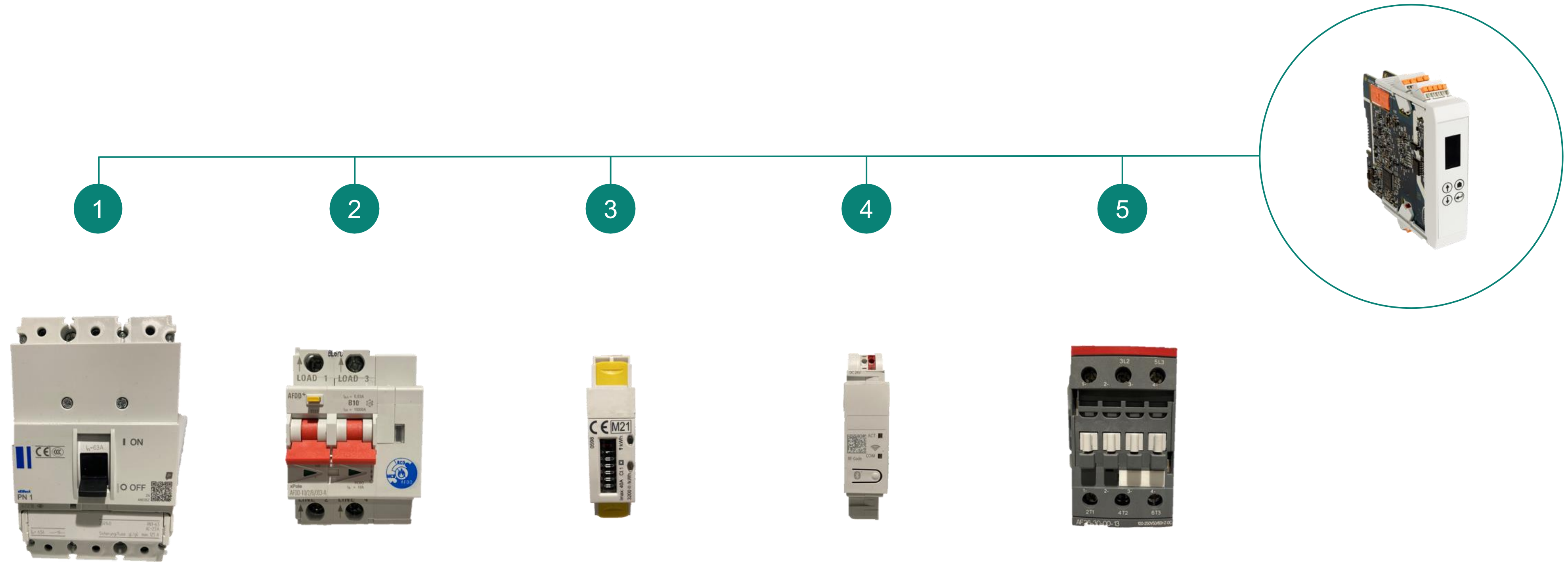


Solid-State Circuit Breaker



Solid-State Relay

Power distribution going smart: Smart circuit breakers integrate multiple functions into one single device



Protect | Arc detect | Measure | Connect | Act

Smart circuit breakers integrate multiple functions into one single device	Encompasses a wide range of components adapted to specific system requirements	Compact, reliable, and cost-effective solid-state solution

Solid-State Circuit Breakers

- Offers secure web/IoT connectivity
- Combine protection, load control, diagnostic and metering in one single device

- Provide noise-less and wear-free load switching with real-time control capability
- Support OCP, AFDD/AFCI and RCD/GFCI – all in one

- Support smart billing, even for sub-branches
- Provide state-of-health diagnostics of connected loads

- Can be applied for AC and DC grids
- Enable smart power balancing and control of peak loads

- Support ZVS and ZCS for smart and soft switching
- Compile with industrial certification standards

- Enable remote load control and diagnostic in real time
- Match the form factor of today's MCBs

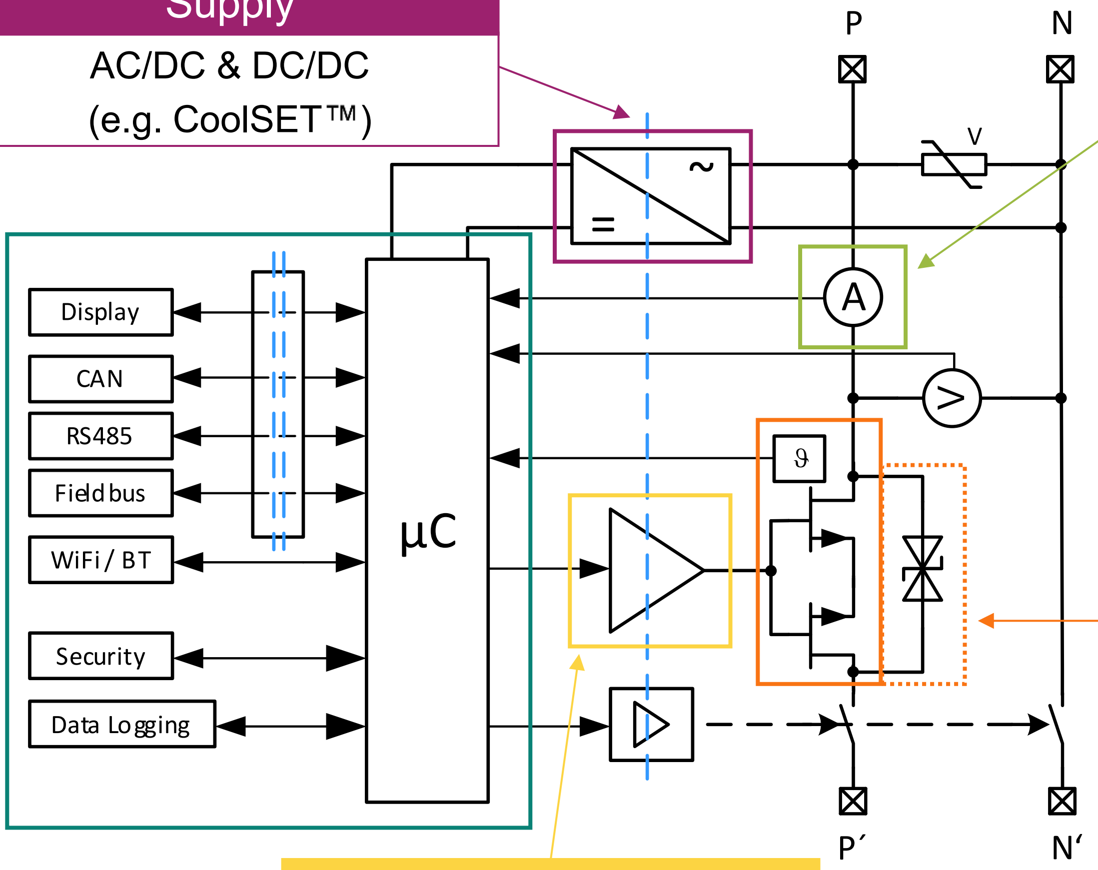
Solid-State Circuit Breakers from a system perspective: Semiconductor solutions overview

µC
Comm
Memory

Microcontroller + Connectivity + Security + Memory (e.g. PSoC™, XMC™ ISOFACE™ EXCELON™ F-RAM)

Supply

AC/DC & DC/DC (e.g. CoolSET™)



Sensing

I / V / ϑ - Sensing (e.g. XENSIV™)

Power stage

Clamping & Protection Solution w/ companion devices

Power Switch
(e.g. CoolMOS™, CoolSiC™)

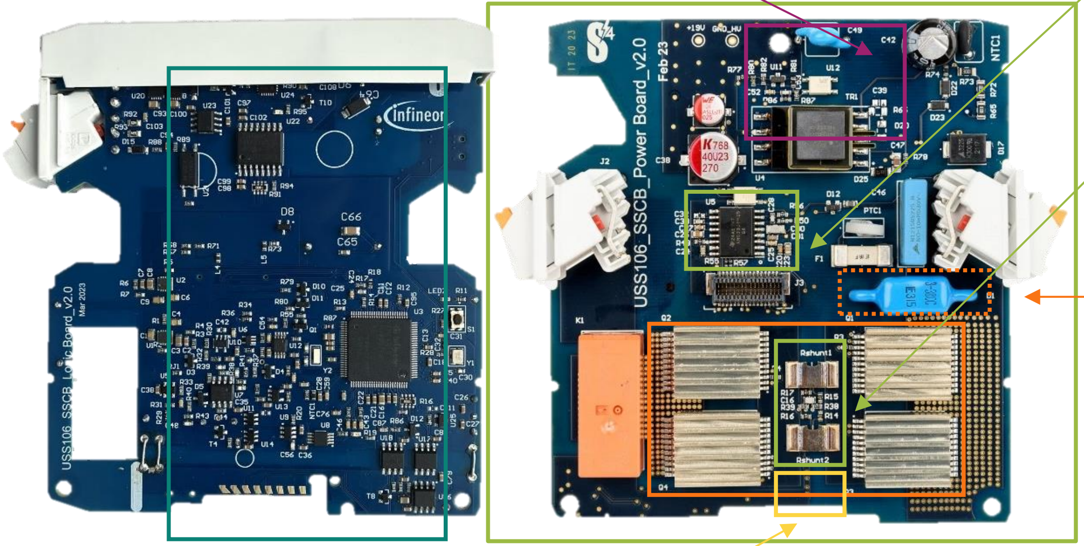
Control

Gate-Drivers (e.g. EiceDRIVER™)

Security

Security (OPTIGA™)

Solid-State Circuit Breakers from a system perspective: Semiconductor solutions overview



µC
Comm
Memory

Microcontroller + Connectivity + Security + Memory (e.g. PSoC™, XMC™ ISOFACE™ EXCELON™ F-RAM)

Supply

AC/DC & DC/DC
(e.g. CoolSET™)

Sensing

I / V / ϑ - Sensing
(e.g. XENSIV™)

Power stage

Clamping & Protection Solution w/ companion devices

Power Switch
(e.g. CoolMOS™, CoolSiC™)

Security

Security
(OPTIGA™)

Control

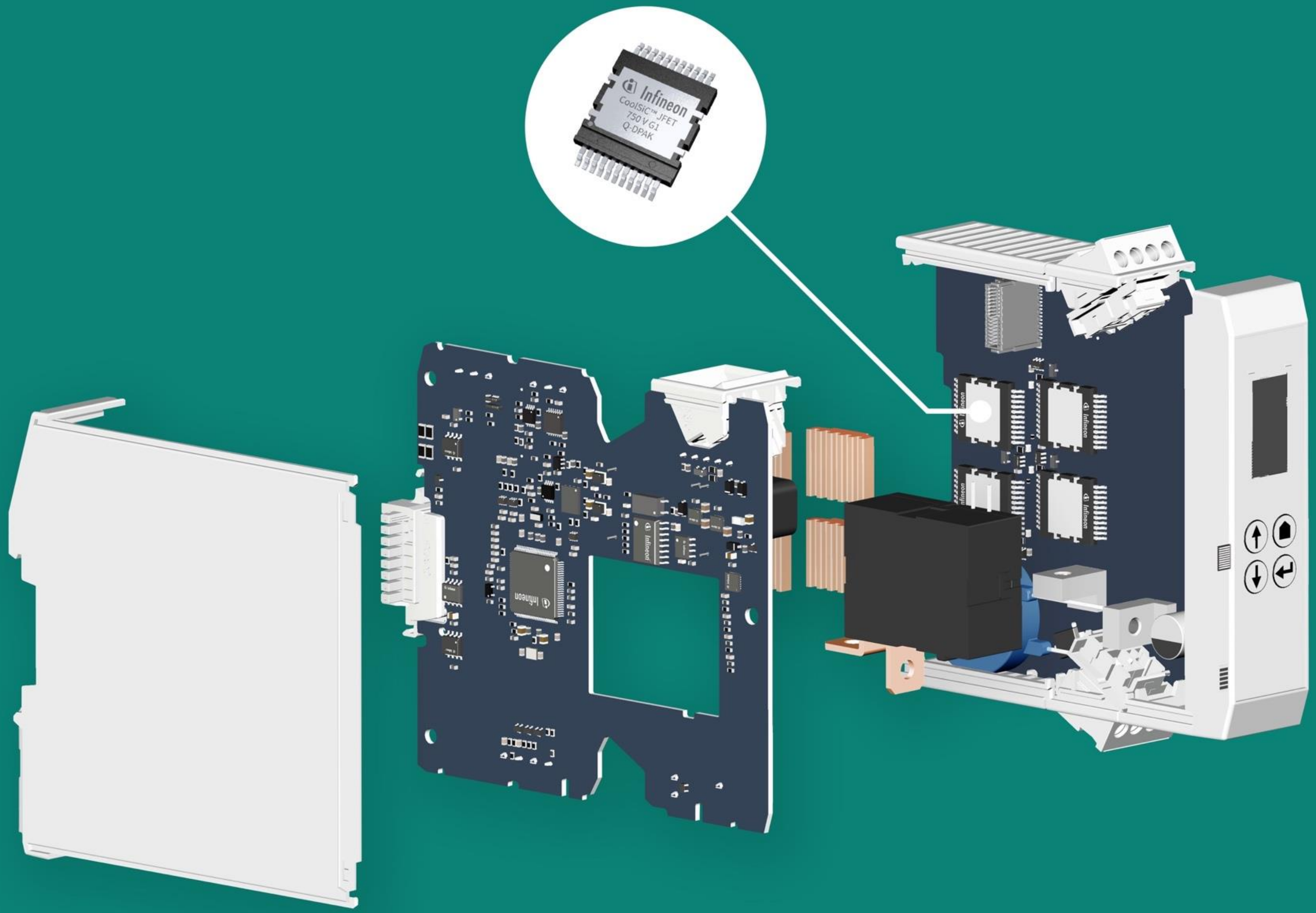
Gate-Drivers
(e.g. EiceDRIVER™)

System understanding is the solid basis for our solution path: SSCB demonstrator

Efficient kit for AC-DC solid state circuit breaker evaluation: REF_SSCB_AC_DC_1PH_16A
Efficient kit for AC-DC solid state circuit breaker evaluation: REF_SSCB_AC_DC_1PH_SIC

CoolSiC™ JFET

CoolSiC™ JFET technology is designed to unlock efficiency and sustainability in power solutions, enabling a greener tomorrow



CoolSiC™ JFET: The heart of HV Solid-State Power Distribution

Energy savings

Provides ground-breaking ultra-low $R_{DS(on)}$ 1.6 mΩ at 750 V and 2.3 mΩ at 1200 V V_{BDss}

Integration and scalability

Developed for ease-of-integration, scalability and manufacturability for industrial and automotive applications

Robustness and reliability

Designed and tested to handle the extreme over-voltage, over-current and short-circuit conditions

Applications

- SSCB
- Data Center
- Battery disconnect
- eFuses and SSR

Infineon's new CoolSiC™ JFET 750 V / 1200 V discrete portfolio

CoolSiC™	$R_{DS\ (on,typ)}$ [mΩ]	Q-DPAK
750 V	**1.6**	**IJCQ75RM16J1** BiC
	2.2	IJCQ75RM22J1
	4.1	IJCQ75RM41J1
1200 V	**2.3**	**IJCQ120RM23J1** BiC
	2.6	IJCQ120RM26J1
	5.0	IJCQ120RM50J1
	6.1	IJCQ120RM61J1

Battery disconnect

Solid State Motor Soft Starter

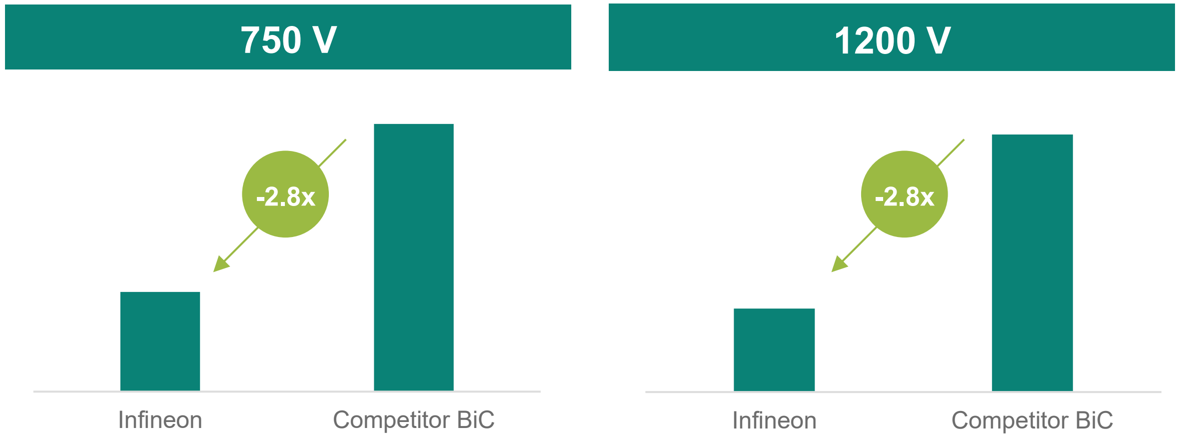
eFuses and SSR

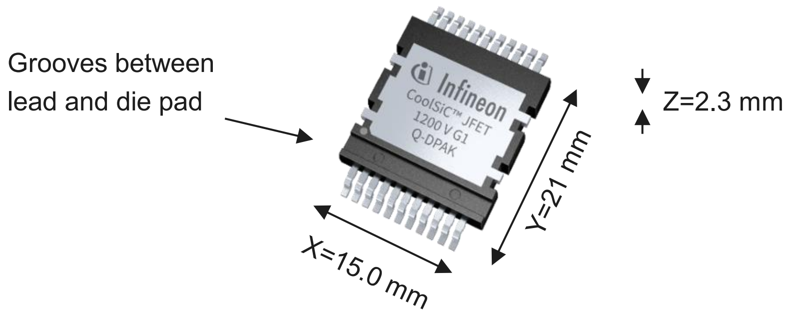
Hot swap

SSCB

New CoolSiC™ JFET technology achieving **industry-leading lowest $R_{DS(on)}$ per device**

$R_{DS\ (on,typ)}$



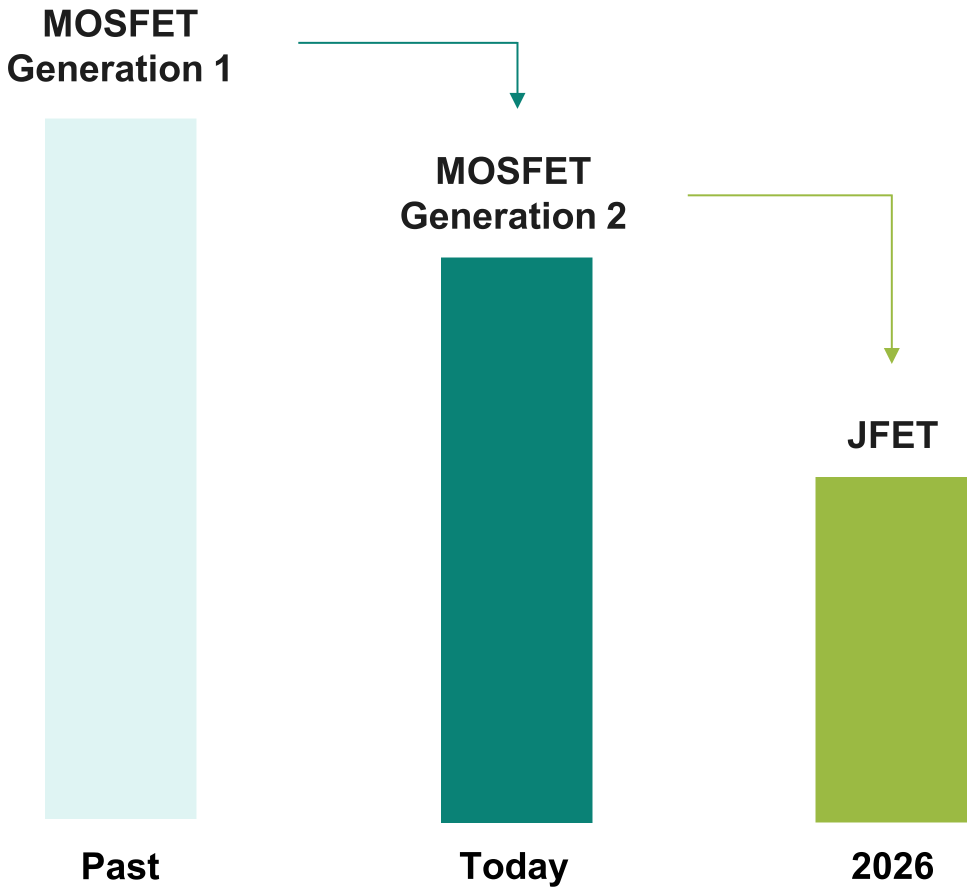


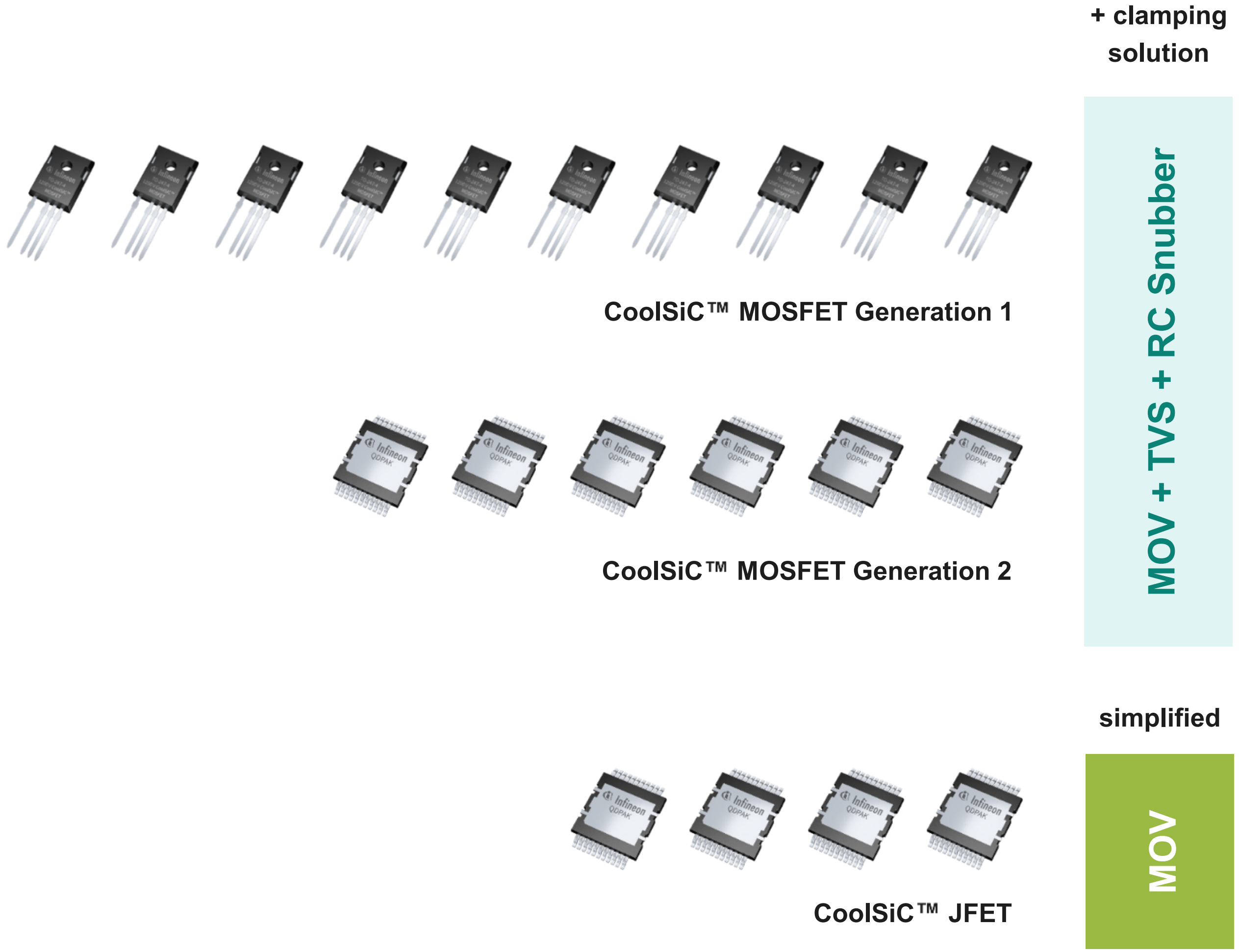
BiC: Best-in-class

Disclaimer: $R_{DS(on)}$ values and part numbers are subject to finalization

CoolSiC™ JFET: Leading competitiveness and miniaturization of smart power distribution solutions

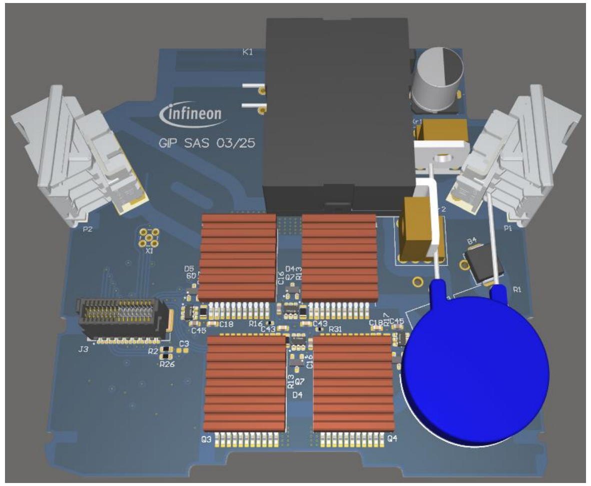
Ron_{hot} x € FOM Scaling of 1,200 V / 750 V SiC FET Technologies
T_j = 105°C

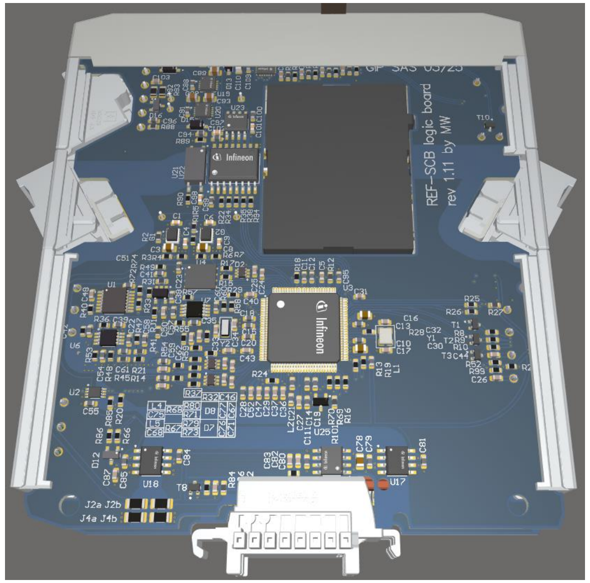




Estimated number of power semiconductor required per pole for 32 A SSCB

SSCB Demonstrator: Feature overview & implementation





Demonstrator target ratings

- V_{nom}: 230 V_{AC} / 400 V_{DC} or 400 V_{AC} / 700 V_{DC}
- I_{nom}: 60 A
- Topologies:
  - 1P - N,
  - 3P - N (stacked, cascaded)
  - L+ - L-
  - Cooling: non-isolated passive, integrated

Implementation

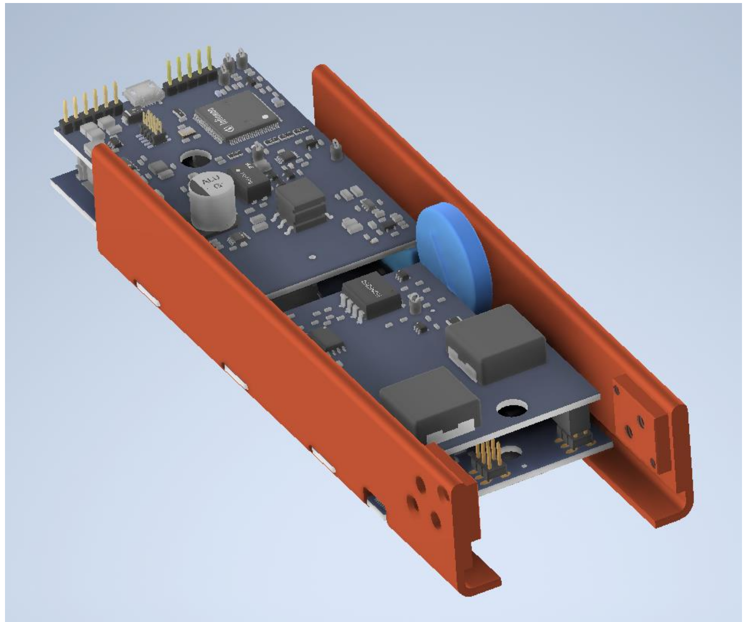
- Output Stage: Q-DPAK
  - Topology: 2s x 2p
  - Technologies:
    - CoolSiC™ JFET 1200 V / 2.5 mΩ
    - CoolSiC™ JFET 750 V / 1.6 mΩ
- Clamping: TVS / MOV (L-L‘; L-N)
- Xensiv™ TMR Current Sensor TLE5571
- Mechanical separation contact: bistable relay
- µC: XMC4500

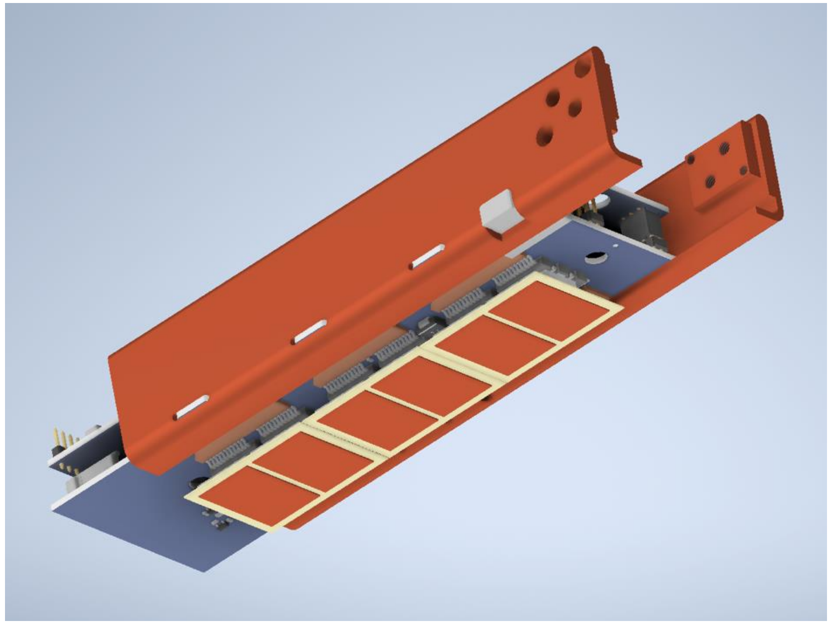
Protection and control features

- Protection Schemes
  - Overload, user programmable
  - Overcurrent, user programmable
- Actuation
  - ZVS, ZCS
- Measurements
  - V_{in}, V_{out}, I_{load}, PF, THD, FFT, T_j
- Communication Interfaces
  - CAN (isolated, frontside)
  - UART (isolated, backplane)
  - INH IO

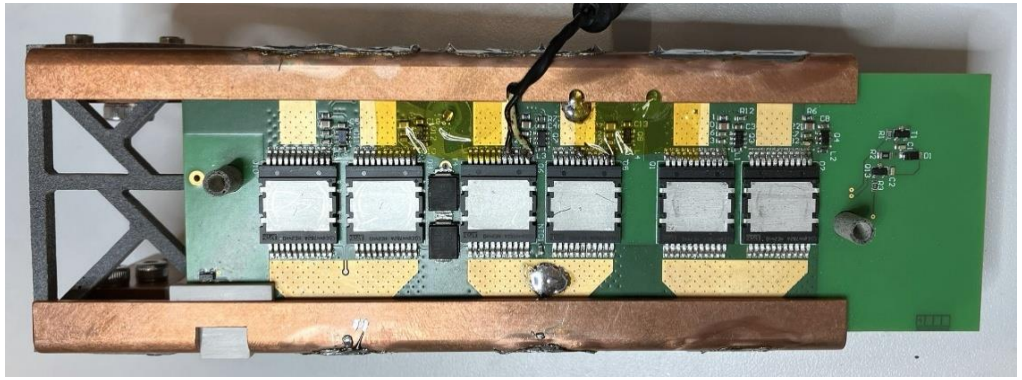
Solid-State Battery Disconnect (SSBD) demonstrator: CoolSiC™ JFET Q-DPAK

- Current in / out connections on same side
- Improved sensing structure (R_{insert}< 1 µΩ)
- Increased cross-section of busbars (120 mm²)
- Dimensions: 60 x 40 x 192 mm





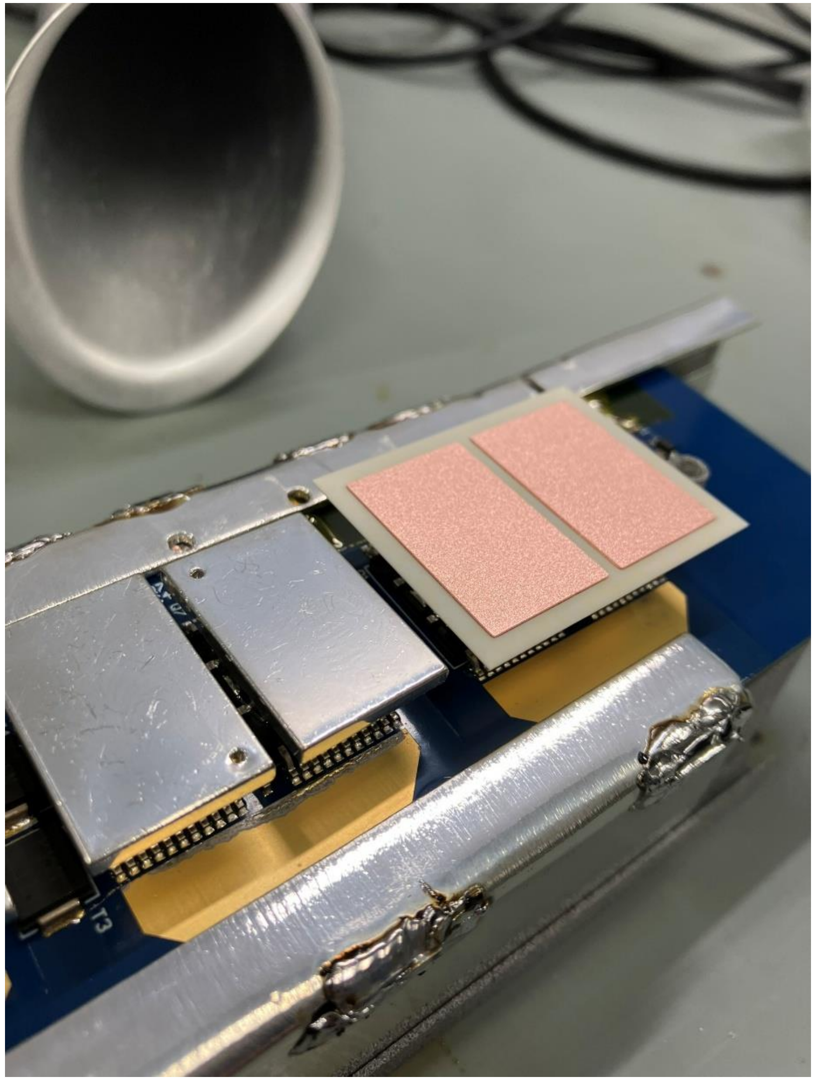
SSBD demonstrator: CoolSiC™ JFET Q-DPAK

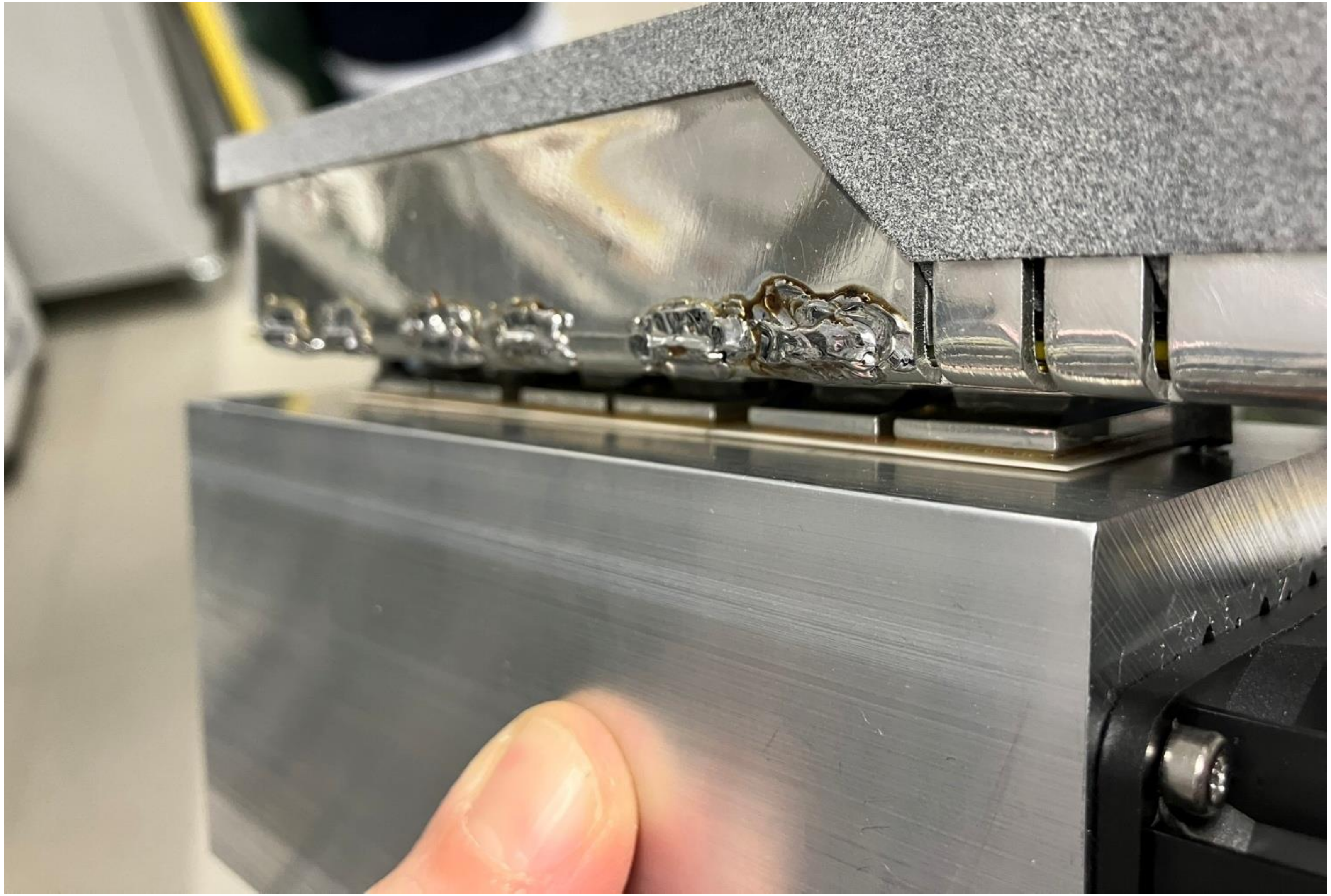


Voltage	< 850 V DC	Unipolar blocking
Current	800 A(*) DC	Water cooling
Additional Features	– Voltage and current measurement – Software defined trip characteristic – Fast short circuit shut down – Pre charger (optional)	
Product	6 x IJCQ120RM23J1	
$R_{DS(on)}$	730 µΩ @ 25C	Total resistance
Technology	JFET	1200 V
Temperature	-40 °C ... 85 °C	Ambient
Dimensions	204 x 62 x 41 mm	l x w x h
Connection	25 x 5 mm²	Busbar – screw connection

(*) simulated, to be confirmed

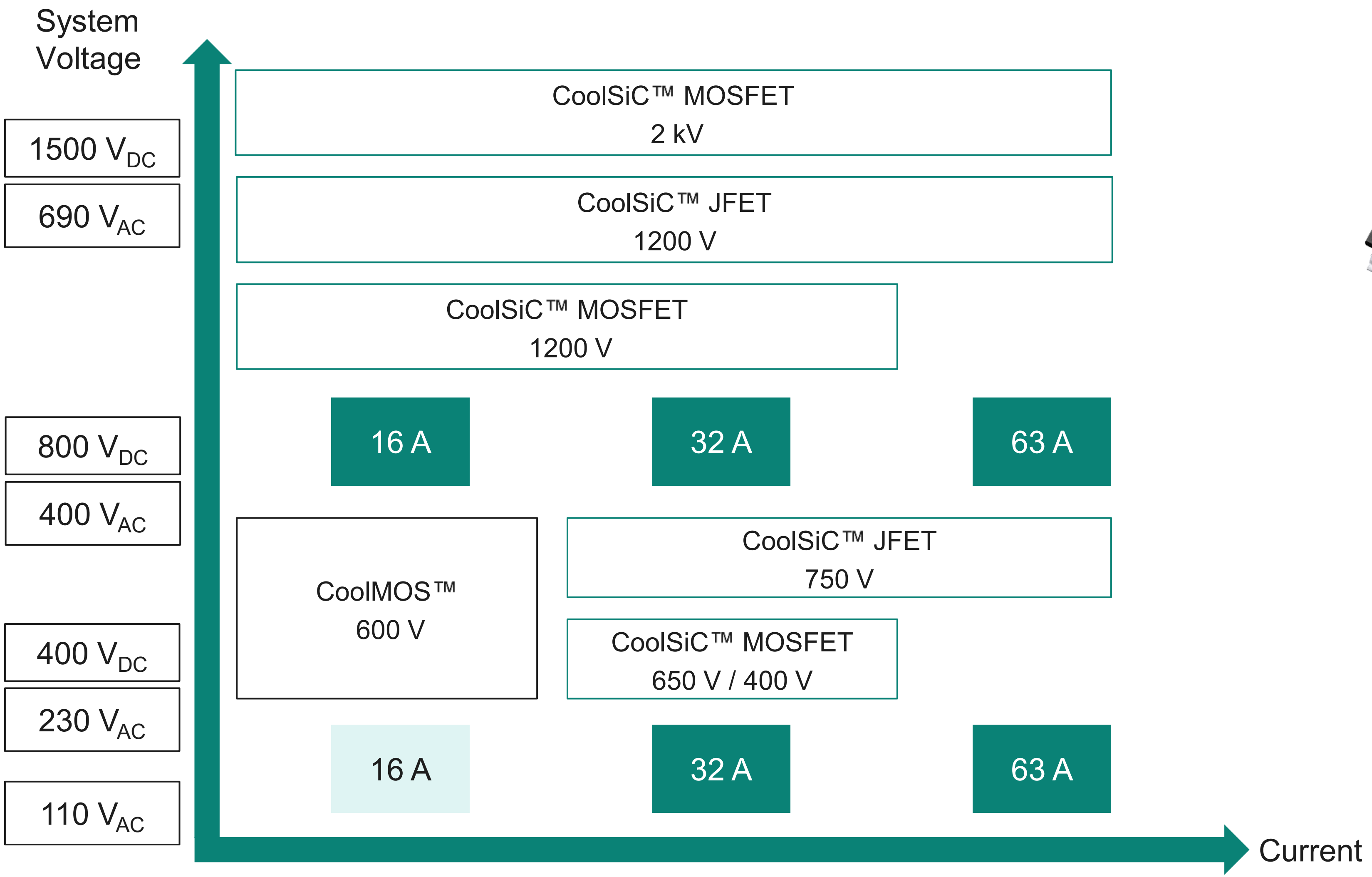
SSBD demonstrator: CoolSiC™ JFET Q-DPAK

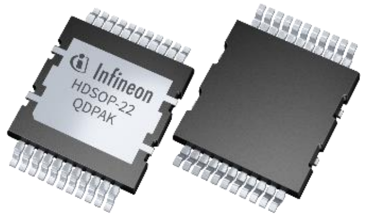




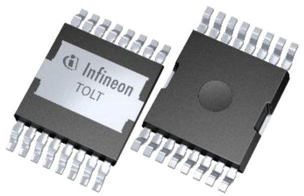
Infineon's offering for Solid-State Circuit Breakers

Solid-State Circuit Breakers focus areas: Complementary discrete and power module portfolio



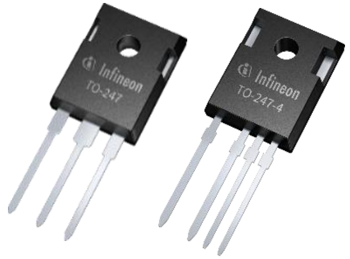


Q-DPAK



TOLT

D2PAK-7



TO-247

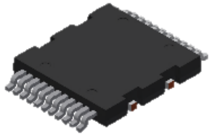
600 V CoolMOS™ S7 and CoolMOS™ 8

- Best-in-class $R_{DS(on)}$ in the SJ MOSFET market
- Reduced conduction losses to reach higher efficiency
- Improved thermal resistance

Learn more

600 V CoolMOS™ S7/S7T

600 V CoolMOS™ 8

$R_{DS(on,max)}$ [mΩ]v	 TO220	 TOLL	 QDPAK TSC	 QDPAK BSC	TO247-3	TO247-4
65	IPP60R065S7	IPT60R065S7	IPDQ60R065S7	-	-	-
37-40	IPP60R040S7/ IPP60R037CM8	IPT60R040S7/ IPT60R037CM8	IPDQ60R040S7/ IPDQ60R037CM8	IPQC60R040S7	IPW60R037CM8	IPZA60R037CM8
22	IPP60R022S7	IPT60R022S7	IPDQ60R022S7	-	-	-
16-17	IPP60R016CM8	IPT60R016CM8	IPDQ60R017S7/ IPDQ60R016CM8	IPQC60R017S7	IPW60R016CM8	IPZA60R037CM8
7-10	-	-	IPDQ60R010S7/ IPDQ60R007CM8	IPQC60R010S7	-	-

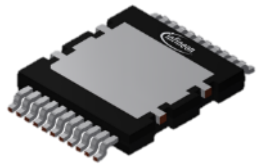
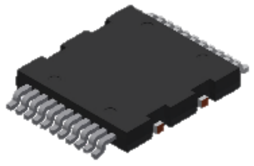
CoolMOS™ 7
CoolMOS™ 8

600 V CoolMOS™ S7T with integrated temperature sensor

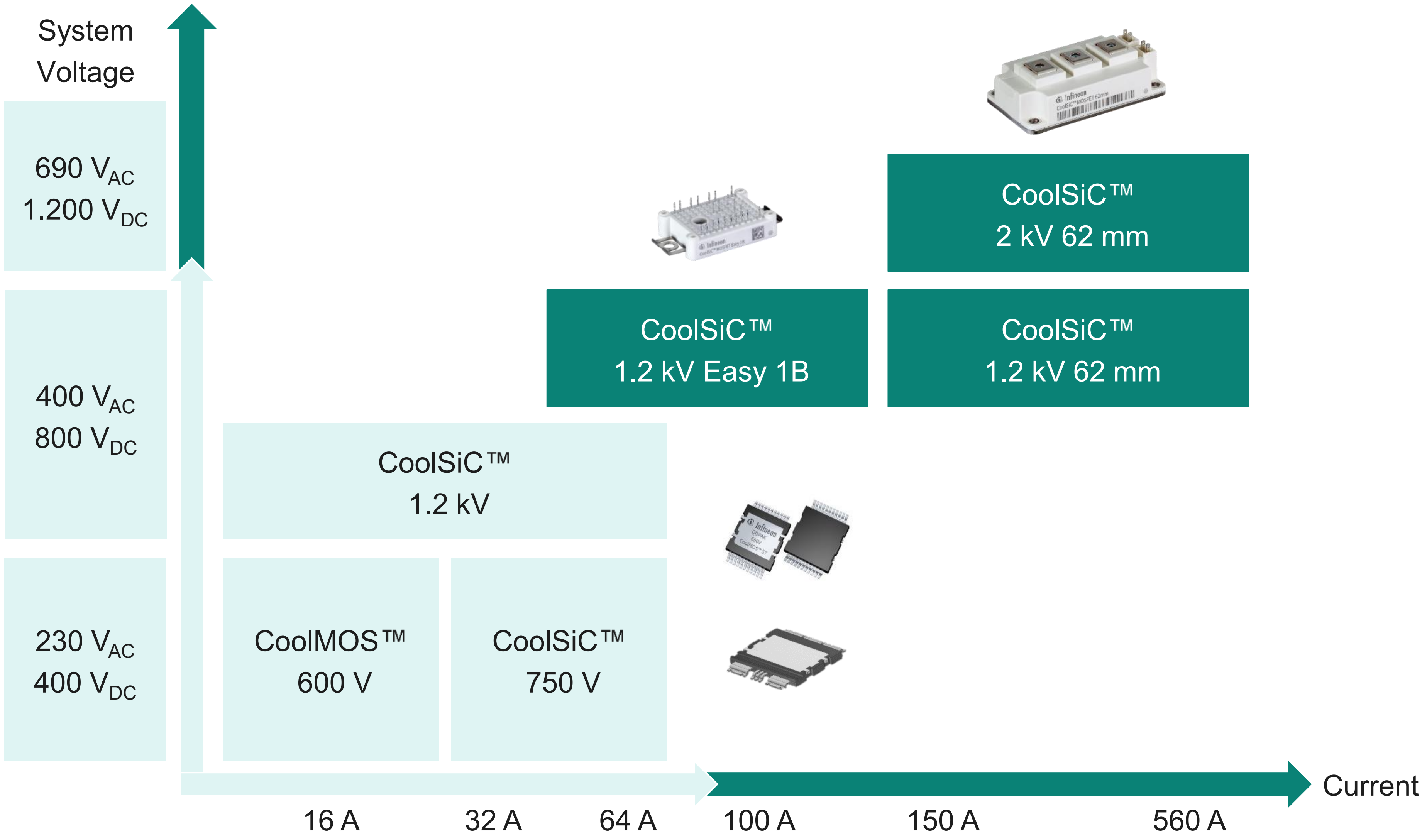
- S7T is the S7 variant with a monolithically embedded temperature sensor
- S7T enables easy integration, lower overall system complexity and reduces system cost.

Learn more

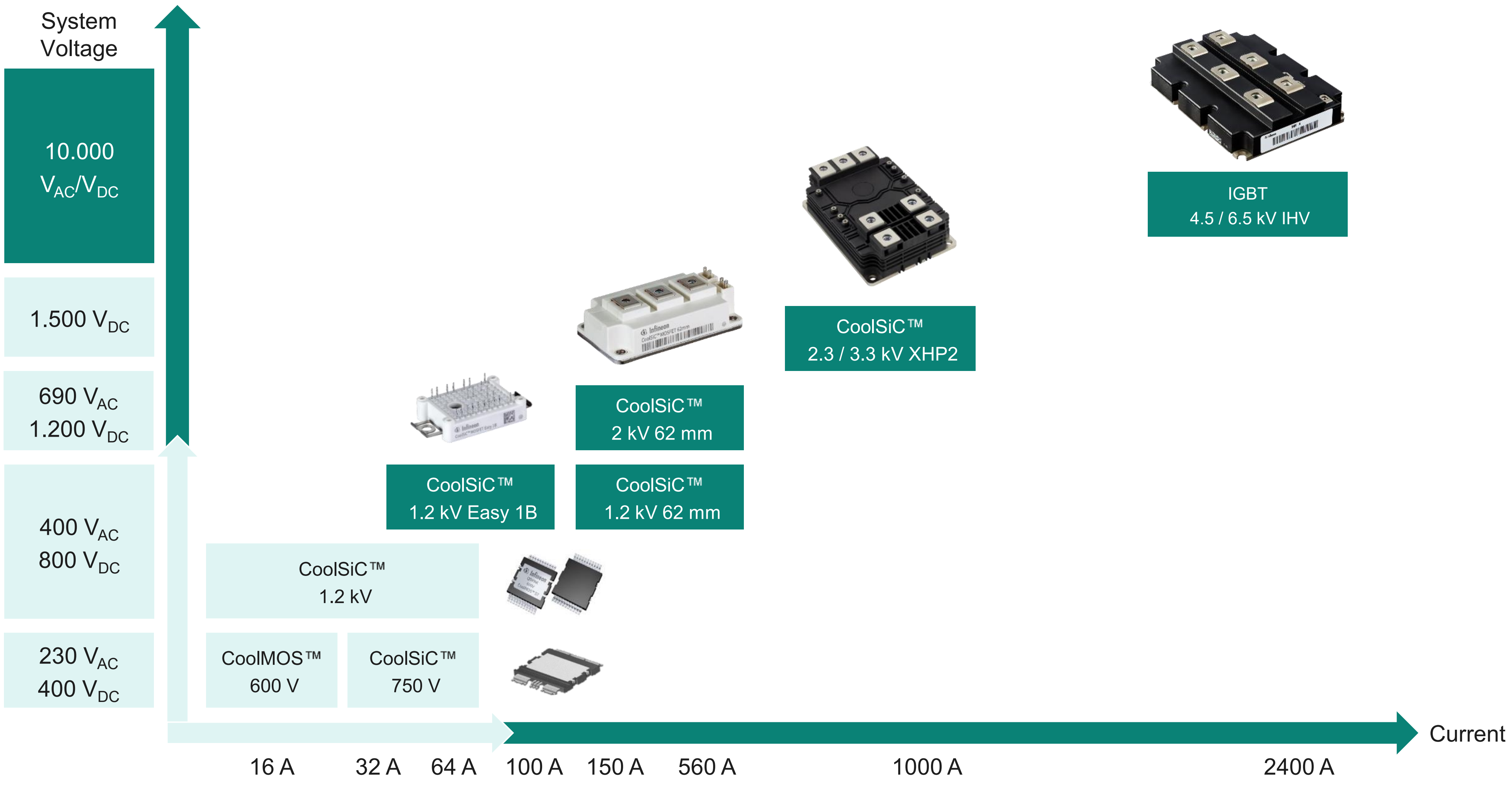
600V CoolMOS™ S7/S7T

$R_{DS(on,max)}$ [mΩ]	 TOLL PG-HSOF-8	 QDPAK TSC PG-HDSOP-22-1	 QDPAK BSC PG-HDSOP-22-101
65	IPT60T065S7	-	-
40	IPT60T040S7	-	-
22	IPT60T022S7	IPDQ60T022S7	IPQC60T022S7
17	-	IPDQ60T017S7	IPQC60T017S7
10	-	IPDQ60T010S7	IPQC60T010S7

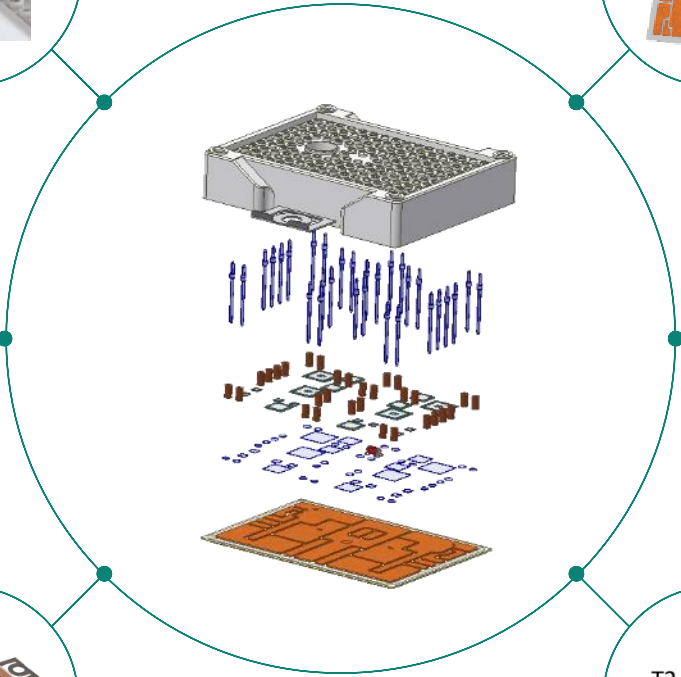
Solid-State Circuit Breakers focus areas:
Complementary discrete and power module portfolio



Solid-State Circuit Breakers focus areas: Complementary discrete and power module portfolio

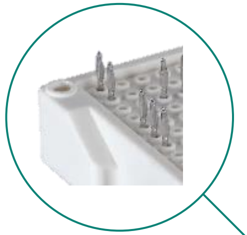


Features and benefits of module designs

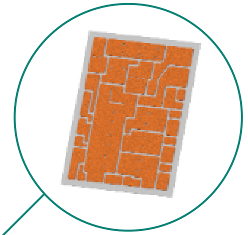


Press-FIT pins

- Reliable contact to PCB
- Very low contact resistance (approx. 0,05 mOhm)
- High volume production capability



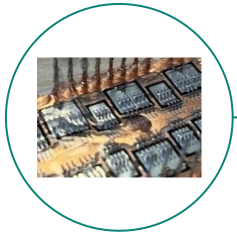
DCB substrate



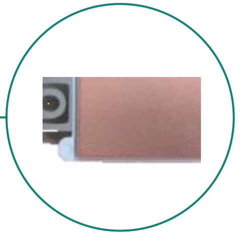
- Low inductive electrical routing
- Heat spreading prevents thermal run-away

Potting gel

- Enclosure of dies in potting gel improving pollution protection
- Reduced creepage distances
- Increased power density



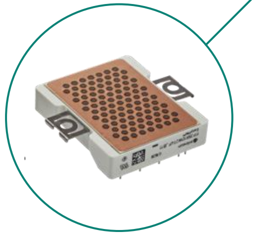
Integrated isolation



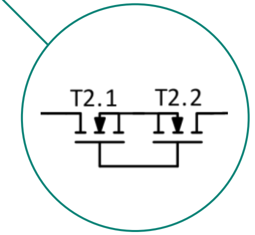
- High thermal conductance
- No additional isolation foil needed
- No gap filler due to very small cavity (< 80 µm)

Pre-applied thermal interface material (optional)

- Reliable handling of high-power losses
- No on-site TIM-Line necessary
- High volume production capability



Flexibility in topologies



- Preset topologies according to customer-specific requirements
- Flexible pin-grid
- Pre-tested, validated and qualified

IGBT technology in Easy packages enable flexible and cost-efficient layouts for compact system designs

Easy 1B and Easy 2B enable **cost-efficient solutions based on IGBT technology**

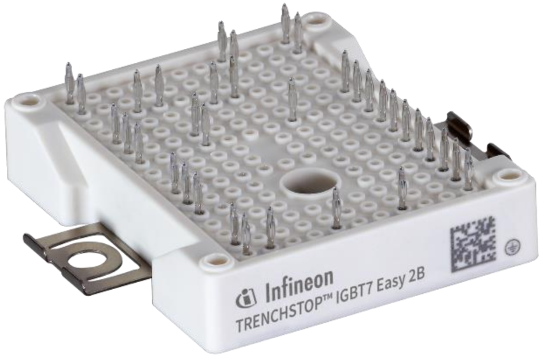
Shortflow capability for **fast adaption of topologies, pinouts and layouts**

Easy packages enable **compact system designs** and a high degree of **automation in production**

High SC capability of appr. **4 x I_{nom}** (IGBT) and appr. **10 x I_{nom}** peak current capability (Diode)[1]

[1]Data based on 1200V, 100A, IGBT7 and EC7 diode. Exact values depending pulse timing and operation temperatures. Reference datasheet: FS100R12W2T7

Easy 1B



Easy 2B

Available and released common-emitter modules

Product	V_{CES} [V]	$I_{C,nom}$ [A]	I_{CRM} [A]
FF75R12W1T7E_B11	1200	75	150
FF100R12W1T7E_B11	1200	100	200
FF150R12W2T7E_B11	1200	150	300
FF200R12W2T7E_B11	1200	200	400
Ff300R12W2T7E_B11	1200	300	600

Best-in-class CoolSiC™ MOSFET common-source modules ensure scalability in power classes with low conduction losses

Increasing voltage and current levels increase the **potential for module solutions**
- High level of parallelization feasible
- Thermal connection to heatsink with or without baseplate
- Isolated substrate by integrated ceramic

1200 V and 2000 V **common-source modules in rollout** for industrial applications

Wide range portfolio allow **holistic framesize planning** and scalability of power classes

Easy 1B 1200 V modules

- 1200 V CoolSiC™ MOSFET module available
- Common-Source topology
- R_{dson} = 7 … 17 mΩ
- I_{nom} = 50 ... 120 A

62mm 1200 V and 2000 V modules

- 1200 V and 2000 V CoolSiC™ MOSFET rollout ongoing
- Common-Source topology
- R_{dson} = 1.6 … 5.5m Ω
- I_{nom} = 180 ... 560 A

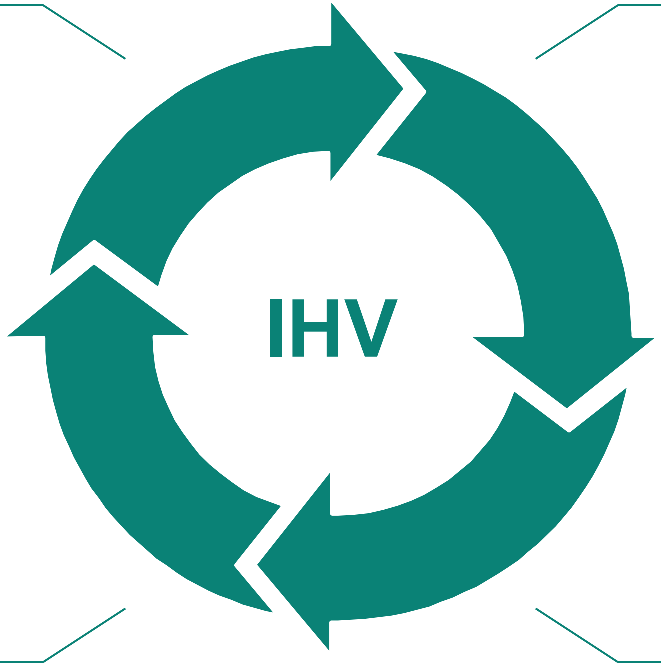
CoolSiC™ MOSFET common-source module portfolio rollout

Product	V_{DSS} [V]	$R_{DS,on}$ @ 25°C [mΩ]	I_{nom} [A]	I_{DRM} [A]
FF17MR12W1M1H_B17	1200	16.2	50	100
FF7MR12W1M1H_B17	1200	5.8	120	240
FF6MR12KM1H_S	1200	5.5	180	360
FF3MR12KM1H_S	1200	3.2	280	560
FF2MR12KM1H_S	1200	2.1	420	840
FF1MR12KM1H_S	1200	1.6	560	1120
FF5MR20KM1H_S	2000	5.2	200	400
FF4MR20KM1H_S	2000	3.5	300	600
FF3MR20KM1H_S	2000	2.6	400	800

IHV modules are everywhere. Why?

Modules based on demanding application requirements

Modern semiconductor and housing technologies



Proven quality by decades of field operation of millions of modules

Highest reliability and robustness

IHV family

What is IHV?

Industrial **H**igh **V**oltage IGBT module

- IHV A: high isolation capability 10.4 kV (4.5 kV & 6.5 kV)
- IHV B: isolation capability 6.0 kV (3.3 kV & 4.5 kV)

Voltage class / current ratings

3300 V
- B: 825 – 2400 A

4500 V
- A: 400 – 1500 A
- B: 1200 – 1800 A

6500 V
- A: 250 – 1000 A

Configurations

- Single switch (FZ)
- Chopper (FD)
- Double diode (DD)

IHV A
4.5 & 6.5 kV

IHV B
3.3 & 4.5 kV

IGBT4 opens new horizons

IHV B modules with 15 years of field experience

IGBT3

FZ1000- & FZ1500R33HE3

- Well established technology in IHV B (3.3 kV)
  - Nominal current ratings up to 1500 A
  - Standard power cycling capability
  - Two housing sizes for different current ratings

IGBT4

FZ1600- & FZ2400R33HE4
FZ1200- & FZ1800R45HL4_S7

- 3.3 kV and 4.5 kV IGBT4 in IHV-B
- 60% power density increase
- Double power cycling capability for demanding applications (compared to IGBT3 and competition)

IHV A modules with 25 years of field experience

IGBT3

FZ250- & FZ500- & FZ750R65KE3
FZ800- & FZ120R45KL3_B5

- Well established technology in IHV A (6.5 kV & 4.5 kV)
  - Nominal current ratings up to 1200 A
  - Standard power cycling capability
  - Two housing sizes for different current ratings

IGBT4

FZ1000R65KE4
FZ675R65KE4

- 6.5 kV IGBT4 in IHV-A
- 35% power density increase
- Double power cycling capability for demanding applications (compared to IGBT3 and competition)

Infineon