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Virtual Testing of Overtemperature Protection Algorithms in Automotive Smart Fuses

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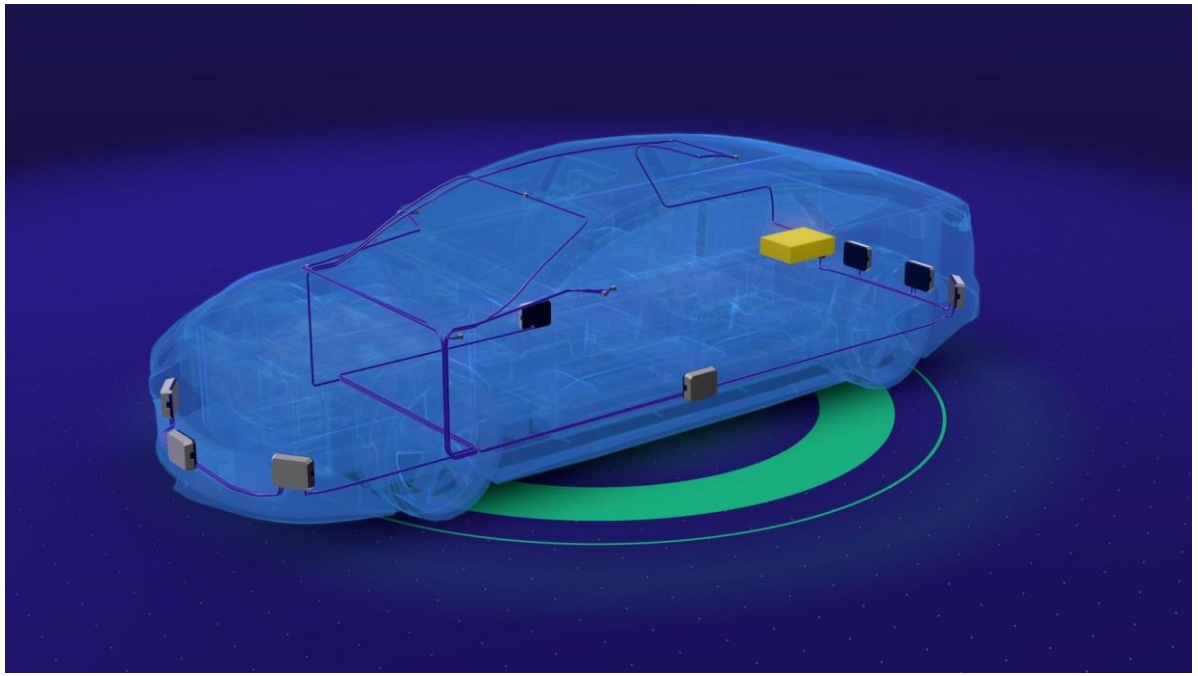
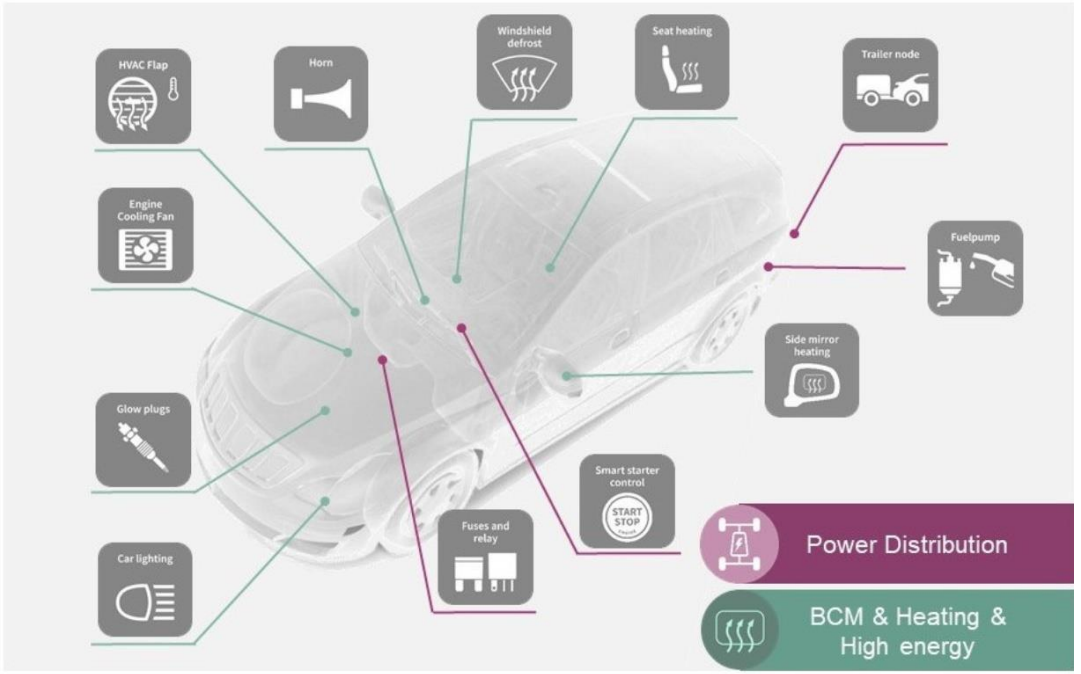
accellera SYSTEMS INITIATIVE

Introduction to Automotive Smart Fuses

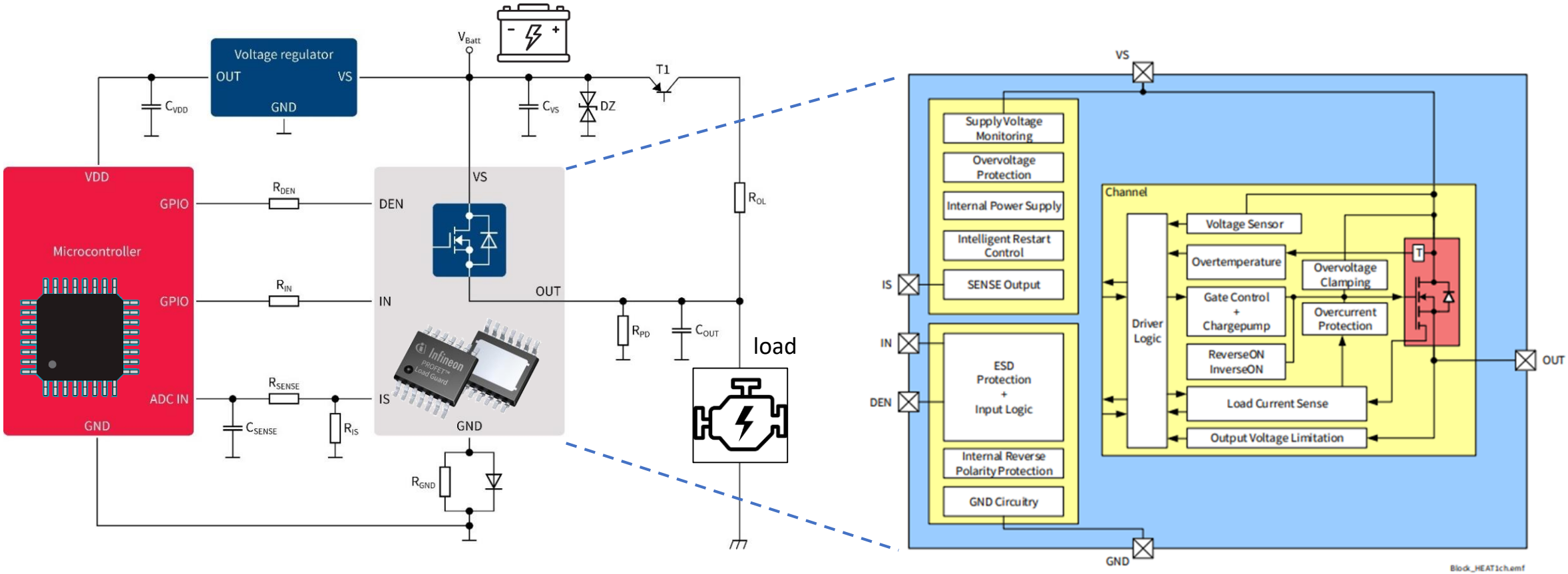


Source: CARIAD



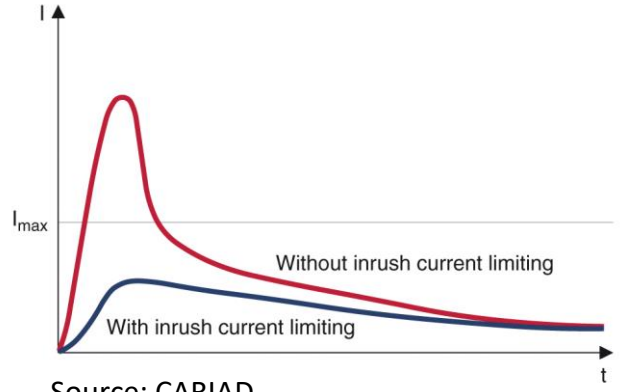
Source: IFX online

Introduction to Automotive Smart Fuses



Source: [Infineon Datasheet (Infineon-BTS7002-1EPP-DataSheet-v01_10-EN.pdf)]

Benefits of Smart Fuses



Source: CARIAD

- Intelligent power management
- Virtual sensor integration
- Savings in cable harness and increased EV range
- Improving reuse factor of HW components
- More flexible regarding mounting location within the car
- Dynamic rerouting within the automotive E/E architecture
- Dynamic FW updates possible

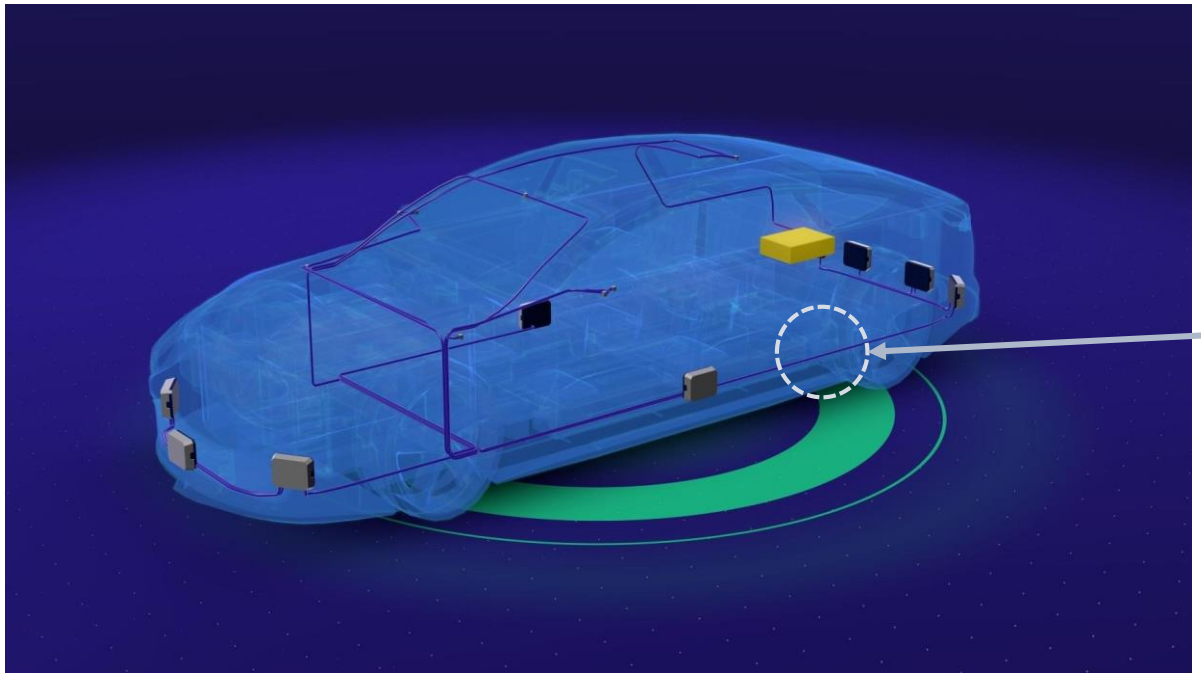
Challenge: Increased V&V effort for SW and HW

Benefits of Virtual Testing

- Development and test of target SW long before HW availability
- Detect and debug issues from dynamic interactions early
- Reducing risk of physical damage
- Avoiding expensive test setups and complex logistics
- Simplifying variant handling
- Easy to distribute, deploy and scale
- Accessibility, debugging and tracing

Challenge: Model development and simulation infrastructure

Introduction to Automotive Smart Fuses



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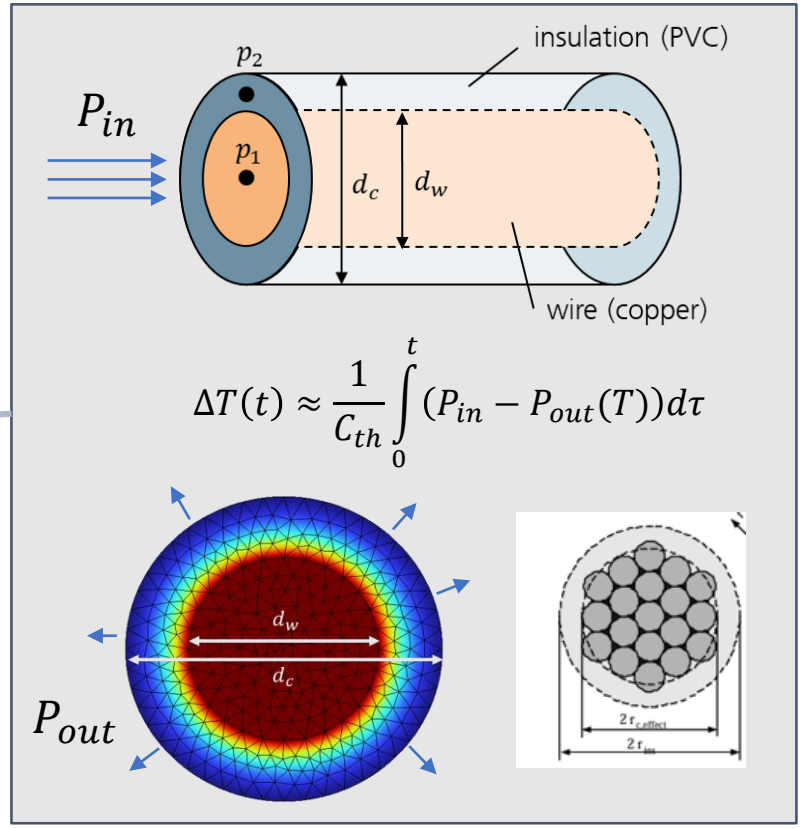
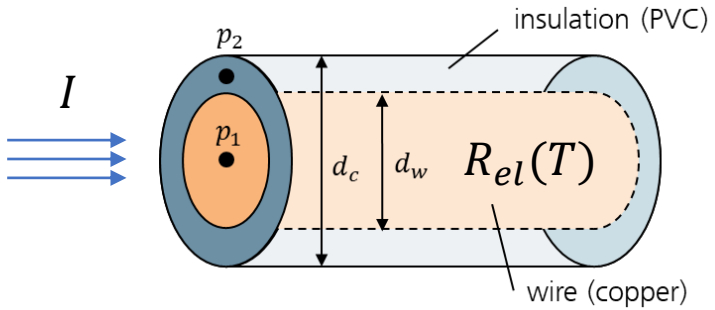
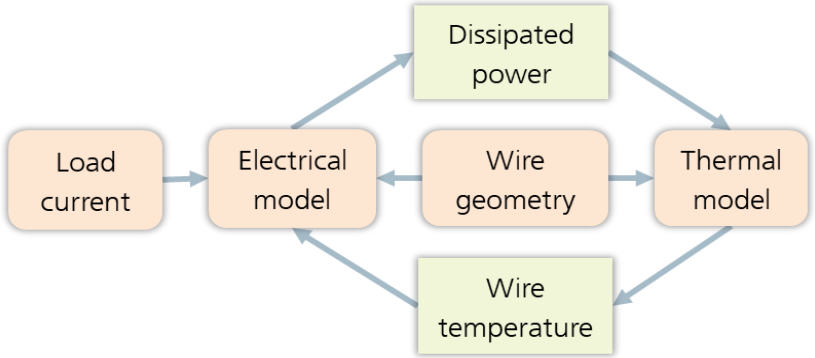
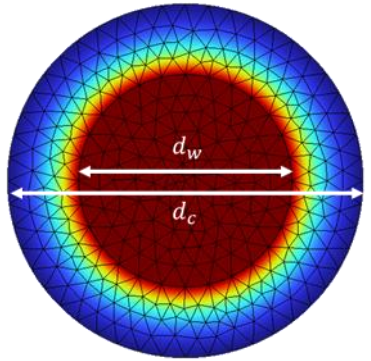


The Electrothermal Coupling Problem

$$P = R_{el}(T) \cdot I^2$$



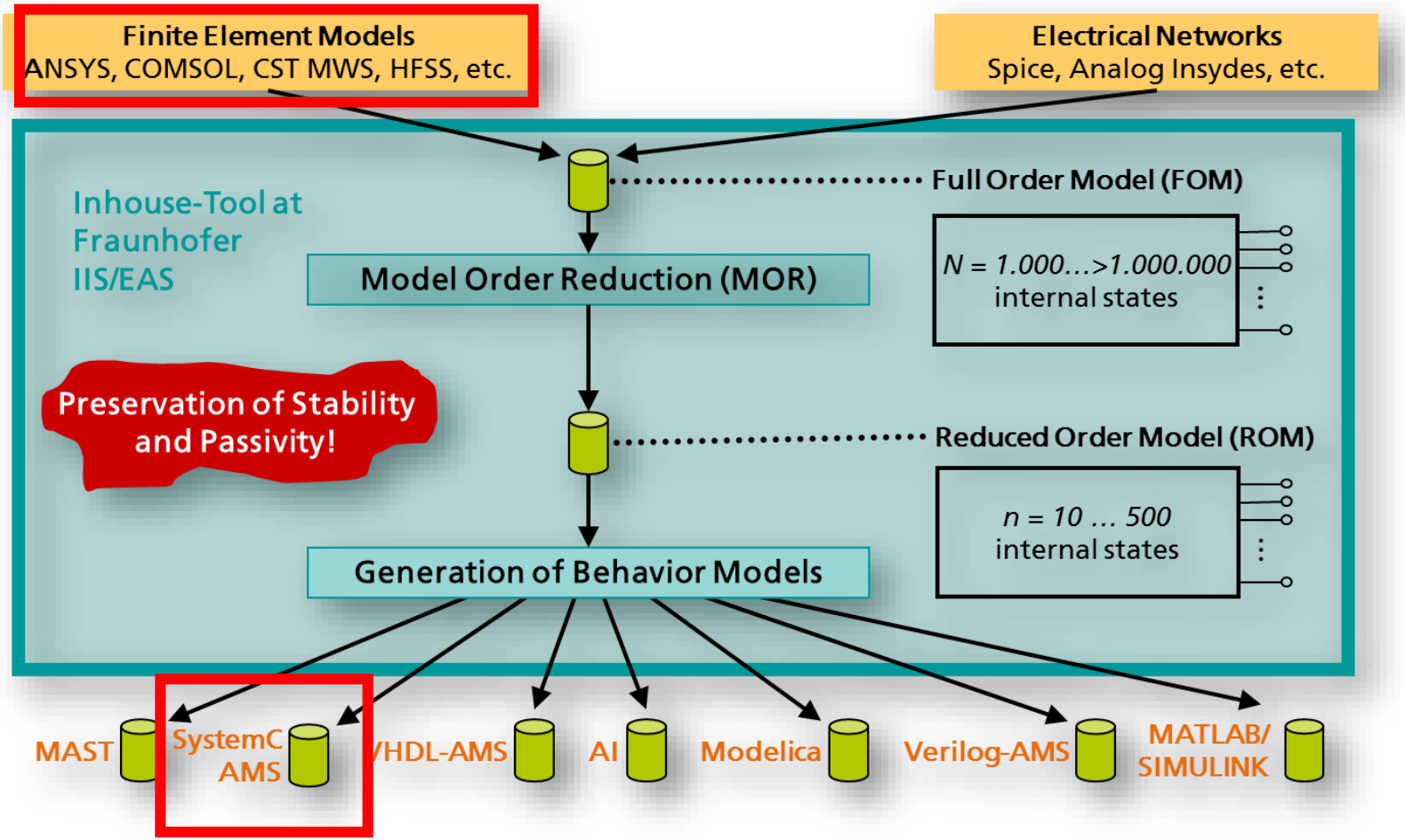




$$\Delta T(t) = \frac{1}{C_{th}} \int_0^t P(\tau) d\tau$$

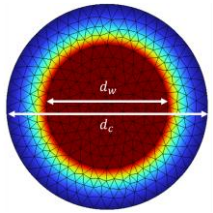
Model Order Reduction for Linear Systems

- FEM model can be huge, which is difficult to integrate with other tools
- Solution: Model order reduction and integration as state-space model

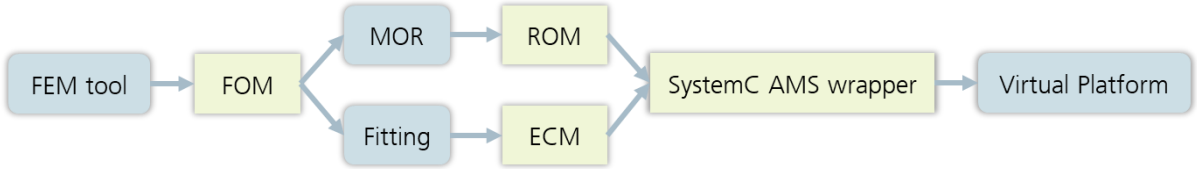


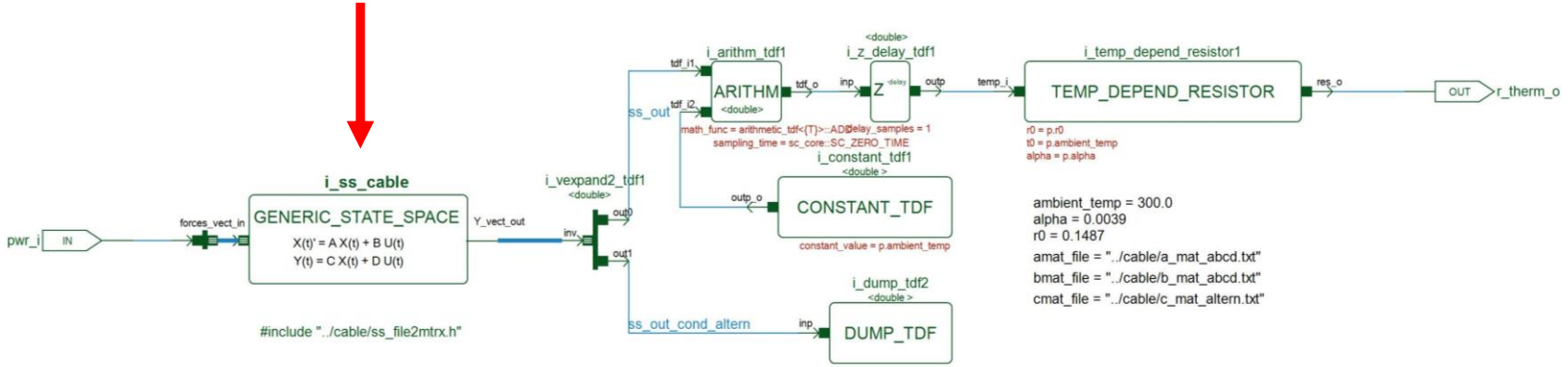
Cable Model Creation Flow

- Starting with FE model of cable
- Krylov-based MOR
- Exported as (linear) state-space system for SystemC AMS



Parameter	Value
Effective wire cross-sectional area	$A = 6\ \mathrm{mm}^2$
Cable diameter (copper+PVC)	$d_c = 5\ \mathrm{mm}$
Wire diameter (copper)	$d_w = 3\ \mathrm{mm}$
Cable length	$l_c = 1\ \mathrm{m}$
Electrical resistance	$R = 2.5\ \mathrm{m\Omega}$
Maximum temperature	$T_{max} = 125°C$
Heat transfer coefficient (thermal boundary condition)	$h = 5\frac{\mathrm{W}}{\mathrm{m^2K}}$





Thermal Modelling in SystemC AMS

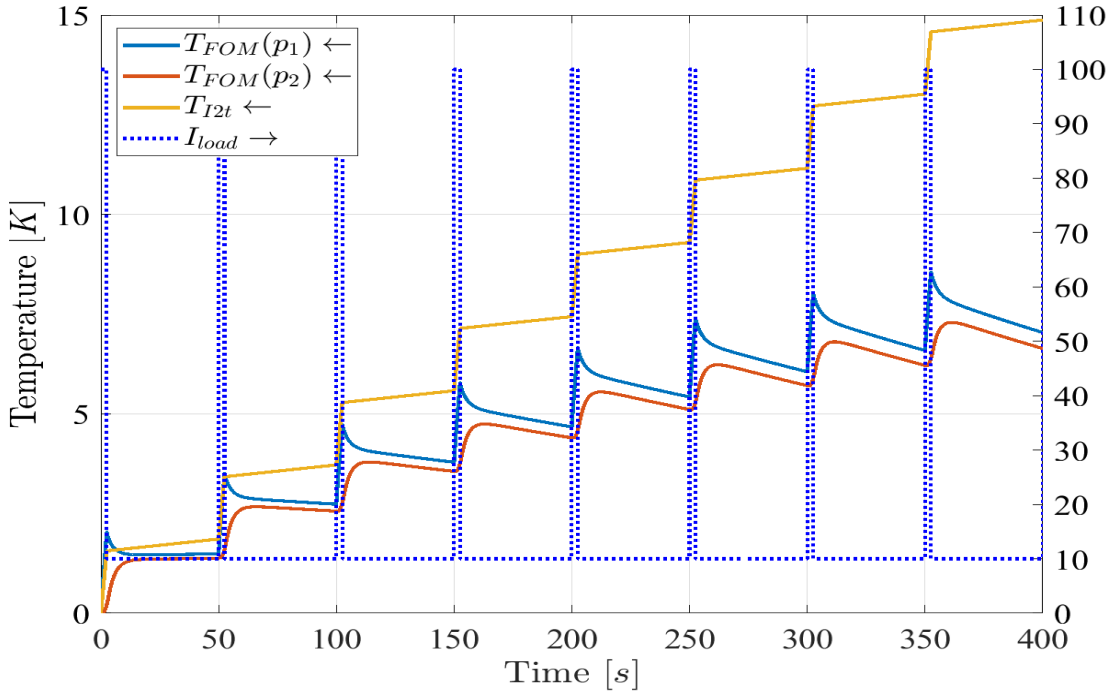
- SF requires modelling of electrothermal interactions
- Overview of different modelling approaches and their comparison

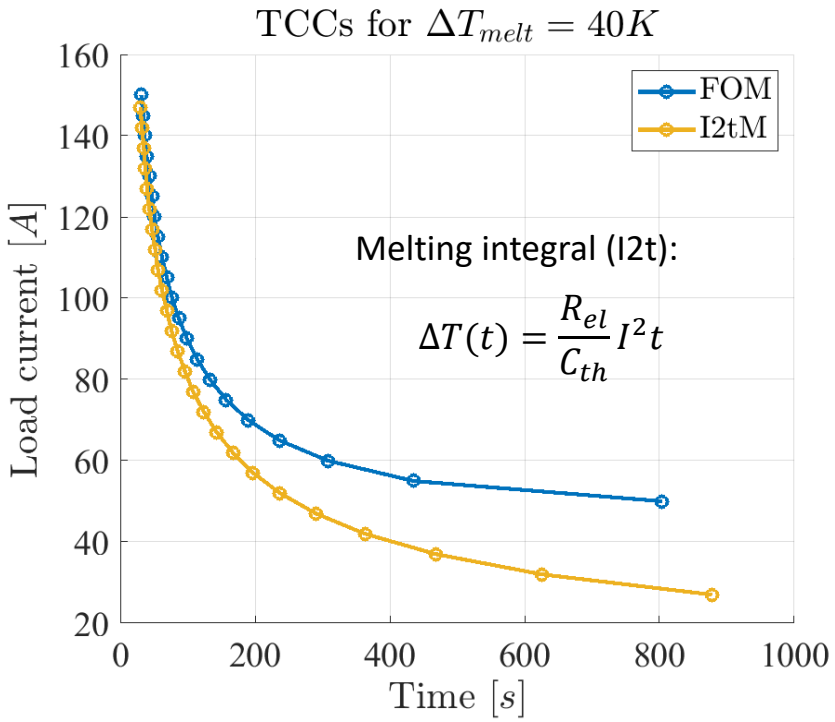
Model name	Abbreviation	Method of model creation	Type of model	Accuracy
Full-order model	FOM	FEM software	LTI system (large)	High
Reduced-order model	ROM	Model order reduction	LTI system (small)	Medium
Equivalent circuit model	ECM	Lumped system synthesis	RC netlist (small)	Low
Melting integral model	I2tM	Known from literature	Analytical expression	Coarse upper bound

- Effective integration into system-level simulation required

Thermal Modelling in SystemC AMS

- Full order model (FOM) vs. I2t model



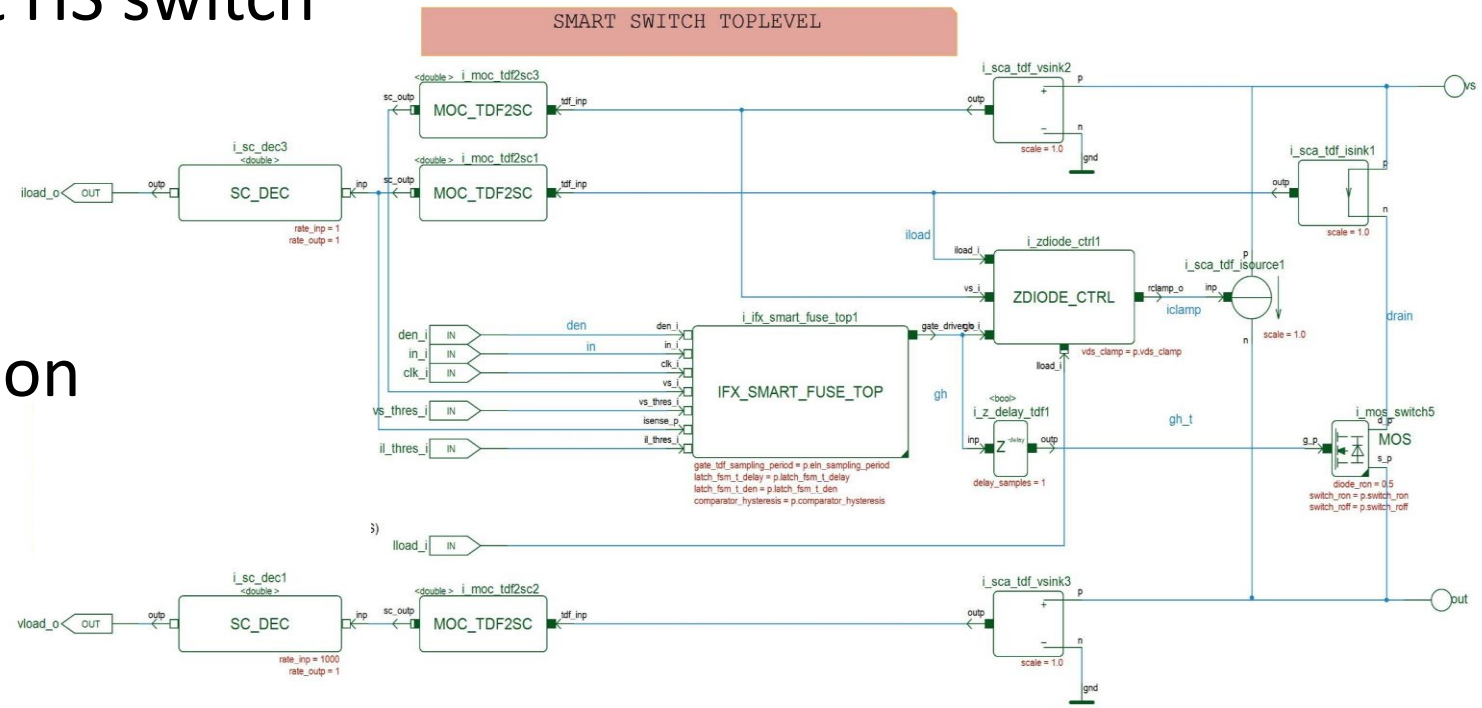


Melting integral (I2t):

$$\Delta T(t) = \frac{R_{el}}{C_{th}} I^2 t$$

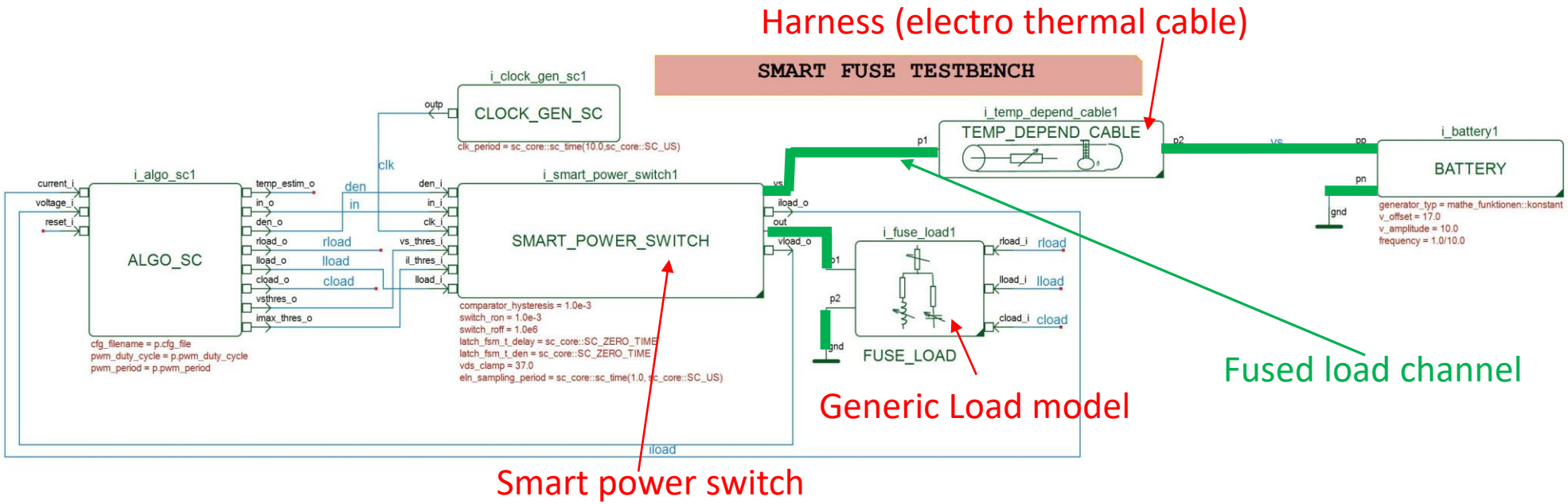
Smart Fuse Model in SystemC AMS

- Main component is smart HS switch
- Contains diagnostic functionalities, e.g. overtemperature protection
- Controlled by FW running on ECU



Smart Fuse Model in SystemC AMS

- TB contains SF connected to load model and harness cable



Smart Fuse Model in SystemC AMS

- Controlling/estimation algorithm implemented as SW
- Comparison of different estimation algorithms

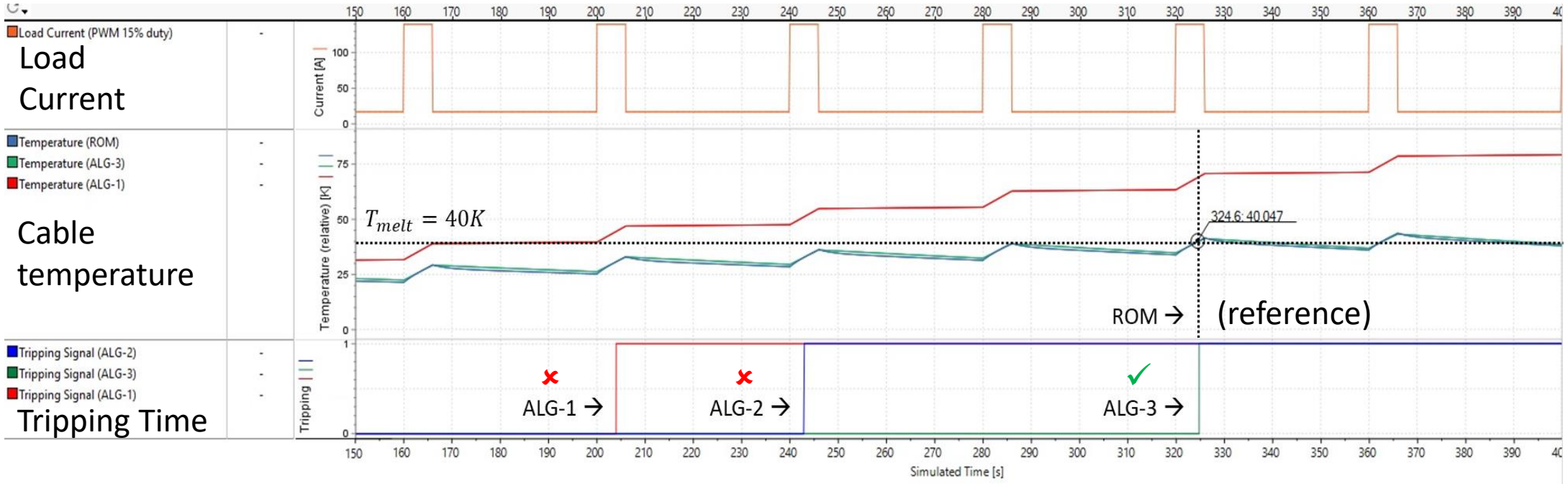
Algorithm	Description	Output
ALG-1	Numerical integration of I2t value	Temperature
ALG-2	Binned digital counter	Tripping time
ALG-3	Novel physics-based algorithm	Temperature

- Example implementation for ALG-1: $$\Delta T(t_N) \approx \frac{R_{el}}{C_{th}} \sum_{k=N-n}^{N} I_k^2 \cdot (t_k - t_{k-1})$$

- Starting SF evaluation at algorithmic level

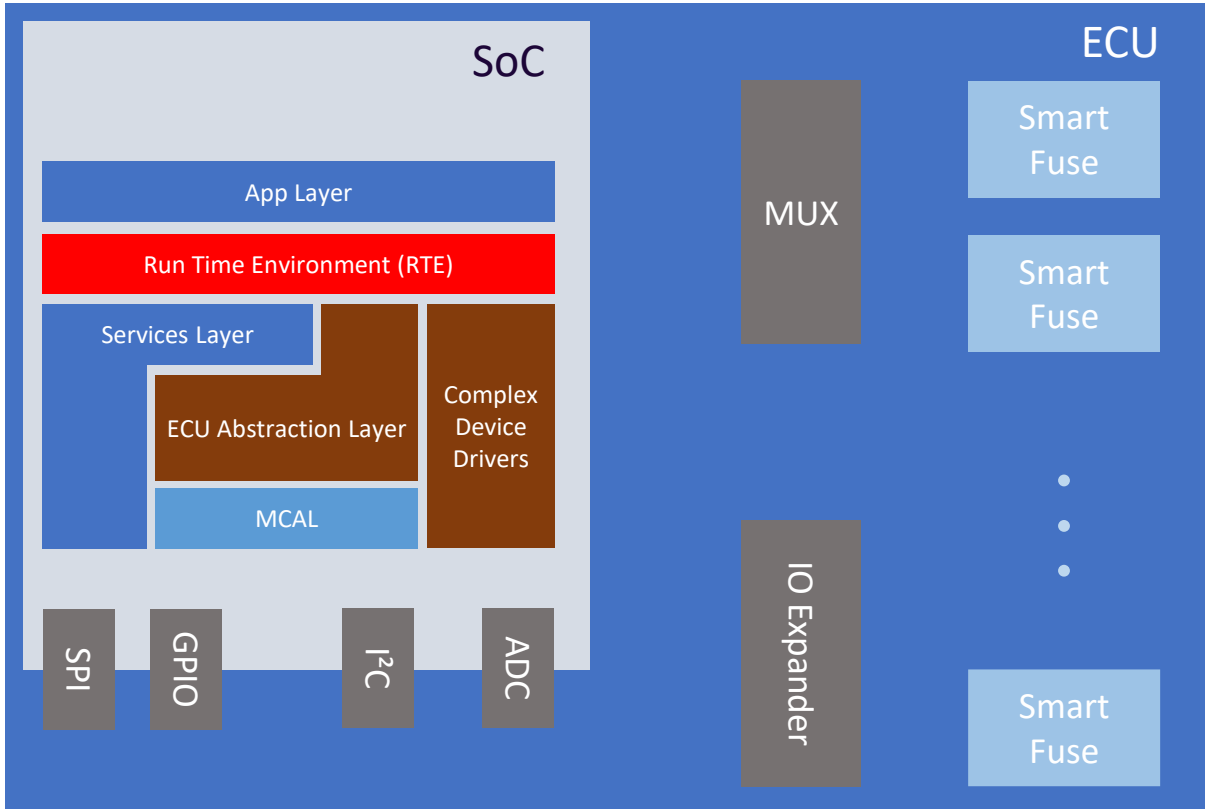
Smart Fuse Model in SystemC AMS

- Comparison of tripping time of the three ALGs for $\Delta T_{melt} = 40K$



Virtual Testing of a Zone Controller ECU

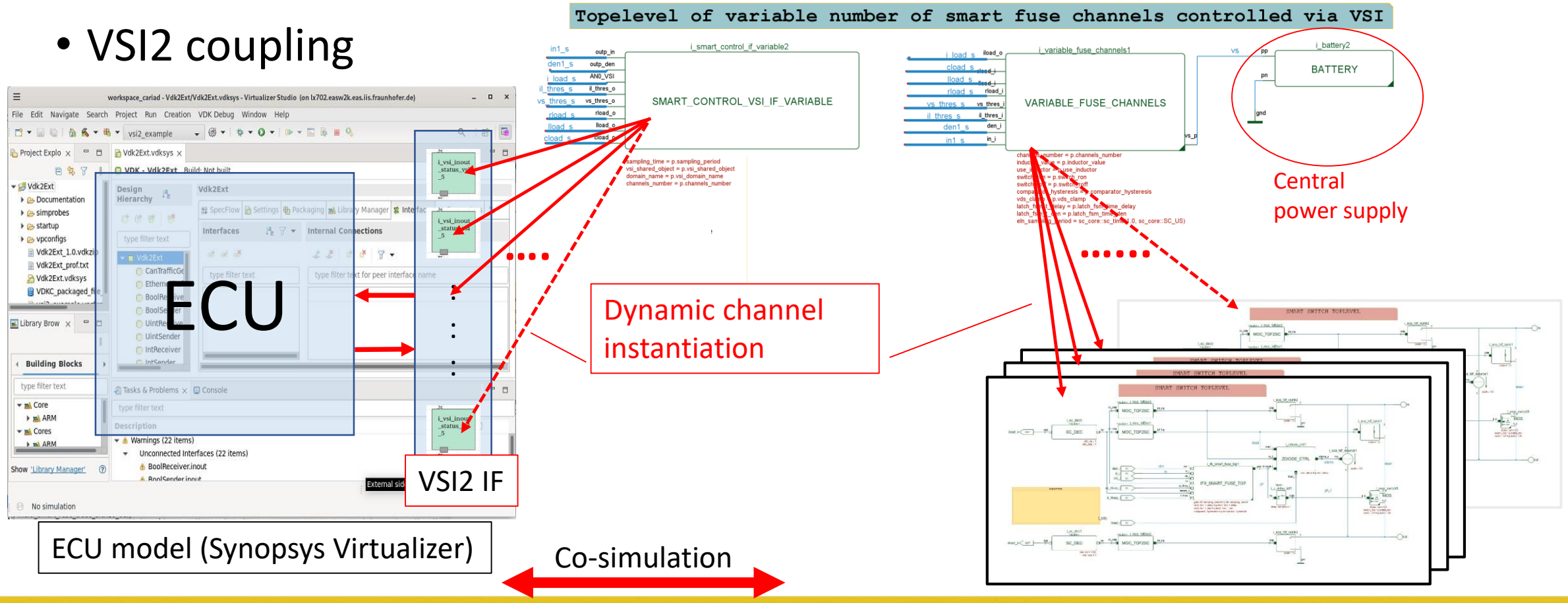
- Zonal architecture in the car improves wire length and weight
- Connects to a high number of actuators and sensors
- Responsible for efficient power and data distribution within the E/E architecture



Source: CARIAD

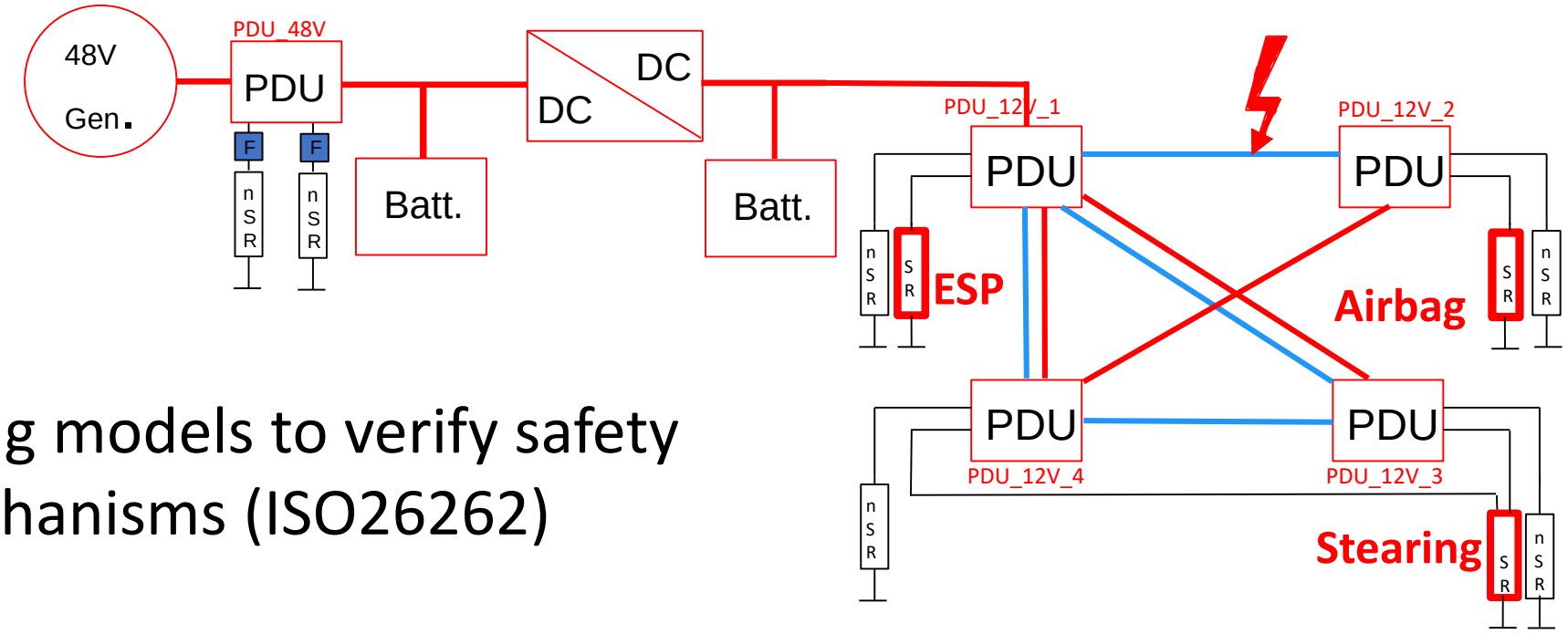
Virtual testing methodology

- VSI2 coupling



Safety Critical Aspects of E/E Architctures

- Rerouting for safety relevant harness loads in case of faults



- Using models to verify safety mechanisms (ISO26262)

Summary and Outlook

- Smart Fuses (SF) have many advantages but are highly complex to verify due to their heterogeneous nature
- We demonstrated virtual SF testing of overtemperature protection, including mixed-signal electronics, SW and physical modeling, bridging the gap between COMSOL, COSIDE and Synopsys Virtualizer
- Outlook:
  - Improving model performance when using many channels
  - Improving ROM by parametric MOR
  - CI/CD integration
  - Server-based fault-injection via CCI during runtime

Bundesministerium für Bildung und Forschung

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