Key Note Speech HV & Emerging Applications

Stockholm, 18. May 2016

Cost-Aware η-ρ-σ Multi-Objective Optimization of SiC Power Electronic Converter Systems

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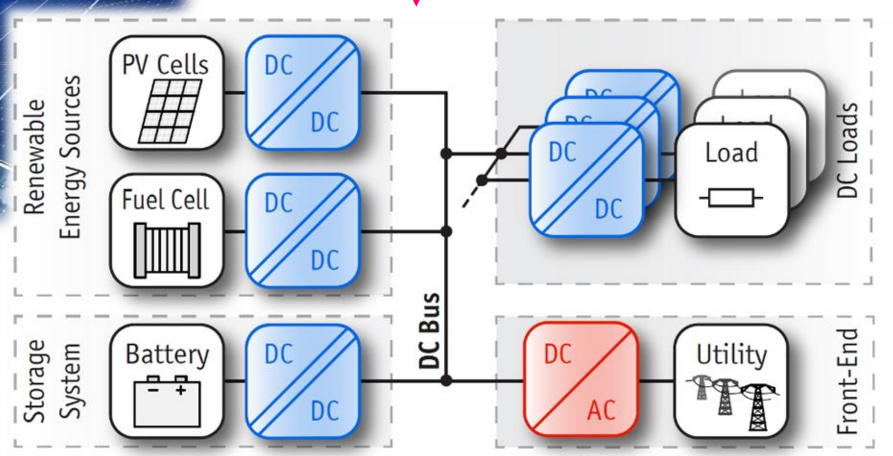
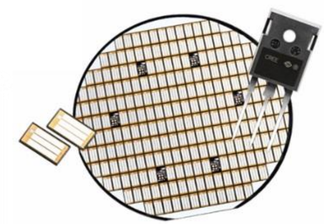
Motivation

Potential of SiC
Design Challenge
Multi-Objective Optimization
Virtual Prototyping

▶ Potential of SiC in Next Generation Renewable Energy Systems

Residential DC Microgrid System





- **SiC for Universal DC/DC Converter Systems**
  - Bidirectional Power Flow
  - Galvanic Isolation
  - Wide Voltage Range
- **SiC for DC/AC Grid-Tied PV Inverter Systems**
  - Low Costs
  - High Partial Load Efficiency
  - High Reliability

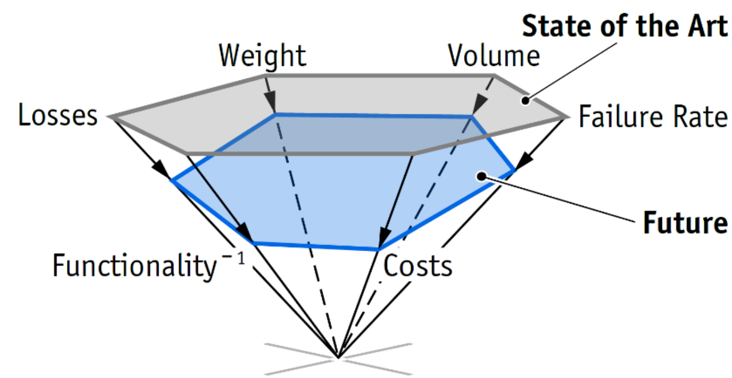
▶ Design Challenges

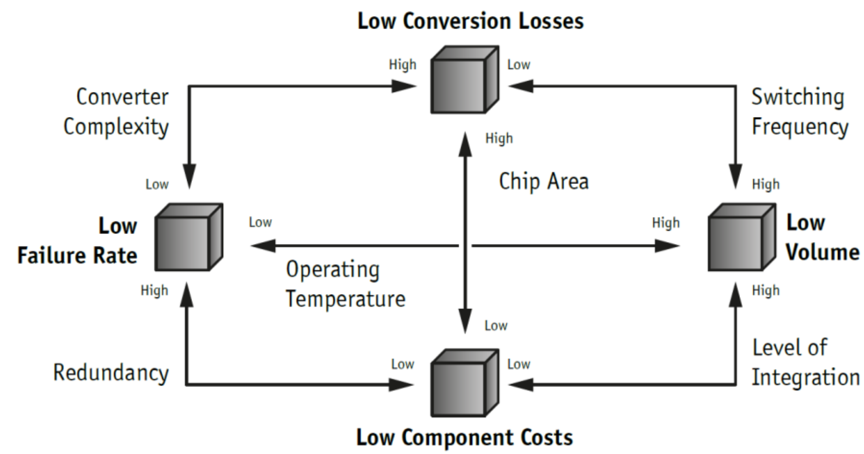
- **SiC Converter Design Target:**
  Improve Converter Performance

- **State-of-the-Art Analysis and Design Methodologies**
  - Single-Objective Optimization (e.g. Efficiency OR Power Density)
  - No Cost Considerations
  - Non-Systematic Hardware Prototyping

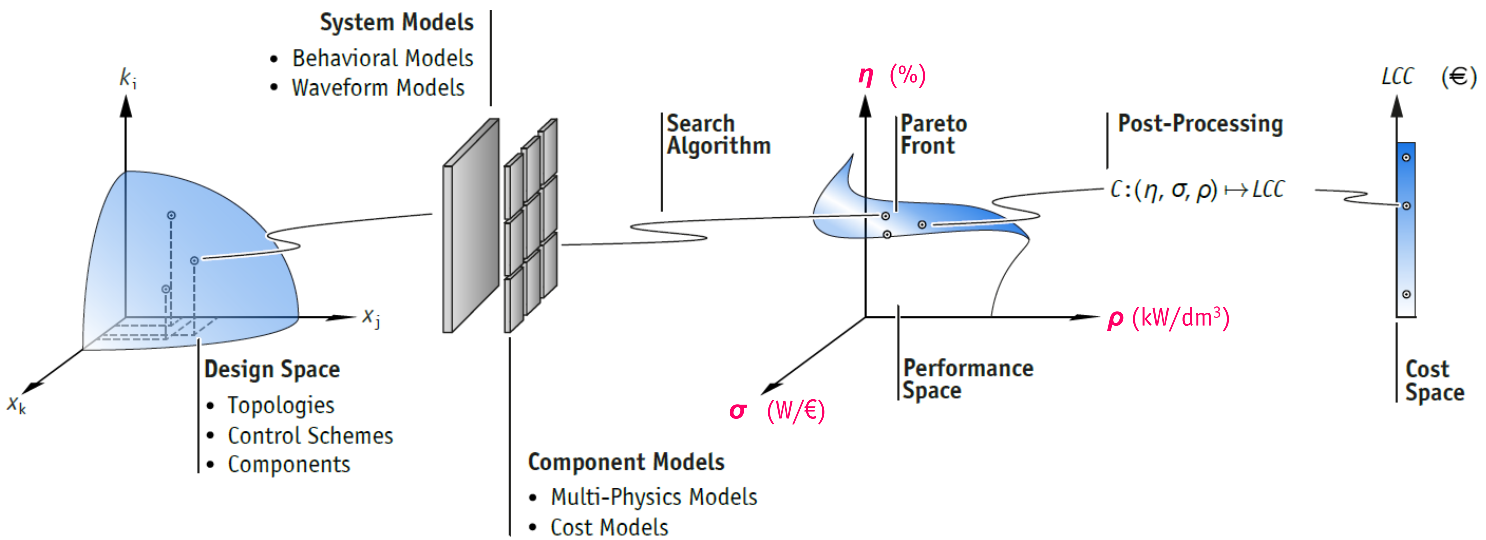
- **Mutual Coupling of Performance Measures**
  ▶ Concurrent Improvement not Possible

- **Expensive SiC**
  ▶ Costs are Most Important Criterion in Industry





▶ Advanced η-ρ-σ Virtual Prototyping Design Methodology



- ▶ Systematic Approach
- ▶ Comprehensive and Detailed Modeling
- ▶ Multi-Objective Pareto Optimization
- ▶ Consideration of Efficiency, Volume (Weight), and Costs

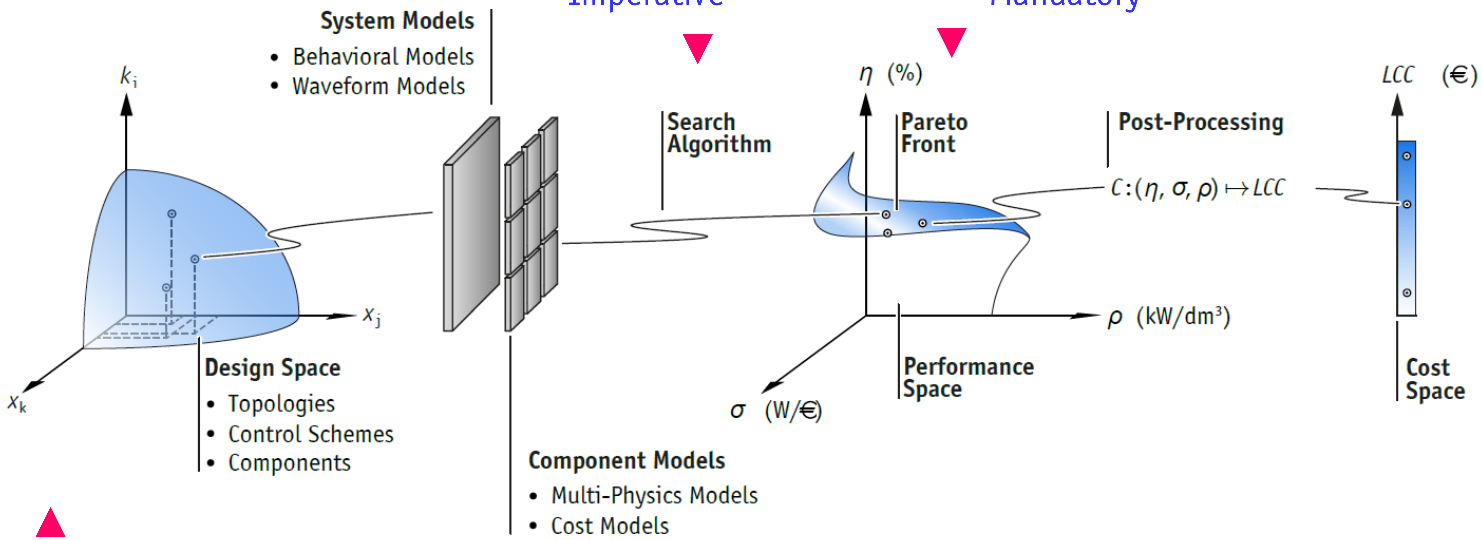
Challenges

Computational Efficiency

- Only Standard Computational Means Available
- Intelligent Optimization and Efficient Code Imperative

Big Data

- 10s of Gigabytes of Results
- Powerful Analysis Tools Mandatory



Complexity

- High # of Design Variables (up to 100)
- Continuous / Discrete Variables

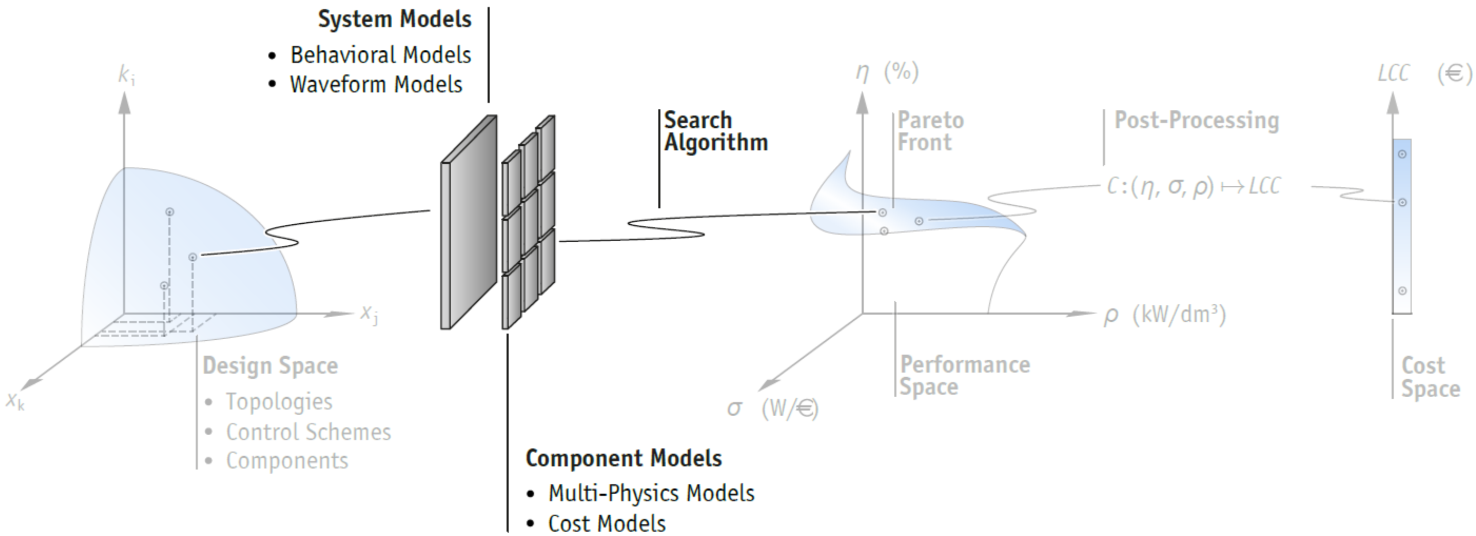
Modeling Accuracy

- Decisive Impact on Significance and Resilience of Results

Virtual Prototyping Routine

System-Level Optimization
Component-Level Optimization
System Modeling
Multi-Physics Modeling
Costs Modeling

▶ Main Virtual Prototyping Routine



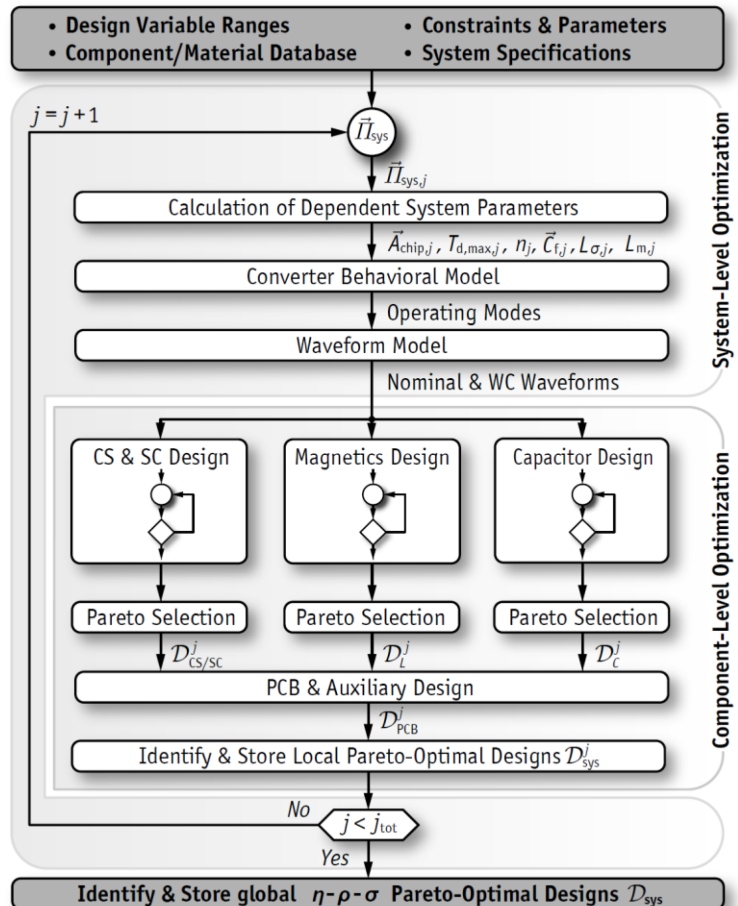
▶ Main Virtual Prototyping Routine

- **Distinction Between System- and Component-Level Optimization**

- **Waveforms Couple Component Performance**

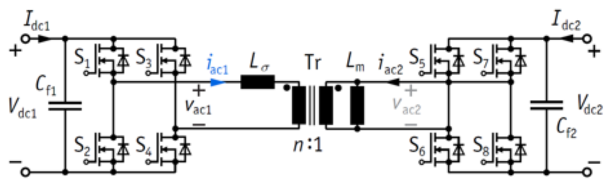
- **System-Level Variables Determine the Waveforms**
  - Topology
  - Modulation Scheme $(f_{sw},\ldots)$
  - Component Values $(L, C,\ldots)$
- **System-Level Variables are Computational Expensive**

- **Independent Optimization of Components Based on Component-Specific Design Variables**

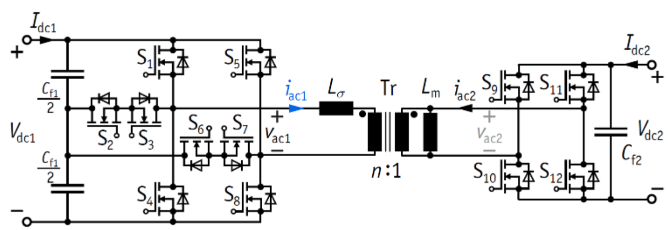


▶ System-Level Design and Optimization

- **Topology Iteration**
  - Conventional 3L-DAB

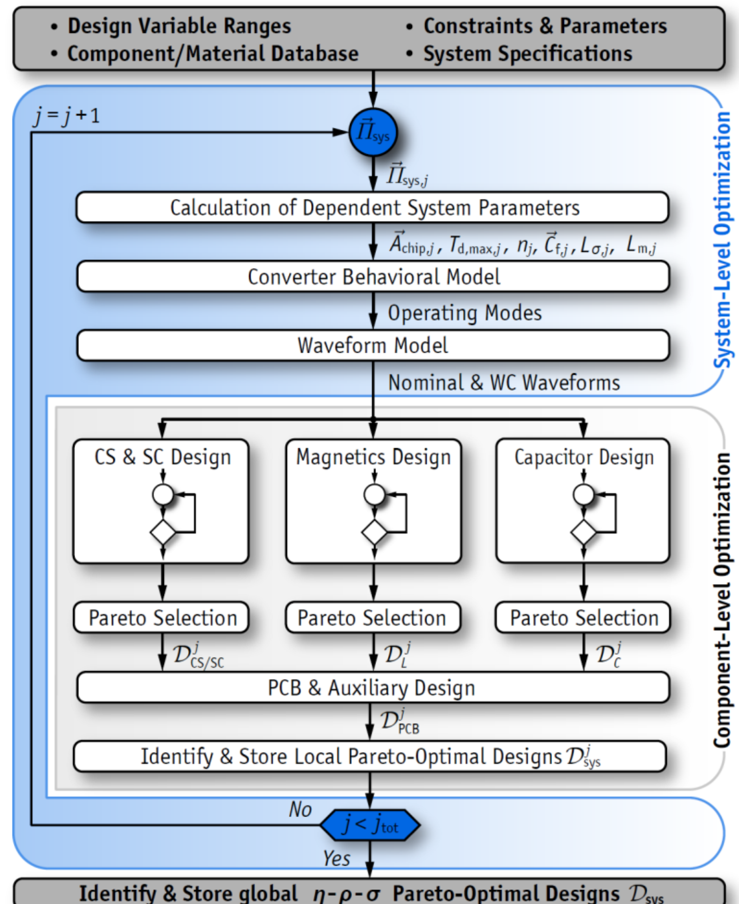


  - Advanced 5L-DAB



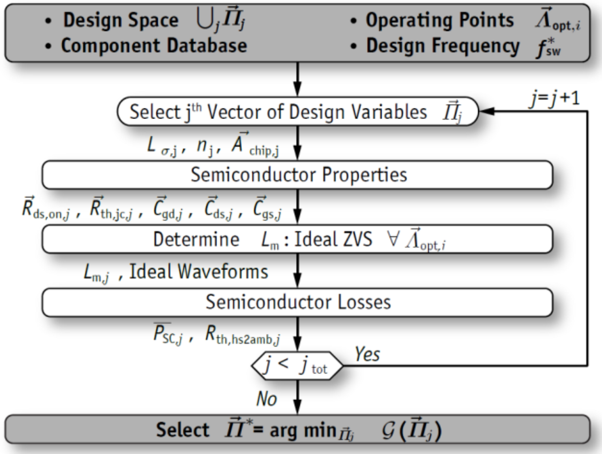
- **Switching Frequency Iteration**

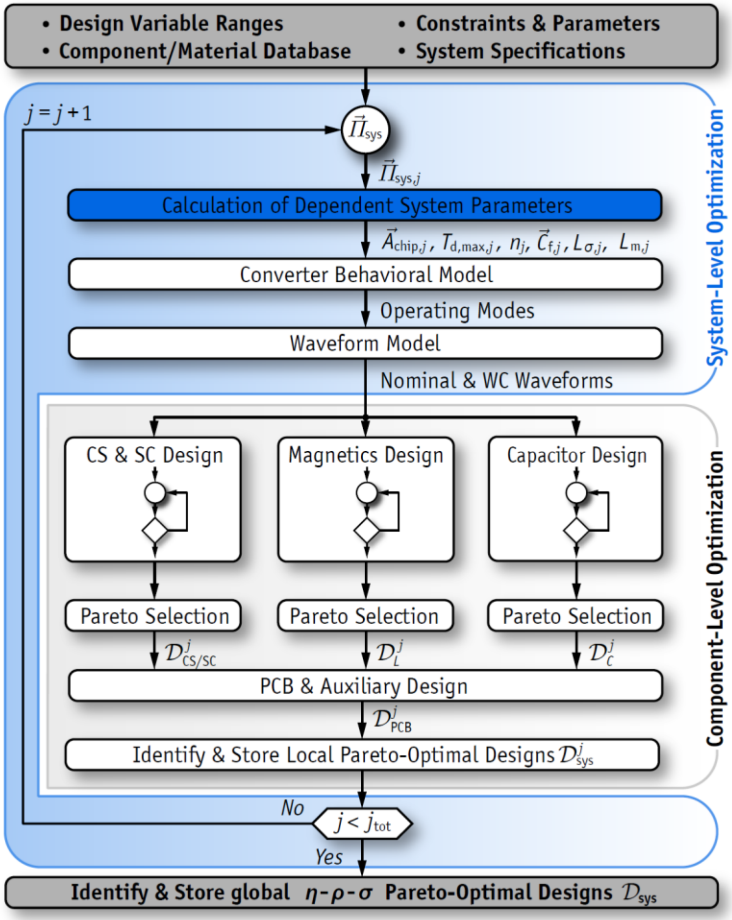
$f_{sw} \in [50, 75, \ldots 300]$ kHz



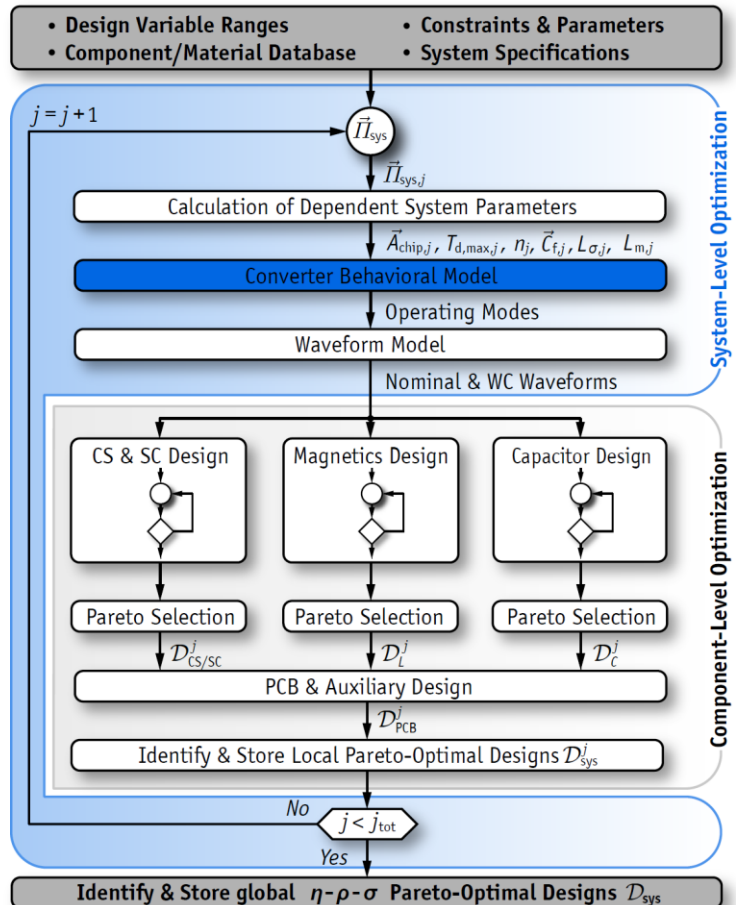
▶ System-Level Design and Optimization

- **Choose Remaining System Parameters Based on Off-Line Optimization**
  - Transformer Turns Ratio n
  - Series Inductance L_σ
  - Magnetizing Inductance L_m
  - Chip Areas $A_\mathrm{chip,prim}$, $A_\mathrm{chip,sec}$
  - Maximum Dead Time $T_\mathrm{dead,max}$



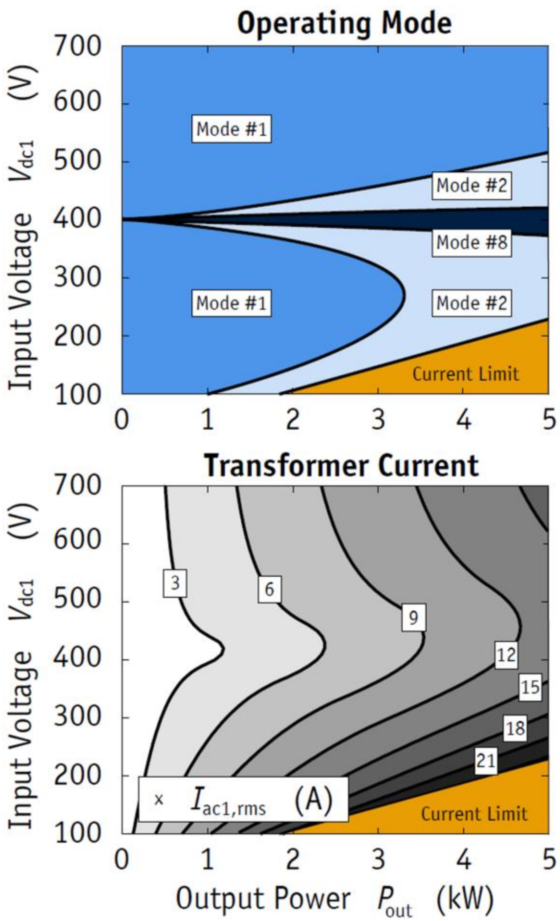


▶ Converter Behavior Model

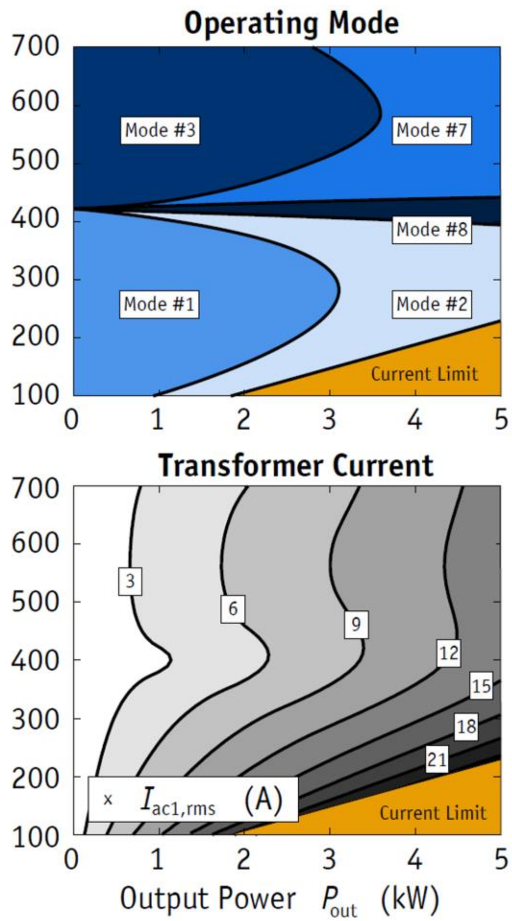


▶ Converter Behavior Model

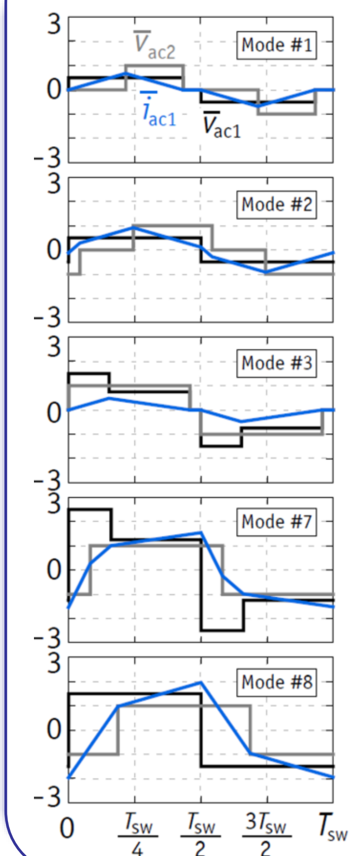
■ 3-Level Dual Active Bridge



■ 5-Level Dual Active Bridge



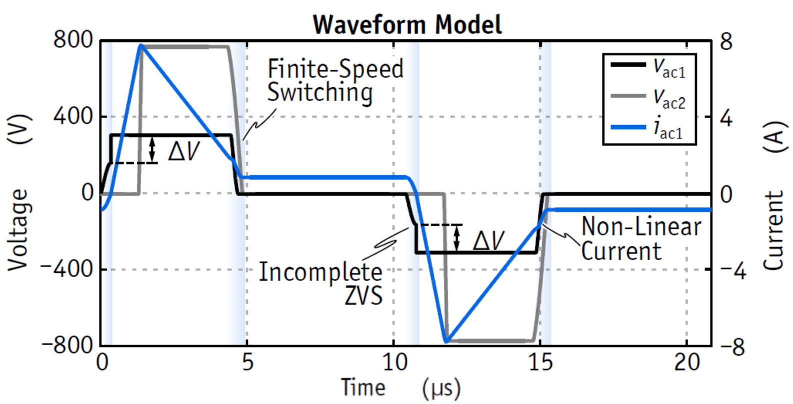
Modes



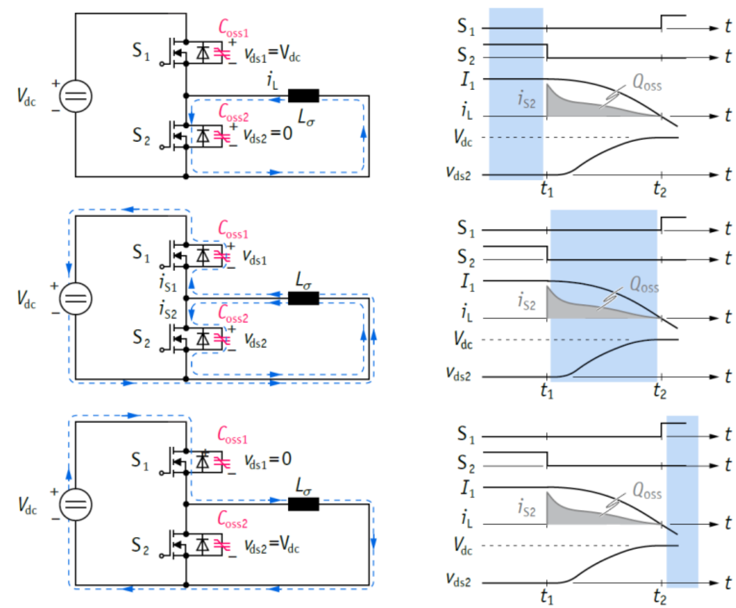
▶ Waveform Model

- **Precise Waveforms Essential for Accurate Component Dimensioning**

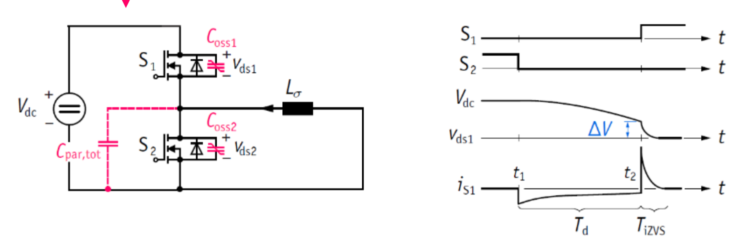
- **Consideration of Non-Linear Switching Transitions**
  - Finite-Speed Switching due to C_{oss} and Parasitic Capacitances
  - Mandatory to Detect ZVS / Incomplete ZVS
  - Modifies Transferred Power – Emulation of Controller Activities Required



Complete ZVS: $\frac{1}{2} L_\sigma I_1^2 \geq Q_{oss}(V_{dc}) \cdot V_{dc}$



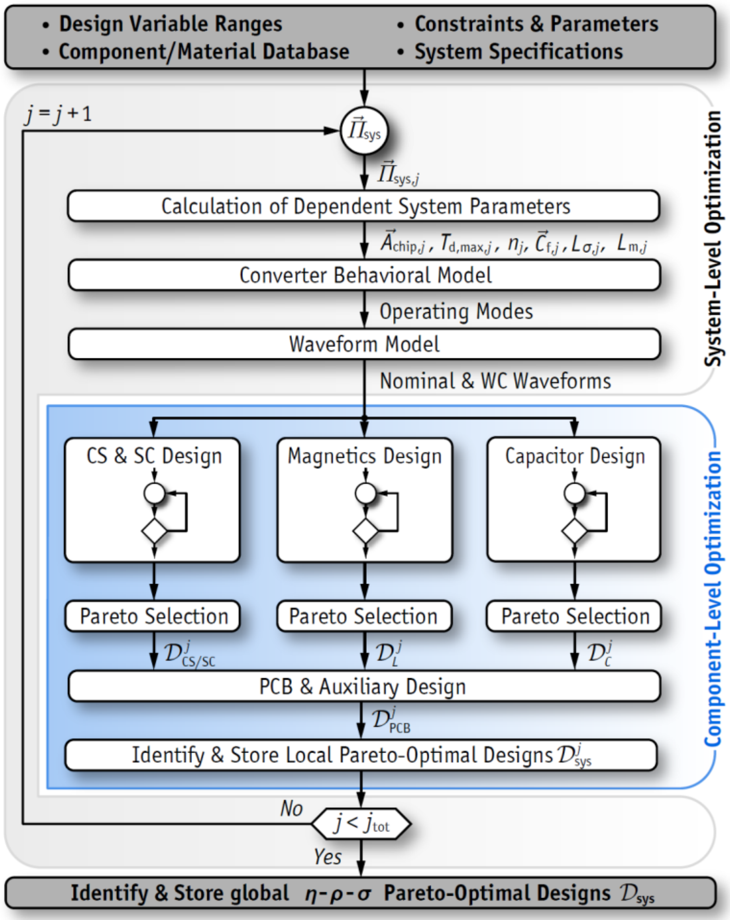
Incomplete ZVS: $\frac{1}{2} L_\sigma I_1^2 < Q_{oss}(V_{dc}) \cdot V_{dc}$



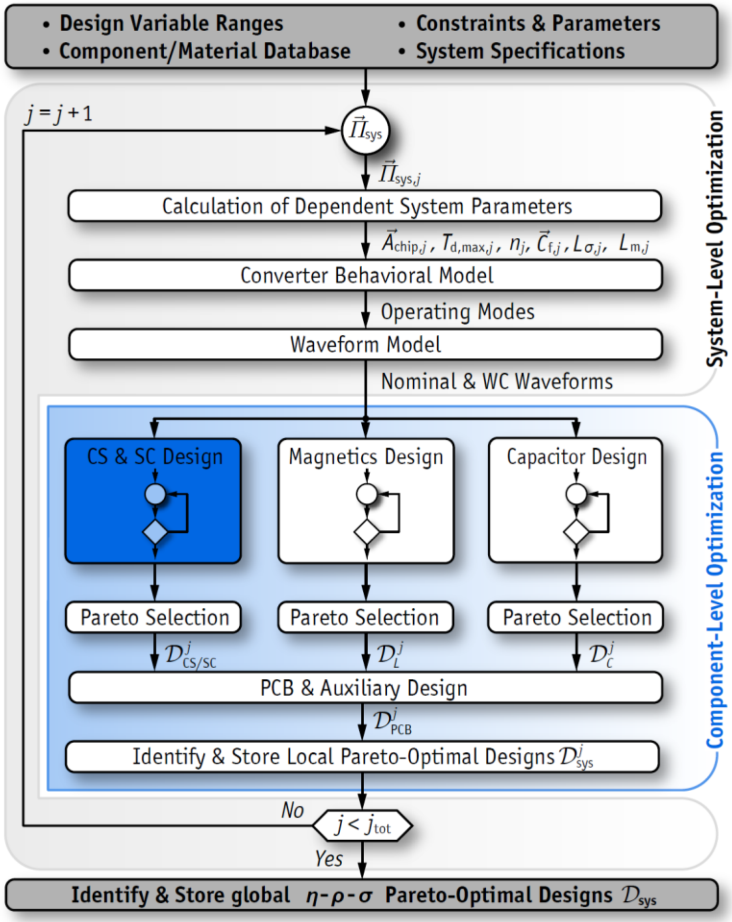
▶ Component-Level Design and Optimization

- **Waveforms as Prerequisite of Component Dimensioning**
  - Nominal Operating Point Waveforms
  - Worst Case Operating Point Waveforms

- **Independent Optimization of Components Possible**
  - Neglect of Undesired/Small Parasitic Electromagnetic Coupling
  - Neglect of Undesired/Small Parasitic Thermal Coupling
  - Only Considered Coupling Effect is Desired/Dominant Conducted Waveforms



▶ Semiconductor and Cooling System Design Routines

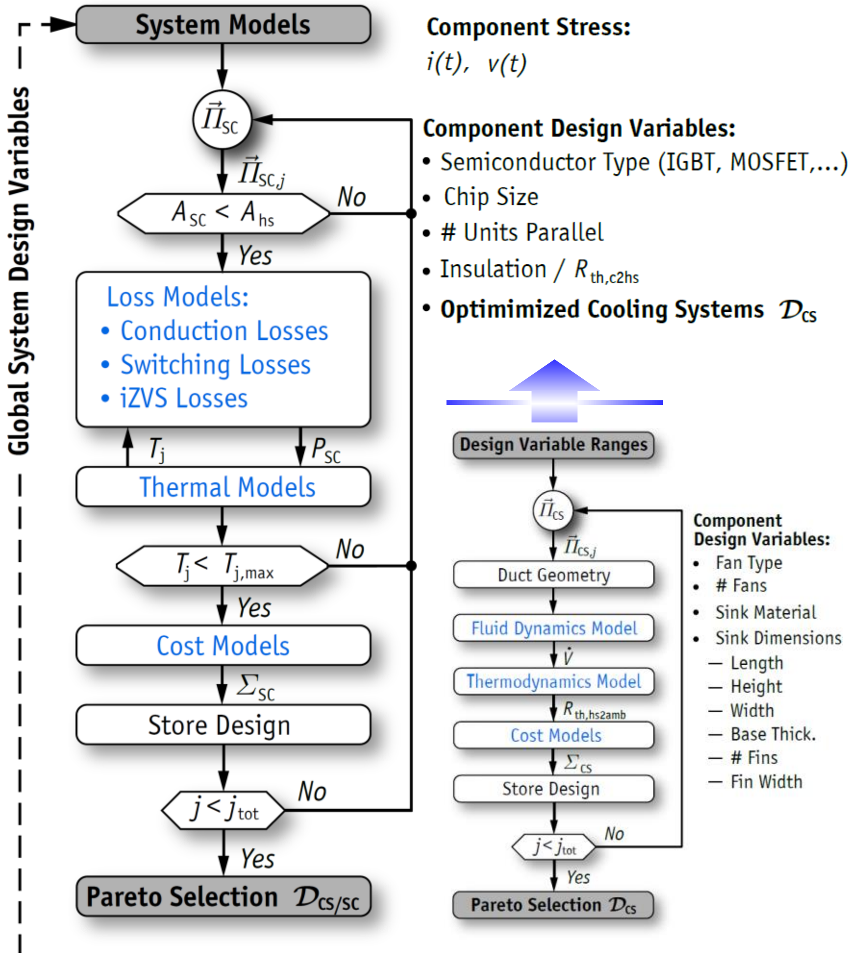


▶ Semiconductor and Cooling System Design Routines

- **Semiconductor and Cooling System Optimization**
  - Combined Optimization
  - Multi-Physics and Cost Models
  - Various User-Defined Constraints
  - Only Optimized Cooling Systems

- **Optimized Cooling Systems Based on Off-Line Routine**

- **Temperature-Dependent Semiconductor Losses**
  - Iterative Temperature/Loss Calculation Until Sufficient Convergence
  - Numeric Approach – No Closed-Form Solutions

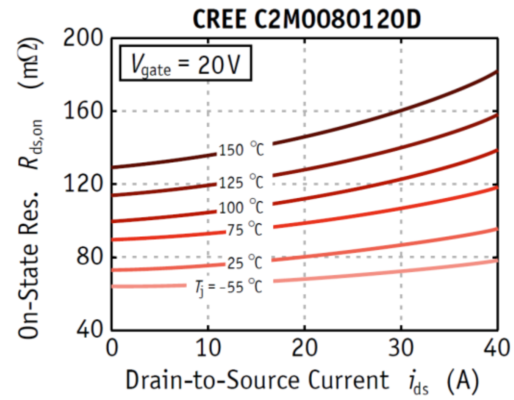


Semiconductor Multi-Physics Modeling (1)

Conduction Loss Model

- Takes into Account the Time-Varying Current
- Temperature-Dependent
- Interpolated Data Sheet Parametrization

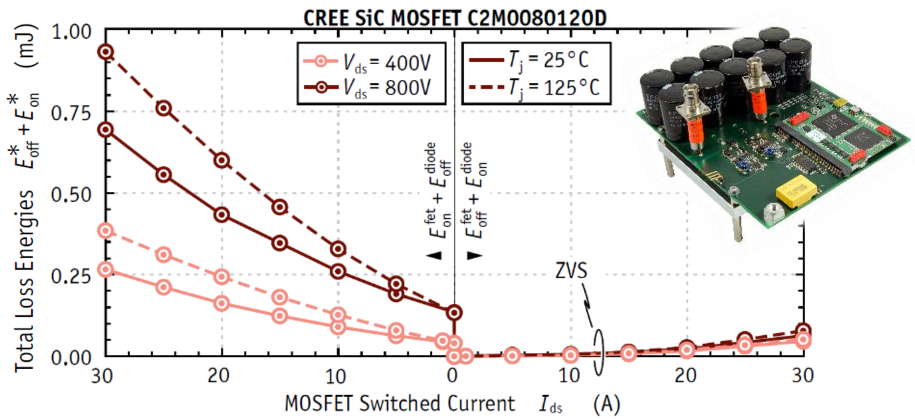
$$P_c^{\text{fet}}\left(i_{ds}(t), T_j, V_{gate}\right) = \frac{1}{T}\int_0^T R_{ds,on}\left(i_{ds}(t), T_j, V_{gate}\right)\cdot i_{ds}^2(t)\,dt$$



Switching Loss Model

- Data Sheet Parametrization Insufficient
- Measured Switching Losses

$$P_{sw}\left(I_{on}, I_{off}, V_{on}, V_{off}, T_j\right) = \frac{1}{T}\cdot\sum_i^{N_{sw}}\left[E_{on}\left(I_{on,i}, V_{on,i}, T_j\right) + E_{off}\left(I_{off,i}, V_{off,i}, T_j\right)\right]$$

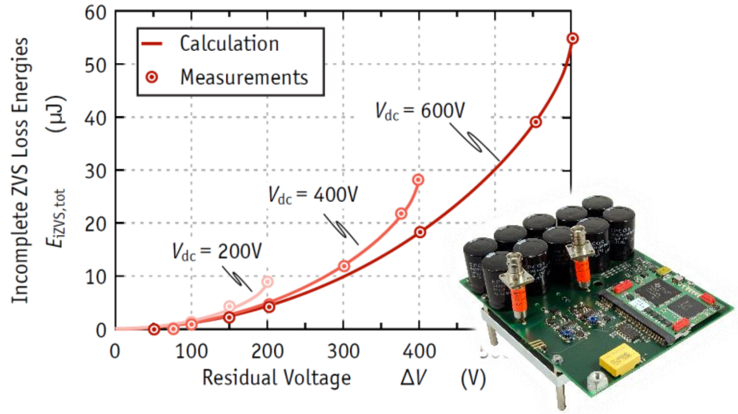


▶ Semiconductor Multi-Physics Modeling (2)

Incomplete ZVS Loss Model

- Incomplete Charg./Discharg. of C_{oss}
- Analytical Approach Instead of Involved Measurements
- Experimental Verification

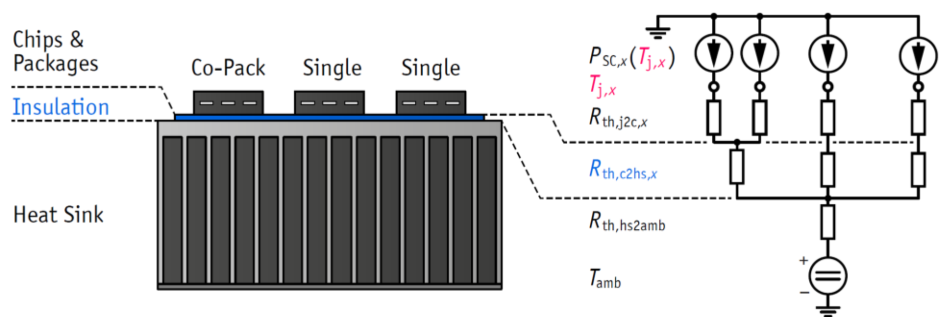
$$P_{iZVS} = f_{sw} \cdot \left[E_{oss2}(\Delta V) + \frac{1}{2} \cdot C_{par,tot} \cdot \Delta V^2 + \Delta Q_{dc} \cdot V_{dc} - \left(E_{oss1}(V_{dc}) - E_{oss1}(V_{dc} - \Delta V) \right) \right]$$



Thermal Model

- Links Junction Temperature and Semiconductor Losses

$$T_{j,x} = T_{amb} + R_{th,j2c,x} \cdot P_{SC,x}(T_{j,x}) + R_{th,c2hs,x} \cdot \sum_{i=1}^{N_{co}} P_{SC,i}(T_{j,i}) + R_{th,hs2amb} \cdot \sum_{i=1}^{N_{cs}} P_{SC,i}(T_{j,i})$$



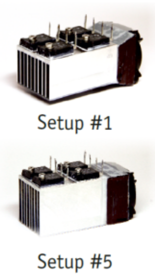
▶ Cooling System Multi-Physics Modeling

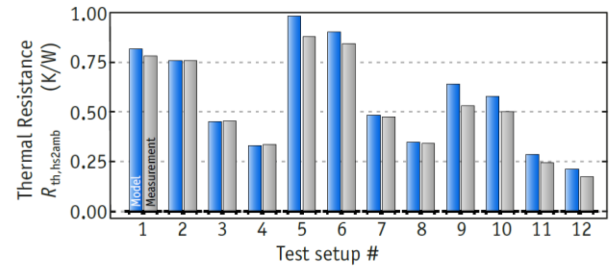
- **Fluid Dynamics Model**
  - Determine Air Flow in Heat Sink

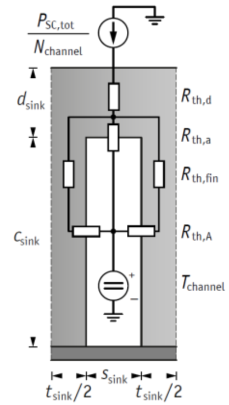
$$\dot{V} : \Delta p_{\mathrm{tot}}(\dot{V}) - \Delta p_{\mathrm{fan}}(\dot{V}) = 0$$

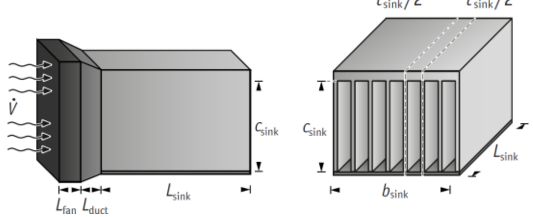
- **Thermodynamics Model**
  - Calculate Thermal Resistance
  - Analytical Model with Empirical Parameters
  - Experimentally Verified Models

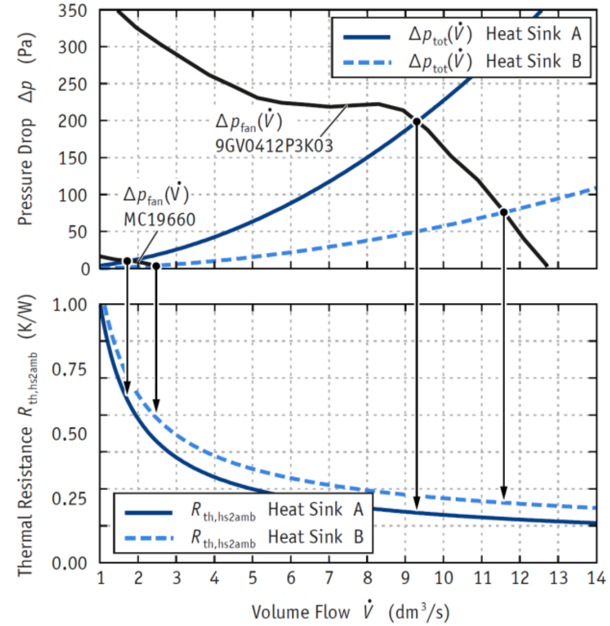
$$R_{\mathrm{th,conv}}(\dot{V}) = \left[\rho_{\mathrm{air}}\, c_{\mathrm{air}}\, \dot{V} \cdot \left(1 - e^{-\frac{h \cdot A_{\mathrm{eff}}}{\rho_{\mathrm{air}}\, c_{\mathrm{air}}\, \dot{V}}}\right)\right]^{-1}$$



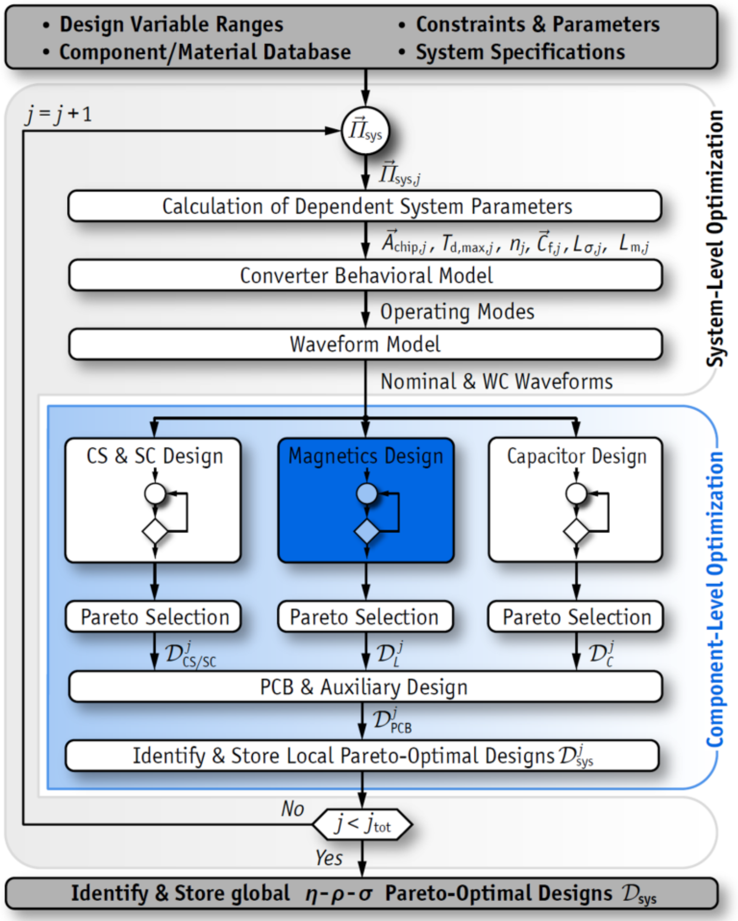






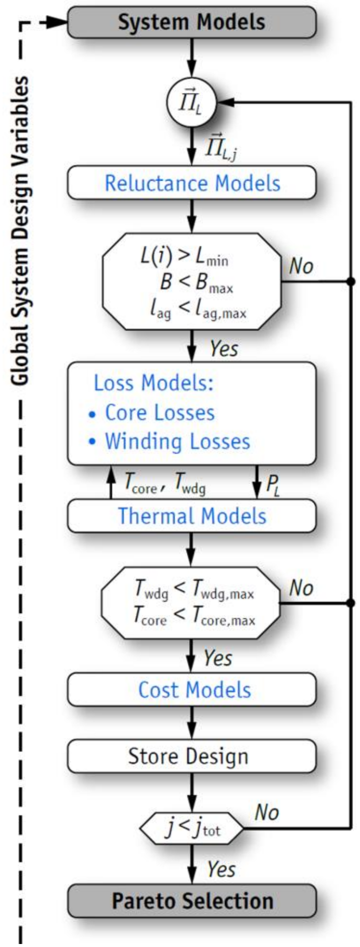


▶ Magnetics Design Routine



Magnetics Design Routine

- **Magnetics Optimization**
  - Component Values Given by Iteration of Global System Loop
  - Multi-Physics and Costs Models
  - User-Defined Constraints
- **Very High Number of Design Variables**
- **Temperature-Dependent Core and Winding Losses**
  - Iterative Temperature/Loss Calculation Until Sufficient Convergence
  - Numeric Approach – No Closed-Form Solutions



Component Stress/Values:

$\sum_n \hat{I}_{(n)}$, $i(t)$, $v(t)$ / L^*, n^*

Component Design Variables:

- Core
  - Type (E-, U-, Toroid,...)
  - Dimensions
  - # Air Gaps
  - # Stacked Cores
  - Material
- Coil Former
  - Dimensions
  - Material
- Winding
  - Type (Round, Litz,...)
  - Dimensions
  - # Turns
  - Material
  - Insulation

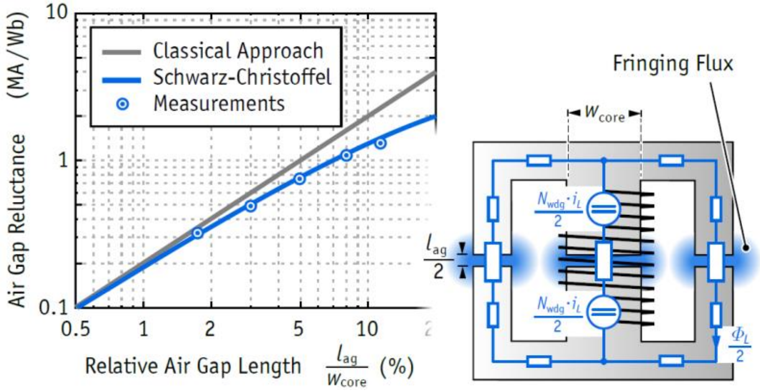
Magnetics Multi-Physics Modeling (1)

Reluctance Model

- Non-Linear Core Material Permeability
- Air Gap Reluctance Calculation Considers the Fringing Flux

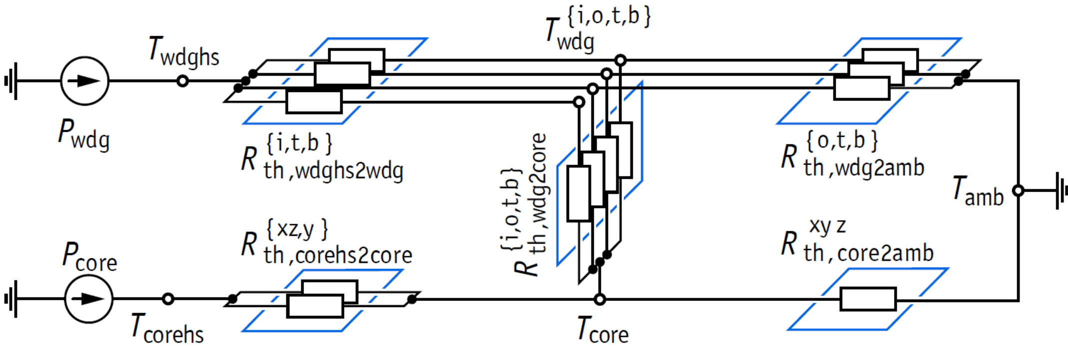
$$N_{wdg} \cdot i_L = \Phi_L \cdot \left[\frac{l_{mag,core}}{\mu_0 \; \mu_r(B) \; k_{fill} \; A_{core}} + R_{mag,ag} \right]$$

$$R_{mag,ag} \propto \mu_0 \left[\frac{w_{core}}{l_{ag}} + \frac{2}{\pi} \left(1 + \ln \frac{\pi h_w}{4 l_{ag}} \right) \right]$$



Thermal Model

- Anisotropic 3D Resistance Network
- Heat Transfer Mechanisms
  - ▶ Conduction
  - ▶ Radiation
  - ▶ Natural Convection

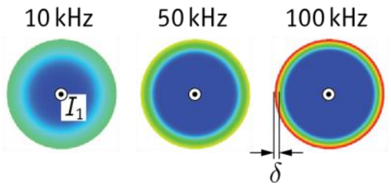


▶ Magnetics Multi-Physics Modeling (2)

Winding Loss Models

- Contribution of Skin and Proximity Effects Depending on Winding Geometry

$$P^{x}_{\text{wdg}}(T_{\text{wdg}}) = \sum_{n=1} R_{\text{dc}}(T_{\text{wdg}}) \cdot \boldsymbol{X}\left(\xi(T_{\text{wdg}}, f_n)\right) \cdot \hat{I}^{2}_{L(n)}$$



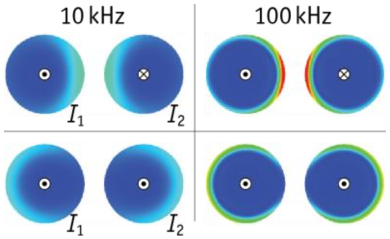
Round and Litz Wire

- Analytical Approach
- Mirroring Method for H_{ext}

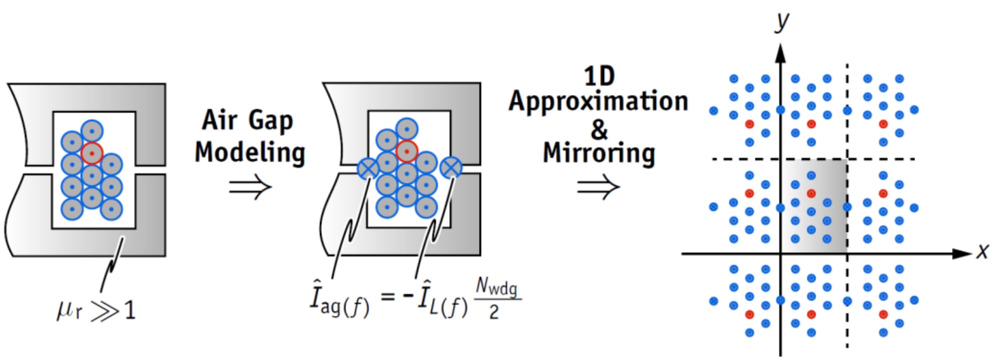
Flat and Foil Winding

- 1D Approximations Inaccurate
- Interpolated Off-Line 2D FEM-Simulations

Skin and Proximity Effect ▶



Mirroring Method ▶

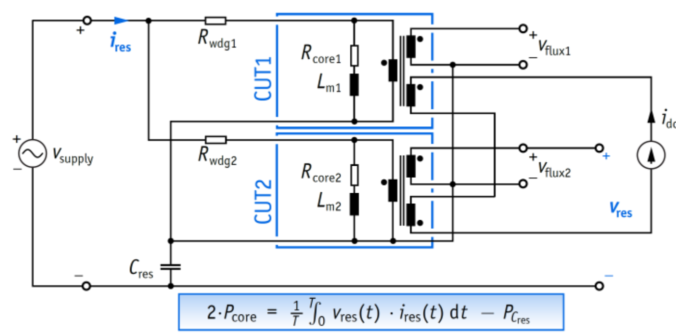


▶ Magnetics Multi-Physics Modeling (3)

■ Core Loss Models

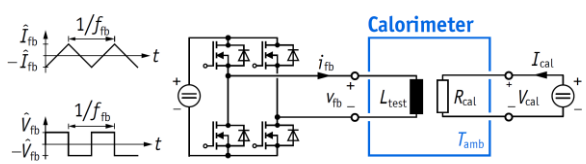
- i^2GSE Appr. with Operating Point-Dependent Steinmetz Parameters from Loss Map

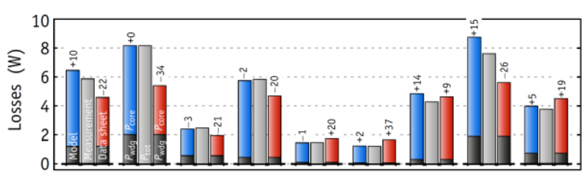
$$P_{\text{core}}^{\text{HF}} = k_{\text{fill}}\, V_{\text{core}} \cdot \frac{1}{T} \sum_{i}^{N_{\Delta B}} \overline{k_i}\, |\Delta T_i|^{1-\alpha_i}\, |\Delta B_i|^{\beta_i}$$

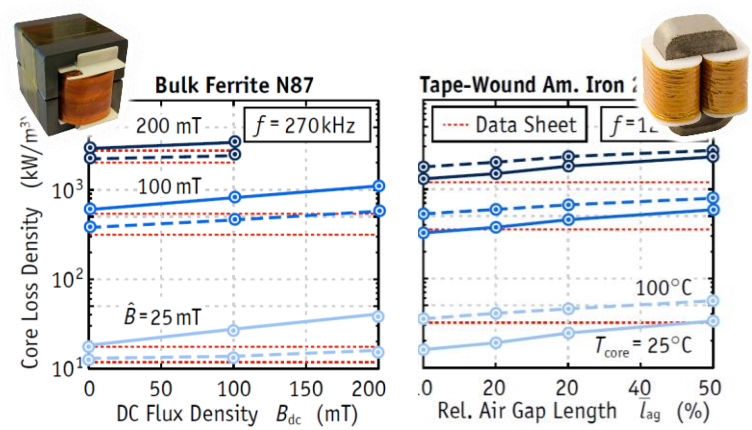


■ Multi-Parametric Core Loss Meas.

- Advanced Core Loss Measurement Setup
- Exp. Verification with Calorimetric Setup
- Mean Error < 10 % – Factor 2 Better than DS







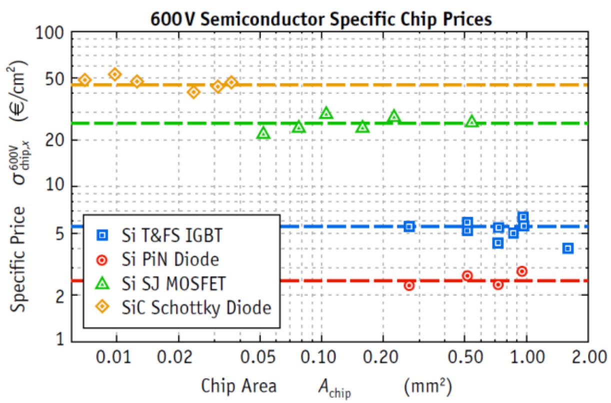
Cost Modeling

- **Novel Cost Models for i) Semiconductors, ii) Magnetics, iii) Capacitors, iv) Cooling Systems, v) PCBs and vi) Auxiliaries**

- **Challenges**
  - Non-Measurable and Confidential Cost Data, Distributor Prices Unreliable
  - Complexity of Cost Structure
  - Non-Product-Related Cost Factors (E.g. MOQ, Currency...)
  - Time-Dependence of Costs

- **Approach**
  - Direct Manufacturer/Industry Data for Large MOQ to Minimize Overheads
  - Intuitive Models with Physical Variables
  - Quotes Only in € or $ and Similar MOQ > 10 000 Units
  - Regular Updates

Semiconductor Costs Model: $\Sigma_{SC}(A_{chip}) = \sigma_{chip,x} \cdot A_{chip} + \Sigma_{pack,x}$



Chip technology:	Si T&FS IGBT	Si PiN Diode	Si SJ MOSFET	SiC Schottky Diode	SiC V-DMOSFET
$\sigma^{600\,V}_{chip,x}$ (€/cm²)	5.52 [1]	2.46 [2]	27.34 [3]	46.24 [4]	
$\sigma^{1200\,V}_{chip,x}$ (€/cm²)	6.57 [1]	4.46 [2]		86.47 [5]	72.01 [6]
Package type:	**TO-247**	**SOT-227**	**SP1**	**SP3**	**SP4**
$\Sigma_{pack,x}$ (€/Unit)	0.55	8.10	7.62 [7]	10.01 [7]	15.06 [7]

1) Infineon IGBT 4   2) Infineon EmCon   3) Infineon CoolMos C7
4) Cree/Wolfspeed Z-REC Gen 3   5) Cree/Wolfspeed Z-REC Gen 4
6) Cree/Wolfspeed Z-FET Gen 2   7) Microsemi

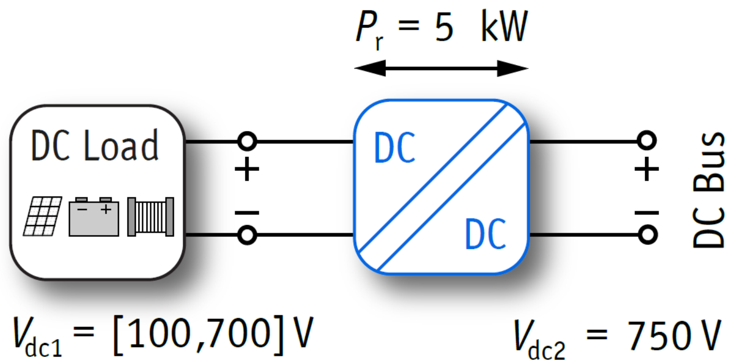
Results Case Study I:

DC/DC Converter System

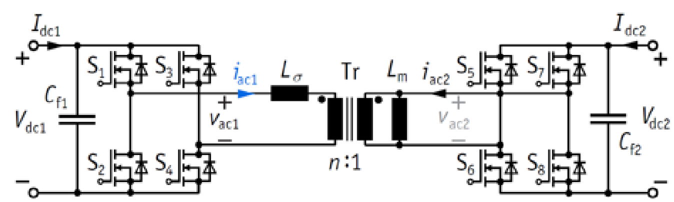
Residential DC Microgrid Application
Multi-Objective Optimization
Hardware Prototype

▶ Universal DC/DC Converter System for Residential DC Microgrid Applications

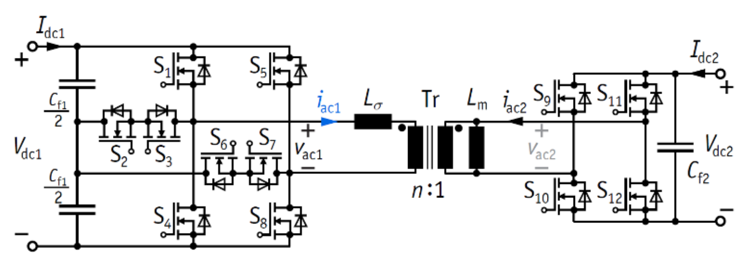
- **High Converter Functionality Required for Universal Application**
  - Wide Input Voltage Range V_{dc1}=[100,700] V
  - Galvanic Isolation
  - Bidirectional Power Flow
  - High Part Load Efficiency



- **Conventional 3-Level Dual Active Bridge (3L-DAB)**

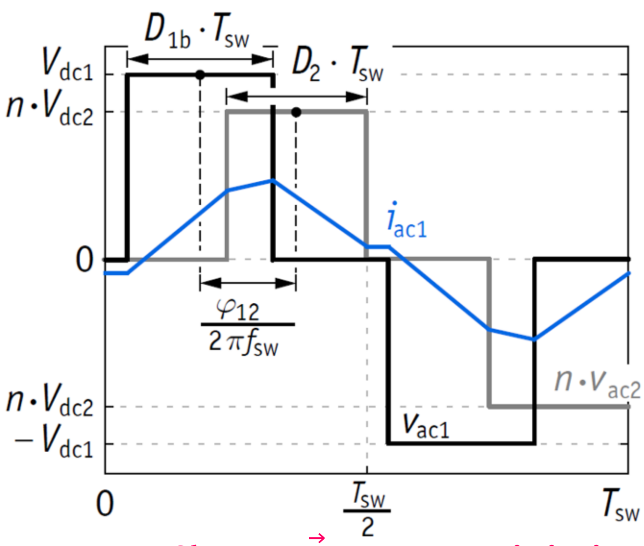


- **Advanced 5-Level Dual Active Bridge (5L-DAB)**
  - 5 Instead of 3 Voltage Levels on Input Side
  - Higher DOF Allows for Adv. Modulation

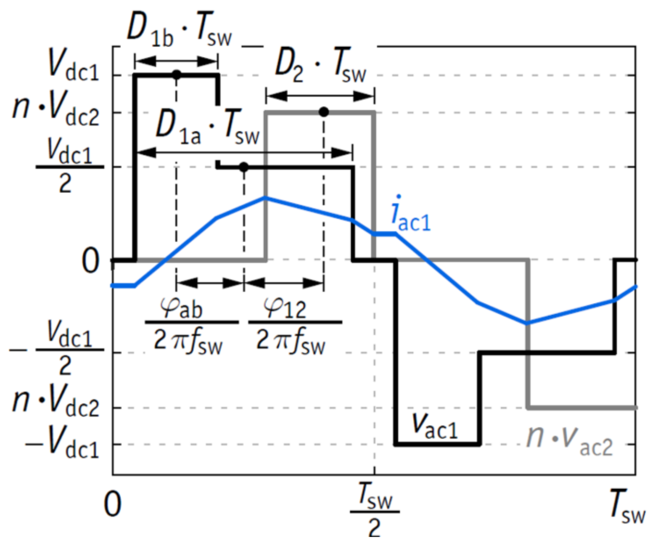


▶ Converter Modulation Schemes

■ **3L-DAB**



■ **5L-DAB**



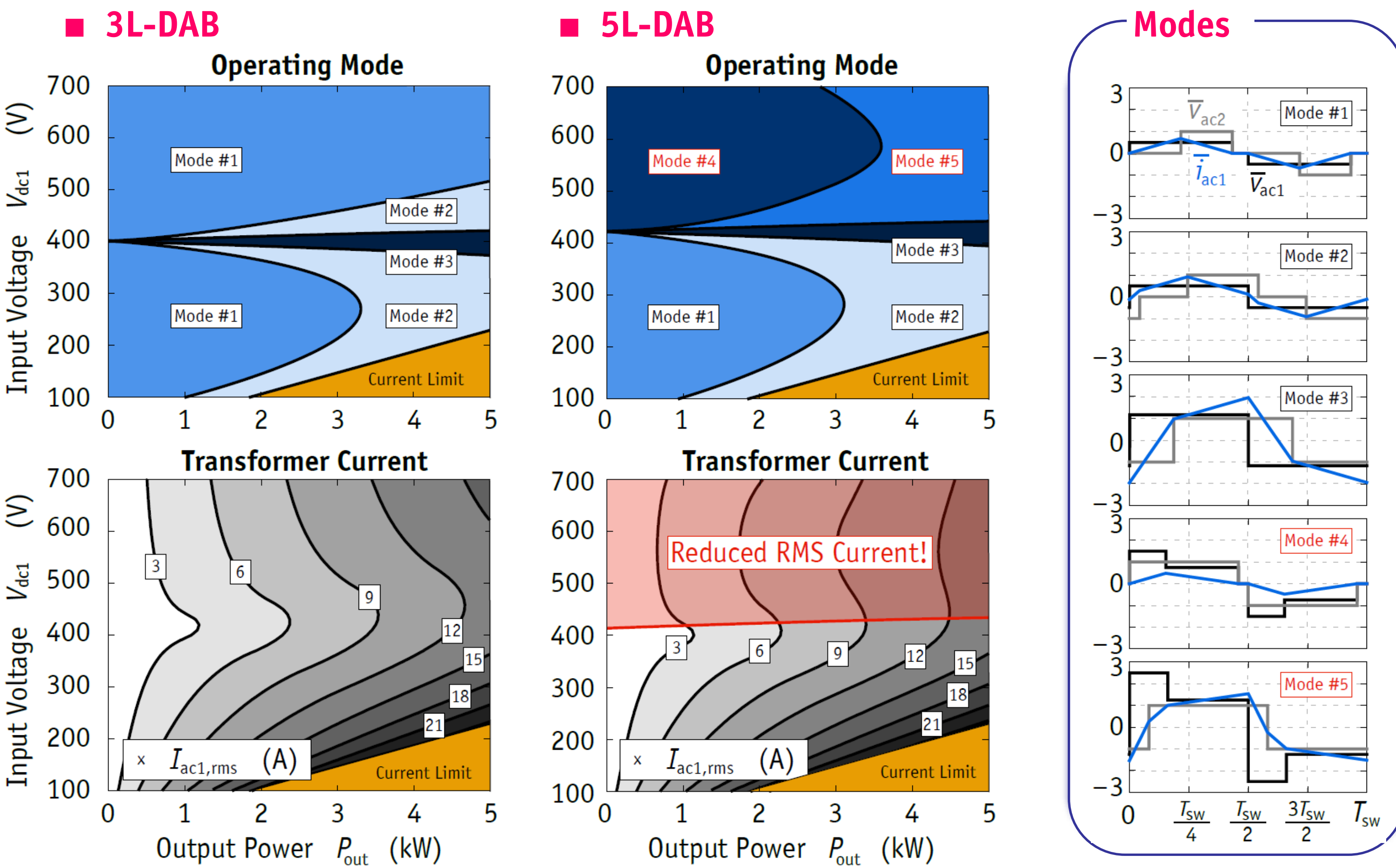
Choose $\vec{\Xi}$ so as to Minimize Transformer RMS current I_{ac1rms}

$\vec{\Xi}_{\mathrm{3LDAB}} = (D_{1b}, D_{1b}, D_2, 0, \varphi_{12})^\top$ $\vec{\Xi}_{\mathrm{5LDAB}} = (D_{1a}, D_{1b}, D_2, \varphi_{ab}, \varphi_{12})^\top$

$$\vec{\Xi}^* = \arg\min_{\vec{\Xi}} \; I_{\mathrm{ac1,rms}}(n^*, L_\sigma^*, \vec{\Lambda}^*, \vec{\Xi})$$

with $\vec{\Lambda}^* = (V_{\mathrm{dc1}}^*, V_{\mathrm{dc2}}^*, P_{\mathrm{out}}^*)^\top$

▶ Converter Modulation Schemes



Main Components and Materials

3L-DAB

- Cree SiC MOSFET 80 mΩ 1200 V TO-247
- 2x/1x on Input/Output Side

OR

- Infineon Si IGTB T&F 25 A 1200 V TO-247
- 2x/1x on Input/Output Side

5L-DAB

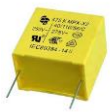
- Scaled Cree SiC MOSFET 600/1200V TO-247
- Variable Chip Sizes with Equal Semiconductor Costs as SiC 3L-DAB

OR

- Infineon Si IGTB T&F 30/25 A 600/1200 V TO-247
- 1x/1x on Input/Output Side

- Optimized Aluminum Heat Sinks
- Range of Low Power DC Fans

- EPCOS N87 Ferrite E & ELP Cores
- Litz Wire with Range of Strand Diameters

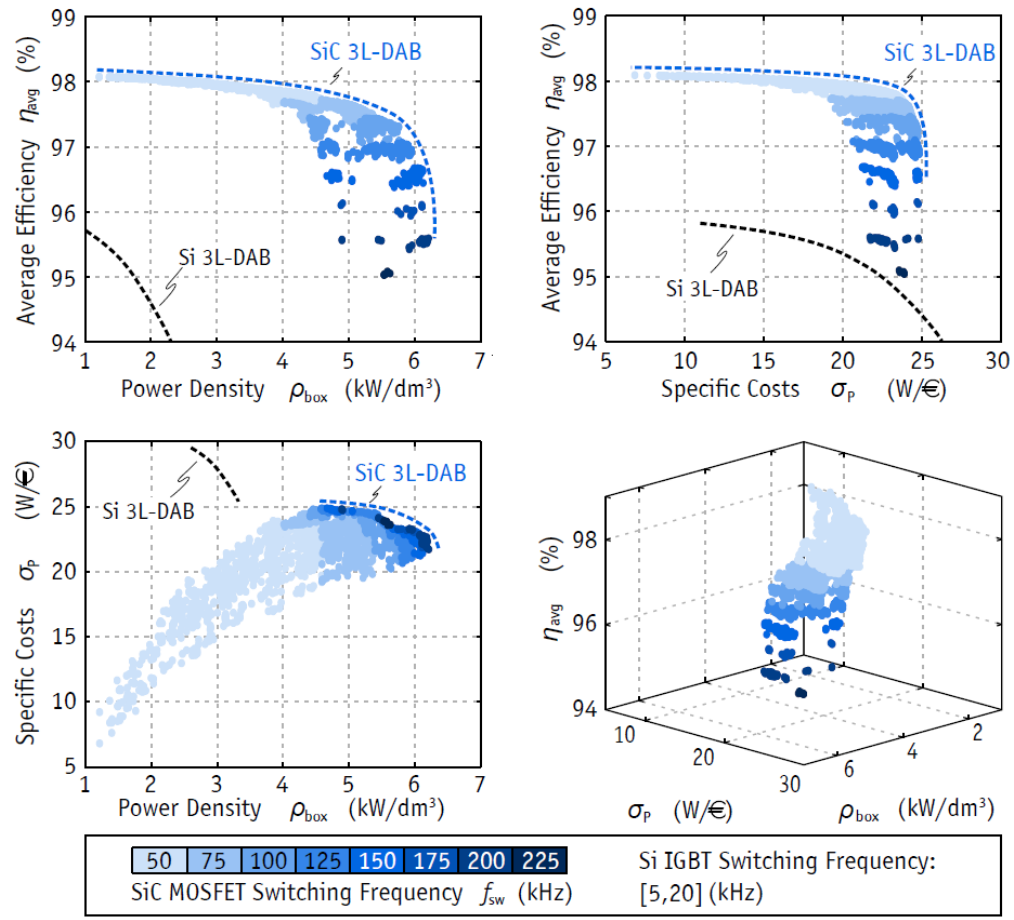


- EPCOS MKP DC Film Capacitors
- 575/1100V Rated

▶ Optimization Results (1)

- **3L-DAB: SiC MOSFET vs. Si IGBT**
  - Higher Power Density of SiC Due to Higher Achievable f_{sw}
  - Higher Efficiency of SiC
    - ▶ Soft Switching (ZVS)
    - ▶ Ohmic Characteristics in Part Load
    - ▶ Smaller Magnetics
  - Higher Initial Costs of SiC Compensated by Lower…
    - ▶ Housing Costs
    - ▶ Installation Costs
    - ▶ Energy Costs (Losses)

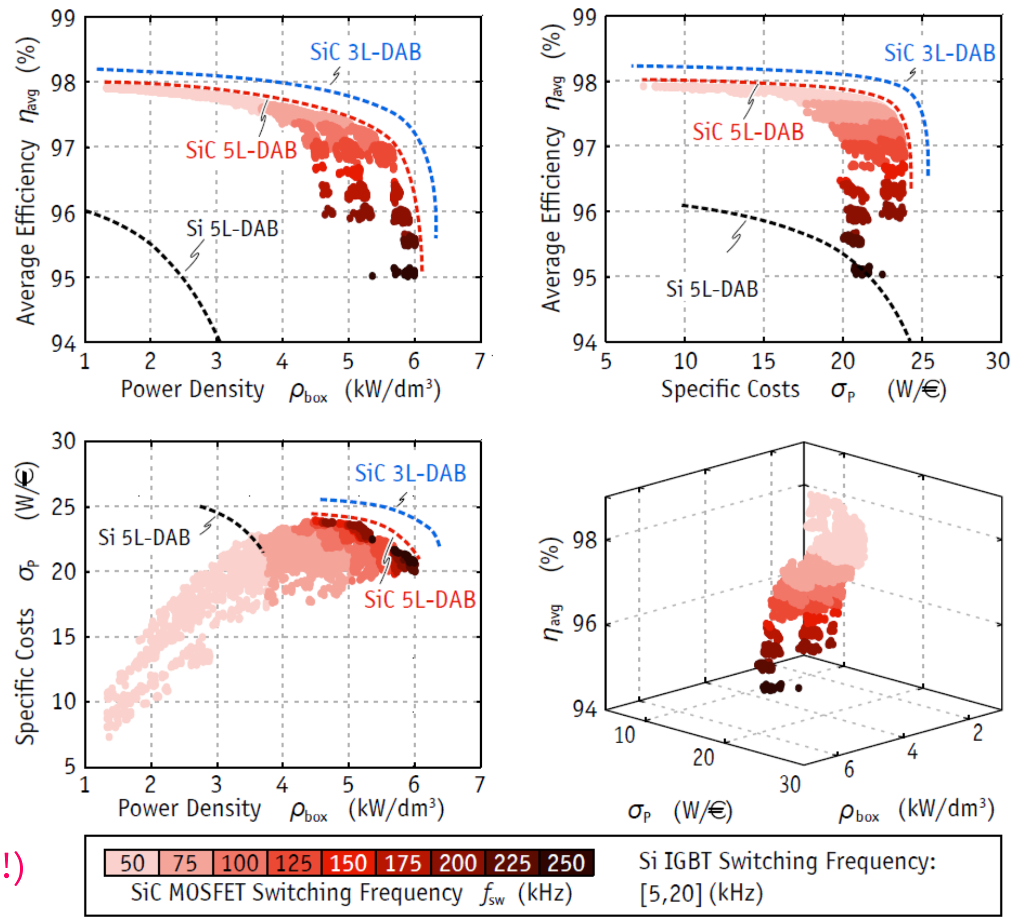
- **SiC MOSFET Clearly Superior!**



▶ Optimization Results (2)

- **SiC 3L-DAB Superior over SiC 5L-DAB**
  - More Efficient
    - ▶ Better Chip Area Utilization Overcompensates Higher RMS Currents
  - Higher Power Density
    - ▶ Smaller Capacitors As No Midpoint Balancing Required
  - Lower Costs
    - ▶ Lower # of Gate Drivers
  - Simpler and More Reliable

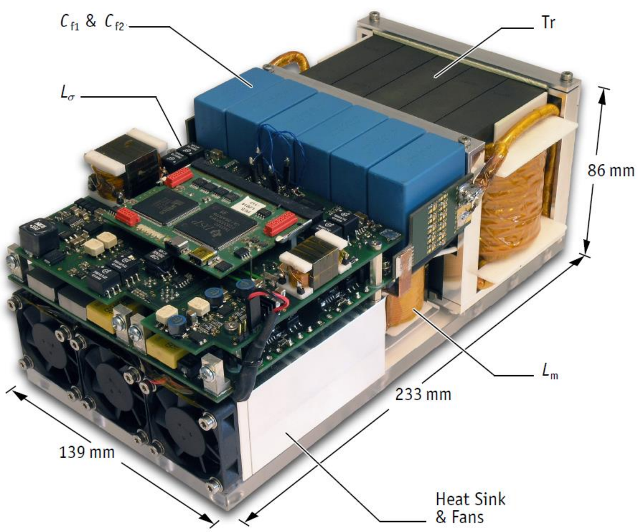
- **Power Density Limitation**
  - Limited Relative Dead Time
    - ▶ Less Charge Available at High f_{sw}
    - ▶ Loss of Complete ZVS
  - Capacitive Parasitics (Packaging!) As Limiting Factor

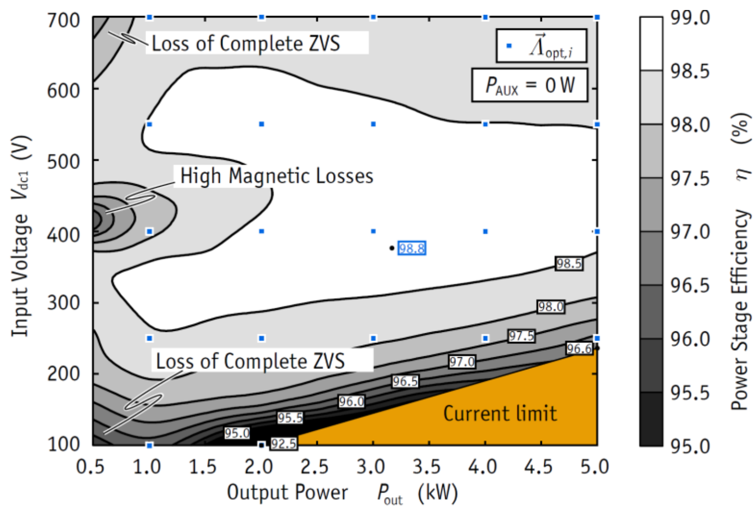


▶ Experimental Verification – Hardware Prototype

- **SiC 3L-DAB Hardware Prototype**
  - P = 5 kW
  - f_{sw} = 48 kHz
  - V_i = [100,700] V
  - V_o = 750 V

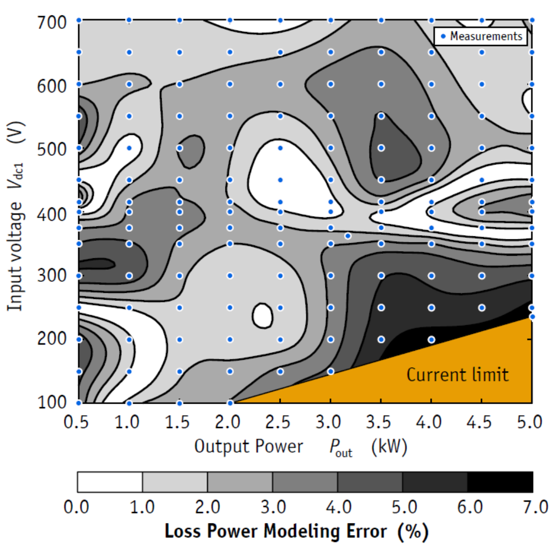
- **Power Density 1.8 kW/dm^3**
- **Peak Efficiency 98.5 %**
- **Average Efficiency 97.6 %**
- **High Efficiency / Power Density Despite High Level of Functionality**

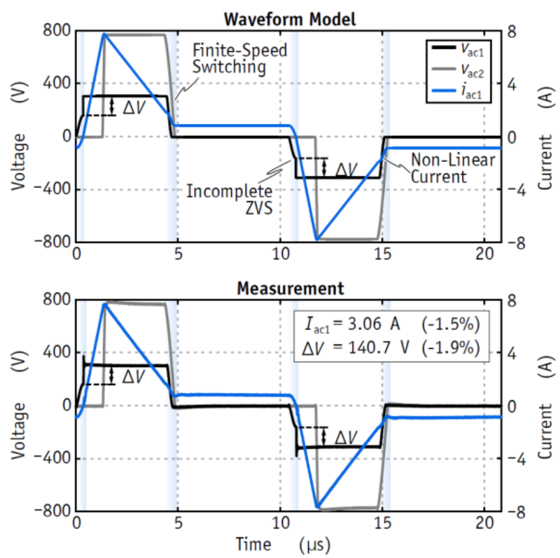


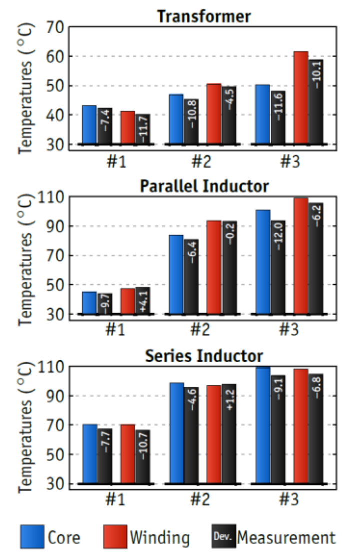


▶ Experimental Verification – Model Accuracy

- **Excellent Loss Model Accuracy**
  - Mean Error: 2.5 %
  - Max. Error 6.8 %
- **High Waveform Model Accuracy**
  - Non-Linear Switching Transitions
  - Incomplete ZVS
- **High Thermal Model Accuracy**
  - Error Range: -15/+5 %
  - Conservative



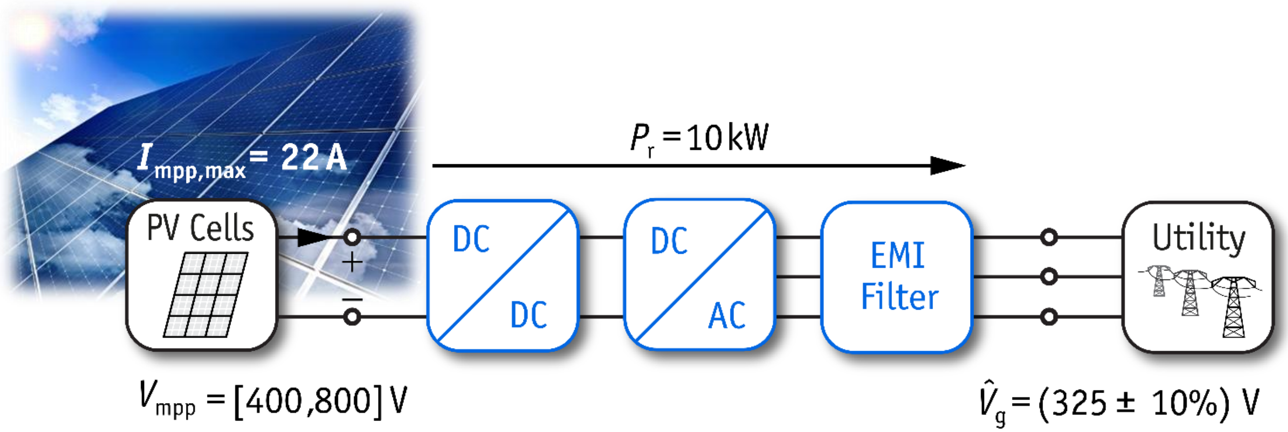




Results Case Study II:
DC/AC Converter System

Residential PV Application
Concepts
Multi-Objective Optimization
LCC Analysis

▶ PV Converter System for Residential Applications

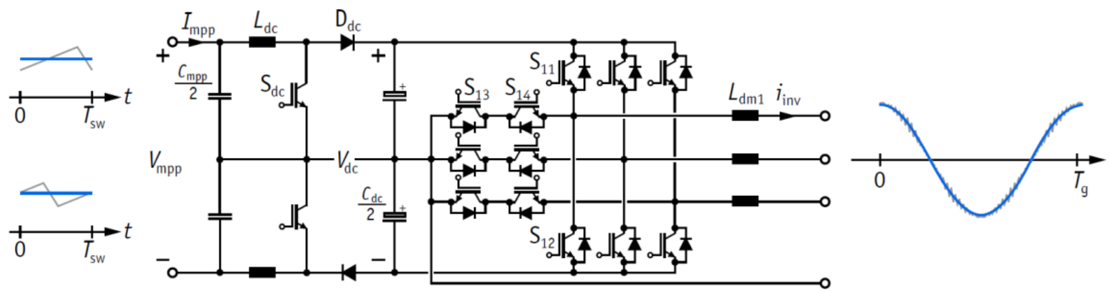


- **3-Stage Multi-String 3-Phase PV Converter System**
  - Boost Stage (MPP Voltage Range)
  - DC/AC Inverter Stage
  - EMI Filter Stage

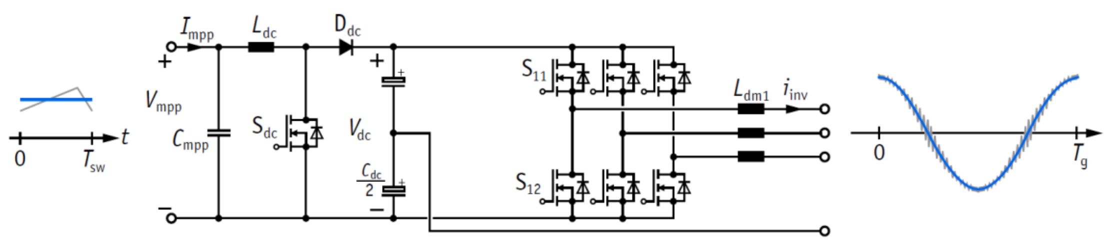
- **Systematic η-ρ-σ-Comparison of Si vs. SiC**
  - Does SiC offer Advantages in PV?
  - Find Useful Frequency Ranges
  - Find Appropriate Core Material

Converter Topologies and Modulation Schemes

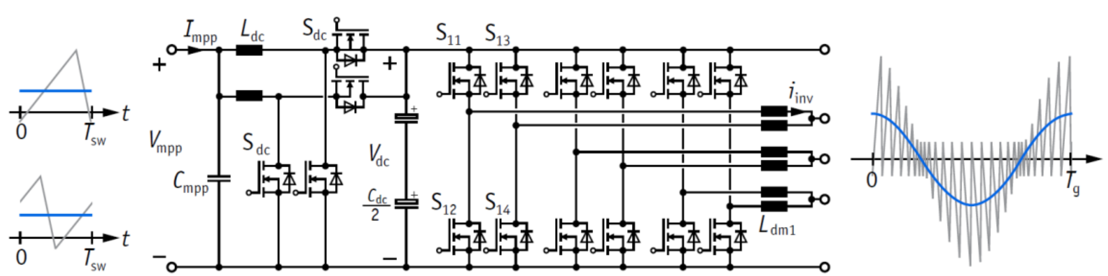
- All Si IGBT
  3-Level PWM
  Inverter
  (3L-PWM)



- All SiC MOSFET
  2-Level PWM
  Inverter
  (2L-PWM)



- All SiC MOSFET
  2-Level Double-
  Interleaved TCM
  Inverter
  (2L-TCM)



Main Components and Materials

Power Semiconductors

3L-PWM

- 6 x Infineon Si IGBT H3 25 A 1200 V / PiN Diode
- 6 x Infineon Si IGBT T&F 30 A 600 V / PiN Diode
- 2 x Infineon Si IGBT T&F 30 A 600 V
- Infineon Si PiN Diode 45 A 600 V

2L-PWM

- 7 x CREE SiC MOSFET 80 mΩ 1200 V
- 1 x CREE SiC Schottky Diode 20 A 1200 V

2L-TCM

- 16 x CREE SiC MOSFET 80 mΩ 1200 V

Cooling System

- Optimized Aluminum Heat Sinks
- Range of Sanyo Low Power Long Life DC Fans

Main Induct.

- METGLAS 2605SA1 Amorphous Iron C Cores
- Solid Round Wire

OR

- EPCOS N87 Ferrite E Cores
- Litz Wire With Range of Strand Diameters

DC Caps

- EPCOS MKP DC Film Capacitors 575V and 1100 V for MPP Cap.
- EPCOS Long Life Al Electrolytic Capacitors 500 V for DC-Link Cap.

Filter

- EPCOS X2 (DM/CM) and Y2 (CM) EMI Capacitors
- Magnetics KoolMu Gapless Powder Cores / Solid Round Wire (DM)
- VAC Vitroperm 250F/500F Nanocrystalline Toroid Cores / Solid Round Wire (CM)

▶ Main Virtual Prototyping Routine

- **Additional Task: EMI Filter Design**
  - Filter Component Values as Dependent System Parameters
  - Off-Line Filter Optimization

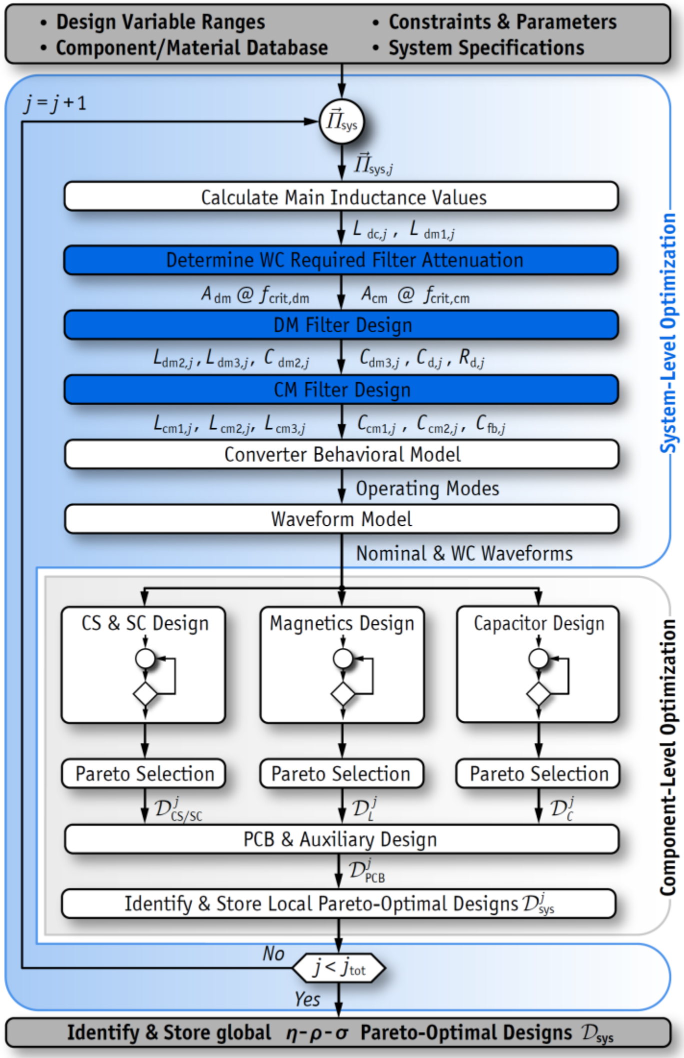
- **Global System Design Variables**
  - Topologies: {3L-PWM, 2L-PWM, 2L-TCM}
  - Switching Frequency
  - Main Inductance Values / Current Ripple

$$\vec{\Pi}_{\text{sys}}^{\text{2LPWM}} : f_{\text{sw}} \in [12,72]\ \text{kHz}\,,\quad \Delta I_{L,\max}^{\text{pp}} \in [5,60]\ \%$$

$$\vec{\Pi}_{\text{sys}}^{\text{3LPWM}} : f_{\text{sw}} \in [6,36]\ \text{kHz}\,,\quad \Delta I_{L,\max}^{\text{pp}} \in [5,60]\ \%$$

$$\vec{\Pi}_{\text{sys}}^{\text{2LTCM}} : f_{\text{sw,min}} \in [12,84]\ \text{kHz}\,,\quad k_{f_{\text{sw}}} \in [4,12]$$

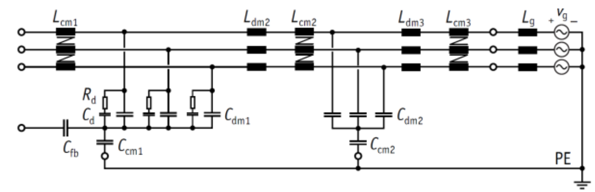
- **Largely Application-Invariant Component Design Routines**



EMI Filter Design Routine

Requirements for EMI Filter Design

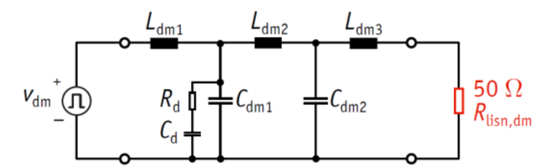
- Determination of DM and CM Harmonic Spectra
- Math. Descr. of Non-Linear QP-Detector Circ.
- Appropriate Routine for Component Selection



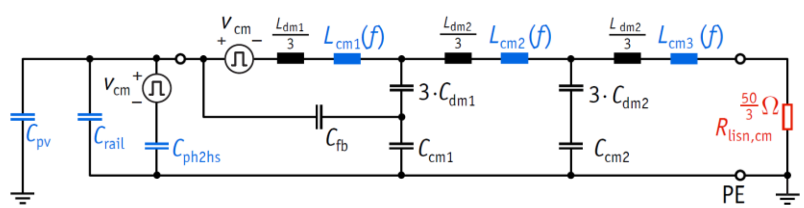
Additional Challenges

- Frequency-Dependence of CM Inductors
- Parasitic Capacitances of Semiconductors to Heat Sink
- Variable Solar Generator Stray Capacitance to Ground

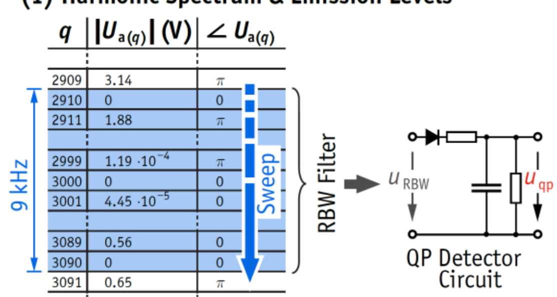
DM ▶ Equiv. Circ.



CM ▶ Equiv. Circ.

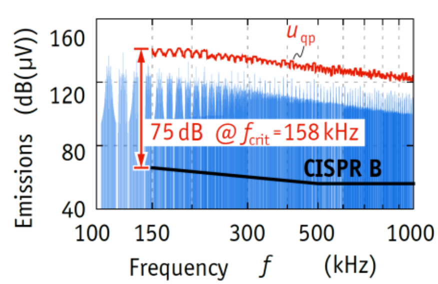


(1) Harmonic Spectrum & Emission Levels

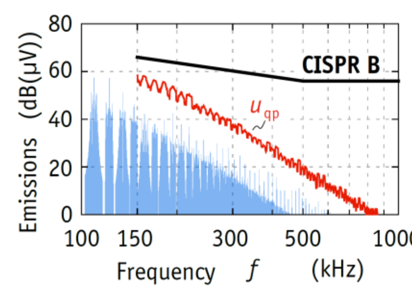


q	$\lvert U_{a(q)} \rvert$ (V)	$\angle U_{a(q)}$
2909	3.14	π
2910	0	0
2911	1.88	π
2999	$1.19 \cdot 10^{-4}$	π
3000	0	0
3001	$4.45 \cdot 10^{-5}$	0
3089	0.56	0
3090	0	0
3091	0.65	π

(2) Required Attenuation



(3) Filter Component Design

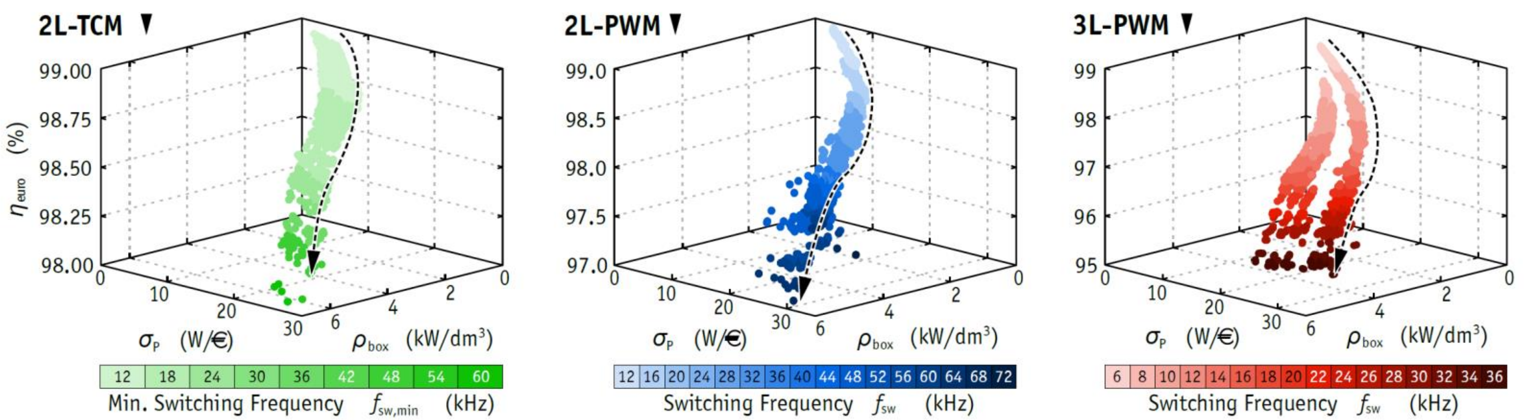


▶ Optimization Results – Pareto Surfaces

- **Total of 48 Design Variables**
- **> 400 000 Pareto-Optimal Designs**

- **Resulting Core Materials**
  - EPCOS Ferrite N87
    ▶ Dominant Results in all Topologies
  - METGLAS Amorphous Iron 2605SA1
    ▶ Dominant Results Only for 3L-PWM

Pareto Surfaces & Sampling Trajectories



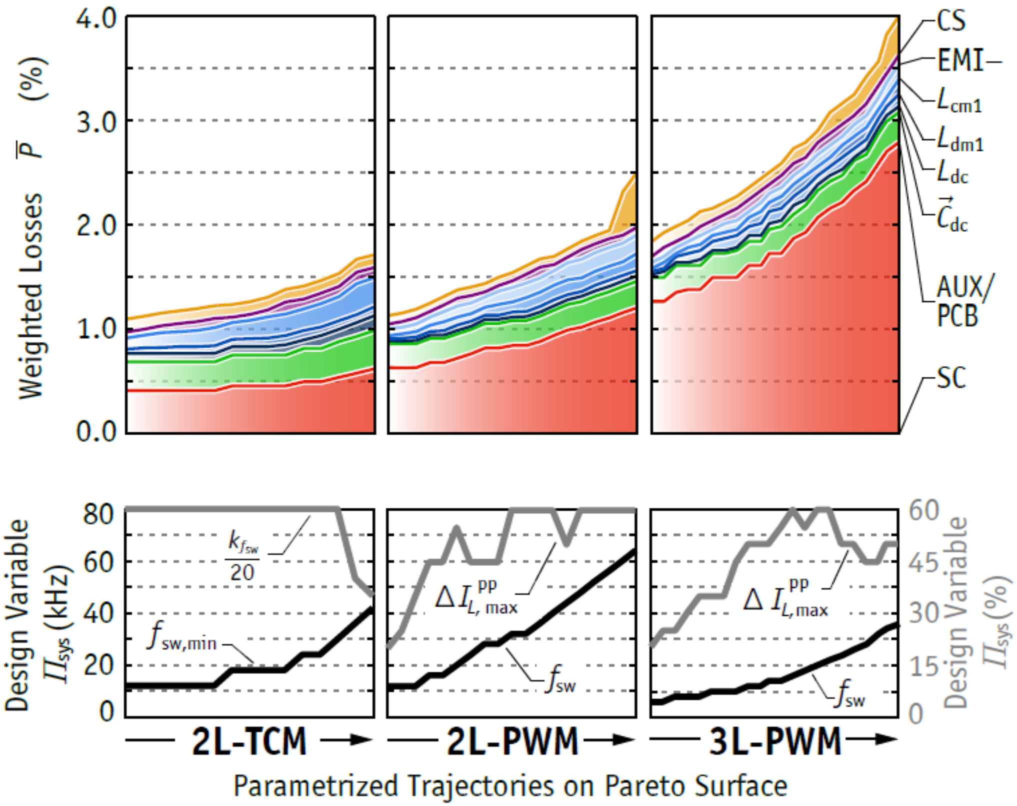
▶ Optimization Results – Pareto Surface Investigations

- **Comparison of Concepts**

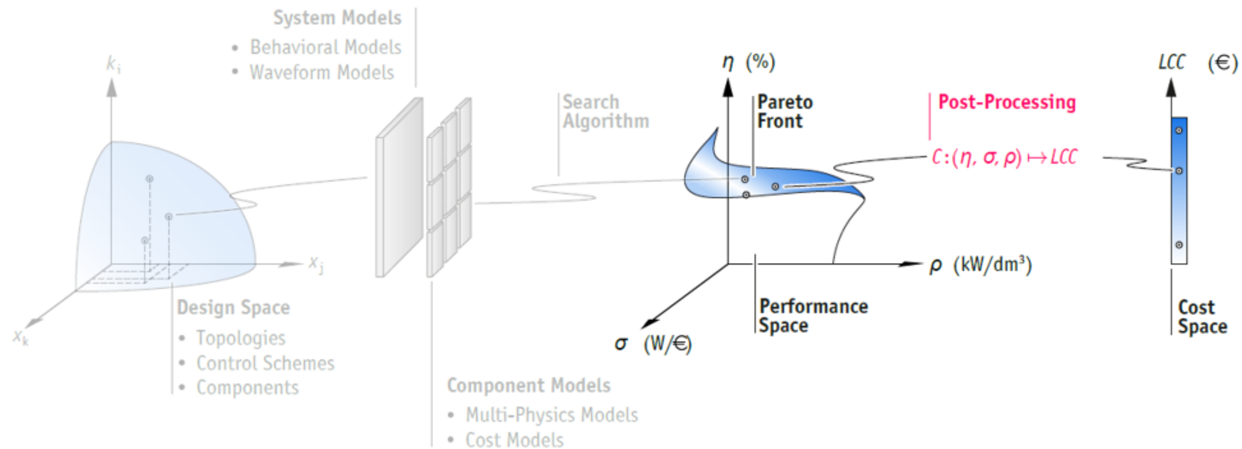
	η	ρ	σ
• 2L-TCM	🙂	🙂	🙁
• 2L-PWM	😐	😐	🙂
• 3L-PWM	🙁	🙁	🙂

- **All Concepts Exhibit Both Advantages / Disadvantages**

- **Which is the...**
  ...Best Concept?
  ...Best Dimensioning?



▶ Optimization Results – LCC Post-Processing



- **Mapping into 1D Cost Space to Facilitate Selection of Candidate System**
- **Proposed:**

Life Cycle Costs (LCC) / Net Present Value (NPV) Analysis

$$LCC = \Sigma_{\text{components}} + \sum_{n=1}^{N_{\text{life}}} \left[\Sigma_{\text{capital}}(q) + \Sigma_{\text{loss}}(\sigma_{\text{kWh}}) \right] \cdot \frac{1}{(1+q)^n}$$

$N_{\text{life}} = 10$ years $\quad q = 5\ \%/\text{year} \quad \sigma_{\text{kWh}} = 0.2\ €/\text{kWh}$

▶ Optimization Results – LCC Post-Processing

■ Best System

SiC 2L-PWM @ 44kHz/50% Ripple

- 22% Lower LCC than Si 3L-PWM
- 5% Lower LCC than SiC 2L-TCM

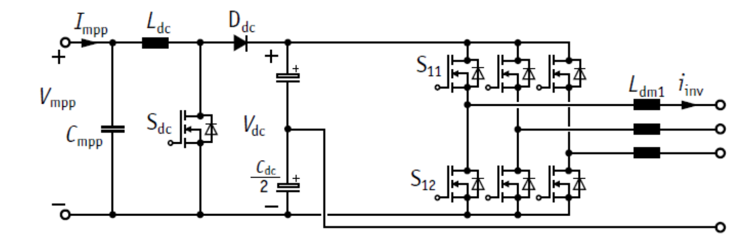
■ Further Advantages

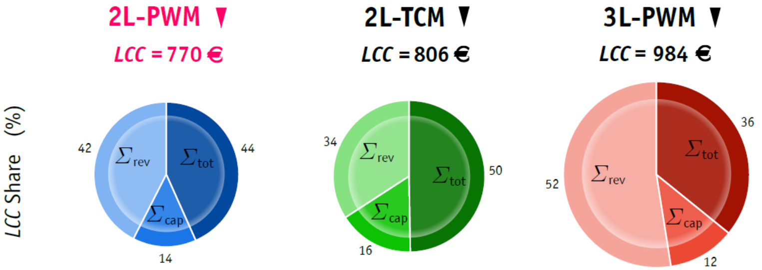
- By Far Simplest Design
- Lowest Engineering/Manufacturing Costs
- Presumably Highest Reliability

■ Unique Benefits from Combination SiC / 2L Topology / High-Ripple Op.

- 2L Topology
  - ▶ Highest Chip Utilization
  - ▶ Lowest Component Costs
- High Ripple
  - ▶ Inexpensive Ferrite Inductors
  - ▶ ZVS in Part Load Operation

Best System: SiC 2L-PWM





$\Delta I^{pp}_{L,max}$	50 %		50 %
f_{sw}	44 kHz	[24, 288] kHz	18 kHz
$\bar{P}_{tot}$	1.77 %	1.48 %	2.79 %
$V_{box,tot}$	2.17 dm^3	1.75 dm^3	2.81 dm^3
Σ_{tot}	335 €	402 €	354 €

► Summary & Conclusions

- **Advanced Virtual Prototyping Design Methodology for η-ρ-σ Multi-Objective Optimization of Power Electronic Converter Systems**

- **Usefulness of Implemented Virtual Prototyping Routine**
  - Solution to Complex Problems Feasible (48 Design Variables Demonstrated)
  - Extensive and Accurate of Modeling Framework
  - Unprecedented Detail of Results
  - Multitude of Post-Processing Possibilities (e.g. LCC Analysis)

- **Case Studies: i) Bidirectional Isolated Wide-Voltage-Range DC/DC and ii) PV DC/AC Converter Systems**
  - Only Multi-Objective Approach on System Level Can Reveal the Full Potential of SiC
  - Combinations of SiC and Simple Topologies are Superior

SiC ►
- **Higher Efficiency / Power Density @ Same Costs**
- **Lower Complexity / Higher Reliability**
- **Higher Functionality**

Questions