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Vishay Diodes Group

NEW FRED Pt® GEN 5:

THE OPTIMIZED SOLUTION FOR CHARGING APPLICATIONS

Market Development Diodes

Objectives

- Insight on today's power electronic design challenges
- What is Fred Pt® Gen 5 all about?
- Fred Pt® Gen 5 diode solutions for unidirectional battery chargers
  - Introduction to battery chargers
  - Schematic with function description and diode stress related
  - Focus on input Vienna stage
  - Focus on LLC stage
- Key takeaways

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Design Challenges

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Future Marketing Trends

The evolution of energy conversion systems has sped up over the last few years, driven by two main factors:

- The development of a **sustainable mobility** based on electrical and hybrid vehicles
- The need to efficiently utilize **alternative energies** to the combustion of fossil fuels

This evolution requires all manufactures and users of conversion systems connected to the grid to redesign their products in order to make them more **Flexible, Light, and Efficient.** Only in this way can we face the future challenge of global electrification without risking a collapse of the electric grid.

An efficient energy conversion based on advanced semiconductor technology can satisfy these requirements, without sacrificing tight control over component costs to remain competitively price on the open market.

The Challenges in Today's Power Electronic Designs

Trends for Power Electronic Designs

- Usage of faster switching devices to obtain higher efficiency
- A higher speed of power semiconductor may introduce more EMI issues
- Usage of devices enables a smaller form factor (higher power density)
- Adopt solutions (components and topology) without increasing costs
- Reliability and ruggedness of power designs

Fred Pt® Gen 5 Technology

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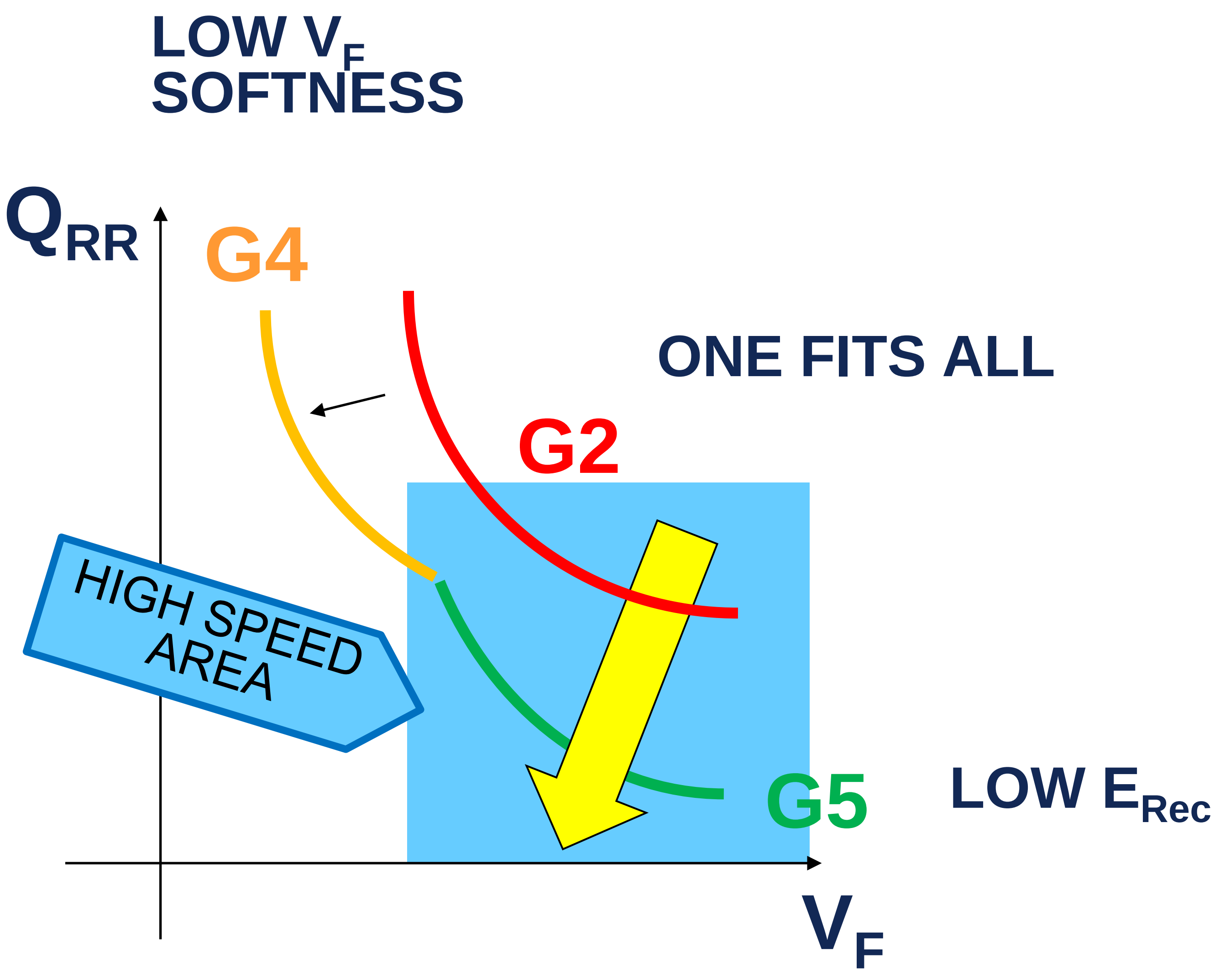
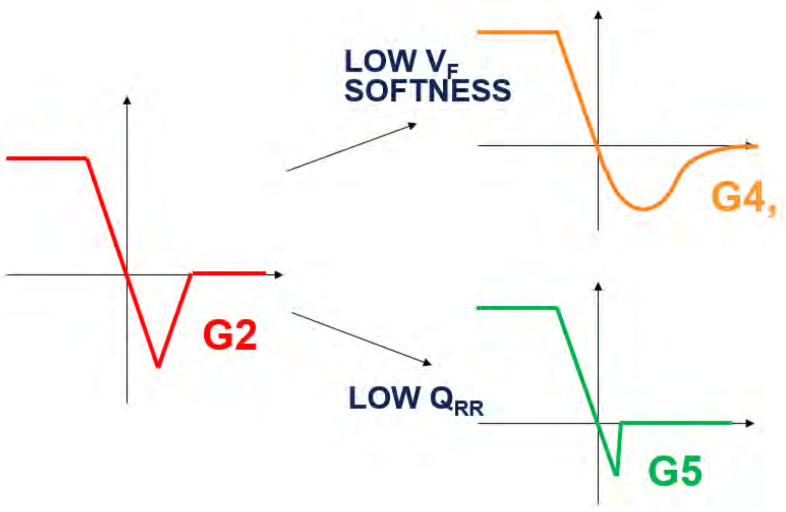
FRED Pt® Ultrafast Platform Performances at a Glance





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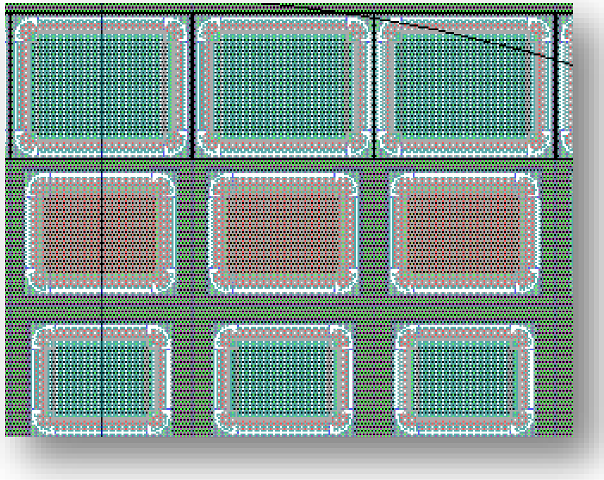
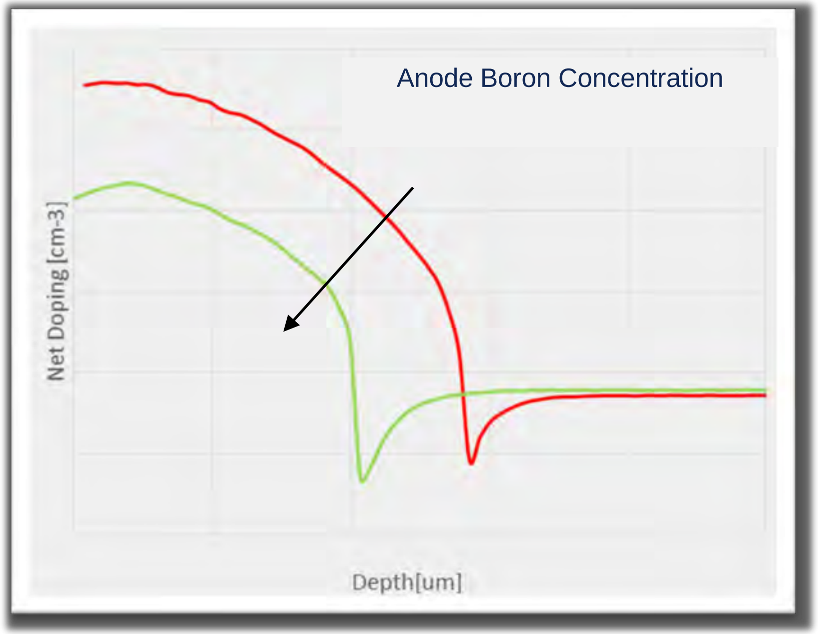
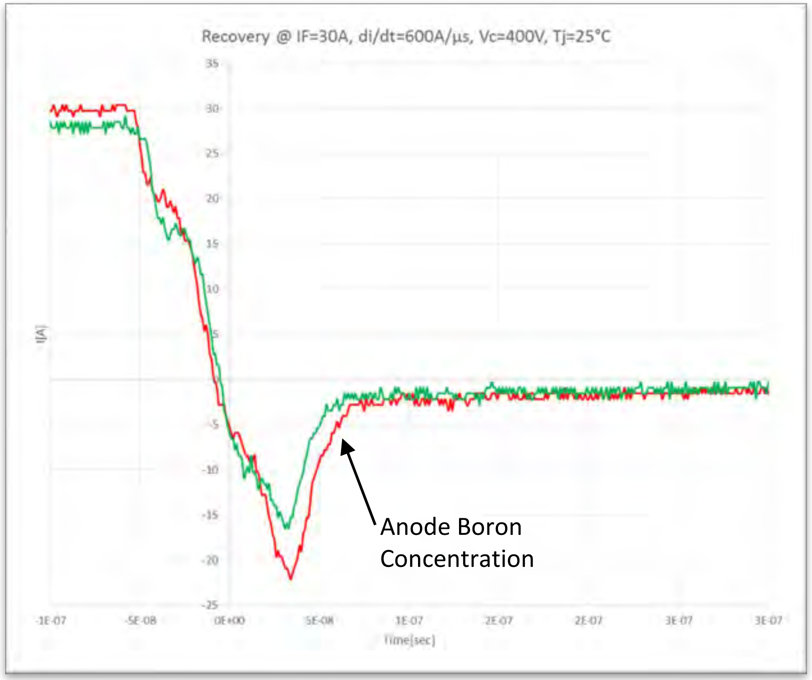
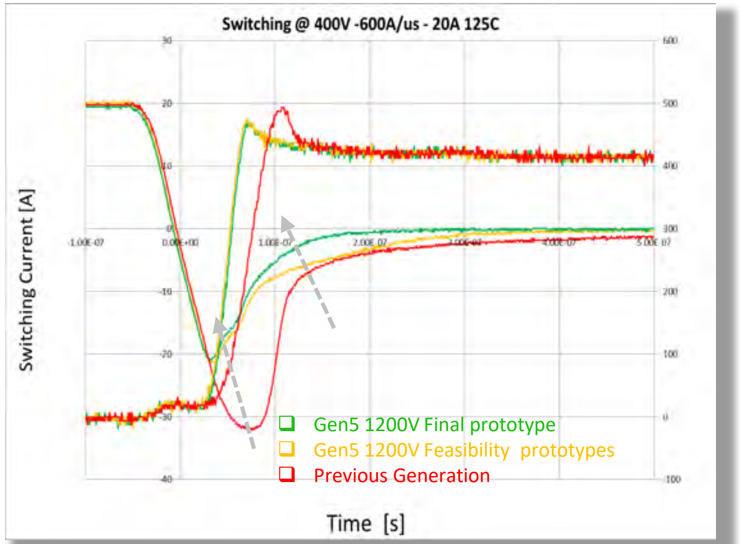
- Free carrier injection from the anode side controlled with an anode doping profile
- Lower injection allows for faster carrier removal during switching transitions → more efficient switching
- Lower Irrm and good softness are the result of optimized carrier injection from the anode side
- Chip size has been optimized to reach the best trade-off between conduction losses and Erec

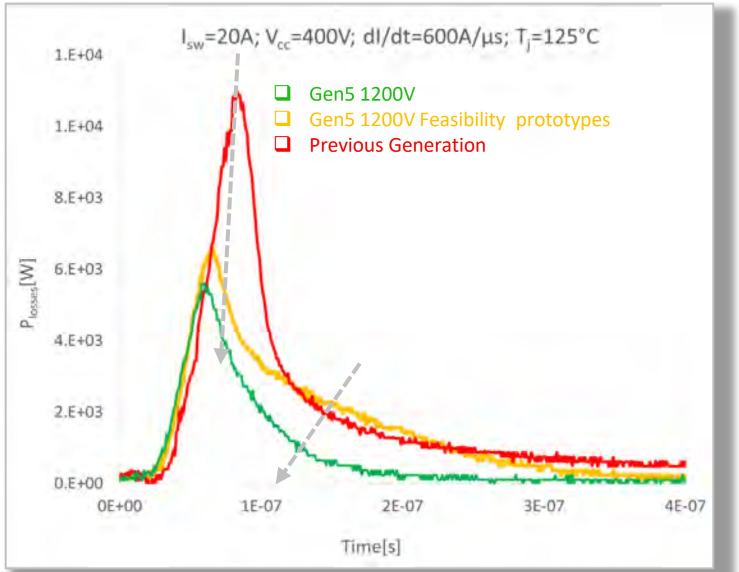






FRED Pt® Gen 5 1200 V – Hyperfast Recovery Diode

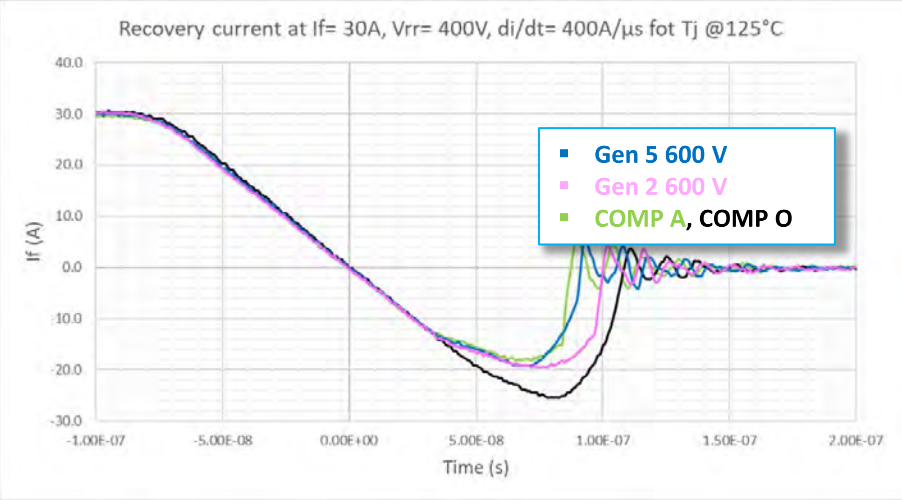




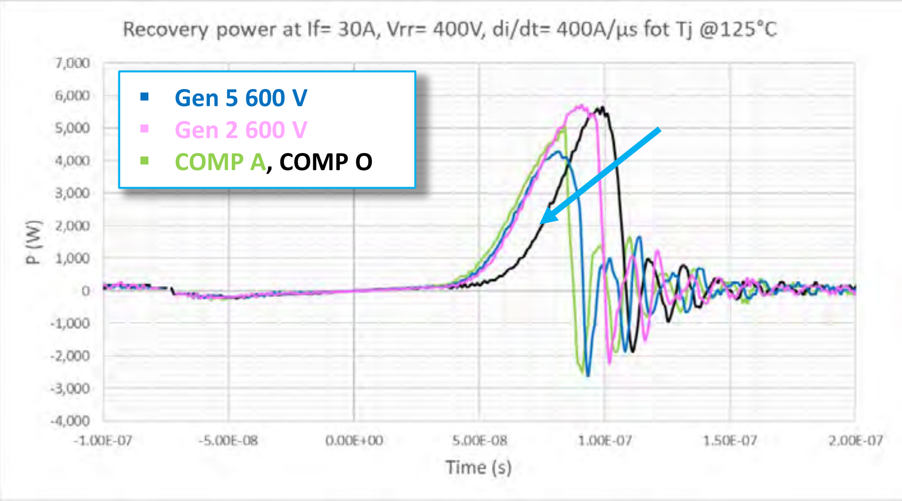
P/N	Erec (uJ)	Delta
Previous Generation	831	+92 %
Feasibility Prototype	605	+40 %
Best Competitor on Market	433	reference
Gen 5 1200 V Final Prototype	355	-18 %

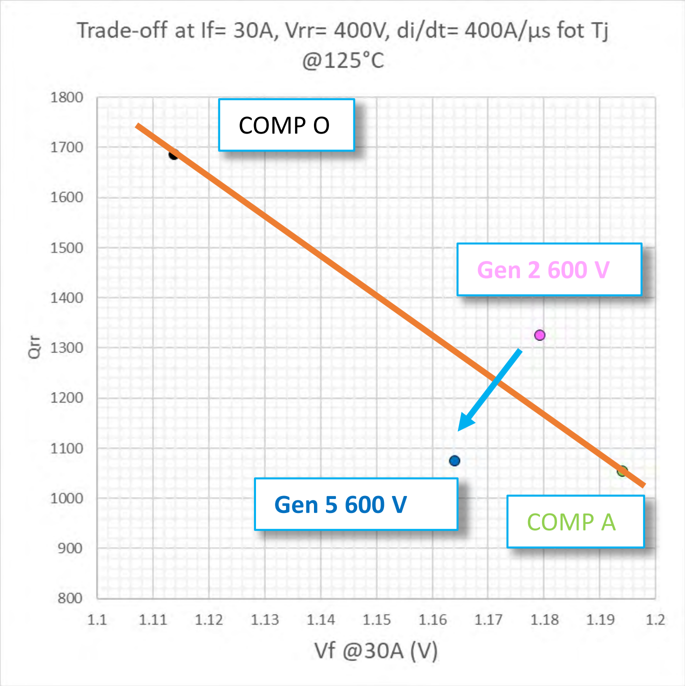
- More than 90 % improvement in Erec over the previous generation
- Lowest Erec among direct competitors
- -18 % of lost switching energy by fine-tuning and shaping the current recovery curve

FRED Pt® Gen 5 600V – Hyperfast recovery diode



P/N	V_F (V)	Erec (uJ)	Delta
COMP O	1.12	160	+33.3 %
Gen 2 600 V	1.18	178	+48.3 %
COMP A	1.20	123	~5 %
Gen 5 600 V	1.16	120	reference





- More than a 30% improvement in Erec compared to the previous generation
- Lowest Erec among direct competitors
- Best trade-off of Erec vs. V_F

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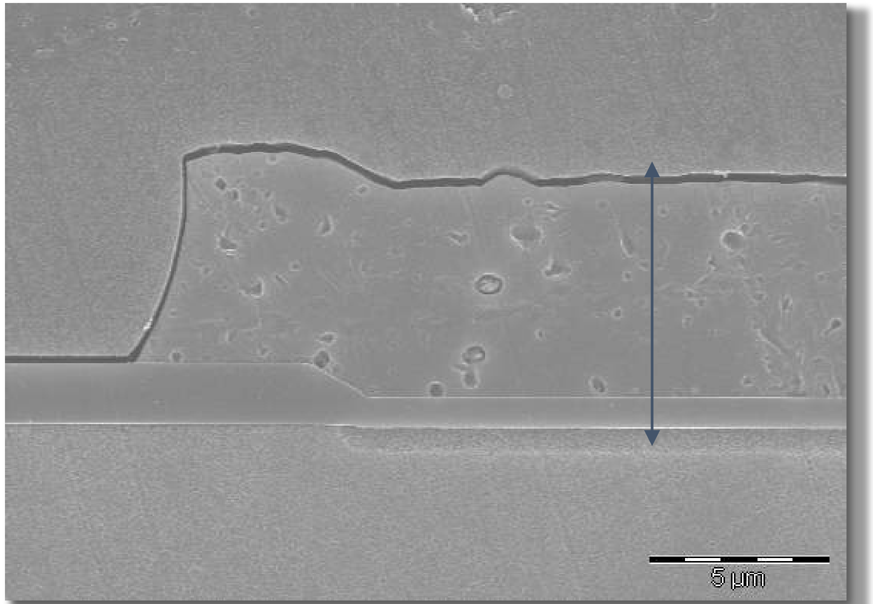
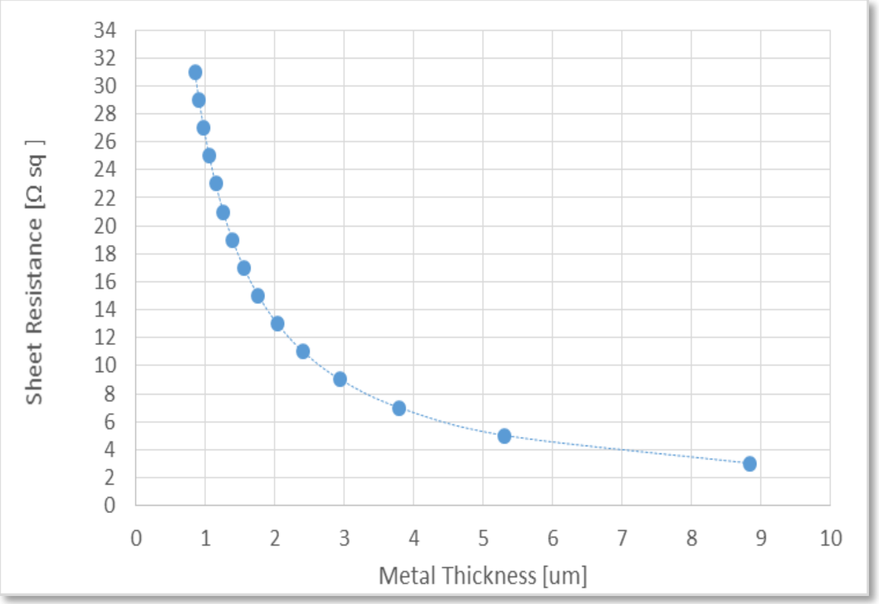
- Front metal thickness increased for diode ruggedness and reliability





- Improved metal contact sheet resistance with reduced forward voltage drop at high current

- Improved robustness to bonding and testing processes

- Extra boost to high current capability due to lower sheet resistance

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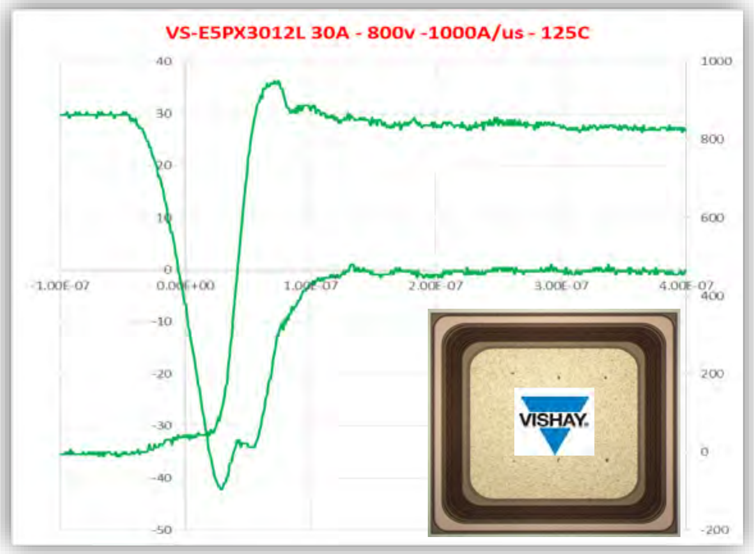
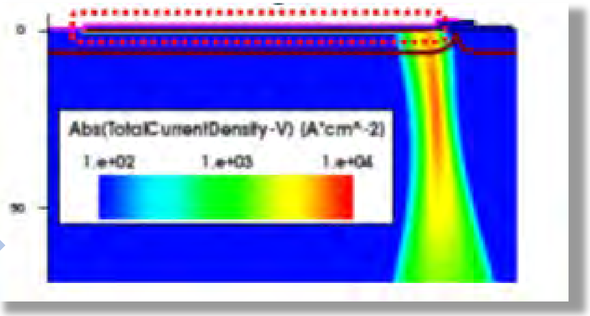
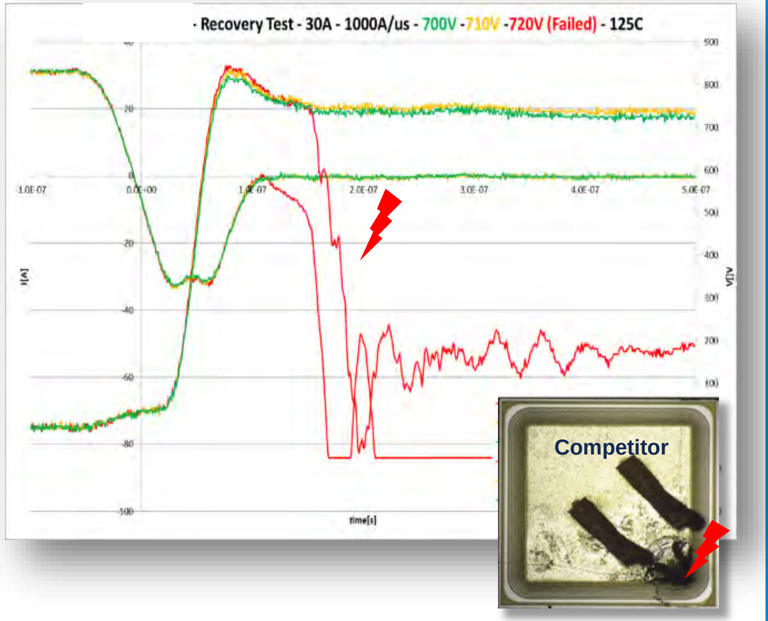
FRED Pt® Gen 5 1200 V - Technologies





Fully optimized design: simulated reverse current density capability



- Die termination has been redesigned to improve REOS
- Capability to withstand high voltage and high-density current switching

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Fred Pt® Gen 5 for Unidirectional Battery Charger

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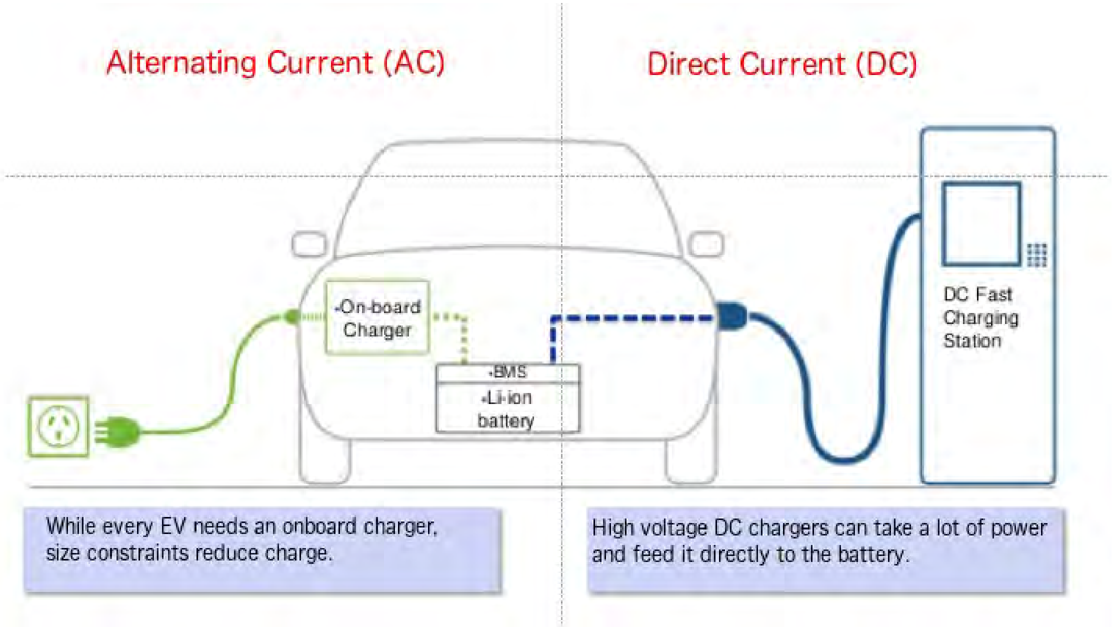
Introduction to Battery Chargers

Battery chargers are mainly divided into two families: fast battery chargers (fixed stations) and on-board battery chargers (OBC).

Usually fast chargers are unidirectional, have a large amount of available power, are supplied with 3-phase lines, can work with high power bypassing onboard chargers (ex. CHAdeMo 2.0 could provide 400 kW), and automatically match the battery’s voltage requirement.

OBCs are smaller and can be connected to many power sources, like 110 Vac 1-phase to 3-phase 400 Vac, and the range of power goes from 3 kW to 22 kW. They are usually unidirectional chargers but are sometimes divided into two sections: one unidirectional with the largest power and another bidirectional to allow for the possibility of AC voltage on the vehicle.



User — Bidirectional 1.5 kW — kW

Grid — Unidirectional — **kW**

Vehicle battery

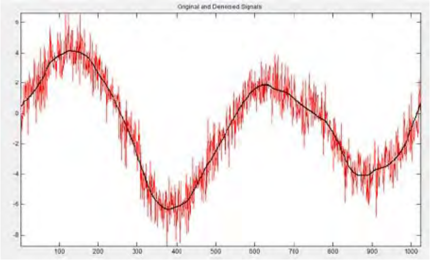
Introduction to Battery Chargers

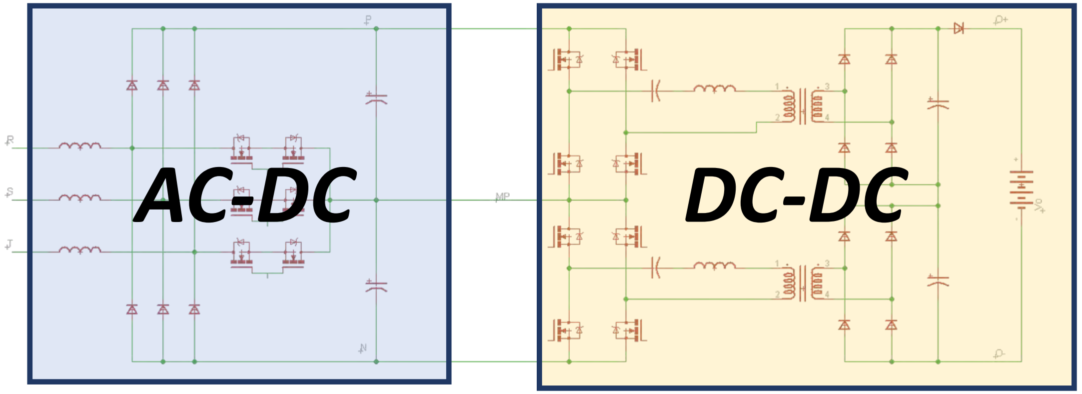
A battery charger is a complex system that should interface with the AC line with his characteristic (not always as expected) and with a delicate system that is the vehicle battery. To guarantee the energy capability and long of the vehicle’s battery, it needs to be charged to a precise value.

To meet these requirements, the battery charger is built with two stages:

1) The AC/DC stage should be the most “resistive load” for the grid to avoid reactive current and EMI noise, and at the same time should be robust enough to withstand all disturbances present on the grid (deep voltage, discontinuity, voltage surges)
2) The DC/DC stage should be able to provide the right output voltage at any load condition fixed by the charge state of the battery, and for fast charging, also requires the capability to adapt to the different battery types that can be connected at the charging station

340 Vac to 440 Vac

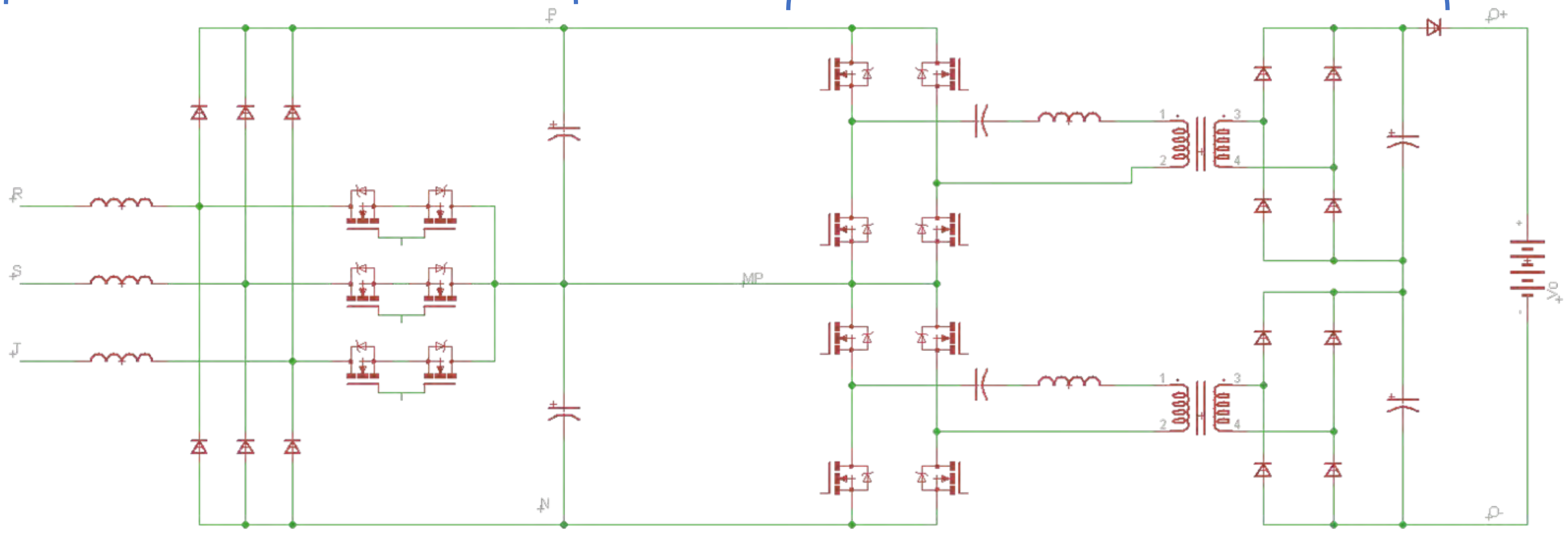




300 V to 800 V

Typical Fast DC Off-Board Battery Charger From 7 k to MW

AC/DC | **DC/DC**

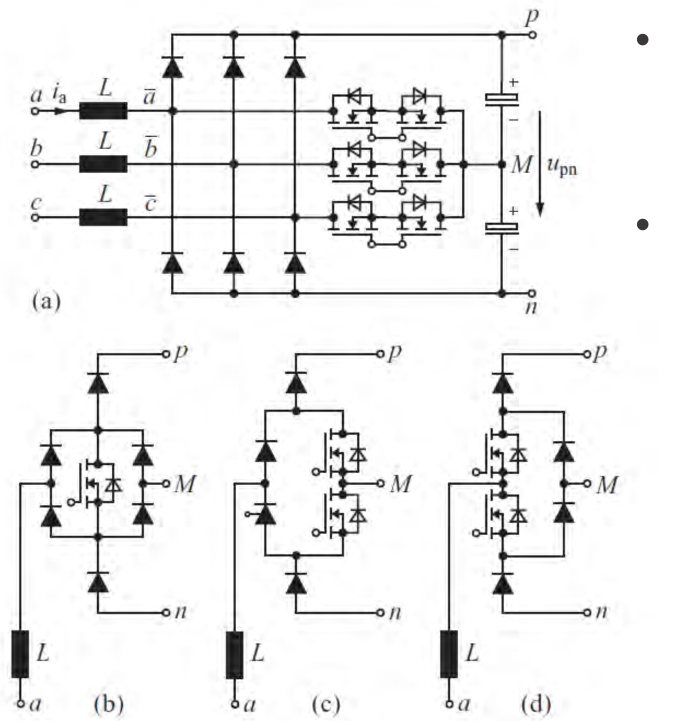


The input stage AC/DC is typically a 3-phase PFC implemented with a T-type Vienna circuit that requires a 1200 V diode and a 600 V MOSFET.

The output stage DC/DC is typically a stack configuration because it allows for the use of a 600 V device for the active switch and rectifier.

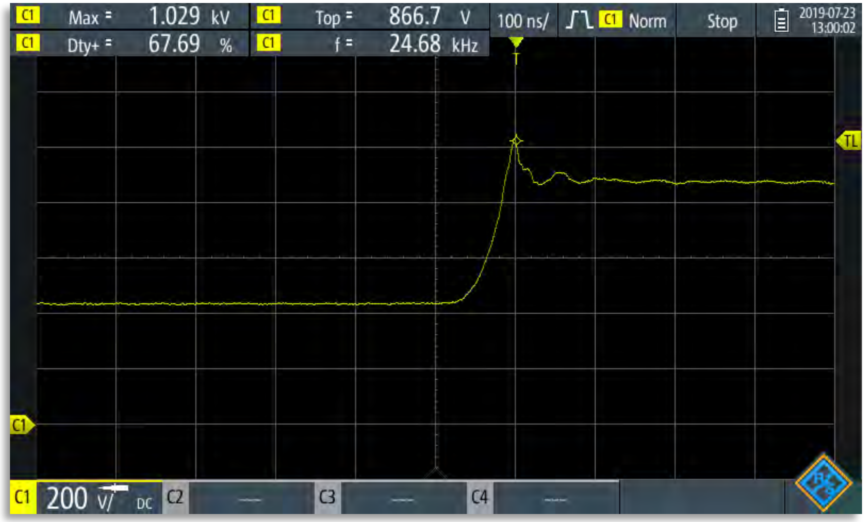
AC/DC With Vienna Rectifier

The criteria for the selection of suitable three-phase PFC rectifier topologies are as follows: sinusoidal input currents (typically a THDi < 3 % is required); ohmic behavior at the line frequency; a controlled DC output voltage that is similar or higher than the amplitude of the line to line input voltage; single-stage power conversion; no galvanic isolation; unidirectional power flow, possibly with the (limited) capability of reactive power compensation; simple circuit topology that features “phase symmetry” and / or “bridge symmetry;” simple modulation and control schemes; and the possibility of achieving high efficiency and / or high power density in the vehicle.



IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 28, NO. 1, JANUARY 2013
The Essence of Three-Phase PFC Rectifier
Systems—Part I
Johann W. Kolar, *Fellow, IEEE*, and Thomas Friedli, *Member, IEEE*

- ***Pro:*** T-type Vienna rectifiers offer the best efficiency because they have the minimum number of “voltage drops” in series. In addition, they enable lower switching losses because the voltage during switching is only half of the DC bus
- ***Cons:*** Limitations include the inrush current, which should be controlled, and the voltage across the diode equals the voltage of the DC bus (despite being half during switching). The high voltage diode should also be fast



AC/DC With Vienna Rectifier

The diode should be able to switch in all conditions while keeping the same switching behavior.

C1: yellow voltage across diode

C2: green diode current

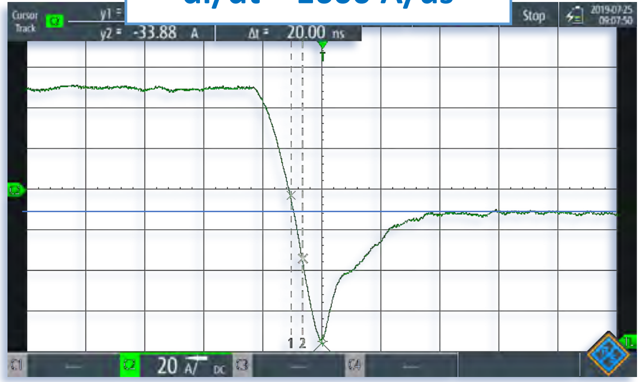
M: cyan instantaneous power Vd*Id

The diode's reverse recovery should have the lowest possible Erec to reduce the losses in the diode and the lowest Irrm to reduce losses induced in the active switch.

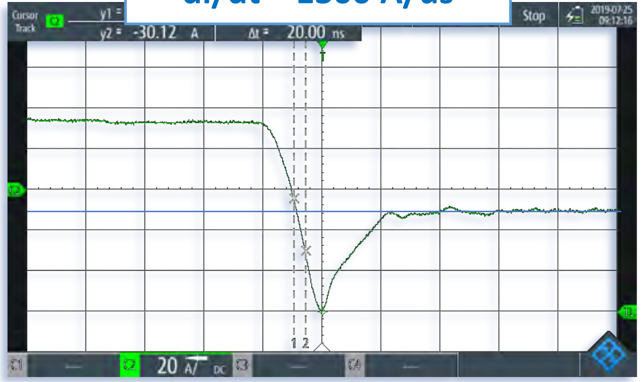
This keeps the recovery at a soft shape to avoid overvoltage, and because the diode is directly connected to the grid, noise present in the switching point must not propagate to the grid.

AC/DC With Vienna Rectifier

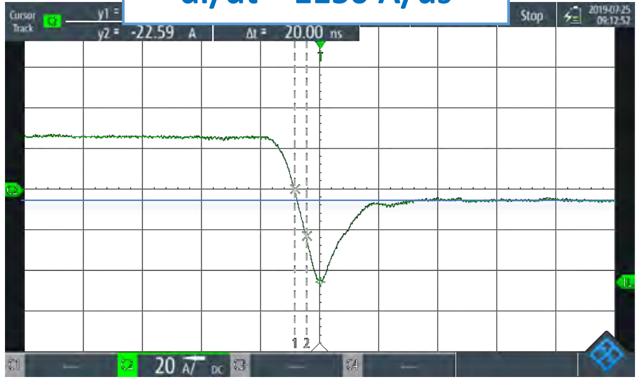
Iout = 40 A,
di/dt = 1600 A/us



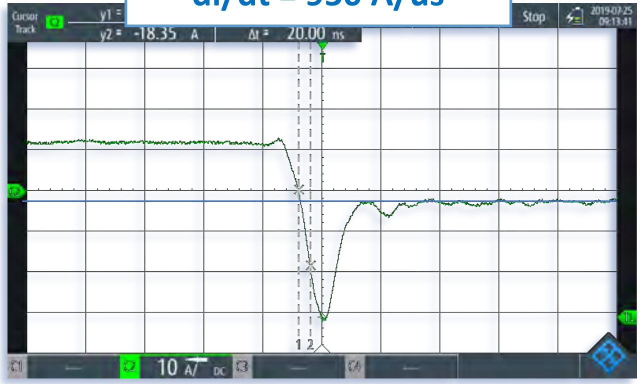
Iout = 30 A,
di/dt = 1300 A/us



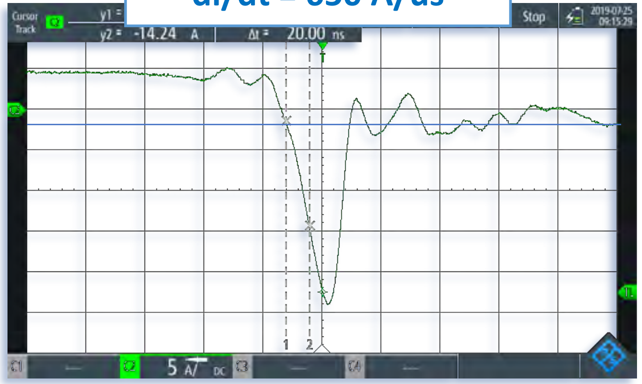
Iout = 20 A,
di/dt = 1150 A/us



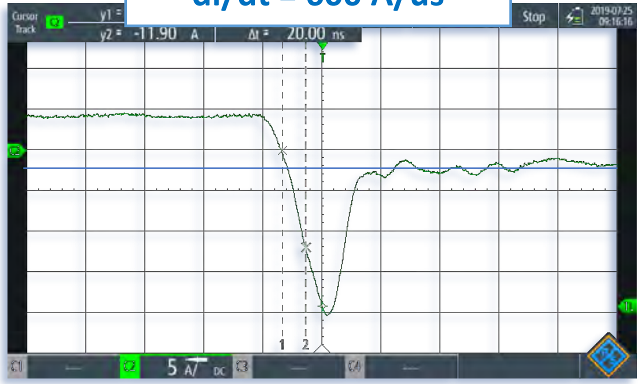
Iout = 10 A,
di/dt = 950 A/us



Iout = 5 A,
di/dt = 650 A/us



Iout = 3 A,
di/dt = 600 A/us



The reverse current behavior keeps the same shape in a wide range of conditions.
The reverse voltage is 400 V and the DC bus is 800 V

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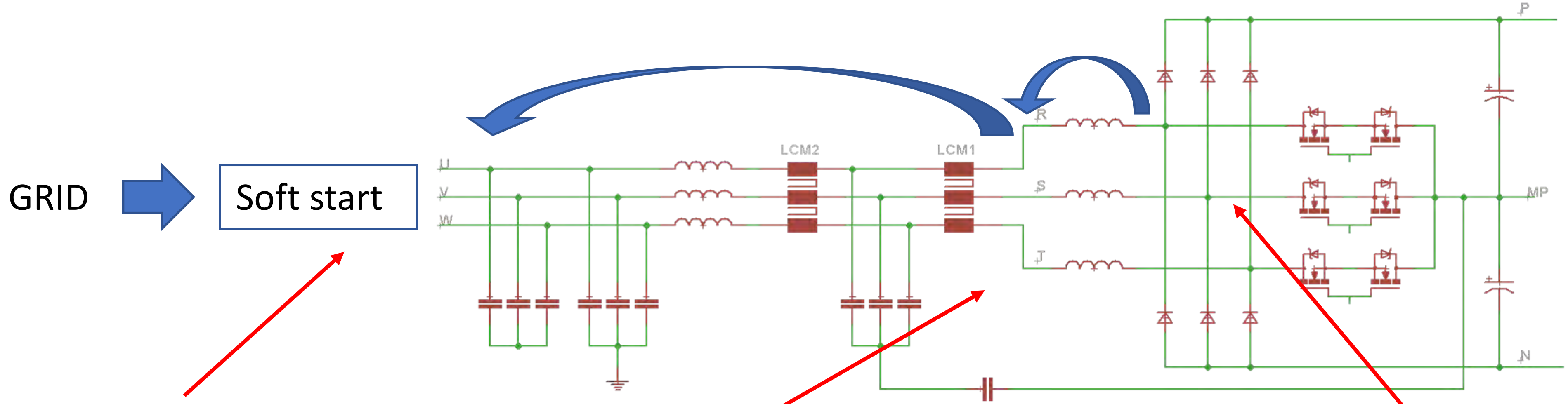
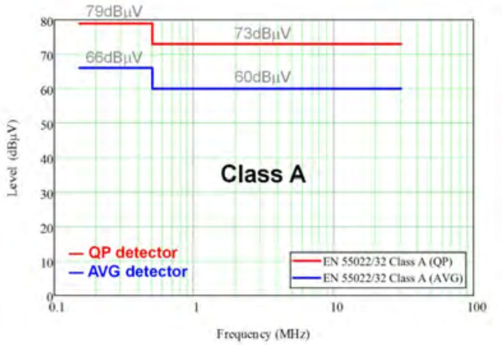
AC/DC With Vienna Rectifier

The reduction of switching losses is possible by adopting a snappy recovery of the diode, but this often induces a level of noise that is not acceptable, and to meet EMC requirements a large input filter is needed.



Here a minimum amount of high frequency is allowed. Only active power should be present

Smaller with frequency, but switching frequency (and harmonics) should be in line with the EMC mask



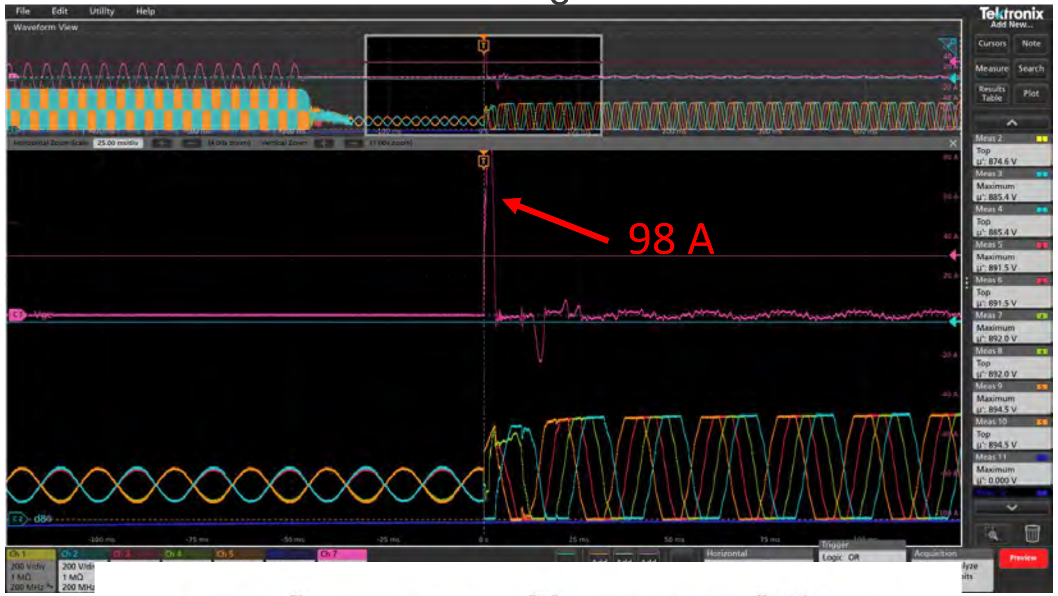
Points where switching has large voltage swing and dv/dt

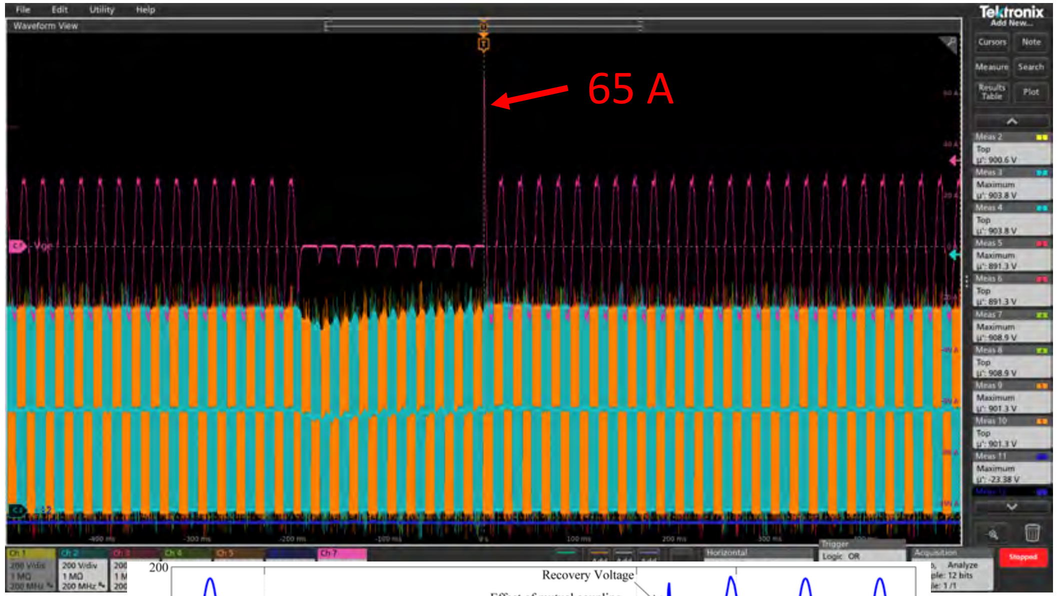
Gen 5 is optimized to provide the maximum efficiency, while keeping the noise low. This allows a lighter input filter to be built, which has advantages in terms of weight and cost.

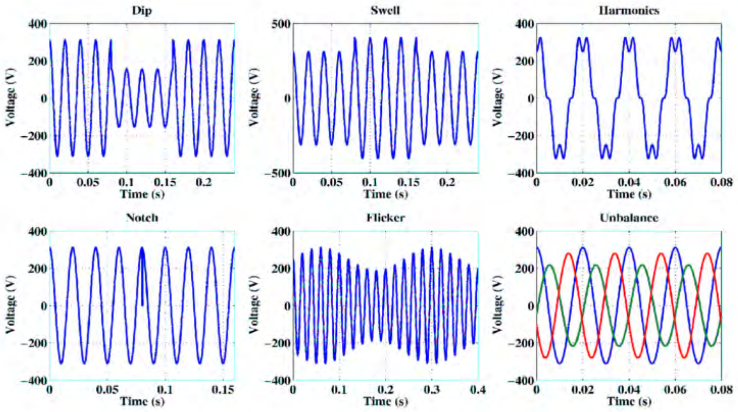
AC/DC With Vienna Rectifier

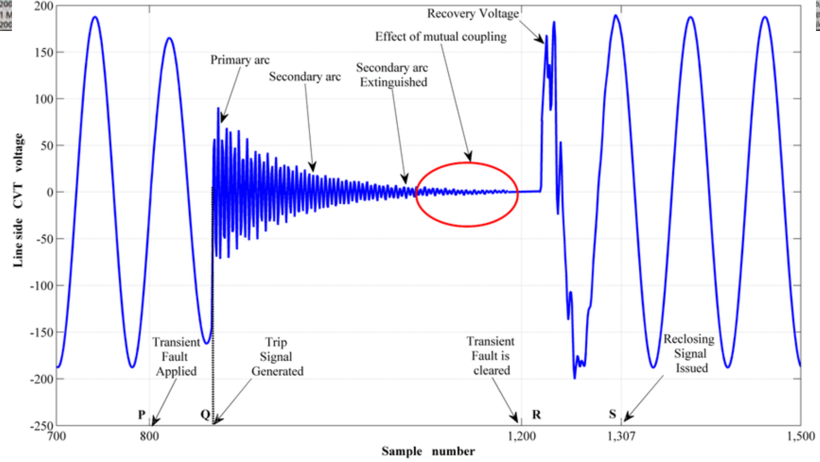
The purpose of the input filter is to prevent the noise generated by switching components (EMI) from reaching the line (EMI), while also preventing noise (EMS, surges, spikes, etc.) from the line from reaching the semiconductors.

A light input filter could expose diodes and MOSFETs to more noise than heavy filters. For this reason, Gen 5 devices are designed to be robust and immune to overstress from the line.



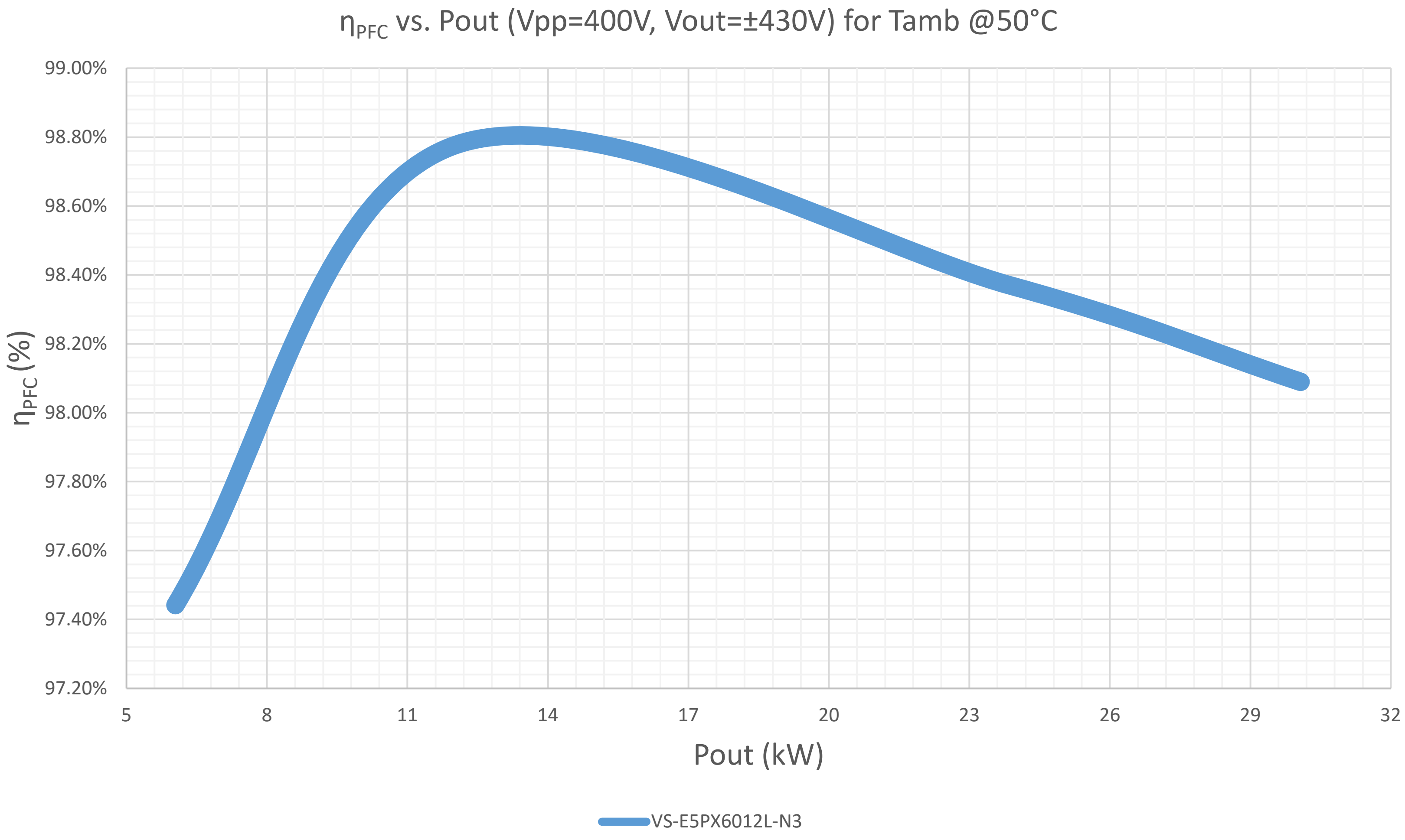




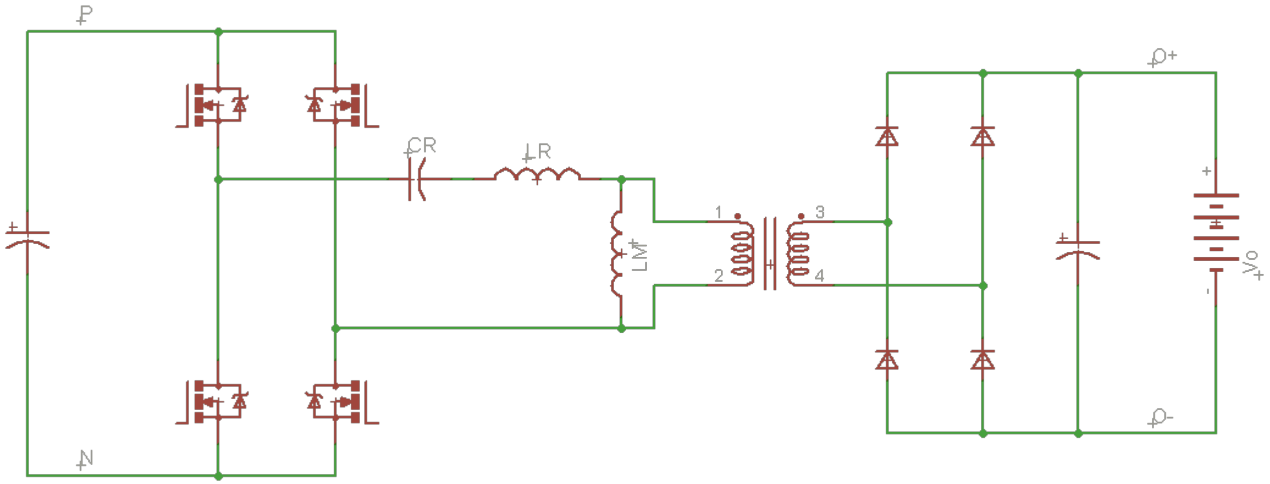


AC/DC With Vienna Rectifier

The efficiency of a commercial fast charger 30 kW (efficiency PFC stage and input filter)



The DC/DC Stage: Why the LLC Converter ? (Pros & Cons)



Pros:

- ZVS turn-on of MOS / IGBT switches
- Soft turn-off of MOS / IGBT switches
- Reduction of driving power (Q_g) of switches
- ZCS turn-off of output HF diodes (near resonance)
- Soft-switching → less EMI troubles!
- Good load regulation near primary resonance
- Higher efficiency! (> 95 % at nominal conditions)

Cons:

- Output voltage range vs. load: loosening of ZVS and ZCS diodes (for hard-recovery) at low voltages; higher rms and high peak currents decrease efficiency
- Higher operative frequencies: increase switching losses for all semiconductors and require optimal passive elements to manage large reactive power
- Controller strategy is more complex, and compared to traditional PWM converter systems, is extremely non-linear

Quality factor: $Q = \frac{\pi^2 n^2}{8 R_{out}} \cdot \sqrt{\frac{L_r}{C_r}}$

Primary resonance: $f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}}$

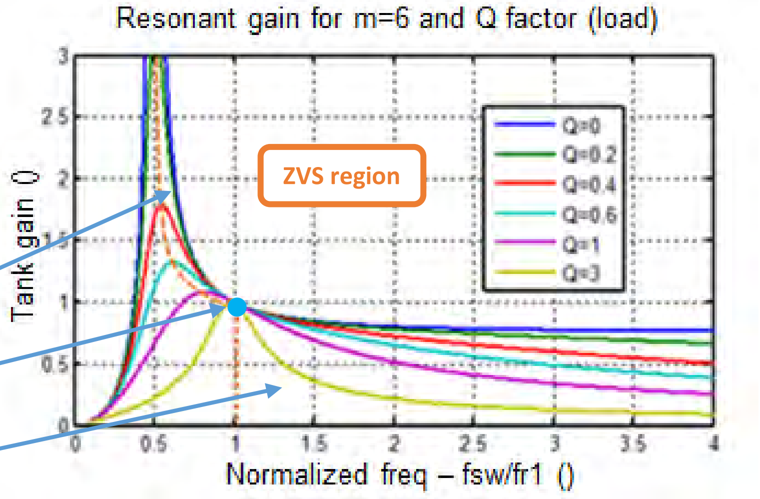
Secondary resonance: $f_{r2} = \frac{1}{2\pi\sqrt{(L_r + L_m) C_r}}$

Inductance factor: $m = \frac{L_r + L_m}{L_r}$

Boost mode: $f_{r2} < f_{sw} < f_{r1}$

Resonant mode: $f_{sw} = f_{r1}$

Buck mode: $f_{sw} > f_{r1}$



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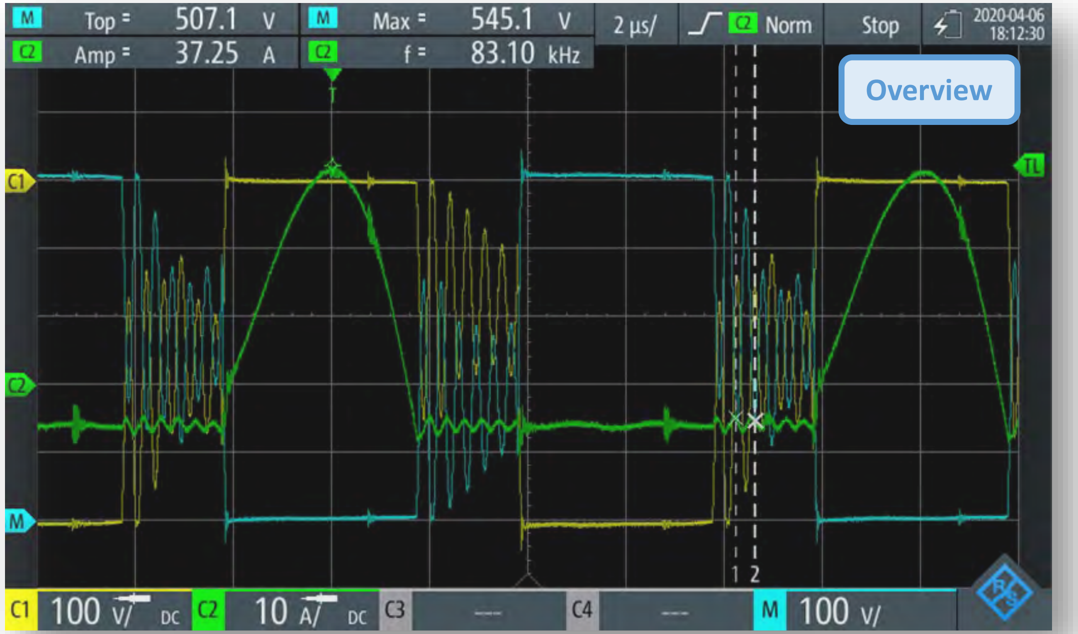
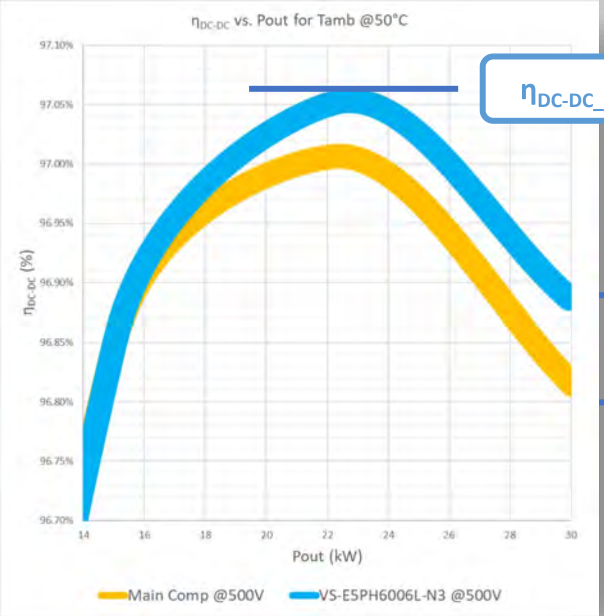
Focus on DC/DC LLC Stage of a 30 kW Fast Charger – “Boost Mode”



An example is provided of single-output diode waveforms (4 FB HF parallel rectifiers used) for V_{out} = 500 V and I_{out} = 60 A. The LLC works in “boost mode” in the inductive region, below the primary resonant frequency and above the secondary resonance, ensuring ZCS at diode turn-off and ZVS at turn-on for the input bridge switches.

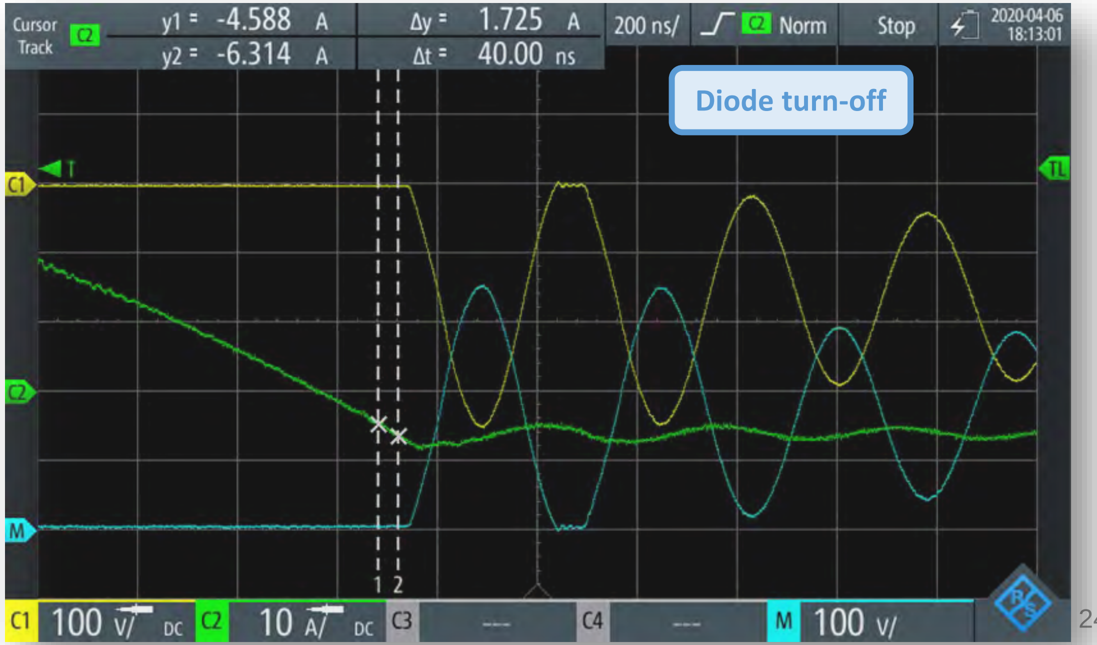
- Fsw = 83 kHz
- Vrr_{top} ≈ 500 V
- Vrr_{pk} ≈ 540 V
- Ipk = 38 A

- di/dt = 43 A/µs
- ZCS operation



η_{DC-DC_pk} ≈ 97.05 %

$\Delta\eta_{DC-DC}$ ≈ 0.07 %
ΔP_{losses} ≈ 20 W @ 30 kW

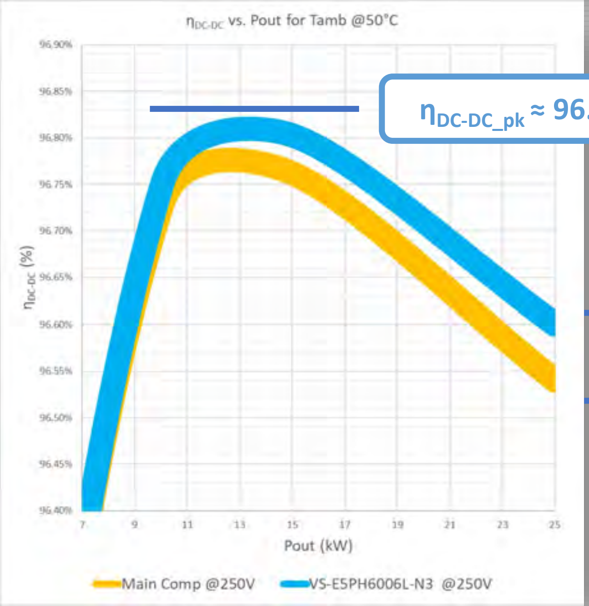


Focus on DC/DC LLC Stage of a 30 kW Fast Charger – "Resonant Mode"

An example is provided of single-output diode waveforms for V_{out} = 250 V and I_{out} = 100 A. The LLC works at the resonant frequency (see the perfect sinusoidal shape of the current). This operating point represents a boundary condition for real diode recovery (low di/dt related), and thus becomes an important factor in total power losses. The ZVS at turn-on for the input bridge switches is guaranteed by design.

- Fsw =125 kHz
- Vrr_{top} ≈ 250 V
- Vrr_{pk} ≈ 270 V
- Ipk = 41 A

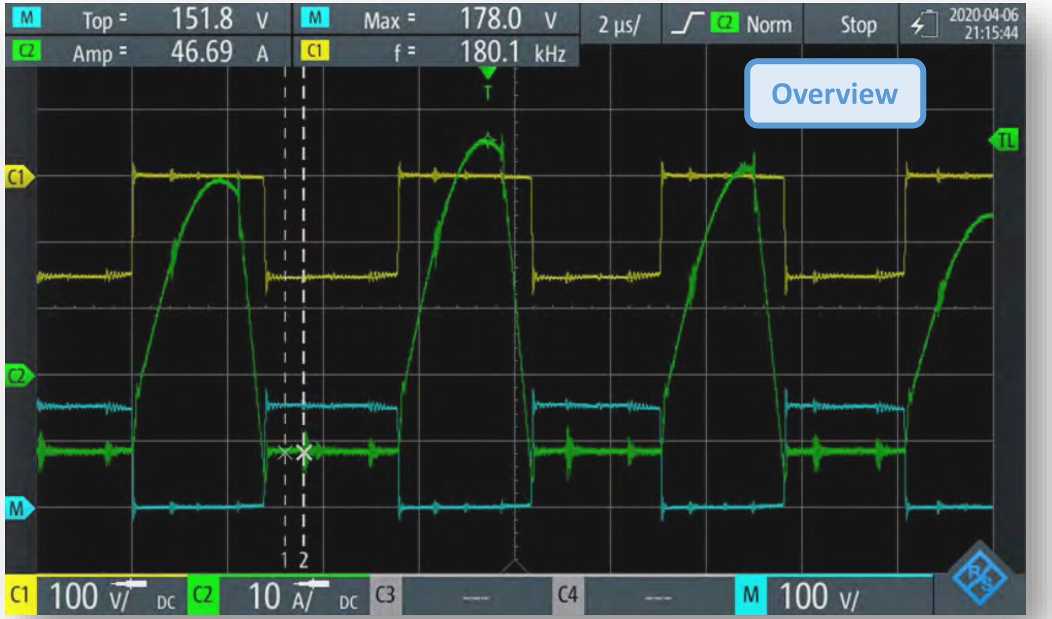
- di/dt = 43 A/µs
- light hard-recovery



$\eta_{DC\text{-}DC\_pk}$ ≈ 96.81 %

$\Delta\eta_{DC\text{-}DC}$ ≈ 0.06 %
ΔP_{losses} ≈ 18 W @ 25 kW

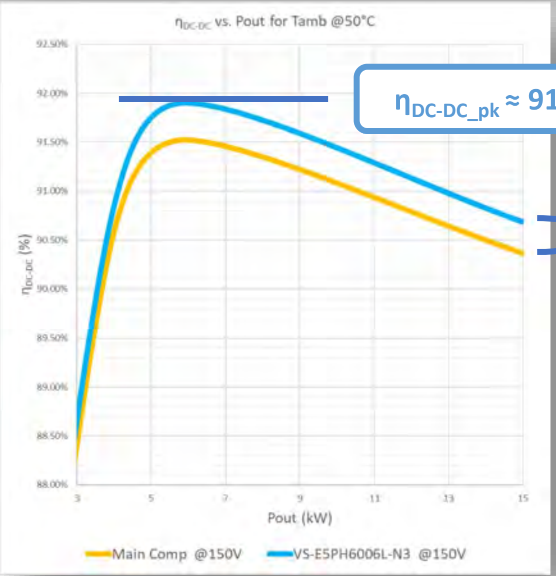
Focus on DC/DC LLC Stage of a 30 kW Fast Charger – “Buck Mode”



An example is provided of single-output diode waveforms for V_{out} = 150 V and I_{out} = 100 A. The LLC works deep in buck mode, above and far from the resonant frequency. The losses associated with hard reverse recovery are evident and the weight is significant. To deliver the same output current at la ower voltage, diodes are much more stressed from both an rms current and recovery energy point of view. The total efficiency of the stage decreases for higher fsw effects.

- Fsw = 180 kHz
- Vrr_{top} ≈ 150 V
- Vrr_{pk} ≈ 180 V
- Ipk = 47 A

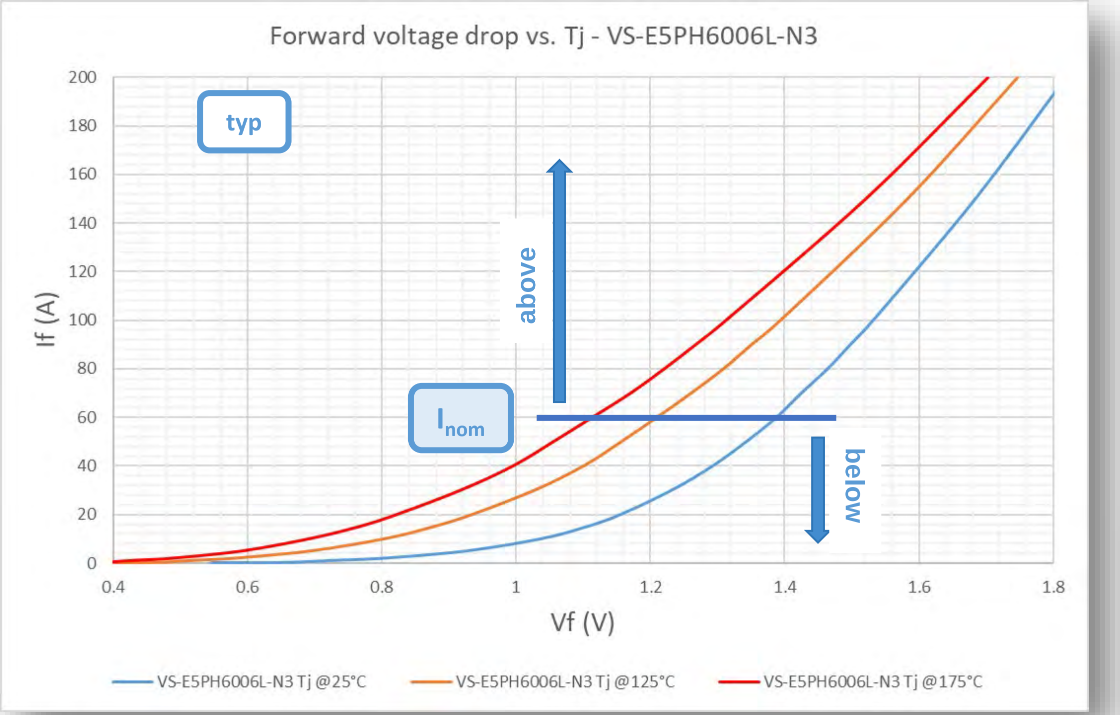
- di/dt = 82 A/µs
- hard-recovery



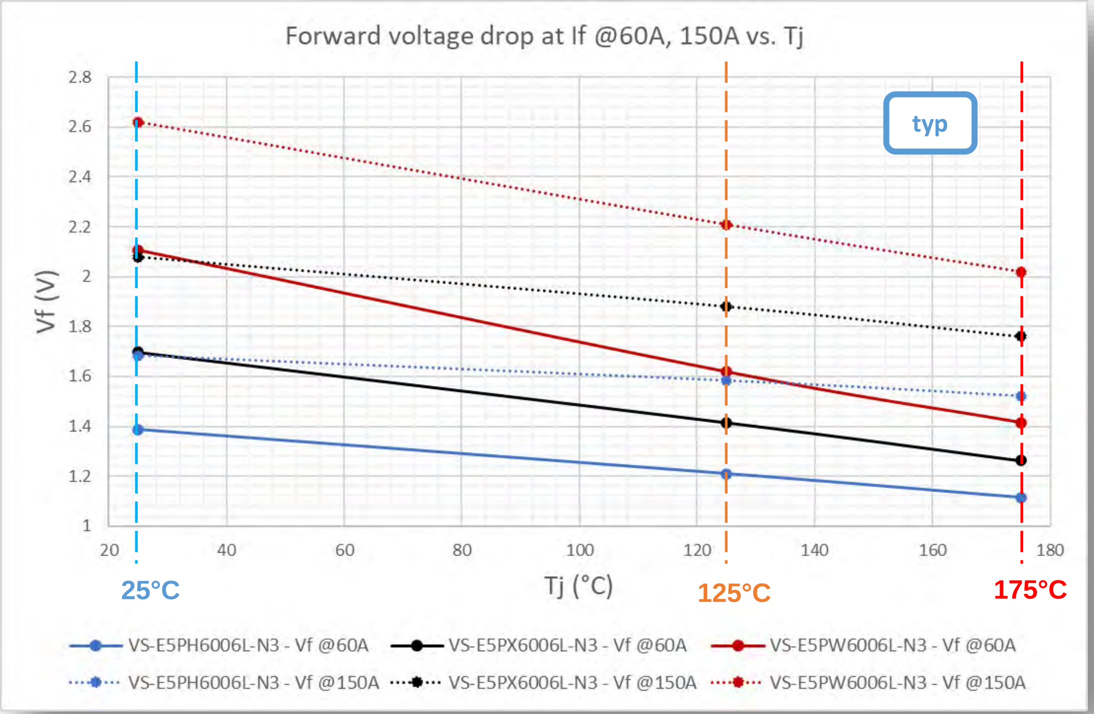
$\eta_{DC\text{-}DC\_pk}$ ≈ 91.90 %

$\Delta\eta_{DC\text{-}DC}$ ≈ 0.32 %
ΔP_{losses} ≈ 48 W @ 15 kW

Diode Forward Voltage Drop Under Control – Gen 5 600 V



In the left plot, VF vs. Tj of Gen 5 600 V “H series” didoes is illustrated. At up to 4x the nominal current (60 A diode example), the forward voltage decreases in accordance with the temperature. Between 1/3 and 1/2 (3/4) of nominal current, the VF sensitivity to Tj reaches its maximum value. This is very useful for conduction loss compensation when recovery losses become significant, especially for higher switching frequencies. Above the nominal current, the voltage drop coefficient is lower, helping to keep VF under control for surge currents and spikes.



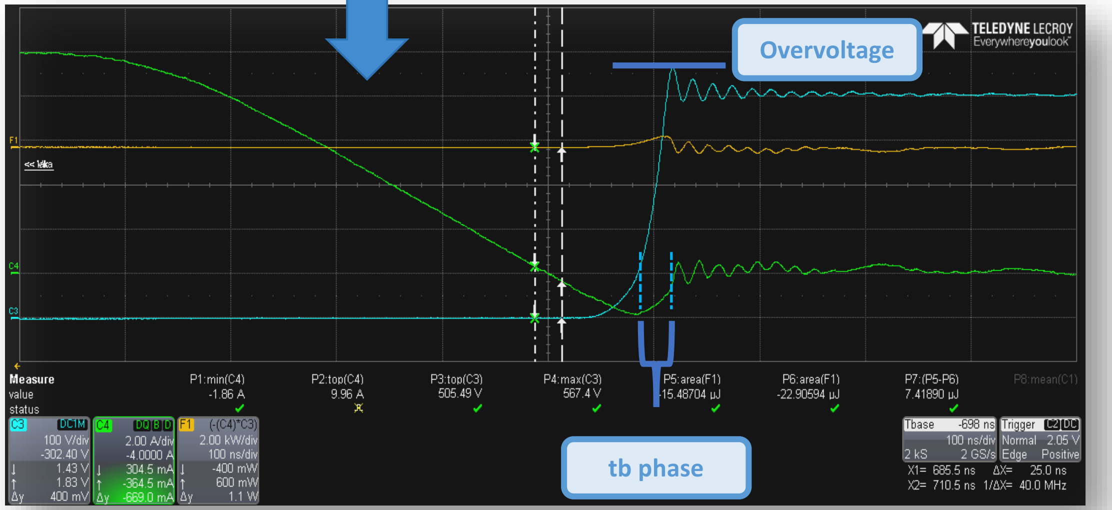
In the right plot, VF vs. Tj for two current levels and different speeds of Gen 5 diode are represented. Moving to a faster diode, the negative VF thermal coefficient for a given current injection increases. On the opposite side, the coefficient decreases when moving to higher current for a specific PN.

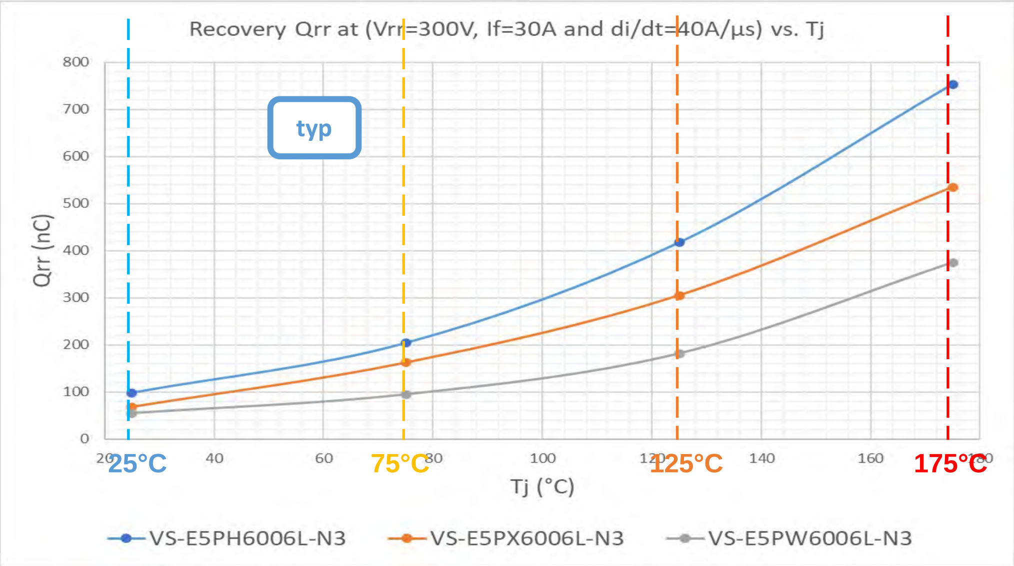
When conduction losses contribute to most of the total losses, diode heatsink sharing with other components could be possible for system optimization.

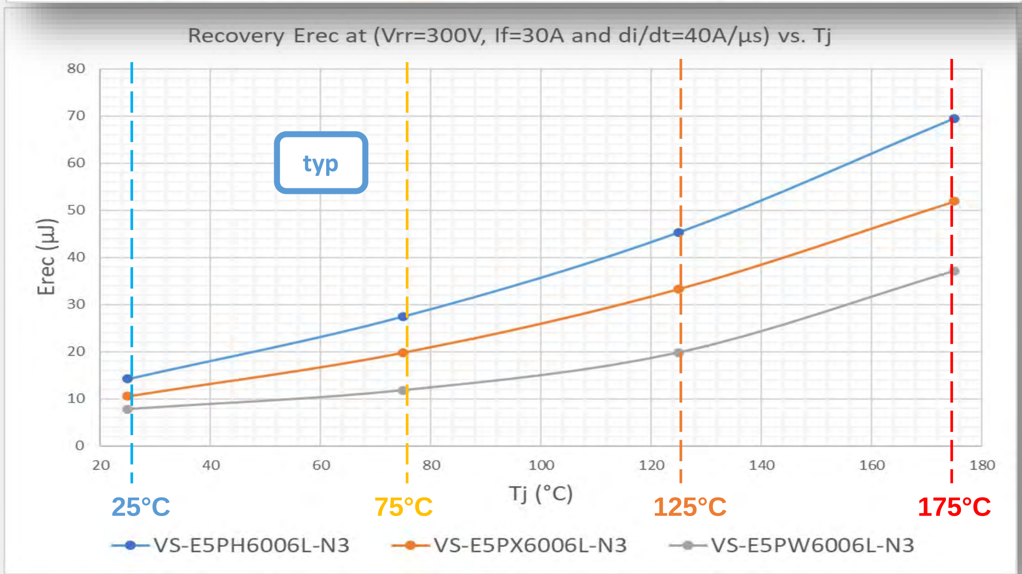
Diode Recovery Losses to Avoid Thermal Runaway – Gen 5 600 V

In the right-side plots, the typical recovery Qrr and Erec vs. Tj for Gen 5 600 V diodes of different available speed are discussed. Reference test conditions are aligned with that of a possible LLC DC/DC SMPS that works in the central zone of the “buck region,” where hard-recovery occurs. The trendline among 25 °C and 175 °C is almost parabolic: this is a key feature to avoid thermal runaway when the diode is stressed at low output voltages. Looking at the speed, the “W series” shows half of the losses vs. “H speed” at Tj @125°C.

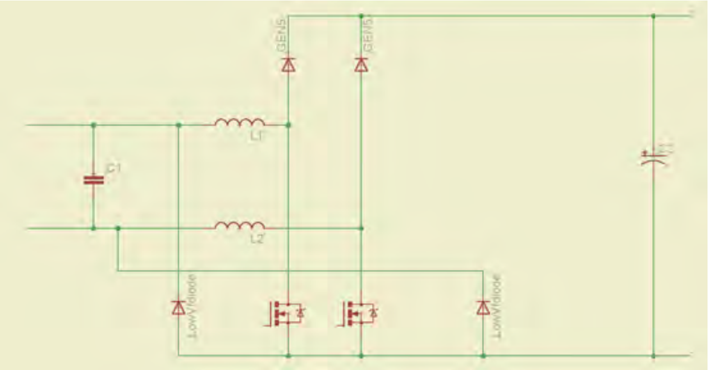
Below, an example of waveforms for higher Vrr (500 V): the dI_{rect}/dt during the tb phase of recovery is well controlled in order to avoid overvoltage stresses on the diodes and the EMI nightmare of the system without using snubbers.



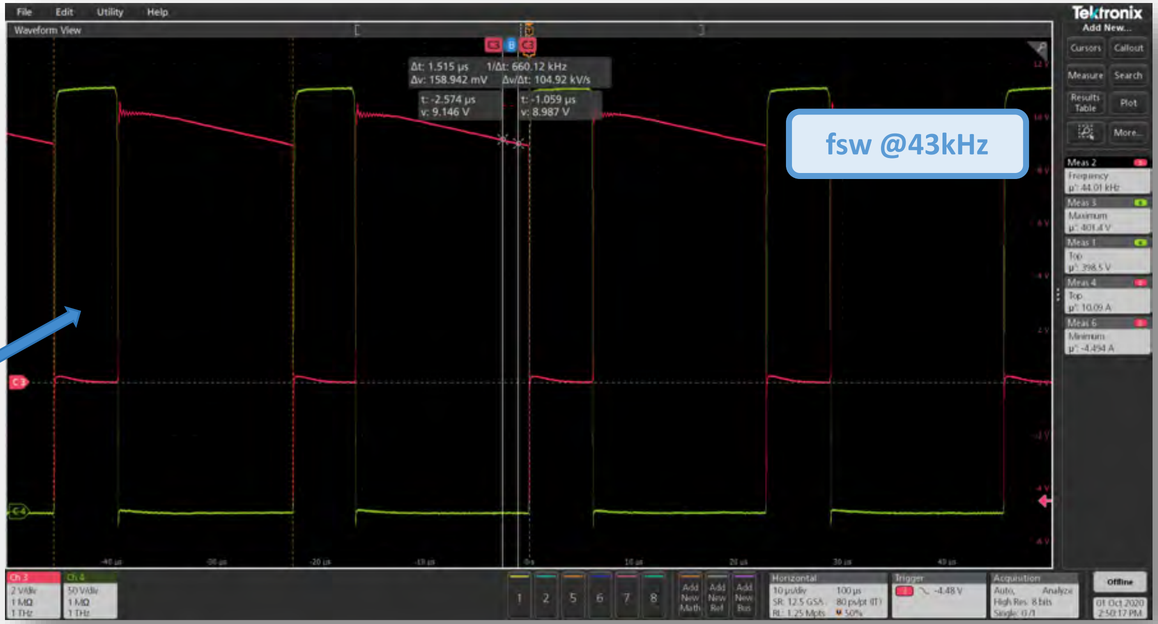


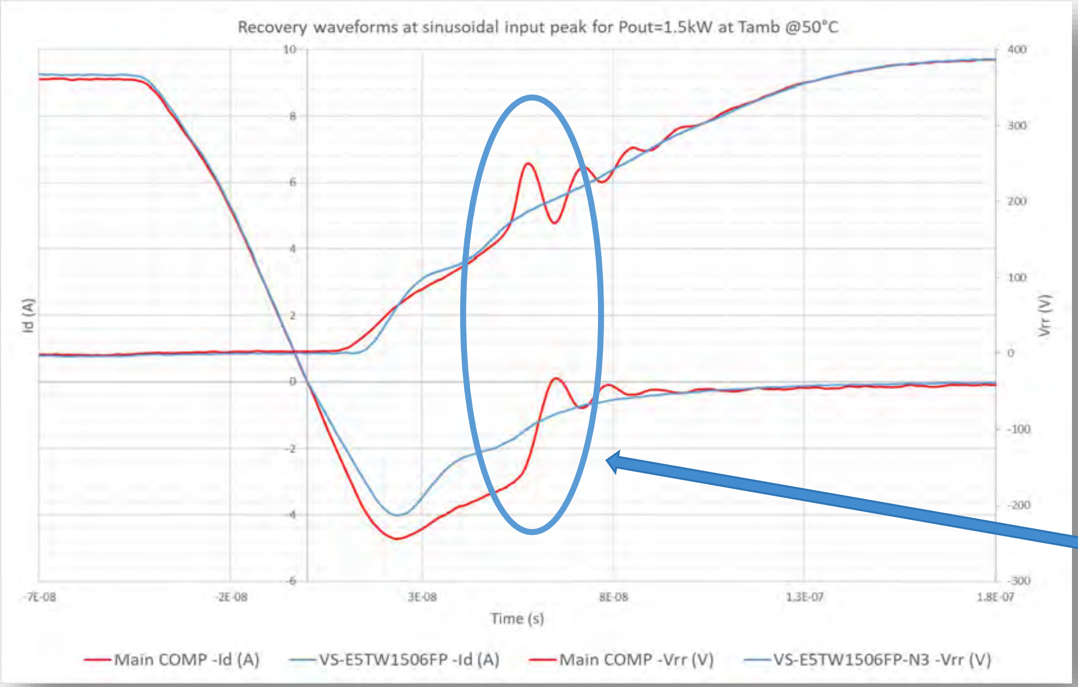


Gen 5 600 V CCM Hard-Recovery Appl.: PFC Stages from 300 W to kW



Vka (green) and Iak (red) on diode at sinusoidal peak, 230 V @ 1.5 kW





In order to reduce BOM costs and PCB size, and increase power density, the actual PFC trend is to move to higher fsw (from 15 kHz -20 kHz to 40 kHz – 70 kHz). Si diodes must be faster than the previous generation and cost effective to be a valid alternative to SiC devices.

Reverse recovery at medium di/dt (200 A/µs-500 A/µs) should be balanced with VF since it is adopted in the CCM mode converter. To avoid generating interference and creating EMI filter sizing issues, the dynamic transient must be clear with a soft recovery tail. A certain robustness to line surge (IFSM) is mandatory when the bulk capacitor is initially charged.

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Key takeaways

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FRED Pt® 600V Product Portfolio

$I_{F(AV)}$	SPEED	D²PAK 2L (TO-263AB)	TO-220	TO-247			TO-220FP (isolated)	TO-3PF (isolated)	
		Single	Single	Single (2-Pin)	Single (3-Pin)	Dual	Single	Single	Dual
12 A	H								
	X						VS-E5TX1206FP-N3		
	W						VS-E5TW1206FP-N3		
15 A	H	VS-E5TH1506S2LHM3	VS-E5TH1506-M3 (1)						
	X	VS-E5TX1506S2LHM3	VS-E5TX1506-M3 (1)				VS-E5TX1506FP-N3		VS-C5ZX3006FP-M3
	W						VS-E5TW1506FP-N3		VS-C5ZW3006FP-M3
20 A	H	VS-E5TH2106S2LHM3							
	X	VS-E5TX2106S2LHM3							
	W								
30 A	H	VS-E5TH3006S2LHM3	VS-E5TH3006-M3 (1)	VS-E5PH3006L-N3 (2)	VS-A5PH3006L-N3 (2)	VS-C5PH3006L-N3 (2)			
	X	VS-E5TX3006S2LHM3	VS-E5TX3006-M3 (1)	VS-E5PX3006L-N3 (2)	VS-A5PX3006L-N3 (2)	VS-C5PX3006L-N3 (2)			
	W			VS-E5PW3006L-N3 (2)		VS-C5PW3006L-N3 (2)			
60 A	H			VS-E5PH6006L-N3 (2)	VS-A5PH6006L-N3 (2)				
	X			VS-E5PX6006L-N3 (2)	VS-A5PX6006L-N3 (2)				
	W			VS-E5PW6006L-N3 (2)					
75 A	H			VS-E5PH7506L-N3 (2)					
	X			VS-E5PX7506L-N3 (2)					
	W								

Released Part

Under Development - Release in Q1 2022

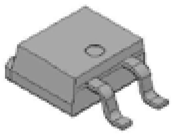
Under Development - Release in Q2 2022

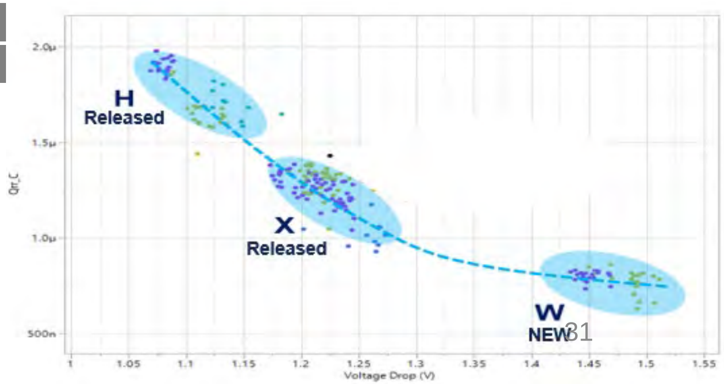
(1) For AEC-Q101 Part Number replace "-M3" with "THN3"

(2) For AEC-Q101 Part Number replace "-N3" with "HN3"

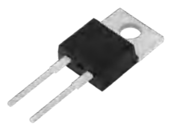
WHAT'S NEW

- ❑ "W" speed with lower Qrr than "X"
- ❑ Isolated packages (TO-220FP and TO-3PF)
- ❑ D2PAK 2-Leads to increase creepage distance





FRED Pt® 1200V Product Portfolio

$IF_{(AV)}$	SPEED	D^2PAK 2L (TO-263AB)	TO-220		TO-247	
		Single	Single	Dual	Single	Dual
8 A	H		VS-E5TH0812-M3 [1]			
	X		VS-E5TX0812-M3 [1]			
15 A	H	VS-E5TH1512S2LHM3	VS-E5TH1512-M3 [1]			
	X	VS-E5TX1512S2LHM3	VS-E5TX1512-M3 [1]			
20 A	H	VS-E5TH2112S2LHM3				
	X	VS-E5TX2112S2LHM3				
30 A	H	VS-E5TH3012S2LHM3	VS-E5TH3012-M3 [1]	VS-C5TH3012-M3	VS-E5PH3012L-N3 [2]	VS-C5PH3012L-N3 [2]
	X	VS-E5TX3012S2LHM3	VS-E5TX3012-M3 [1]	VS-C5TX3012-M3	VS-E5PX3012L-N3 [2]	VS-C5PX3012L-N3 [2]
60 A	H				VS-E5PH6012L-N3 [2]	VS-C5PH6012L-N3
	X				VS-E5PX6012L-N3 [2]	VS-C5PX6012L-N3
75 A	H				VS-E5PH7512L-N3	
	X				VS-E5PX7512L-N3	

Released Part

Under Development - Release in Q1 2022

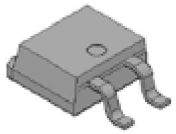
Under Development - Release in Q2 2022

[1] For AEC-Q101 Part Number replace "-M3" with "THN3"

[2] For AEC-Q101 Part Number replace "-N3" with "HN3"

WHAT'S NEW

- D2PAK 2 Leads to increase creepage distance



- Increase current rating up to 75 A in TO-247 package

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What Are the Key Features of 600 V and 1200 V Fred Pt® Gen 5?

- Ultrafast diode with optimized Erec and Irrm
- 600 V and 1200 V breakdown voltage
- Best in class among Si UF diodes in terms of Erec
- Optimized for high speed resonant SMPS operation (LLC)
- AEC-Q101 extended up to 2000 h

What Are the Key Benefits of 600 V and 1200 V Fred Pt ® Gen 5?

- Limit current stress on the switch
- Improved light- and full-load efficiency in automotive and industrial resonant SMPS
- Improved system reliability
- Price competitiveness compared to alternative offerings in the market

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Thank You

VISHAY

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