CURENT
CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

Experience with WBG Converters and Motor Drives

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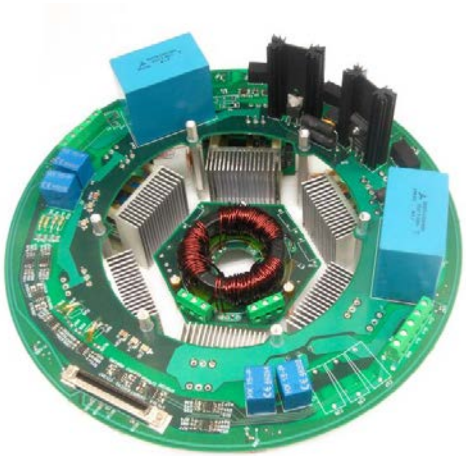
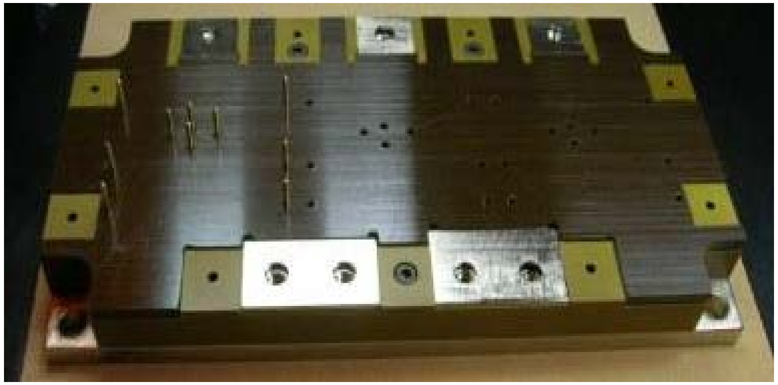
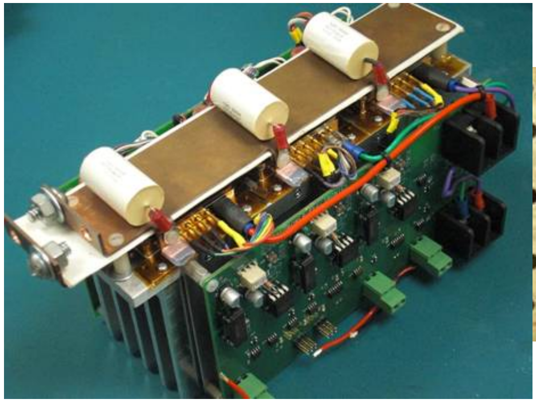
WBG Related Work

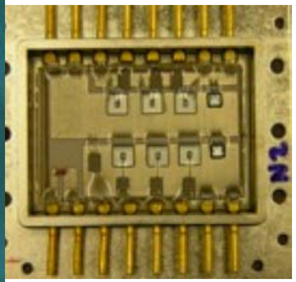


250 ˚C SiC High-density Three-level Motor Drive

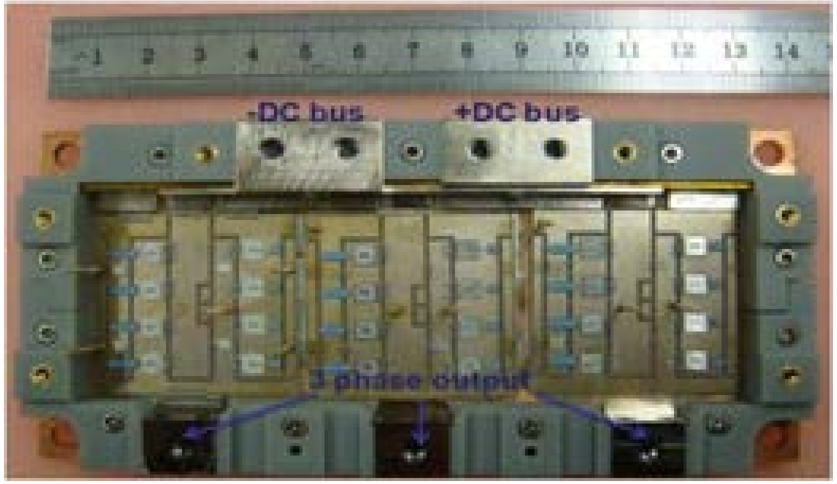


60 kW SiC Three-phase Inverter Module

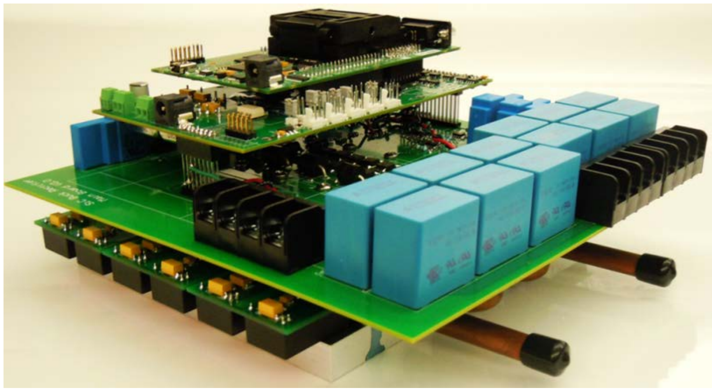




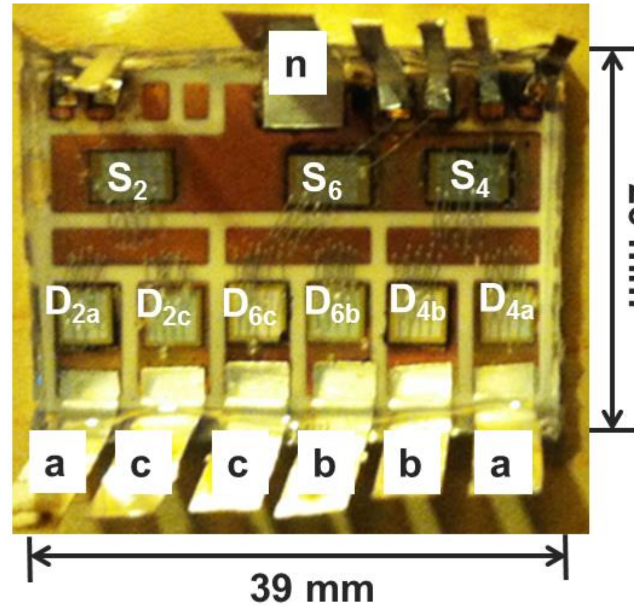
18 kW All SiC Inverter



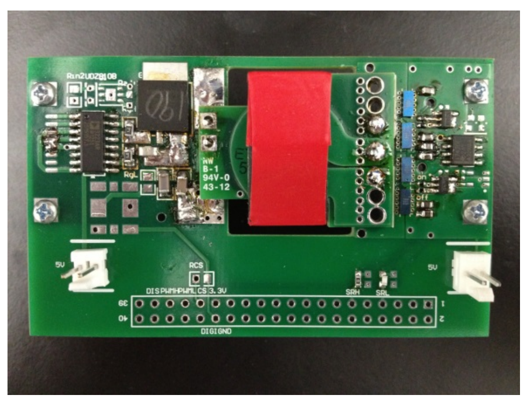
WBG Related Work



7.5 kW, 480V to 400V
98.8% SiC Rectifier

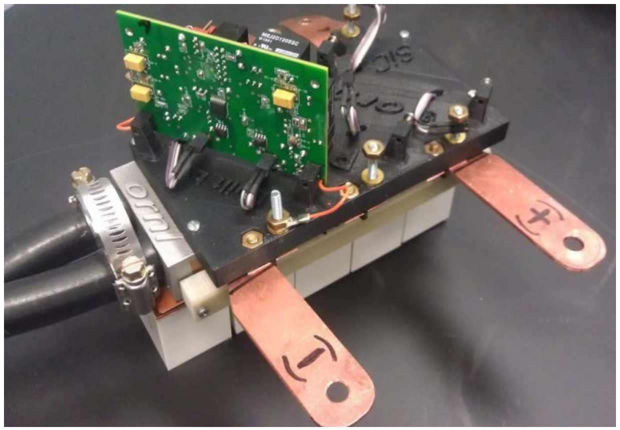


480V to 400V Low Loss
SiC Rectifier Module



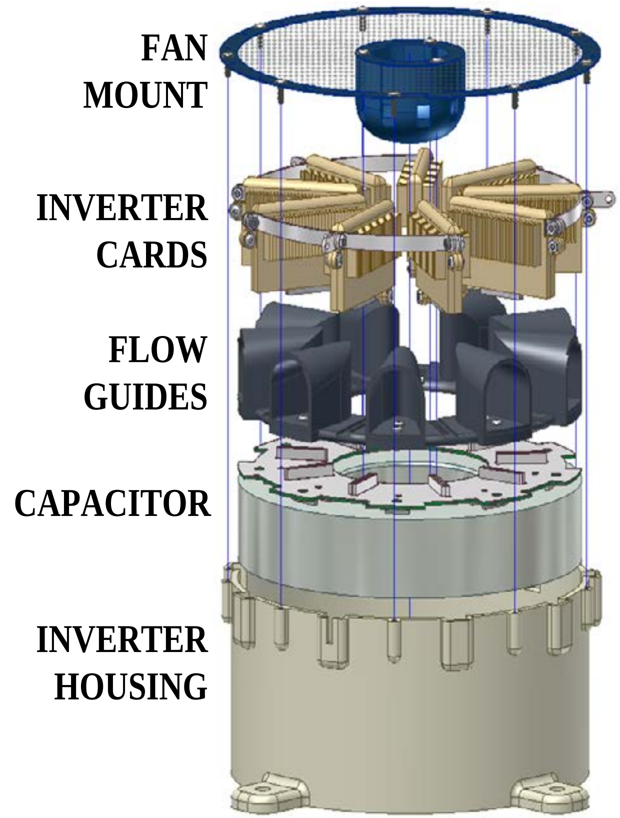
300W, 400 to 12 V,
96.6% GaN DC/DC IBC

WBG Related Work - ORNL



50% PRINTED ALL-SiC Inverter

100A/1200V SiC Phase-leg Module with Integrated Cooling



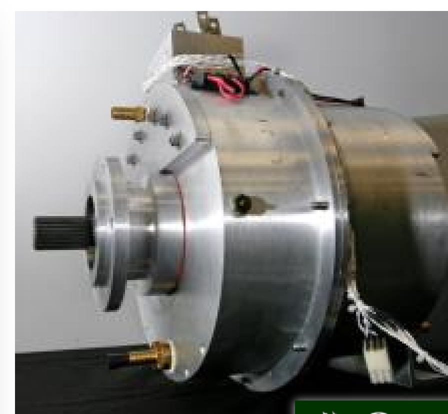
ORNL Motor R&D

- Machine Types
  - Field Excitation
    - Novel Flux Coupling
    - Brushless Field Excitation
  - SR Motors
  - Axial Gap
- Development and Utilization of New Materials Complimentary to WBG Drive
  - High Frequency
  - Low Loss

Novel Flux Coupling Motor

Axial Gap Stator

16,000 rpm Brushless Field Excitation (BFE) Motor



Multiple Isolated Flux Path SR Motor

Uncluttered Rotor (CVT)

WBG Based Motor Drives

- **Wide band-gap (WBG) vs. Silicon**
  - High breakdown electric field → High breakdown voltage
  - High thermal conductivity → High operation temperature
  - High drift velocity → High switching-speed capability

- **Benefits of high switching-speed performance**
  - Low switching loss → Less cooling requirement, high power efficiency
  - Short switching time → Reduced dead time, improved power quality; Increased switching frequency, high power density

- **Can we fully utilize this potential advantage of WBG semiconductor in motor drives?**
  - Interference between upper & lower switches in a phase-leg (Cross talk)
  - Interaction between PWM inverter and induction motor

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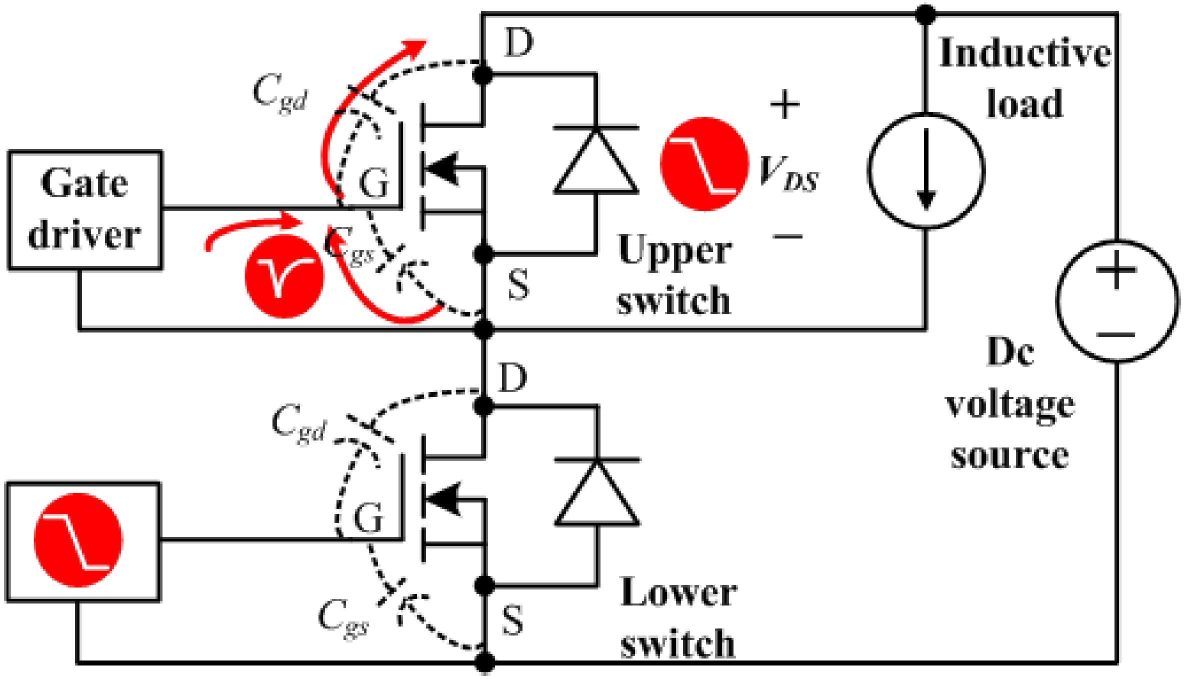
Cross Talk in a Phase Leg



Phase-leg configuration

Turn-on transient — Positive spurious gate voltage ↑ → Shoot-through current

Cdv/dt ↑ → **worse**

Turn-off transient — Negative spurious gate voltage ↑ → Overstress gate terminal

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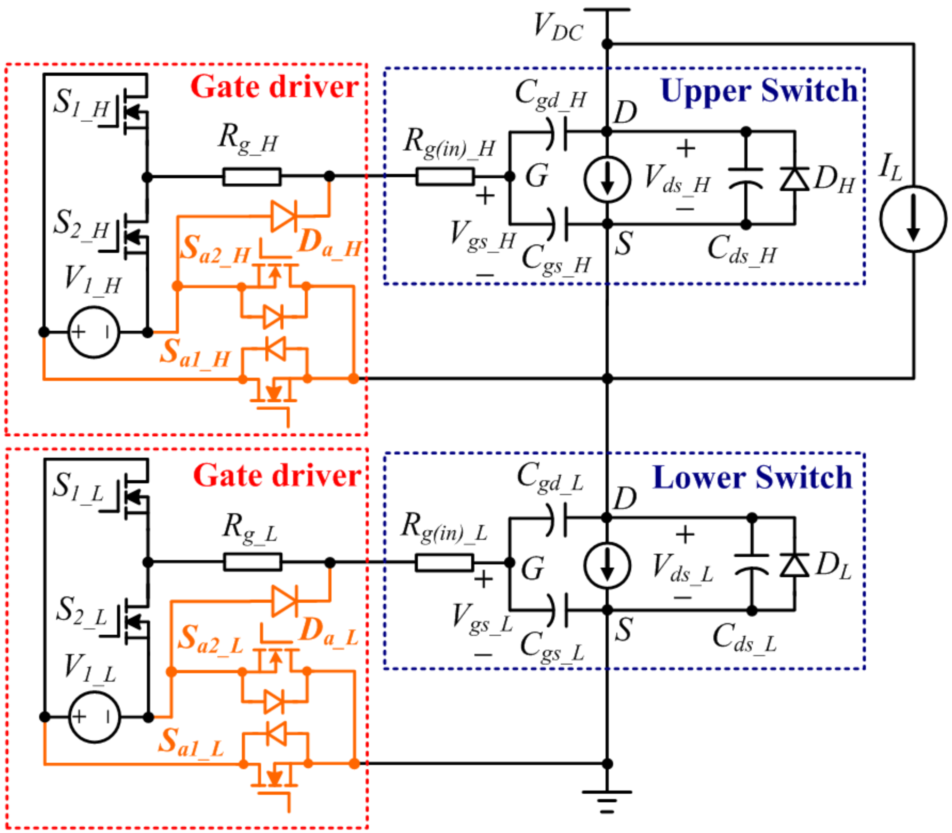
WBG (SiC) vs. Si on Cross Talk

TABLE I. Characteristics of Several Comparable Si/SiC Power Devices

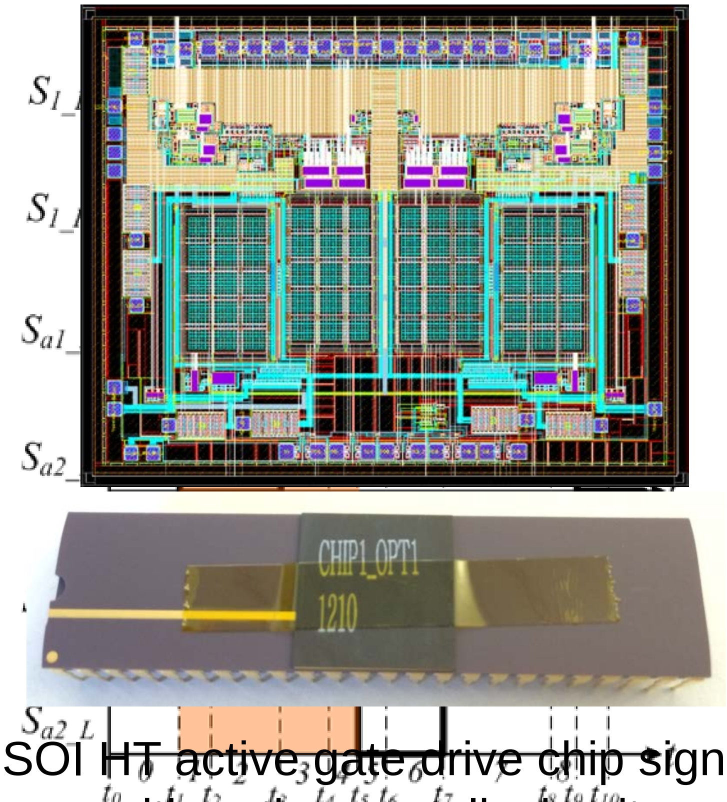
Type	Manufacturer	Model	V_{DS} / I_D (100 °C)	Q_{gs}	$V_{gs(th)}$ (25 °C)	$V_{gs\_max(-)}$
Si IGBT	IR	IRGP20B120U	1200 V / 20 A	169 nC	4.5 V	-20 V
Si MOSFET	Microsemi	APT34M120J	1200 V / 22 A	560 nC	4.0 V	-30 V
SiC MOSFET	CREE	CMF20120D	1200V / 24 A	90.8 nC	2.5 V	-5 V

- **Properties of SiC devices**
  - Faster switching speed
  - Lower threshold voltage
  - Lower maximum allowable negative gate voltage
- **WBG (SiC) devices in a phase-leg are easily affected by cross talk**
  - Leading to extra switching losses & reliability issues
  - Have to slow down the switching speed?

Active Gate Driver for Cross Talk Suppression



Active gate driver w/ gate assist circuit



SOI HT active gate drive chip signals with anti-cross talk circuitry

Logic signals

- **Compared with conventional gate driver, gate assist circuit adds**
  - Two auxiliary transistors (S_{a1_H}, S_{a2_H} or S_{a1_L}, S_{a2_L}) along with one diode (D_{a_H} or D_{a_L}) for each device in a phase-leg.

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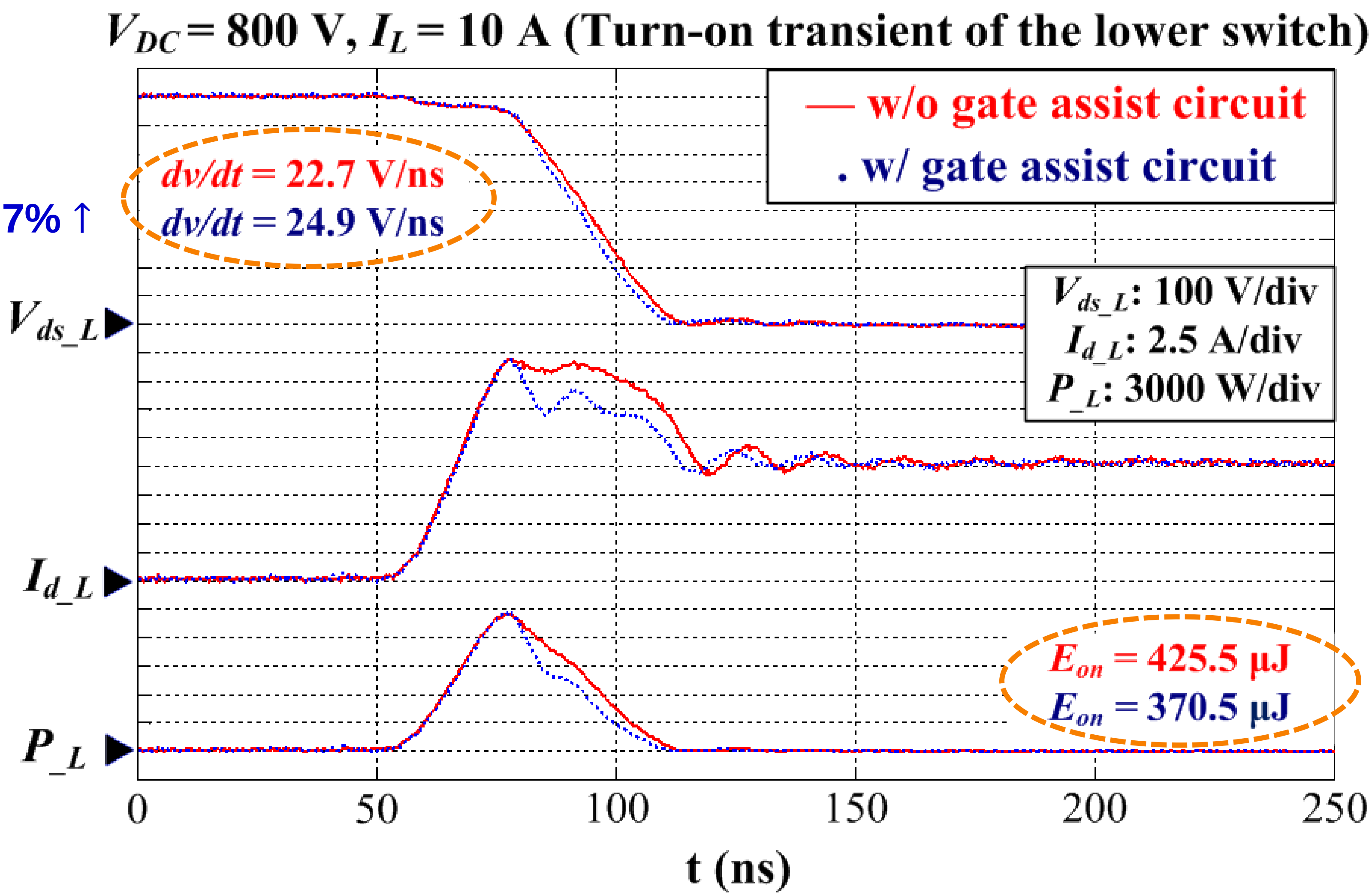
Turn-on Transient of the Lower Switch

9.7% ↑



55.0 µJ ↓

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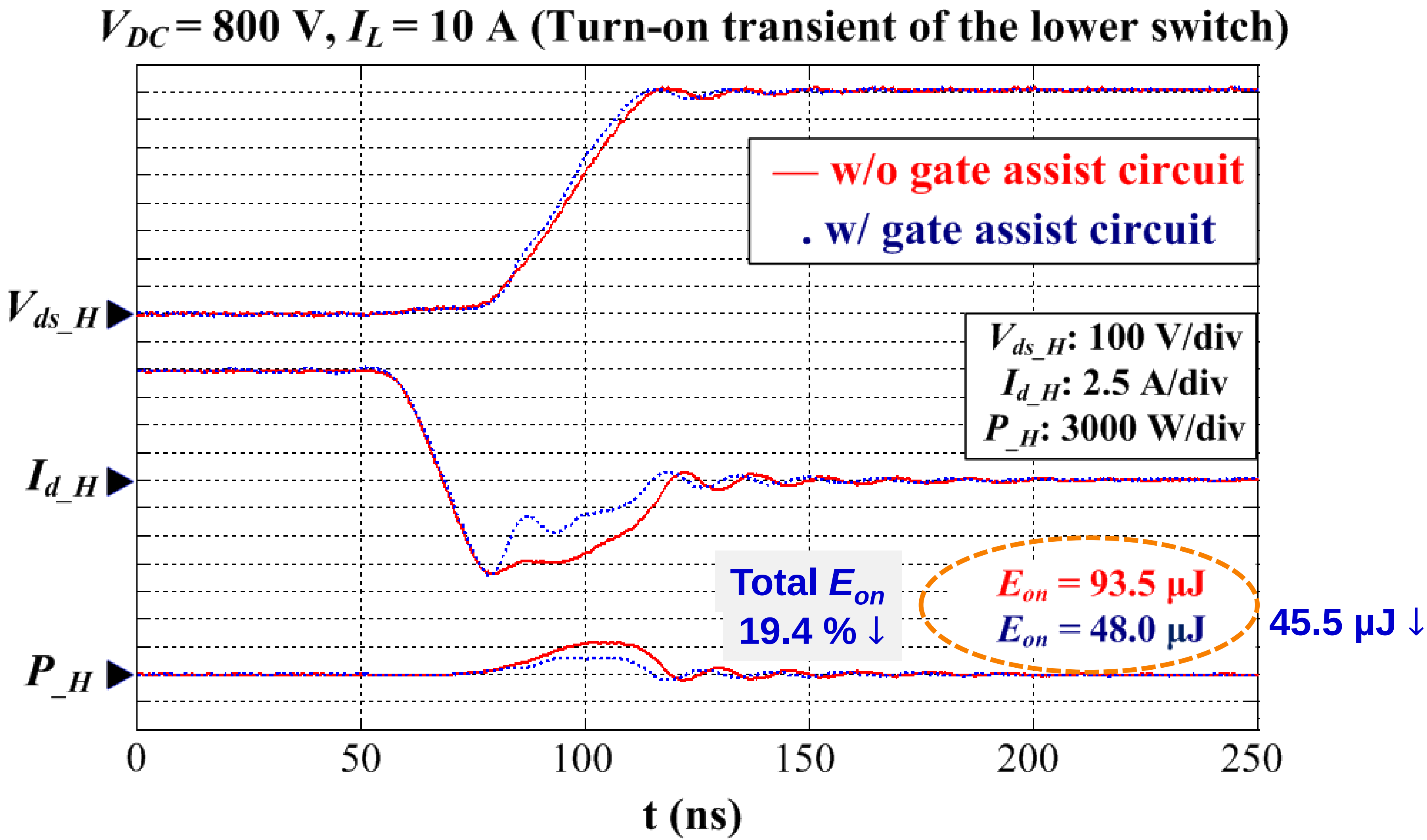
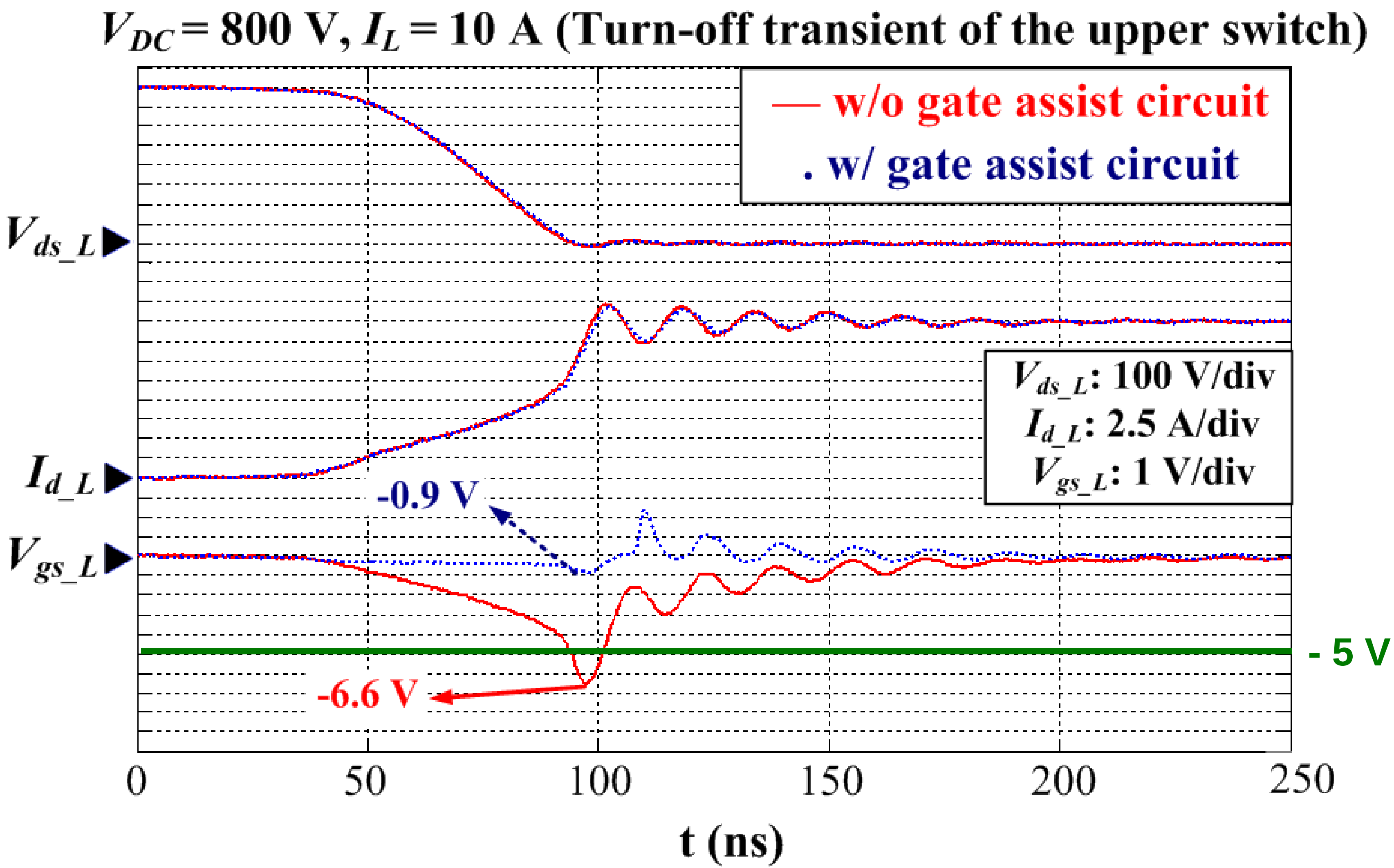
Turn-on Transient of the Lower Switch

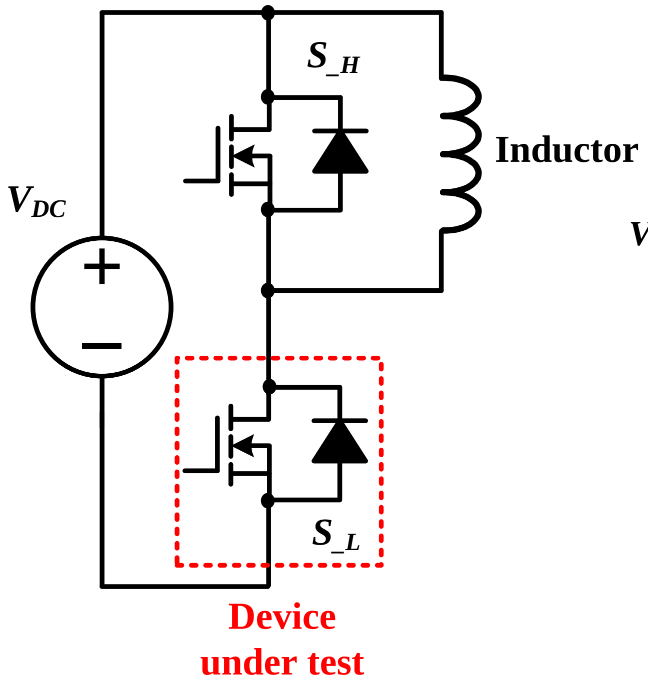


Turn-off Transient of the Upper Switch

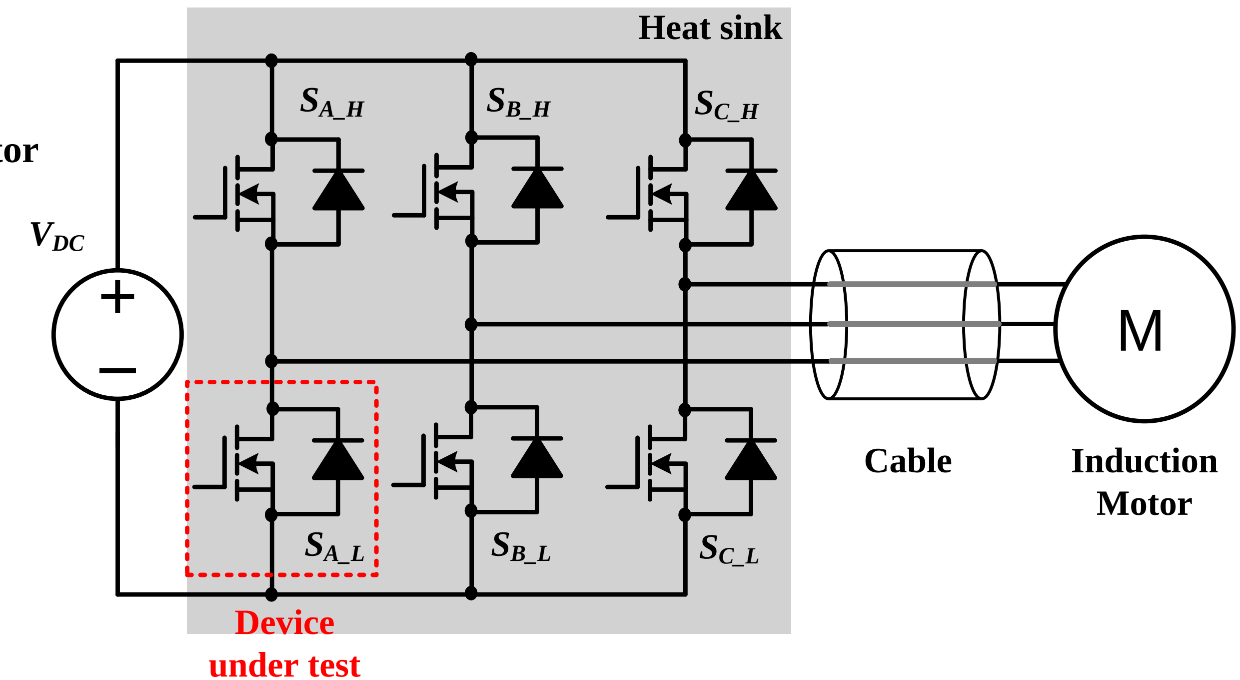


Non-motor Inductive Load vs. Induction Motor

- ❑ **Switching behavior plays a significant role on motor drives design**
  - Thermal management, dead time, switching frequency
- ❑ **Double pulse tester (DPT) with optimally-designed inductor load is a well-accepted method for switching performance evaluation**
- ❑ **Actual switching performances in motor drives are different**



Double pulse tester circuits



Three-phase PWM inverter fed motor drives

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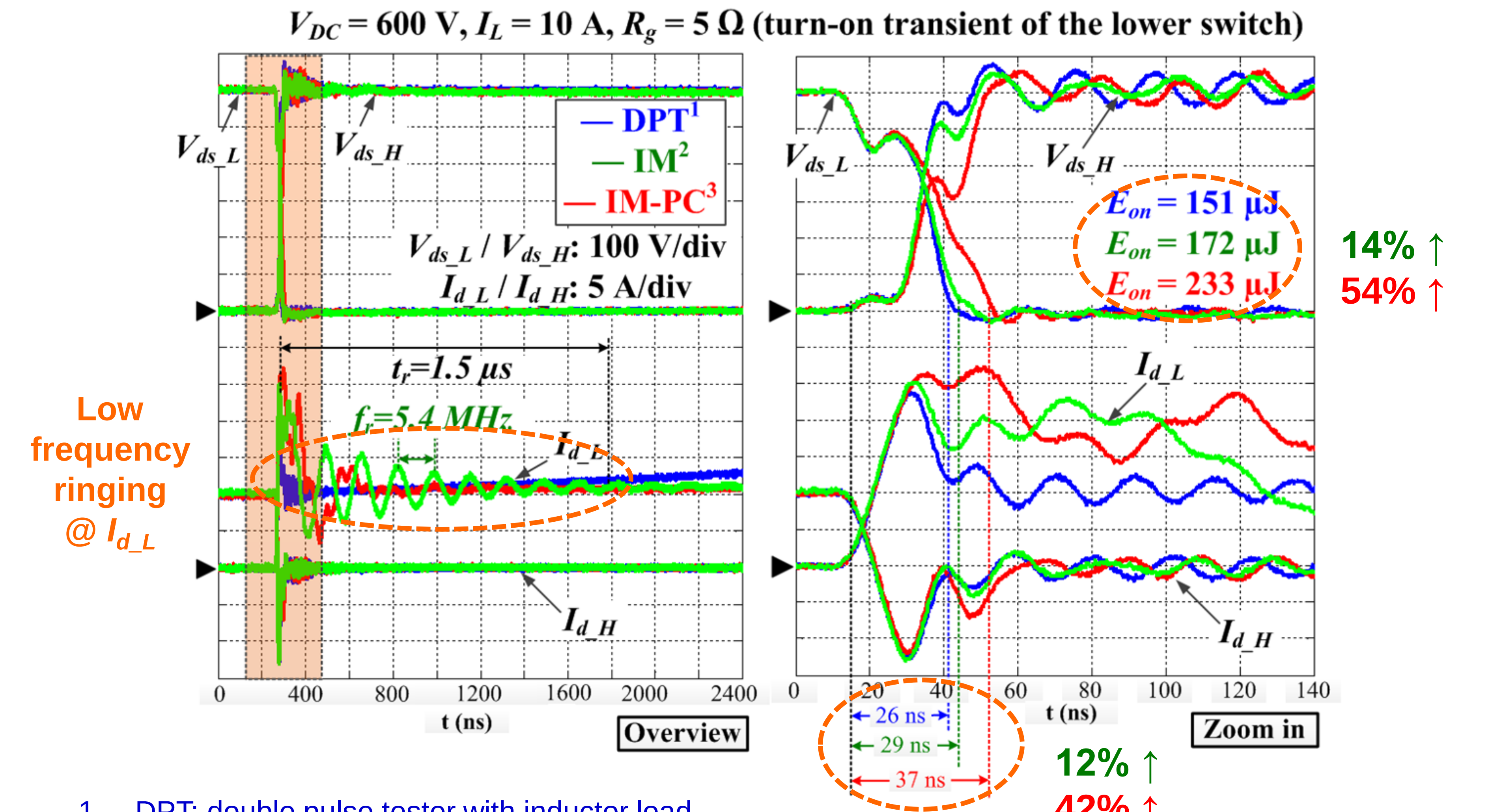
Switching Waveforms Comparison (Turn-on)



1. DPT: double pulse tester with inductor load
2. IM: pulse tester with 10 HP induction motor (IM)
3. IM-PC: pulse tester with 10 HP induction motor (IM) plus 6.6 feet power cable (PC)

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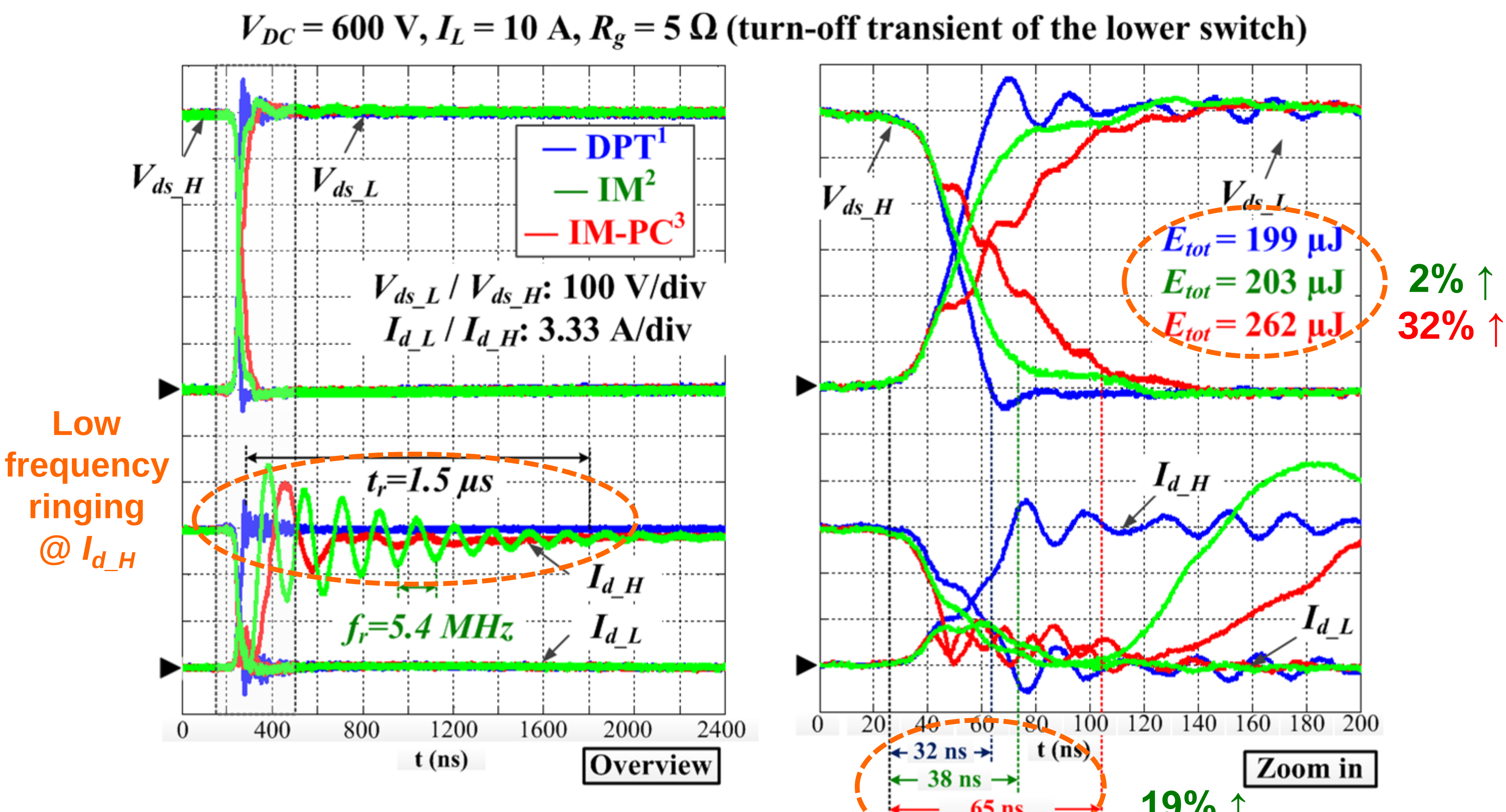
Switching Waveforms Comparison (Turn-off)



1. DPT: double pulse tester with inductor load
2. IM: pulse tester with 10 HP induction motor (IM)
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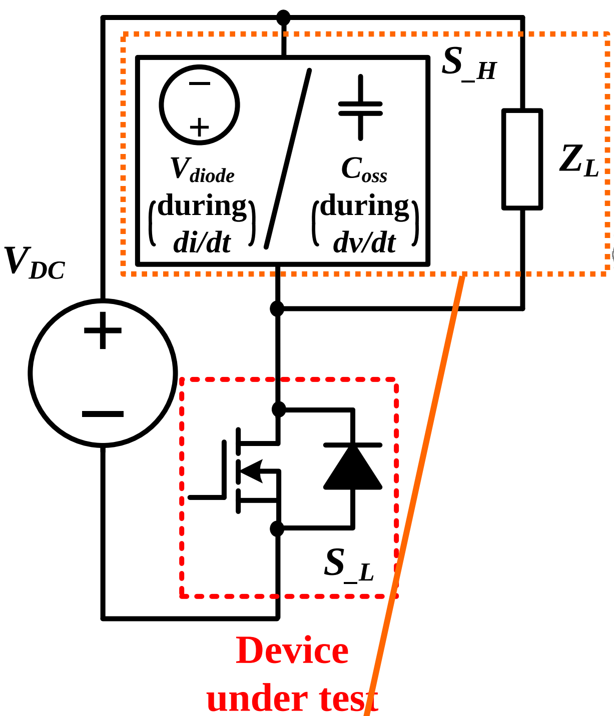
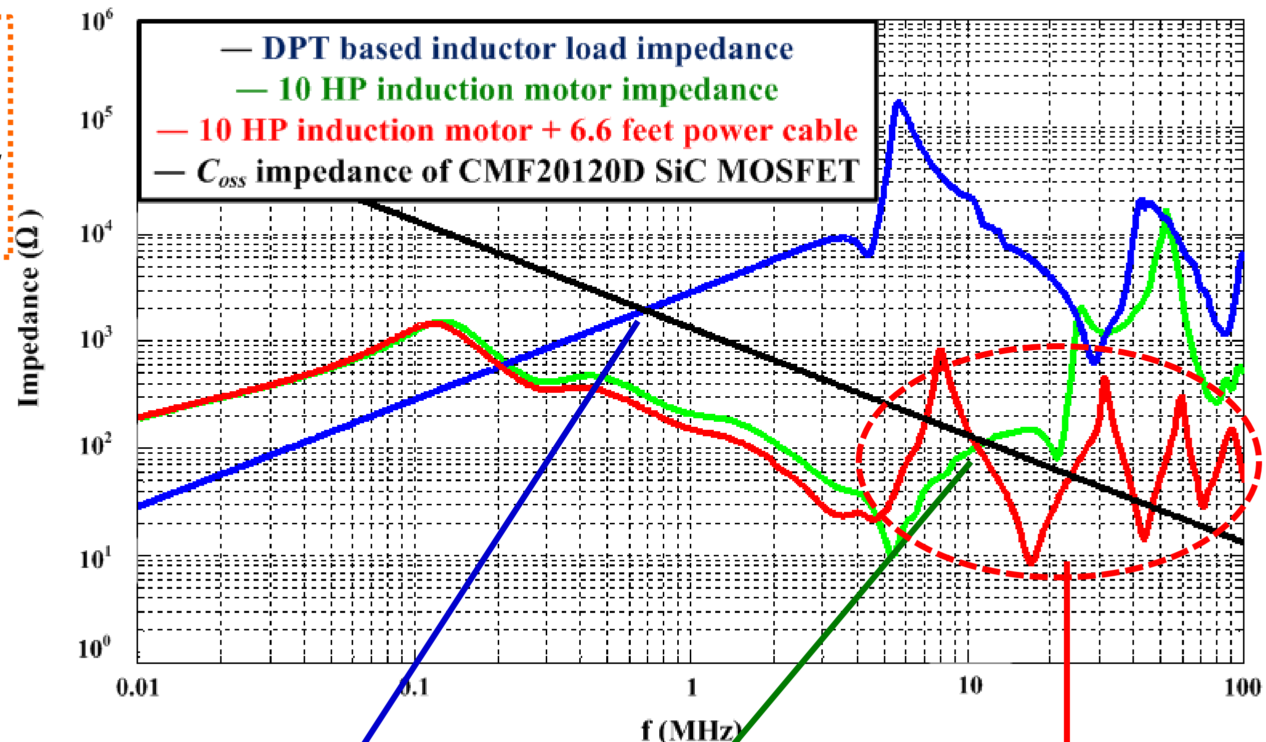
High-frequency Impedance Comparison





Z_L paralleled with C_{oss} during *dv/dt*

- Ideally, $|Z_L| >> |C_{oss}|$ @ HF
  Z_L has little impact on switching
- Practically, Z_L will affect switching if $|Z_L|$ is comparable to $|C_{oss}|$ @ HF

For DPT based inductor load $|Z_L| > |C_{oss}|$ @ 700 kHz

For 10 HP induction motor $|Z_L| > |C_{oss}|$ @ 10 MHz

For induction motor + cable, $|Z_L|$ is comparable to $|C_{oss}|$ until 50 MHz

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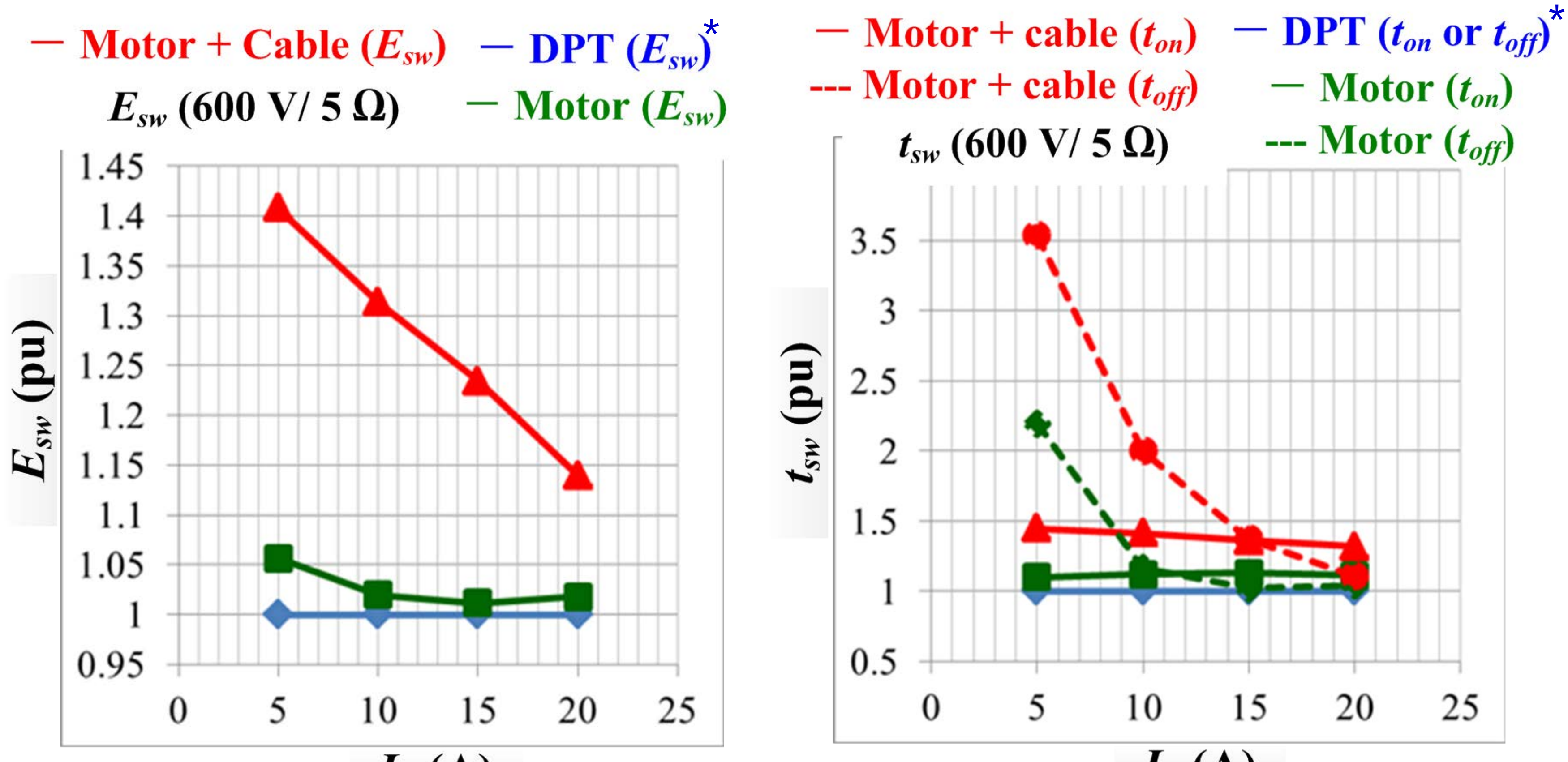
Impact of Motor on Motor Drives Design



* Other data are normalized based on DPT

- ❑ Cooling system cannot be designed based on switching loss from typical DPT
- ❑ Switching frequency and dead time cannot be set based on switching time from DPT

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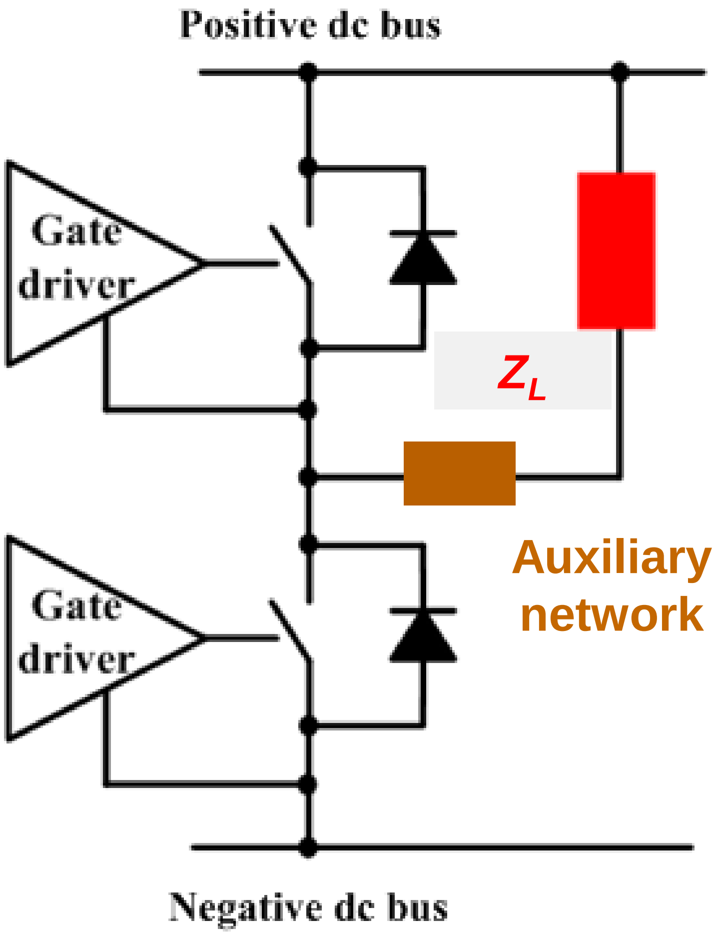
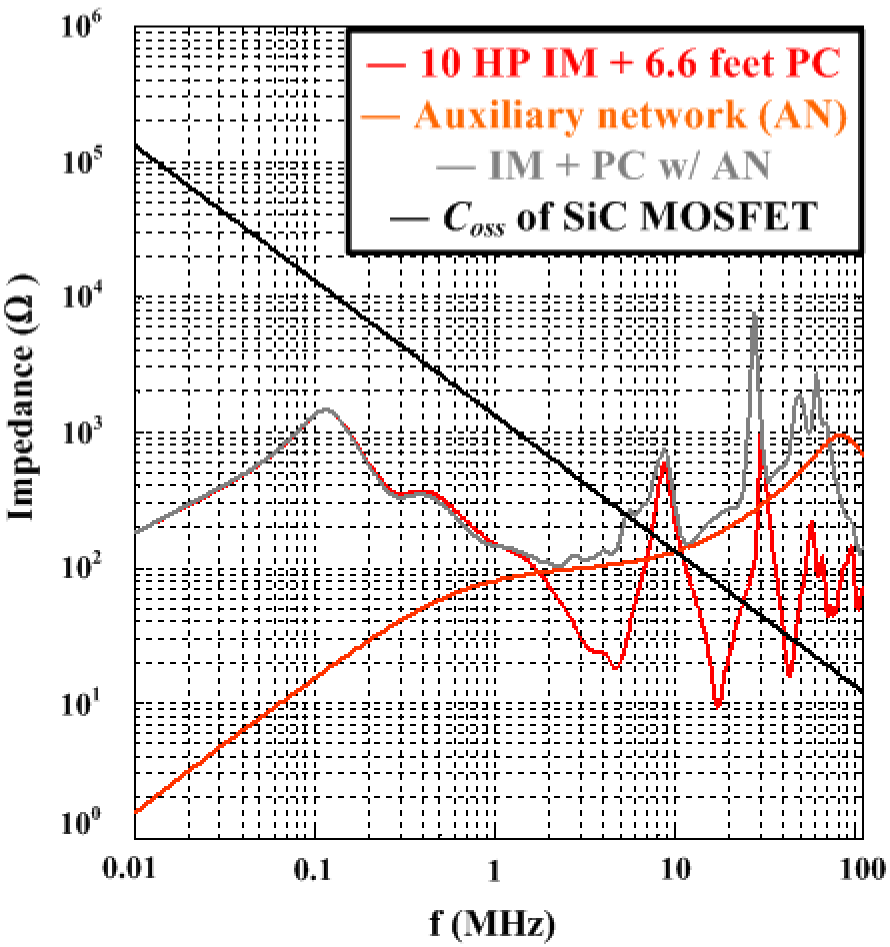
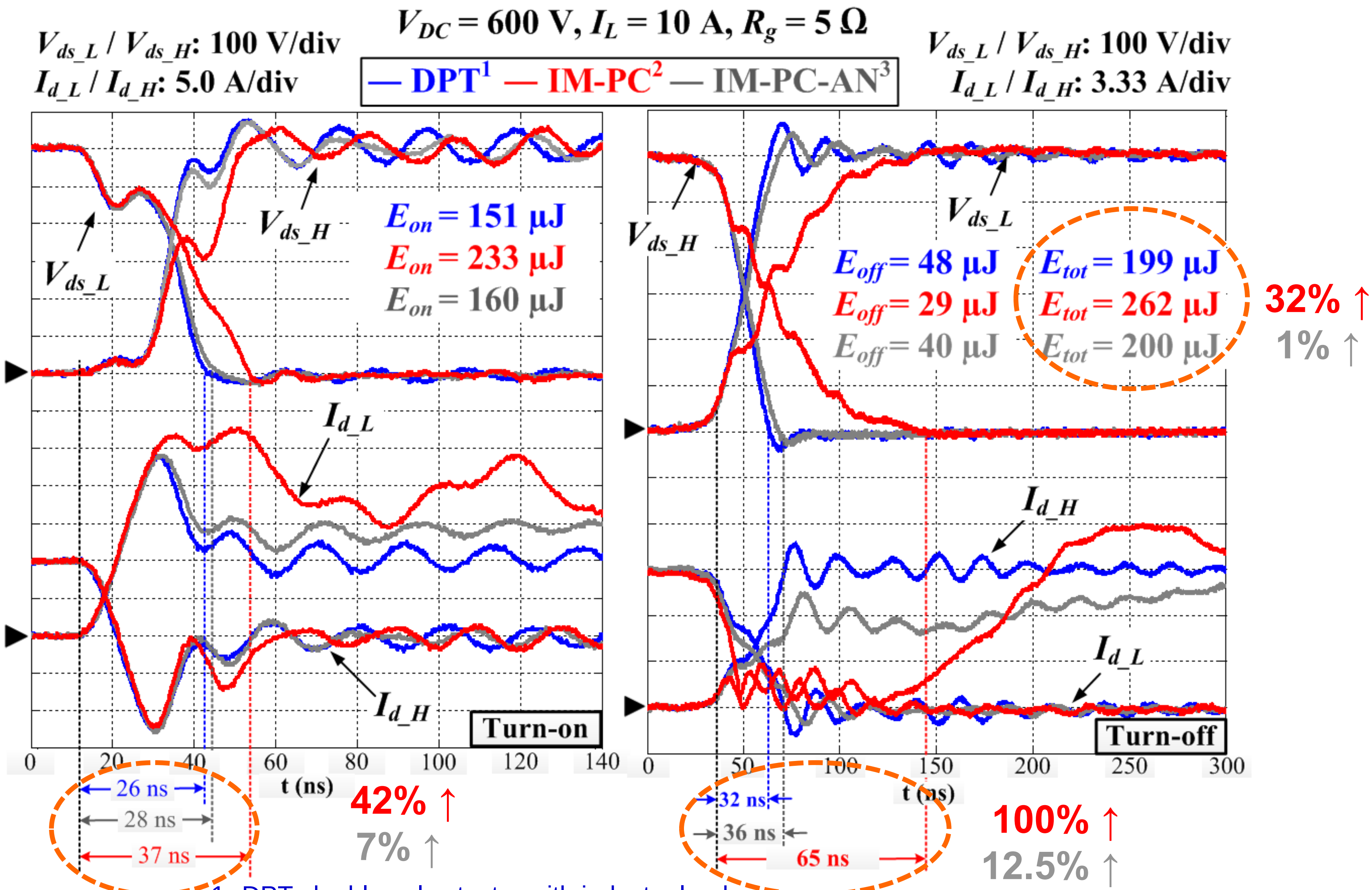
Auxiliary Network to Improve HF Impedance





- ❑ Insert an auxiliary network to increase high frequency impedance of induction motor

Switching Waveforms Comparisons



1. DPT: double pulse tester with inductor load
2. IM-PC: pulse tester with induction motor + power cable
3. IM-PC-AN: pulse tester with IM + PC + auxiliary network

Summary

- **High switching-speed performance of WBG in motor drives**
  - **Interference between upper & lower switches (cross talk)**
    - Short-through current causes turn-on energy loss increase, tested up to 19% and dv/dt reduction by 10%
    - Spurious negative gate voltage beyond required range
  - **Interaction between PWM inverter & induction motor**
    - Switching energy loss increased by 32%
    - Switching time increased by 42% during turn-on and doubled during turn-off
- **Better utilization of WBG devices in PWM motor drives**
  - **Active gate driver circuitry for cross talk suppression**
  - **Consider motor load characteristics in the design and operation of PWM inverter**
  - **Integrated design/operation methodology**

Acknowledgements

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