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# Current Sharing Measurements in Multi-Phase Switch Mode DC-DC Converters

Peter J. Pupalaikis, Teledyne LeCroy
Istvan Novak, Oracle
Lawrence Jacobs, Teledyne LeCroy


# Speakers

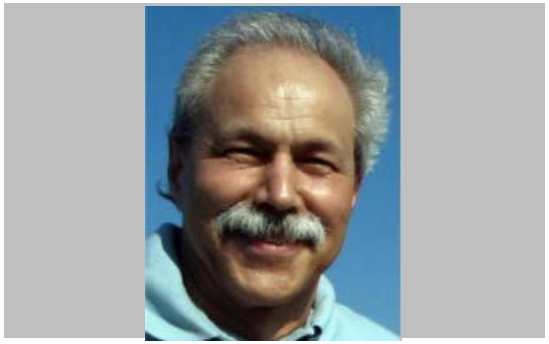
## Peter J. Pupalaikis, Vice President, Technology Development

Peter J. Pupalaikis was born in Boston, Massachusetts in 1964 and received the B.S. degree in electrical engineering from Rutgers University, New Brunswick, New Jersey in 1988. He joined LeCroy Corporation (now Teledyne LeCroy), a manufacturer of high-performance measurement equipment located in Chestnut Ridge, New York in 1995 where he is currently Vice President, Technology Development, managing digital signal processing development and intellectual property. His interests include digital signal processing, applied mathematics, signal integrity and RF/microwave systems.
Prior to LeCroy he served in the United States Army and has worked as an independent consultant in embedded systems design.
Mr. Pupalaikis holds forty-three patents in the area of measurement instrument design and has contributed a chapter to one book on RF/microwave measurement techniques. In 2013 he became an IEEE fellow for contributions to high-speed waveform digitizing instruments. He is a member of Tau Beta Pi, Eta Kappa Nu and the IEEE signal processing, instrumentation, and microwave societies.

# Speakers

## Istvan Novak, Senior Principal Engineer

Besides signal integrity design of high-speed serial and parallel uses, he is engaged in the design and characterization of power-distribution networks and packages for mid-range servers. He creates simulation models, and develops measurement techniques for power distribution. Istvan has twenty plus years of experience with high-speed digital, RF, and analog circuit and system design. He is a Fellow of IEEE for his contributions to signal-integrity and RF measurement and simulation methodologies.



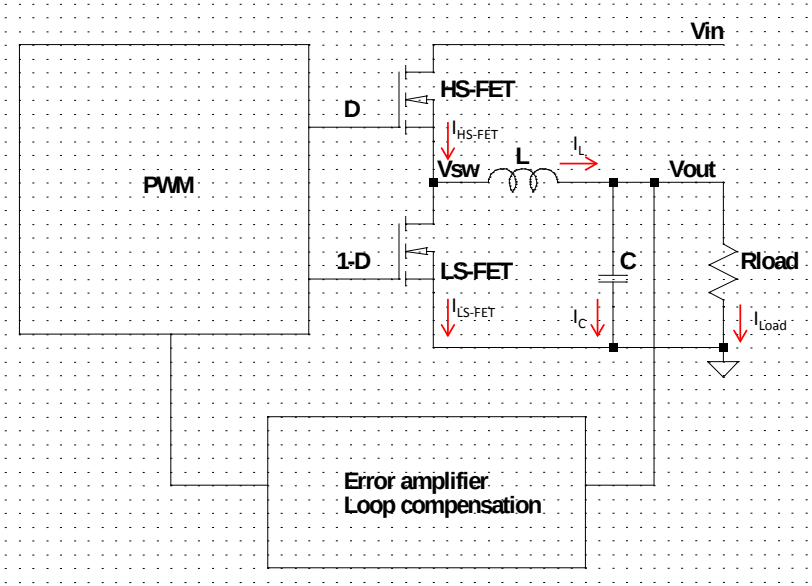
## Lawrence Jacobs, Manager, Probe Development Group

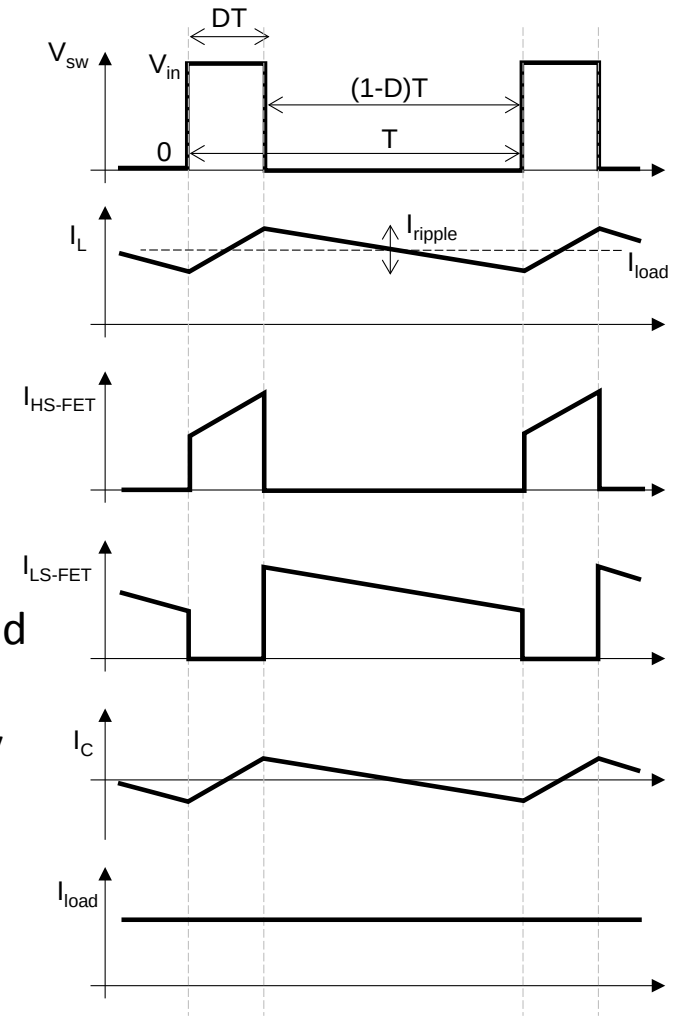
Lawrence Jacobs was born in Palo Alto, California, in 1963. He received the B.S. degree in electrical engineering from Stanford University and the M.S. degree in electrical engineering from Santa Clara University in 1985 and 1990, respectively. He joined LeCroy Corporation (now Teledyne LeCroy), a manufacturer of high-performance measurement equipment located in Chestnut Ridge, New York in 1999 where he is presently managing the probe development group. His interests include precision analog and high frequency electronics design and measurement. Mr. Jacobs holds fourteen patents.

# Outline

- Introduction, motivation
- Current Measurement options
  - Current probe around conductor
  - Using Rdson
  - Using RC network across inductor
  - Using sense resistor
  - Sense resistor and RC probe tip measurement comparison
- Measuring Current Sharing
  - Three-phase supply measurements
  - Two-phase supply measurements
  - Six-phase in situ current sharing monitoring
- Conclusions

# Introduction, Motivation



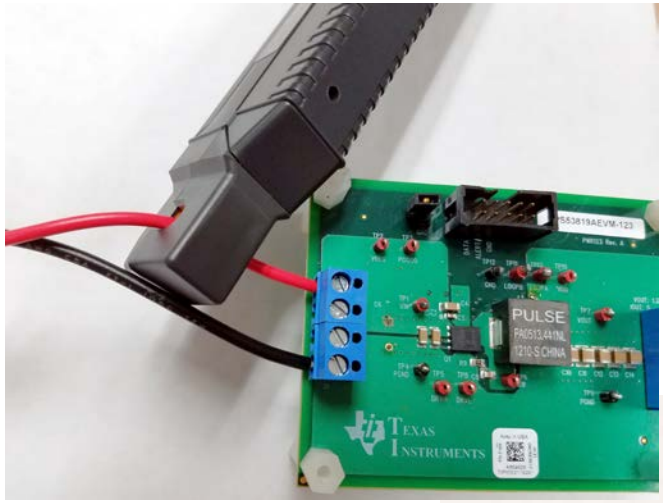




- High-current buck regulators (typically above 40A) need multiple phases
- DC and transient load current must be shared equally
- Improper current sharing can result in
  - Thermal overstress
  - Overcurrent shutdown
  - Reduced efficiency
- Challenge: current-sharing control loop may be inaccessible to user

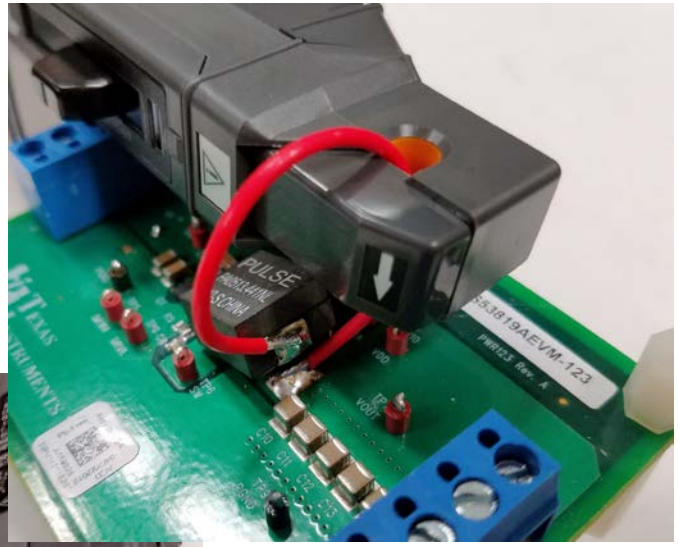
# Current Measurement

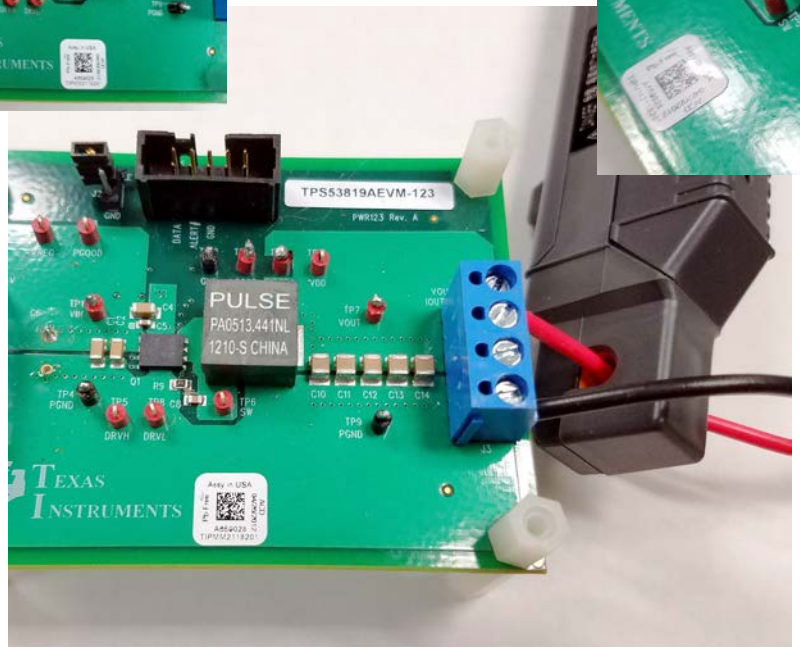
## Probe around conductor

Input-current measurement




Inductor-current measurement

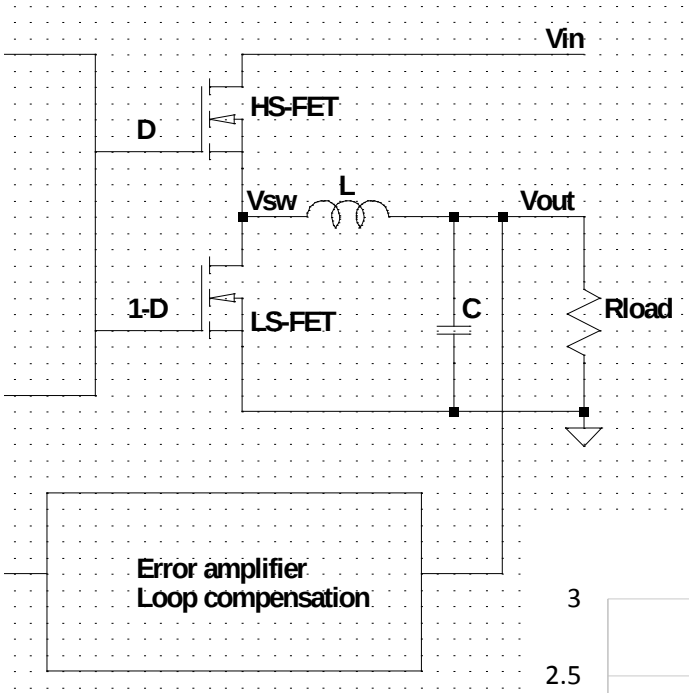


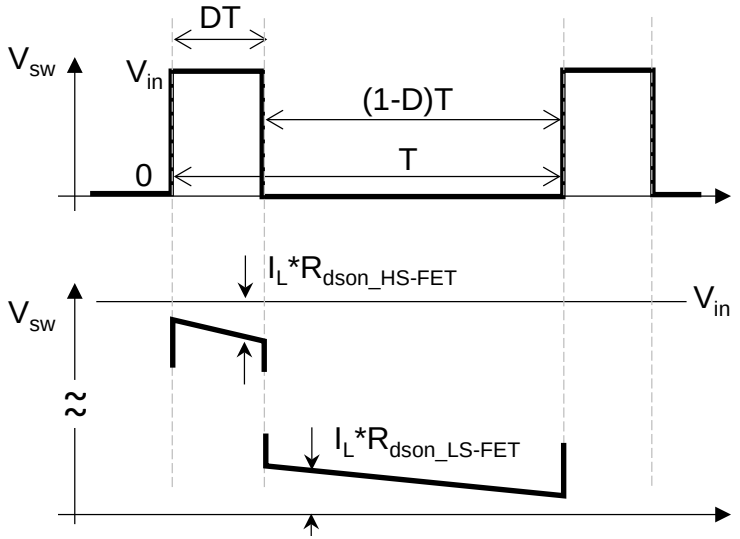




Output-current measurement

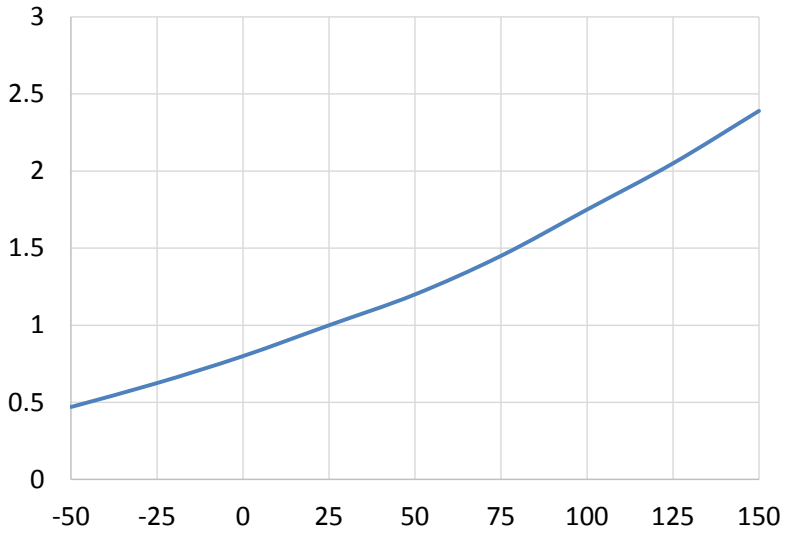
# Current Measurement

## Using Rdson



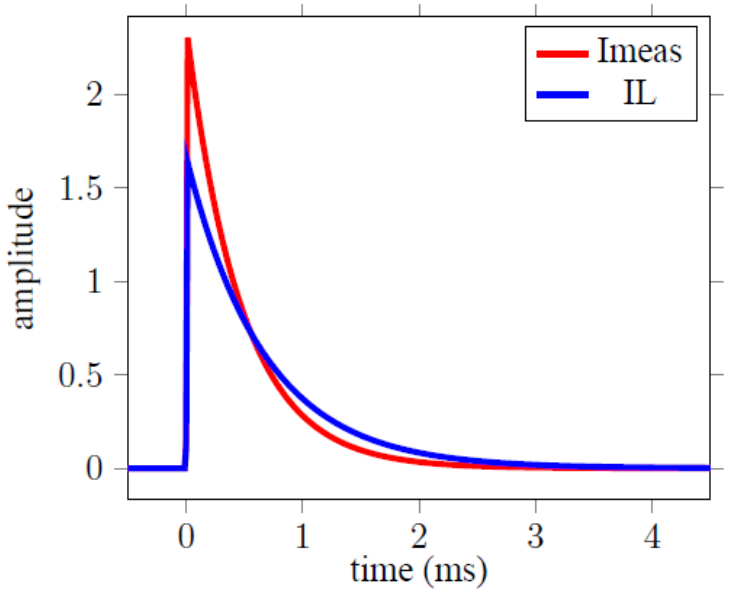




Normalized Rdson vs. temperature [-]

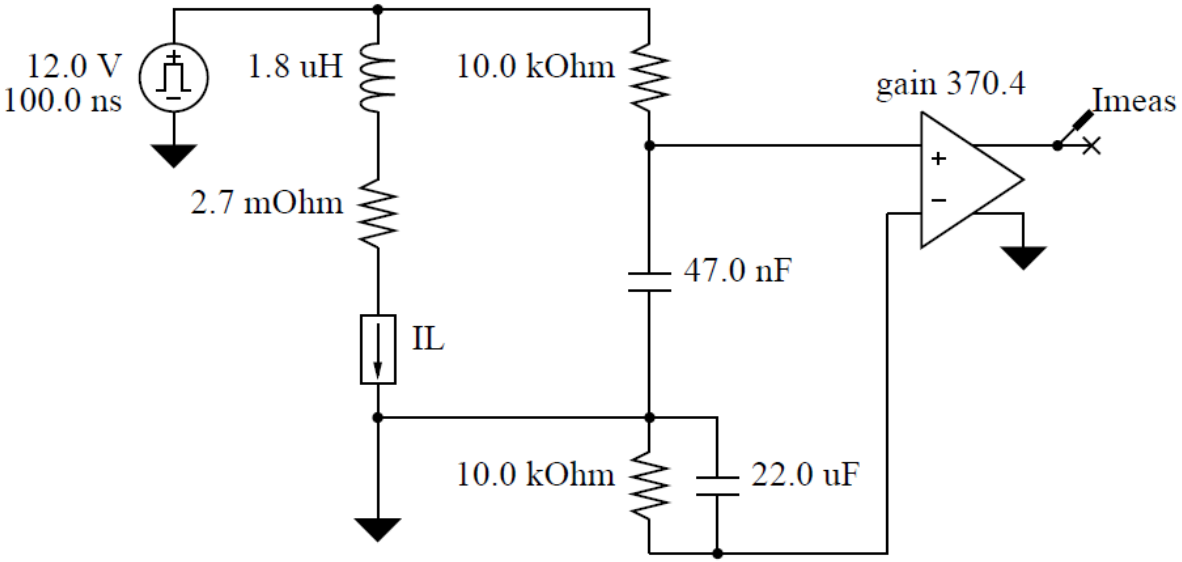


# Current Measurement

## Using RC network across inductor




(b) output waveforms showing time-constant mismatch

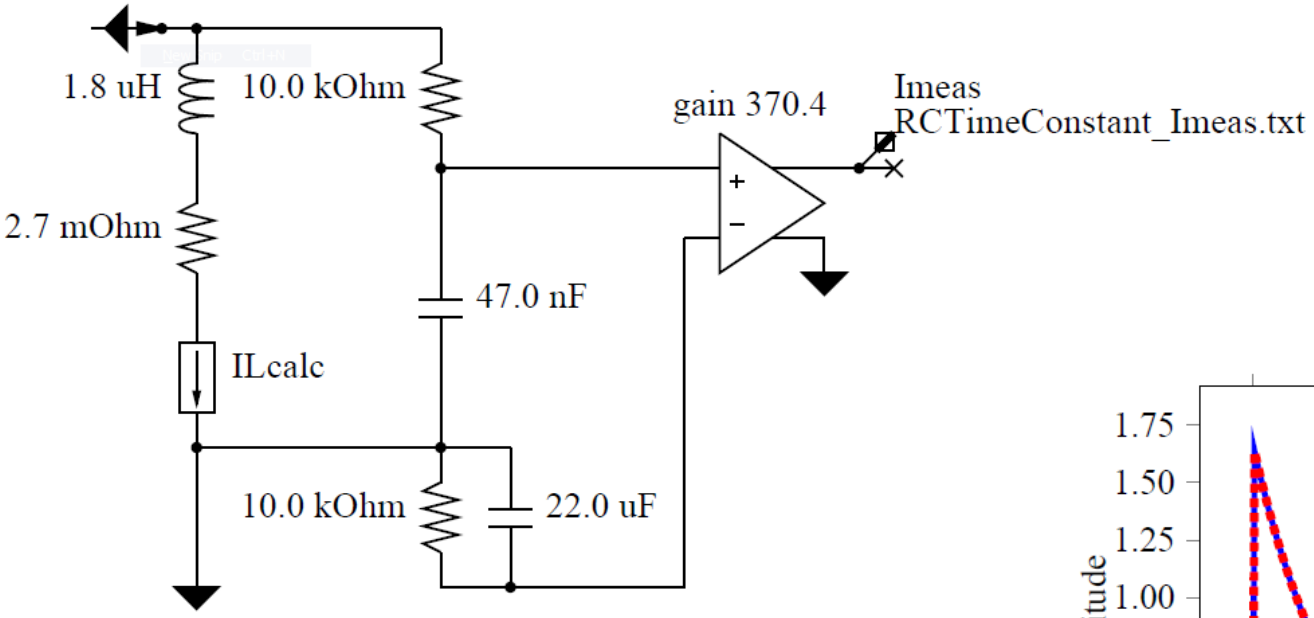



(a) simulation of current measurement with 12 Volt pulse

Error occurs if time constants differ

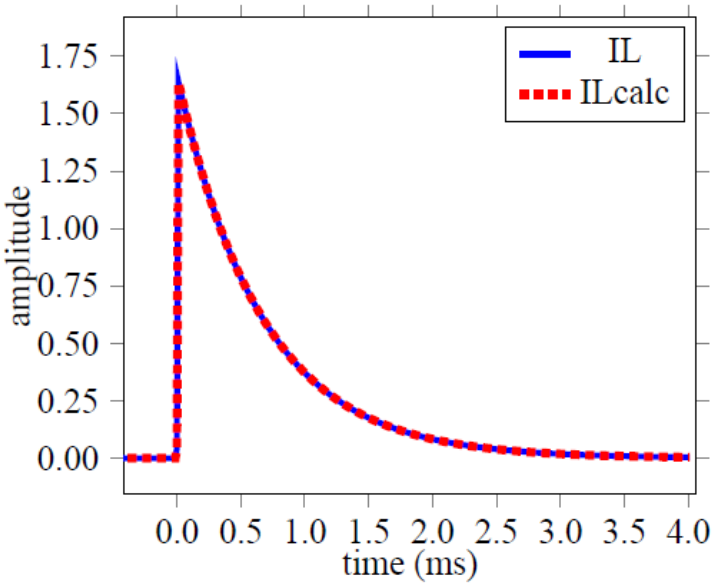
# Current Measurement

## Using RC network across inductor




(a) Virtual Probe arrangement to determine actual current

Error is eliminated by Virtual Probe

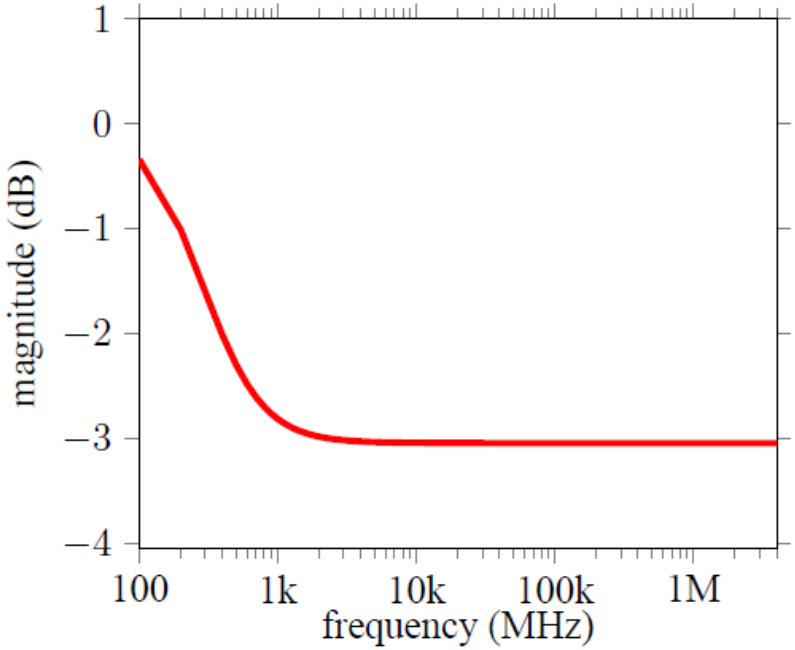



(b) Virtual Probe calculated current waveform

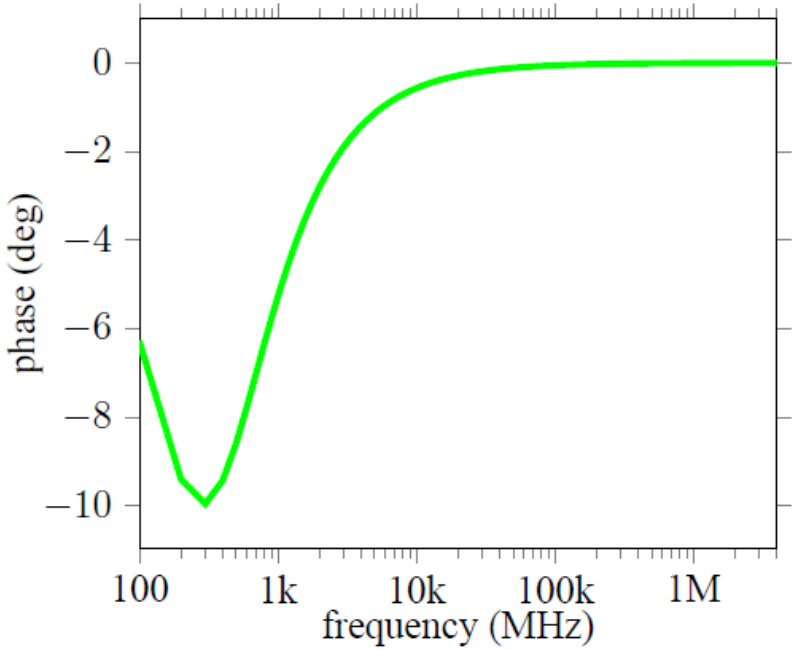
# Current Measurement

## Using RC network across inductor

Virtual Probe transfer functions



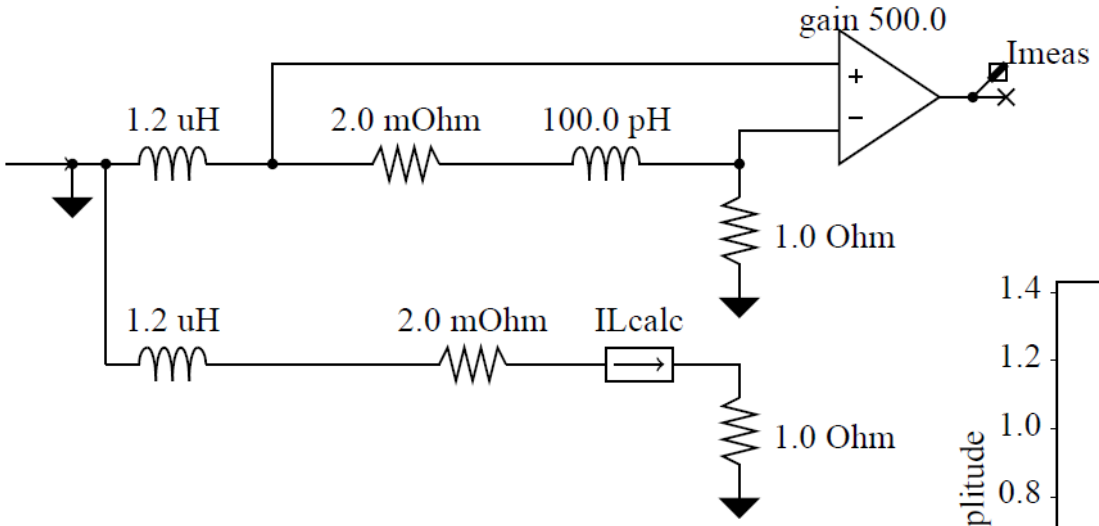

(c) Virtual Probe magnitude response



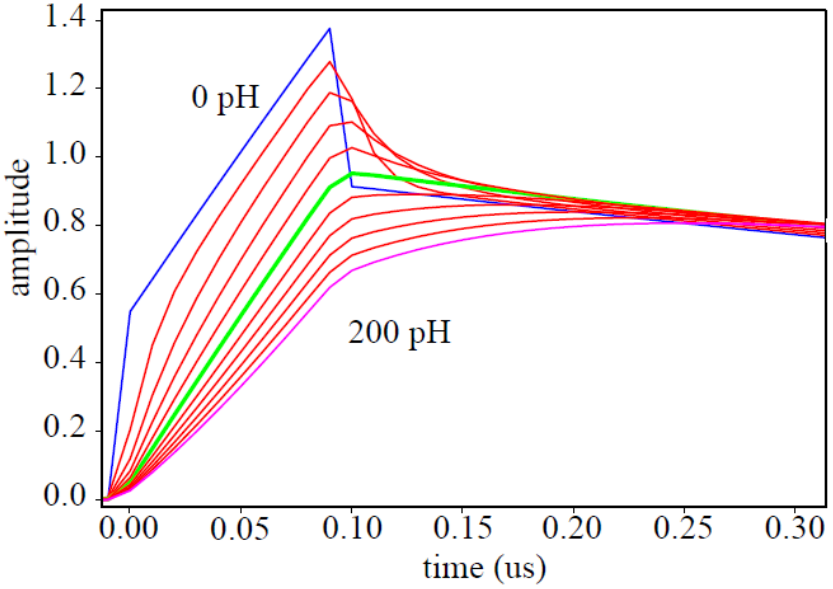

(d) Virtual Probe phase response

# Current Measurement

## Using sense resistor




(a) Virtual Probe arrangement to determine actual current



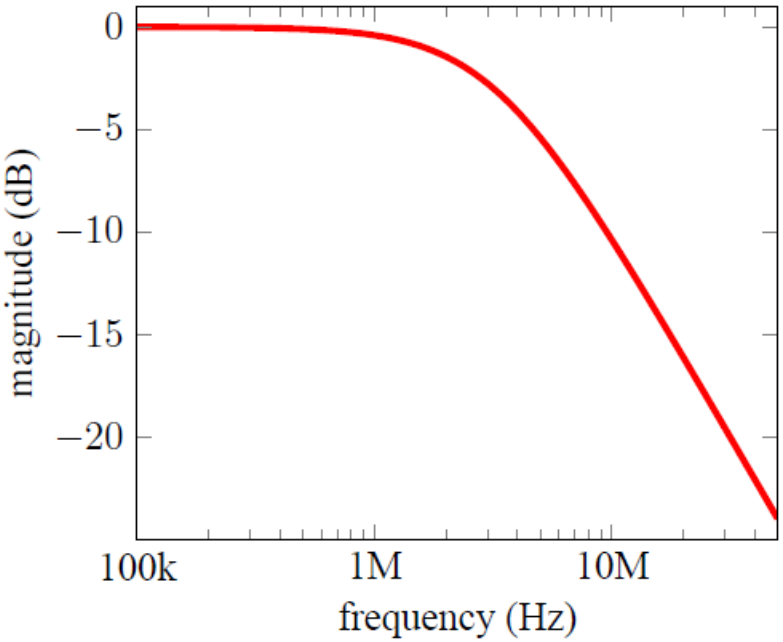

(b) Virtual Probe calculated current waveform

- Series inductance of sense resistor introduces error
- Sense resistor reduces efficiency

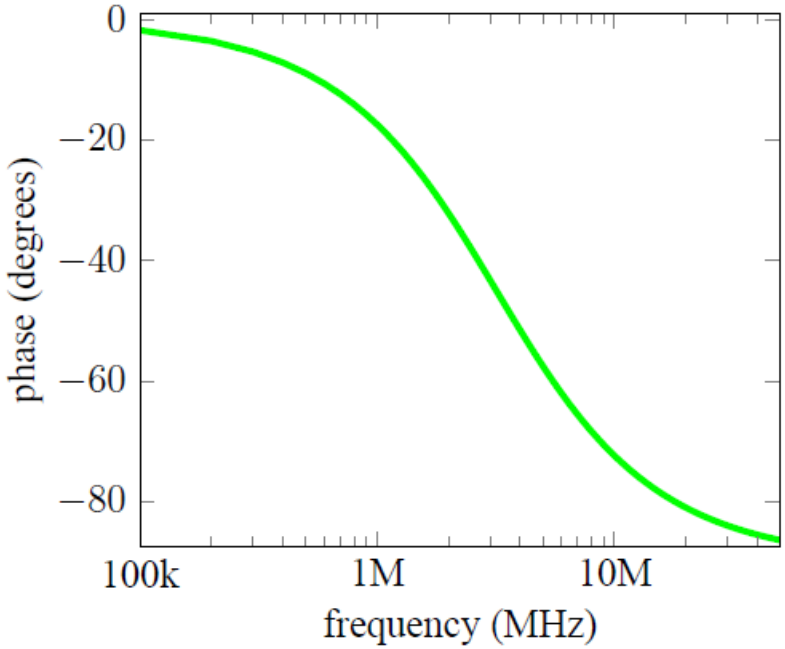
# Current Measurement

## Using sense resistor

Virtual Probe transfer functions



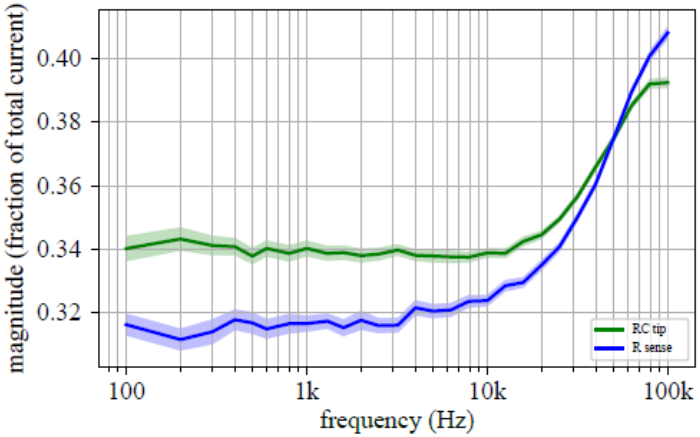

(c) Virtual Probe magnitude response



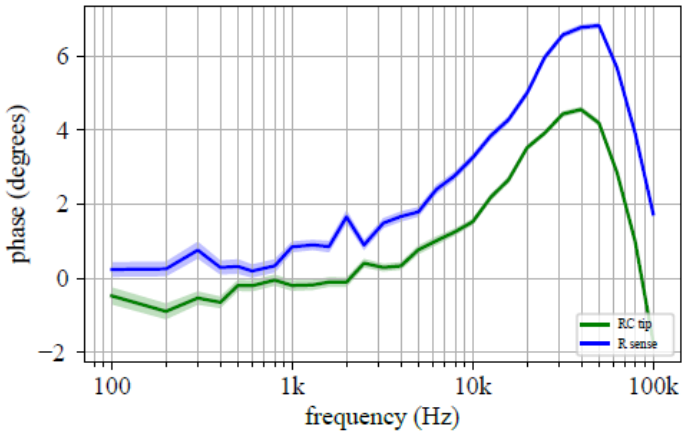

(d) Virtual Probe phase response

# Current Measurement

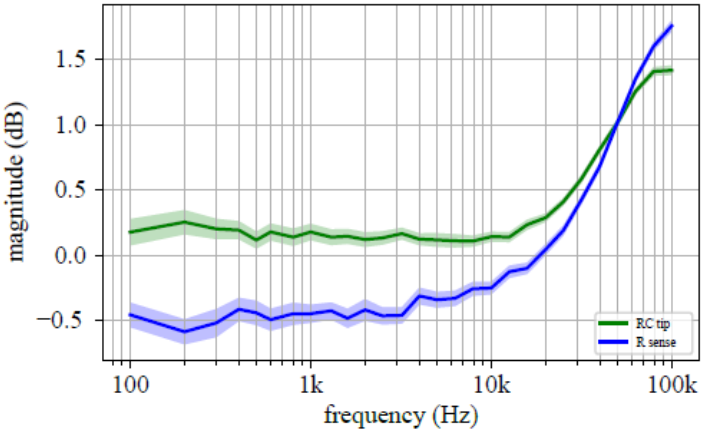
## Sense resistor and RC tip comparison



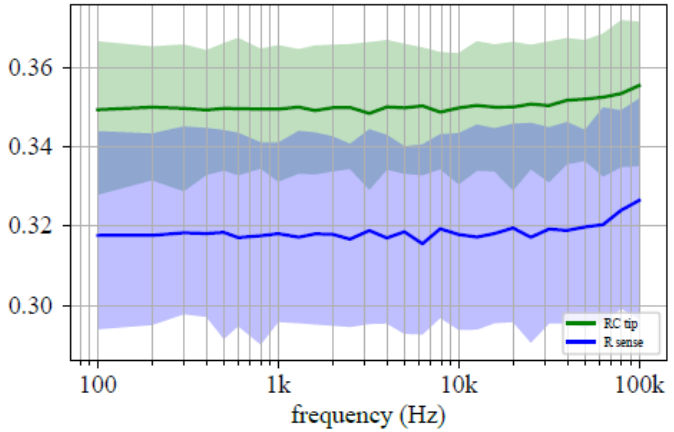

(a) current sharing fraction




(b) current sharing phase




(c) current sharing transfer funcion



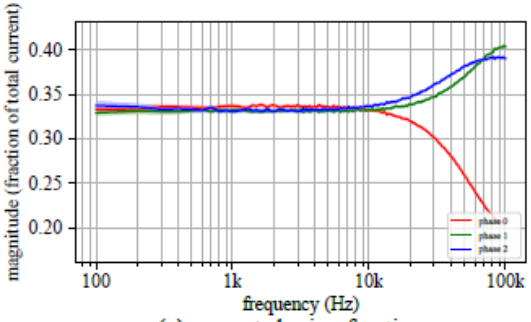

(d) current sharing transfer funcion

# Current Sharing Measurements

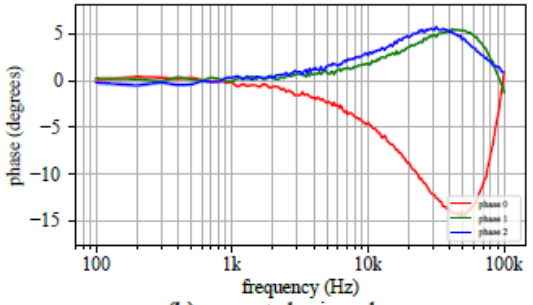
Load transients can be

- Sinusoidal, small or large signal
- Pulse, small or large signal
- Burst
- Active load (monitor mode)

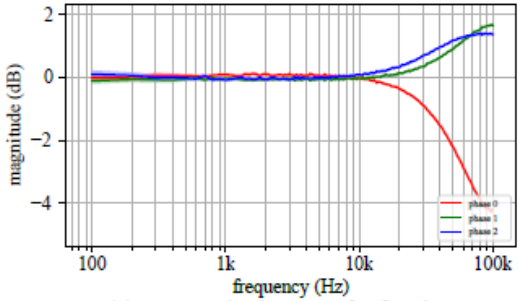
# Three-phase Converter



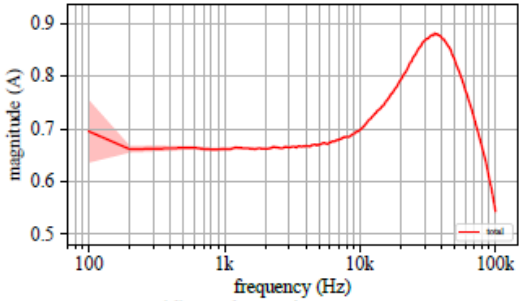
(a) current sharing fraction



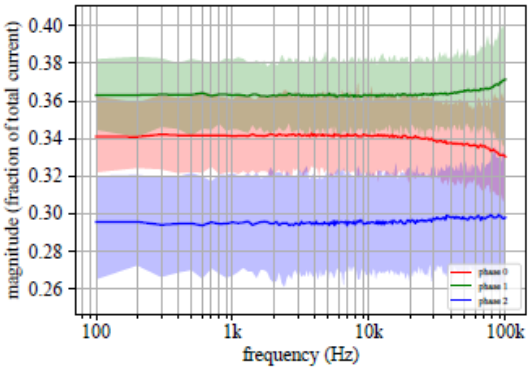
(b) current sharing phase



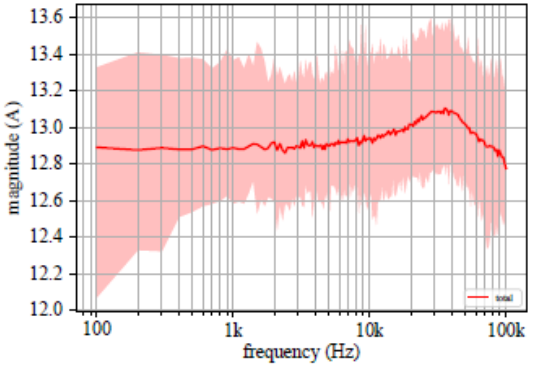
(c) current sharing transfer funcion



(d) total transient current

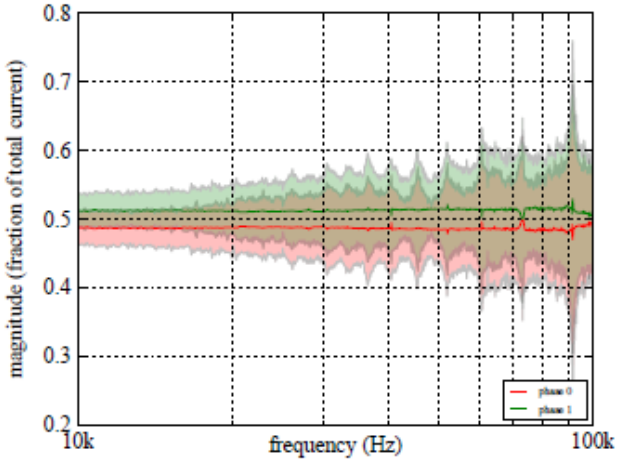


(e) current sharing transfer funcion

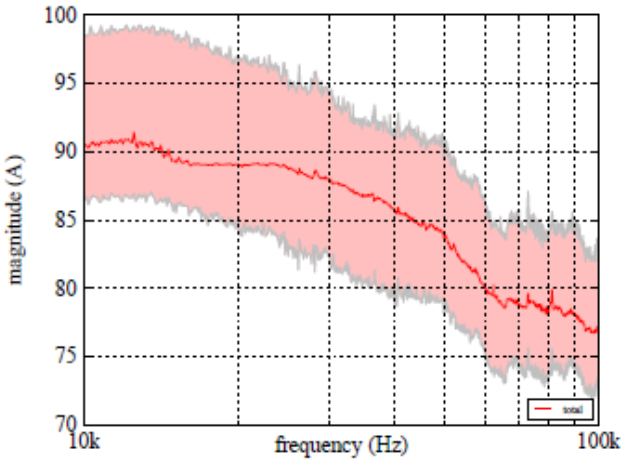


(f) total transient current

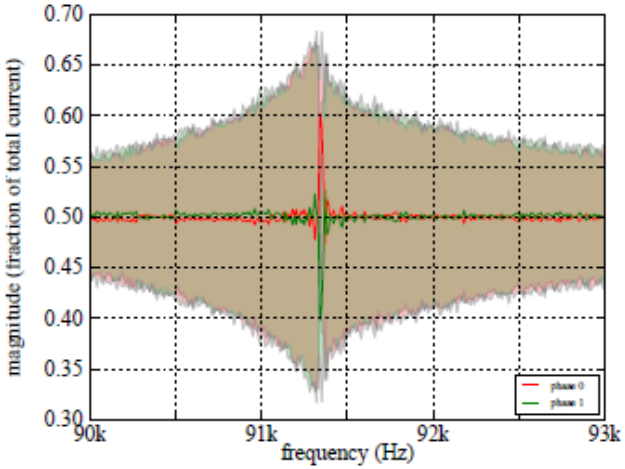
# Two-phase Converter



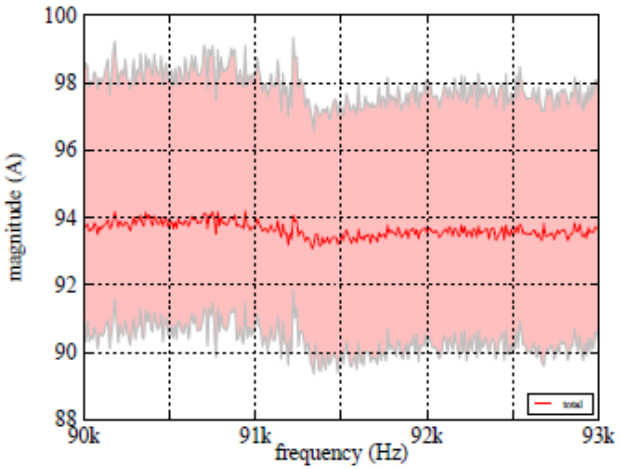

(a) current sharing fraction




(b) total current

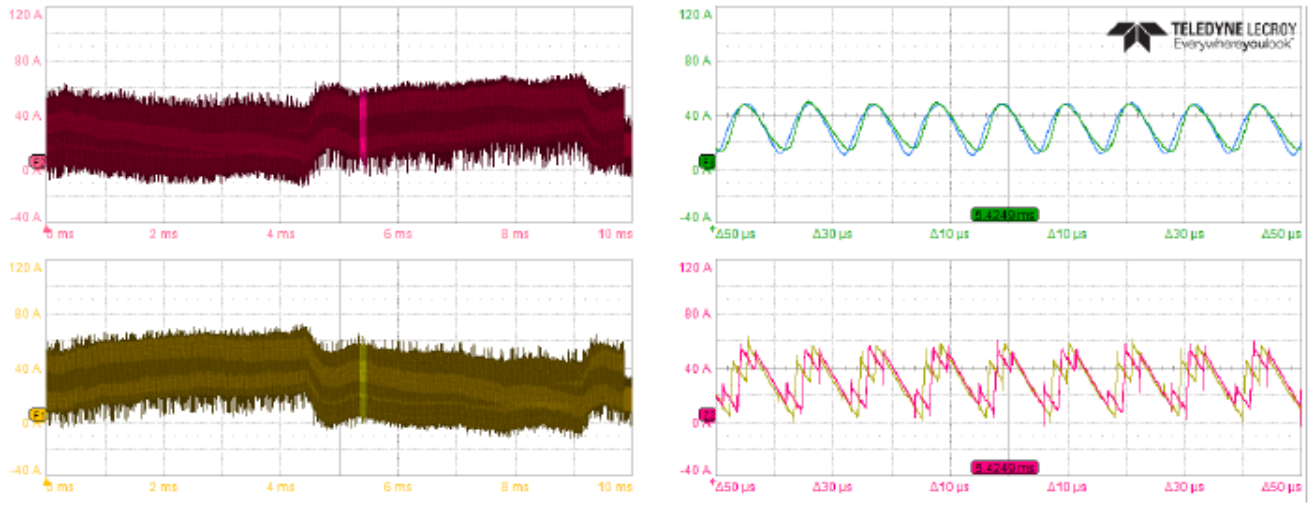



(c) current sharing fraction

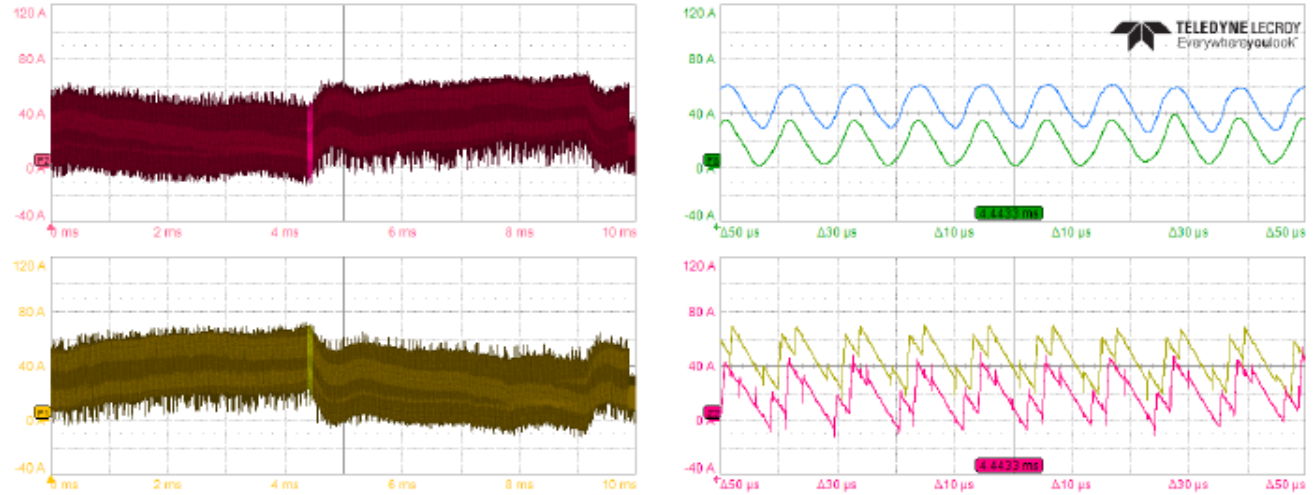



(d) total current

# Burst Mode

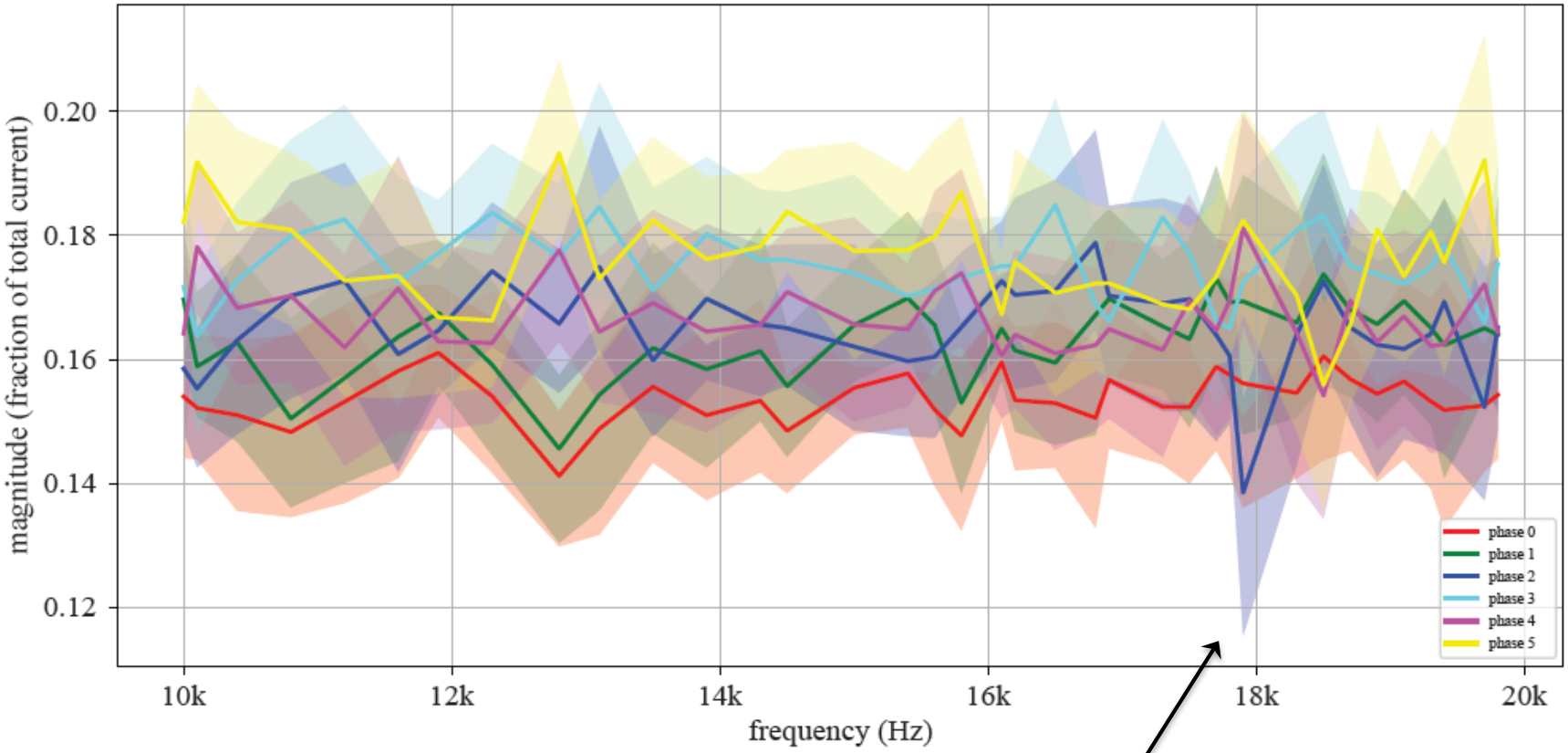



(a) good current sharing



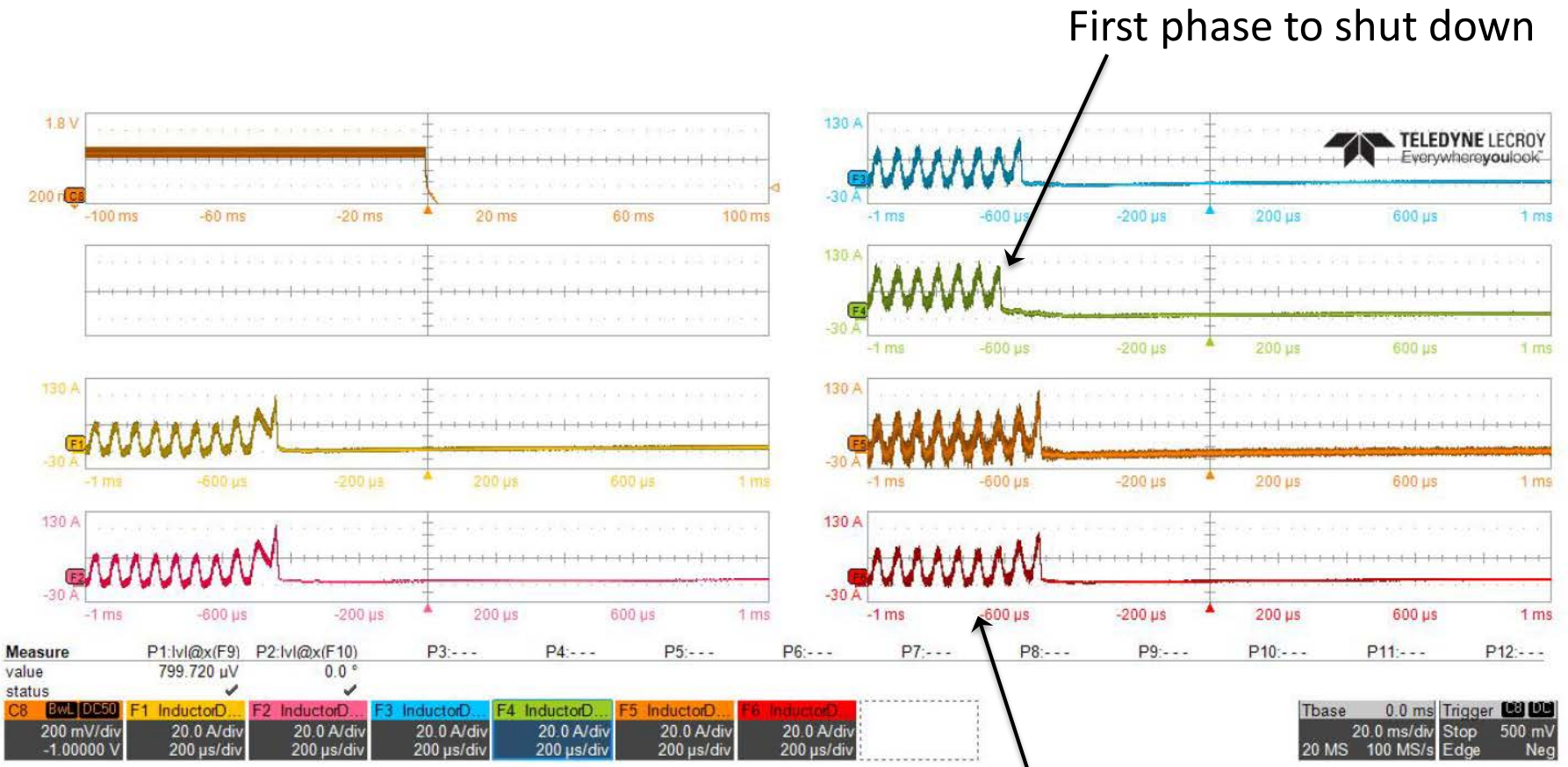

(b) poor current sharing

# Monitor Mode




Large deviation from equal current sharing

# Six-phase In-situ Monitoring



# Conclusions

- Error-prone home-made inductor-current measuring setup is replaced with professional setup
- DSP correction of time-constant differences enables the use of generic RC probe tips
- DSP can also correct for ESL of sense resistors
- Behavior of closed current-sharing loops can be assessed by applying internal or external transient stimulus
- Frequency-domain response can be obtained by automatically identifying the signatures of current fluctuations

# Acknowledgements

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# More Information


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# Thank You!

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QUESTIONS?