High Precision Power Measurement of SiC Inverters

- With wide band current sensors -

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POWER ELECTRONICS 2019

Error Factors of Power Measurement for High Freq. Inverter Evaluation

1. Voltage amplitude error (including frequency characteristics)
2. Current amplitude error (including frequency characteristics)
3. **Effect of noise**
4. **Effect of Phase Error for Power Measurement**

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Effect of noise

Miniaturization and High-Frequency

Why?

Stylish Smart Green

Miniaturization gives us reduction in volume, and weight.

- **High flexibility in design**
- **High efficiency power transformation**

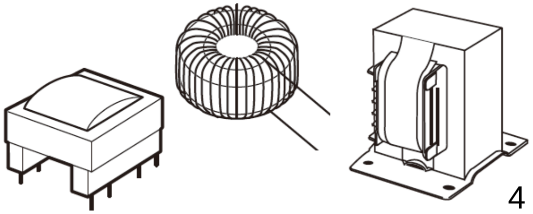
  → Reducing resources and energy loss.

As you know

Power of *L* and *C* in electric circuits are defined as

<u>2π*fL*</u> and <u>2π*fC*</u>

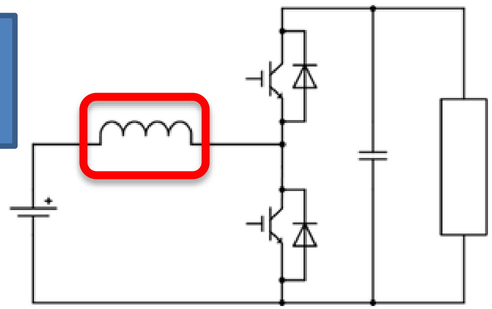
Frequency *f* have to be high to keep same power



DC/DC Converter & AC/DC Converter

DC/DC Converter (Boost Chopper)

Switching Frequency:
Around 10kHz to 50kHz

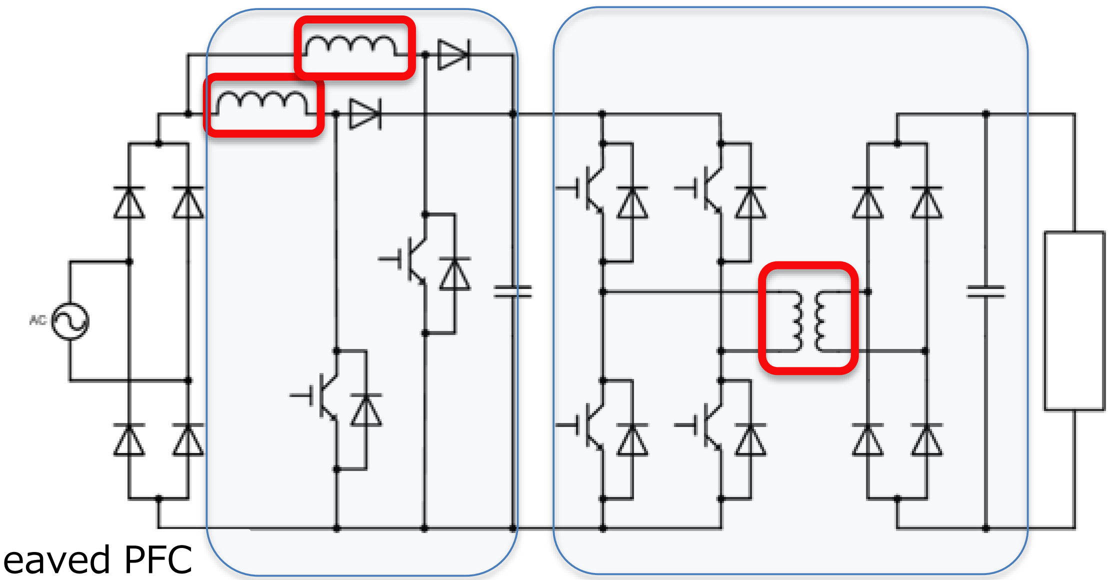


Thanks to higher switching frequencies, reactors and isolation transformers are miniaturized

AC/DC Converter (PFC isolated type)

Switching Frequency:
Mainly 10kHz to 100kHz

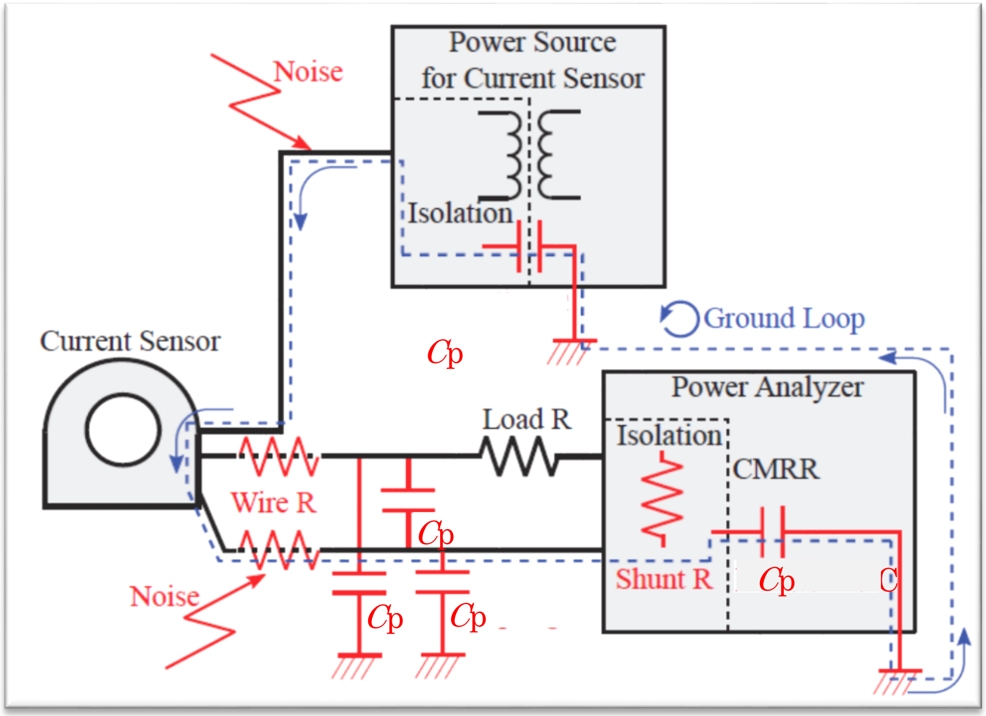
Isolated DC/DC Converter



Interleaved PFC

PFC : Power Factor Correction

Effects of higher switching frequency for measurement



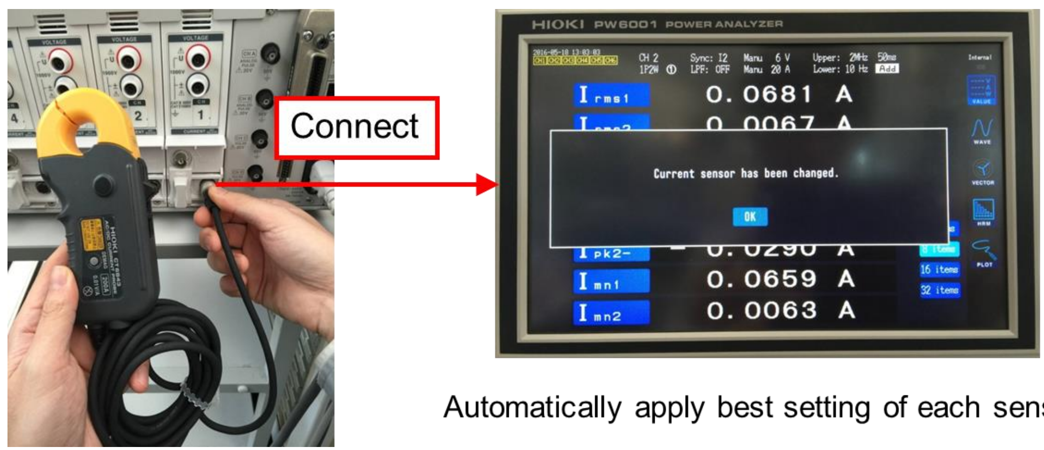
Large effects of noise with higher *f* for 2π*f*Cp (*C*p: Parasitic Capacitance)

Noise disturbance for Current Measurement

Ideal Current Sensors for Power Analyzers

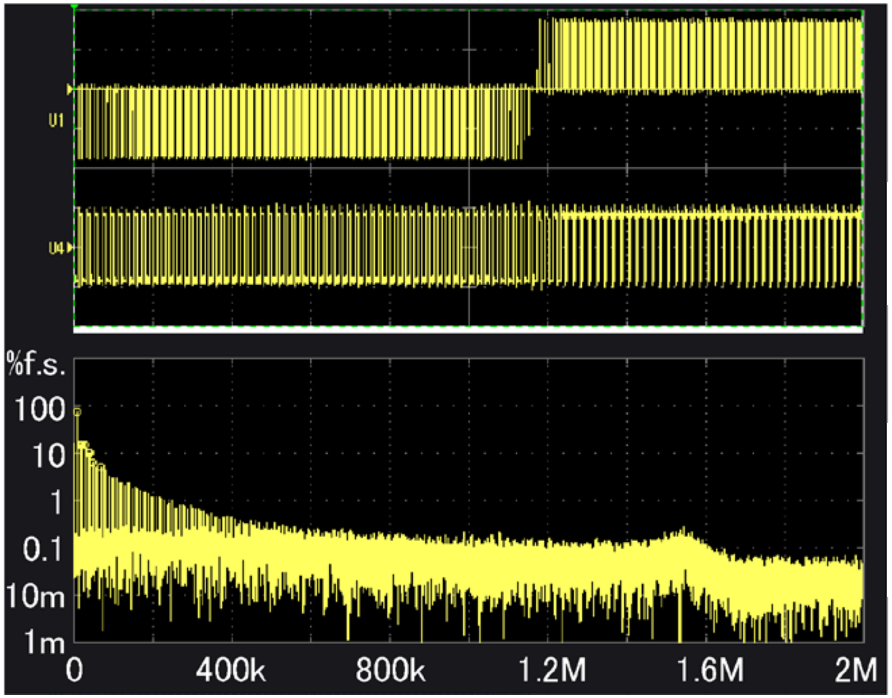
To reduce the effect of noise, current sensors are desired directly connected to power analyzer.

- Sensor output is connected to a power analyzer.
- Sensor power is supplied from a power analyzer.
- Sensor type, output rating, and power analyzer measurement range are automatically recognized and defined.
- Superior shielded connection with one common Earth.



Automatically apply best setting of each sensor.

Effects of Common-Mode Voltage



Line – line voltage

Common-mode voltage

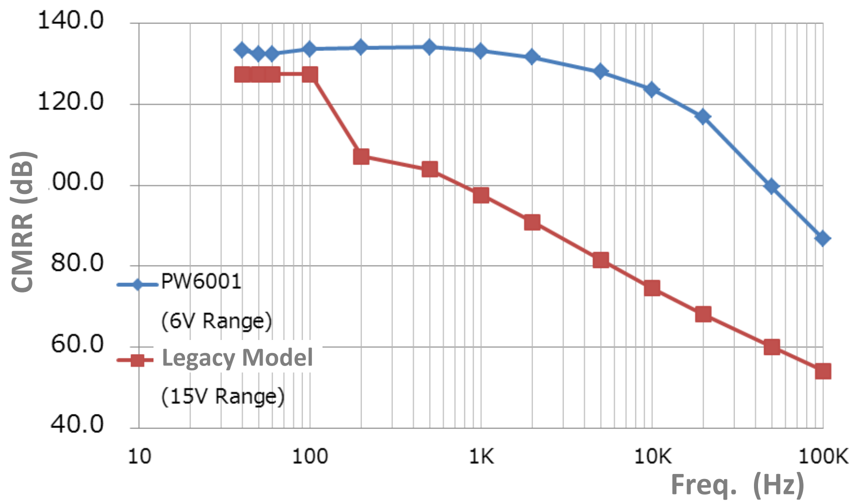
FFT spectrum of common-mode voltage

Common-mode voltage of inverter output

Switching devices emit common-mode voltage which includes switching frequency and its harmonic components

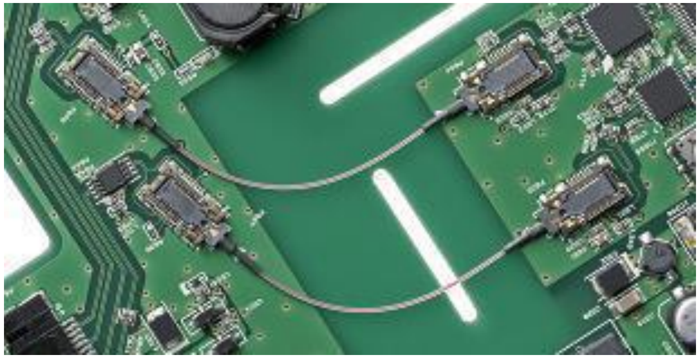
SiC and GaN devices give us higher switching frequency

Achieved Better Noise Resistivity (CMRR) Performance of Power Analyzer



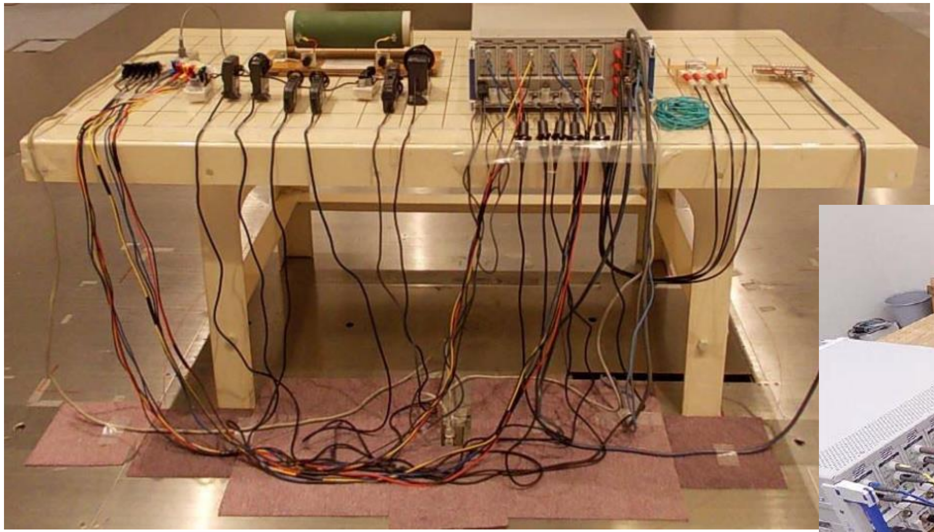
Inverter measurement: Requires better noise resistivity
PW6001: 80dB(=0.01%) at 100kHz
→1kVrms common mode noise results in measured value as 0.1Vrms

Solid metal shielding

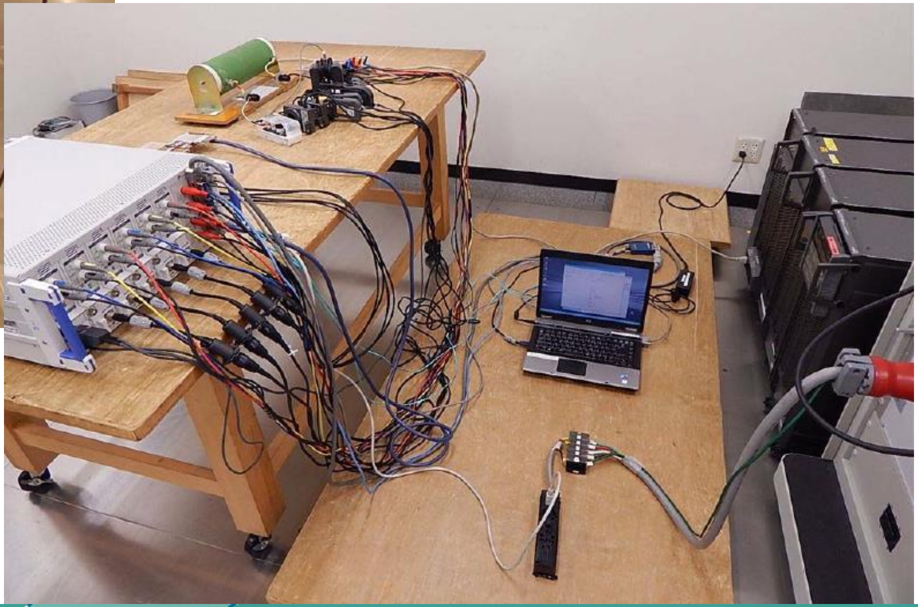


Optical isolation

Noise Immunity Test for Power Analyzer and Current Sensors



Appearance of noise immunity test at third party organization.



Cleared all immunity tests in combination

If there are any problem, we can improve either or both of power analyzer and current sensors.

Error Factors of Power Measurement for Inverter Evaluation

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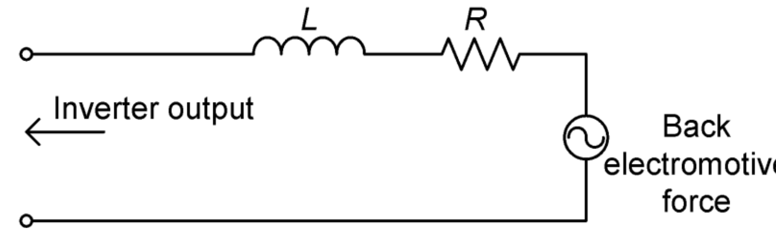
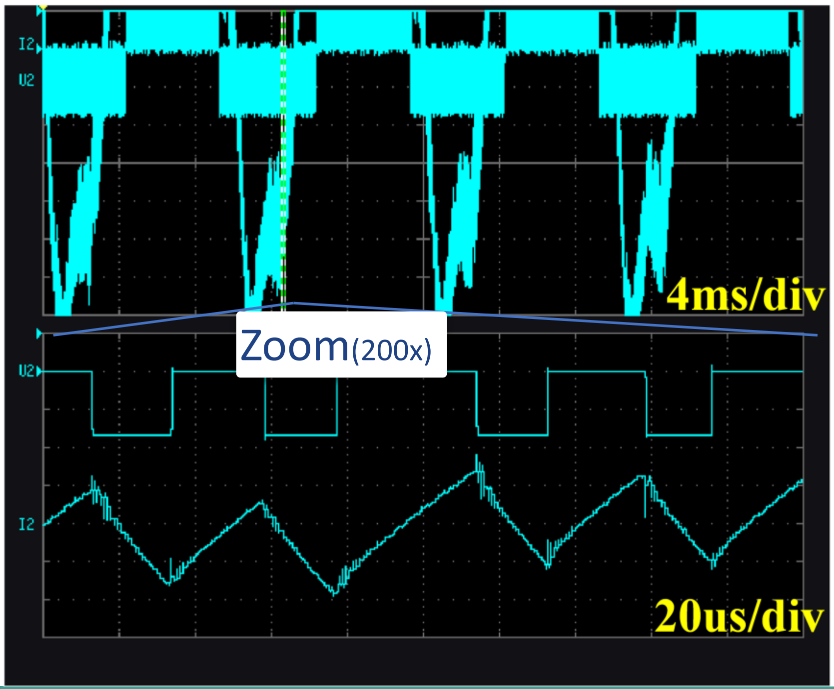
Effect of Phase Error for Power Measurement

$Z = R + j\omega L = R + j*2\pi f L$



Reactor's equivalent circuit (1-phase)



Voltage waveform

Current waveform

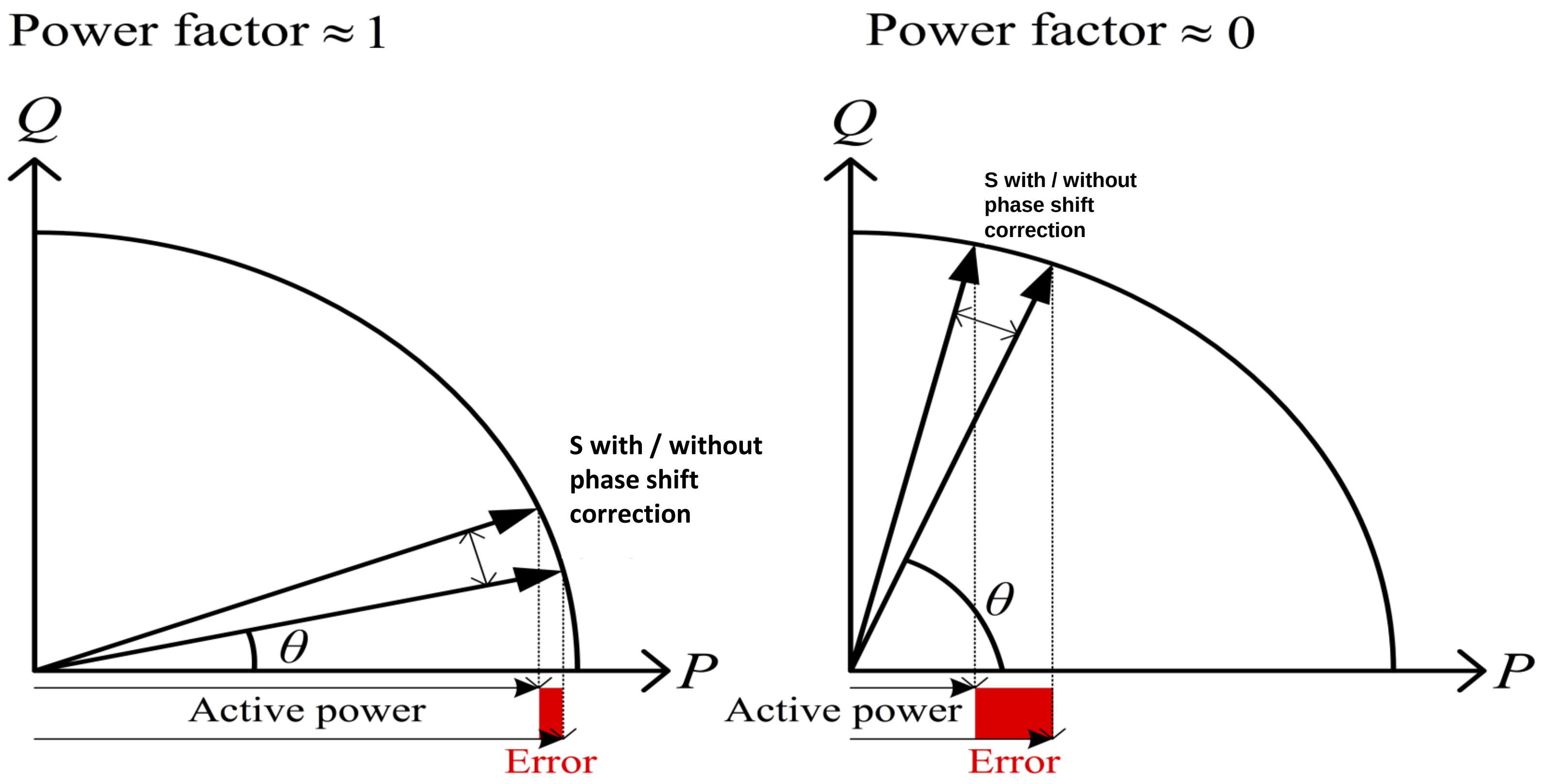
Voltage waveform

Current waveform

Current has phase lag to voltage waveform at higher frequency. That means "low power factor".

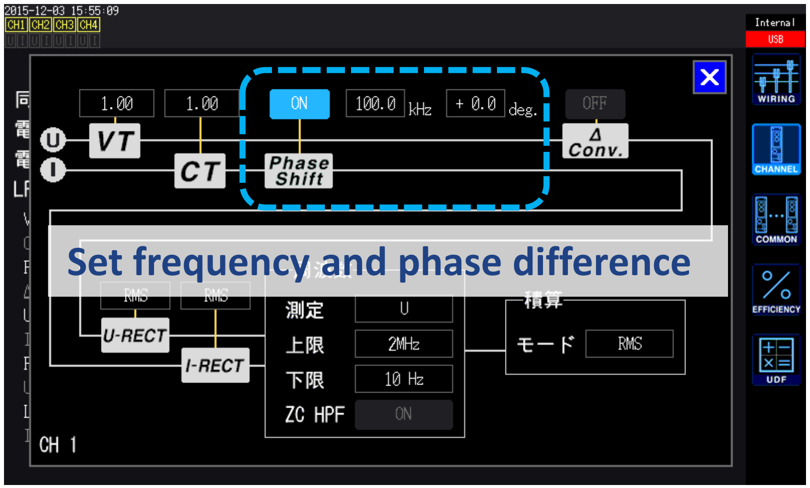
Precise power measurement at high frequency and low power factor are required for inverter and reactor loss measurement.

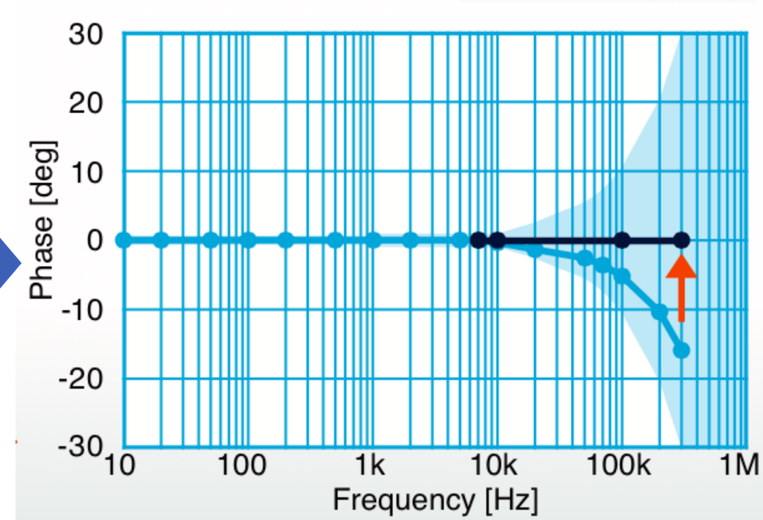
Effect of Phase Error for Power Measurement



Phase error affects a lot for the power measurement at low power factor.

Phase Shift Function to Reduce the Voltage and Current Phase Error

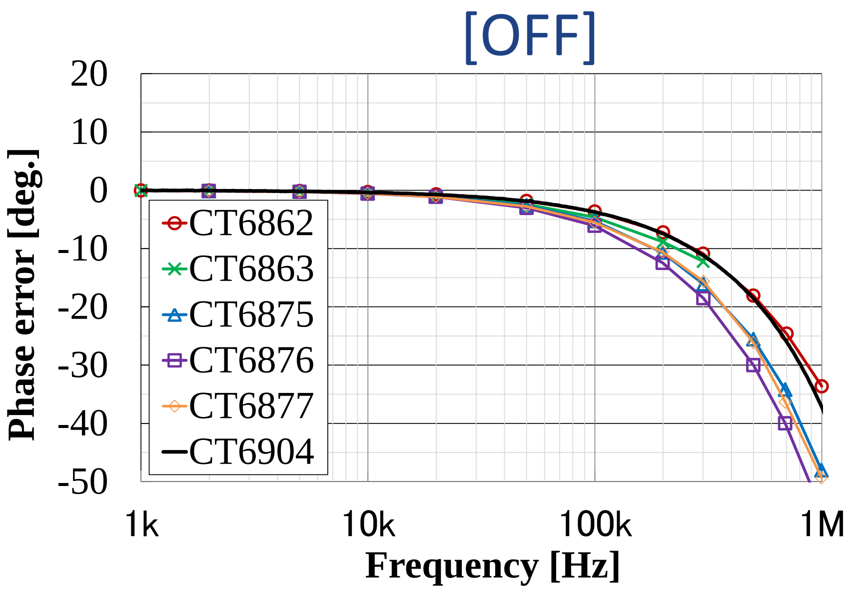


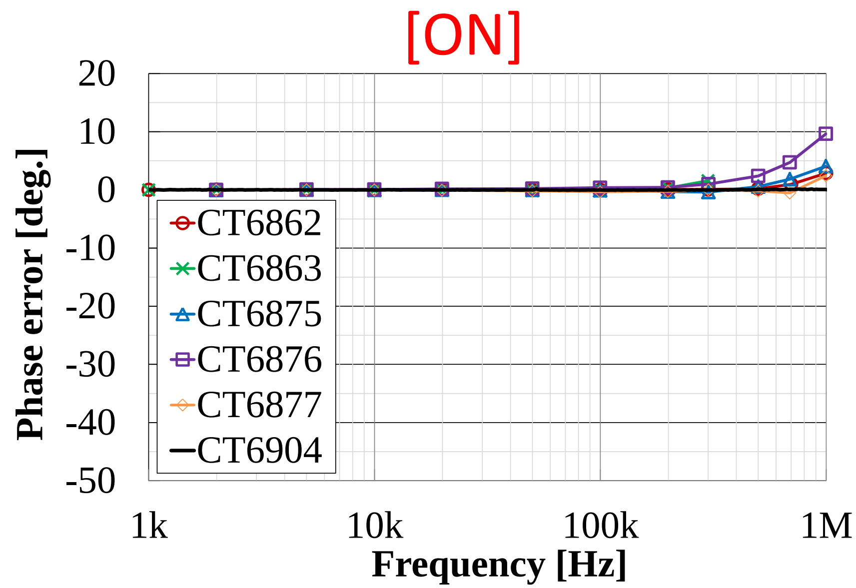


Phase shift function

- Only one point compensates the whole bandwidth (Sensor specific frequency and phase error)
  - Hioki's current sensors have almost no individual difference
  - Hioki's current sensors have quite uniform time delay at all frequency band
- The time resolution of phase compensation is equivalent to 0,5ns. (0,018º at 100kHz)

Effectiveness of Phase Shift Function (Current Sensor)



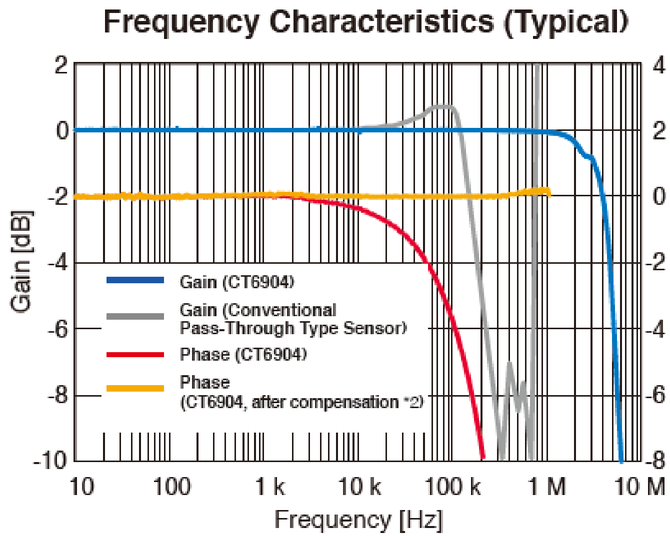


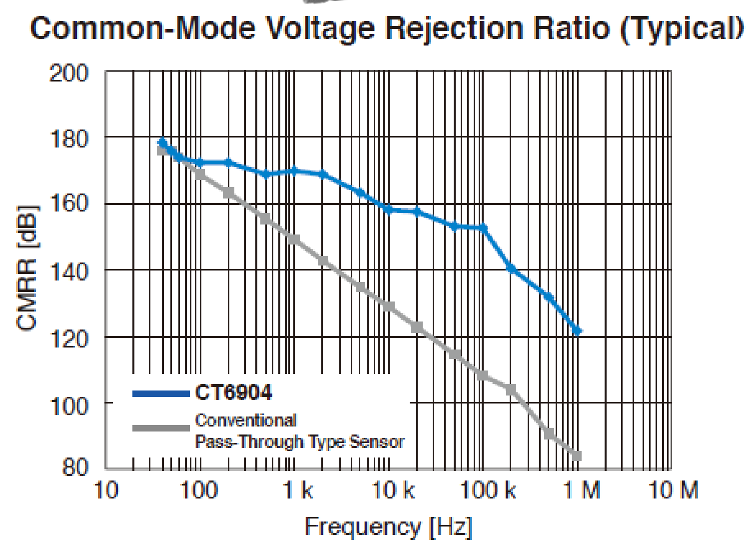
- Effectively minimizing phase errors at high frequencies
- Flat performance up to 200kHz
- With CT6904: Flat performance up to 1MHz

Ultra-High Performance Current Sensor CT6904

Very wide bandwidth and excellent noise resistivity achieved by:

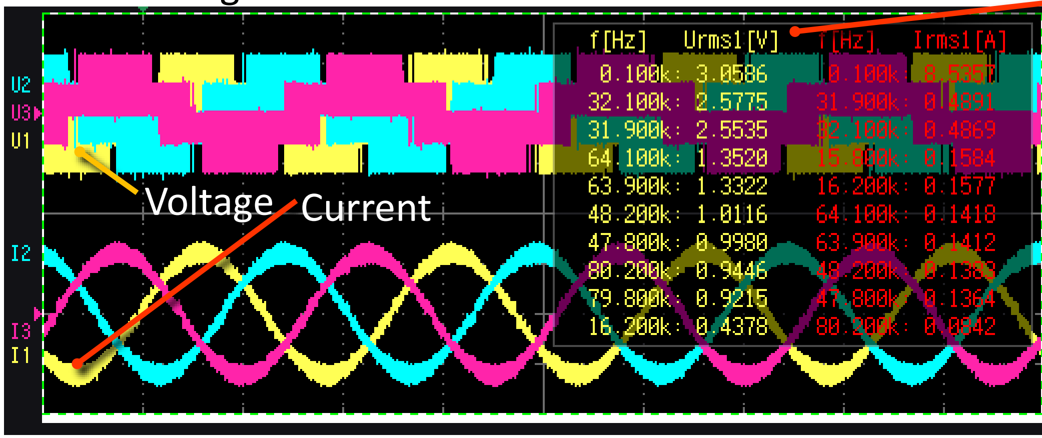
- Broadband flux gate zero-flux method
- New opposed split coil technology
- Solid shield crafted from machined metal





Characteristic of inverter waveform

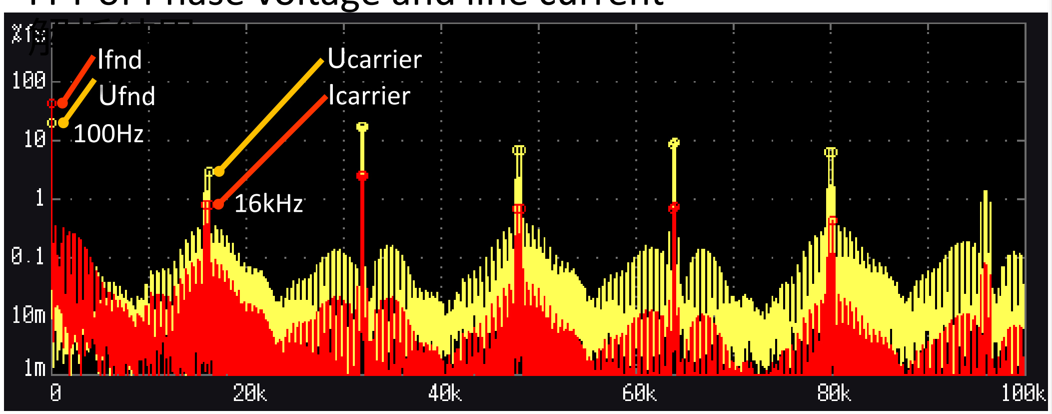
Phase voltage and line current



FFT Top 10 Results

- ✓ Output voltage and current of PWM Inverter are distorted waveform consist of harmonic components
- ✓ Current waveform is similar to sinewave compared to PWM voltage.

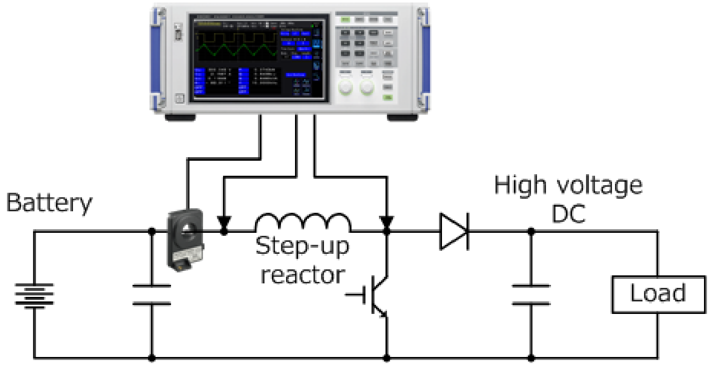
FFT of Phase voltage and line current



Carrier: 16 kHz

- ✓ Component: Fundamental (Modulated) wave, (Switching) carrier, and their Harmonics
- ✓ Voltage has components more than 100 kHz
  Current is composed of harmonics up to 5th order as the load is reactive

Reactor Loss Measurement

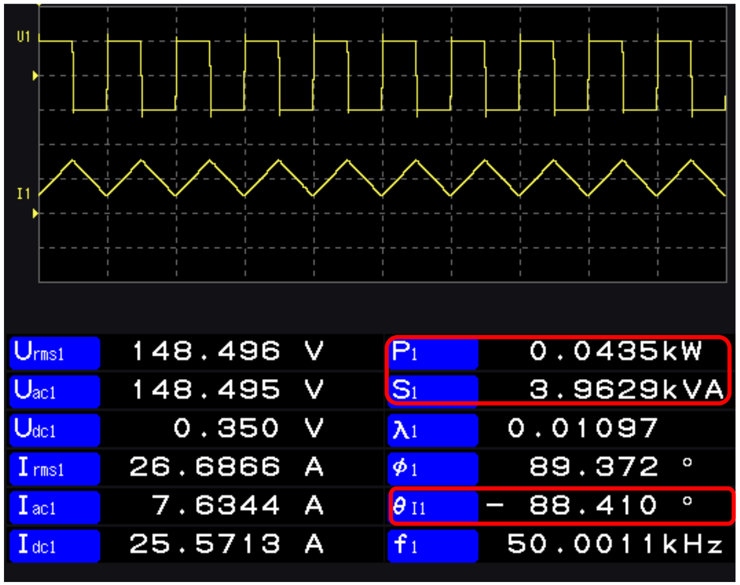


Switching Frequency f : 50kHz
Apparent Power S : 3.96kVA
Active Power P : 43.5W
Power Factor λ : 0.011
Phase θ : 88.41deg

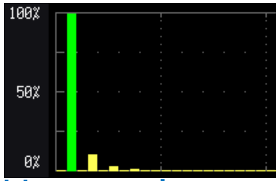
Current waveform: Ramp wave
3rd; 11%, 5th; 4%, 7th; 2%

Effective power is measured with 0.1 % accuracy up to 7th harmonic components

Voltage/Current waveform, Reactor loss (W)



1:	100.000
2:	0.083
3:	11.100
4:	0.020
5:	3.994
6:	0.008
7:	2.038
8:	0.005
9:	1.233
10:	0.003
11:	0.825
12:	0.001

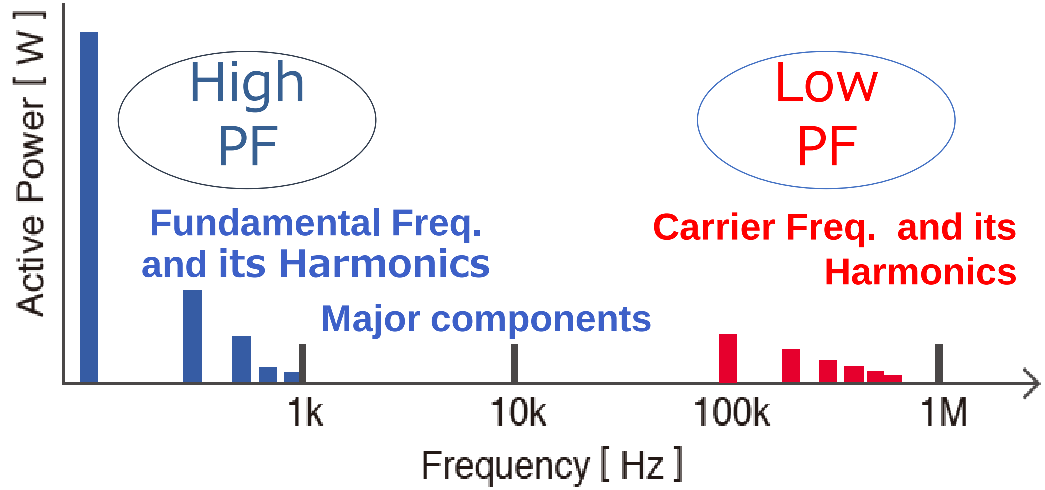


Harmonic components of ramp current

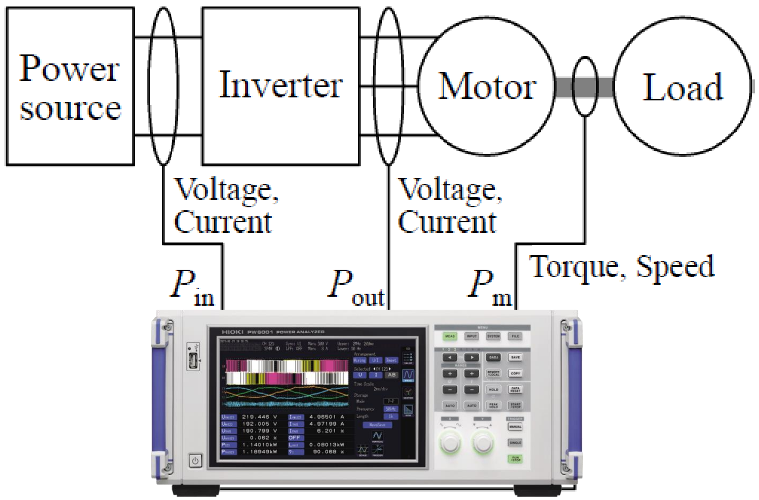
Measuring an Inverter's Output Power

Inverters generate PWM-modulated output that includes the fundamental (modulated) and carrier (switching) frequency and their harmonic components.

What harmonic orders are needed to measure inverter power accurately?
⇒The ability to measure voltage, current, and phase accurately up to **5th or 7th order of the carrier frequency** is sufficient in order to measure power with an error of 0,1% or less.



Measuring the Efficiency of Inverters and Motors



Efficiency, $\eta = P_{out} / P_{in}$

Loss, $P_{loss} = P_{in} - P_{out}$

Good tip for more stable and higher-precision measurement

- Take all measurements simultaneously
- Set the optimal synchronization source

Summary

- Electric power at switching frequency and its harmonic components shall be measured accurately to evaluate the inverter efficiency.
- Power analyzer must have strengthened resistance to noise which is emitted from inverter.
- As a power of inverter has higher switching frequency, it has a very low power factor and a phase error affects an accurate measurement a lot. HIOKI offers the Phase Compensation Function to improve this phase error.
- HIOKI is only one manufacturer in the world who develops both power analyzers and current sensors. This is why we can offer the Phase Compensation Function and superior CMRR for ideal power measurement.
- HIOKI's current sensors CT6904, CT6875, CT6876 and CT6877 have high performance characteristics.

Visit booth 7 for more information and a life demonstration

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