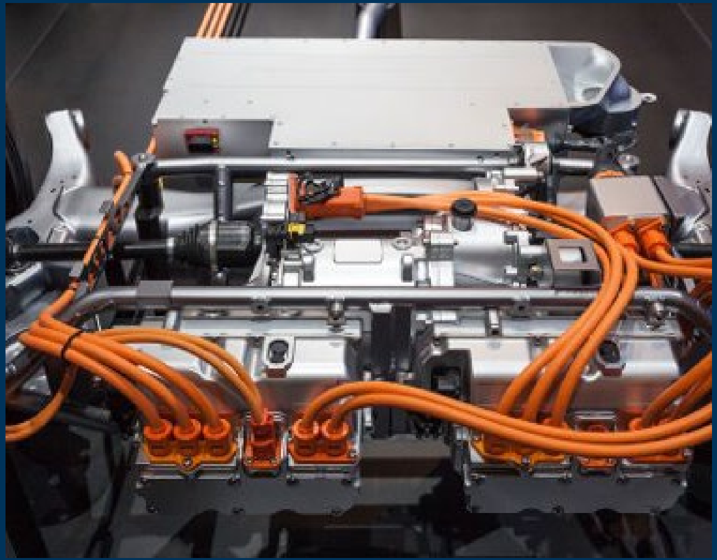
HBM Prenscia Technology Day

Virtual Seminar Series



Analysis of Electric Powertrain Measurements – Torque, Power, Efficiency, Vibration

Presented by Dr. Andrew Halfpenny

Chief Technologist, HBM Prenscia

HBK

Session #2: Electrical Power Testing & Analysis

Analysis of Electric Powertrain Measurements – Torque, Power, Efficiency, Vibration

Abstract

The theoretical and real-world range of an electric vehicle may differ significantly. To maximize the range and overall efficiency of the vehicle, it is necessary to understand and characterize how the vehicle is used and determine through meticulous measurement and analysis where efficiency losses occur.

Quantifying AC power is particularly difficult. Unlike the conventual electricity grid, electric vehicles convert DC to AC using an electrical inverter. Using pulse-width modulation, these produce a frequency-modulated, non-sinusoidal, transient waveform. This presentation introduces the concept of AC power analysis post-processing. Starting with steady-state sinusoidal waveforms, it explains the basic concepts of Active, Reactive, Apparent Power, and the Power Factor. It then considers the effect of non-sinusoidal and transient waveforms. Digital Signal Processing (DSP) techniques are introduced that take advantage of high-speed digitized data.

The presentation covers the following methods of AC power analysis - Time-averaging methods: Windowed-statistical method - time domain, PSD/CSD method - frequency domain; Instantaneous methods: Clarke transform method - time domain, Hilbert transform method - frequency domain. A case study shows the advantages of each method based on real data from an electric vehicle.

About the presenter, Dr. Andrew Halfpenny

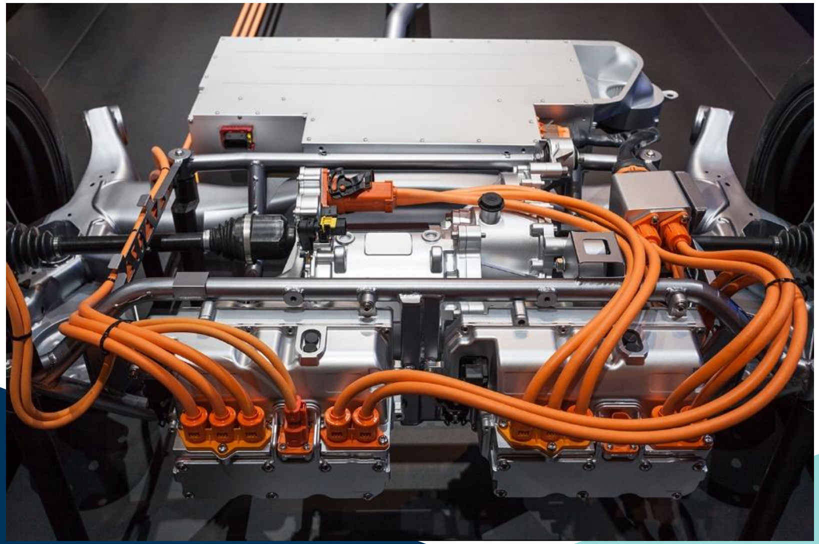
Dr. Halfpenny has a PhD in Mechanical Engineering from University College London (UCL) and a Masters in Civil and Structural Engineering. With over 25 years of experience in structural dynamics, vibration, fatigue and fracture, he has introduced many new technologies to the industry including: FE-based vibration fatigue analysis, crack growth simulation and accelerated vibration testing. He holds a European patent for the 'Damage monitoring tag' and developed the new vibration standard used for qualifying UK military helicopters. He has worked in consultancy with customers across the UK, Europe, Americas and the Far East, and has written publications on Fatigue, Digital Signal Processing and Structural Health Monitoring. He sits on the NAFEMS committee for Dynamic Testing and is a guest lecturer on structural dynamics with The University of Sheffield.

Analysis of Electric Powertrain Measurements – Torque, Power, Efficiency, Vibration

FOCUS ON AC POWER ANALYSIS IN ELECTRIC VEHICLES

Dr Andrew Halfpenny

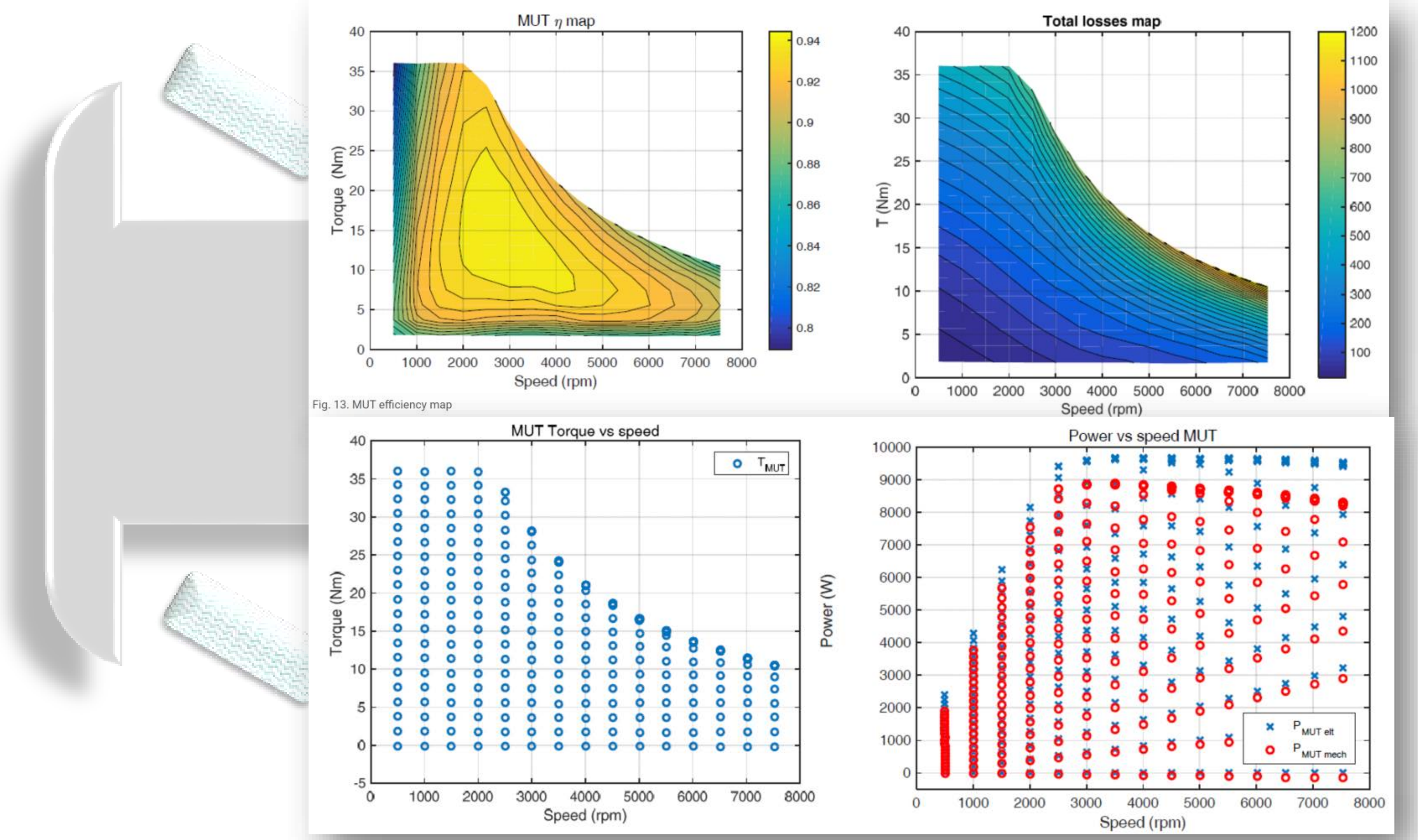
Director of Technology – nCode Products



Efficiency of an Electrical Vehicle

Energy conversion & efficiency losses

DC ⟷ Eff ⟷ AC ⟷ Eff ⟷ Mechanical ⟷ Eff ⟷ Kinetic



- Battery DC
- Inverter DC-AC
- Motor AC
- Transmission
- Whole vehicle

Efficiency of an Electrical Vehicle

Energy conversion & efficiency losses

DC ⟷ Eff ⟷ AC ⟷ Eff ⟷ Mechanical ⟷ Eff ⟷ Kinetic

DC power ☺

$P = UI$

Mech power ☺

$P = QS$

Kinetic power ☺

GPS Glyph

- Inertial resistance $F_I = ma$
- Gradient resistance $F_\alpha = mg\sin(\alpha)$
- Aerodynamic resistance $F_L = \frac{1}{2}\rho C_d A_s v^2$
- Rolling resistance $F_R = mgC_{rr}$

- Conventional AC Power Grid
  - Waveform: Sinusoidal
    - **Active** – consumed by resistive load
    - **Reactive** – out-of-phase component, not consumed but negates power on the grid and can cause grid instability
- EV Power
  - Waveform: Non-sinusoidal, varying amplitude & frequency
    - **Active** – consumed to drive the vehicle
    - **Reactive** – not consumed but causes efficiency losses
- 3-phase / multi-phase

What we want:

1. An ***accurate measurement*** of **Active** power to maximize
2. A ***robust inference*** of **Reactive** power to minimize

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Agenda

1. Definitions for pure sine AC
    - Active, Reactive, Apparent power, and the Power factor
    - Analytical and Digital signal definitions
2. Inverter Analysis – *Time-averaging methods*
    - Windowed-statistical method – *time domain*
    - PSD/CSD method – *frequency domain*
3. Inverter Analysis – *Instantaneous methods*
    - Clarke transform method – *time domain*
    - Hilbert transform method – *frequency domain*
4. GlyphWorks Post-processing Case Studies

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Definitions for pure sine AC

Active, Reactive, Apparent power, and the Power factor
Analytical and Digital signal definitions

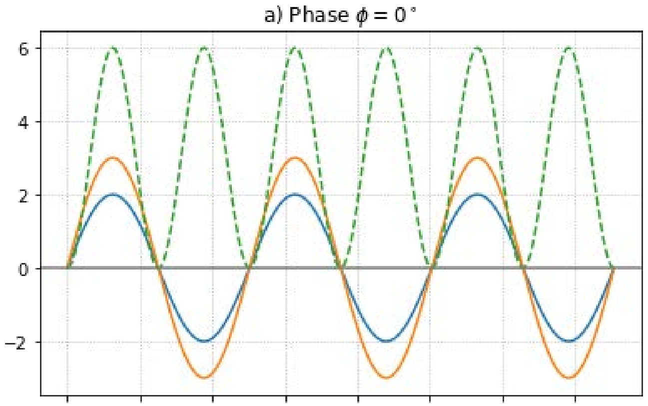
Pure Sine AC: *Active and Reactive Power*

AC voltage: $u(t) = U\cos(\omega t)$

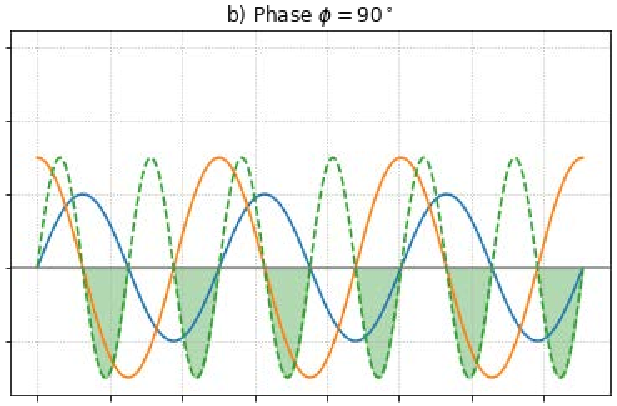
AC current: $i(t) = I\cos(\omega t + \phi)$

Instantaneous power: $p(t) = u(t)\,i(t)$

Convention:
- U = amplitude of voltage
- I = amplitude of current



Power factor $\cos(\phi) = 1.0000$
Active power $P = 3.0000$
Reactive power $Q = 0.0000$
Apparent power $S = 3.0000$



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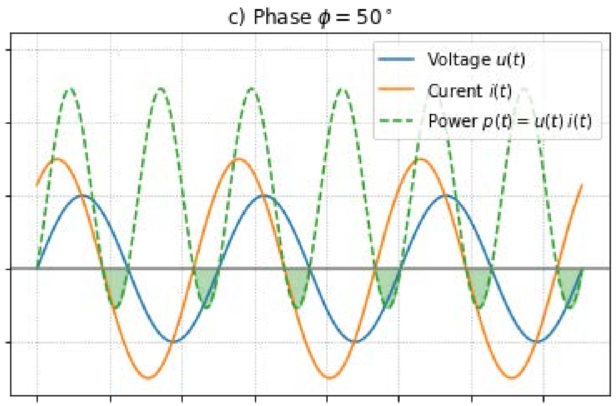


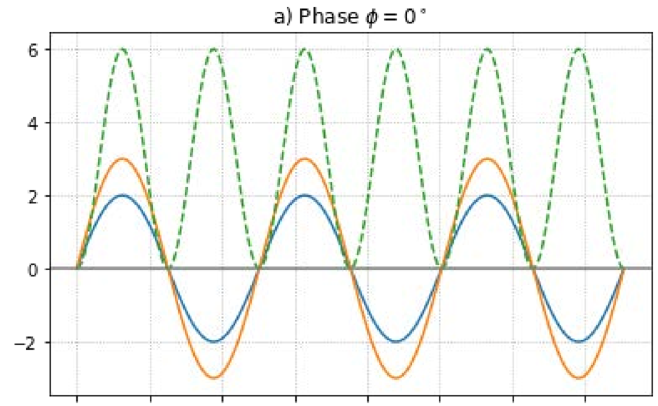
Power factor $\cos(\phi) = 0.6428$
Active power $P = 1.9284$
Reactive power $Q = 2.2981$
Apparent power $S = 3.0000$

- Instantaneous power frequency 2x input voltage and current frequency
- Instantaneous power is wholly +ve
- All energy is consumed by the load "**Resistive**" load

- Same instantaneous power frequency and amplitude
- Instantaneous power is equally +ve and –ve (zero mean)
- No energy is consumed by the load "**Reactive**" load

- Same instantaneous power frequency and amplitude
- Instantaneous power has some +ve and –ve (non-zero mean)
- Some energy is consumed, some is not "**Active**" and "**Reactive**" load

Pure Sine AC: *Active and Reactive Power*



Power factor $\cos(\phi) = 1.0000$
Active power $P = 3.0000$
Reactive power $Q = 0.0000$
Apparent power $S = 3.0000$

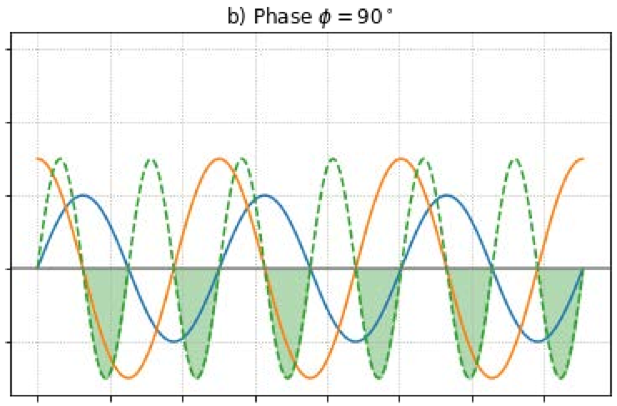
$$\begin{aligned} p(t) &= u(t)\ i(t) \\ &= U\cos(\omega t) \times I\cos(\omega t) \\ &= U I \cos^2(\omega t) \\ &= \frac{UI}{2}\Big[1 + \cos(2\omega t)\Big] \end{aligned}$$

Frequency 2x input

Makes it +ve

Amplitude (Apparent power)

Wholly resistive load: PF = 1

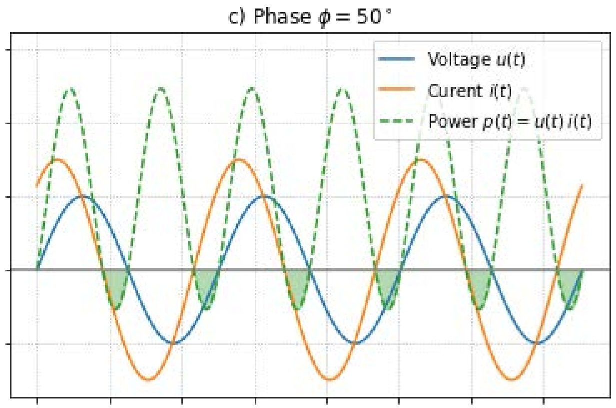


Power factor $\cos(\phi) = 0.0000$
Active power $P = 0.0000$
Reactive power $Q = 3.0000$
Apparent power $S = 3.0000$

$$\begin{aligned} p(t) &= u(t)\ i(t) \\ &= U\cos(\omega t) \times I\sin(\omega t) \\ &= \frac{UI}{2}\Big[\sin(2\omega t)\Big] \end{aligned}$$

- Same Apparent power
- Same frequency
- Zero mean
  equal +ve and -ve

Wholly reactive load: PF = 0



Power factor $\cos(\phi) = 0.6428$
Active power $P = 1.9284$
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Apparent power $S = 3.0000$

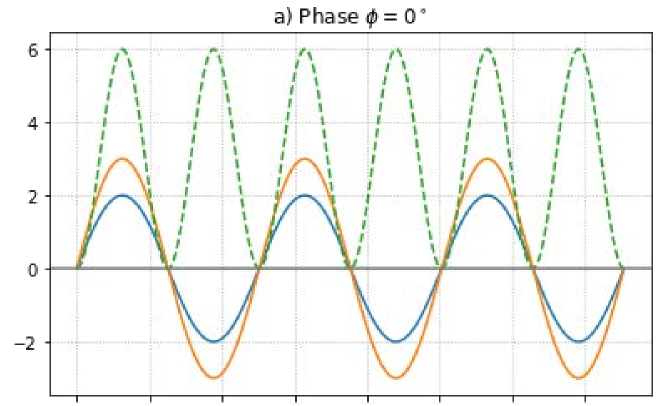
$$\begin{aligned} p(t) &= u(t)\ i(t) \\ &= U\cos(\omega t) \times I\cos(\omega t + \phi) \\ &= \frac{UI}{2}\Big[\cos(2\omega t + \phi) + \cos(\phi)\Big] \end{aligned}$$

- Same Apparent power
- Same frequency
- Mean offset

$$\mu = \frac{UI}{2}\cos(\phi)$$

$\cos(\phi)$ is known as the 'Power Factor (PF)'

Pure Sine AC: *Active and Reactive Power*



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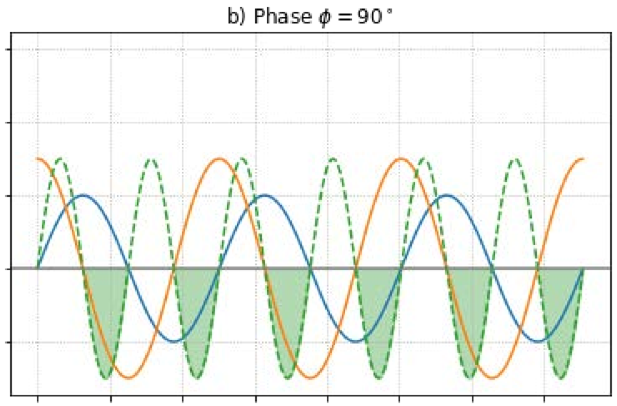

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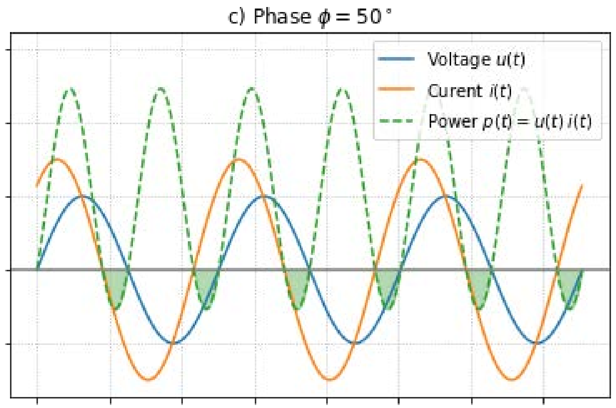

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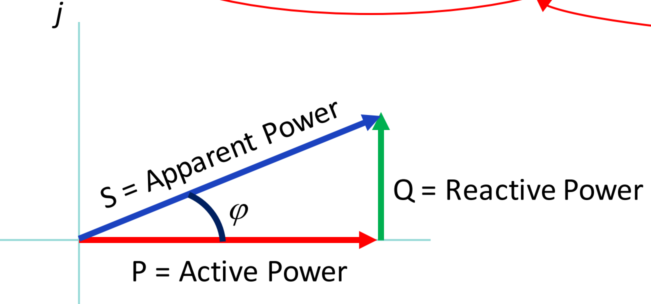
$$
\begin{aligned}
p(t) &= u(t)\ i(t) \\
&= U\cos(\omega t) \times I\cos(\omega t) \\
&= U I \cos^2(\omega t) \\
&= \frac{UI}{2}\Big[1 + \cos(2\omega t)\Big]
\end{aligned}
$$

$$
\begin{aligned}
p(t) &= u(t)\ i(t) \\
&= U\cos(\omega t) \times I\sin(\omega t) \\
&= \frac{UI}{2}\Big[\sin(2\omega t)\Big]
\end{aligned}
$$

$$
\begin{aligned}
p(t) &= u(t)\ i(t) \\
&= U\cos(\omega t) \times I\cos(\omega t + \phi) \\
&= \frac{UI}{2}\Big[\cos(2\omega t + \phi) + \cos(\phi)\Big] \\
&= \frac{UI}{2}\Big[\cos(2\omega t)\cos(\phi) + \sin(2\omega t)\sin(\phi) + \cos(\phi)\Big] \\
&= \frac{UI}{2}\cos(\phi)\Big[1 + \cos(2\omega t)\Big] + \frac{UI}{2}\sin(\phi)\Big[\sin(2\omega t)\Big]
\end{aligned}
$$

Amplitude	
Active power	$P = \frac{UI}{2}\cos(\phi)$
Reactive power	$Q = \frac{UI}{2}\sin(\phi)$
Apparent power	$S = \frac{UI}{2} = \sqrt{P^2 + Q^2}$
Power factor	$PF = \cos(\phi) = \frac{P}{S}$



Power Triangle

Instantaneous Power $p(t)$ is the weighted sum of the Active and Reactive

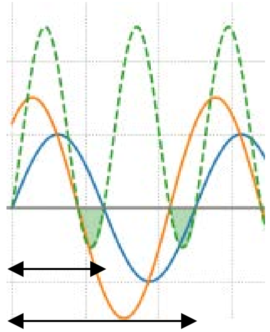
Pure Sine AC: *Active and Reactive Power*

$$u(t) = U\cos(\omega t) \qquad i(t) = I\cos(\omega t + \phi)$$

Analytical Definitions	Digital Definitions

Active Power

$$P = \frac{UI}{2}\cos(\phi)$$



mean$(u \times i)$

$$P = \text{mean}\big(u(t)\,i(t)\big) \implies \frac{1}{N}\sum_{n=1}^{N} u_n\, i_n$$

$$= \frac{1}{2\pi}\int_{-\pi}^{\pi} U\cos(\omega t)\cdot I\cos(\omega t+\phi)dt \qquad = \frac{UI}{2}\cos(\phi)$$

Apparent Power

$$S = \frac{UI}{2}$$

rms$(u) \times$ rms(i)

$$S = \text{rms}(u)\cdot\text{rms}(i)$$

$$\text{rms}\big(I\cos(\omega t+\phi)\big) = \sqrt{\frac{1}{2\pi}\int_{-\pi}^{\pi}\big(I\cos(\omega t+\phi)\big)^2 dt} \implies \frac{I}{\sqrt{2}}$$

$$\therefore S = \frac{UI}{2}$$

Reactive Power

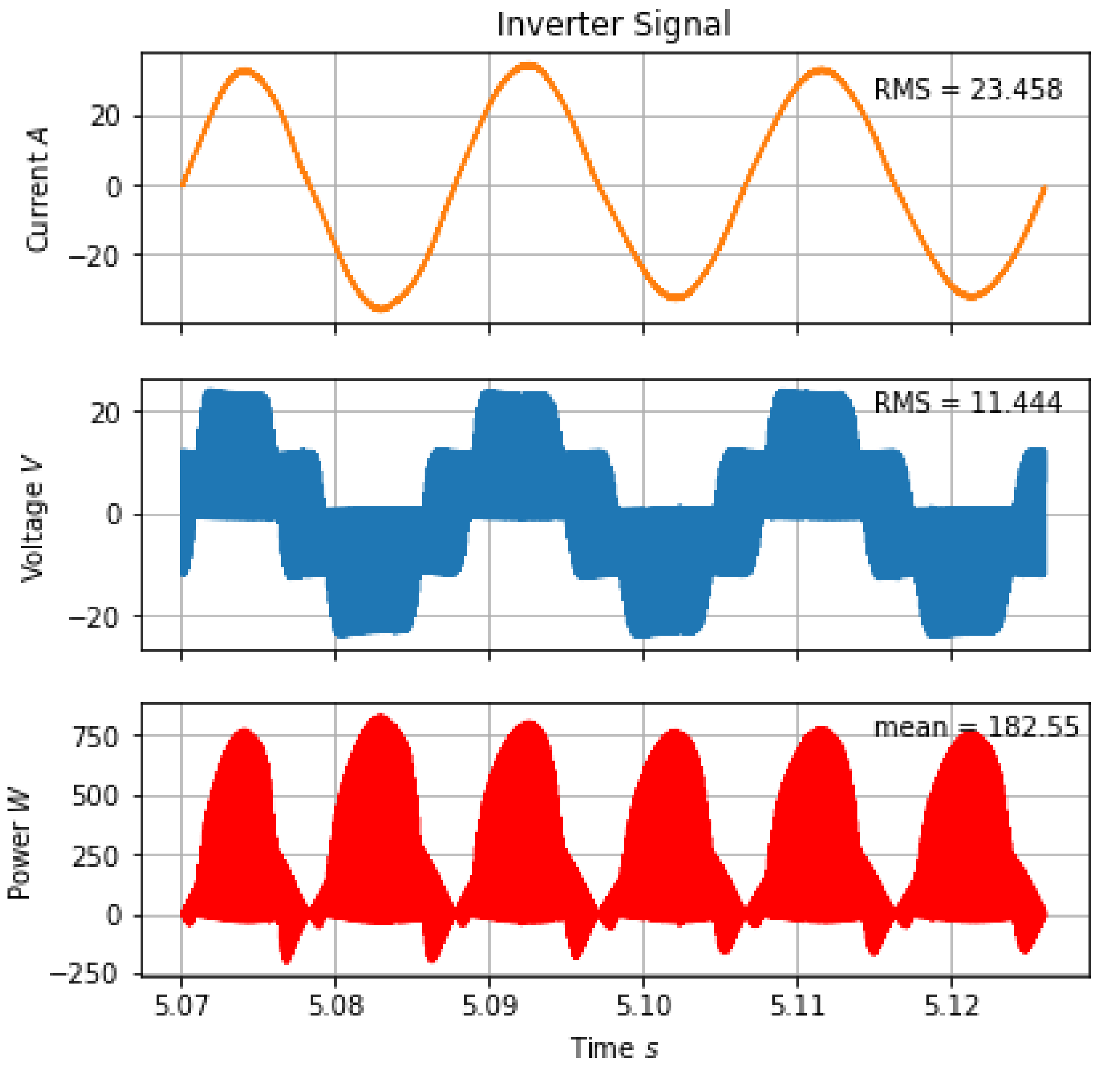
$$Q = \frac{UI}{2}\sin(\phi)$$

$$|Q| = \sqrt{S^2 - P^2} \qquad = \frac{UI}{2}\sin(\phi)$$

Inverter Analysis – *Time-averaging methods*

Windowed-statistical method – *time domain*
PSD/CSD method – *frequency domain*

Typical Inverter Signal



$$\text{Active Power } P = \text{mean}\big(u(t)\, i(t)\big) = \mathbf{182.55}\ \text{W} \quad \checkmark$$

$$\text{Apparent Power } S = \text{rms}\big(u(t)\big) \times \text{rms}\big(i(t)\big)$$
$$= 11.444 \times 23.458 = \mathbf{268.45}\ \text{VA}$$

$$\text{Reactive Power } Q = \sqrt{S^2 - P^2}$$
$$= \sqrt{268.45^2 - 182.55^2} = \mathbf{196.83}\ \text{VAr}$$

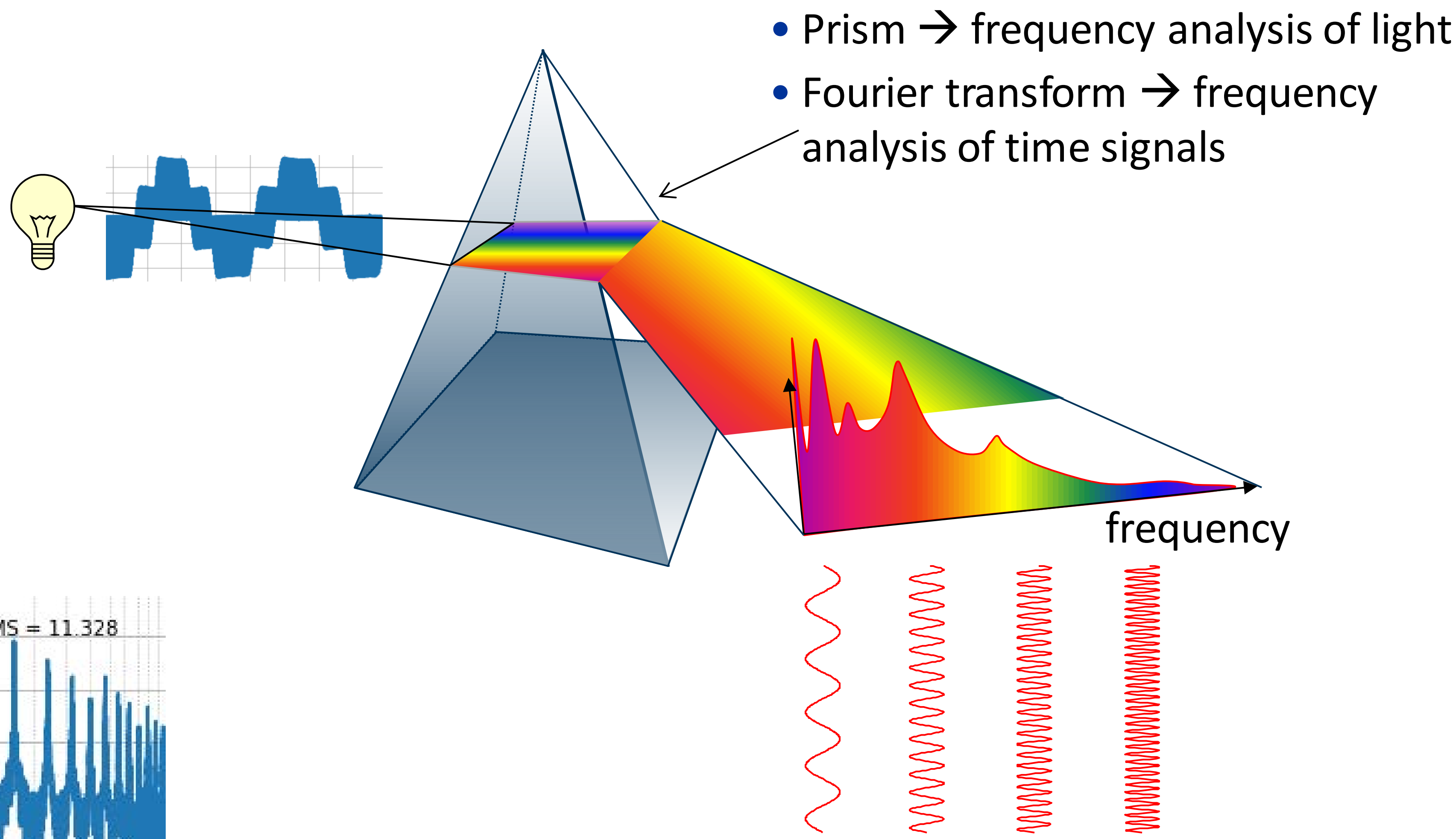
Expecting $Q \ll P$ Found $Q > P$

What's happened

- Active power is correct by definition ✓
- This definition of 'Apparent Power' merges all the frequencies together into one *(RMS)* before calculating power
- It is often more helpful to apply the calculation to each frequency separately

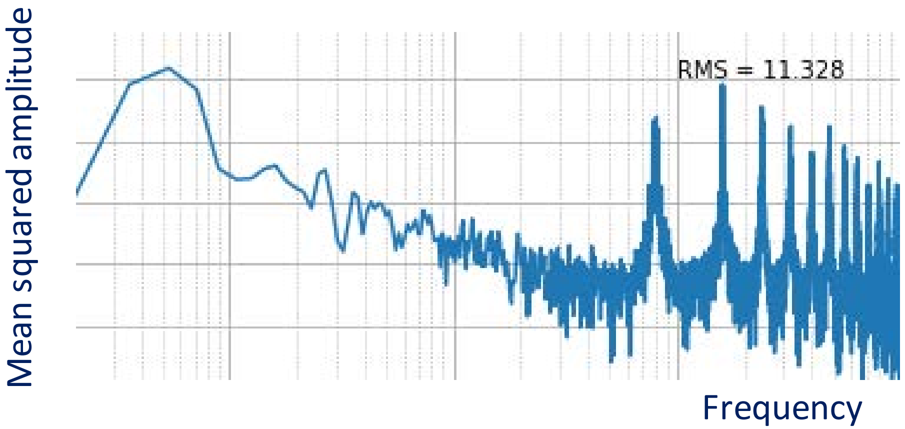
Frequency Domain Method

- Decompose inverter signal into its sinusoidal components using Fourier Transform

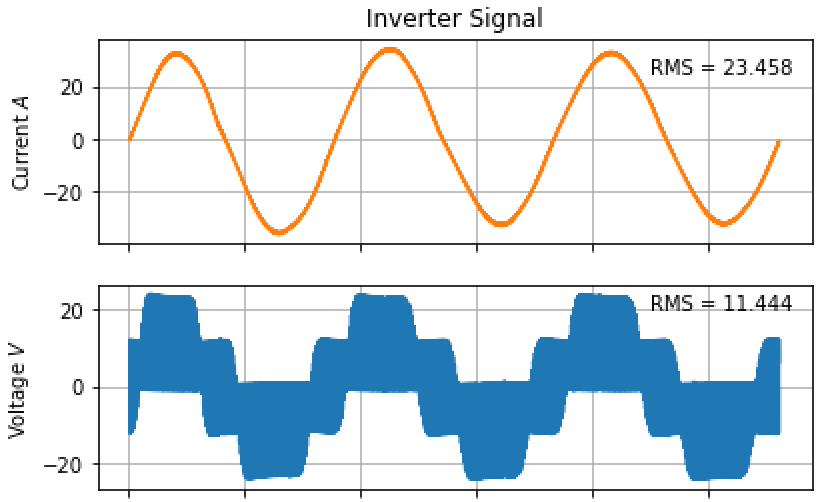


Power Spectral Density (PSD) curve

$$RMS = \sqrt{\text{Area under PSD}}$$



Frequency Domain Method – *PSD*

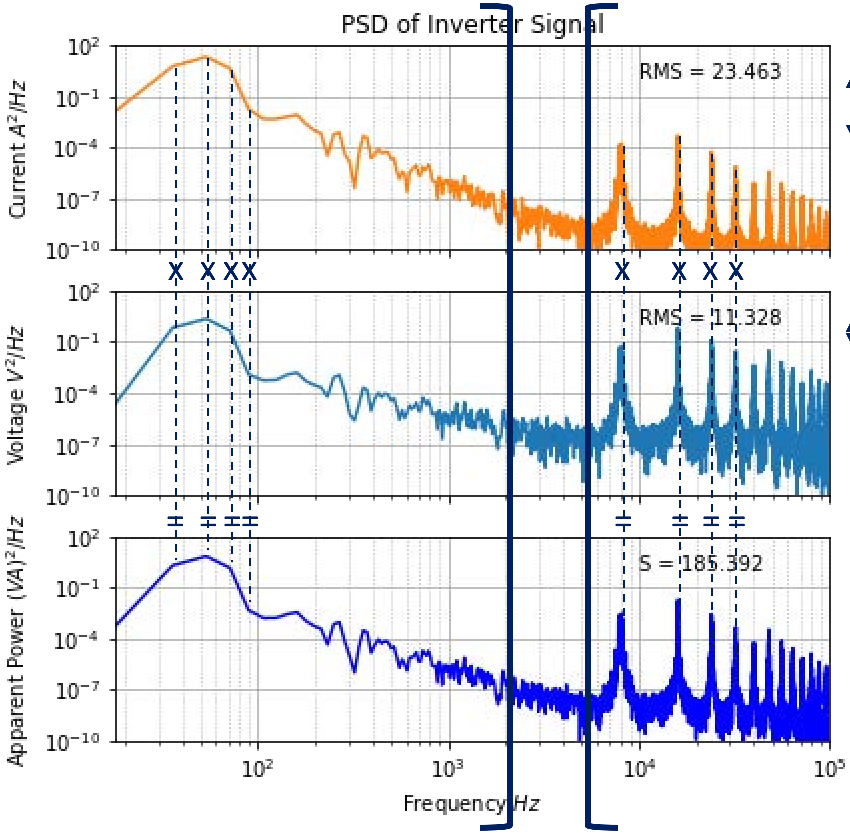


PSD

Fundamental frequency

Spectral gap

Switching harmonics



4 orders

Similar magnitude

Calculate RMS frequency by frequency then sum them

From previous page definition 1:

$$P = 182.55 \text{ W}$$

$$S = \frac{1}{2}\sum_h U_h \sum_h I_h = 268.45 \text{ VA}$$

$$Q = \sqrt{S^2 - P^2} = 196.83 \text{ VAr}$$

definition 2:

$$P = 182.55 \text{ W}$$

$$S = \frac{1}{2}\sum_h U_h I_h = 185.39 \text{ VA}$$

$$Q = \sqrt{S^2 - P^2} = 32.34 \text{ VAr}$$

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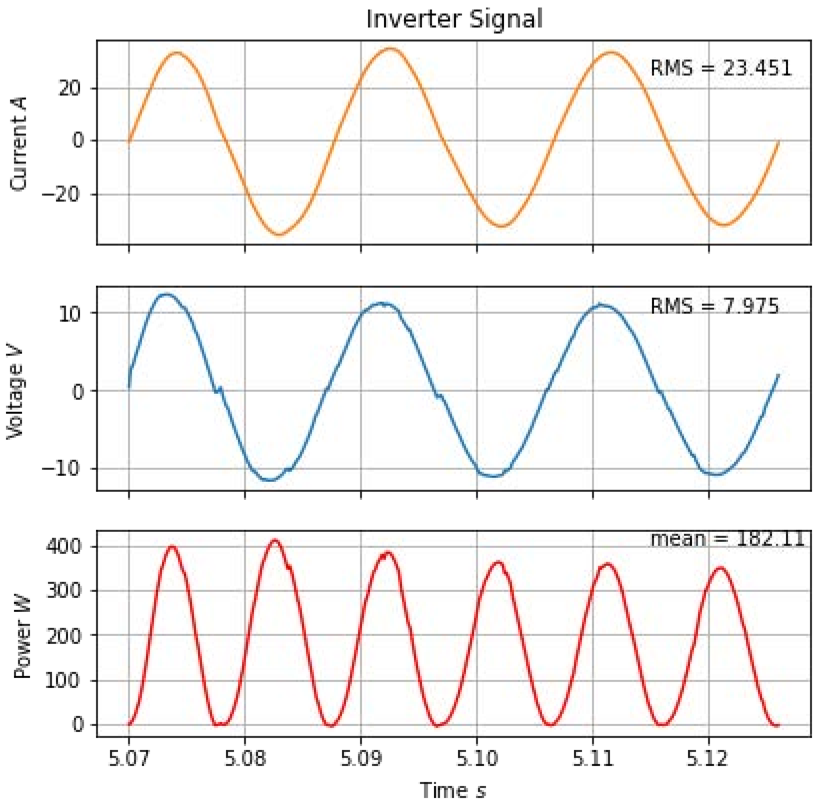
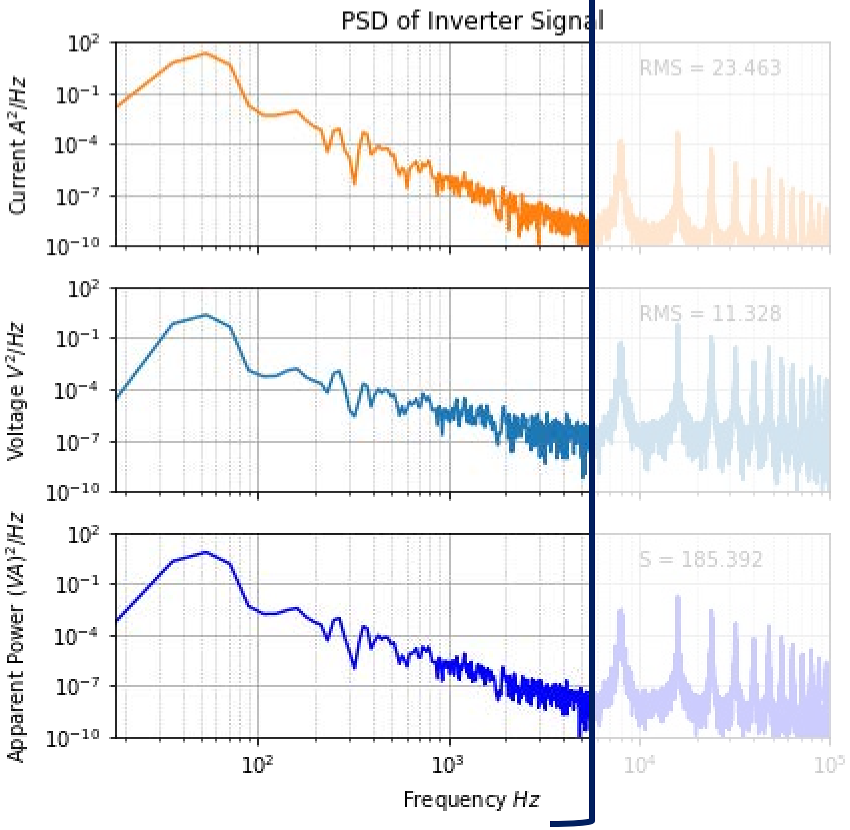
Filtered Time Domain Method



PSD

Fundamental frequency



Apparent power definition 1:
Filtered to fundamental

$$P = 182.11\ \mathrm{W}$$

$$S = \frac{1}{2} \sum_h U_h \sum_h I_h = 187.02\ \mathrm{VA}$$

$$Q = \sqrt{S^2 - P^2} = 42.57\ \mathrm{VAr}$$

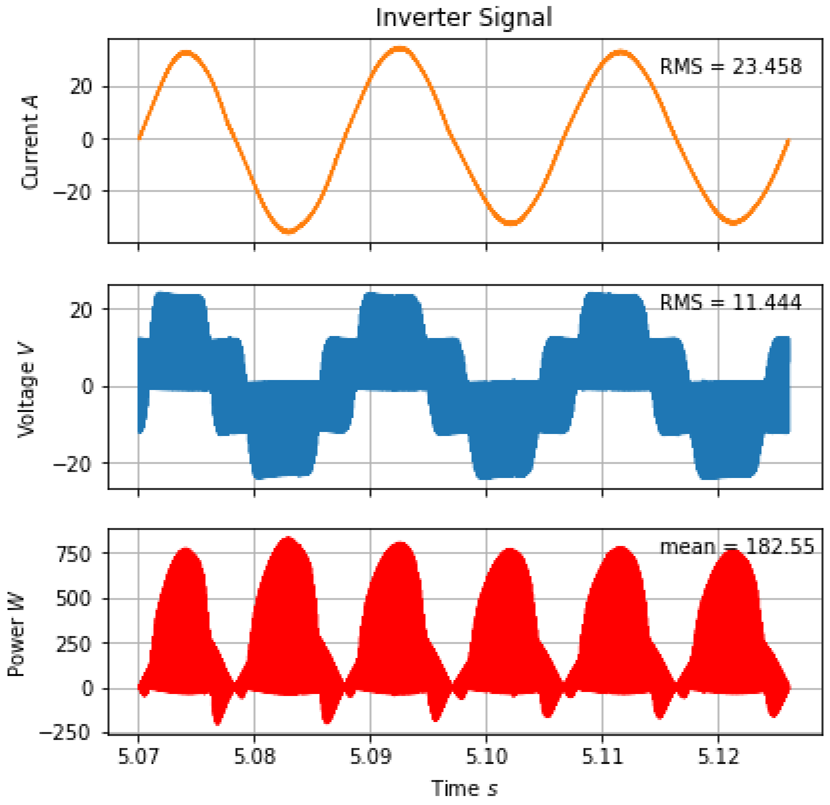
definition 2:

$$P = 182.55\ \mathrm{W}$$

$$S = \frac{1}{2} \sum_h U_h I_h = 185.39\ \mathrm{VA}$$

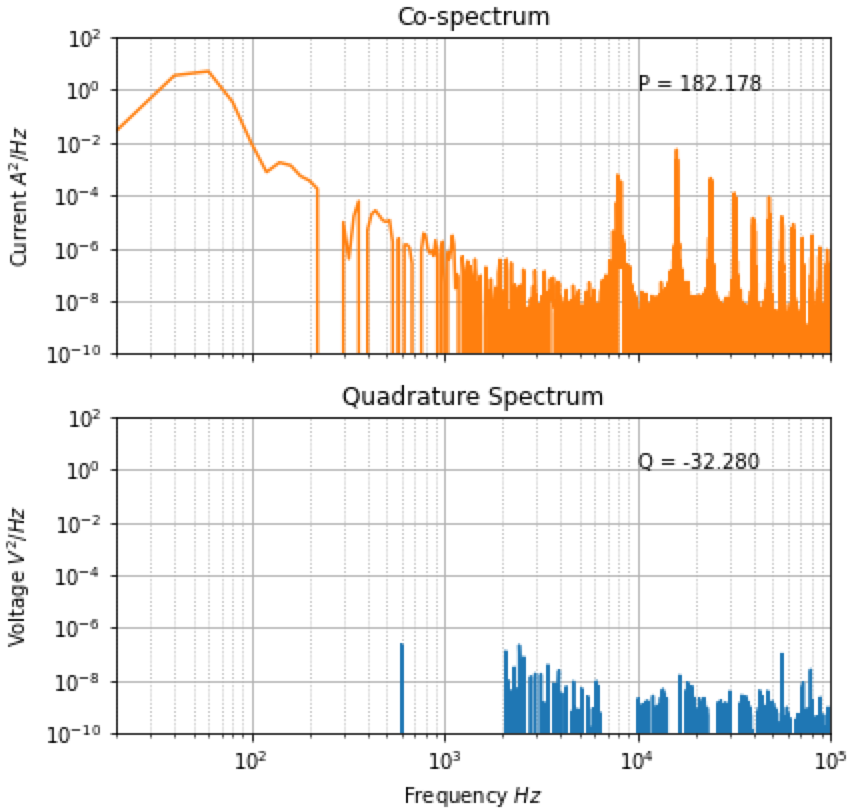
$$Q = \sqrt{S^2 - P^2} = 32.34\ \mathrm{VAr}$$

Frequency Domain Method – *CSD*



CSD

$$P = \text{Area under Co−Spectrum}$$
$$Q = \text{Area under quadrature spectrum}$$



$$P = \sum_h \frac{U_h I_h}{2} \cos(\phi_h)$$

$$Q = \sum_h \frac{U_h I_h}{2} \sin(\phi_h)$$

- mean power ≈ P = 182.178
- Q = -32.280 is a more robust inference

Conclusion: Time-averaging Methods

Time-domain method

$$P = \text{mean}\left(i(t)\ u(t)\right)$$

$$S = \text{RMS}\left(i(t)\right) \times \text{RMS}\left(u(t)\right)$$

$$Q = S \sin\left(\cos^{-1}\left(\frac{P}{S}\right)\right)$$

- Pure sine method
- For preferred definition of Q, use low-pass filter to isolate the fundamental frequency
- Excellent time resolution is possible *(down to half-cycle in the best systems)*
- Ideal for analysing dynamic EV systems & WLTC *(Worldwide Harmonised Light Vehicle Test Procedure)*

Frequency-domain method

$$P = \text{area}\left(\mathcal{R}e\left[csd\left(i(t), u(t)\right)\right]\right)$$

$$Q = \text{area}\left(\mathcal{I}m\left[csd\left(i(t), u(t)\right)\right]\right)$$

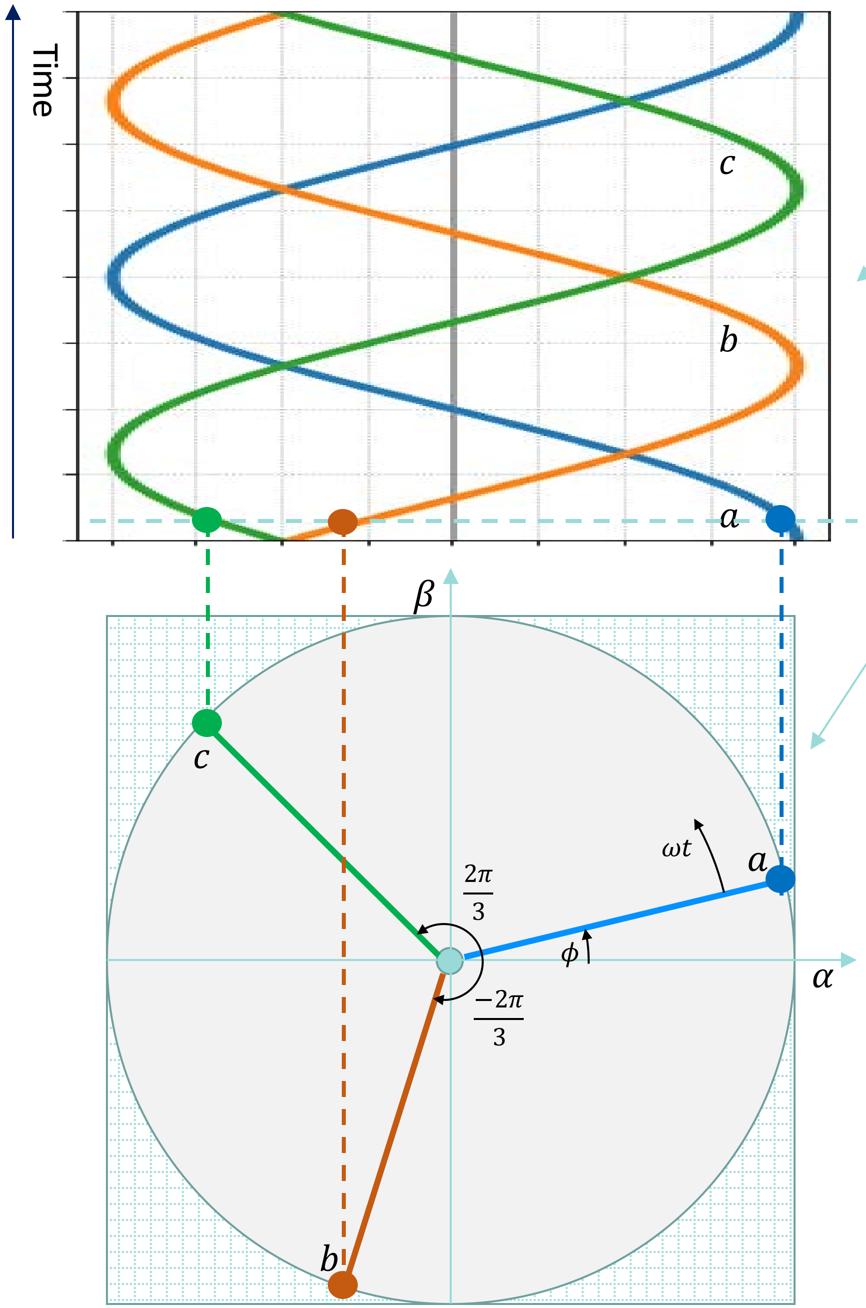
$$S = \text{area}\left(\left|csd\left(i(t), u(t)\right)\right|\right)$$

- Broadband method *(preferred definition of Q)*
- Time buffer (2^n *points*) insensitive to cycle edges
- Large time buffer required to capture low-frequency fundamental
- Large buffer gives poor time resolution
  - Not ideal for dynamic EV systems & WLTC

Inverter Analysis – *Instantaneous methods*

Clarke transform method – *time domain*
Hilbert transform method – *frequency domain*

Direct Quadrature Transformation – α, β

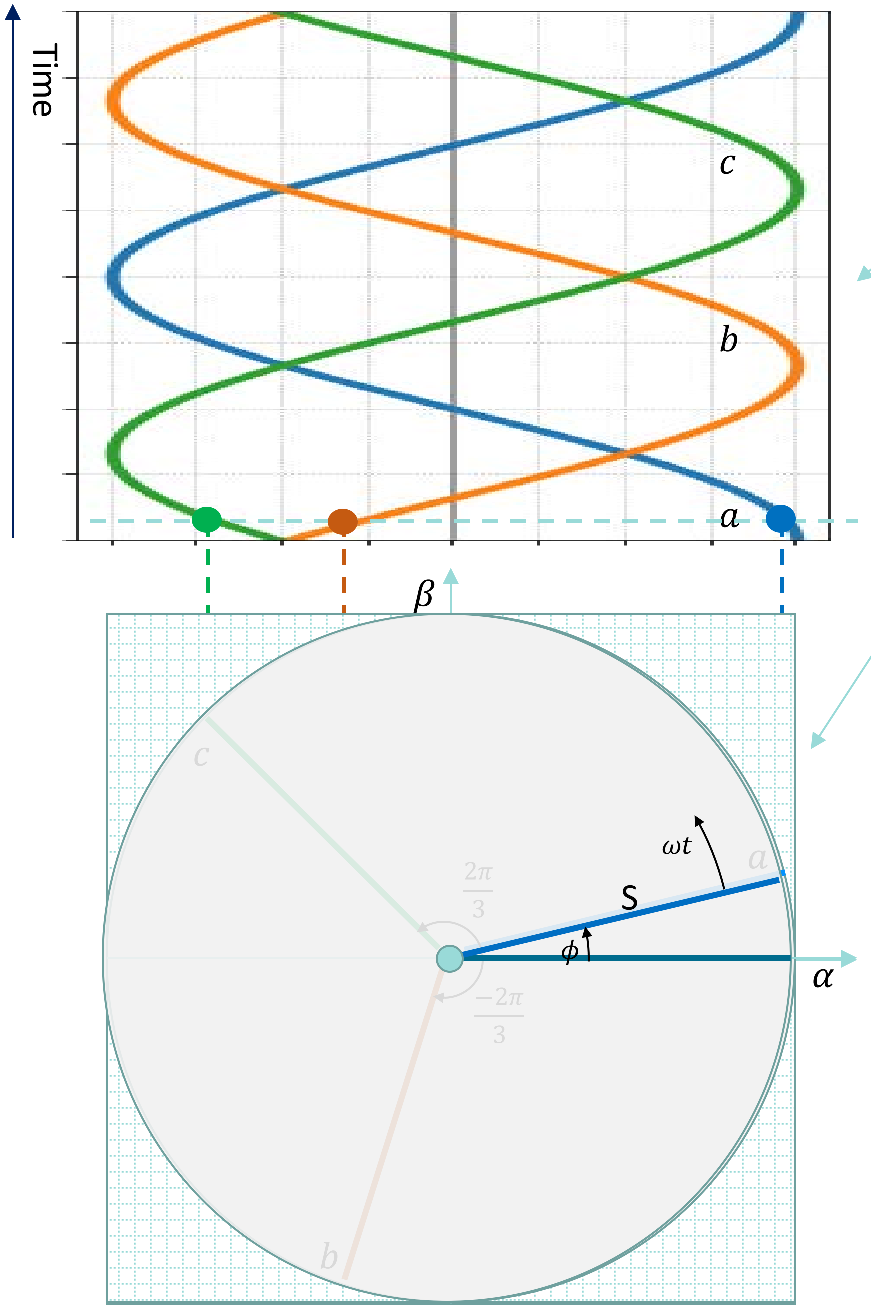


Digitized data – **millions** of recorded values

If all 'phases' are:
- sinusoidal
- equal & constant amplitude
- equal & constant angular spacing

then the locus of the phasor is circular

Direct Quadrature Transformation – α, β



Digitized data – **millions** of recorded values

If all 'phases' are: - sinusoidal
- equal & constant amplitude
- equal & constant angular spacing

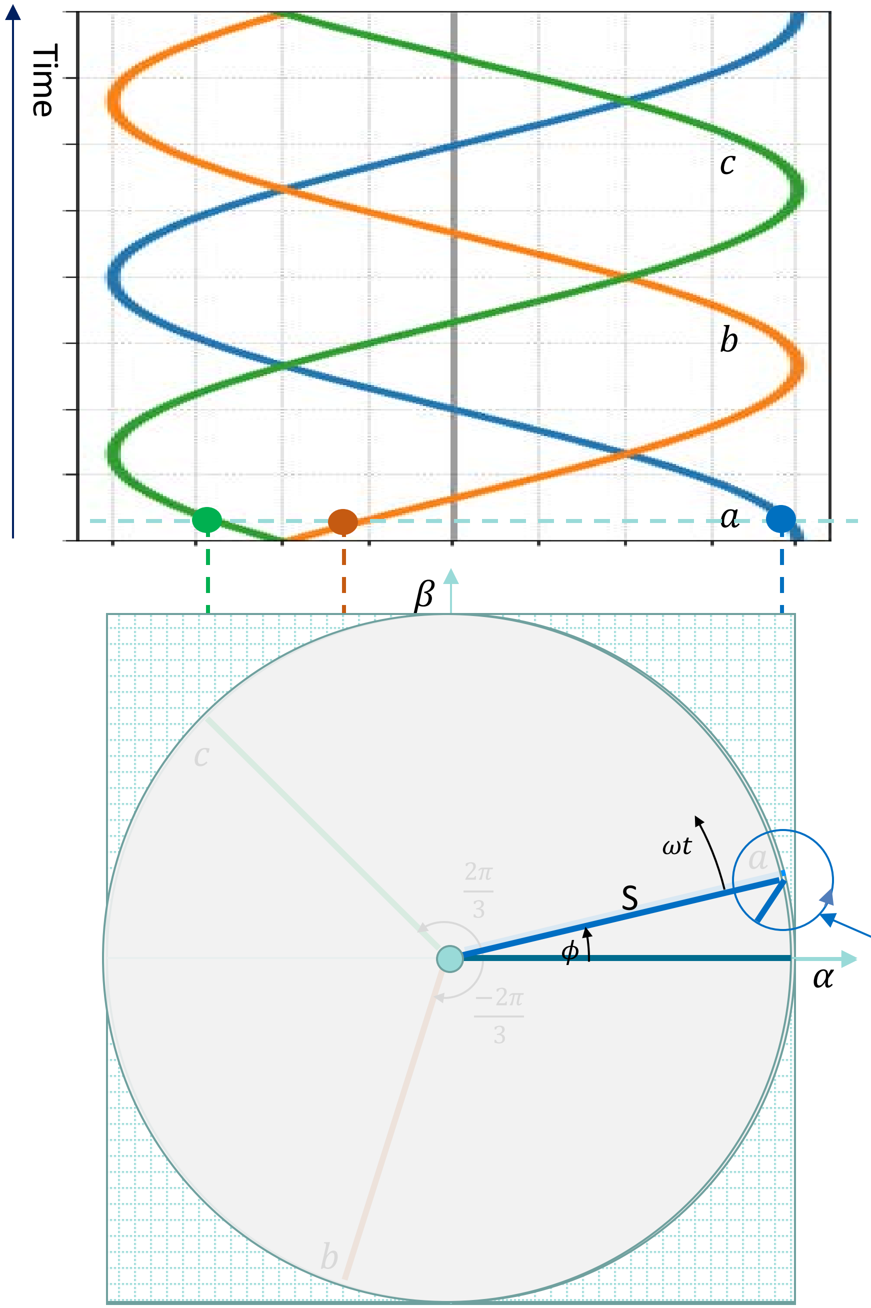
then the locus of the phasor is circular

Polar coordinates

Digitized data completely described using just **3 values**:

- S – amplitude (radius of phasor)
- ϕ – initial phase angle (relative to some reference line α)
- ω – rotational frequency (or line frequency)

Direct Quadrature Transformation – α, β



Polar coordinates

E.g. Calculate power from voltage and current signals

$$p(t) = u(t) \times i(t)$$

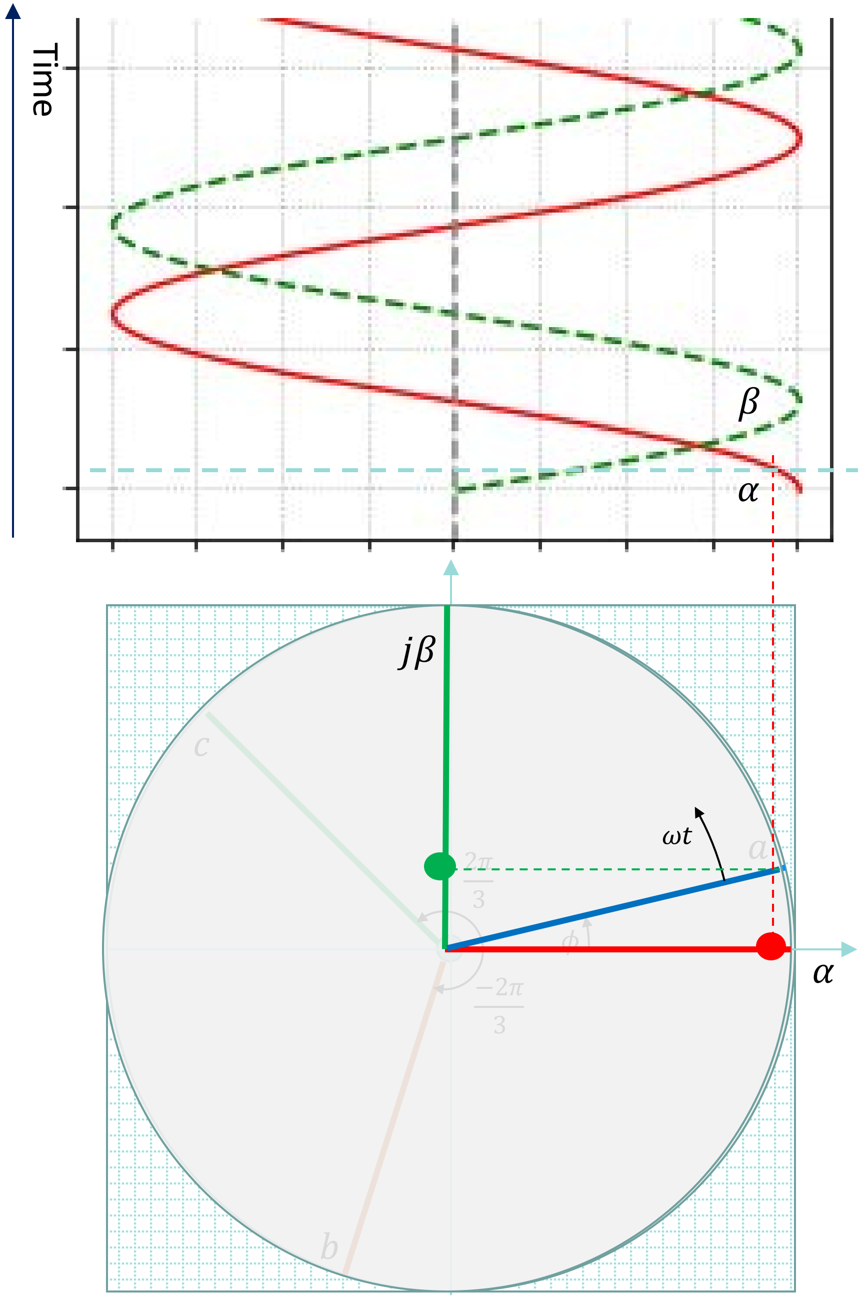
$$= S_u \cos(\omega t + \phi_u) \times S_i \cos(\omega t + \phi_i)$$

If $\phi_u = \phi_i$ then the power is wholly Active

If $\phi_i \neq \phi_i$ then the power will comprise a ratio of Active and Reactive components

Nice and easy
The basis for most hand calcs
No good for digitized data
Inflexible for changing waveforms
Doesn't easily support additional harmonics

Direct Quadrature Transformation – α, β



Rectangular coordinates

Digitized data completely described using 2 values at each point

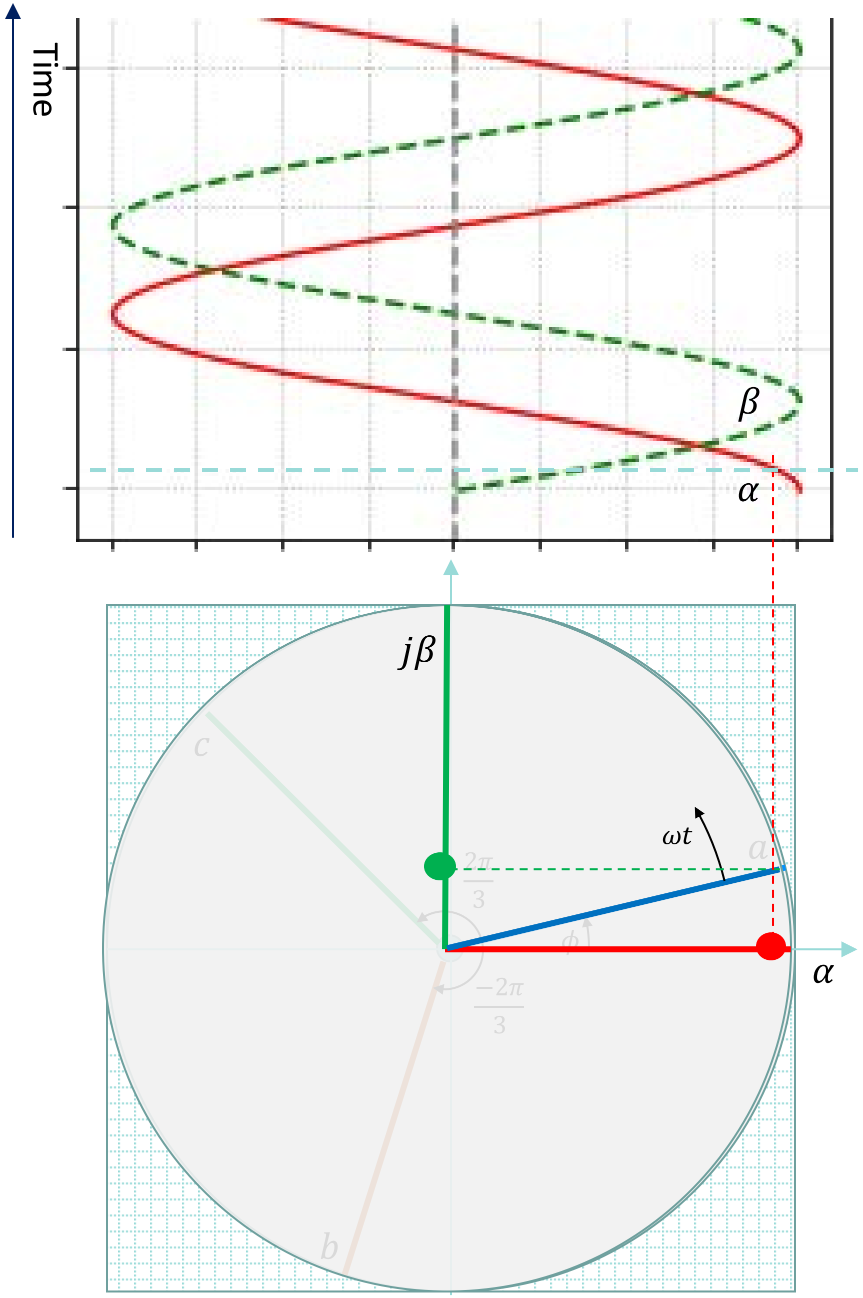
- $\alpha(t)$ – the x (or *Real* axis)
- $\beta(t)$ – the y (or *Imaginary* axis)

Pros and Cons

Cons: More values (α, β at each point)

Pros: Ideal for digitized data
No need to assume - equal & constant amplitude S
- equal & constant angular spacing
- constant line frequency ω
Phasor can change length with each point
Phasor can move backward and forwards with changing ϕ
Fast linear analysis using complex number theory

Direct Quadrature Transformation – α, β



E.g. Calculate power from voltage and current signals

$$[P + jQ](t) = \underbrace{[\alpha_u + j\,\beta_u](t)}_{\text{Complex voltage}} \times \underbrace{[\alpha_i - j\,\beta_i](t)}_{\text{Complex current}}$$

Question:

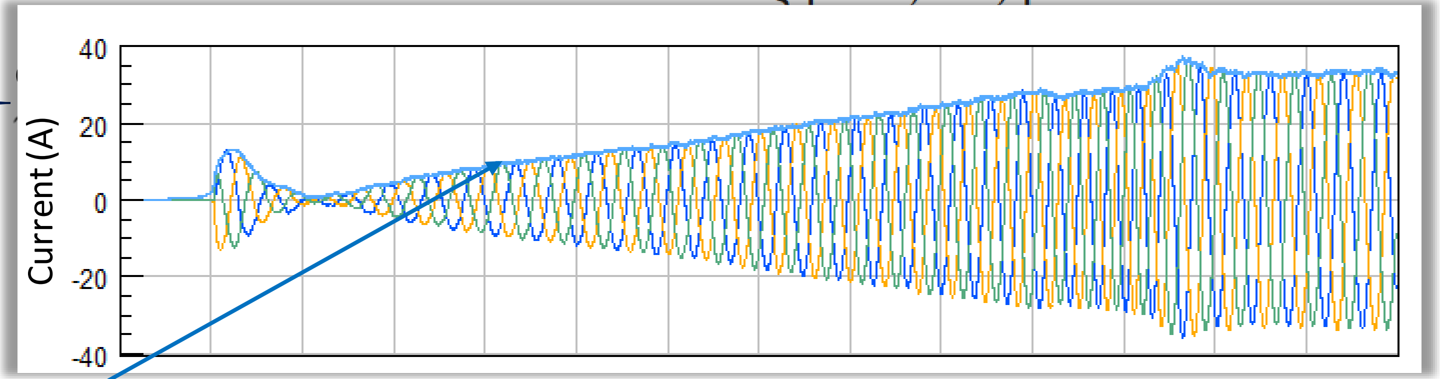
How do we calculate α, β from the time signal of voltage and current?

1. Clarke transform – *time domain*
2. Hilbert transform – *frequency domain*

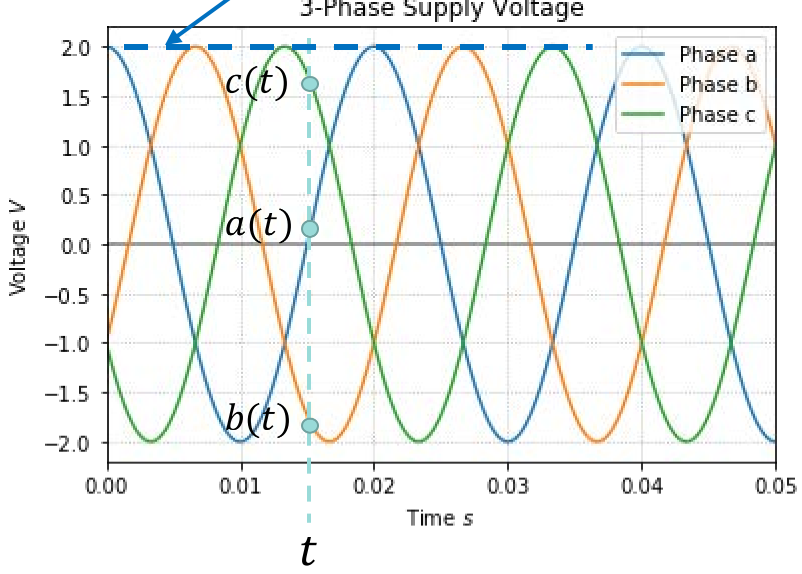
Clarke transform – *time domain*

- Uses all 3-phase values *simultaneously* to calculate α and β
  - Assume all phases have same amplitude
  - Assume phases are equally spaced (120°)
  - Assume signals are sinusoidal
  - Assume they do not change rapidly

$$\alpha = \frac{2}{3}\left[a - \frac{b}{2} - \frac{c}{2}\right]$$

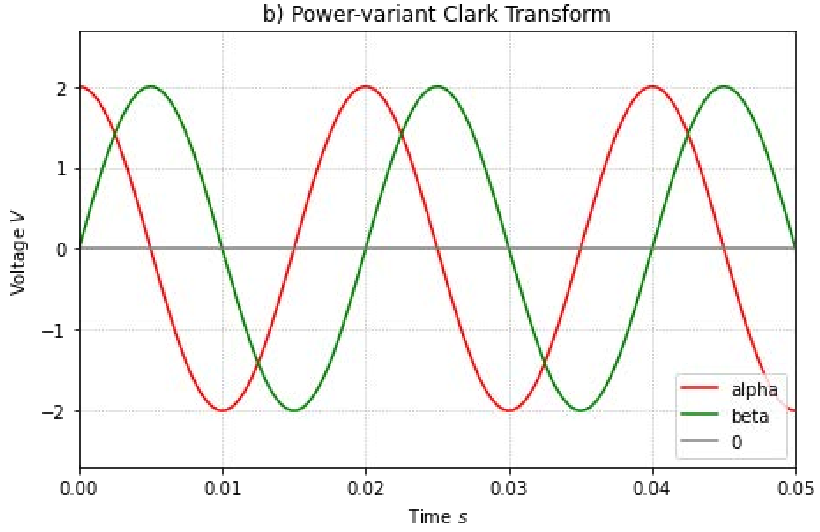


Instantaneous amplitude $|\alpha + j\,\beta|$



$\alpha(t)$ Active

$\beta(t)$ Reactive



Hilbert transform – *frequency domain*

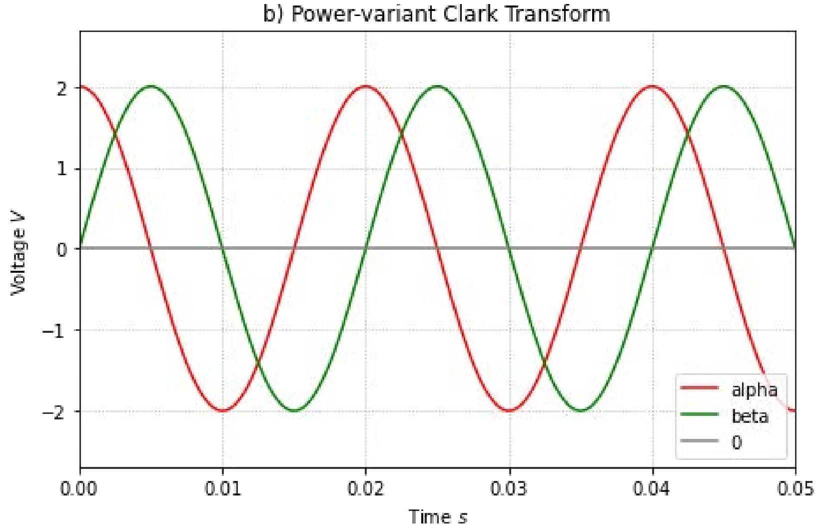
$$\left[\alpha_u + j\,\beta_u\right](t) = \mathcal{F}^{-1}\left\{\mathcal{H}\left[\mathcal{F}\left(u(t)\right)\right]\right\}$$

1. Fourier transform signal $\mathcal{F}[a(t)]$
2. Set all negative frequency components to zero $\mathcal{H}(\,)$
3. Inverse Fourier transform $\mathcal{F}^{-1}(\,)$
4. α is the real part and β is the imaginary

Hilbert Transform

- Uses Fourier to create α and β directly
  - Works on single phase at a time and combines them later
  - Suitable for single and multi-phase
  - Phases can be imbalanced
  - Waveforms can be non-sinusoidal
  - Waveforms can change rapidly

$\alpha(t)$ Active $\beta(t)$ Reactive



Comparing the Clarke and Hilbert Transforms

Clarke Transform – *time domain*

- Must be 3-phase
- Must be sinusoidal
- Must be balanced
  - equal & constant amplitude
  - equal & constant angular spacing
- Must be stationary

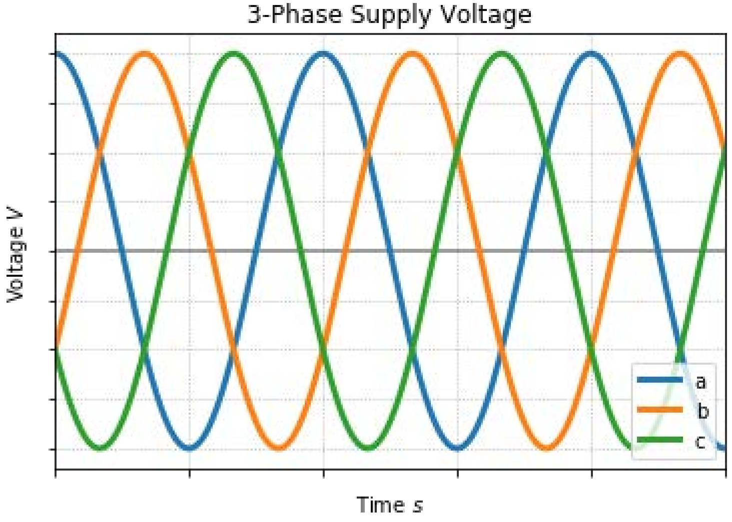
- Suitable for real-time calculations
- Often used for non-sinusoidal waves but suboptimal
- Often used for non-stationary signals but suboptimal
- There is a check for balance ($\gamma = 0$)

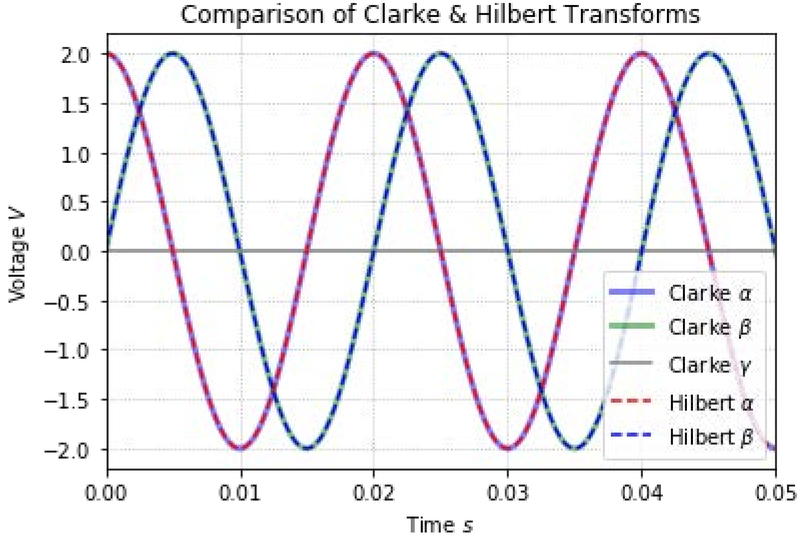
Hilbert Transform – *frequency domain*

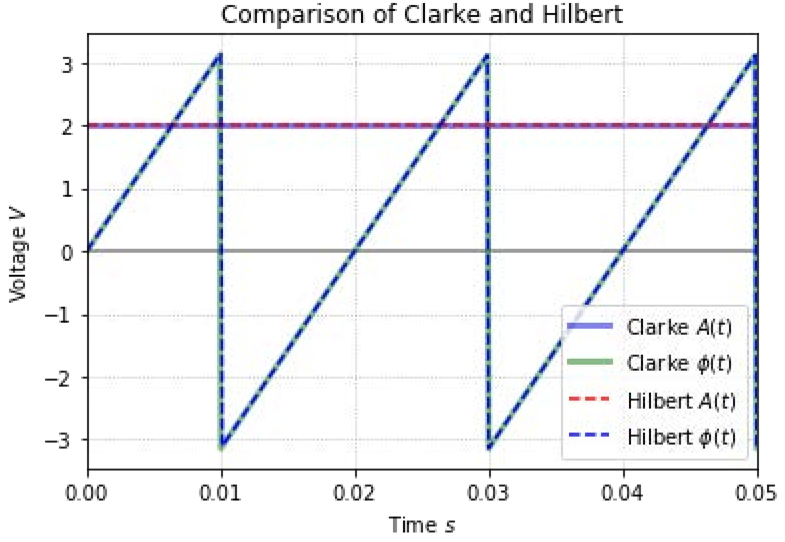
- More complex computational analysis
  - Requires large FFT buffers
- Unsuitable for real-time calculations must be off-line post-processed

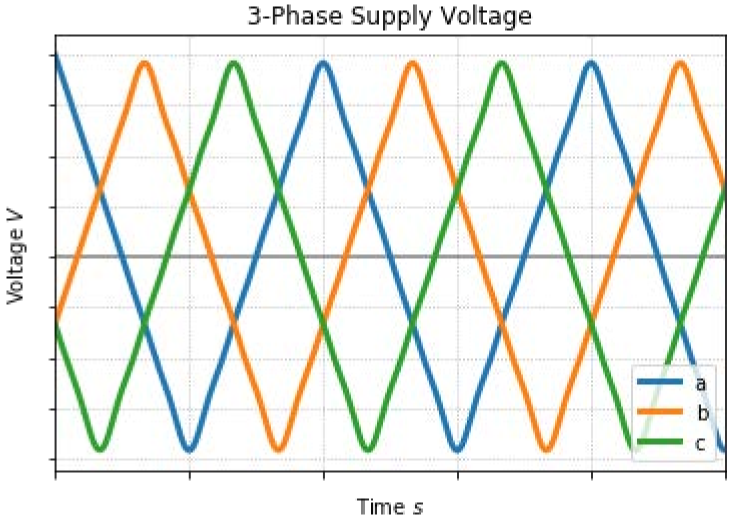
- Fast
- Suitable for single and multi-phase
- Suitable for non-sinusoidal waves
- Suitable for transient signals

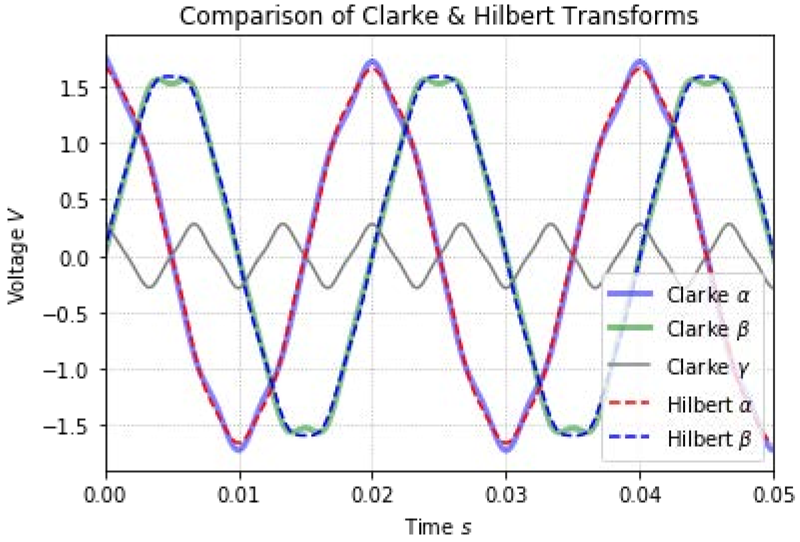
Comparing the Clarke and Hilbert Transforms

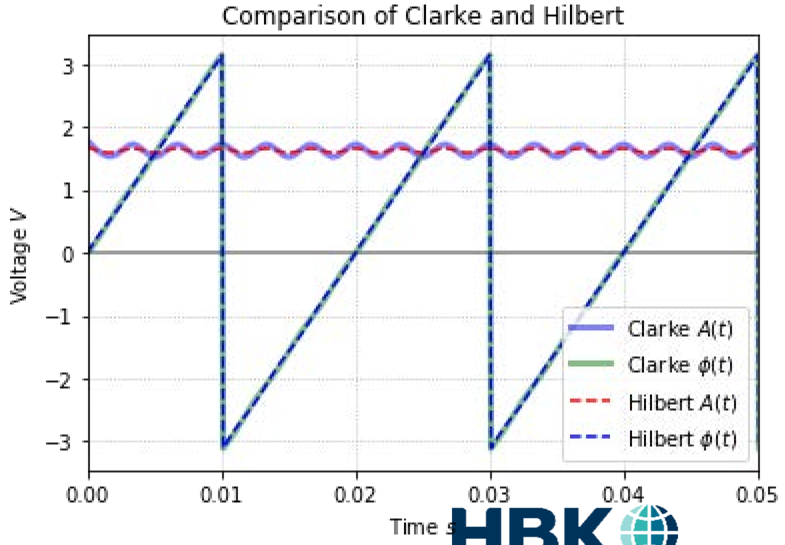












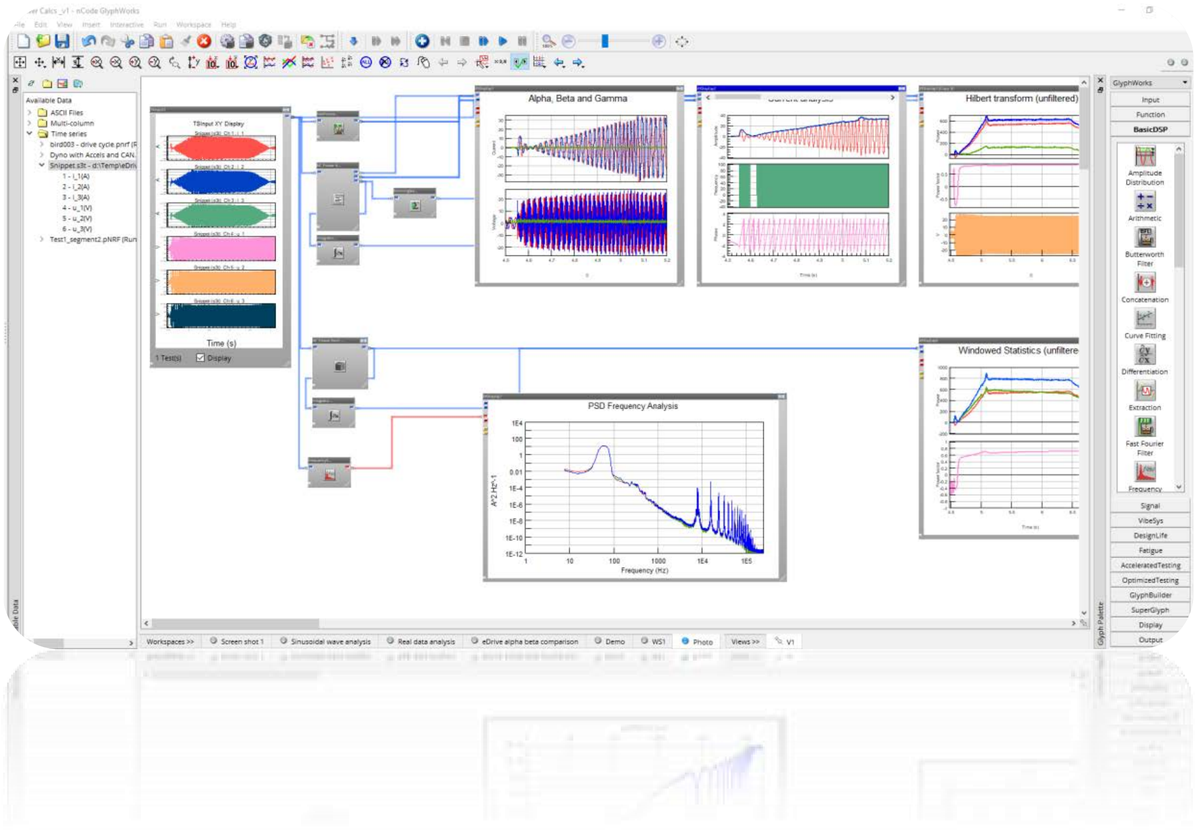
GlyphWorks Post-processing Case Studies

GlyphWorks EV Power Post Processing

1. An EV engineer wants to use the **Windowed Statistical Method** to calculate the power factors at the fundamental frequency

2. An EV engineer wants to compare the **Clarke** and **Hilbert** methods to calculate the power factors at the fundamental frequency

3. An EV engineer wants to use the **Hilbert** method to optimize the inverter switching profile



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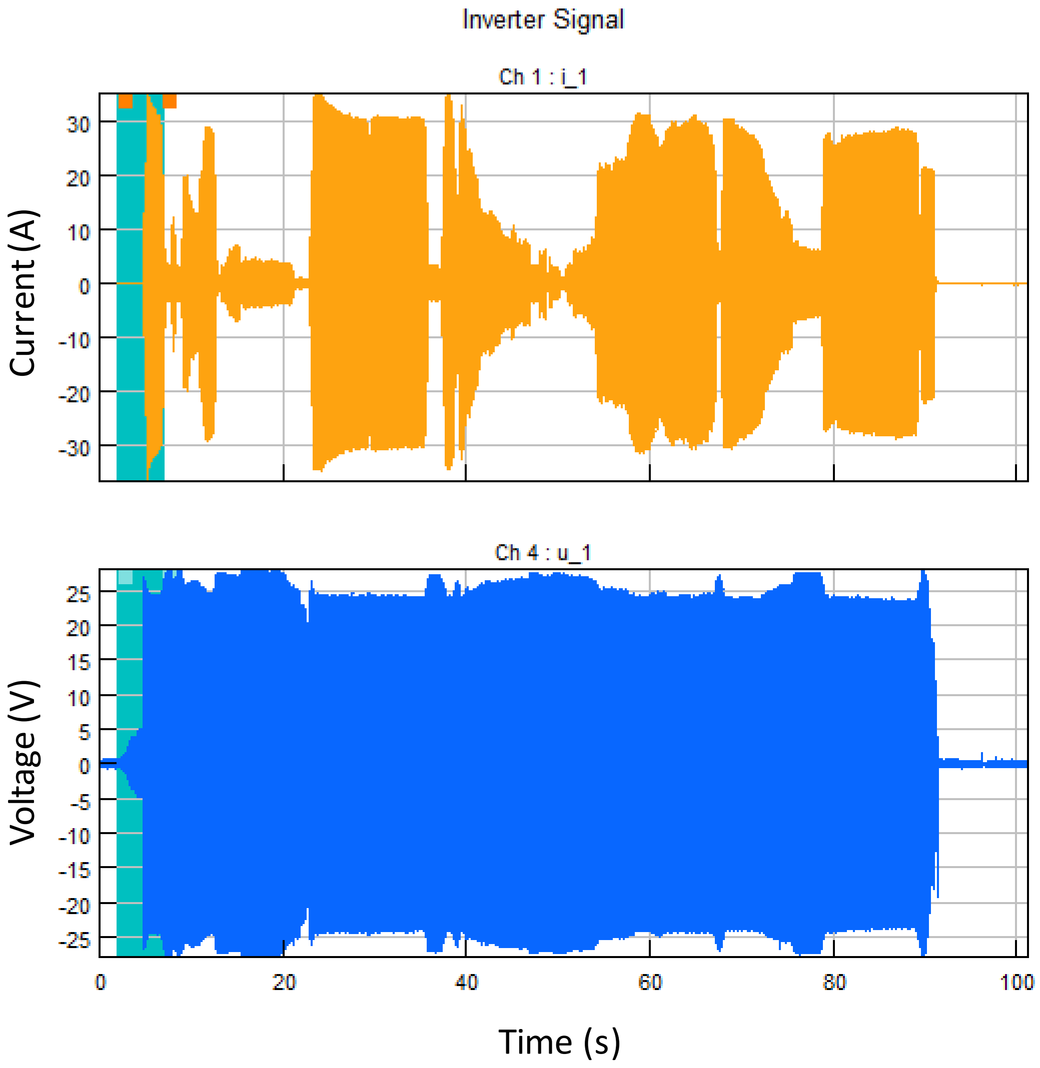
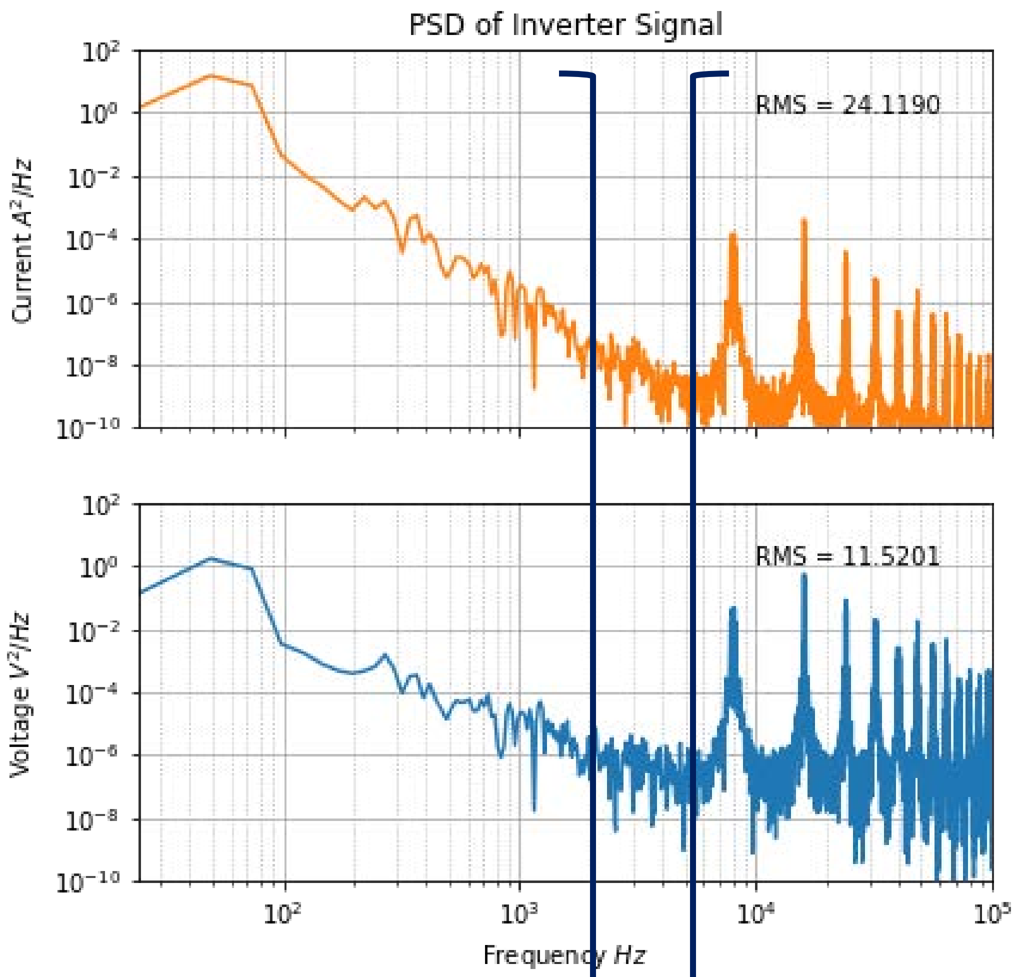
Measured Time Signal





Fundamental frequency

Spectral gap

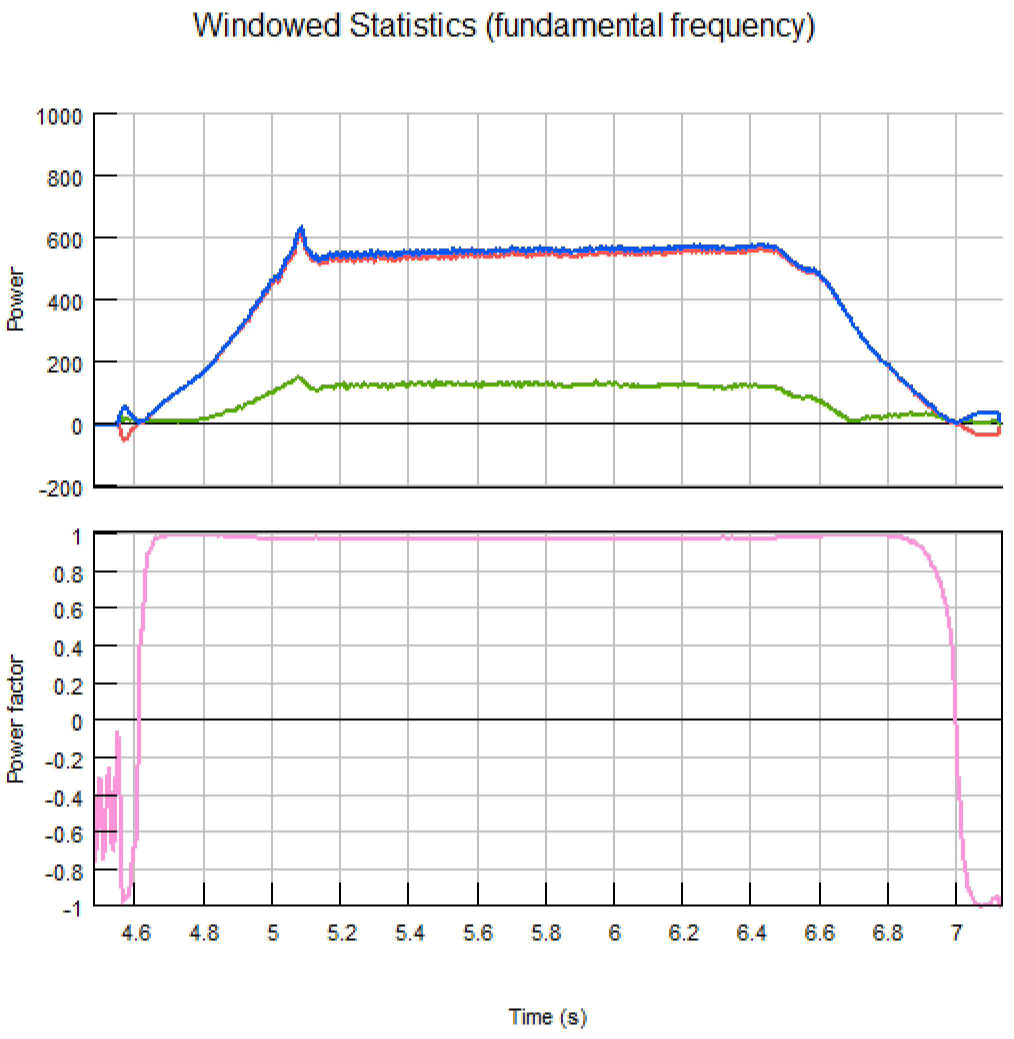
Switching harmonics

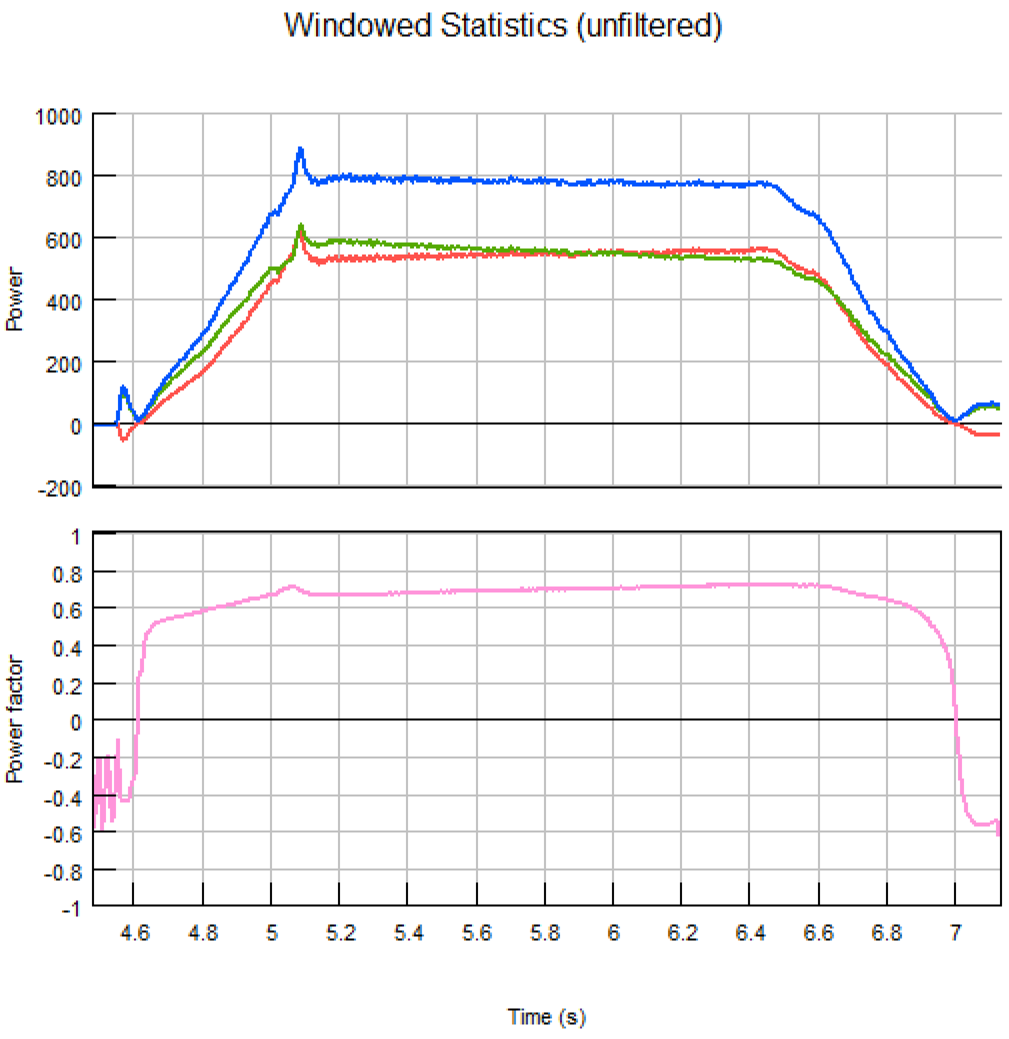
HBK
HOTTINGER BRÜEL & KJÆR

User Story 1

Active, Reactive, Apparent power

An EV engineer wants to use the **Windowed Statistical Method** to calculate the power factors at the fundamental frequency

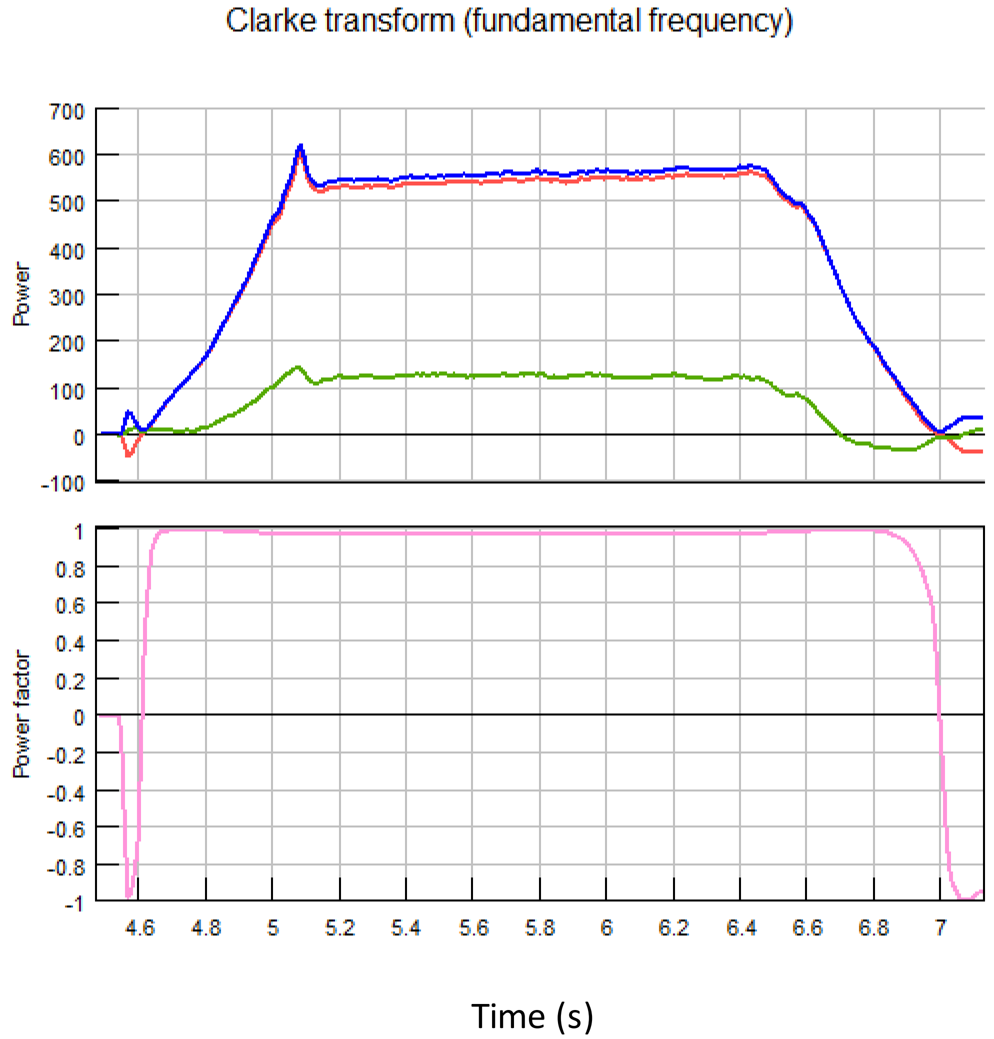


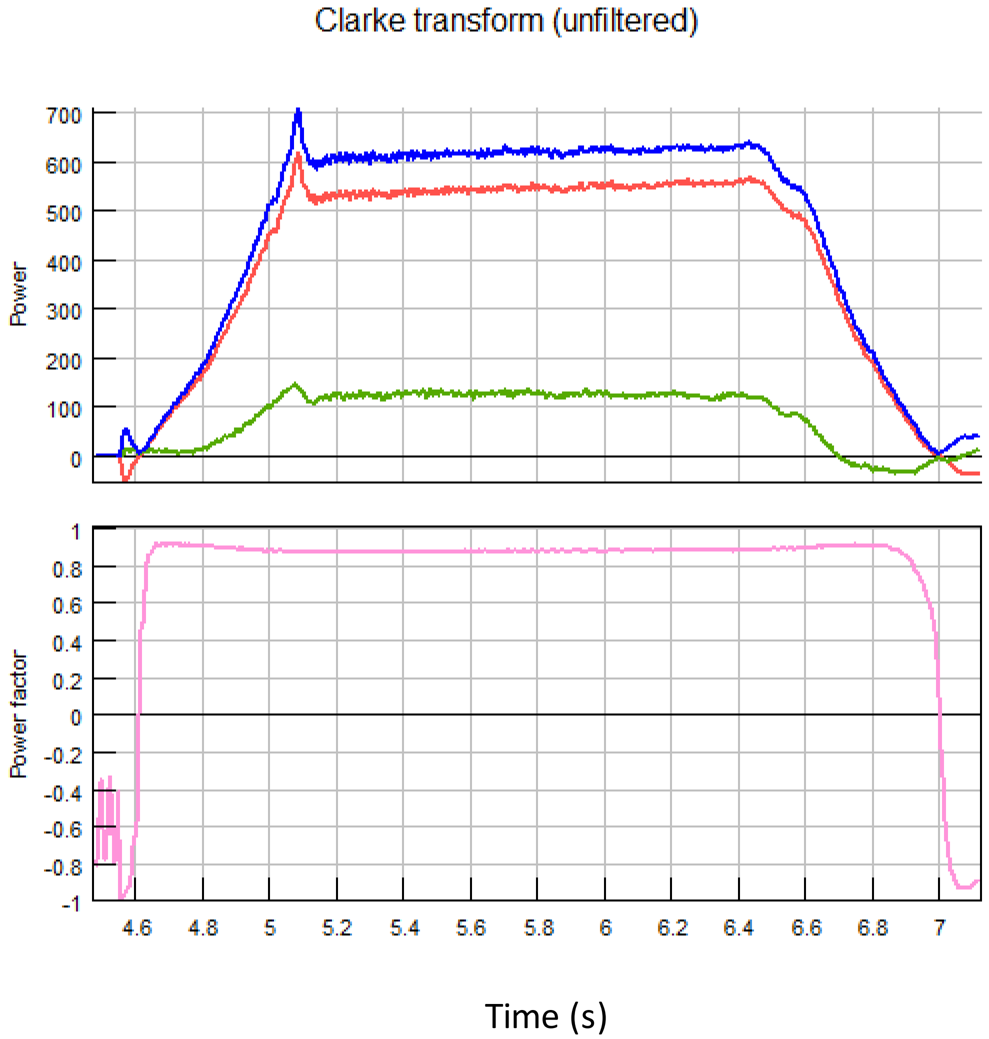


User Story 2

An EV engineer wants to compare the **Clarke** and **Hilbert** methods to calculate the power factors at the fundamental frequency

Active, Reactive, Apparent power



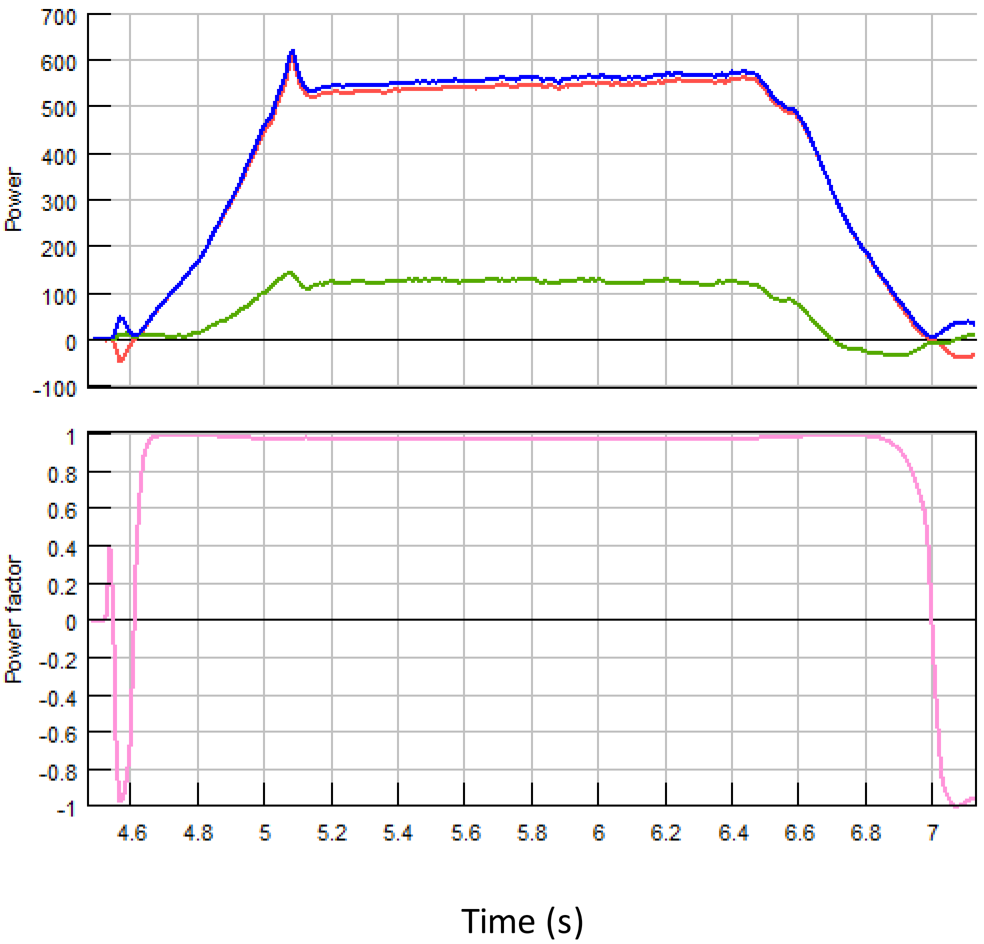


User Story 2

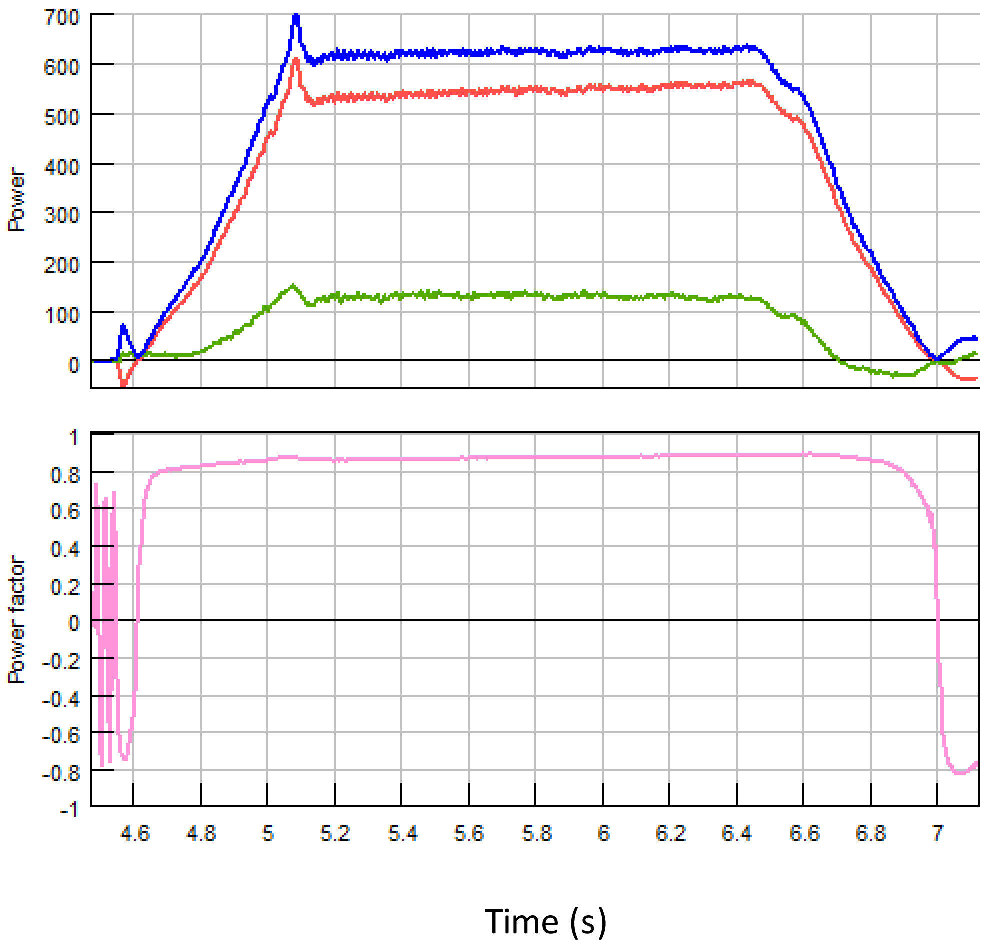
Active, Reactive, Apparent power

An EV engineer wants to compare the **Clarke** and **Hilbert** methods to calculate the power factors at the fundamental frequency

Hilbert transform (fundamental frequency)



Hilbert transform (unfiltered)

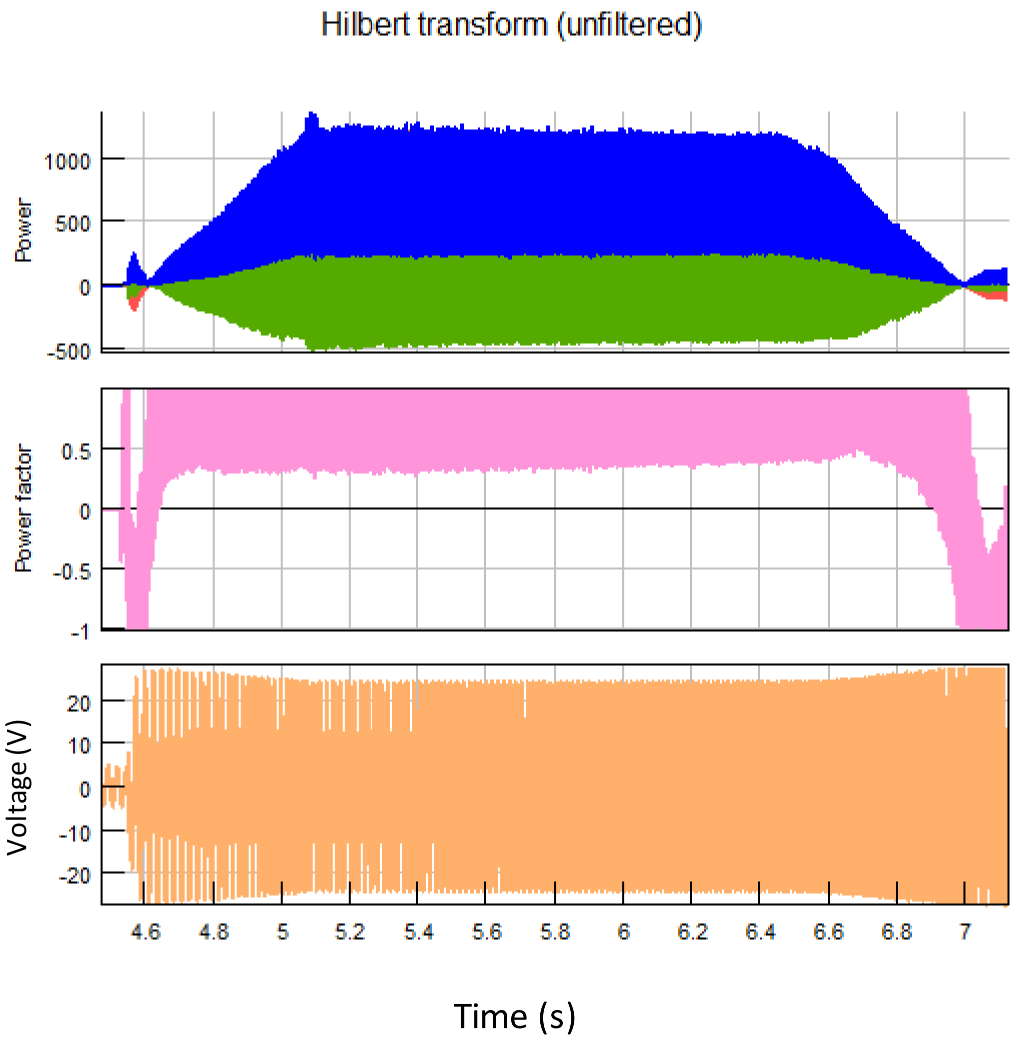


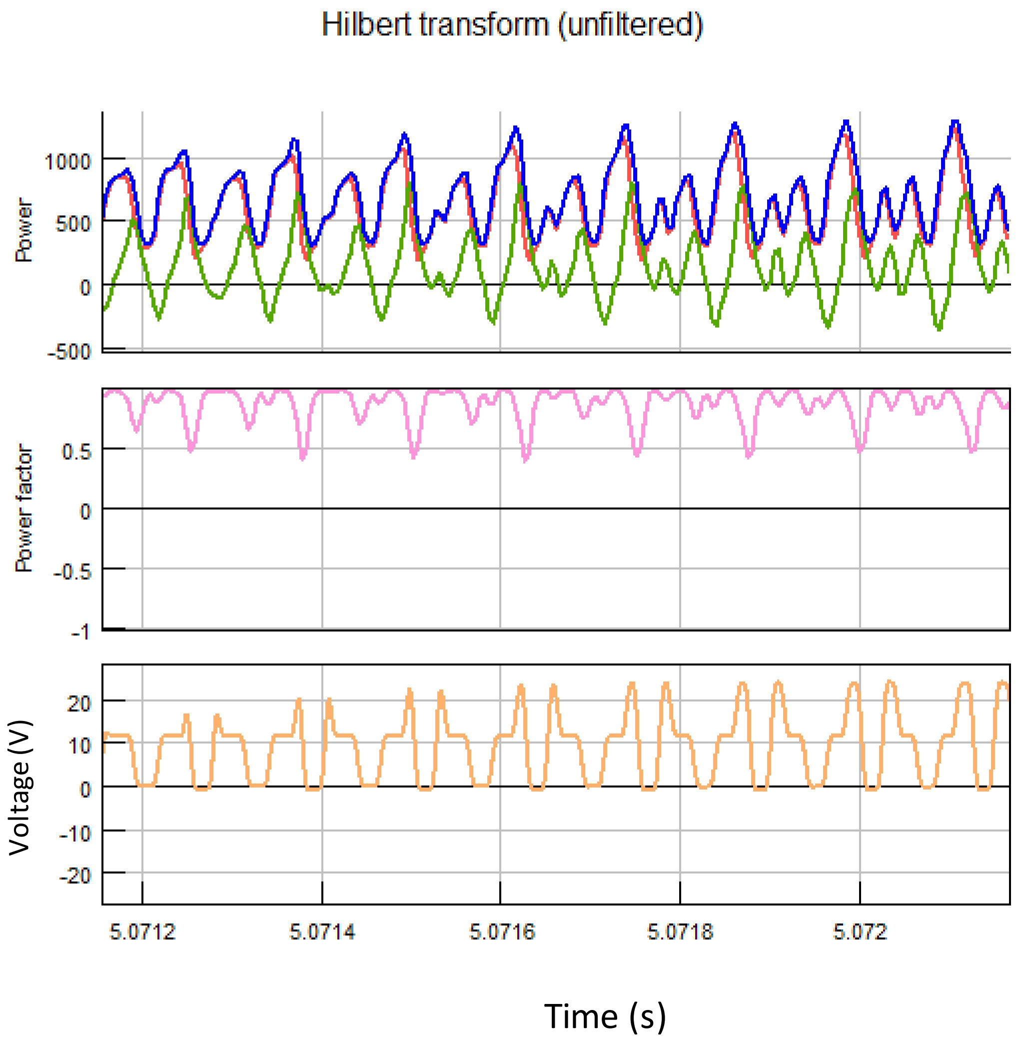
User Story 3

An EV engineer wants to use the **Hilbert** method to optimize the inverter switching profile

Active, Reactive, Apparent power

Progressively zoom-in to see switching effects





Conclusion

Conclusion

Definitions: Pure Sine AC

Presentation Objective

- **Maximize EV efficiency** – AC Inverter/motor system

Non-sinusoidal, dynamic AC power

- **Active** – consumed to drive the vehicle
- **Reactive** – not consumed but causes efficiency losses

What we want

1. An ***accurate*** measurement of **Active** power to maximize
2. A ***robust inference*** of **Reactive** power to minimize

Definitions - *Active, Reactive, Apparent & Power Factor*

- Analytical & Digital definitions
- Pure sine & broadband signals

Time-averaging methods

Fundamental frequency

Windowed-statistical method – *time domain*

- Pure sine method
- For preferred definition of Q, use low-pass filter to isolate the fundamental frequency
- Excellent time resolution possible *(down to half-cycle in the best systems)*
- Ideal for analysing dynamic EV systems & WLTC *(Worldwide Harmonised Light Vehicle Test Procedure)*

PSD method – *frequency domain*

- Broadband method
- Large fft buffer gives poor time resolution
  Not ideal for dynamic EV systems & WLTC

Conclusion

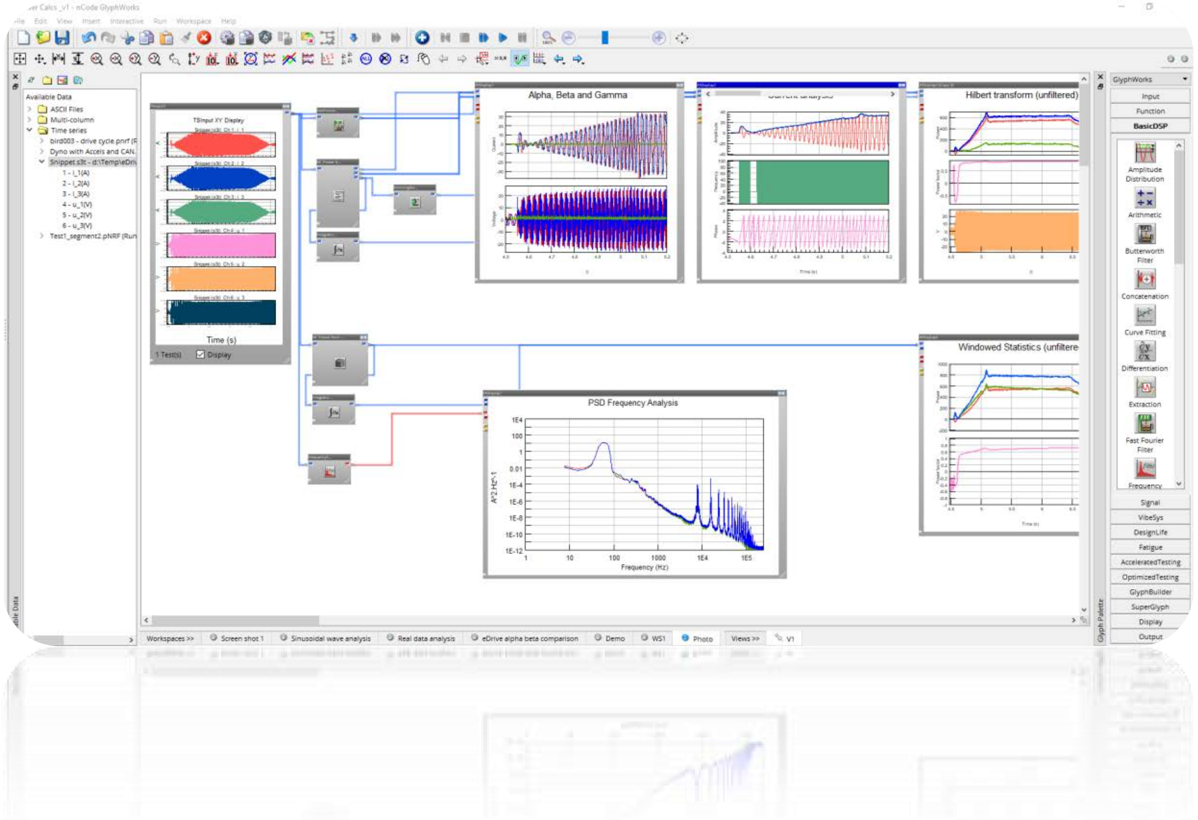
Instantaneous methods

Fundamental & inverter switching high-frequencies

- Clarke transform method – *time domain*
  - Suitable for **real-time** calculations
  - Must be **3-phase**
  - Ideally should be: sinusoidal, balanced & stationary

- Hilbert transform method – *frequency domain*
  - Unsuitable for real-time applications
  - Suitable for single and **multi-phase**
  - Suitable for **non-sinusoidal** waves
  - Suitable for **dynamic** signals

GlyphWorks EV Power Post-processing



Thank You

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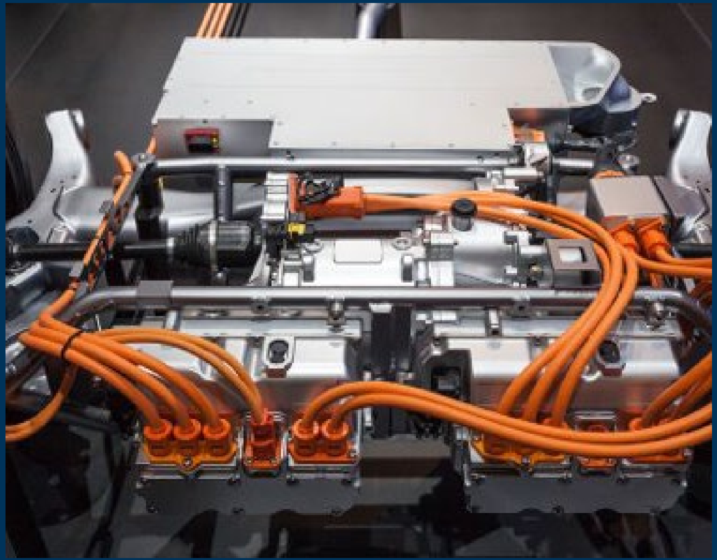
Q&A

- (no questions)

HBM Prenscia Technology Day

Virtual Seminar Series



Analysis of Electric Powertrain Measurements – Torque, Power, Efficiency, Vibration

Presented by Dr. Andrew Halfpenny
Chief Technologist, HBM Prenscia
HBK

Session #2: Electrical Power Testing & Analysis