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Adaptive-window PMU algorithms using cascaded boxcar filters to meet and exceed C37.118.1(a) requirements

Dr. Andrew Roscoe

EURAMET
European Association of National Metrology Institutes

EMRP
European Metrology Research Programme
Programme of EURAMET

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ENG52 SmartGrid II
SMART GRID METROLOGY

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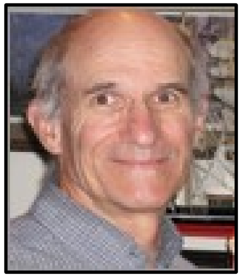

Ken Martin,
Chair, IEEE Synchrophasor Working Group

C37.118.1a-2014

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IEEE Standard for Synchrophasor Measurements for Power Systems

IEEE Power & Energy Society

Sponsored by the
Power System Relaying Committee

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3 Park Avenue
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USA

28 December 2011

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IEEE Standard for Synchrophasor Measurements for Power Systems

Amendment 1: Modification of Selected Performance Requirements

IEEE Power and Energy Society

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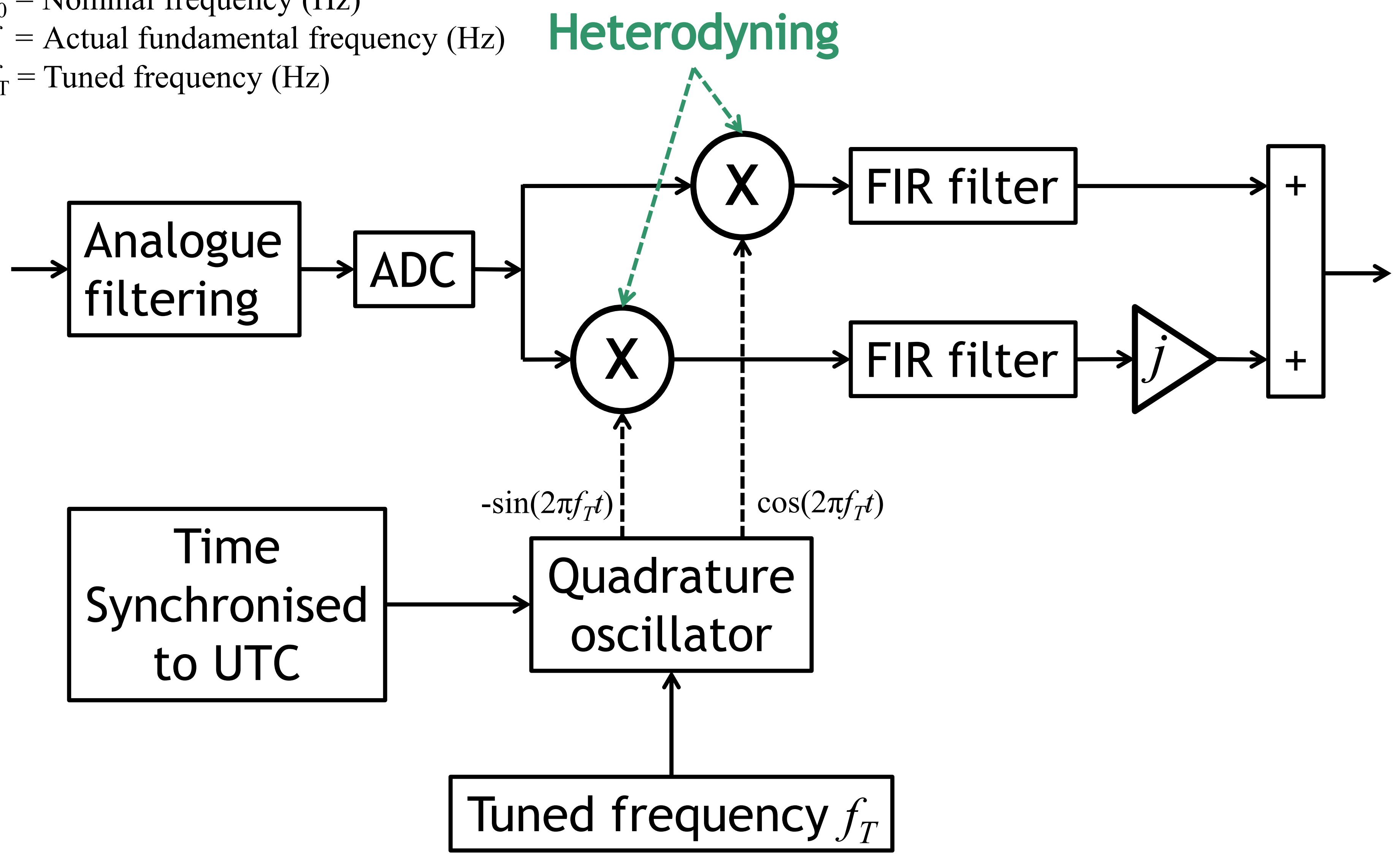
USA

IEEE Std C37.118.1a™-2014
(Amendment to
IEEE Std C37.118.1™-2011)

IEC/IEEE 60255-118-1

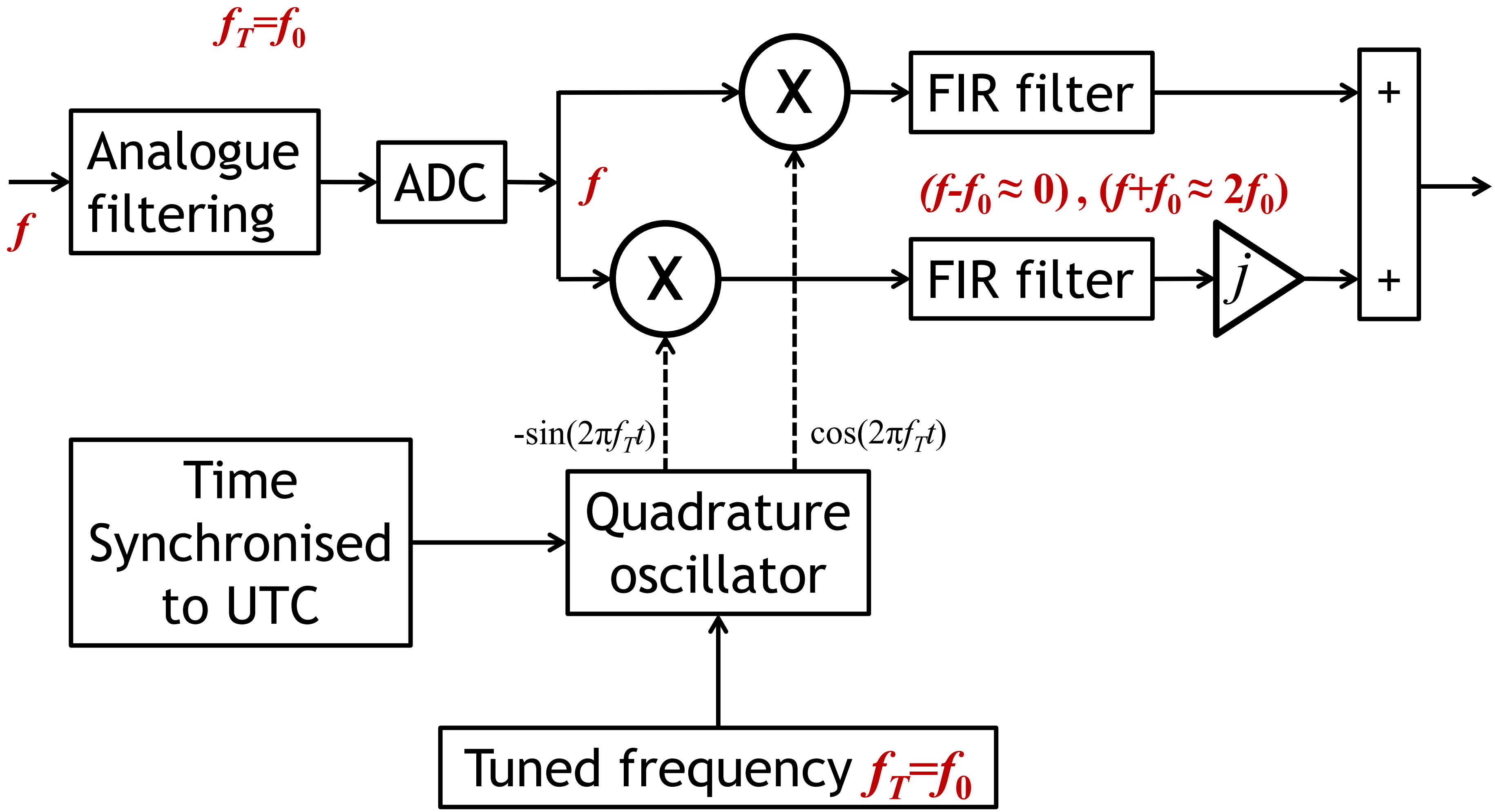
General PMU architecture (single phase section)

f_0 = Nominal frequency (Hz)
f = Actual fundamental frequency (Hz)
f_T = Tuned frequency (Hz)



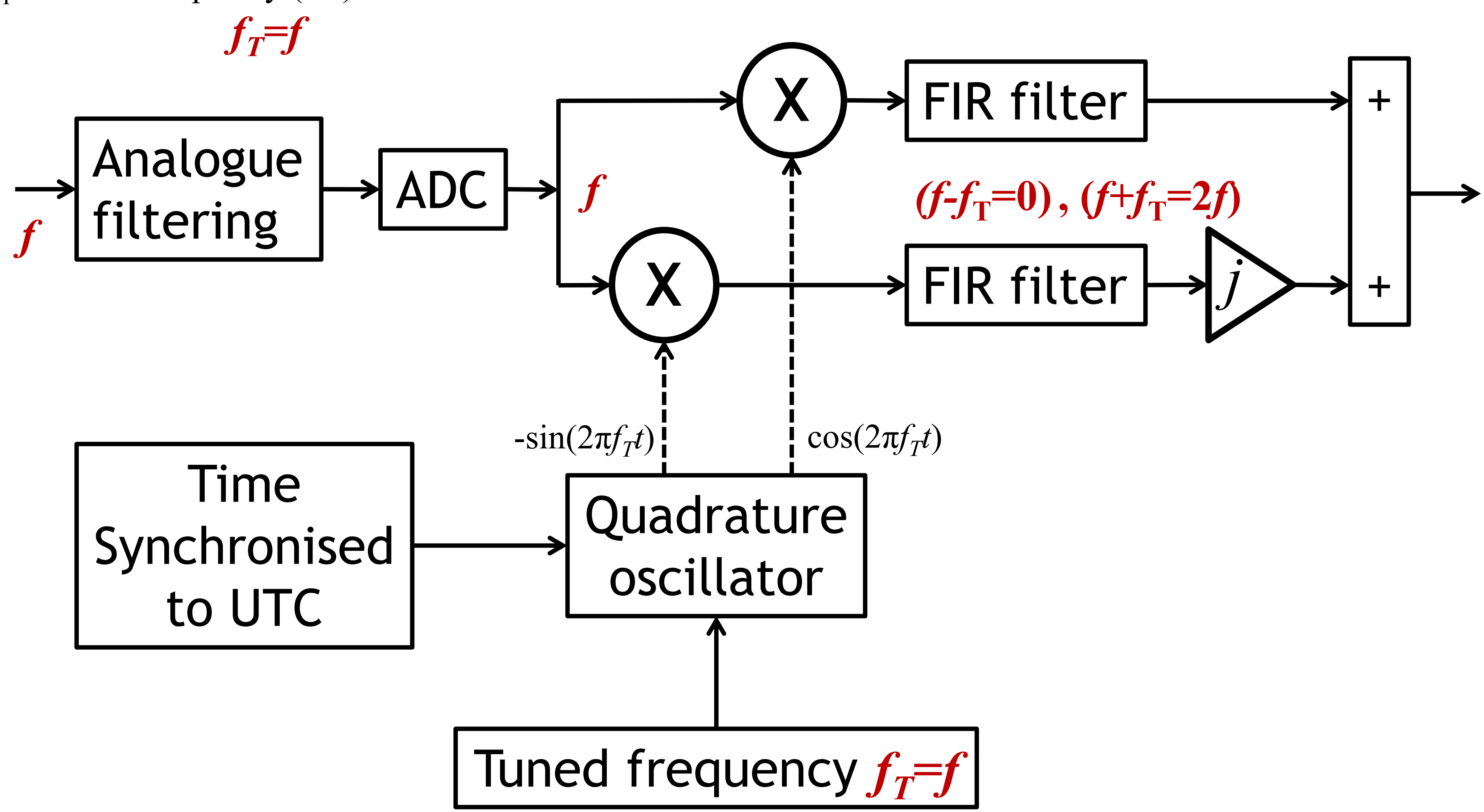
Fixed-filter PMU architecture (single phase section)

f_0 = Nominal frequency (Hz)
f = Actual fundamental frequency (Hz)
f_T = Tuned frequency (Hz)



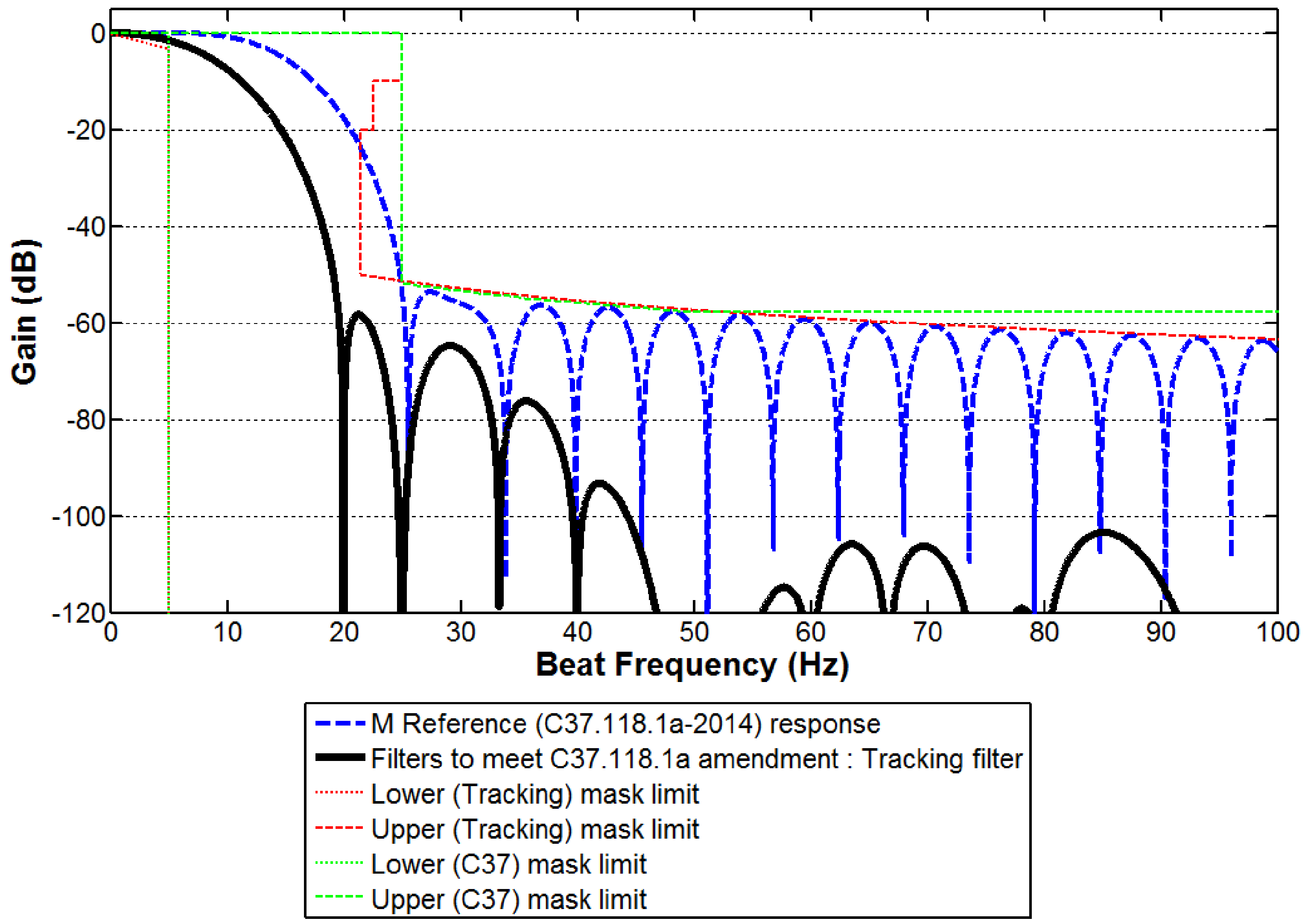
Frequency-tracking PMU architecture (single phase section)

f_0 = Nominal frequency (Hz)
f = Actual fundamental frequency (Hz)
f_T = Tuned frequency (Hz)

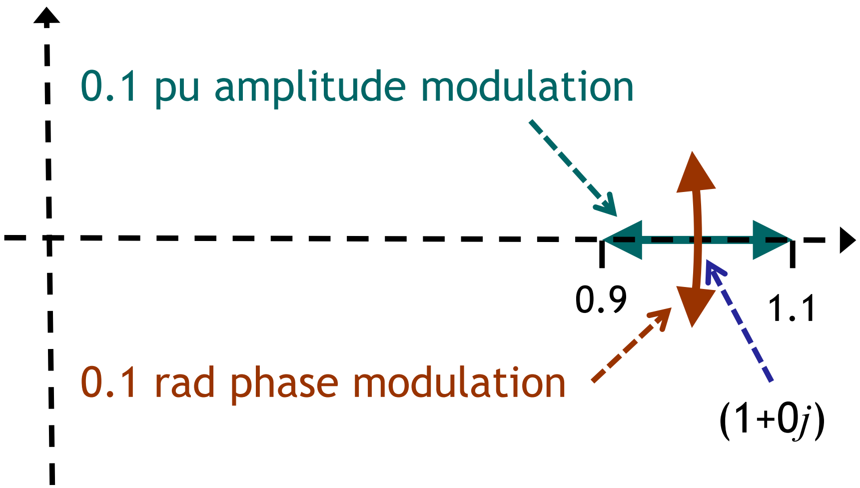


Reference vs. Tracking filter example

f_0=50, Reporting rate 50 Hz



The effect of modulation in the bandwidth test



$$V = \frac{M}{2} e^{j2\pi f_M t} + \frac{M}{2} e^{-j2\pi f_M t}$$

$$V_{Meas} = F(f_M)\frac{M}{2} e^{j2\pi f_M t} + F(-f_M)\frac{M}{2} e^{-j2\pi f_M t}$$

$$TVE = \left| V_{Meas} - V \right|$$

$$\left| F(f_M) - 1 \right| < \frac{TVE_{Limit}}{M}$$

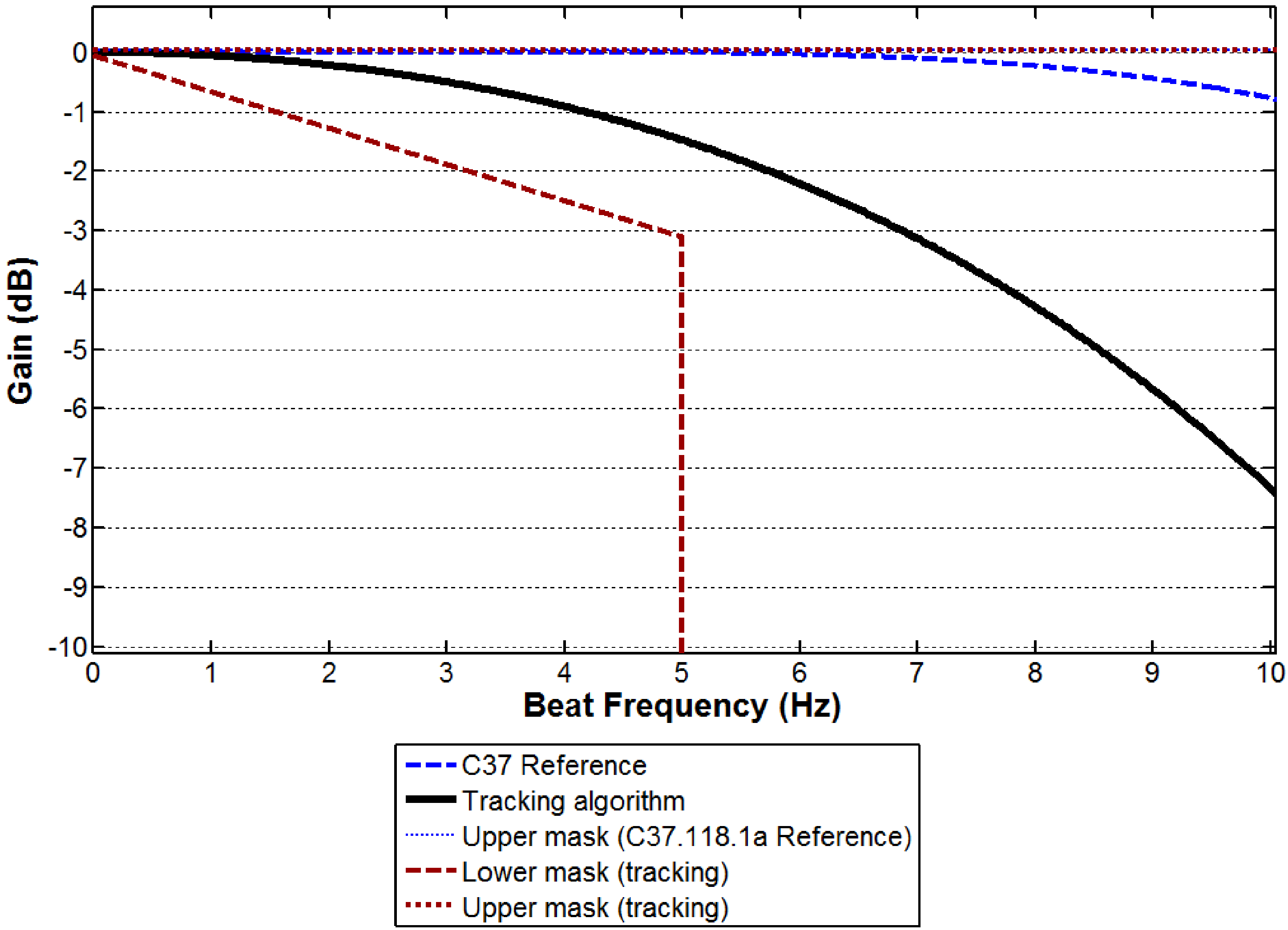
$$\left| F(f_M) \right| > 1 - \frac{0.03}{0.1}$$

$$\left| F(f_M) \right| > 0.7$$

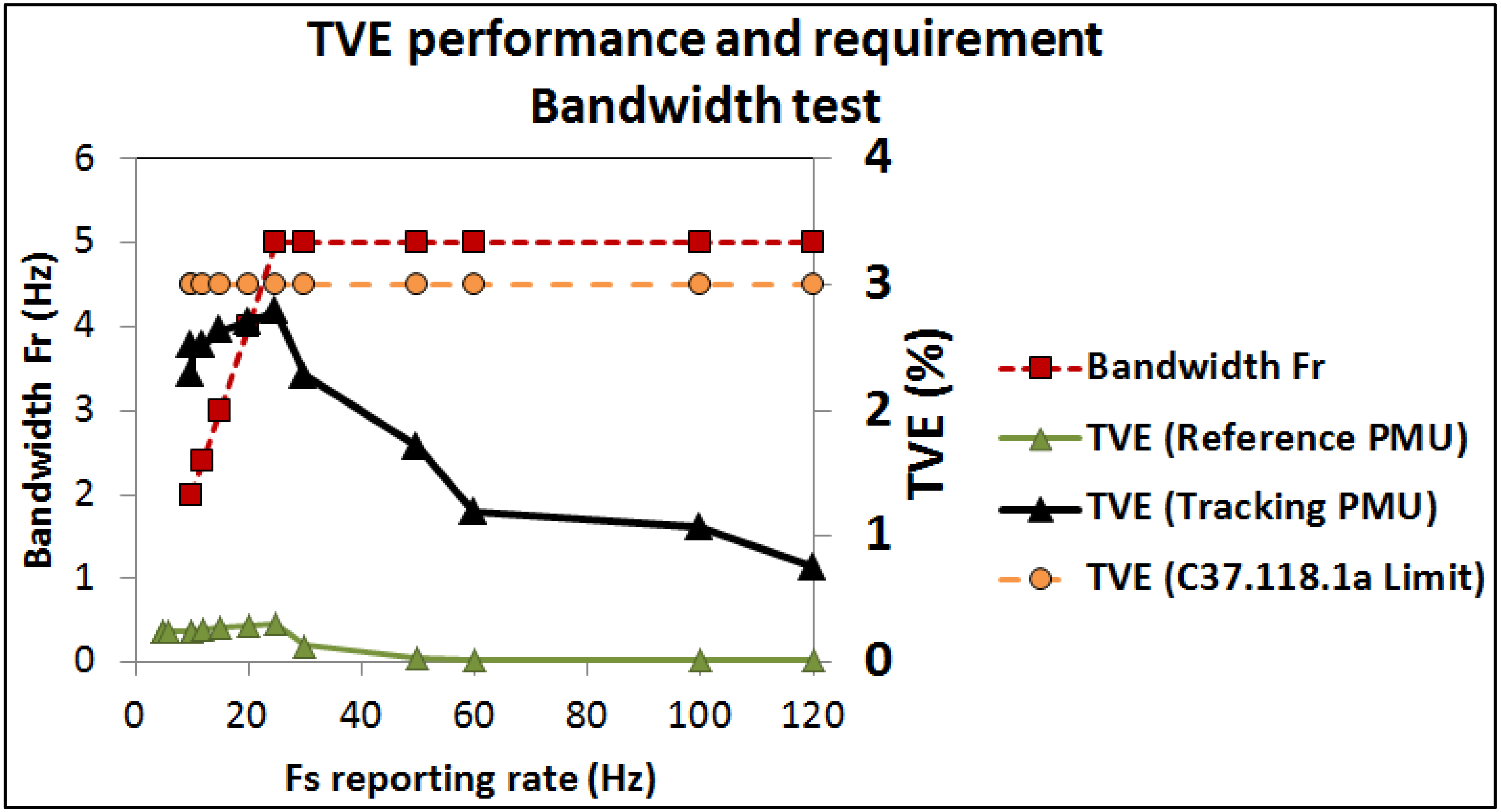
$F(f_M)$ > -3.098 dB

Reference vs. Tracking filter example

f_0=50, Reporting rate 50 Hz



Bandwidth test – TVE

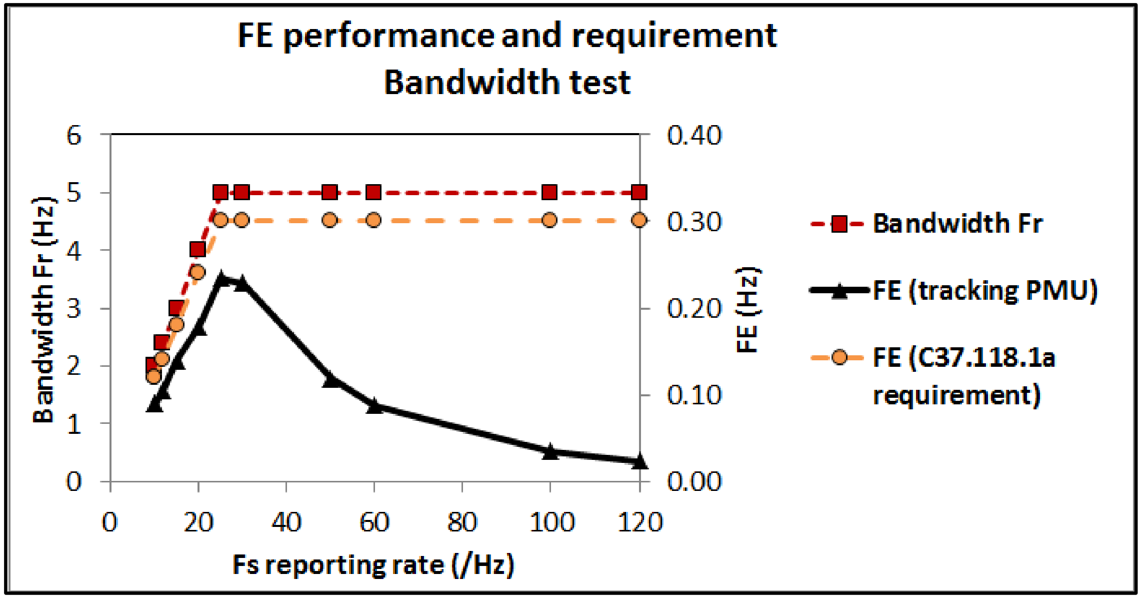


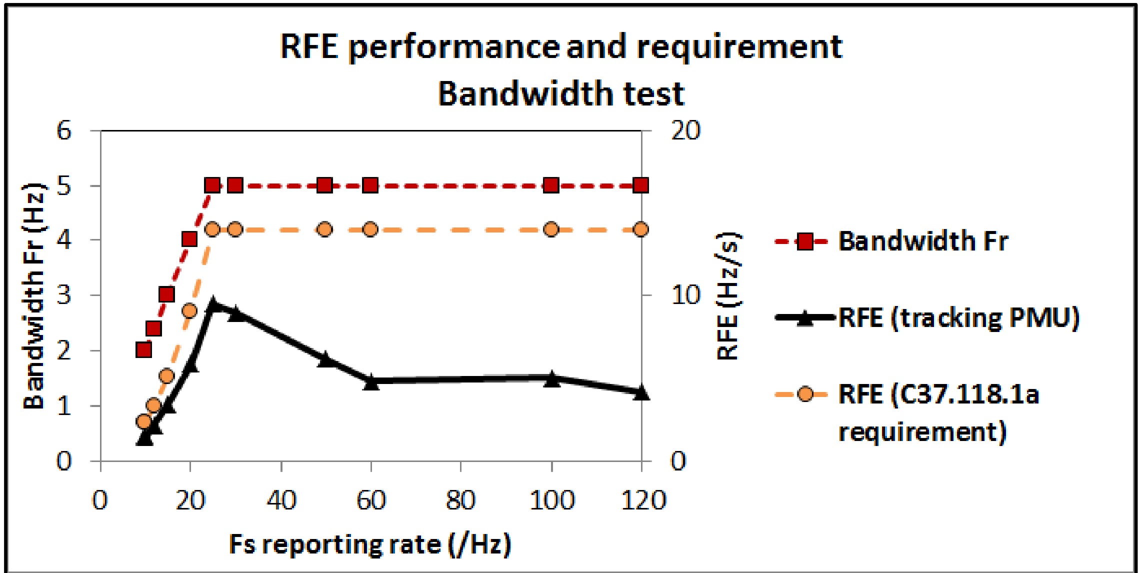
Bandwidth testing

C37.118.1a-2014

F & ROCOF performance limits	Error requirements for Compliance					
	P Class			M Class		
Reporting Rate F_S (Hz)	F_r (Hz)	Max FE	Max RFE	F_r (Hz)	Max FE	Max RFE
10	1	0.03	0.6	2	0.12	2.3
12	1.2	0.04	0.8	2.4	0.14	3.3
15	1.5	0.05	1.3	3	0.18	5.1
20	2	0.06	2.3	4	0.24	9.0
25	2	0.06	2.3	5	0.30	14
30	2	0.06	2.3	5	0.30	14
50	2	0.06	2.3	5	0.30	14
60	2	0.06	2.3	5	0.30	14
Formulas	$\min(F_S/10,2)$	$0.03 * F_r$	$0.18*\pi*F_r$ 2	$\min(F_s/5,5)$	$0.06 * F_r$	$0.18*\pi*F_r^2$

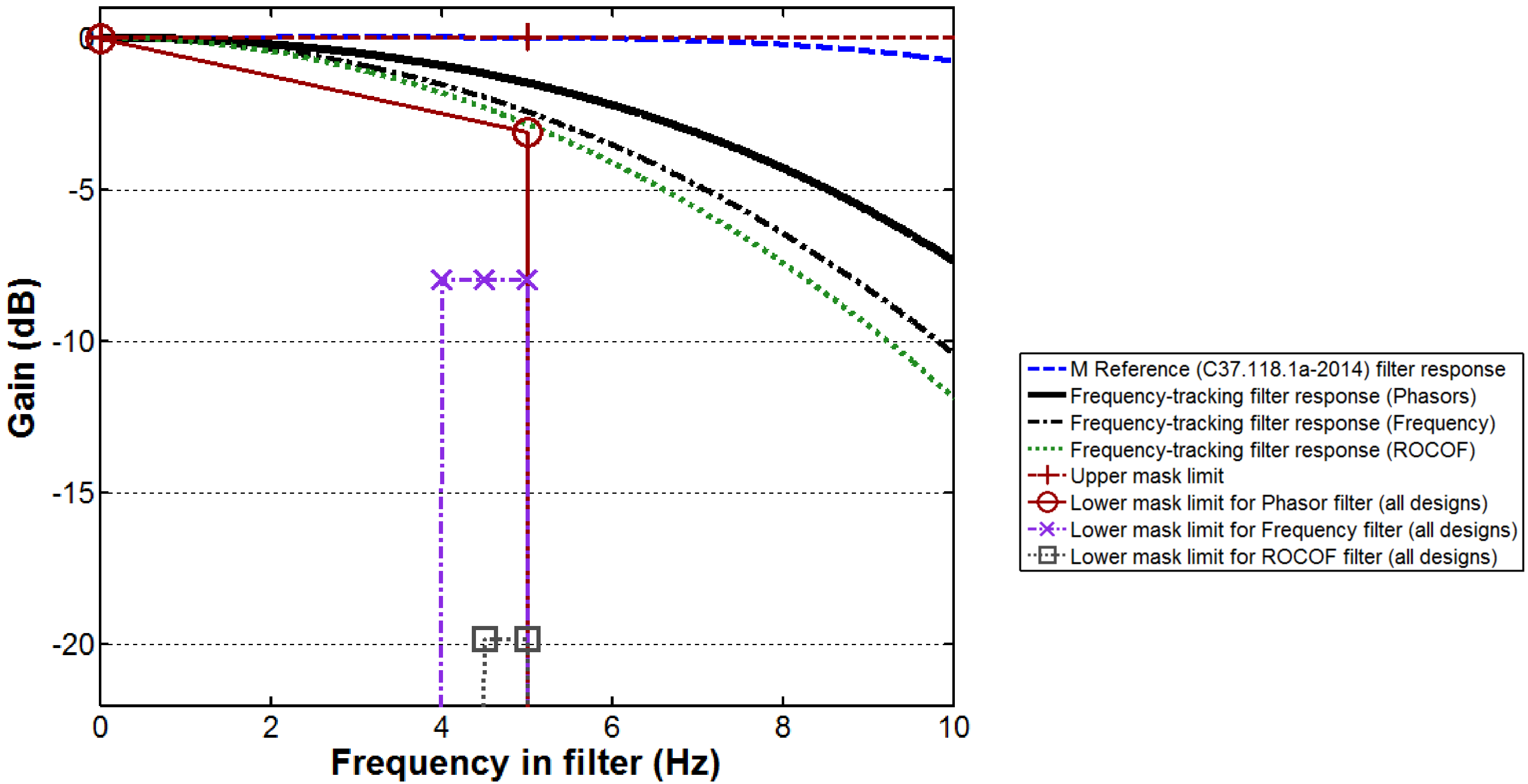
Bandwidth test – Frequency Error (FE) & ROCOF ERROR (RFE)





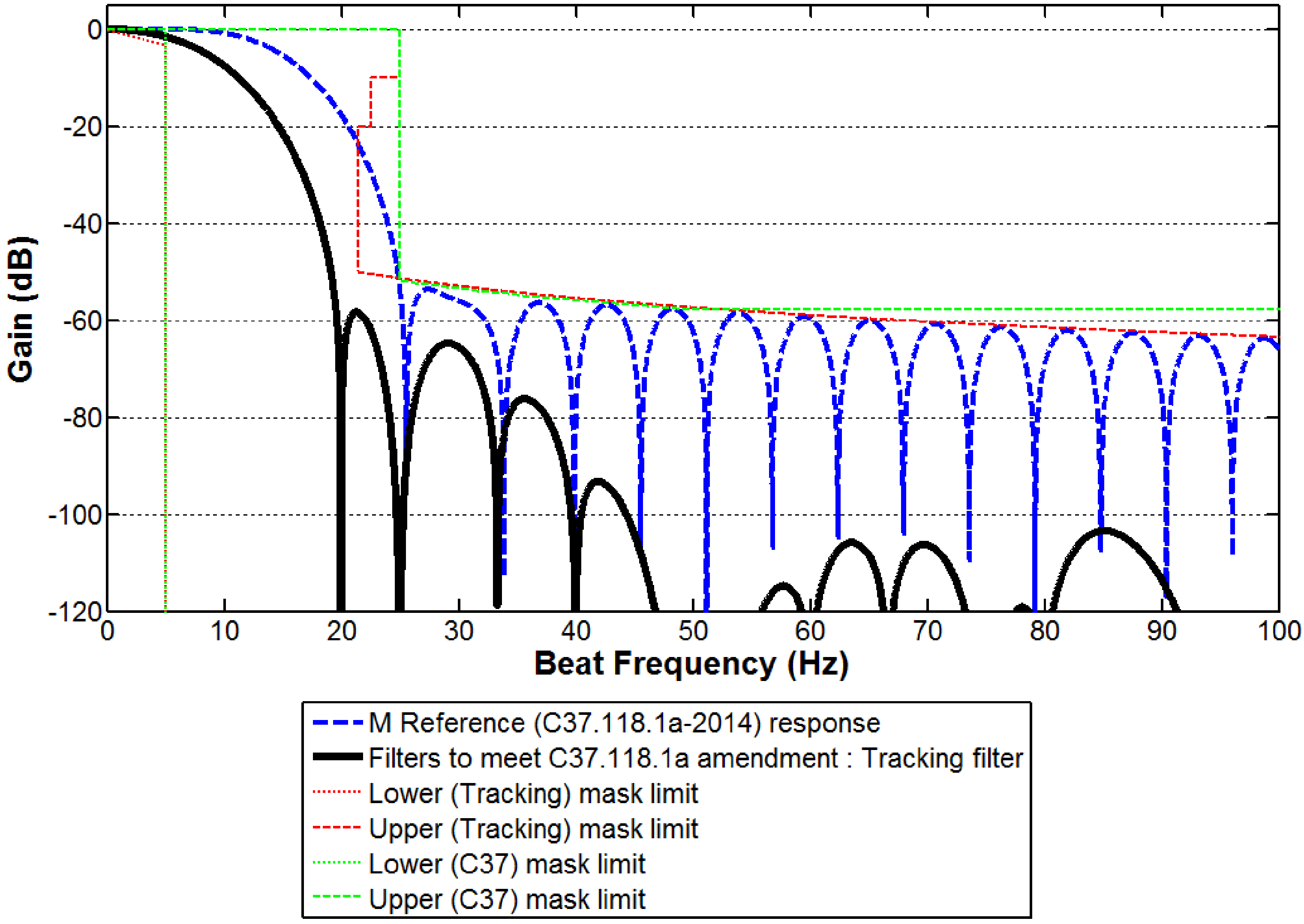
Reference vs. Tracking filter example

f_0=50, Reporting rate F_S=50 Hz



Reference vs. Tracking filter example

f_0=50, Reporting rate 50 Hz

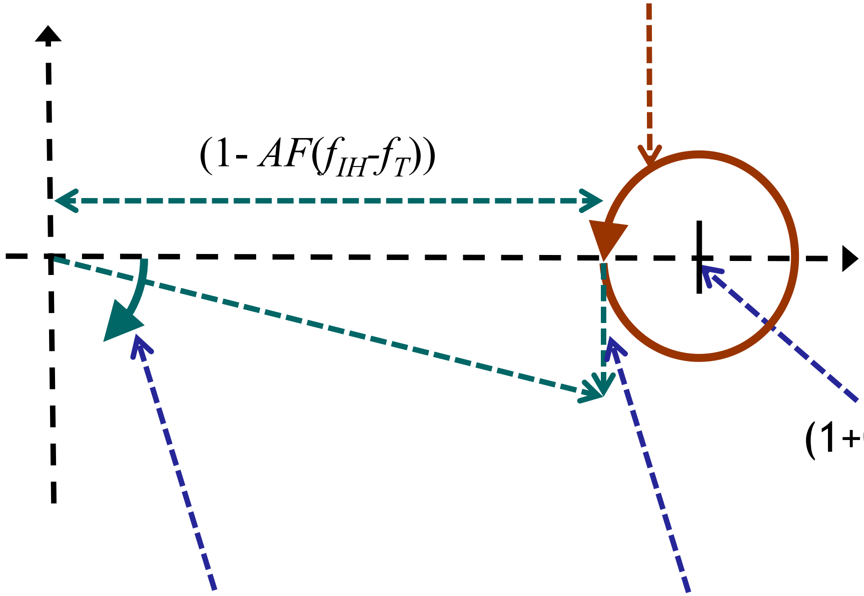


Frequency error during OOB testing

Interharmonic at $2\pi f_{IH}$

Radius $AF(f_{IH}\text{-}f_T)$

- where A=0.1 pu
- $F(f_{IH}\text{-}f_T)$ is filter gain at $(f_{IH}\text{-}f_T)$
- Deviation rotates at $2\pi\cdot(f_{IH}\text{-}f)$



Frequency deviation

$$\frac{2\pi \cdot (f_{IH} - f) \cdot AF(f_{IH} - fT)}{2\pi \cdot (1 - AF(f_{IH} - fT))}$$

Trajectory speed at closest approach

$2\pi\cdot(f_{IH}\text{-}f) \cdot AF(f_{IH}\text{-}f_T)$

Determining the required filter Mask for OOB testing

Frequency deviation

$$\frac{2\pi \cdot (f_{IH}-f) \cdot AF(f_{IH}-fT)}{2\pi \cdot (1-AF(f_{IH}-fT))}$$

Frequency deviation

$$\frac{\cancel{2\pi} \cdot (f_{IH}-f) \cdot AF(f_{IH}-fT)}{\cancel{2\pi} \cdot (1\cancel{-AF(f_{IH}-fT)})}$$

$$F(f_{IH} - f_T) < \frac{FE_{max}}{A \cdot (f_{IH} - f)}$$

Minimum separation of the interharmonic from the tuned (heterodyne) frequency. Sets the width of the mask.

Maximum separation of the interharmonic from the fundamental frequency, when $(f_{IH} - f_T)$ is minimum, sets the gain (attenuation) Required at the “closest” mask point.

Out-of-Band testing, f=f_0
All algorithms

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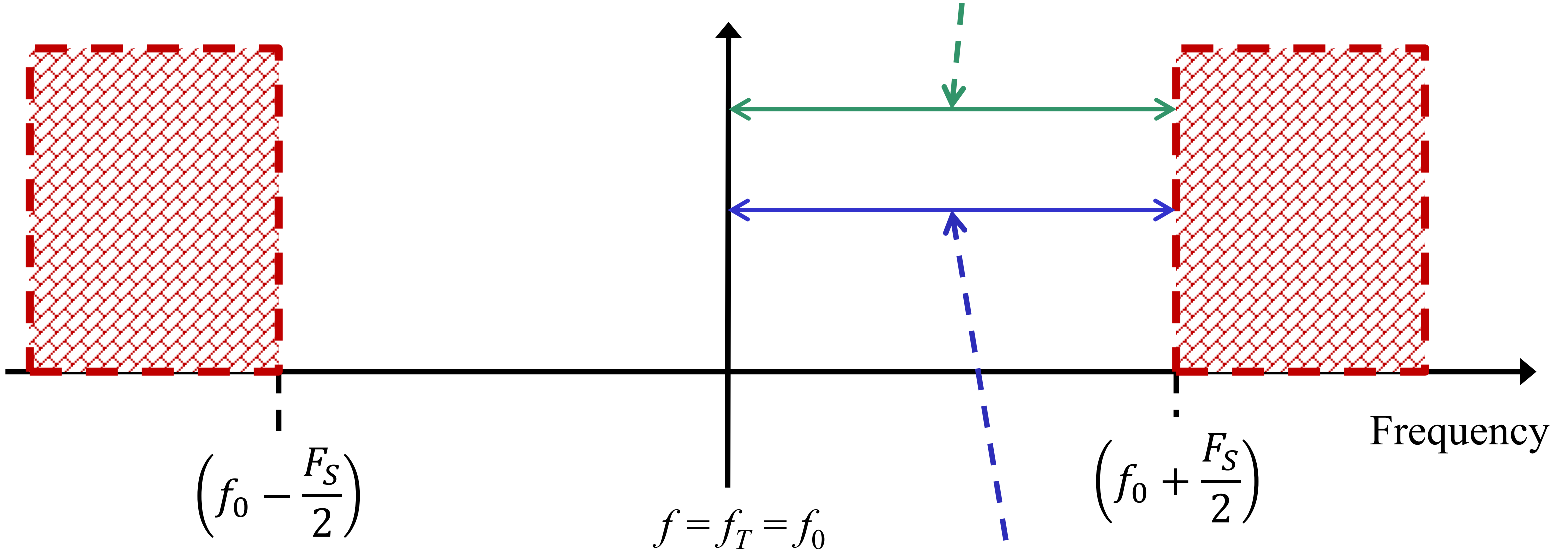
f_0 = Nominal frequency (Hz)
f = Actual fundamental frequency (Hz)
f_T = Tuned frequency (Hz)

Frequency in filter = $(f_{IH} - f_T)$

Minimum f_{IH} (upper) $= \left(f_0 + \frac{F_S}{2}\right)$

Minimum $(f_{IH} - f_T) = \left(f_0 + \frac{F_S}{2}\right) - f_0 = \left(\frac{F_S}{2}\right)$



Maximum $(f_{IH} - f) = \left(f_0 + \frac{F_S}{2}\right) - f_0 = \left(\frac{F_S}{2}\right)$

Mask width is "normal" $\left(\frac{F_S}{2}\right)$ and $(f_{IH} - f)$ tracks exactly with $(f_{IH} - f_T)$.

Out-of-Band testing, $f = f_0 - \frac{F_S}{20}$

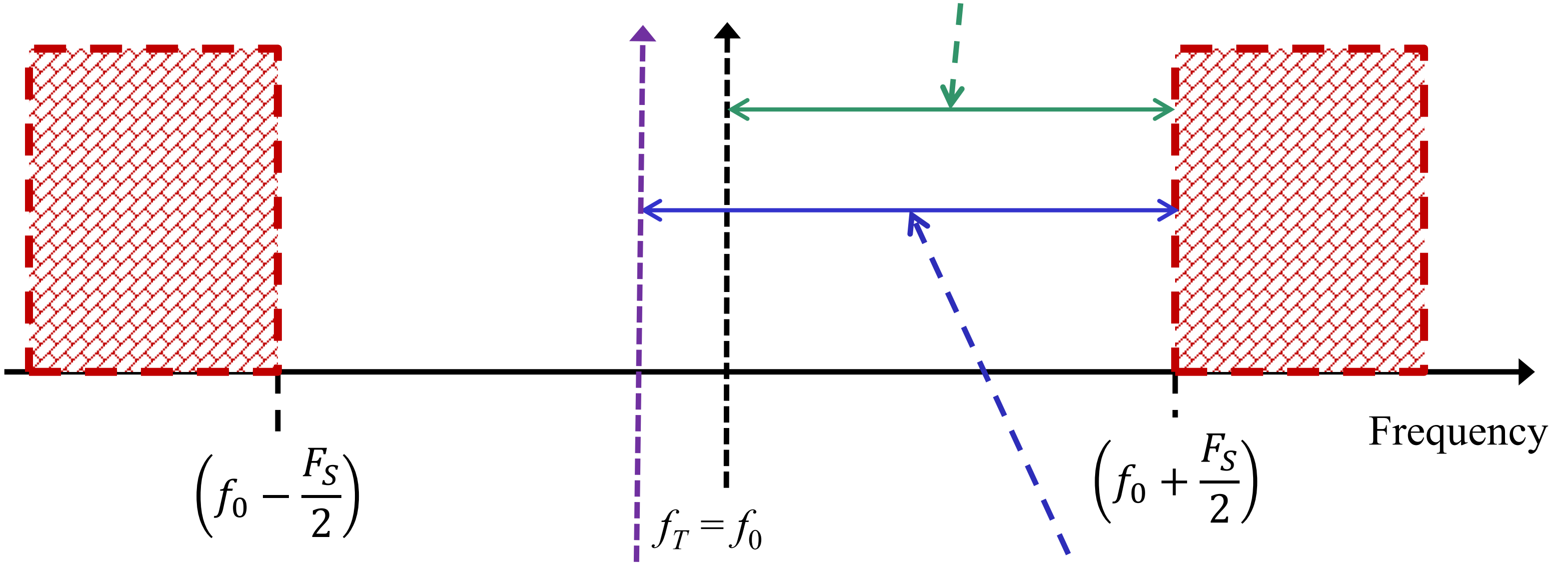
Fixed-filter algorithm

f_0 = Nominal frequency (Hz)
f = Actual fundamental frequency (Hz)
f_T = Tuned frequency (Hz)

Frequency in filter = $(f_{IH} - f_T)$

Minimum f_{IH} (upper) = $\left(f_0 + \frac{F_S}{2}\right)$

Minimum $(f_{IH} - f_T) = \left(f_0 + \frac{F_S}{2}\right) - f_0 = \left(\frac{F_S}{2}\right)$



$f = f_0 - \frac{F_S}{20}$

Maximum $(f_{IH} - f) = \left(f_0 + \frac{F_S}{2}\right) - (f_0 - \frac{F_S}{20}) = \left(1.1 \frac{F_S}{2}\right)$

Mask width is "normal" $\left(\frac{F_S}{2}\right)$ but gain needs to be reduced by $20 \cdot log \left(\frac{1}{1.1}\right)$ = 0.83 dB, at the closest frequency, from what you might expect.

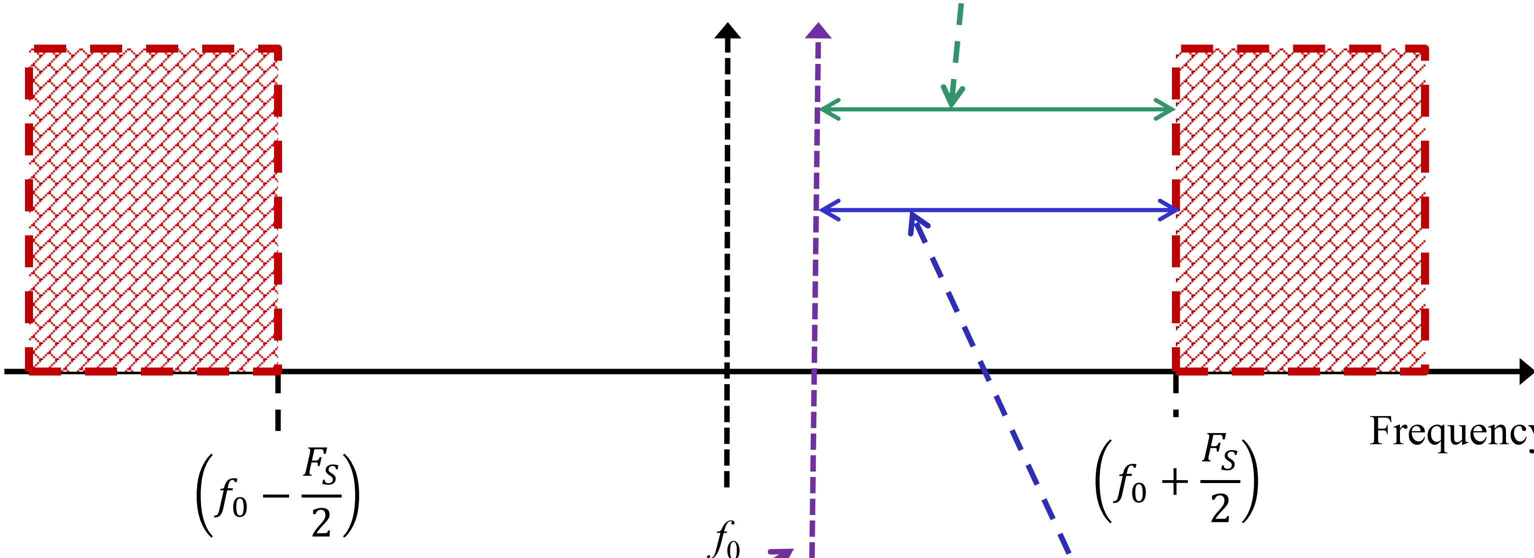
Out-of-Band testing, $f = f_0 + \frac{F_S}{20}$
Frequency-tracking algorithm

f_0 = Nominal frequency (Hz)
f = Actual fundamental frequency (Hz)
f_T = Tuned frequency (Hz)

Frequency in filter = $(f_{IH} - f_T)$

Minimum f_{IH} (upper) = $\left(f_0 + \frac{F_S}{2}\right)$

Minimum $(f_{IH} - f_T) = \left(f_0 + \frac{F_S}{2}\right) - \left(f_0 + \frac{F_S}{20}\right) = 0.9\left(\frac{F_S}{2}\right)$

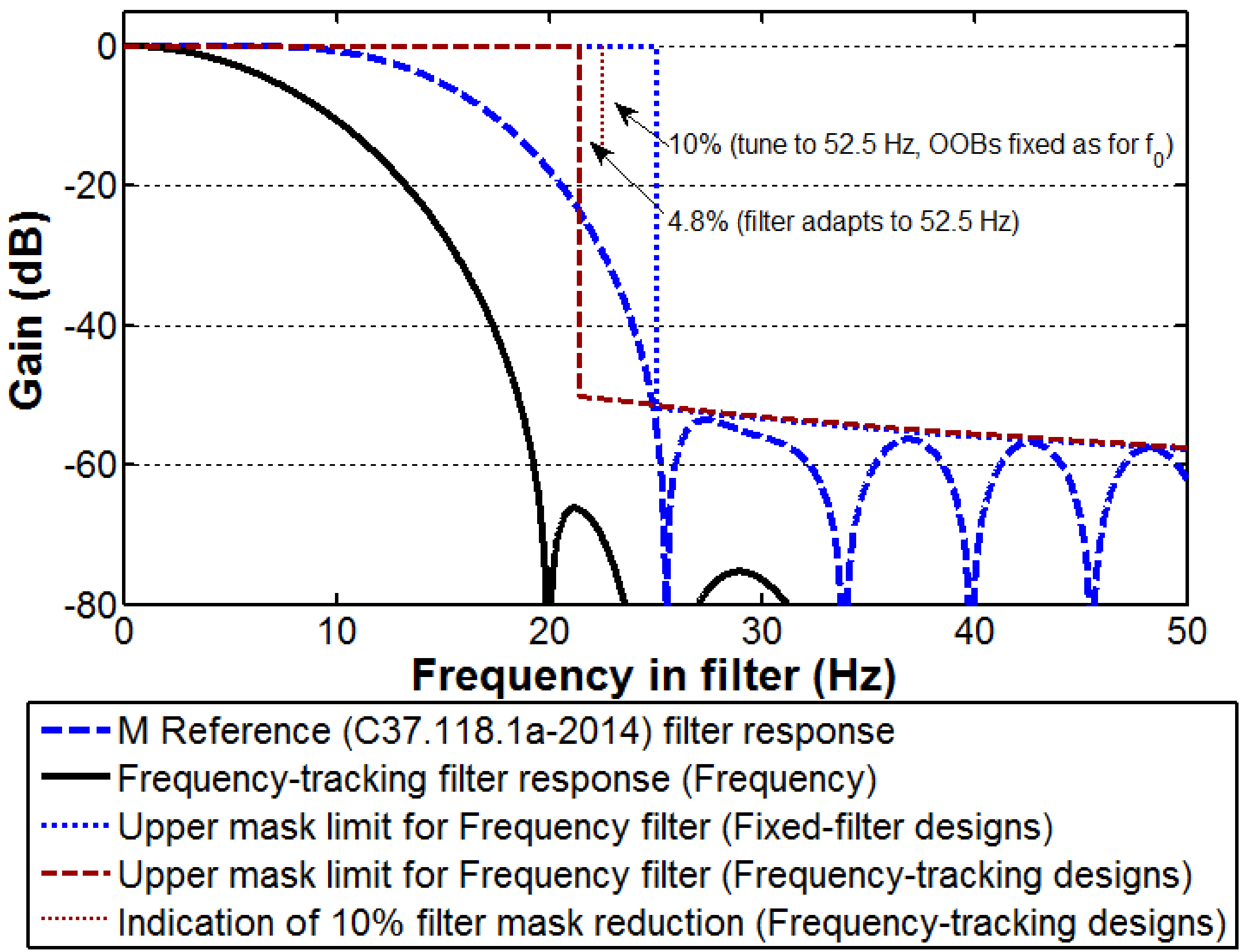


$f = f_T = f_0 + \frac{F_S}{20}$

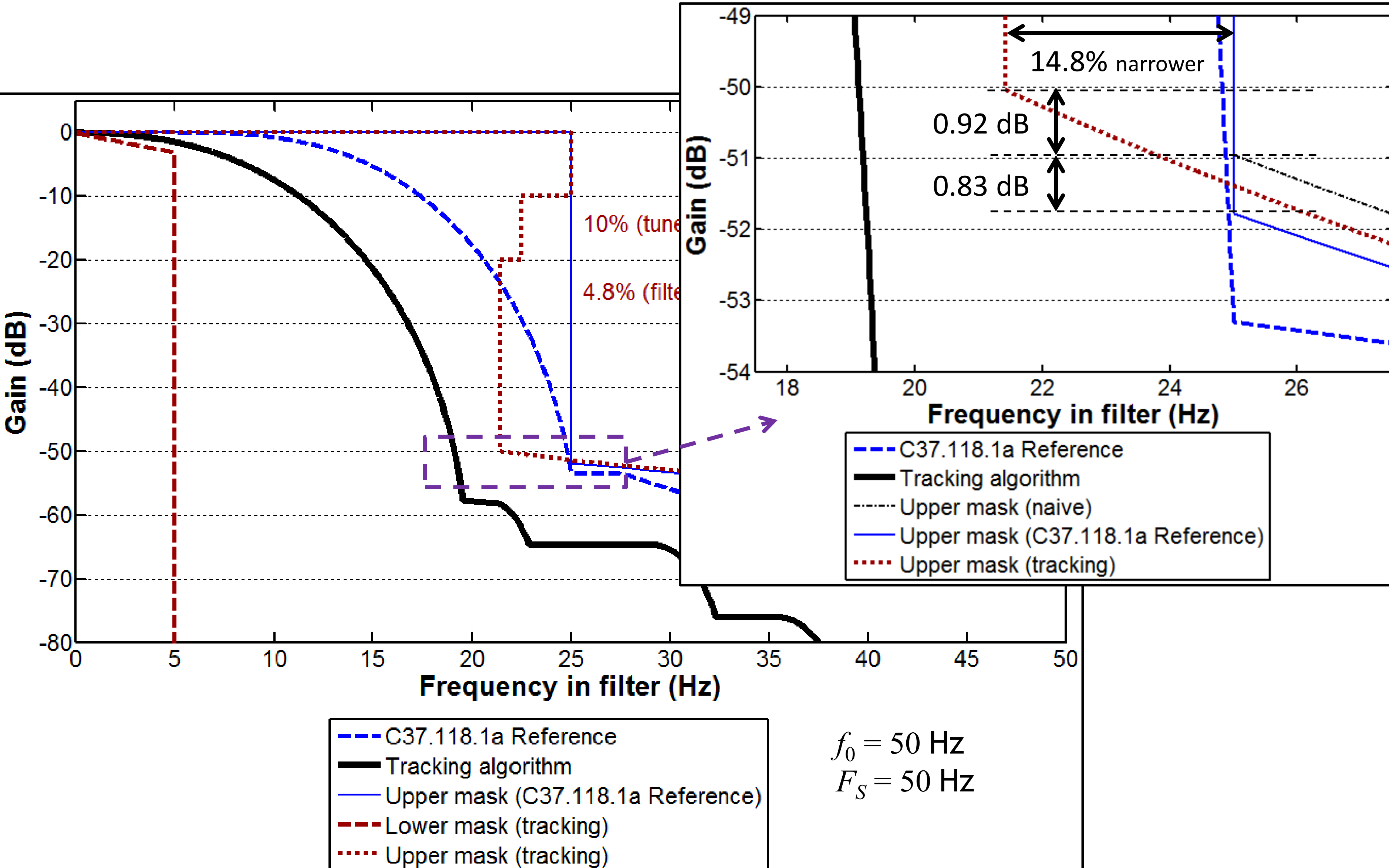
Maximum $(f_{IH} - f) = \left(f_0 + \frac{F_S}{2}\right) - \left(f_0 + \frac{F_S}{20}\right) = \left(0.9\frac{F_S}{2}\right)$

Mask frequency width is reduced by 10% from $\left(\frac{F_S}{2}\right)$ but gain can be $20 \cdot log\left(\frac{1}{0.9}\right)$ = 0.92 dB higher, at the closest frequency, from what you might expect.

Simplified OOB requirements and examples, f_0=50 Hz, F_S=50 Hz

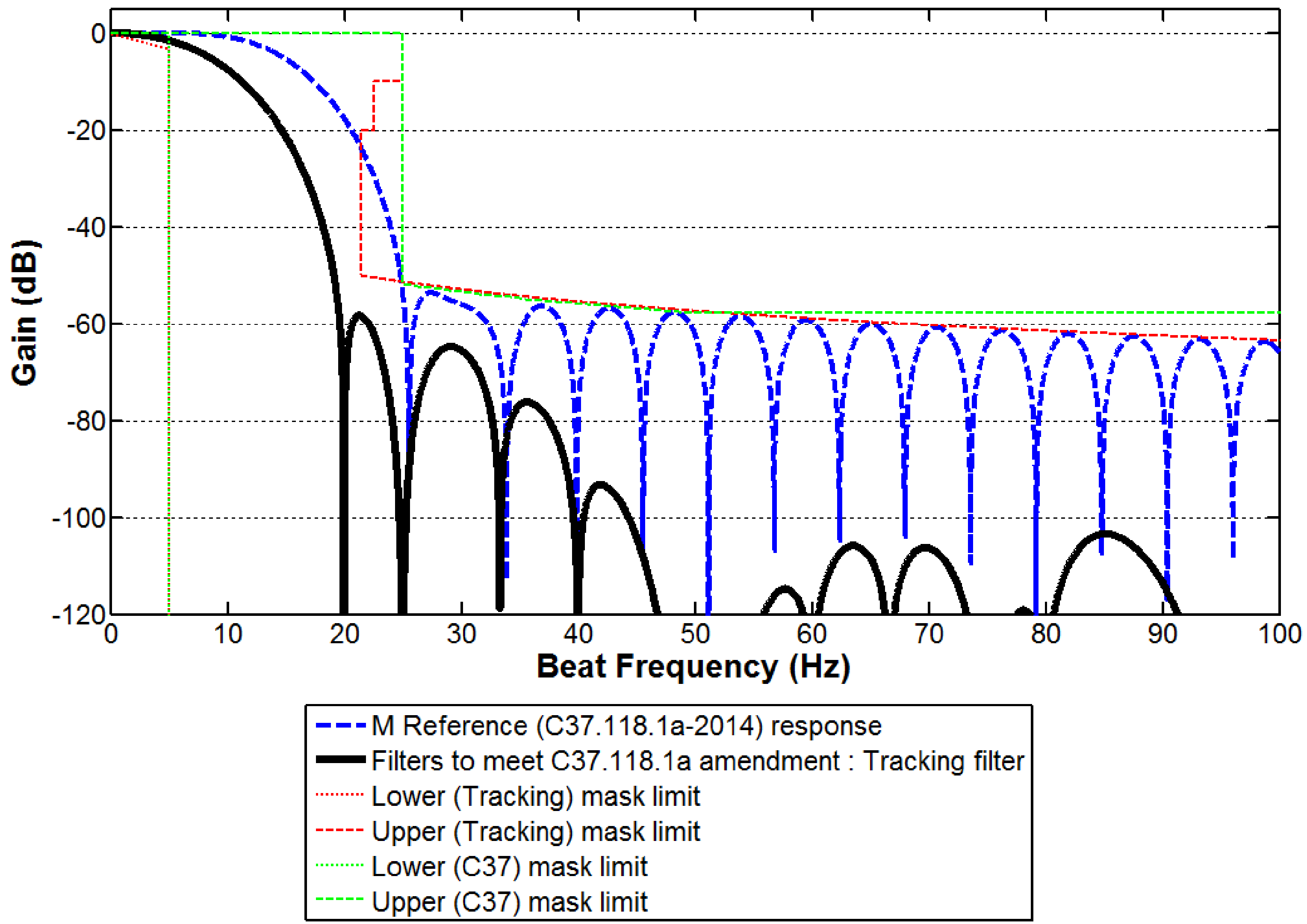


Simplified OOB requirements and examples, f_0=50 Hz, F_S=50 Hz

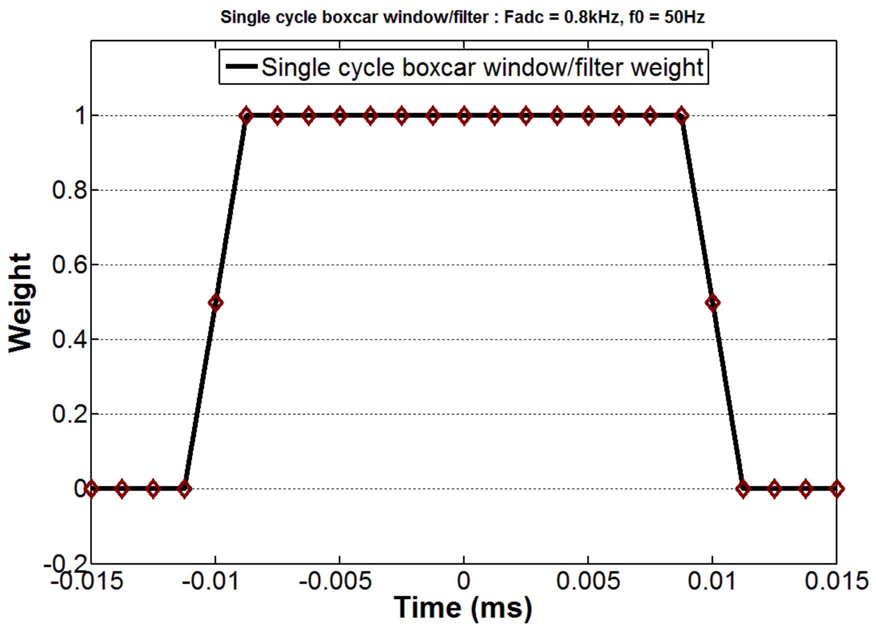


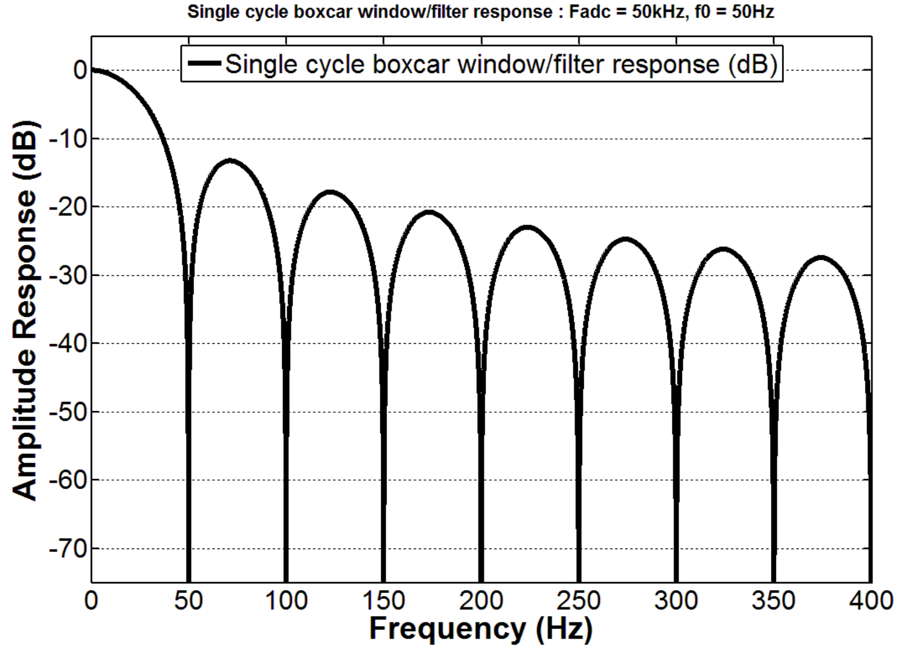
$f_0 = 50$ Hz
$F_S = 50$ Hz

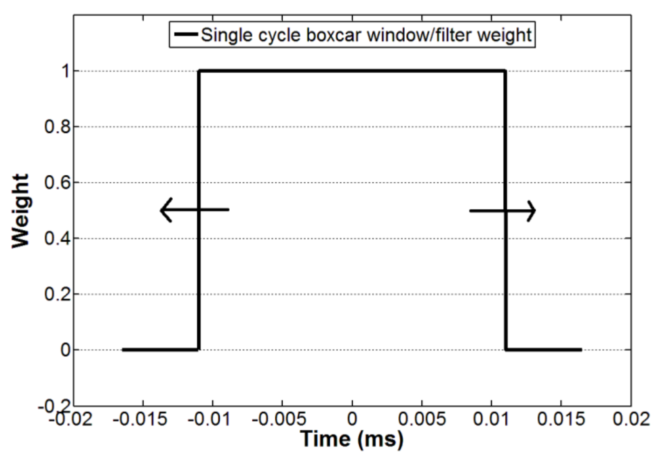
Cascaded boxcar filters, f_0=50 Hz, F_S=50 Hz

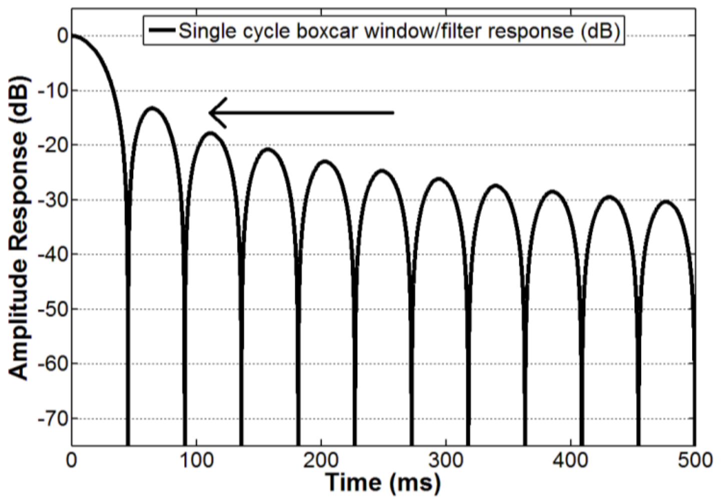


Boxcar filter properties

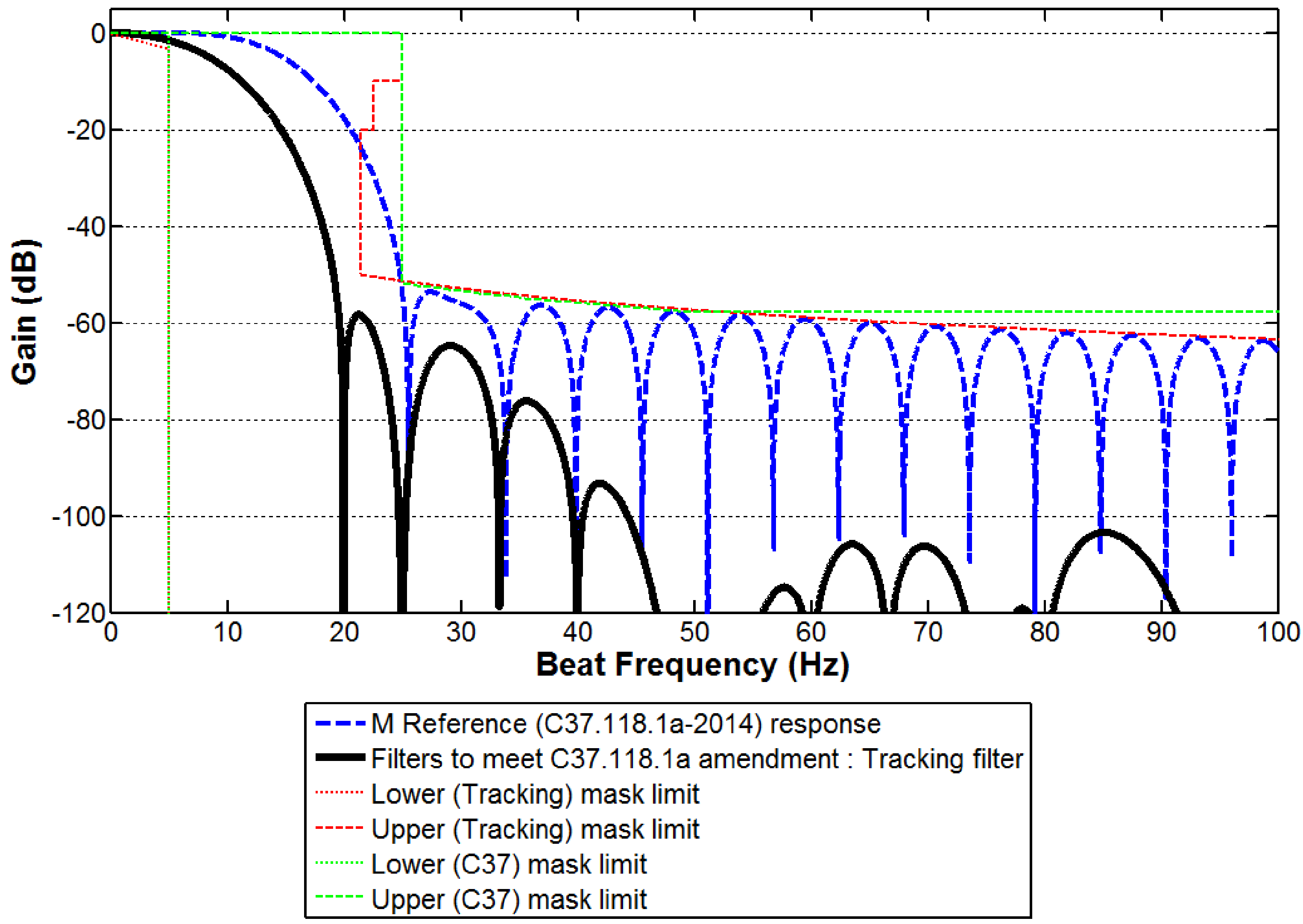




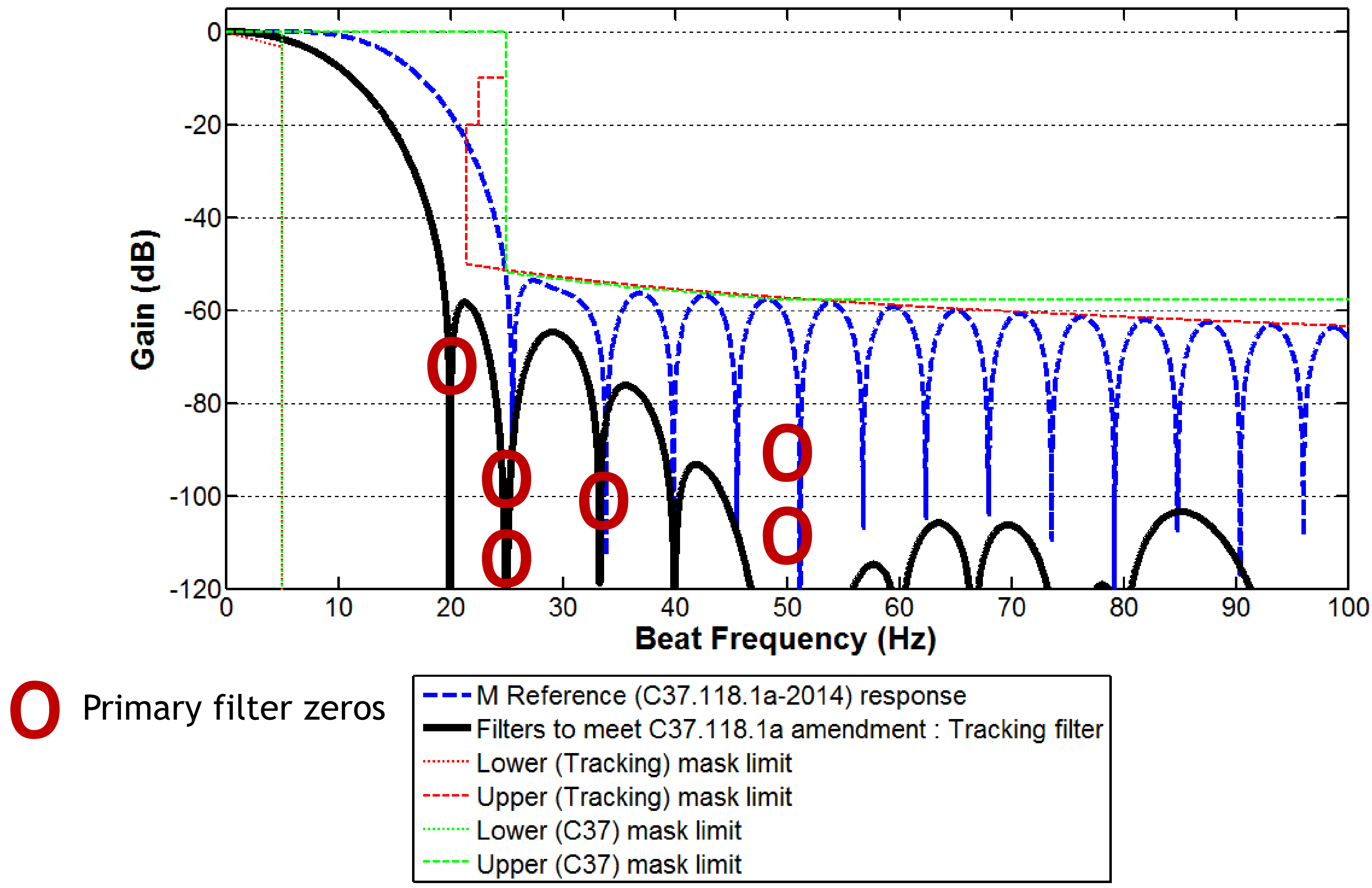




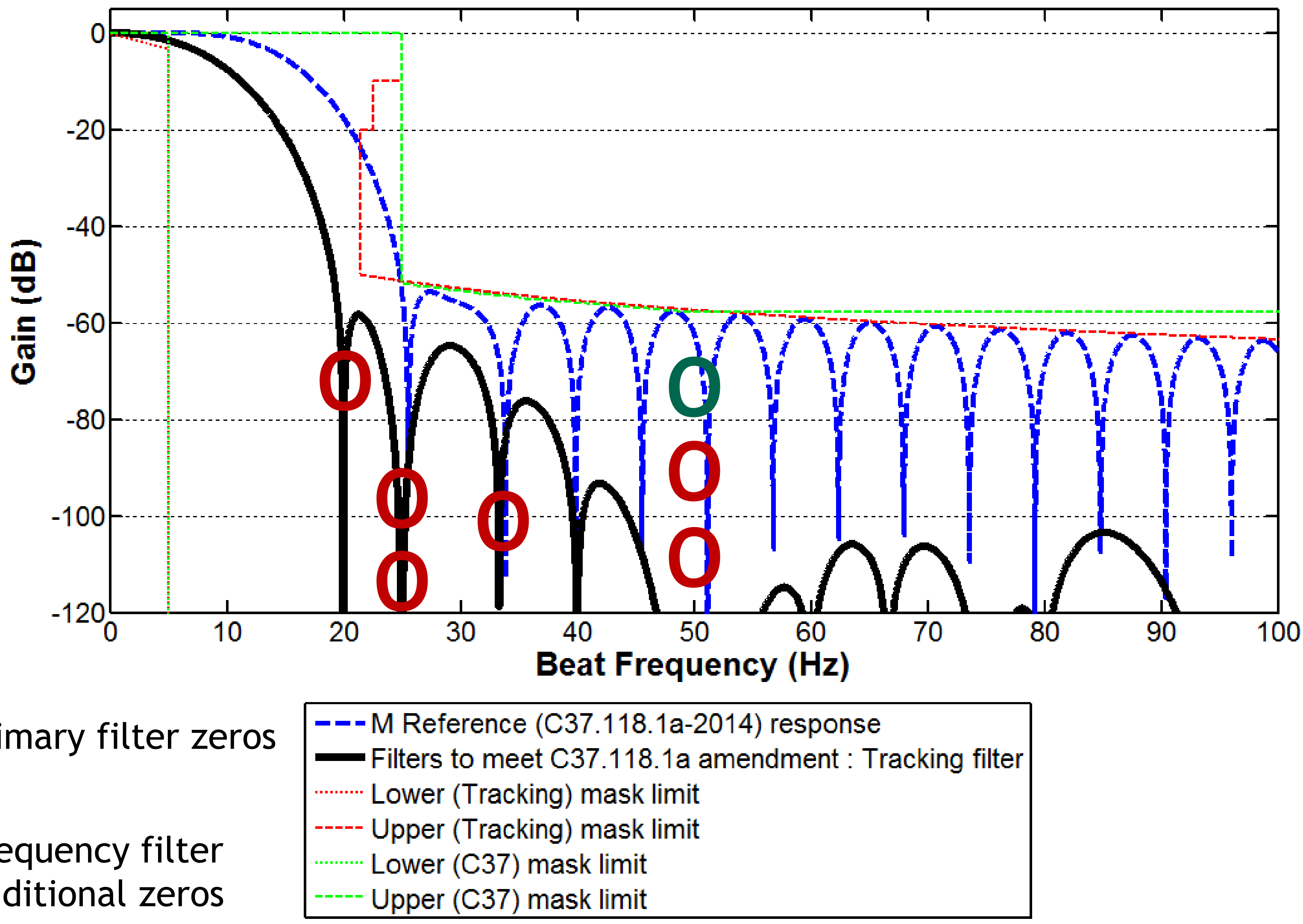
Cascaded boxcar filters example, f_0=50 Hz, F_S=50 Hz



Cascaded boxcar filters example, f_0=50 Hz, F_S=50 Hz



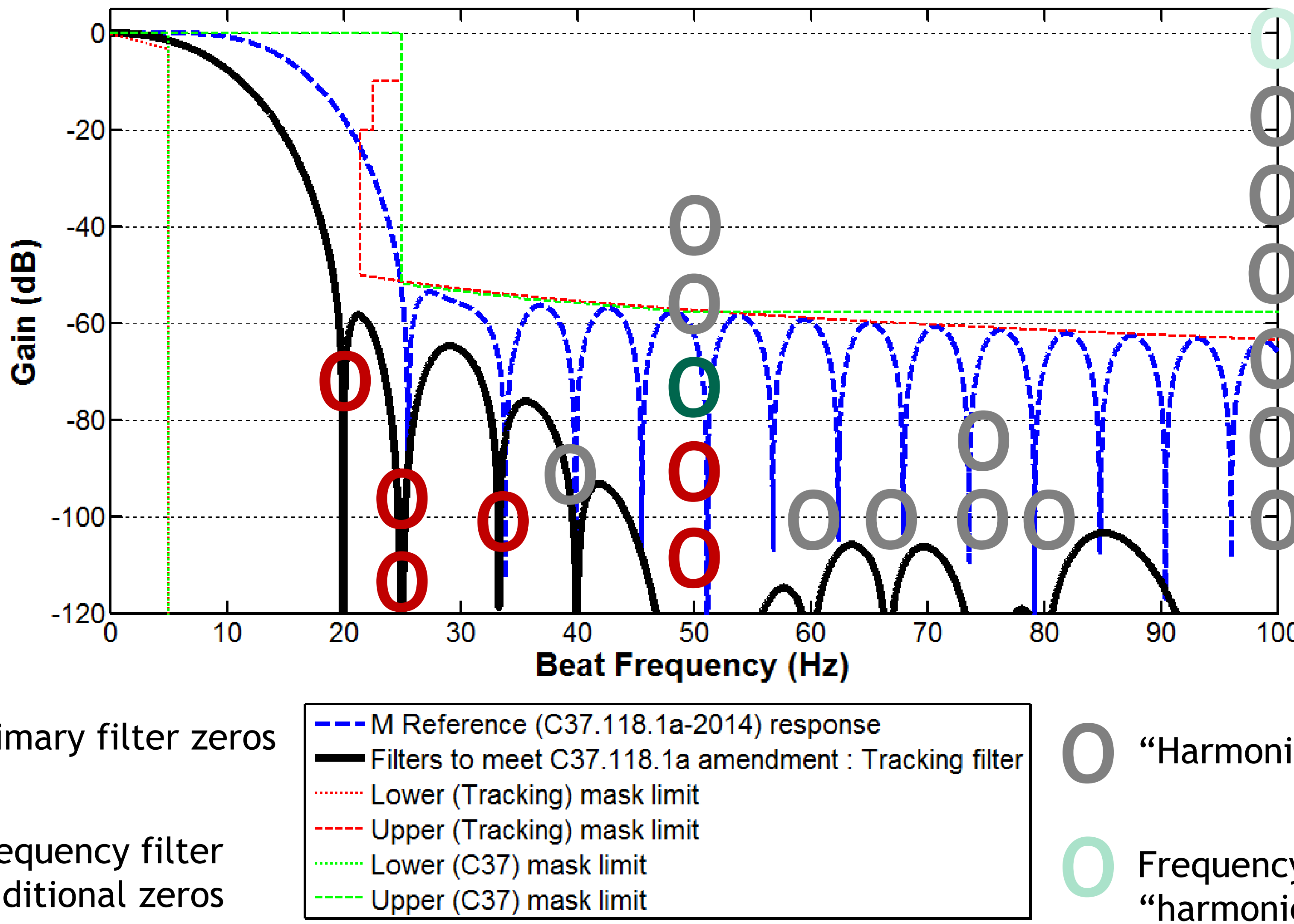
Cascaded boxcar filters example, f_0=50 Hz, F_S=50 Hz



O Primary filter zeros

O Frequency filter Additional zeros

Cascaded boxcar filters example, f_0=50 Hz, F_S=50 Hz



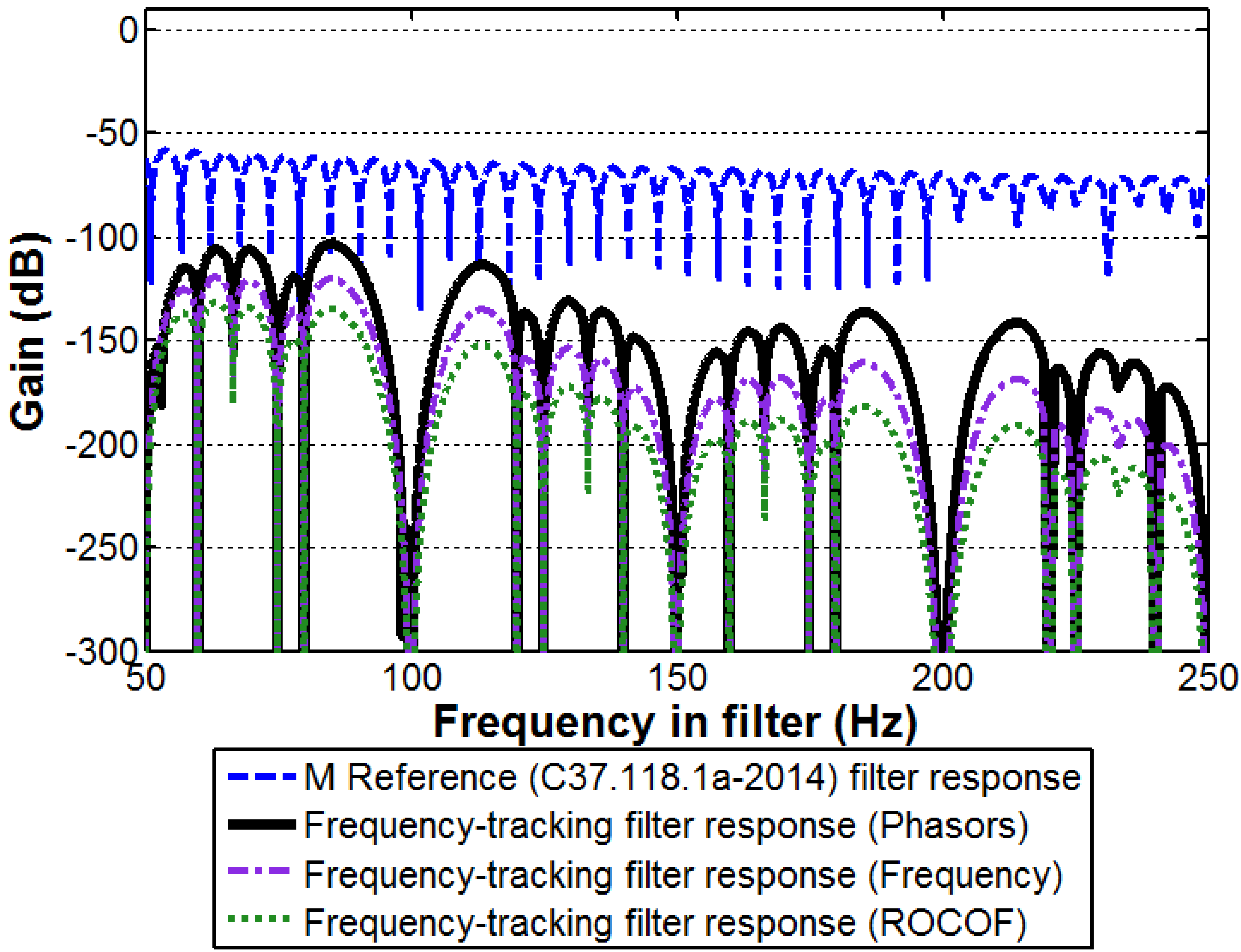
O Primary filter zeros

O Frequency filter Additional zeros

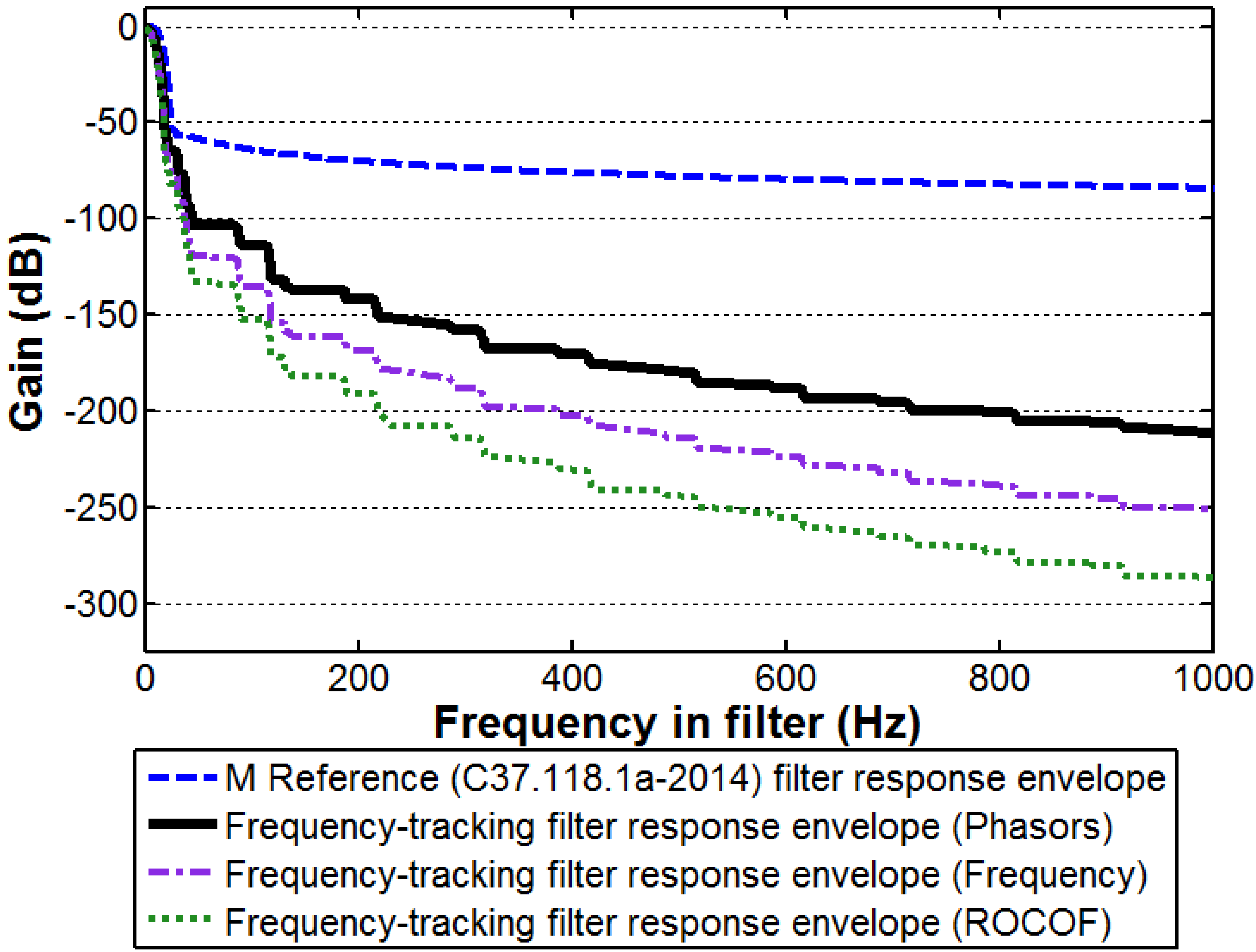
O "Harmonic" zeros

O Frequency filter "harmonic" zeros

Cascaded boxcar filters example, f_0=50 Hz, F_S=50 Hz



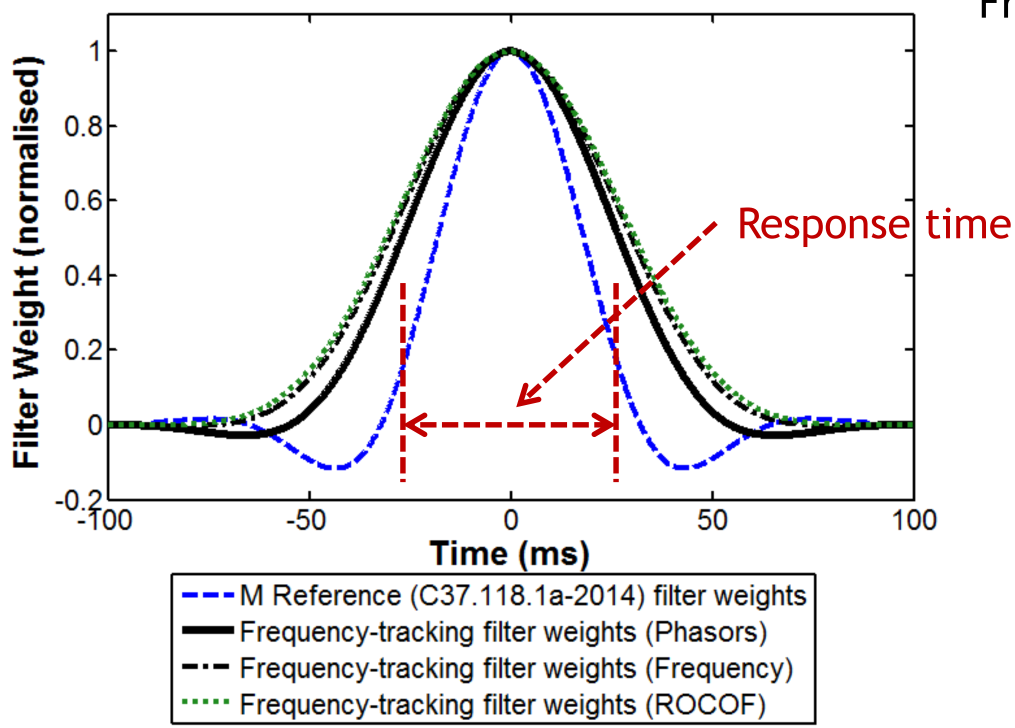
Cascaded boxcar filters example, f_0=50 Hz, F_S=50 Hz



Cascaded boxcar filters example, f_0=50 Hz, F_S=50 Hz

10 cycles, ~200ms at f=50 Hz
Latency ~5 cycles, ~100ms at f=50 Hz

Additional Frequency (and ROCOF) filtering



Example software architecture

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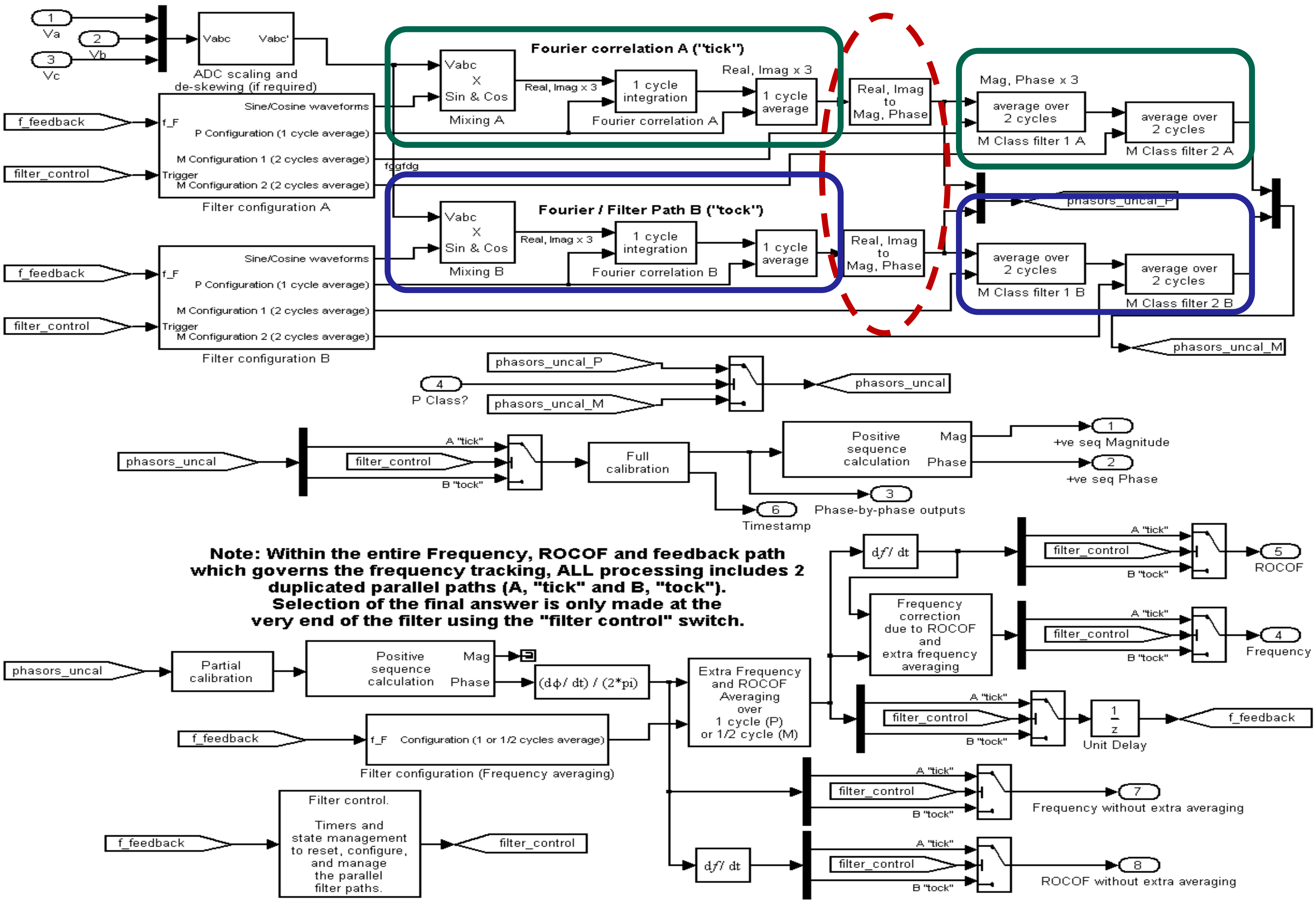
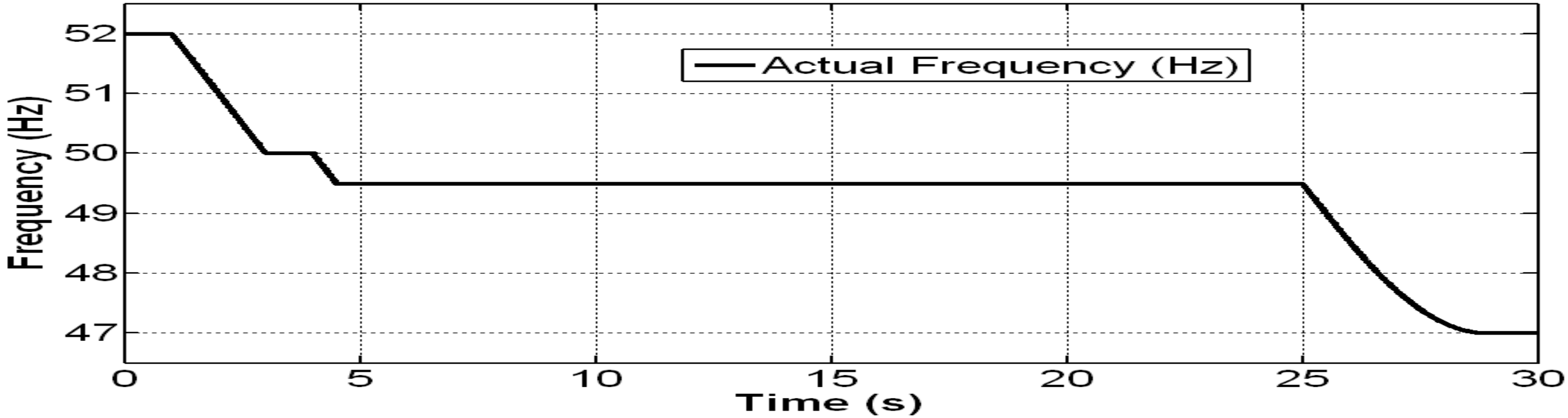


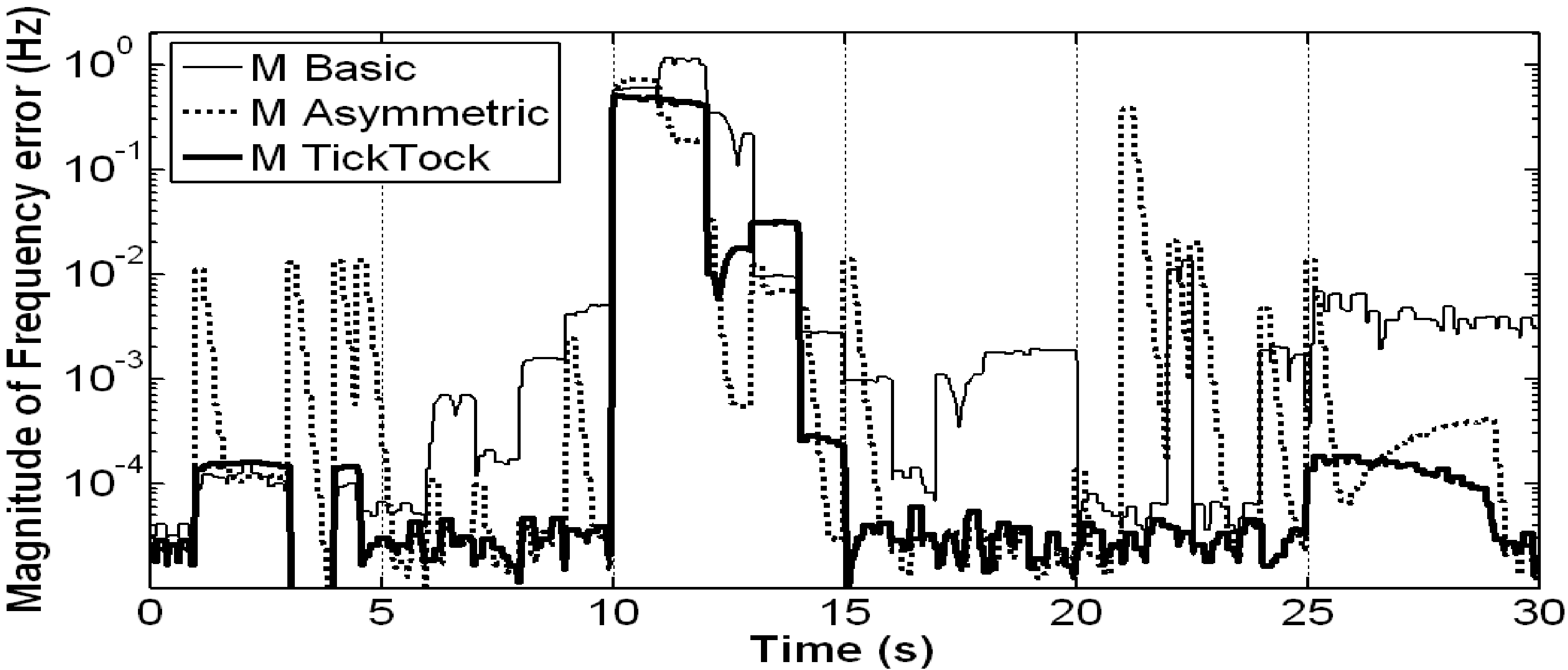
Code execution speed

- 30-60μs Typical execution time per frame for M class PMU (Motorola MVME5500). Supports >10kHz reporting.
- Calculation rate does NOT increase for longer-window (lower reporting rate) devices, as long as the NUMBER of cascaded boxcar filter sections is kept constant.
  - But fast-access memory requirement does ($\propto$ Window length).
- Can easily be extended to "Harmonic PMU" applications.
  - # Calculations expand $\propto$N harmonics, memory expands $\propto$N harmonics and $\propto$ Window length

- Compare with
  - Least Squares and "TFT" algorithms, # calculations proportional to window length
  - FFT algorithms for harmonic PMUs, # calculations proportional to (window length)*log(window length)
  - Kalman filter methods, # calculations proportional to the number of filter zeros squared (matrix multiplications).

Non-standard tests and real-world conditions





Unfinished work - Increased fault tolerance for frequency and ROCOF - 27th August 2013 example – P class

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Power outage in Glasgow after worker hits live cable

The worker was injured after making contact with a live cable on a building site in Allan Glen Place

A worker has been injured after making contact with a live cable at a building site in Glasgow city centre.

Police Scotland said there was a short power outage in the north of the city following the incident at Allen Glen Place at about 12:00 on Tuesday.

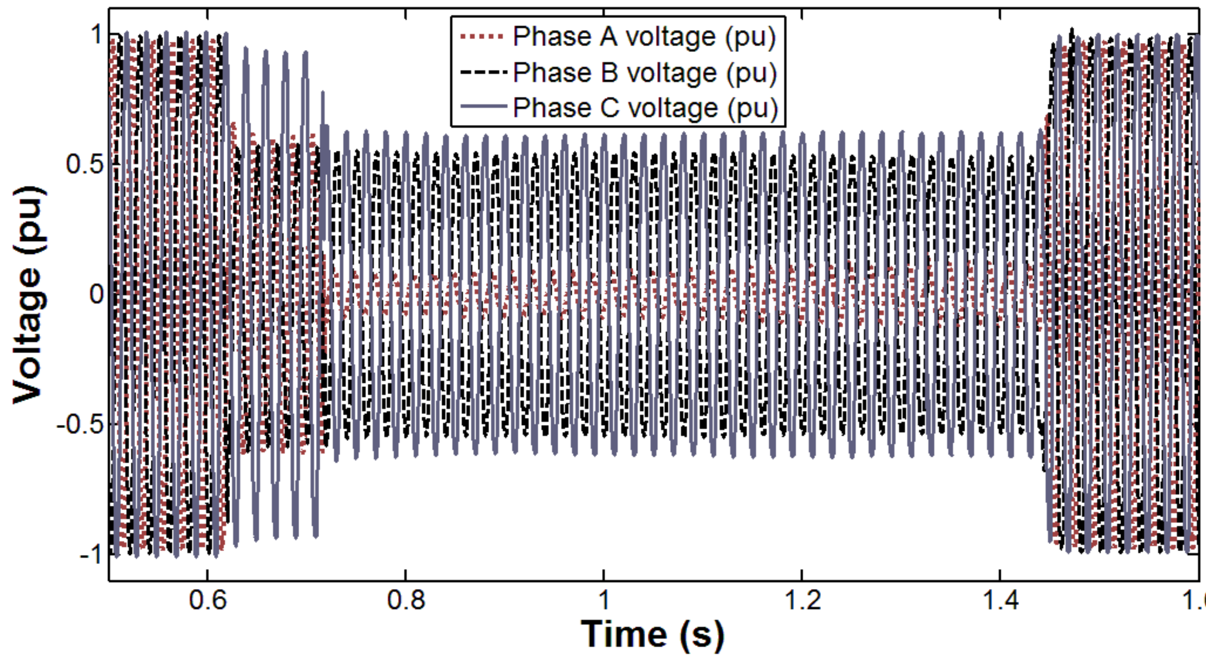
The injured man was taken to nearby Glasgow Royal Infirmary. Details of his condition are not yet known.

Emergency services remain at the scene. The incident has been reported to the Health and Safety Executive.

Scottish Power officials are also at the scene.

It is understood that people in the area reported hearing a "loud bang and explosion" when the incident occurred.

The power supply was restored a short time later.



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Power outage in Glasgow after worker hits live cable

The worker was injured after making contact with a live cable on a building site in Allan Glen Place

A worker has been injured after making contact with a live cable at a building site in Glasgow city centre.

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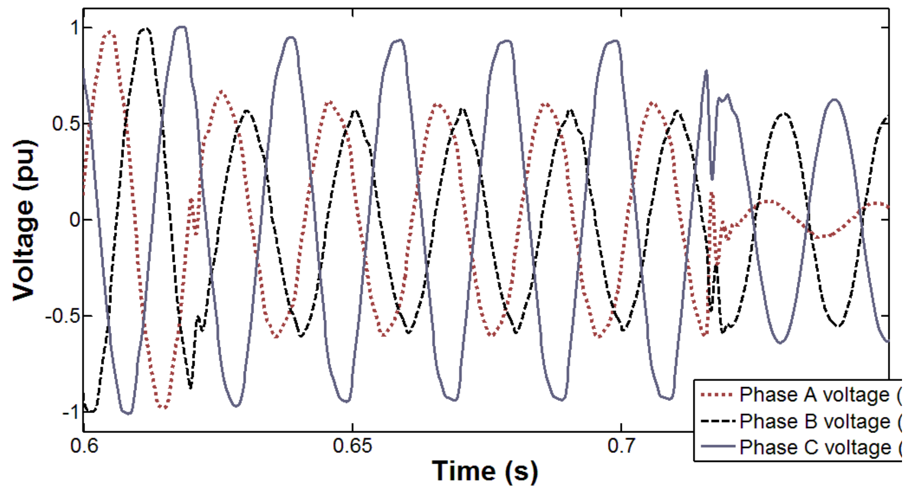

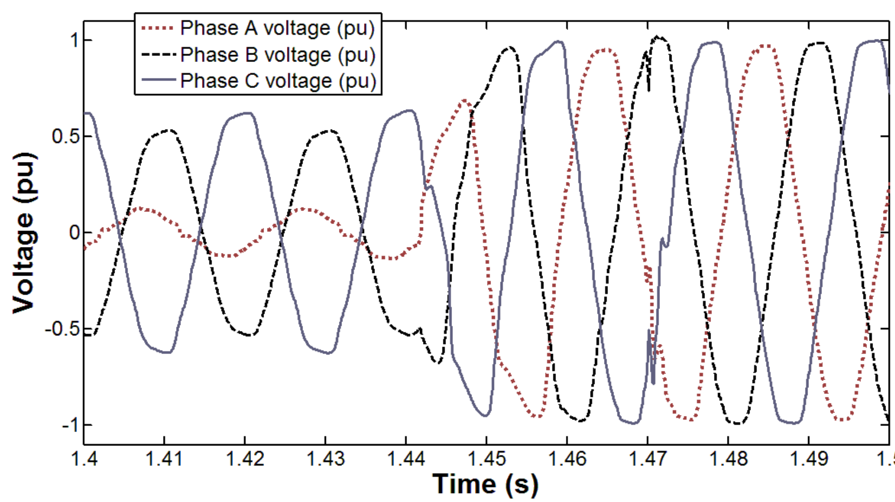

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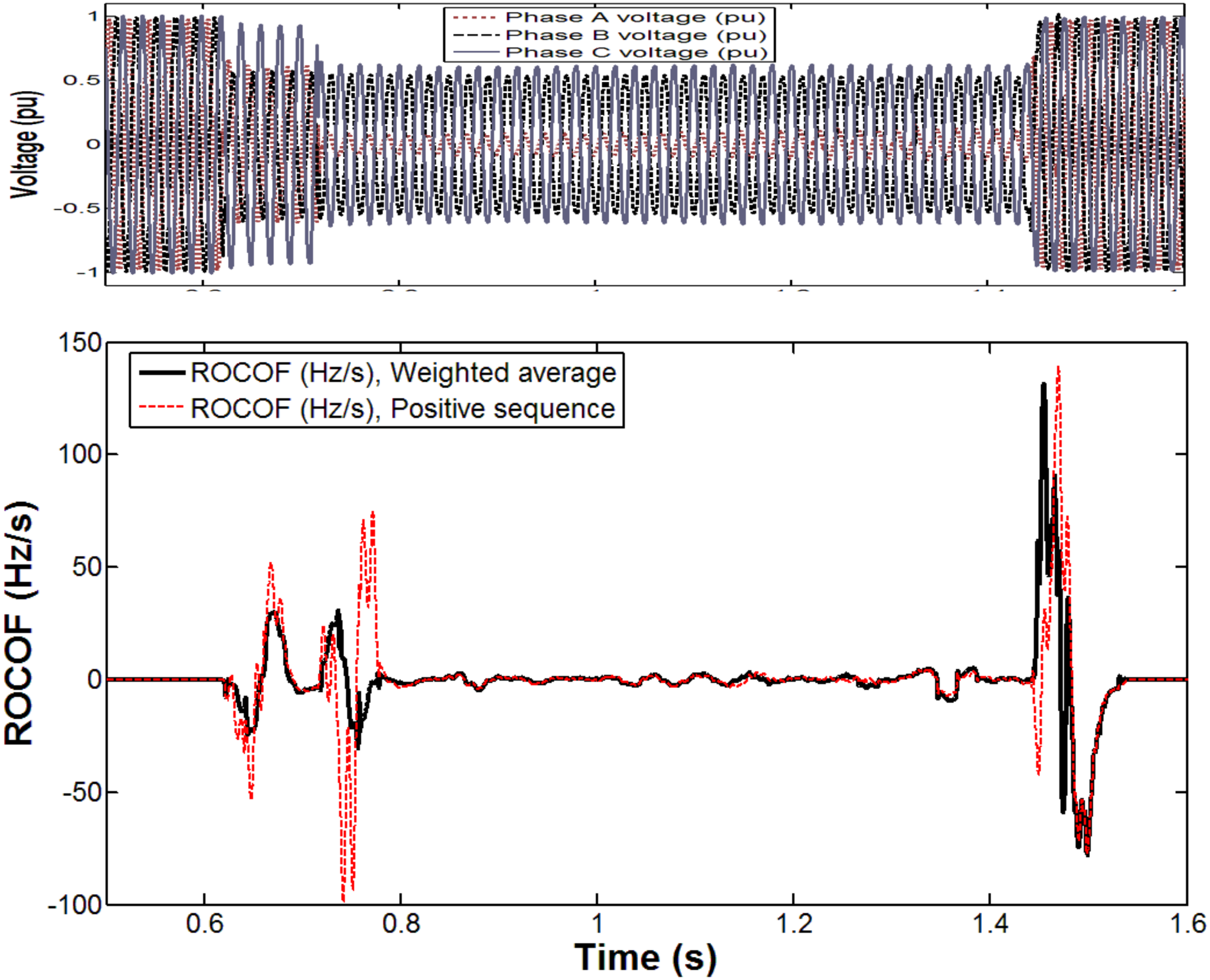

Future considerations/work:

- Implement in hardware!
- Continuing input to standards development.
- Accurate revenue metering.
- Synchronised Power Quality assessment and PQ “metering”!
- Combinations of adaptive and fixed boxcars to provide “Uniform Aggregated Weighting” (Welch’s method) via repeated windows at fixed (i.e. 20ms) intervals, while also providing adaptive-zero-placement for off-nominal frequency.
- Integrating PMU algorithms within HVDC controllers?
- Aggregation of PMU ROCOF data across a geographically wide network to determine “system ROCOF” and required “inertial” responses.
  - “Enhanced Frequency Control Capability (EFCC)” with National Grid, Alstom, Belectric, Centrica, Flextricity & University of Manchester.

END