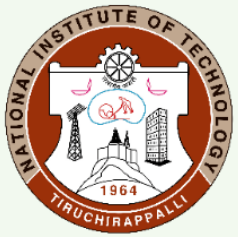

20th National Power Systems Conference
NPSC 2018
"TOWARDS A SUSTAINABLE ENERGY FUTURE
THROUGH EFFICIENT, SMART AND GREEN TECHNOLOGIES"

Filtering of Noisy Frequency Measurements Using Coherence between Multiple Measurements

Paper ID: 1570467149

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December 15, 2018

Introduction

- Modern power systems: Distributed generation and storage.
- Power electronic interface: Controlled power injection.
- Distributed generation: can improve small-signal stability margins[1].
- Objective: Distributed control of power systems.
- Power oscillation damping: Bus frequency measurements.
- Renewable energy sources: Distribution level integration.
- Bus frequency: noisy and distorted due to harmonics[2].

Can bus frequency measurements be filtered properly even in lower voltage levels to accurately identify the swing frequencies?

[1] M. Singh, A. Allen, E. Muljadi, and V. Gevorgian (2014), "Oscillation damping: A comparison of wind and photovoltaic power plant capabilities"

[2] O. Samuelsson (2001), "Load modulation for damping of electro-mechanical oscillations"

Conventional Filtering

- Objective:
  - Identify dominant mode frequencies.
  - Minimal phase lag due to filtering (for control applications).
- Ambient condition: low signal-to-noise ratio (SNR).
- An example: Butterworth low-pass filter:
  - Lower order: lesser attenuation.
  - Higher order: higher phase-lag.
- Alternative approach:
  - Identify the system trends from historian data.
  - Allow selective frequency components to pass.
  - Negligible phase lag in the filter pass-band components.

Correlation between Measurements

- Measurements: Output + Noise.

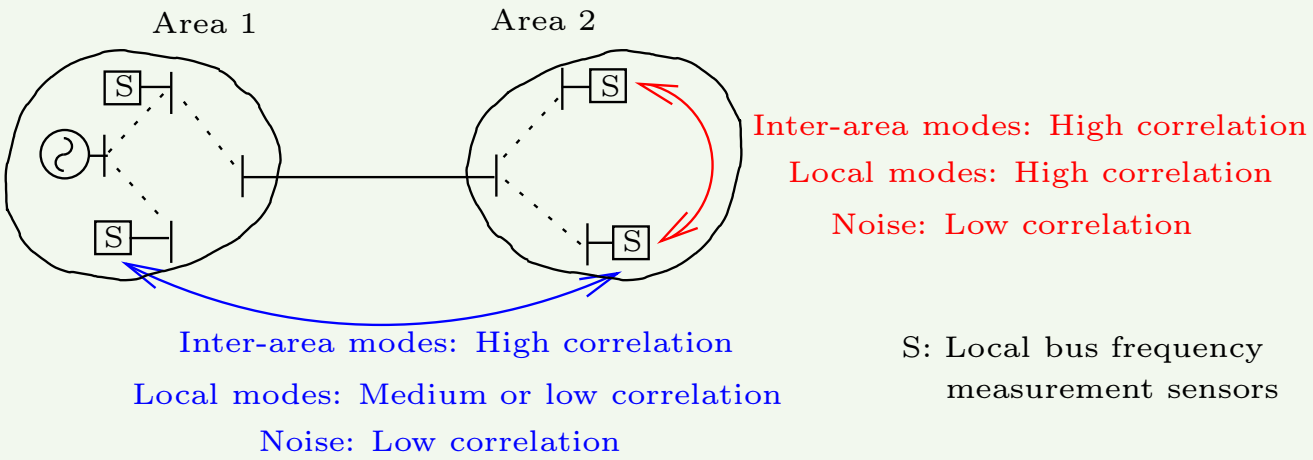


Figure: Correlation between multiple modes

- Multiple measurements (non-local signals using WAMS): expected to be correlated at the system frequencies.
- Coherence function[3]: measure of correlation between two signals.

[3] Bendat and Piersol, Random data: analysis and measurement procedures

Coherence Based Filtering

- Coherence function: Normalized measure of correlatedness.
- Correlation: Correlated at a frequency f if $\geq$ threshold.
- Identify correlated frequency components using historian data.

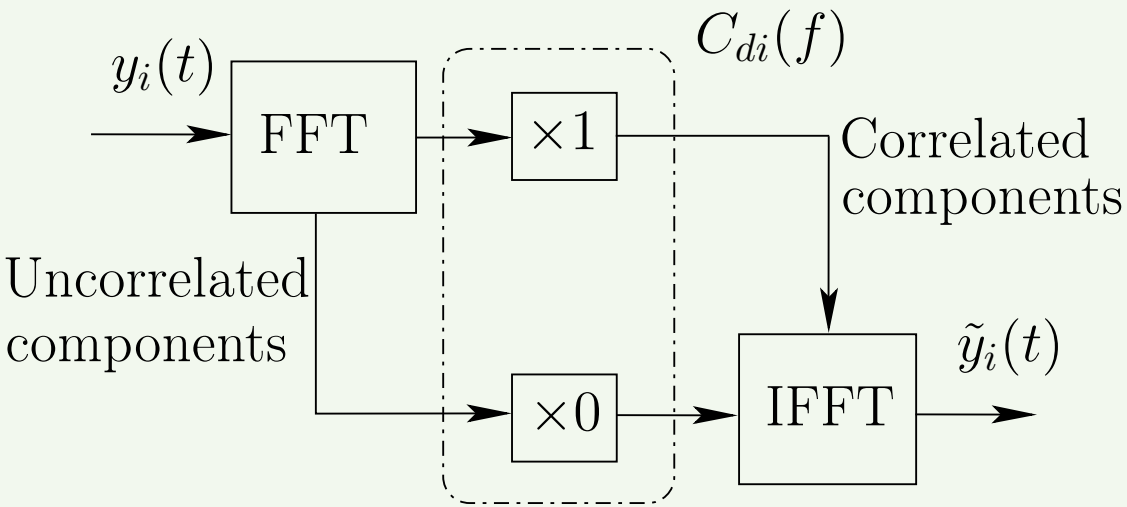


Figure: Coherence based filtering

Application in Power Systems

- Non-linear system: past data at multiple operating points.
- Coherence function: Requires non-local measurements.
- Coherence based filter: Represented as an FIR filter.
- Real time filtering: Requires only local measurements.

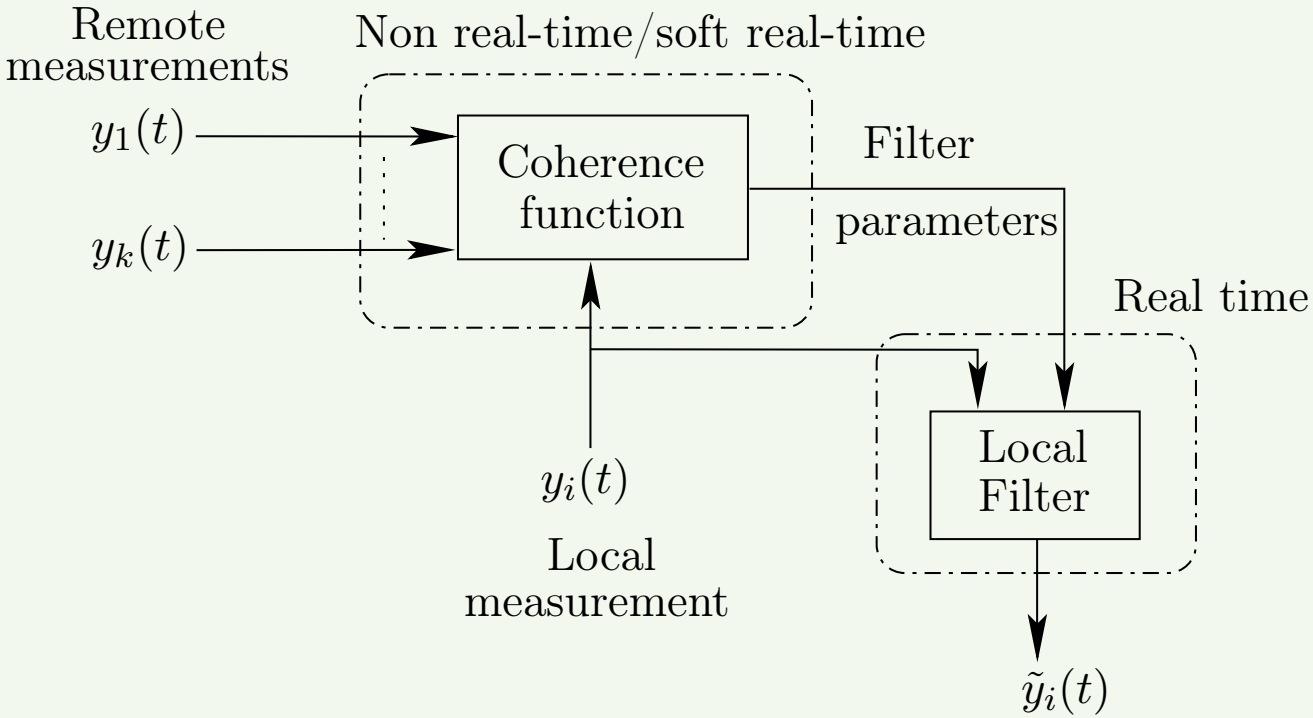


Figure: Schematic of the filtering process

Damping Controller

- Bus frequency measurement: needed for distributed damping controllers, frequency based load-shedding.
- Objectives:
  - Identify oscillations accurately without significant phase delay.
  - Do not track fast changes (glitches).

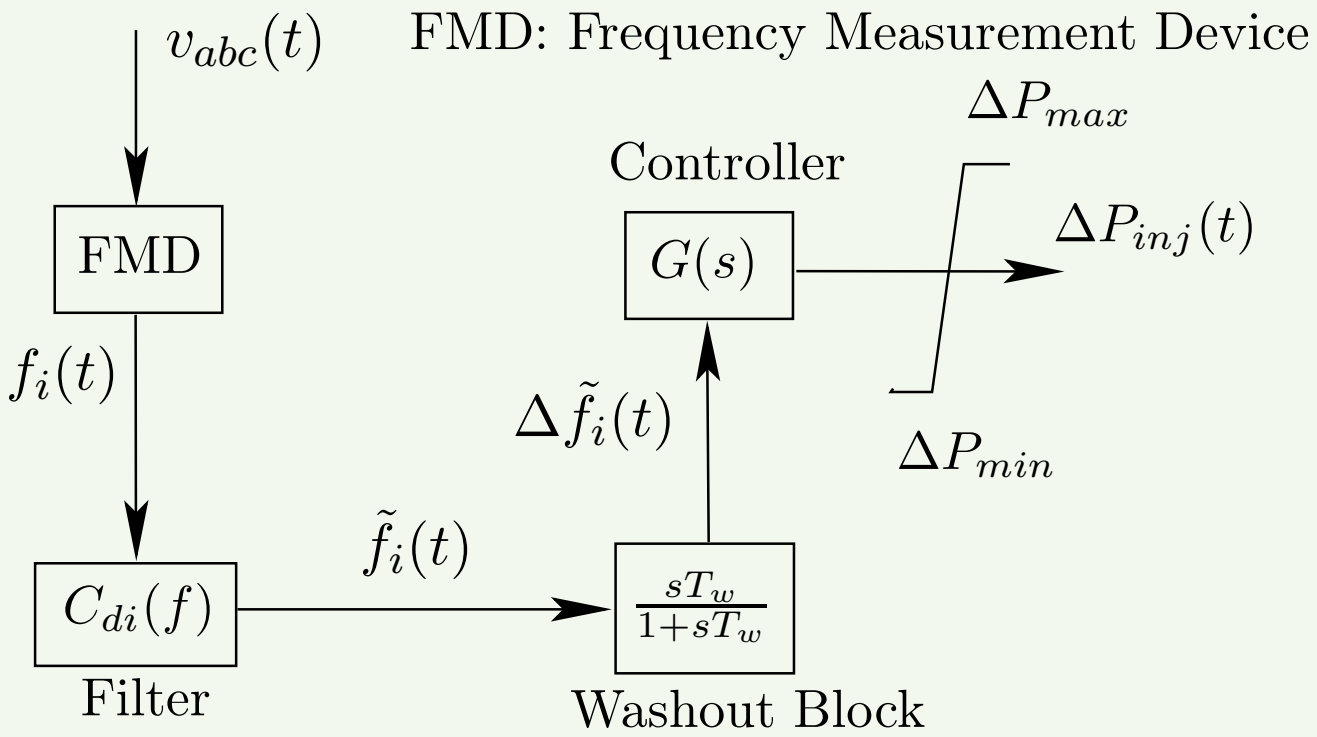


Figure: Coherence filter based distributed damping controller

Real Time Filtering Capability

- Only local measurements are needed: Robust to communication failure and cyber threats.
- Coherence function estimation: Computationally expensive but offline.
- Filtering process: $2n$ flops, $\mathcal{O}(n)$ complexity, where n is inversely proportional to the frequency resolution.
- Filtering delay: Delay for the $2n$ flops, almost negligible with fast DSP boards.
- Centralized control algorithm: Periodically tune the filter parameters using recent measurements.

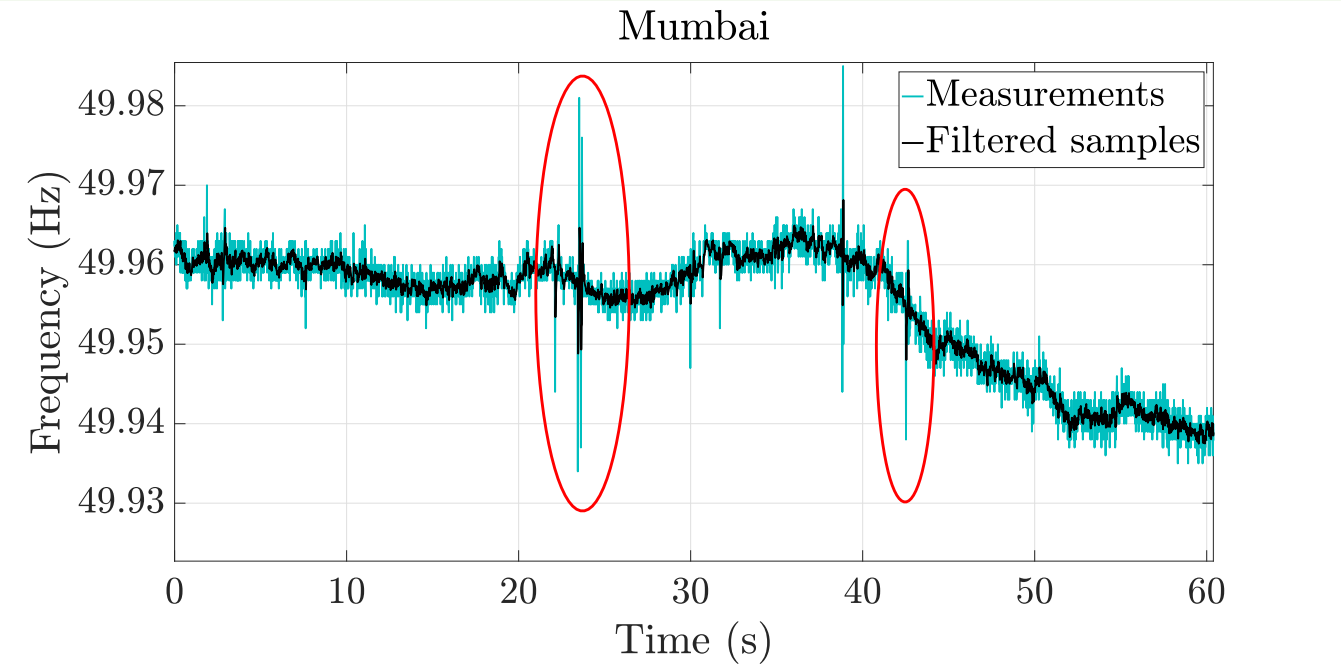
Case Study: Indian Grid

- Frequency measurements from distribution voltage level[4]: `www.ee.iitb.ac.in/~anil`
- Three locations are considered: Mumbai, Kanpur and Kharagpur.
- Sampling rate: 50 Hz.
- Frequency resolution for correlation check: 0.01 Hz.
- Number of data points needed for filtering (n): 5001.
- For brevity, we shall present here the studies of Kharagpur only.

[4] K. A. Salunkhe, G. Gajjar, S. A. Soman, and A. M. Kulkarni (2014), "Implementation and applications of a Wide Area Frequency Measurement System synchronized using Network Time Protocol"

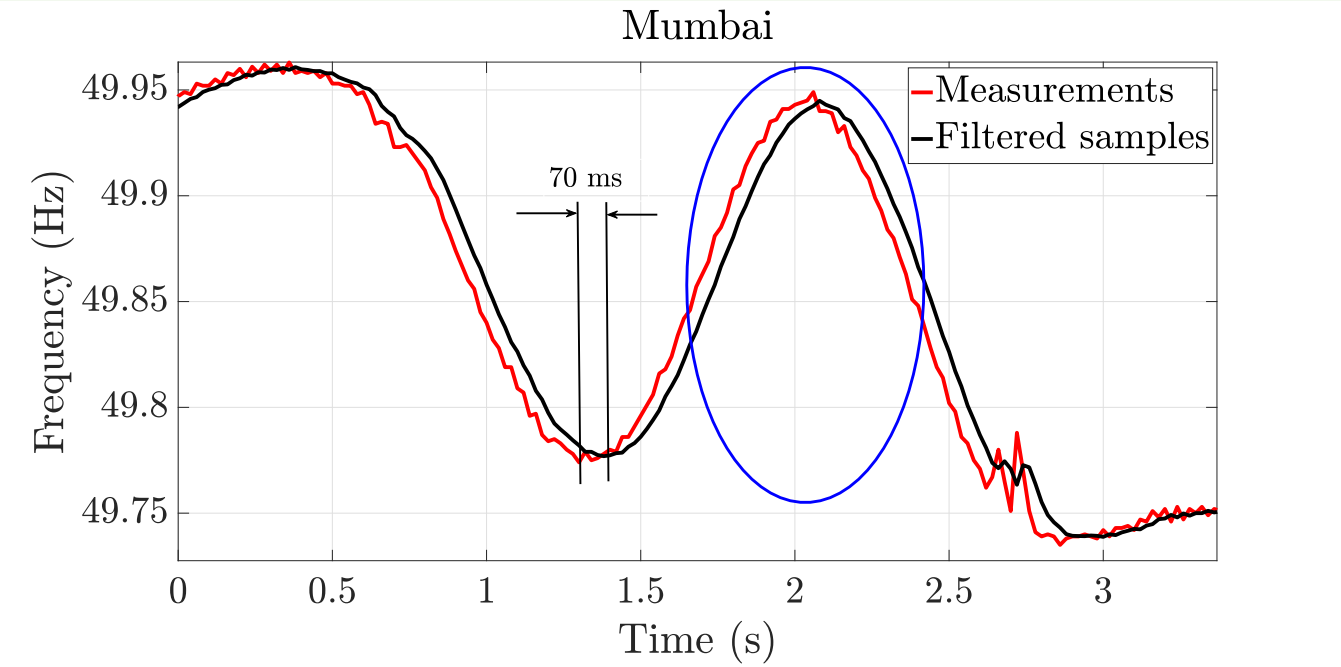
Low Pass Butterworth Filter

- First order low pass Butterworth filter: cut-off $\approx$ 3 Hz.



- Sudden spikes in the frequency measurements are tracked.
- Causes unnecessary switching of the devices.

Low Pass Butterworth Filter



- Significant phase lag $\approx 25^\circ$ at 1 Hz $\implies \approx$ 70 ms.
- Requires additional phase compensation for control applications.

Coherence Function

- Coherence function calculated @ resolution of 0.01 Hz.

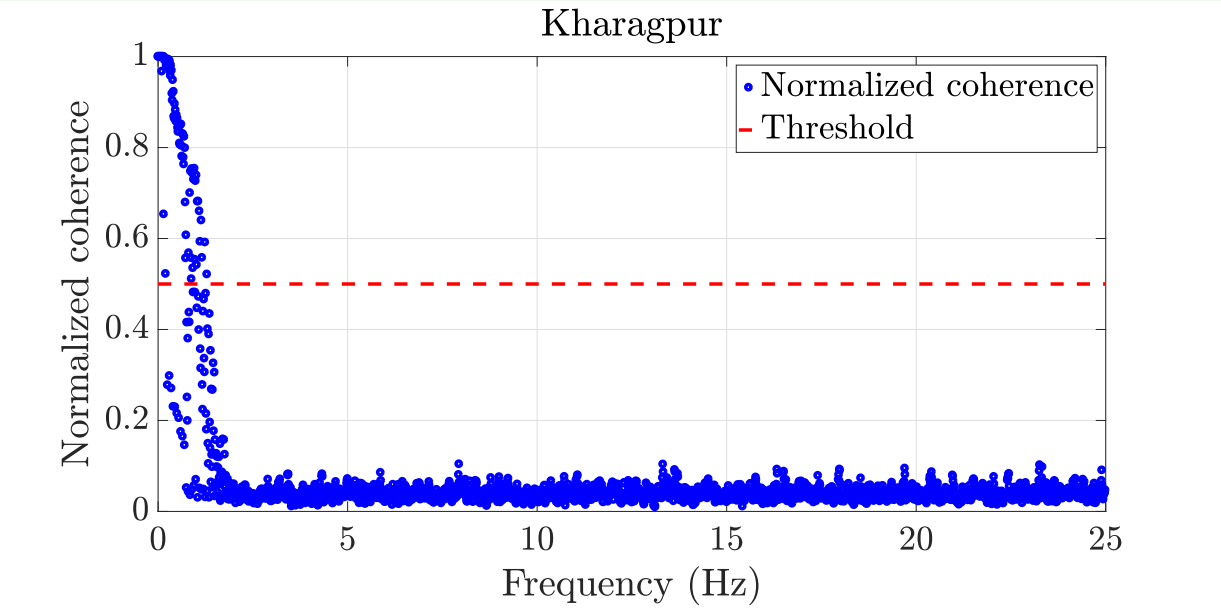


Figure: Coherence function

- Observations: Correlated frequency components are only up to around 2–3 Hz (consistent with the range of swing dynamics).

Filtering of Ambient Measurements

- Ambient measurement window:
  7:21:00 PM - 7:21:40 PM on 12.03.2014

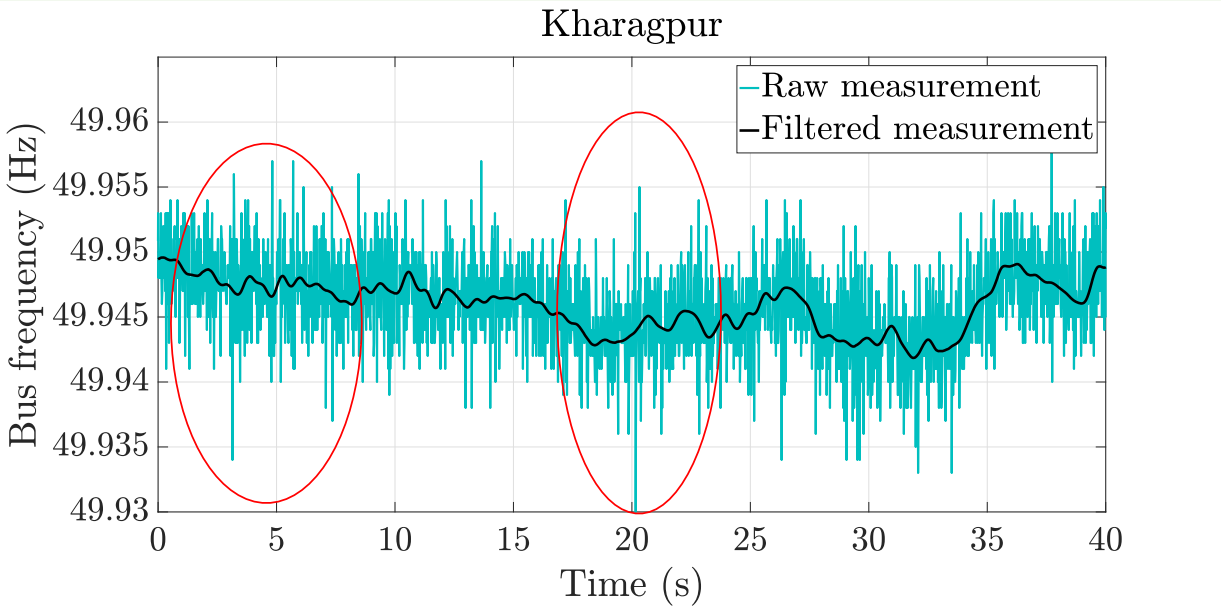
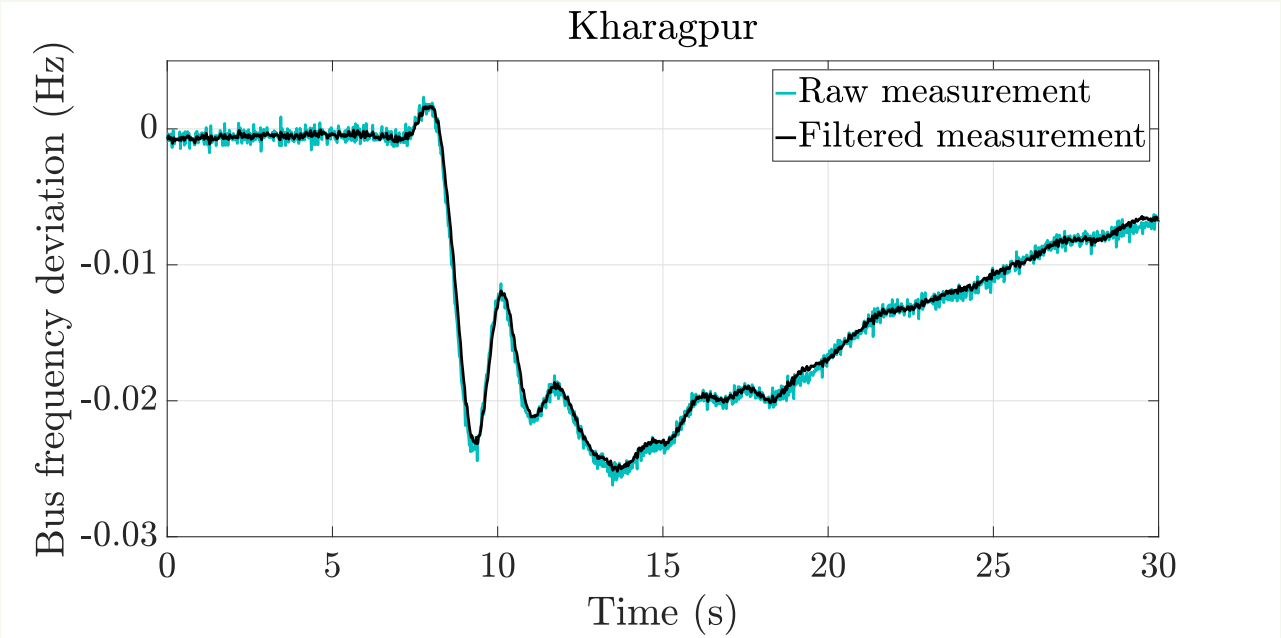


Figure: Filtering of ambient measurements

- Observations:
  - Sudden spikes in frequency measurements are not tracked.
  - Negligible phase (time) delay in the filtered response.
  - SNR is significantly improved.

Filtering of Ringdown Waveforms

- Measurement window: Generation trip at Mundra 7:21:52 PM - 7:22:22 PM on 12.03.2014



- Observations:
  - Sudden spikes in frequency deviations are not tracked.
  - Insignificant phase (time) delay in the filtered response.

Conclusions

- Conventional low pass filtering: may not be sufficient for lower voltage level.
- Alternate approach: Estimate the correlated frequency components and perform digital filtering.
- Can be implemented for real-time applications with minimal computation delay.
- Negligible phase shift in the filtering process.
- Do not need non-local measurements for real-time filtering.
- Measurement based process: Independent of system operating condition, size and topology.

Thank You !!

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