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Small-signal Approximations of Frequency Estimation Algorithms

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Introduction

- Frequency estimation is becoming important for real-time applications such as wide-area oscillation damping, primary frequency regulation, and synthetic inertia
- In feedback control applications, it is critical to consider the dynamic behavior of the algorithm (sensor). This can be difficult because, in their native formulations, the algorithms are complex and often-nonlinear.
- Small-signal linear approximations ease the technical burden for users.

Approximations of Several Algorithms

- In the paper, approximations are derived for four algorithms: DFT -based (most PMUs), adaptive notch filter (ANF), moving average filter-based phase-locked-loop (MAF-PLL), and extended Kalman filter (EKF).
- Derivations use mathematical techniques including Taylor series and the averaging theorem.
- Assumptions: near-nominal operation and averaging away double-frequency dynamics

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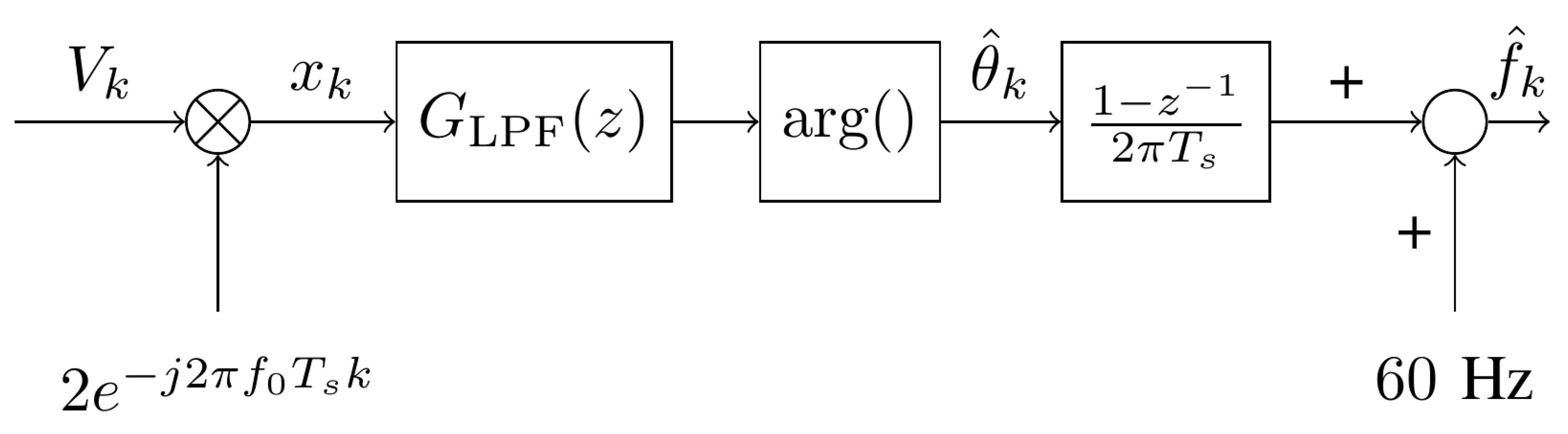
DET-based (PMU) Algorithm

Actual



Approximate

$$\frac{\Delta \hat{f}}{\Delta f} = G_{\text{LPF}}(z)$$

ANF

Actual

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -\theta^2 x_1 - 2\zeta\theta x_2 + 2\zeta\theta^2 V$$
$$\dot{\theta} = -\gamma x_1 \theta^2 V + \gamma\theta x_1 x_2$$

Approximate

$$\frac{\Delta \hat{f}}{\Delta f} = \frac{\gamma\omega_0^2}{2s^2 + 2\zeta\omega_0 s + \gamma\omega_0^2}$$

EKF

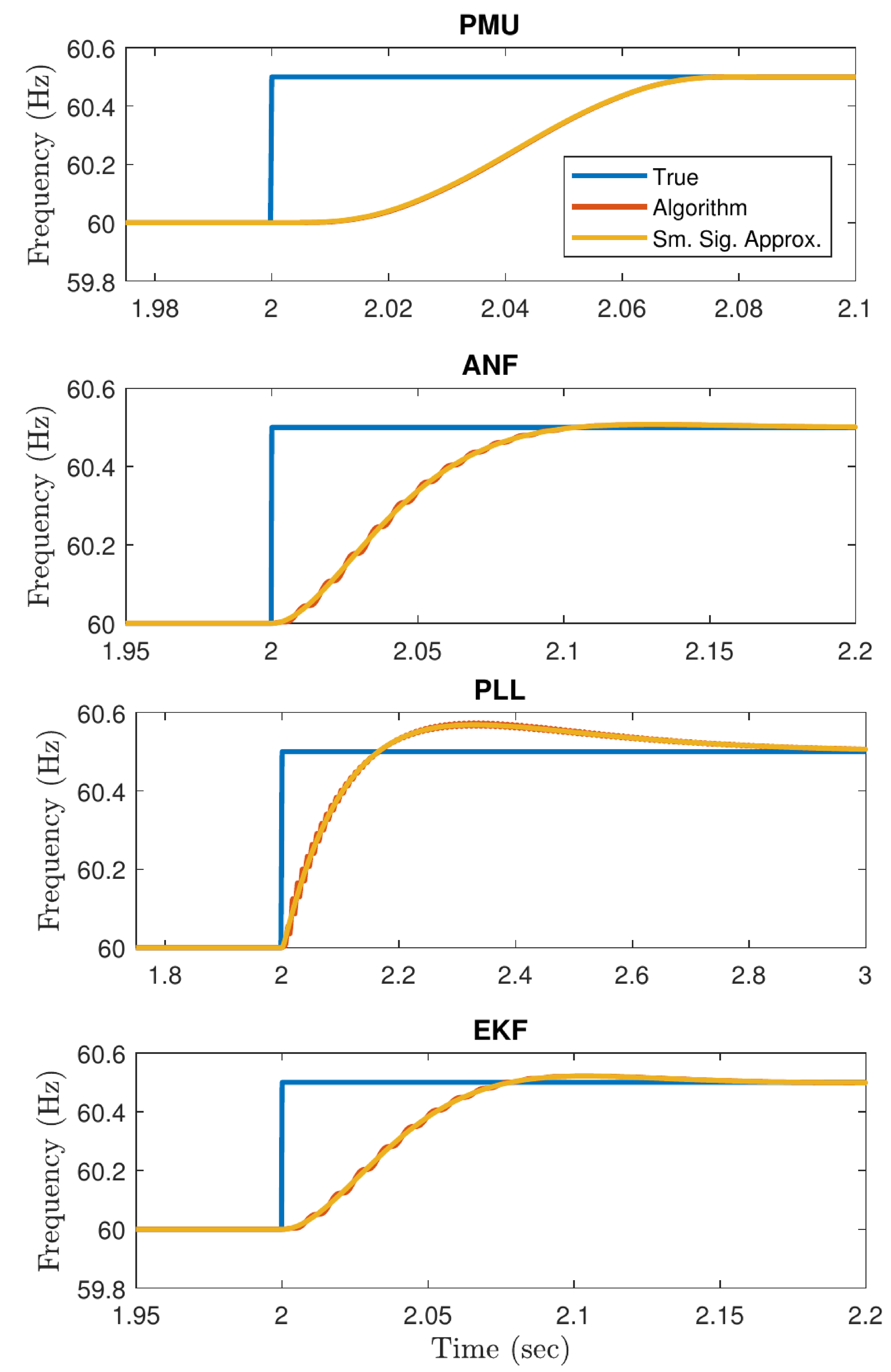
Actual

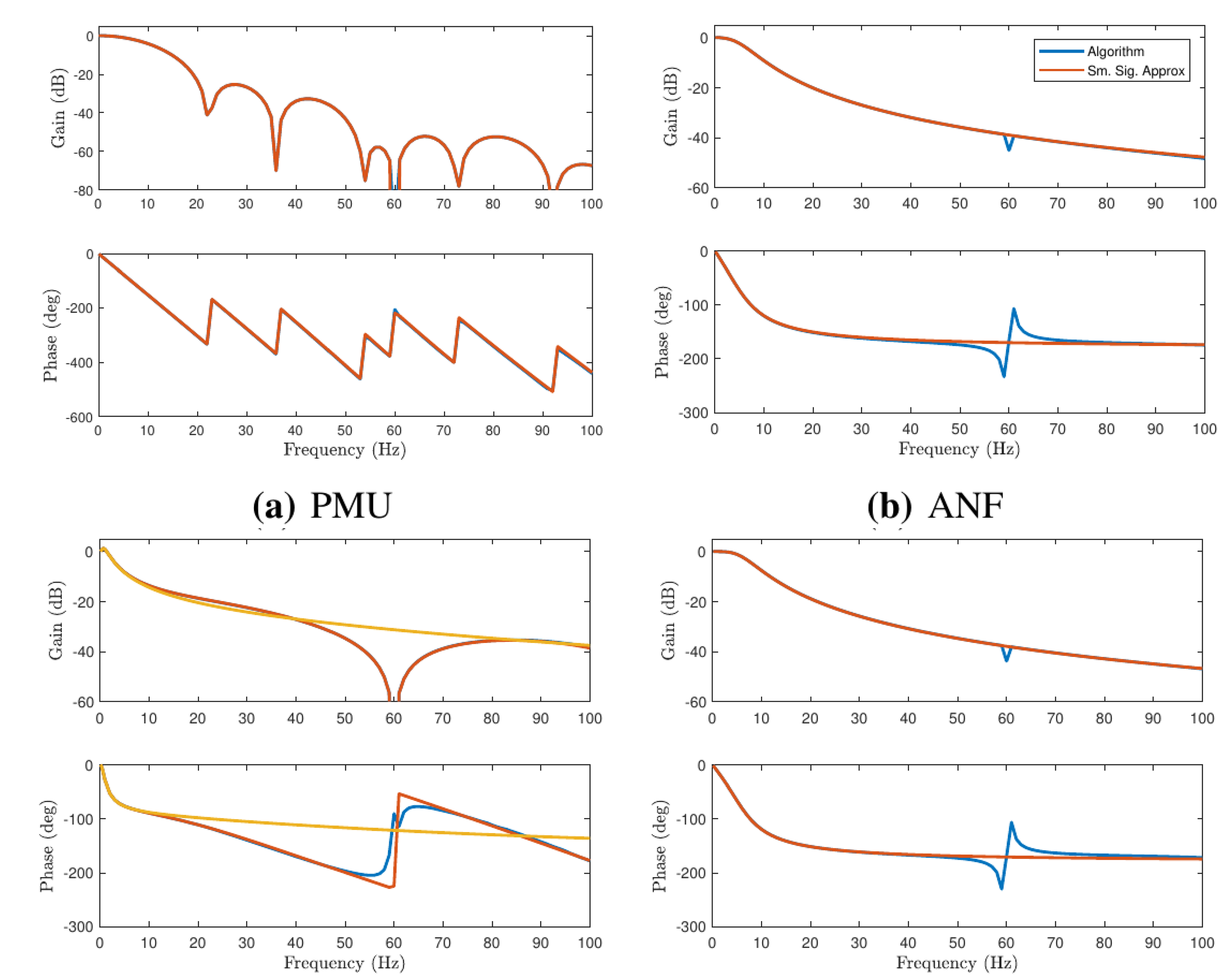
$$\hat{x}_k = (I - K_k H_k) g(\hat{x}_{k-1}) + K_k V_k$$
$$H_k = \begin{bmatrix} 0 & 1/2 & 0 & 1/2 \end{bmatrix}$$
$$g(\hat{x}_k) = \begin{bmatrix} \hat{x}_{1_k} \\ \hat{x}_{1_k}\hat{x}_{2_k} \\ \hat{x}_{3_k} \\ \hat{x}_{3_k}\hat{x}_{4_k} \end{bmatrix}$$

Approximate

$$\frac{\Delta \hat{f}}{\Delta f} = \frac{k_1 z}{2z^2 + (k_2 + k_1 - 4)z + 2 - k_2}$$
$$\bar{K}_k = \begin{bmatrix} k_1 e^{-j2\pi f_0 T_s k} \\ k_2 e^{-j2\pi f_0 T_s k} \\ k_1^* e^{j2\pi f_0 T_s k} \\ k_2^* e^{j2\pi f_0 T_s k} \end{bmatrix}$$

Simulation Verification





(a) PMU (b) ANF (c) PLL (d) EKF

Applications

- Simplified tuning
- Easy incorporation in positive-sequence simulations
- Sensor model for feedback controller design

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