Stability and Control of Systems with High Penetration of Converter Interfaced Generation

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Integration of Renewables

Renewables are typically **C**onverter **I**nterfaced **G**eneration (**CIG**).

Small penetration levels are easily handled.

Large penetration levels create issues:

- Grid behavior changes: what are they?
- Stability performance: what stability means?
- 100% penetration: can we operate these systems?

Are there important requirements that need to be specified now (considering that new units may last more than 40 years), to allow the system to operate correctly, even if this operation is completely different from today?

Present Approach / Status

Question raised and studied for years is integration of renewables in the context of **adequacy**: power/demand equilibrium taking into account the variability of weather parameters.

Less Studied Issues:

Grid behavior when only power converters feed it.

Is frequency still relevant when there is no physical link between load/production and frequency? Is frequency response relevant?

What is the meaning and role of Area Control Error under these conditions? Reserves? Customer Owned Resources?

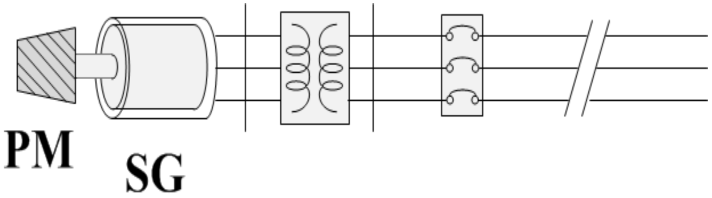
Present Approach / Challenges

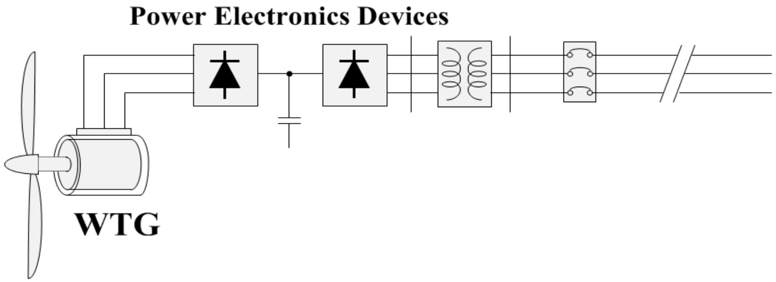
New control schemes and operational rules may need to be defined → Minimized disruptions.

New protection approaches may need to be developed: Present protection schemes are based on a clear separation between fault currents and normal load currents. Converter interfaced generation limits fault currents to values comparable to load currents. This presents a huge challenge and renters present protection schemes ineffective.

Fault detection must be revisited. It must be based on new principles. We have developed a dynamic state estimation based approach which has been fully validated in the laboratory and it is now in field trials under a NYSERDA project.

Comparison of Synchronous Generator vs. Converter-Interfaced Generation System





$$\ddot{\delta} = \frac{1}{2H}(P_m - P_e) - \frac{\varsigma}{2H}\dot{\delta} \quad \Rightarrow$$

Tight coupling between synchronous generator (SG) and power grid.

1. Stabilizing forces during transients.
2. Inertia and slow frequency and phase-angle changes.
3. High fault and transient currents can be tolerated.

Loose coupling between wind-turbine generator (WTG) and power grid.

1. Lack of stabilizing forces, control based operation.
2. Lack of inertia, Fast frequency and phase-angle changes.
3. Limited fault current, indistinguishable from load currents.

Problems for power systems with high penetration of CIG systems:

During transients, the operating constraints of the inverters may be exceeded to the point of damaging the inverters or causing the shutdown of the inverters → crow bar and low voltage ride through.

Objective:

Design Predictive Inverter Control that minimizes the transients by: (a) feedback of frequency and the rate of change of frequency at local and remote sites, and (b) sluggish frequency and angle control to “follow” bulk power system.

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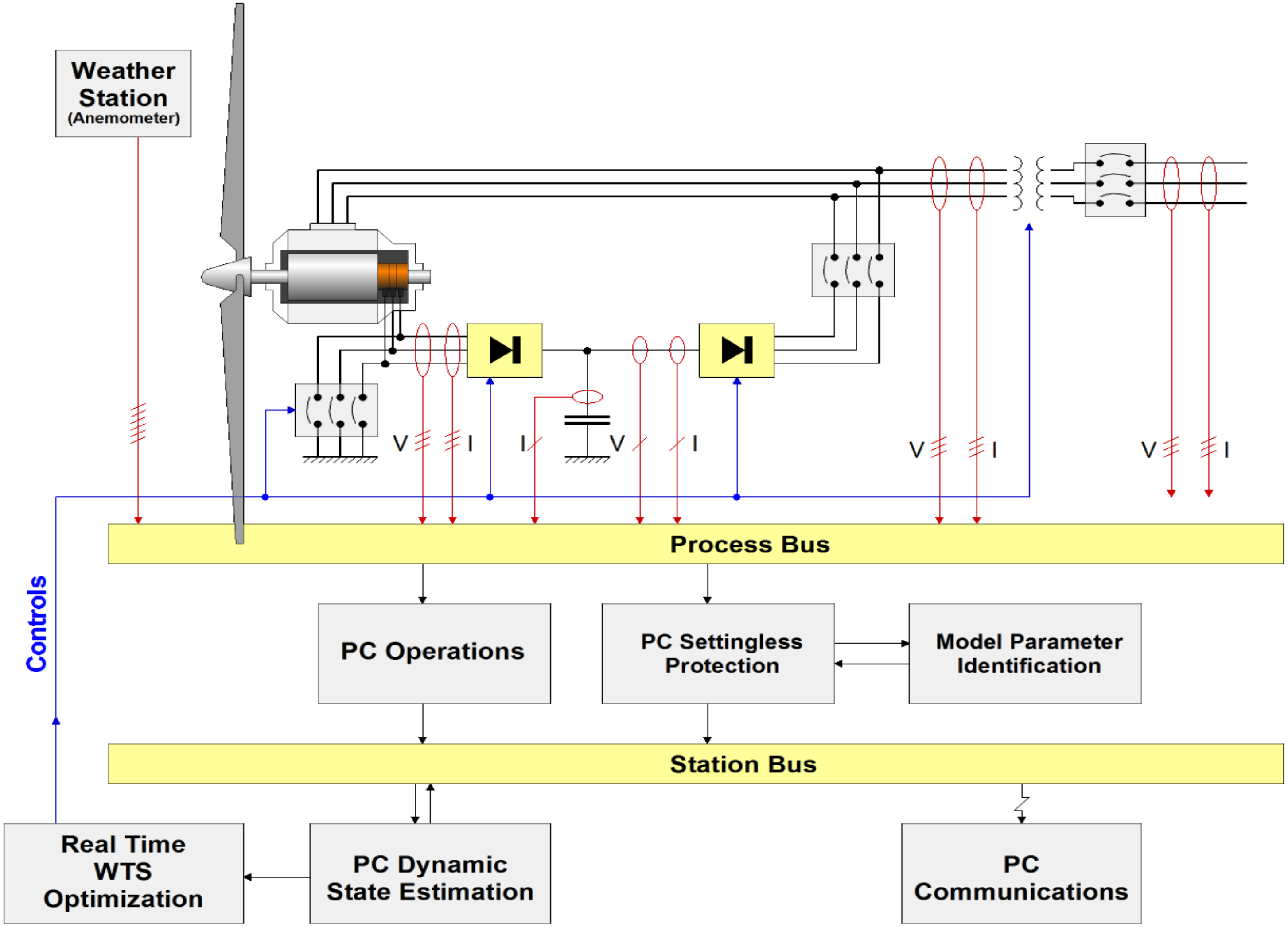
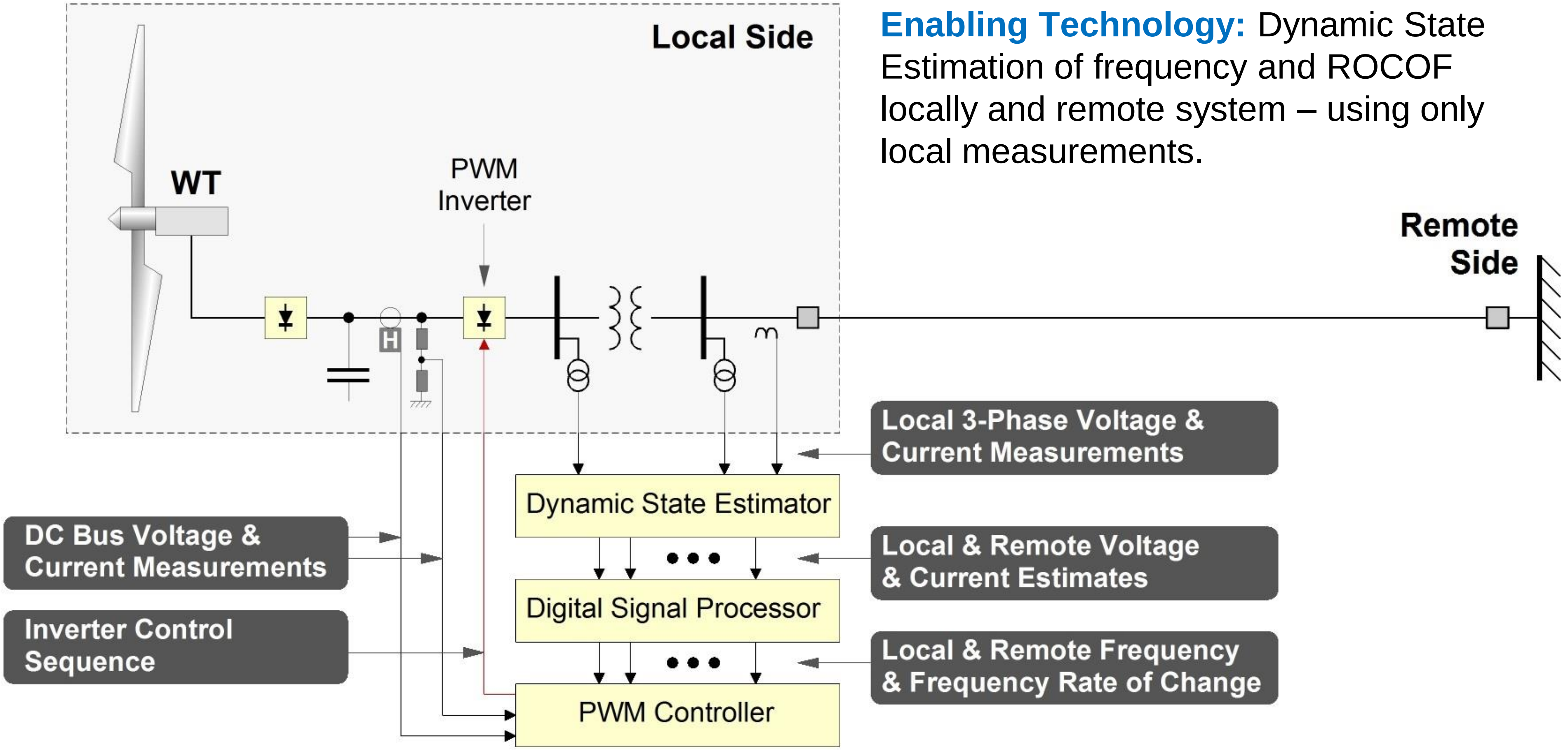
Approach: Distributed Real Time Dynamic Estimation Based Protection & Control



Predictive Inverter Control Enabled by Dynamic State Estimator

Objectives: Control a CIG system to smoothly follow the oscillations of the system and avoid excessive transients.
Minimize possibility of low voltage ride through activation.

Enabling Technology: Dynamic State Estimation of frequency and ROCOF locally and remote system – using only local measurements.



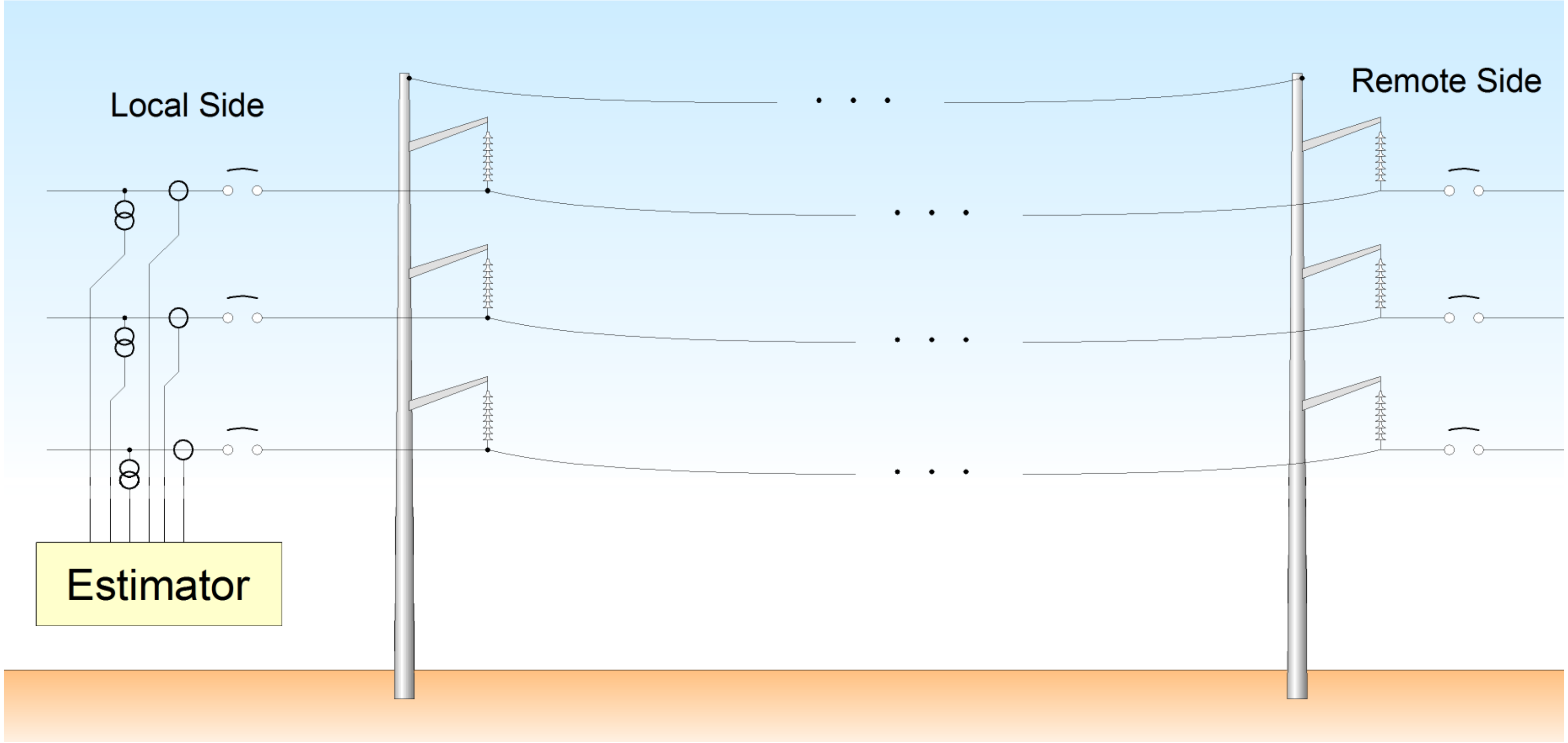
Dynamic State Estimation Performance

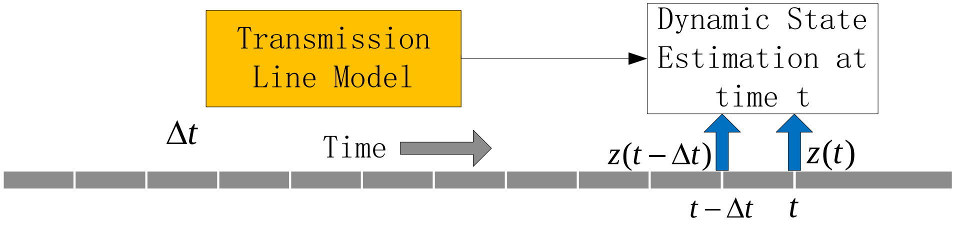
Local & Remote Side f and df/dt Estimation

Measurements: 3-phase *local voltage and current* measurements

Target: Estimate three-phase *local & remote* states including f and df/dt

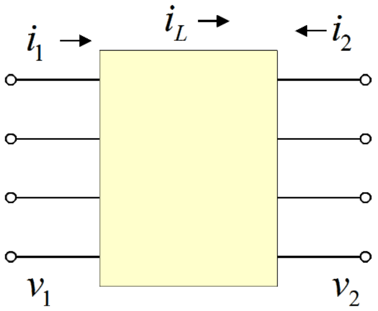
Can Dynamic State Estimation using local side data only provide accurate estimates frequency and ROCOF at remote side? (eliminates need for telemetering and all associated reliability problems)

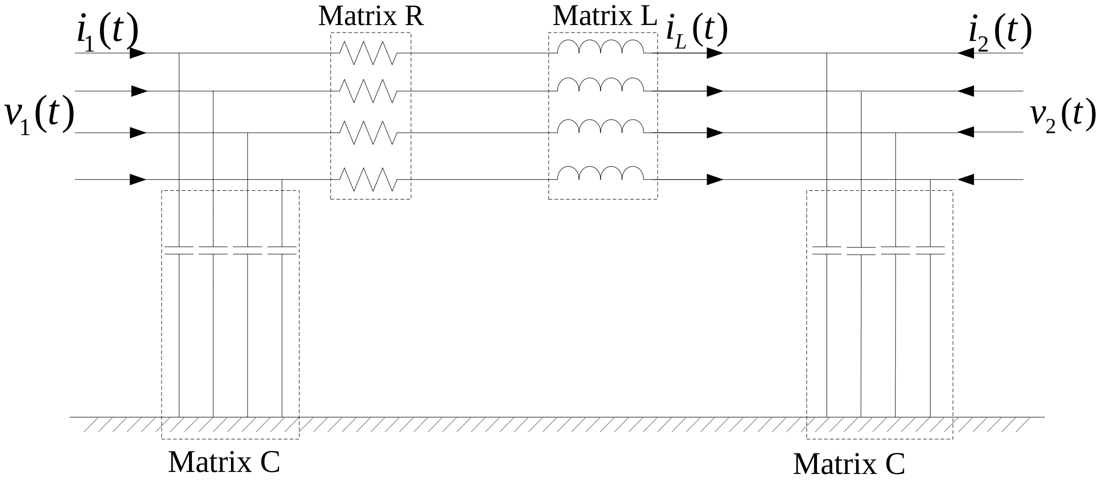




Transmission Line Model

Single-section model





Compact Form

$$\begin{bmatrix} i_1(t) \\ i_2(t) \\ \mathbf{0} \end{bmatrix} = A \cdot \begin{bmatrix} v_1(t) \\ v_2(t) \\ i_L(t) \end{bmatrix} + B \cdot \frac{d}{dt} \begin{bmatrix} v_1(t) \\ v_2(t) \\ i_L(t) \end{bmatrix}$$

Quadratic Integration

$\xrightarrow{}$

Algebraic Form

Algebraic Quadratic Form

$$\begin{bmatrix} i_1(t) \\ i_2(t) \\ \mathbf{0} \\ i_1(t-\Delta t) \\ i_2(t-\Delta t) \\ \mathbf{0} \end{bmatrix} = Yeqx \cdot \begin{bmatrix} v_1(t) \\ v_2(t) \\ i_L(t) \\ v_1(t-\Delta t) \\ v_2(t-\Delta t) \\ i_L(t-\Delta t) \end{bmatrix} + Neqx \cdot \begin{bmatrix} v_1(t-2\Delta t) \\ v_2(t-2\Delta t) \\ i_L(t-2\Delta t) \end{bmatrix} + Meq \begin{bmatrix} i_1(t-2\Delta t) \\ i_2(t-2\Delta t) \\ \mathbf{0} \end{bmatrix}$$

$$State: \quad v_1(t), v_2(t), i_L(t), \quad t = h, 2h, 3h, \ldots.$$

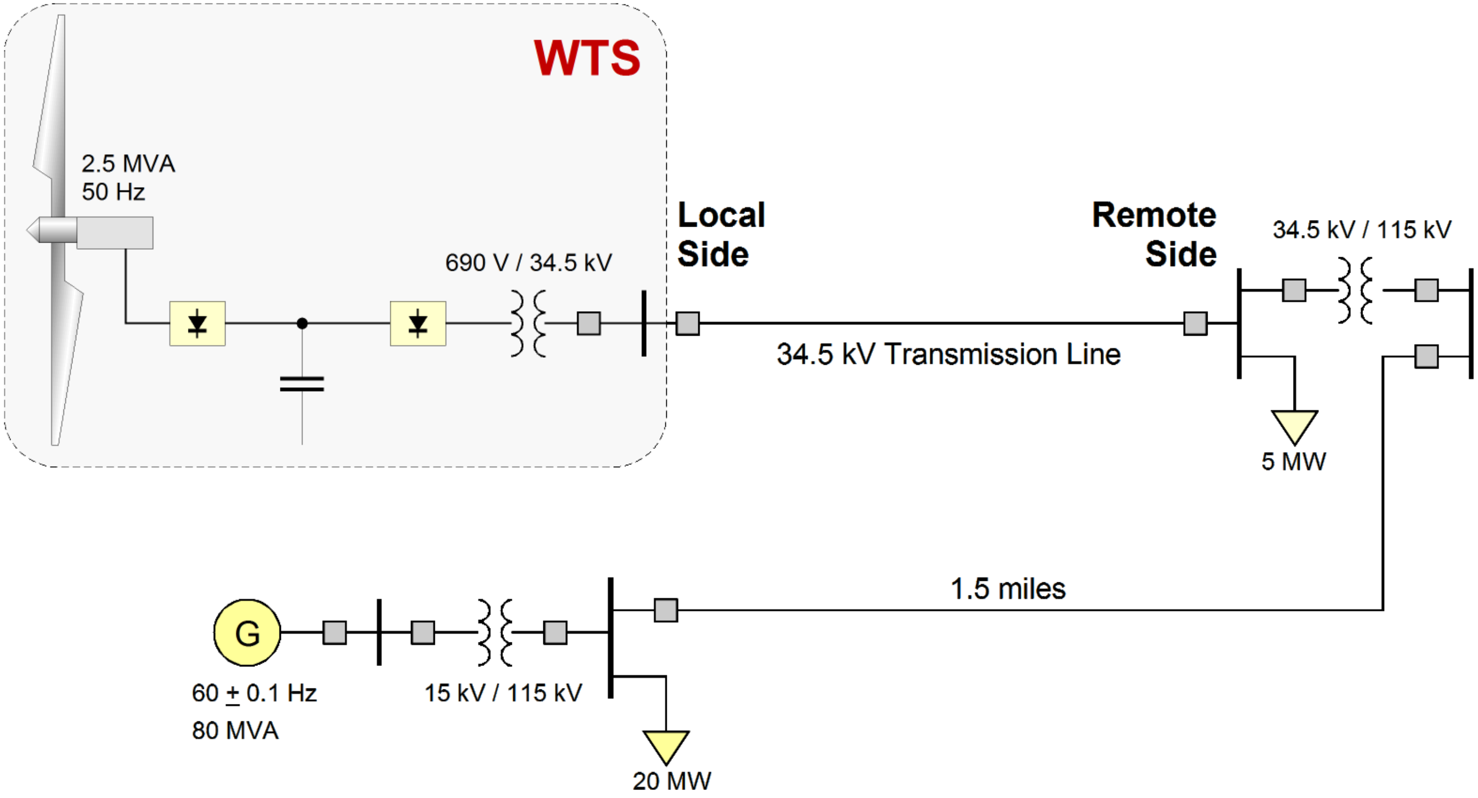
Approach: Unconstraint, Constraint, Extended Kalman Filter

Numerical Experimentation

- A Wind Turbine System (WTS), with 50 Hz voltage input
- An oscillating source with frequency 60 ± 0.1 Hz
- A 34.5kV Transmission line,

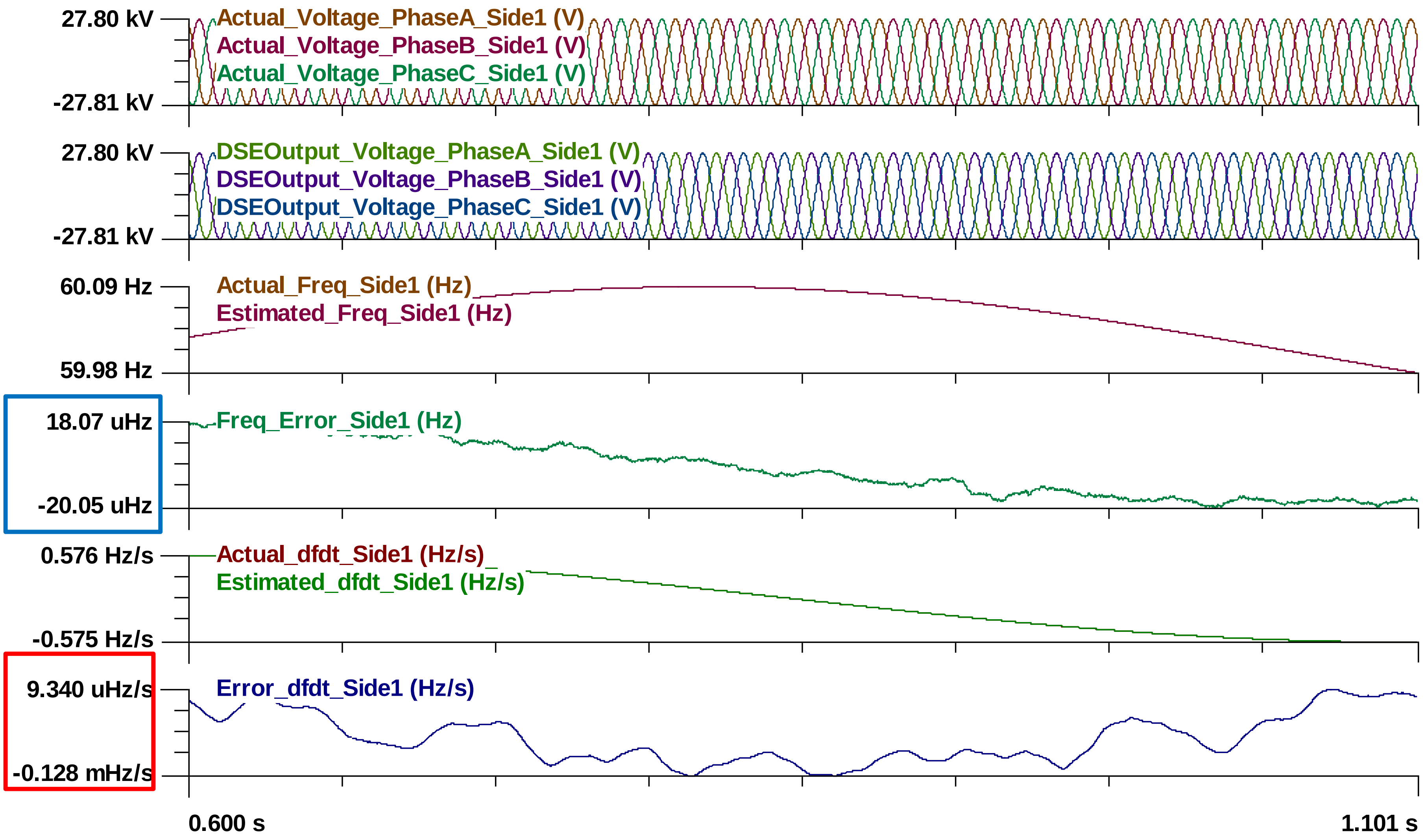
  measurements at the **Local** side only

  Results have been obtained for different lengths of line



Results: 2.5 miles – Side 1

SE: Unconstraint, Constraint, Extended Kalman Filter



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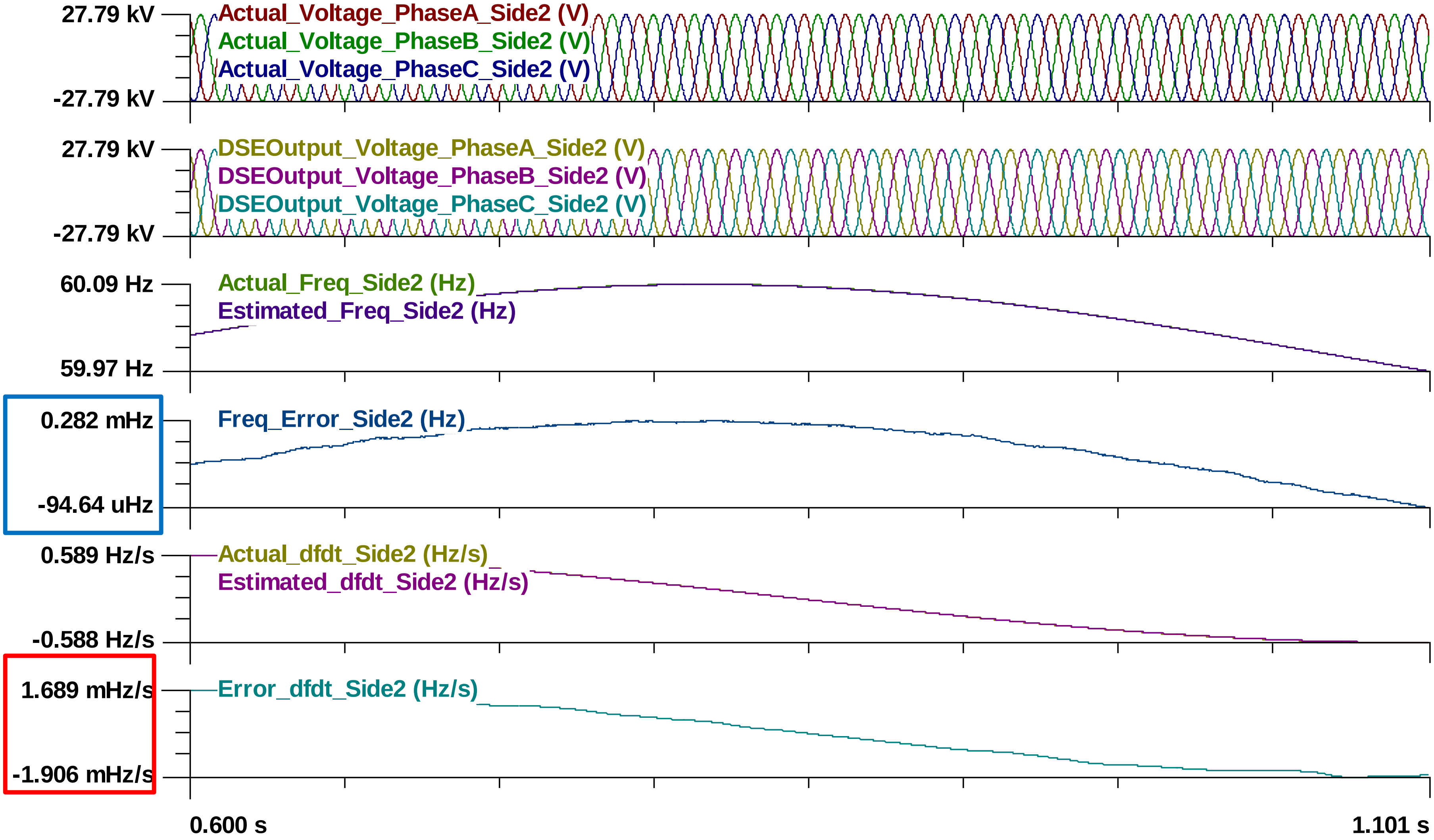
Results: 2.5 miles – Side 2

SE: Unconstraint, Constraint, Extended Kalman Filter



Summary of Results – f and df/dt

Frequency : 59.98Hz ~ 60.09Hz, Rate of Change: -0.6 ~ 0.6Hz/s

Side 1 Results

Case number	Line length	Frequency error	dFreq/dt error
1	$1.5\ miles$	$-1.887\times10^{-5} \sim 1.827\times10^{-5}\ Hz$	$-1.24\times10^{-4} \sim -2.602\times10^{-6}\ Hz/s$
2	$2.5\ miles$	$-2.005\times10^{-5} \sim 1.807\times10^{-5}\ Hz$	$-1.28\times10^{-4} \sim 9.340\times10^{-6}\ Hz/s$
3	$4\ miles$	$-1.853\times10^{-5} \sim 1.803\times10^{-5}\ Hz$	$-1.35\times10^{-4} \sim 4.507\times10^{-6}\ Hz/s$

Side 2 Results

Case number	Line length	Frequency error	dFreq/dt error
1	$1.5\ miles$	$-6.513\times10^{-5} \sim 1.77\times10^{-4}\ Hz$	$-1.144\times10^{-3} \sim 1.049\times10^{-3}\ Hz/s$
2	$2.5\ miles$	$-9.464\times10^{-5} \sim 2.82\times10^{-4}\ Hz$	$-1.906\times10^{-3} \sim 1.689\times10^{-3}\ Hz/s$
3	$4\ miles$	$-1.29\times10^{-4} \sim 4.51\times10^{-4}\ Hz$	$-2.896\times10^{-3} \sim 2.751\times10^{-3}\ Hz/s$

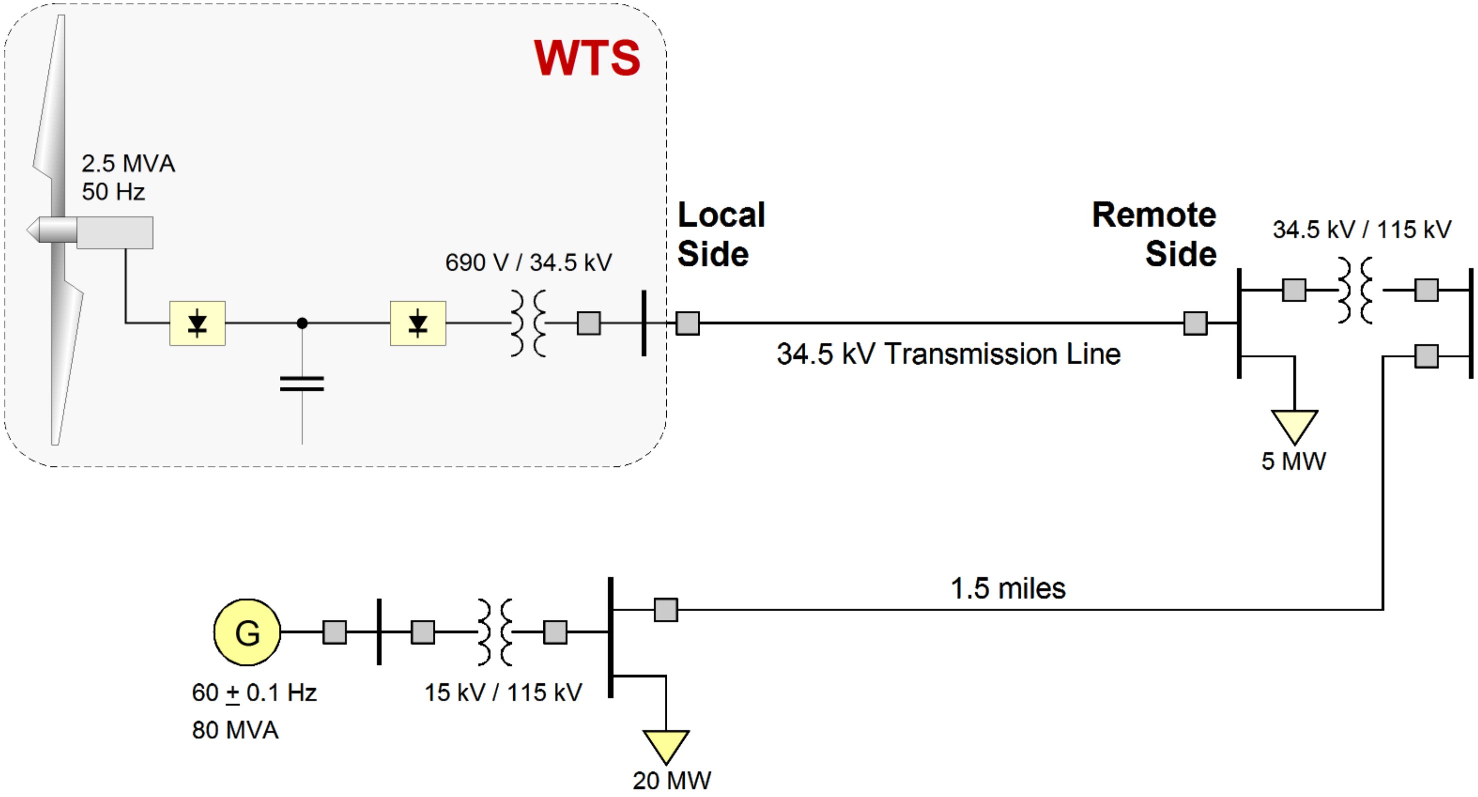
CIG Performance with Supplementary Controls

Example Test System

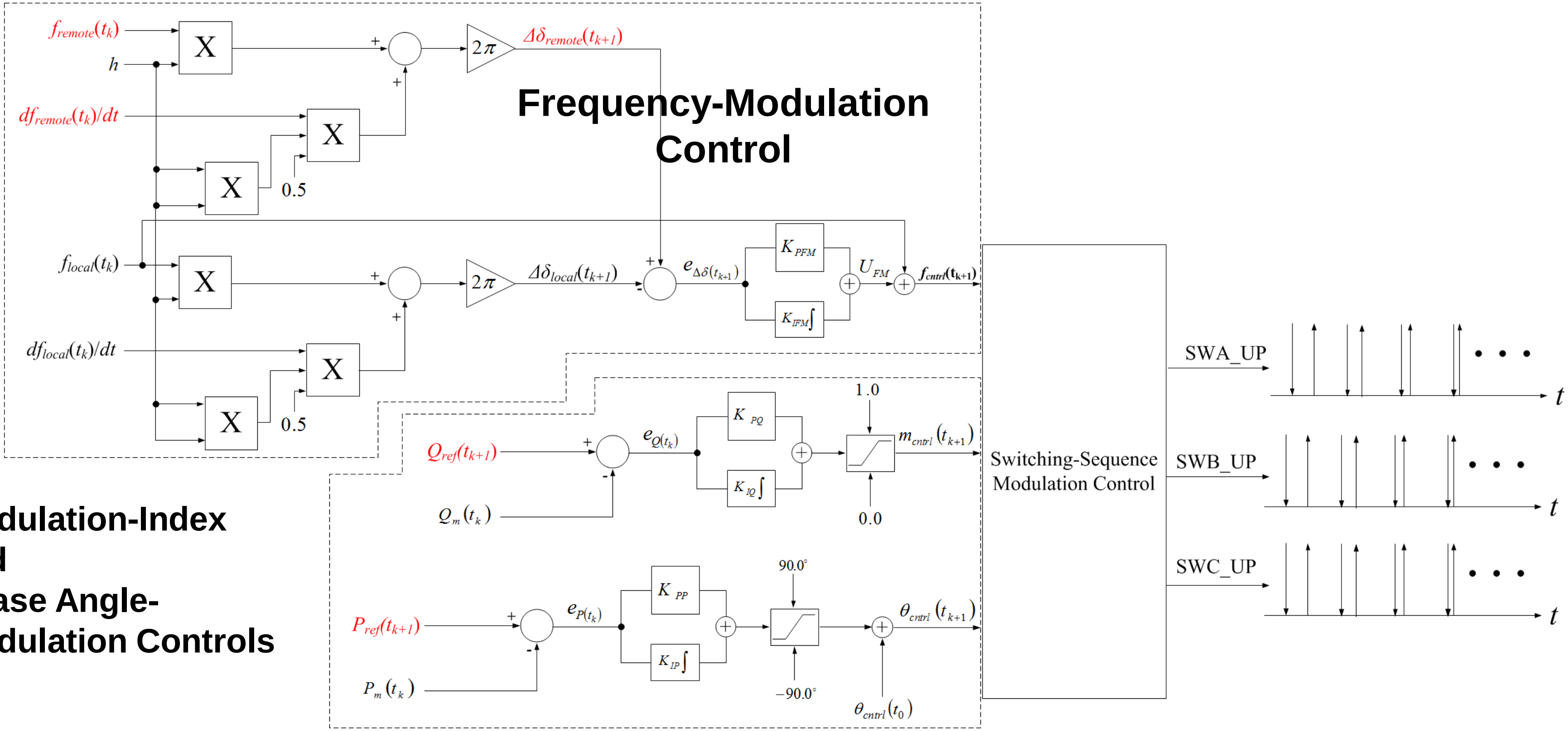
WTS Connected to Power Grid via a 34.5 kV Line

Simulate Transients in Power Grid and Observe Inverter Operation and Response

Physically based/high fidelity modeling of: inverter, wind generator, transmission lines, transformers, etc. Use of quadratic modeling/quadratic integration method (QMQI)



Frequency-Modulation, Modulation-Index, Phase Angle-Modulation Controls (P-Q Mode) - PWM Controller



Frequency-Modulation Control

Modulation-Index and Phase Angle-Modulation Controls

Frequency-modulation control "gradually" modulates the frequency of converter switching sequences to slowly synchronize with remote-end system (**time compression** of switching signals)
Modulation-index and phase-angle modulation controls modulate the amplitude and phase angle of the AC output voltage by controlling the duty ratio and start time of switching sequences (**time shifting** of switching signals).

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Frequency- and Phase Angle-Modulation Controls (P-Q Mode)

Switching-Sequence Definition (Time Scaling and Translation)

Negative Edge:

$$ct_{(2i)a} = \frac{\theta_{cntrl}}{2\pi \cdot f_{cntrl}} + \frac{i}{f_S} + f_N\left(f_S, \frac{i}{f_S} + \frac{\theta_{cntrl}}{2\pi \cdot f_{cntrl}}, m_{cntrl} \right), \quad i = 0, 1, 2, \ldots, 10$$

$$f_N(a, b, c) = solve(c \cdot \cos(2\pi \cdot f_{cntrl} \cdot t) = 2 \cdot a \cdot (t - b), t), \quad i = 0, 1, 2, \ldots, 10$$

Positive Edge:

$$ct_{(2i+1)a} = \frac{\theta_{cntrl}}{2\pi \cdot f_{cntrl}} + \frac{i}{f_S} + f_P\left(f_S, \frac{i}{f_S} + \frac{\theta_{cntrl}}{2\pi \cdot f_{cntrl}}, m_{cntrl} \right), \quad i = 0, 1, 2, \ldots, 9$$

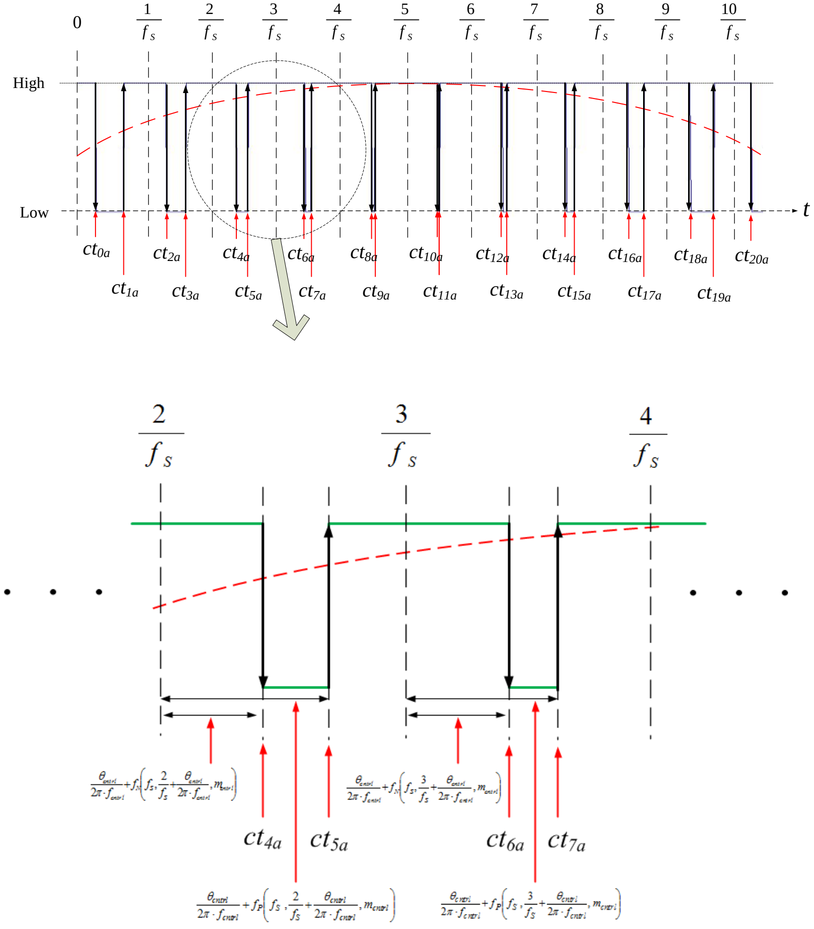
$$f_P(a, b, c) = solve\left(c \cdot \cos(2\pi \cdot f_{cntrl} \cdot t) = -2 \cdot a \cdot \left(t - b - \frac{1}{a} \right), t \right), \quad i = 0, 1, 2, \ldots, 9$$

where:

fs: Switching frequency (Hz).

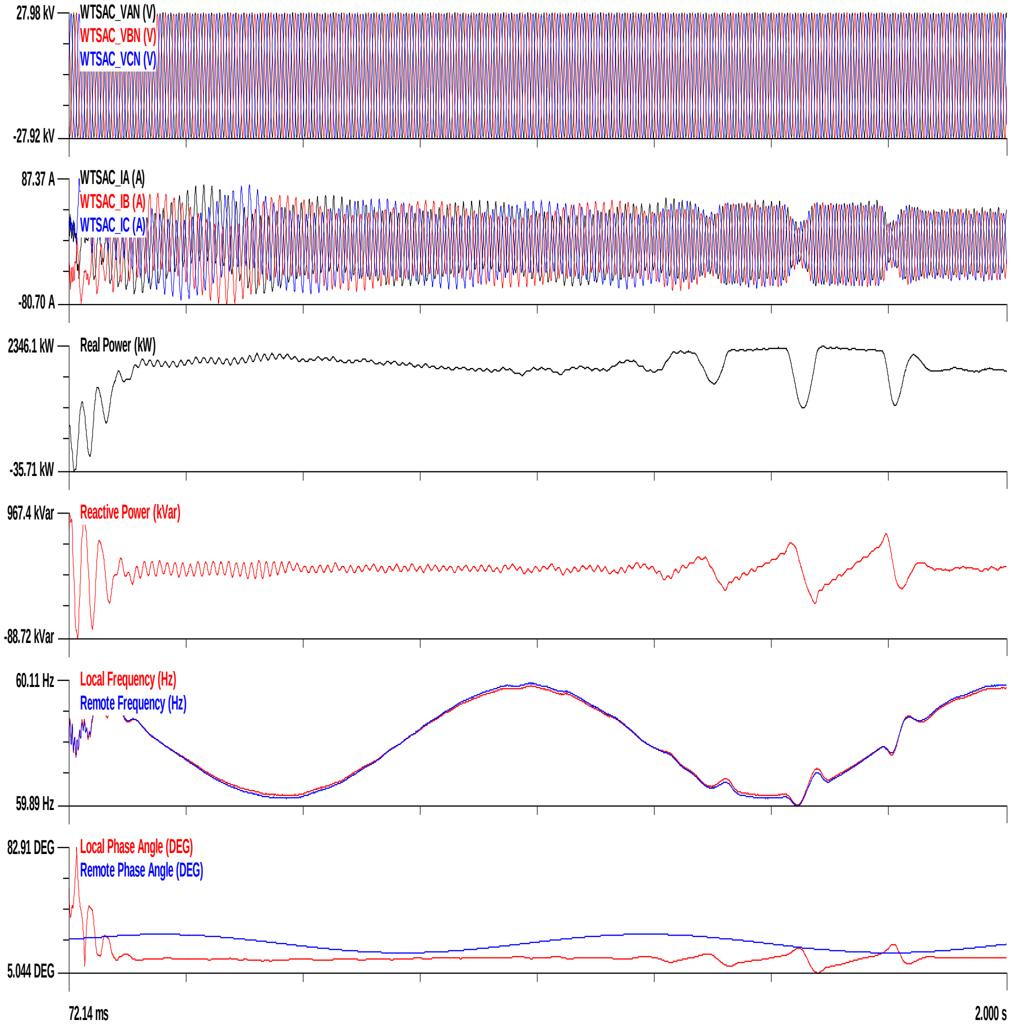
$f_N(a, b, c)$: A function for calculating the negative-edge time per each sampling period (sec).

$f_P(a, b, c)$: A function for calculating the positive-edge time per each sampling period (sec).



Simulation Results:

CIG System without Predictive Inverter Control



Simulation test case: remote converter-interfaced generation (CIG) experiences a frequency oscillation:

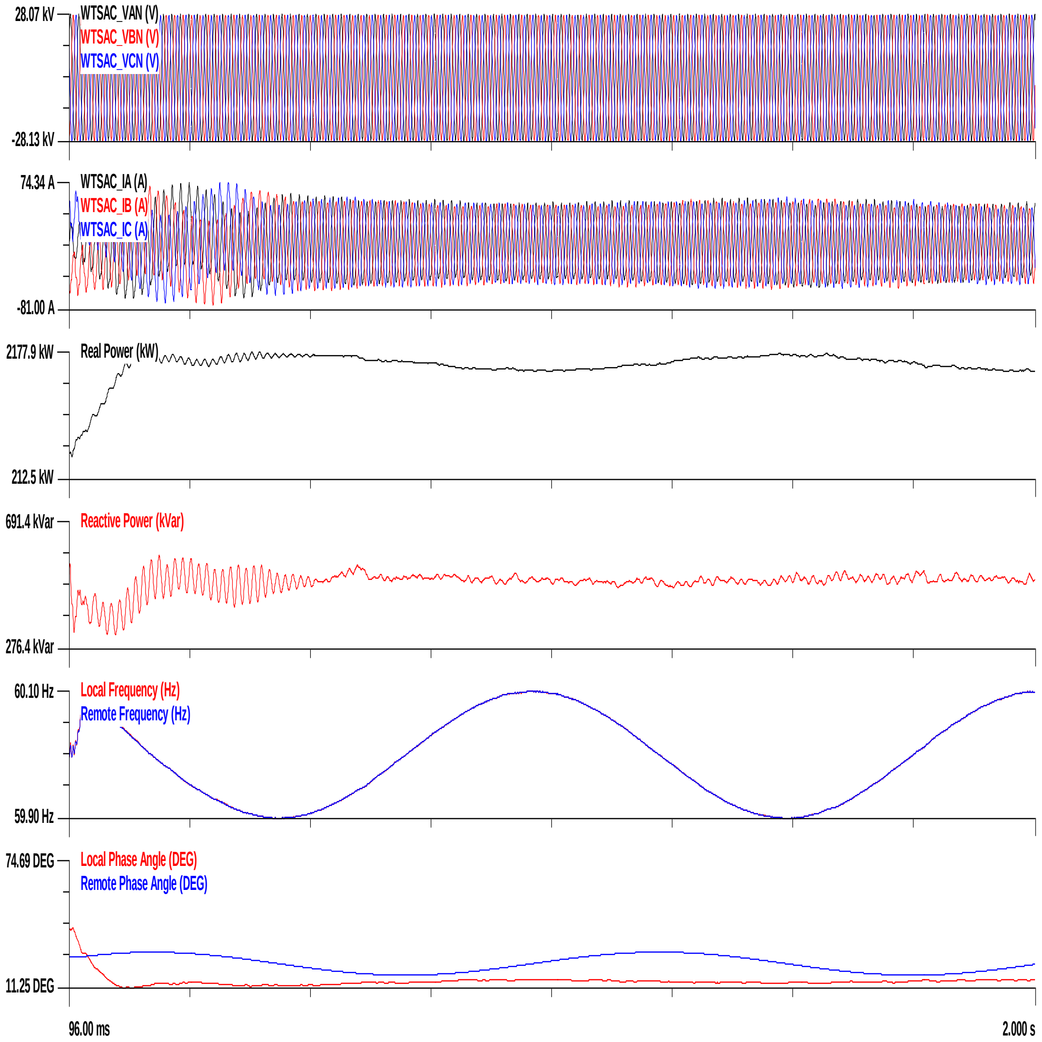
$$60 + 0.1\sin\left(2\pi \cdot \mathrm{t}\right) Hz$$

Local CIG under traditional inverter controller.

The two CIGs operate with oscillating frequencies (synchronize with time lag) and generate transients that may lead to occasional mis-firing of electronic switches.

Simulation Results:

CIG System with Predictive Inverter Control



Simulation test case: remote converter-interfaced generation (CIG) experiences a frequency oscillation:

$$60 + 0.1\sin\left(2\pi \cdot \mathrm{t}\right) Hz$$

Local CIG under predictive inverter controller.

The two CIGs operate with frequencies that track each other and the phase angle across the circuit matches the produced power of the inverter. Transients are practically near zero. Inverter tracks system motion.

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Summary:

New methods for control and operation of CIG need to be developed for synchronizing CIGs along large geographical areas and minimize transients.

Dynamic State Estimation based protection is well suited for CIG systems.

Dynamic state estimation provides the necessary signals for supplementary stabilizing controls and predictive controls.

CIG systems can be controlled in such a way that the CIG smoothly follows the oscillations of the system and avoids excessive transients and activation of low voltage ride through controls, i.e. provides stabilization control to the CIG.

The Old Faithful…

Collaborators:
Vijay Vittal, ASU
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GRAs:
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Yu Liu
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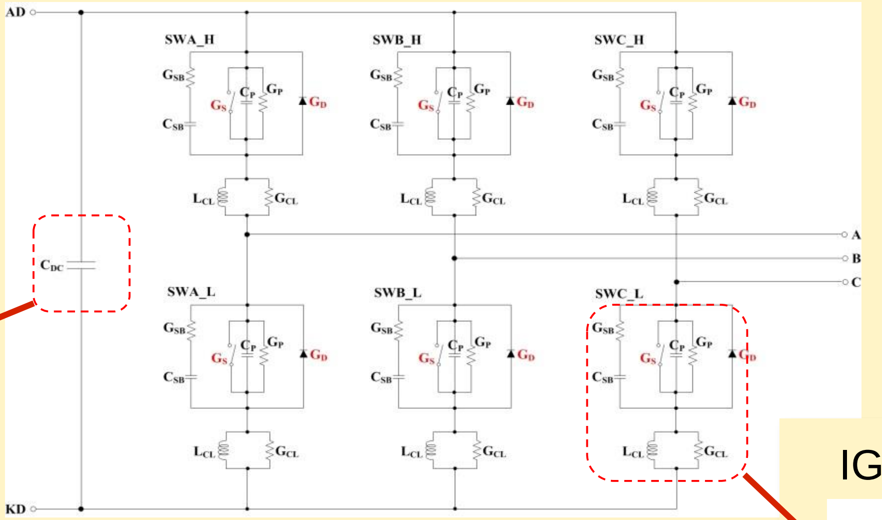
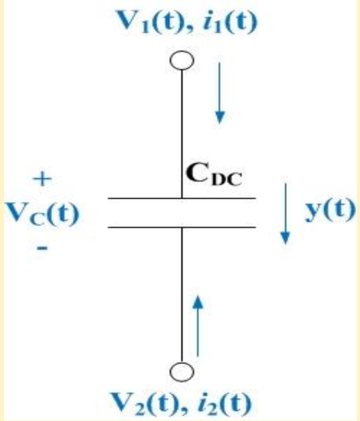
Physically-Based Modeling for CIG system

Three-Phase Two-Level PWM Converter

Three-Phase Two-Level PWM Converter



DC-Side Capacitor



The 3-phase 2-level PWM converter model consists of a DC-side capacitor and six IGBT-based switch models.

IGBT-based Switch