Grid-Tie Inverter Simulation Desktop App

May 30, 2025

Contents

1 Introduction

This is a desktop-app for simulating grid-tied inverters, supporting various topologies, control strategies, DC sources, and grid conditions. It provides a graphical interface for configuring parameters, visualizing waveforms, and performing frequency-domain analysis (Bode plots). The software is designed for modeling inverter behavior under different operating conditions.

2 Functioning Logic

- **Main Application (`main.c`)**: Initializes the GTK application, creates an 800x600 window, and manages the simulation loop using `g_timeout_add` (16 ms, $\approx$ 60 FPS). Handles user interactions (start, pause, reset, parameter changes) and resets parameters to defaults.
- **User Interface (`interface.c`, `style.css`)**: Features a horizontal layout with a scrollable control panel and waveform drawing area. Includes dropdowns (inverter type, design, MPPT, control, DC source, grid condition), sliders (voltage, frequency, phase, PLL gains, time step), buttons (start, pause, reset, configure DC, analysis), and status labels (PLL lock, islanding, grid, DC parameters). Uses a teal-themed CSS with Fixedsys font.
- **DC Source Configuration (`GleichstromquellenModellierung.c`)**: Provides a window for configuring PV (irradiance, temperature, series/parallel panels), battery (SoC, type, charging state), and fuel cell (power demand) parameters, updating in real-time.
- **Frequency Analysis (`FrequenzbereichsUndKleinsignalanalyse.c`)**: Supports Bode plot analysis with configurable frequency range (0.01 Hz to 100 kHz), operating voltage (100 V to 300 V), and load resistance (1 Ω to 1000 Ω). Plots gain and phase using Cairo.
- **Simulation Loop (`Zeitbereichssimulation.c`)**: Manages time-domain simulation with adaptive time steps, updating MPPT, PLL, control, islanding detection, and DC sources.
- **Waveform Visualization (`waveform.c`)**: Draws single-phase or three-phase waveforms with a black background, white grid, and colored lines (red, green, blue for phases A, B, C), scaling voltages to ±400 V.

3 Simulation Logic

The simulation operates in the time domain with an adaptive time step, updating the inverter state based on user inputs and physical models.

- **Time Step Calculation (`calculate_time_step`)**:
  - Adapts time step based on frequency deviation and output change:
    - Frequency deviation: $|f_{\mathrm{PLL}} - 50|/50$
    - Output change: $\sqrt{\sum_{i=0}^{2}(V_{\mathrm{out},i} - V_{\mathrm{prev},i})^2}$
  - Scales time step:
    - 10% of $\Delta t_{\max}$ for large deviations ($> 5\%$ frequency or $> 10\,\mathrm{V}$).
    - 50% of $\Delta t_{\max}$ for moderate deviations ($> 2\%$ frequency or $> 5\,\mathrm{V}$).
    - Clamped: $0.1\,\mathrm{ms} \leq \Delta t \leq \Delta t_{\max}$ (default 10 ms).
- **Simulation Step (`simulation_step`)**:

- Increments: $t_{\text{sim}} = t_{\text{sim}} + \Delta t$
  - Updates MPPT, PLL, control, islanding detection, and DC source sequentially.
- **Simulation Update (`simulation_update`):**
  - Runs every 16 ms if active.
  - Updates GUI (PLL lock, islanding, grid, DC parameters) and redraws waveforms.
  - Stops simulation if islanding detected.

4 Physics Models

The software models the inverter system, DC sources, grid, and control using physics-based equations.

4.1 Inverter Output

- **Single-Phase (`single_phase_output`):**

$$V_{\text{out},0} = V_{\text{rms}}\sqrt{2}\sin(2\pi f t + \phi), \quad V_{\text{out},1} = V_{\text{out},2} = 0$$

- **Three-Phase (`three_phase_output`):**

$$V_{\text{out},i} = V_{\text{rms}}\sqrt{2}\sin(2\pi f t + \phi + i \cdot \frac{2\pi}{3}), \quad i = 0, 1, 2$$

- **NPC Inverter (`npc_inverter_output`):**

$$V_{\text{peak}} = V_{\text{rms}}\sqrt{2}, \quad \theta = \mod (2\pi f t + \phi, 2\pi)$$

$$V_{\text{out},0} = \begin{cases} -V_{\text{peak}} & \text{if } \theta < \frac{\pi}{3} \text{ or } \theta \geq \frac{5\pi}{3} \\ V_{\text{peak}} & \text{if } \frac{2\pi}{3} \leq \theta < \frac{4\pi}{3} \\ 0 & \text{otherwise} \end{cases}, \quad V_{\text{out},1} = V_{\text{out},2} = 0$$

- **Flying Capacitor (`flying_capacitor_output`):**

$$V_{\text{out},0} = \begin{cases} -V_{\text{peak}} & \text{if } \theta < \frac{\pi}{5} \text{ or } \theta \geq \frac{9\pi}{5} \\ -\frac{V_{\text{peak}}}{2} & \text{if } \theta < \frac{2\pi}{5} \\ \frac{V_{\text{peak}}}{2} & \text{if } \theta < \frac{4\pi}{5} \\ V_{\text{peak}} & \text{if } \frac{4\pi}{5} \leq \theta < \frac{7\pi}{5} \\ 0 & \text{otherwise} \end{cases}$$

- **Cascaded H-Bridge (`cascaded_h_bridge_output`):**

$$V_{\text{out},i} = \begin{cases} -V_{\text{peak}} & \text{if } \theta_i < \frac{\pi}{3} \text{ or } \theta_i \geq \frac{5\pi}{3} \\ V_{\text{peak}} & \text{if } \frac{2\pi}{3} \leq \theta_i < \frac{4\pi}{3} \\ 0 & \text{otherwise} \end{cases}, \quad \theta_i = \mod (2\pi f t + \phi + i \cdot \frac{2\pi}{3}, 2\pi)$$

4.2 Transformer Effects

- **Transformerless (`apply_transformerless`)**:

$$V_{\text{out},i} = V_{\text{in},i} \cdot 0.98$$

- **Transformer-Based (`apply_transformer_based`)**:

$$V_{\text{out},i} = V_{\text{in},i} \cdot 1.1 \cdot 0.90$$

4.3 DC Sources

- **PV Model (`pv_current`)**:

$$I_{\text{ph}} = (8.21 + 0.00065 \cdot (T - 25)) \cdot \frac{G}{1000} \cdot N_p$$

$$V_t = \frac{N_s \cdot 1.3 \cdot 1.381 \times 10^{-23} \cdot T}{1.602 \times 10^{-19}}$$

$$I_o = \frac{8.21}{\exp\left(\frac{37.6 - 0.123 \cdot (T-25)}{V_t}\right) - 1}$$

$$I = I_{\text{ph}} - I_o \cdot \left(\exp\left(\frac{V/N_s + I \cdot 0.221}{V_t}\right) - 1\right) - \frac{V/N_s + I \cdot 0.221}{415.405} \quad \text{(5 iterations)}$$

$$I_{\text{total}} = I \cdot N_p$$

- **Battery Model (`battery_voltage`)**:

$$V_0 = V_{\text{nom}} \cdot (1 + 0.1 \cdot (\text{SoC} - 0.5))$$

$$R_{\text{int}} = 0.05 \cdot \frac{1}{\text{SoC}}$$

$$V = V_0 - I \cdot R_{\text{int}}$$

$$\Delta\text{Ah} = \left(I \cdot \eta \text{ if charging else } \frac{-I}{\eta}\right) \cdot \frac{\Delta t}{3600}, \quad \text{SoC} = \text{SoC} + \frac{\Delta\text{Ah}}{\text{capacity}}$$

- **Fuel Cell Model (`fuel_cell_voltage`)**:

$$V = 48 - 0.06 \cdot \ln(I + 1) - I \cdot 0.01 - 0.05 \cdot \exp(0.0001 \cdot I)$$

$$I = \frac{P_{\text{demand}}}{V} \quad \text{if } V \cdot I > P_{\text{demand}}$$

- **Hybrid Model**:

$$I_{\text{fc}} = \frac{P_{\text{demand}}}{V}, \quad I_{\text{extra}} = I_{\text{ref}} - I_{\text{fc}}, \quad V = V_{\text{fc}} \text{ or } V_{\text{battery}}$$

4.4 Grid Model

$$R = \begin{cases} 0.4\,\Omega & \text{if normal} \\ 1.0\,\Omega & \text{if weak} \end{cases}, \quad L = \begin{cases} 0.001\,\text{H} & \text{if normal} \\ 0.005\,\text{H} & \text{if weak} \end{cases}$$

$$X = 2\pi \cdot 50 \cdot L$$

$$V_{\text{grid}} = V_{\text{nom}} \cdot f_{\text{factor}} \cdot \sqrt{2} \cdot \sin(2\pi(f_{\text{nom}} + \Delta f)t) + h$$

$$V_{\text{pcc}} = V_{\text{grid}} - I_{\text{inv}} \cdot R - I_{\text{inv}} \cdot X \cdot \cos(2\pi f t)$$

Faults (1 to 1.5 s):

- Sag: $f_{\text{factor}} = 0.5$
- Swell: $f_{\text{factor}} = 1.2$
- Harmonics: $h = 0.05\sin(3 \cdot 2\pi f_{\text{nom}} t) + 0.03\sin(5 \cdot 2\pi f_{\text{nom}} t) + 0.02\sin(7 \cdot 2\pi f_{\text{nom}} t)$
- Frequency Shift: $\Delta f = 2\,\text{Hz}$

5 Algorithms

5.1 MPPT Algorithms

- **Perturb & Observe (`mppt_perturb_observe`)**:

$$\text{If } P > P_{\text{prev}}, \quad V_{\text{mppt}} = V_{\text{mppt}} + \text{sign}(V_{\text{mppt}} - V_{\text{prev}}) \cdot \Delta V$$

$$\text{Else}, \quad V_{\text{mppt}} = V_{\text{mppt}} - \text{sign}(V_{\text{mppt}} - V_{\text{prev}}) \cdot \Delta V$$

$$P_{\text{prev}} = V \cdot I, \quad V_{\text{prev}} = V_{\text{mppt}}, \quad \Delta V = 1\,\text{V}, \quad 100\,\text{V} \le V_{\text{mppt}} \le 300\,\text{V}$$

- **Incremental Conductance (`mppt_incremental_conductance`)**:

$$G_{\text{inc}} = \frac{\Delta I}{\Delta V}, \quad \Delta I = I - \frac{P_{\text{prev}}}{V_{\text{prev}}}, \quad \Delta V = V - V_{\text{prev}}, \quad G = \frac{I}{V}$$

$$\text{If } |G_{\text{inc}}+G| < 0.01, \text{ at MPP; else if } G_{\text{inc}}+G > 0, \quad V_{\text{mppt}} = V_{\text{mppt}}+\Delta V; \text{ else } V_{\text{mppt}} = V_{\text{mppt}}-\Delta V$$

5.2 PLL

$$V_{\text{grid}} = (220 + \sin(0.2t) \cdot 10) \cdot \sqrt{2} \cdot \sin(2\pi(50 + \sin(0.1t))t)$$

$$f_{\text{PLL}} = \frac{1}{\text{period}}, \quad \text{period} = \frac{t - t_{\text{last}}}{N_{\text{cross}} - 1}$$

$$V_{\text{PLL}} = V_{\text{PLL}} + 0.1 \cdot (A_{\text{grid}} - V_{\text{PLL}}) \cdot \Delta t$$

$$e = V_{\text{grid}} \cdot V_{\text{inv}}, \quad \phi_{\text{corr}} = K_p \cdot e + K_i \cdot \int e\,dt$$

$$\phi_{\text{PLL}} = \mod(\phi_{\text{PLL}} + \phi_{\text{corr}} \cdot \Delta t, 2\pi)$$

$$\text{Locked if } |e| < 0.1 \cdot A_{\text{grid}} \cdot V_{\text{inv}} \cdot \sqrt{2}$$

5.3 Control Algorithms

- **Plant Model**:

$$V_{\text{inv}} = d \cdot V_{\text{rms}} \cdot \sqrt{2} \cdot \sin(2\pi f t + \phi), \quad V_{\text{grid}} = V_{\text{grid,rms}} \cdot \sqrt{2} \cdot \sin(2\pi f t)$$

$$\frac{di}{dt} = \frac{V_{\text{inv}} - V_{\text{grid}} - R \cdot I}{L}, \quad I = I_{\text{prev}} + \frac{di}{dt} \cdot \Delta t$$

- **PI Control**:

$$e = I_{\text{ref}} - I_{\text{meas}}, \quad I_{\text{ref}} = I_{\text{ref,ampl}} \cdot \sin(2\pi f t + \phi)$$

$$u = K_p \cdot e + K_i \cdot \int e\, dt, \quad K_p = 0.1, \quad K_i = 5.0$$

- **PR Control**:

$$u = K_p \cdot e + K_i \cdot \int e\, dt + K_r \cdot \sin(2\pi f t) \cdot e, \quad K_r = 50.0$$

- **SMC**:

$$s = e + c \cdot \frac{e - e_{\text{prev}}}{\Delta t}, \quad u = k \cdot \text{sign}(s), \quad c = 0.01, \quad k = 0.5$$

- **MPC**:

$$\text{Cost} = \sum_{j=0}^{1} (I_{\text{ref},j} - I_j)^2, \quad u = \arg\min_d \text{Cost}$$

5.4 Islanding Detection

- **Passive**:
  - OUV: Detect if $V < 193.6\,\text{V}$ or $V > 242\,\text{V}$.
  - OUF: Detect if $f < 49\,\text{Hz}$ or $f > 51\,\text{Hz}$.
  - ROCOF: $|(f - f_{\text{prev}})/(t - t_{\text{prev}})| > 1\,\text{Hz/s}$.
- **Active (AFS)**:

$$f = f + 0.5 \cdot \sin(2\pi \cdot 0.1 \cdot t) \quad \text{if grid connected}$$

$$\text{Detect if } |f - 50| > 0.7\,\text{Hz in islanded mode}$$

5.5 Frequency Analysis

$$G_{\text{controller}} = K_p + \frac{K_i}{s}, \quad G_{\text{plant}} = \frac{1}{s \cdot L + R + \frac{1}{s \cdot C}}$$

$$G = G_{\text{controller}} \cdot G_{\text{plant}}, \quad \text{Gain} = 20 \log_{10} |G|, \quad \text{Phase} = \arg(G) \cdot \frac{180}{\pi}$$