COSEDA usergroupmeeting 2024

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Modeling Cyber-Physical Power Systems using SystemC AMS

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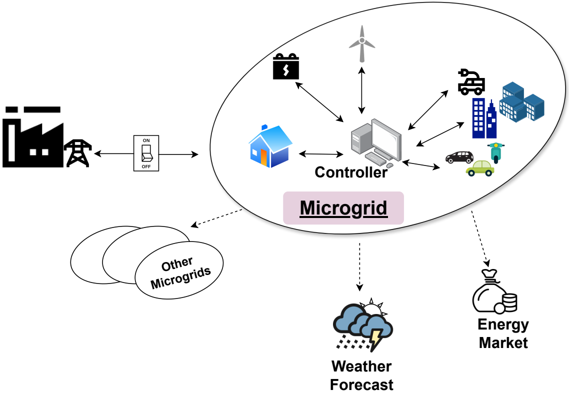
Agenda

1. **Motivation**
2. **Modeling and Simulation of Power Systems using SystemC-AMS**
3. **Use cases**
    - 3.1 Electromagnetic Transients in the Simulation for Open-loop System
    - 3.2 PV-based Grid-following Inverter Design for Microgrid
    - 3.3 Real-time Simulation of a DC Microgrid Model with Constant Resistive Load

Motivation

Microgrid as a Cyber-physical Systems

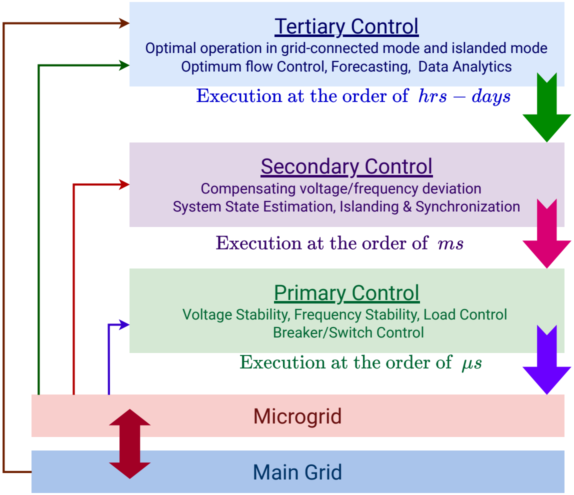


Key Challenges in Microgrid

- Advanced Monitoring and Control for Optimal Operations of Microgrid.
- Optimal selection and installation of microgrid components.

Controls in Microgrid

Proper control of microgrids is a prerequisite for stable and economically efficient operation.



Tertiary Control

Optimal operation in grid-connected mode and islanded mode
Optimum flow Control, Forecasting, Data Analytics

Execution at the order of $hrs - days$

Secondary Control

Compensating voltage/frequency deviation
System State Estimation, Islanding & Synchronization

Execution at the order of ms

Primary Control

Voltage Stability, Frequency Stability, Load Control
Breaker/Switch Control

Execution at the order of μs

Microgrid

Main Grid

How do we select components for microgrids?

- **Load analysis:** Analyze the load profile of the customers or end-users.
- **Generation and storage:** Select and size the generation and storage components of your microgrid, such as solar panels, wind turbines, and batteries, supercapacitors, etc.
- **Inverters and transformers:** Choose the right type, rating, and configuration of your inverters and transformers based on the voltage, current, and power factor of your microgrid
- **Protection and control:** select and size the protection and control components of your microgrid such as circuit breakers, fuses, relays, and switches, and sensors, meters, controllers, and communication devices.

Buying and trying each components one by one is a costly affair, but we may be able to perform a simulation for a given objective to decide what to buy!

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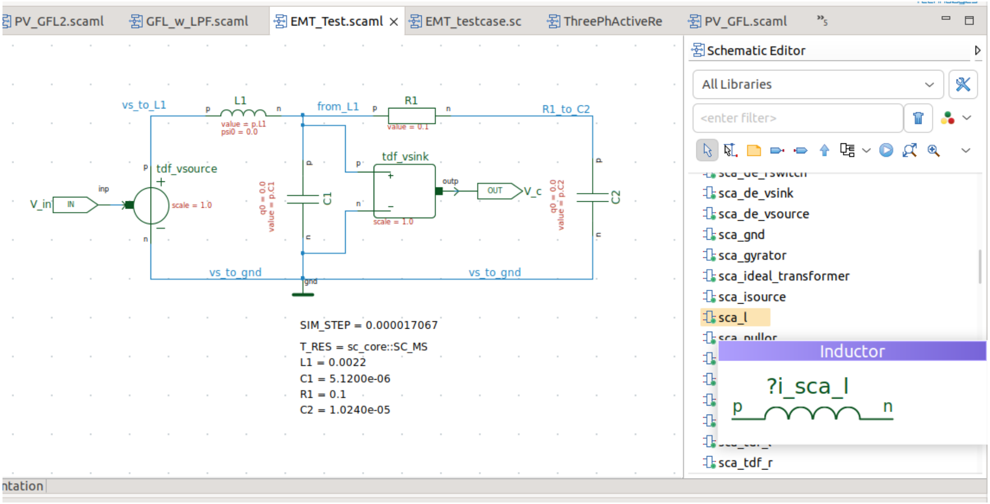
Modeling and Simulation of Power Systems using SystemC-AMS

Model-based Design using COSIDE



SIM_STEP = 0.000017067

T_RES = sc_core::SC_MS

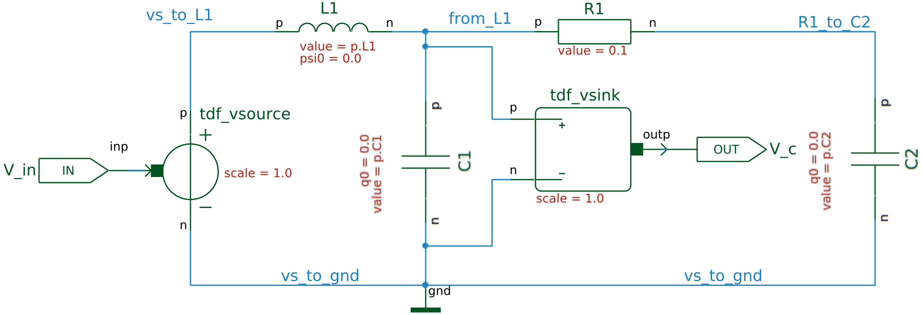
L1 = 0.0022

C1 = 5.1200e-06

R1 = 0.1

C2 = 1.0240e-05

Physical-modeling through ELN MoC

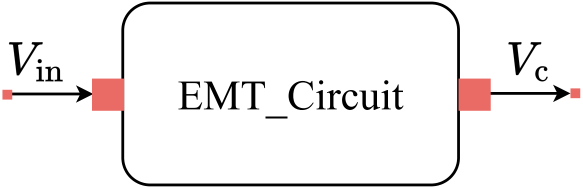


A circuit representating a physical model. This circuit was used to study electromagnetic transient phenomena. Let's call this **EMT Circuit**.

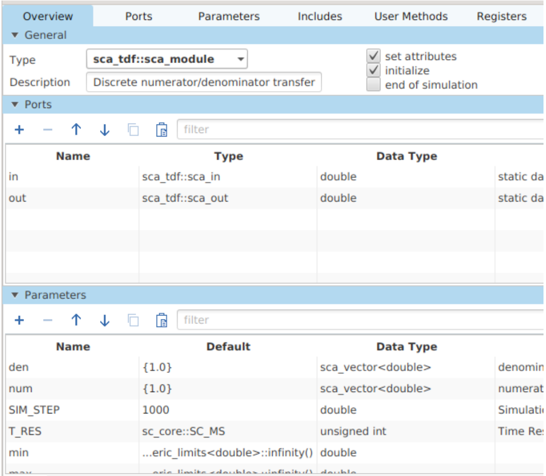
`tdf_vsink` models a voltmeter to measure the voltage across two terminals.

Abstraction of ELN Model

The designed circuit is abstracted as a library component that can be reused for creating more complicated circuitry.



Discrete-time models through TDF MoC-I



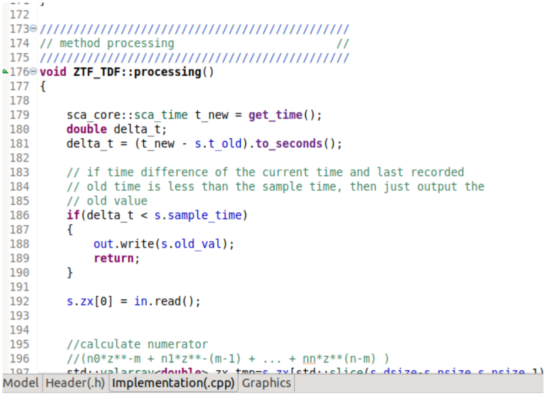
Type: **sca_tdf::sca_module**

Description: Discrete numerator/denominator transfer

☑ set attributes
☑ initialize
☐ end of simulation

Name	Type	Data Type	
in	sca_tdf::sca_in	double	static da
out	sca_tdf::sca_out	double	static da

Name	Default	Data Type	
den	{1.0}	sca_vector<double>	denomin
num	{1.0}	sca_vector<double>	numerat
SIM_STEP	1000	double	Simulati
T_RES	sc_core::SC_MS	unsigned int	Time Re
min	...eric_limits<double>::infinity()	double	

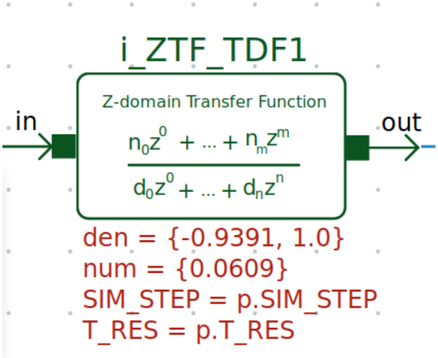


```
}

////////////////////////////////////////////
// method processing                      //
////////////////////////////////////////////
void ZTF_TDF::processing()
{

    sca_core::sca_time t_new = get_time();
    double delta_t;
    delta_t = (t_new - s.t_old).to_seconds();

    // if time difference of the current time and last recorded
    // old time is less than the sample time, then just output the
    // old value
    if(delta_t < s.sample_time)
    {
        out.write(s.old_val);
        return;
    }

    s.zx[0] = in.read();


    //calculate numerator
    //(n0*z**-m + n1*z**-(m-1) + ... + nn*z**(n-m) )
```

Users can implement the functionality of a TDF module in the `processing` function.

Discrete-time models through TDF MoC-II

- Used for implementing discrete models such as z-domain transfer function and discrete-time-based logic.

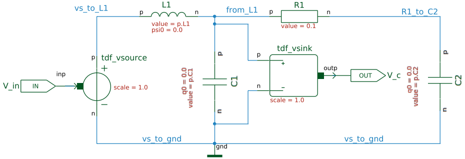


den = {-0.9391, 1.0}
num = {0.0609}
SIM_STEP = p.SIM_STEP
T_RES = p.T_RES

Use cases

Electromagnetic Transients in the Simulation for Open-loop System-I

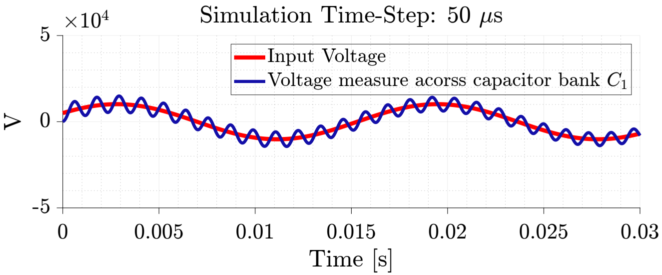
- Electromagnetic transients (EMTs) are short-term events that occur in power systems due to disturbances, faults, lightning strikes, or switching operations.
- EMT circuit example: An equivalent electromagnetic transient model of a wye-connected, solidly-grounded three-phase transformer with two capacitor banks



- The time constant $\tau = R\left(\frac{C_1 C_2}{C_1+C_2}\right) = 3.35 \times 10^{-7}$ sec $\quad C_1 = 5.12\mu F, C_2 = 10.24\mu F$
- Natural response at $\omega_0 = \frac{1}{\sqrt{L(C_1+C_2)}} = 5440 \mathrm{rad/s} \quad \Rightarrow T = \frac{2\pi}{\omega_0} = 1.15$ ms for the inductance $L = 2.2$ mH.

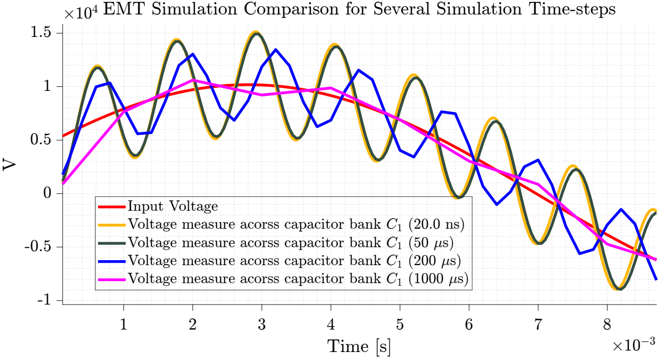
Electromagnetic Transients in the Simulation for Open-loop System-II

- The time step is typically much smaller than the natural response period of the circuit to accurately capture the circuit's transient behavior. We select a simulation time step of 0.05 ms or 50 μs.

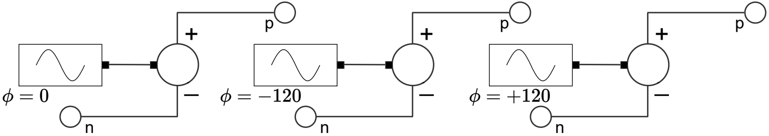


Electromagnetic Transients in the Simulation for Open-loop System-III

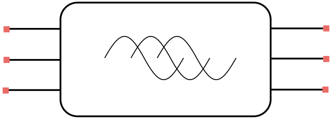
- Conducting the simulation with a substantially smaller time step, while focusing on a narrow region of the input/output signals, reveals that any simulation time step exceeding the system's time constant will not accurately capture the EMT.



Components of Microgrid-I

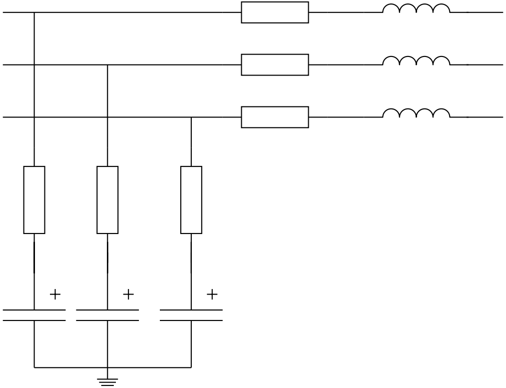


Three-phase Voltage Source



Abstraction of Three-phase Voltage Source

Components of Microgrid-II

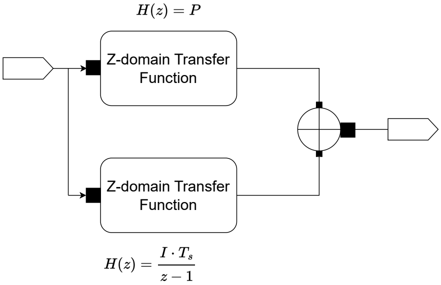


Three-phase Transmission Line

- Lossy transmission line
- Resistance in series with inductance to model transmission line impedance
- Shunt capacitance to the ground with shunt resistance

Components of Microgrid-II

$$y[n] = -\sum_{k=1}^{N} a_k y[n-k] + \sum_{k=1}^{M} b_k x[n-k]$$



z-domain parallel PI Controller using reusable z-domain TDF module.

Components of Microgrid-II

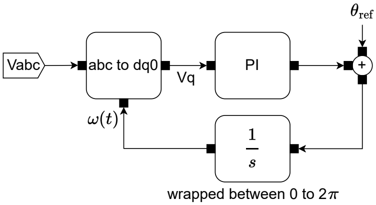
- AC signal's time-varying signal in *abc* reference frame converted to *dq0* reference frame using park transformation

$$d = \frac{2}{3}\left(a\sin(\omega(t)) + b\sin(\omega(t) - 2\frac{\pi}{3}) + c\sin(\omega(t) + 2\frac{\pi}{3})\right)$$

$$q = \frac{2}{3}\left(a\cos(\omega(t)) + b\cos(\omega(t) - 2\frac{\pi}{3}) + c\cos(\omega(t) + 2\frac{\pi}{3})\right)$$

$$z = \frac{1}{3}\left(a + b + c\right)$$

- PLL measures voltage phase angle by controlling the q-component of the three-phase voltage to zero through a PI controller.

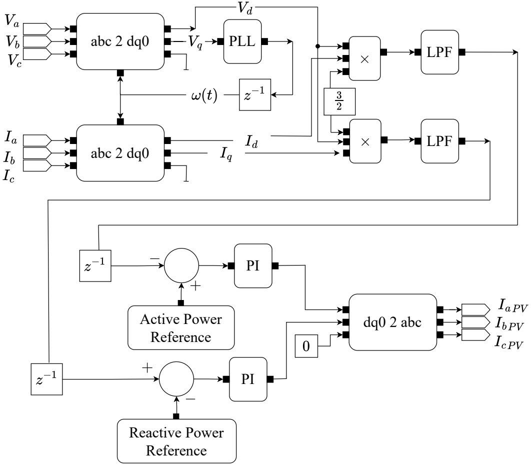


Phase-locked Loop

PV-based Grid-following Inverter Design for Microgrid-I

- Grid-following (GFL) control commonly employed in grid-connected inverters, enabling the inverter to function akin to a current source.
- The principal aim of a GFL inverter is to synchronize with the grid's frequency and to operate as a regulated current source at a designated power output.
- The inverter controller receives the desired active/ reactive power and maintains that.
- GFL inverters are capable of maintaining nearly constant output currents or power levels despite load variations.
- The fine-tuning of active and reactive power is achieved by monitoring the grid voltage, utilizing a Phase-Locked Loop (PLL), and a current control loop, which allows rapid adjustment of the GFL inverter's output current.

PV-based Grid-following Inverter Design for Microgrid-IIa

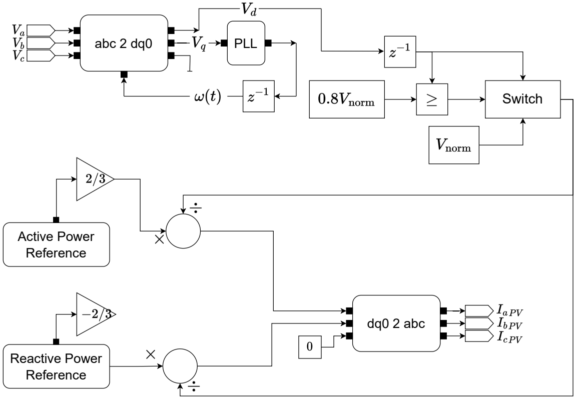


Simplified GFL inverter without inner current loops

- A PI controller operating in a dq-synchronous reference frame in a three-phase system.
- Two separate control loops to manage the direct and quadrature components.
- GFL inverters as PV source for this example.

Yazdani, Amirnaser, and Reza Iravani. **Voltage-sourced converters in power systems: modeling, control, and applications** *Chapter 8, 9.* John Wiley & Sons, 2010.

PV-based Grid-following Inverter Design for Microgrid-IIb



Simplified GFL inverter feedforward model

- Calculates the current references directly from the power references
- current references are fed into $dq - abc$ converter block.
- Can act as a PV source as well for modeling purposes.

Yazdani, Amirnaser, and Reza Iravani. **Voltage-sourced converters in power systems: modeling, control, and applications** *Chapter 8, 9*. John Wiley & Sons, 2010.

PV-based Grid-following Inverter Design for Microgrid-III

The GFL's control objective is to manage the real power, P_s, and the reactive power, Q_s, injected into the grid from the inverter.

$$\begin{aligned} P_s(t) &= \frac{3}{2}[V_{sd}(t)i_d(t) + V_{sq}(t)i_q(t)] \\ Q_s(t) &= \frac{3}{2}[-V_{sd}(t)i_q(t) + V_{sq}(t)i_d(t)] \end{aligned} \tag{1}$$

Given that $V_{sq} = 0$,

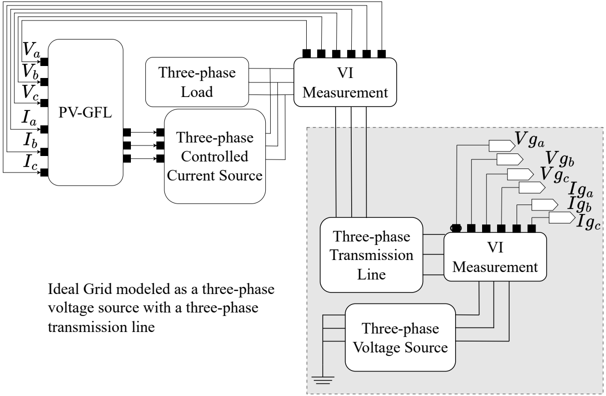
$$\begin{aligned} P_s(t) &= \frac{3}{2}V_{sd}(t)i_d(t) \\ Q_s(t) &= -\frac{3}{2}V_{sd}(t)i_q(t) \end{aligned} \tag{2}$$

From the equations, we derive separate current references in the dq domain,

$$\begin{aligned} i_{d,\mathit{ref}}(t) &= \frac{2}{3V_{sd}}P_{s,\mathit{ref}}(t) \\ i_{q,\mathit{ref}}(t) &= -\frac{2}{3V_{sd}}Q_{s,\mathit{ref}}(t) \end{aligned} \tag{3}$$

where *ref* notation is used for reference signals.

PV-based Grid-following Inverter Design for Microgrid-IV



- PV-GFL model receives three-phase voltage $V_{a,b,c}$ and three-phase current $I_{a,b,c}$ as inputs and outputs regulated current $I_{aPV,bPV,cPV}$ as output.
- The overall model comprises an algebraic loop which can be broken by introducing a delay unit z^{-1} (where is z variable is from z-transform) in the GFL inverter model.

PV-based Grid-following Inverter Design for Microgrid-V

We measure the instantaneous active and reactive power P, and Q using three-phase voltages $V_{a,b,c}$, and currents $I_{a,b,c}$ using the formula from Equation (4) as follows:

$$\begin{aligned} P &= V_a I_a + V_b I_b + V_c I_c \\ Q &= \frac{1}{\sqrt{3}}\Big((V_a - V_b)I_c + (V_b - V_c)I_a + (V_c - V_a)I_b\Big) \end{aligned} \tag{4}$$

where V_a, V_b, V_c are components of the three-phase voltage $V_{a,b,c}$, and I_a, I_b, I_c are components of the three-phase current $I_{a,b,c}$.

Yazdani, Amirnaser, and Reza Iravani. **Voltage-sourced converters in power systems: modeling, control, and applications**. John Wiley & Sons, 2010.

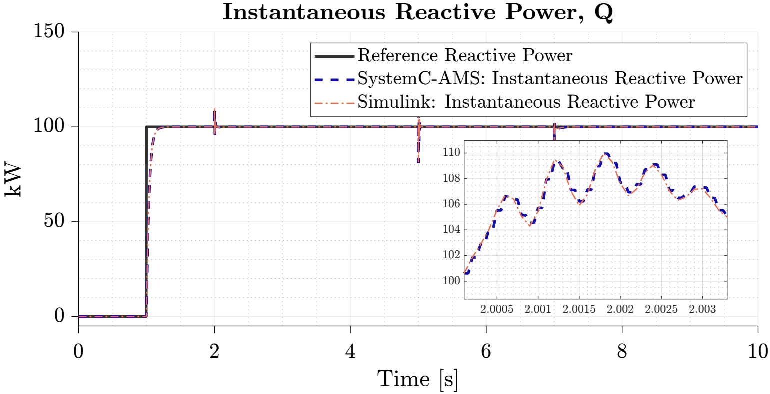
PV-based Grid-following Inverter Design for Microgrid-VI

To conduct the simulation in SystemC-AMS:

- simulation time-step of $50\ \mu\mathrm{s}$
- run the simulation for $10\ \mathrm{s}$
- The three-phase root-mean-square phase-to-phase voltage of 480 V operating at 60 Hz
- The transmission line modeled as a series resistance of $0.01\ \Omega$, a series inductance of $0.0001\ H$, a shunt resistance of $0.15\ \Omega$, and shunt capacitance of $80\ \mu F$.
- The low-pass filter (LPF block) uses the z-domain transfer function $\frac{0.0609}{z-0.9391}$ at the sampling rate of $1000\ \mathrm{Hz}$.

PV-based Grid-following Inverter Design for Microgrid-VII

Step-response and comparison with a Simulink Implementation (GFL inverter without inner current loops):



PV-based Grid-following Inverter Design for Microgrid-VIII

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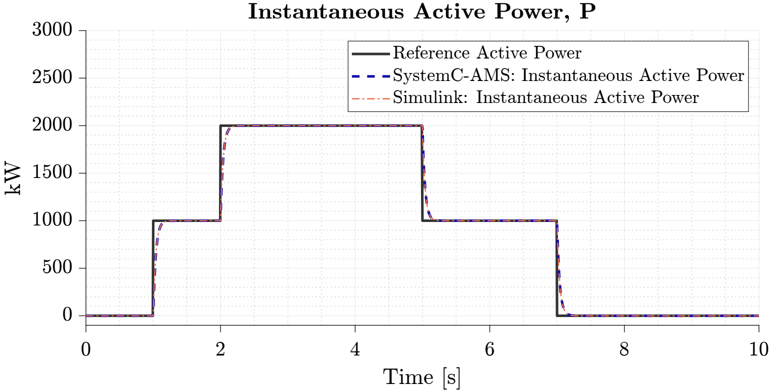
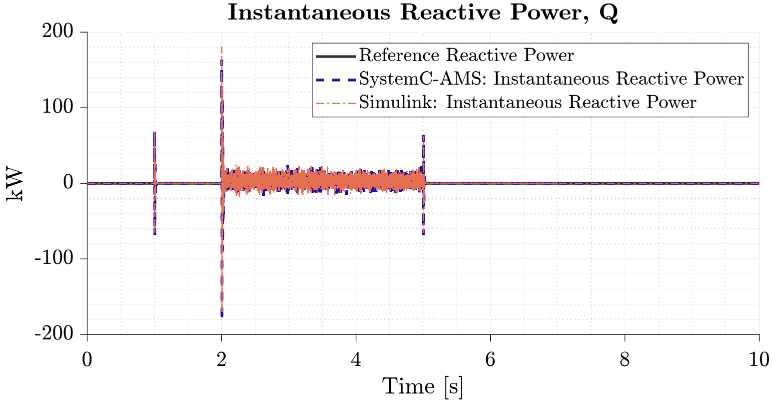
Step-response and comparison with a Simulink Implementation (GFL inverter without inner current loops):



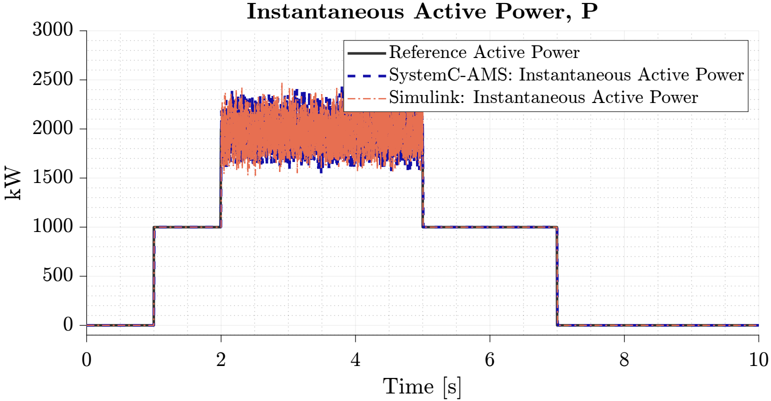
PV-based Grid-following Inverter Design for Microgrid-IX

Step-response and comparison with a Simulink Implementation (GFL inverter feedforward model):



PV-based Grid-following Inverter Design for Microgrid-X

Step-response and comparison with a Simulink Implementation (GFL inverter feedforward model):



PV-based Grid-following Inverter Design for Microgrid-XI

- The RMS error of the instantaneous active power and reactive power compared to the reference for SystemC-AMS and Simulink simulation:

Parameter	**SystemC-AMS Simulation**	**Simulink Simulation**
Without Inner Current Loops		
Active Power RMS Error (kW)	85.78328	85.87311
Reactive Power RMS Error (kVar)	4.35805	4.36262
Feedforward Model		
Active Power RMS Error (kW)	80.39742	80.20730
Reactive Power RMS Error (kVar)	5.92436	5.8789

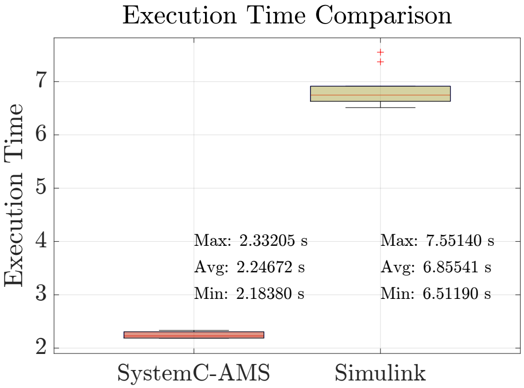
Table: Comparison of RMS Errors for SystemC-AMS and Simulink Simulations for Step Input

RMS Error for active power is will within 1% of the initial amplitude of 1000 kW.

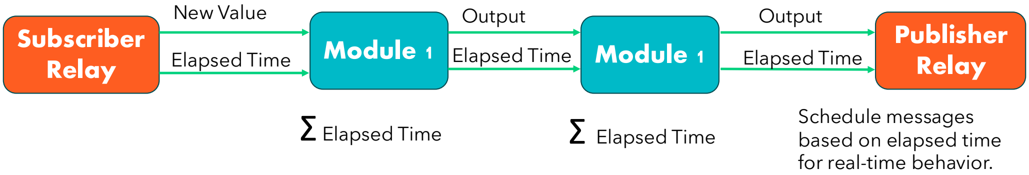
- The first transient takes approximately 0.2 seconds to stabilize.
- RMS error for reactive power between Simulink and SystemC-AMS simulink, while transient lasted were 0.04996 kVar.

PV-based Grid-following Inverter Design for Microgrid-XII

Run-time Comparison: SystemC-AMS implementation 3x faster



Real-time Simulation



Schedule messages based on elapsed time for real-time behavior.

- High-performance C++ Chrono library for measuring time.
- Execution in Ubuntu with PREEMPT RT kernel patch.
- Specify highest CPU priority for execution.
- Disable memory swapping using `mlockall` to prevent page fault for deterministic behavior.

Representative DC Microgrid-I

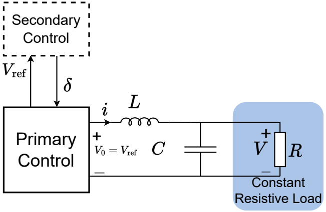
- DC Microgrid consisting of a source converter and a constant resistive load.
- The source converter is modeled as a primary controller and a secondary controller.
- We assume that the converter output voltage is regulated to the reference voltage by the inner control loops, i.e.,

$$V_0 = V_{\text{ref}}$$

- $V_0 = V_{\text{ref}}$ is given by the droop controller which acts as a primary controller in our case:

$$V_{\text{ref}}(t) = \overbrace{V_n}^{\text{Nominal voltage of the DC grid}} - \overbrace{K}^{\text{Droop gain}} i(t)$$

Representative DC Microgrid-II

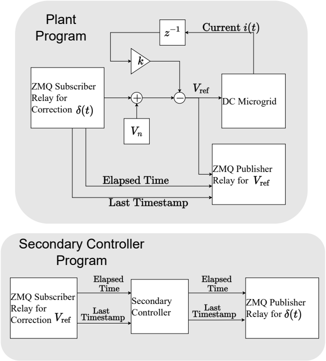


$$
\begin{aligned}
V_n'(t) &= \delta(t) + V_n \\
V_{\mathsf{ref}}(t) &= V_n'(t) - k \cdot i(t) \\
\delta(t) &= \int \overbrace{k_s}^{\substack{\text{Integral Gain} \\ \text{for the} \\ \text{secondary controller}}} (V_n - V_{\mathsf{ref}}(t))dt
\end{aligned}
\tag{5}
$$

- In addition, the primary controller, we have a secondary controller to compensate for the voltage deviation caused by the primary controller.
- Secondary controller is modeled as an integral controller for correction term $\delta(t)$.

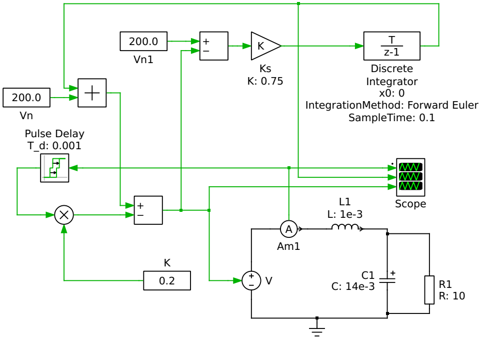
Plant and Controller Simulation for DC Microgrid

- The inductor and capacitor (the equivalent of line impedance, filters, and DC bus capacitor in an actual grid) along with the resistive load constitute a DC microgrid and taken together with the primary controller act as the plant model.
- The Secondary controller is isolated from the plant.
- The Plant and the secondary controller communicate via the ZeroMQ interface.
- The plant is executed at the time-step of 1 ms while the secondary controller is executed at the time-step of 100 ms.

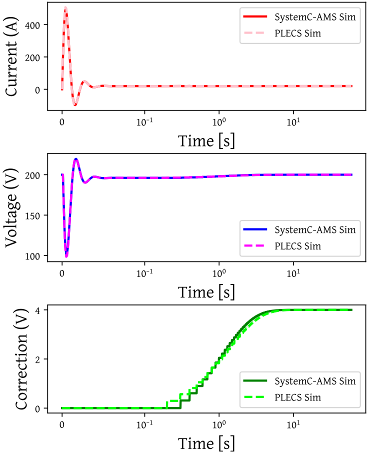


Benchmarking Against PLECS for correctness

PLECS is a widely adopted tool for power electronics simulation. We had reference implementation in PLECS for the overall DC microgrid model (along with the secondary controller). PLECS doesn't allow communicating via network interfaces.



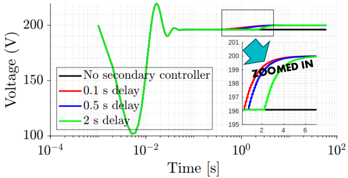
Voltage, Current and Correction Term

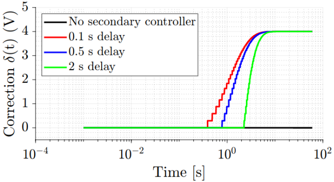


- We measured the current, voltage (adjusted reference voltage from the equations for the secondary controller), and correction terms for real-time simulation and compared them against the PLECS simulation.
- We measured RMS error between two simulations to assess how close they are to each other.

Delayed Start of the Controller

- In a distributed settings (where the plant and the controller are two separate entities) initially, the plant may operate on its own in an open-looper manner.
- Later on the controller may be online and connect with the plant at any point in time in the future.
- To simulate such a scenario, we delay the start of the controller program as compared to the plant program.
- For the DC microgrid situation, the voltage stabilizes later if the controller comes online at a later time.





THANK YOU!!!

Contact: rahul.bhadani@uah.edu

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UNIVERSITY

NC STATE
UNIVERSITY

U.S. DEPARTMENT OF
ENERGY

arpa·e
CHANGING WHAT'S POSSIBLE

Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0001580