MATLAB/Simulink 환경에서 그린 수소 공급망에 대한 솔루션

강효석 부장/Ph.D., 매스웍스코리아
Enabling Green Hydrogen – Supply Chain

Stage 1: Green Hydrogen Production
Stage 2: Hydrogen Distribution
Stage 3: Hydrogen Consumption
Enabling Green Hydrogen – Microgrid

Water \rightarrow \text{Electricity} \rightarrow \text{Hydrogen (gas)}

Wind (speed) \rightarrow \text{Generator} \rightarrow \text{Electrolyzer}

Multi-domain simulation

MATLAB & Simulink

Simscape
Enabling Green Hydrogen – Motivation

Advantages
- 100% sustainable
- storable
- versatile
- transportable

Deltas
- high energy consumption
- high cost
- safety (managing H2)

“Green hydrogen: an alternative that reduces emissions and cares for our planet”
Iberdrola > Sustainability > Green Hydrogen
Enabling Green Hydrogen – Key Takeaways

- Assert feasibility
  - Techno-economic analyses
  - Proven concept

- Secure sustainable and robust operation
  - Design Automation
  - Optimization
Stage 1. Green Hydrogen Production (from renewable energy to gas)
Enabling Green Hydrogen - Challenges

Component design
- electrolyzer
- energy storage
- power converter unit
- generator

Asset digitalization
- anomaly detection
- lifetime estimation
- prognostics development

Plant design
- concept evaluation
- physical requirements
- energy balance

High-level algorithmic design
- supervisory logic
- setpoint definition
Enabling Green Hydrogen – Model Fidelity

milliseconds (ms)  microseconds (us)

Embedded development (component)

seconds minutes

Key performance assessment (system)

months years

Techno-economic Analysis (TEA)

High fidelity

Medium fidelity

Low fidelity

Quasi-steady (8760) simulations
What Is a Quasi-Steady Simulation and Why Is It Important for Techno-Economic Applications?

- Techno-economic assessments are typically conducted across long durations of time at regular time-intervals ranging from 1 minute to 1 hour (1 hour intervals across 1 year is common – a so called 8760 simulation).

- Techno-economic assessments typically do not care about system dynamics but do care about steady-state operational conditions at each time-interval.

- A quasi-steady simulation assumes that, at each time-step, the dynamics of a system are fast enough that they have reached steady-state. It is primarily an algebraic, time-based simulation.

- A quasi-steady simulation therefore provides a foundation for techno-economic assessments.
Reduced Order Modeling

- To incorporate a physical component and its functional control response into a quasi-steady simulation, we need to **remove the dynamics** associated with moving from one operating point to another.

- One way of doing this with an electrical component, is to create a **Thevenin Equivalent model**, with Look-Up Tables (LUTs) that define source voltage and source impedance for a given power level.

- We can also consider the response of a **power converter by creating a LUT that maps duty-cycle to voltage level**.
Enabling Green Hydrogen – TEA (Solar Microgrid)

Performance assessment

Techno-economic analyses

Solar cell & MPPT algorithm

Low fidelity

Medium fidelity

Low fidelity

Reduced Order Modeling (ROM)
Green Hydrogen Production – TEA (Solar Microgrid)
Enabling Green Hydrogen – TEA (Data Re-use)

**The irradiance data** is 8760 TMY3 from National Renewable Energy Laboratory.

**Electricity price data** is one day of data from system operators.
Enabling Green Hydrogen – TEA (Outcome)

H₂ production: Highest grid cost & Lowest solar resource

Elapsed time is 510.209014 seconds.

Lowest grid cost is USD 6761.6456 at Phoenix Sky Harbor Intl AP
Highest solar resource is 497.1227MWh at Daggett Barstow-Daggett AP

Highest grid cost is USD 13217.5585 at Quillayute State Airport
lowest solar resource is 291.2997MWh at Quillayute State Airport

242 years in 500 seconds i.e.
1 year every 2 seconds

Reduced Order Models + Parallel Computing = Agile Insights (decision-making)
Enabling Green Hydrogen – System Performance

- expected H\(_2\) production & water consumption
- suitable control strategy (conditions, use of physical assets)
- energy storage (dimensioning, expected duty regime)
- planning of operations (collect – replace - maintain)
Enabling Green Hydrogen – System Performance
Enabling Green Hydrogen – System Performance
Enabling Green Hydrogen – System Performance
Enabling Green Hydrogen – System Performance
Enabling Green Hydrogen – System Performance
Enabling Green Hydrogen – System Performance

Voltage-based Control

Energy-based Control

38kg

46kg

51%

65%

Medium fidelity
Recap of Green Hydrogen Production

- Assert feasibility
  - Techno-economic analyses
  - Proven concept
Stage 2. Hydrogen Distribution (from tank to consumers)
Enabling Green Hydrogen – Challenges H2 Handling and Usage

(Stage 2)

Transfer (tank-to-cell)

- Optimal components sizing (cooling, storage, compressors)
- Reliable 24/7 software operation
- Meet critical safety requirements
Modeling Gas Systems with Simscape

- Case study: Hydrogen Refueling Station

Compressor → High Pressure Storage → Chiller → Dispenser → Vehicle

- Compressor: 950 bar
- High Pressure Storage: 30 bar
- Chiller: -40°C
- Dispenser: 30 bar - 40°C
- Vehicle: Test case: 30 bar -> 700 bar
  m_H2 = 6 kg
  Δt <300 s
Hydrogen Gas Refuelling Station

copyright MathWorks 2022

Hydrogen Low Pressure Supply

Compressor

Heat Exchanger

Software
Enabling green hydrogen – Case Study
Enabling green hydrogen – Case Study
Algorithm Model and Deployment on Real-time Controller

- Automatic code generation from models
- Reduced coding time & errors
- Hardware independent source code
- Know-how captured in single source (model)

All relevant PLCs supported

<table>
<thead>
<tr>
<th>Vendor</th>
<th>IDE</th>
<th>IEC 61131-3</th>
<th>C/C++</th>
<th>Connections Partner</th>
</tr>
</thead>
<tbody>
<tr>
<td>3B - Smart Software Solutions</td>
<td>CODESYS</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>B&amp;R Industrial Automation</td>
<td>Automation Studio</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Bachmann Electronic</td>
<td>SolutionCenter</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Beckhoff Automation</td>
<td>TwinCAT</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Bosch Rexroth</td>
<td>IndraWorks</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Mitsubishi Electric</td>
<td>CW Workbench</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Omron</td>
<td>Sysmac Studio</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Phoenix Contact</td>
<td>PC WORX</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Rockwell Automation</td>
<td>RSLinx / Studio 5000</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Siemens</td>
<td>TIA Portal / STEP 7</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

PLCs, ECU, custom hardware
Scalable to Certification Workflows Ensuring Highest Quality & Safety

- IEC 61508 - Safety-related systems
- ISO 26262 - Automotive / Motorcycle
- ISO 25119 - Agriculture and Forestry
- EN 50128 - Rail
- IEC 62304 - Medical
- IEC 61511 - Process Control
- DO-178 & DO-254

MATLAB and Simulink
For Verification, Validation and Test
Enabling Green Hydrogen – Challenges H2 Handling and Usage

(Stage 2)

Transfer
(tank-to-cell)

- Optimal components sizing
  (cooling, storage, compressors)
    ➢ Leverage multi-domain simulation platform
- Reliable 24/7 software operation
  ➢ Develop supervisory logic with state-of-the-art V&V capabilities
- Meet critical safety requirements
  ➢ Model-Based Design streamline certification of your embedded systems
Stage 3. Hydrogen Consumption (e-mobility, electrification)
Enabling Green Hydrogen – Challenges H2 Handling and Usage

(Stage 2)

Transfer (tank-to-cell)

- Optimal components sizing (cooling, storage, compressors)
  - Leverage multi-domain simulation platform
- Reliable 24/7 software operation
  - Develop supervisory logic with state-of-the-art V&V capabilities
- Meet critical safety requirements
  - Model-Based Design streamline certification of your embedded systems

(Stage 3)

Consumption (E-mobility)

- Component-level vs system-level simulation
- Optimal system architecture (e.g., fuel cell multi-stack, battery)
- Expensive physical prototype testing
Fuel Cell System in Vehicle

- Fuel Cell System
- Air Handling System
- Cooling / Thermal Management
- Hydrogen Handling System
- Power Distribution Unit
- Balance of Plant (BoP)
- DC/DC Converter
Multiple Domains Used to Simulate Fuel Cell Systems….

Custom Fuel Cell Domain
Multispecies gas network for N₂, O₂, H₂, H₂O

Membrane
Exchange species and generate elec. power & heat, N₂ diffusion

Controllers

Try it out in **R2022a**: `>> sscfluids_fuel_cell`
... and Electrolyzers!

Moist air domain
3-species gas network for $O_2, H_2, H_2O$

Try it out in R2022a:

>> ssc_electrolyzer
High fidelity video in action

Add video of high fidelity fuel cell, 1 min
Fuel cell system operation in an FCV
- Determine instantaneous power demand
- Convert power demand to current demand
- Translate current command to H2 / Air flow commands
- Distribute current demand between battery and fuel cell
Choose the Appropriate Fidelity Level for Fuel Cell System Modeling

Model what you need … when you need it

Model Complexity and Details

Computational Time

Voltage vs. current curve

Lookup-table statistical model no dynamics

Detailed first principles model with gas dynamics

Detailed first principles model without gas dynamics

Model Complexity and Details
Enabling Green Hydrogen – Solution (EMobility/Fuel cells)
Enabling Green Hydrogen – Solution (Electric mobility/fuel cells)
System Level Electrified Propulsion Unit

- Explore design space
  - Example:
    - Config1: 3 Battery Modules, 2 Fuel Cell Stacks
    - Config2: 2 Battery Modules, 3 Fuel Cell Stacks

![Graph showing energy output over time for Config1 and Config2.](image)
Hardware-in-the-Loop

Development Computer

Target Computer

Device Under Test

- Ethernet
- Emulated Sensor Signals, Digital Protocols (CAN)
- Controller Commands
Enabling Green Hydrogen – Challenges H2 Handling and Usage

(Stage 2)
Transfer (tank-to-cell)

- Optimal components sizing (cooling, storage, compressors)
  ➢ Leverage multi-domain simulation platform
- Reliable 24/7 software operation
  ➢ Develop supervisory logic with state-of-the-art V&V capabilities
- Meet critical safety requirements
  ➢ Model-Based Design streamline certification of your embedded systems

(Stage 3)
Consumption (E-mobility)

- Component-level vs system-level simulation
  ➢ Flexible modelling and simulation platform
- Optimal system architecture (e.g., fuel cell multi-stack, battery)
  ➢ Perform trade-off analysis and monte carlo simulations
- Expensive physical prototype testing
  ➢ Reduce physical prototypes, reuse models for Hardware-in-the-Loop tests
User Testimonial – Nuvera Cells

Hydrogen Is the New Diesel: Electrifying Heavy-Duty Vehicles with Nuvera Fuel Cells

Video

“Using modeling and real-time simulation enables Nuvera’s engineers to iterate on their design quickly and allows for experimentation without putting a real engine at risk. “
Enabling Green Hydrogen - Conclusions

- Assert feasibility
  - techno-economic analyses
  - concept evaluation

- Secure sustainable and robust operation
  - design automation
  - optimization
Call to Action

- **Developing Hydrogen Production and Fuel Cell Applications with MATLAB and Simulink**
  - In-depth videos & resources
  - Customer references

- **Additional resources**
  - MATLAB and Simulink for the Utilities and Energy Industry
  - MATLAB and Simulink for Electric Vehicle Development
  - MATLAB and Simulink for Developing Power Generation and Transmission Equipment
  - MATLAB and Simulink for Verification, Validation and Test

- **Shipping examples**
  - PEM Fuel Cell System (2022a)
  - PEM Electrolysis System (2022a)
MATLAB EXPO

Thank you