NASA Mission to MARS Program – Innovative DC Microgrid Proof of Concept for Spacecraft

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Space Grid Management for Human Deep Exploration

Objectives of NASA Phase I Project

- Holomorphic Embedding Load Flow (HELM™) for autonomous spacecraft power systems
- Adapted HELM™ code to analyze non-linearity of DC models
- Benchmarked HELM™ on 300 bus IEEE model to demonstrate reliable solution at point of voltage collapse
- Find synergy between autonomous control of spacecraft power systems with control of AC terrestrial grids and microgrids

Autonomous Control of Spacecraft Power Systems

- Spacecraft Power Systems are DC microgrids that must be extremely robust
- International Space Station (ISS) and manned space missions in near earth orbit have constant ground support from Houston Mission Control Center
- Deep space travel to MARS will require autonomous control due to communication latency
- Communication latency for MARS mission would be anywhere from 15 to 45 minutes depending on the proximity of MARS orbit in relationship to Earth
The Main Challenge

• Communication and recovery times are much longer

<table>
<thead>
<tr>
<th>Mission</th>
<th>Duration of Mission After Incident</th>
<th>Communication Latency Time</th>
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</thead>
<tbody>
<tr>
<td>Deep Space Habitat</td>
<td>9 months to 1 year</td>
<td>15 to 45 mins.</td>
</tr>
<tr>
<td>Apollo/Orion</td>
<td>3 – 5 days</td>
<td>1 to 2 sec.</td>
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<tr>
<td>Mount Everest</td>
<td>1 – 2 days</td>
<td>Real time</td>
</tr>
<tr>
<td>Deep Sea Submersible</td>
<td>8 hours</td>
<td>Real time</td>
</tr>
<tr>
<td>Shuttle</td>
<td>2 – 5 hours</td>
<td>Real time</td>
</tr>
<tr>
<td>Submarine</td>
<td>1 – 2 hours</td>
<td>Real time</td>
</tr>
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• Power Most Critical System On Board Vehicle
  – System need high availability and to operate autonomously for long periods of time

Choice of Cases
IEEE 300 Bus Model

- Hypothetical model of complex AC power grid
- Several nodes near voltage collapse
- HELM™ technology can accurately determine distance to collapse
- A roadmap can be provided back to stable system even if system has partially collapsed
Spacecraft Power System Architecture

- DC-based microgrid
  - Solar arrays
  - Energy storage
  - Power/voltage regulator
  - Sensitive loads

- Highly non-linear components

Non-linear Behavior of Components

- The nonlinear behavior of components results in multiple equilibrium points. The actual equilibrium state is determined by the stability of the equilibrium points.

Finding equilibrium by solving Ordinary Differential Equations:

\[
\frac{dx}{dt} = F(x, y, u, p)
\]

\[
x = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \end{bmatrix}, \quad y = \begin{bmatrix} i_1 \\ i_2 \\ \vdots \end{bmatrix}, \quad u = \begin{bmatrix} V_{\text{ref}} \\ \vdots \end{bmatrix}, \quad p = \begin{bmatrix} I_{SC} \\ V_{OC} \end{bmatrix}
\]

HELM™ Flow DC Adaptation: Diode Example

Diode Example

![Diode Circuit Diagram]

Diode: \( i(u) = I_s ( \exp(\frac{u}{VT}) - 1) \)

- \( VT \approx 25 \text{ mV}, \ I_s = 1 \text{ nA} \)
- \( E = 5 \text{ V}, \ R = 10 \Omega \)

Solution: \( u \approx 498.13 \text{ mV} \)

- Number of DC iterations depend on the initial guess

<table>
<thead>
<tr>
<th>Initial Guess [V]</th>
<th>Number of Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>184</td>
</tr>
<tr>
<td>0.7</td>
<td>11</td>
</tr>
<tr>
<td>1.5</td>
<td>43</td>
</tr>
<tr>
<td>3.5</td>
<td>123</td>
</tr>
</tbody>
</table>

- For Diode element, initial guess
  \( u_0 = VT \cdot \ln[VT/(\sqrt{2}I_s)] \approx 417.2 \text{ mV} \) is usually used

- Better convergence: select the NR iteration step size such that the error norm is minimized and/or limit somehow the change of controlling voltages of nonlinear elements
DC-based HELM for Intelligent Power Control

Power Source → Power and Voltage Regulator → Power Distribution (DC) → Spacecraft Load

DC-based HELM

Backup Energy Storage
Terrestrial Microgrids

- Part of Phase I Project was to demonstrate technology for terrestrial microgrids

Emerging Microgrids will require more robust software

Next Step: NASA Phase II – Orion Spacecraft

- Developing autonomous power systems management for Orion Spacecraft for Mars Mission
- Implementing distributed control architecture for power balancing
- Integrating HELM™ into software for modeling Orion Spacecraft power systems management system