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

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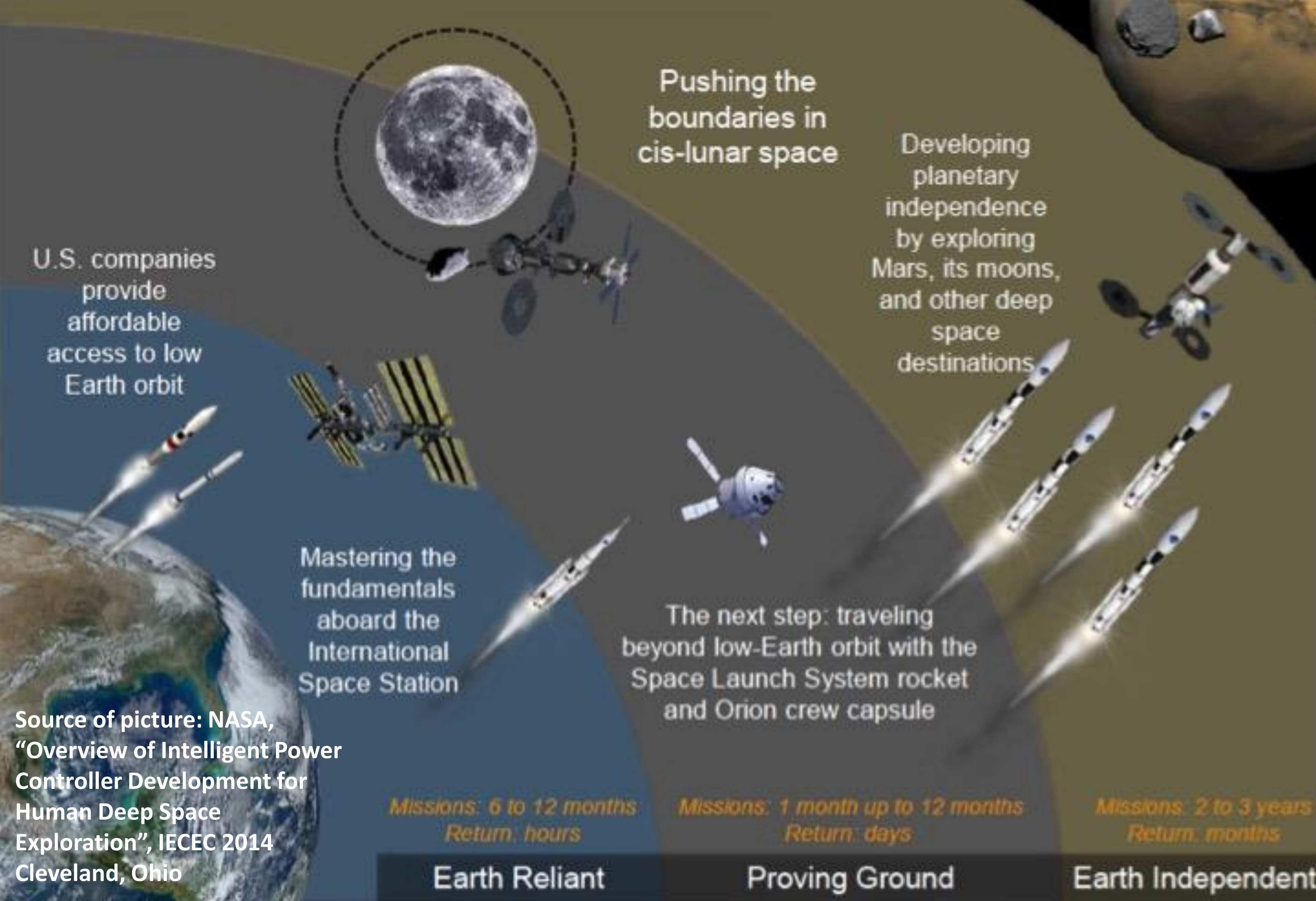
Space Grid Management for Human Deep Exploration



Source of picture: NASA, "Overview of Intelligent Power Controller Development for Human Deep Space Exploration", IECEC 2014 Cleveland, Ohio

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

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HELM™ - Trias, A. "The Holomorphic Embedding Load Flow Method", in Power and Energy Society General Meeting, 2012 IEEE, pp. 1-8, 2012

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

Mission	Duration of Mission After Incident	Communication Latency Time
Deep Space Habitat	9 months to 1 year	15 to 45 mins.
Apollo/Orion	3 – 5 days	1 to 2 sec.
Mount Everest	1 – 2 days	Real time
Deep Sea Submersible	8 hours	Real time
Shuttle	2 – 5 hours	Real time
Submarine	1 – 2 hours	Real time

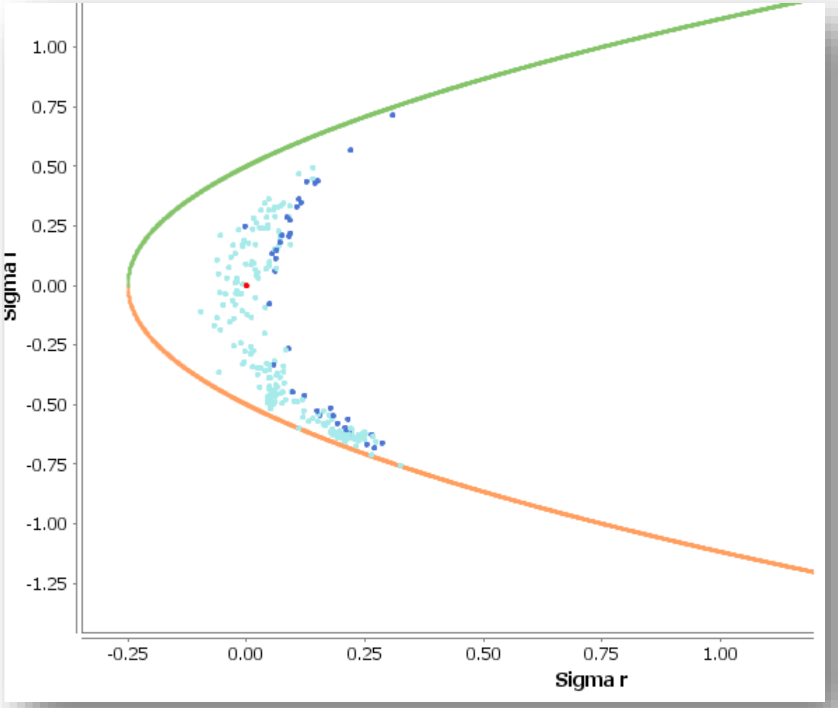
- Power Most Critical System On Board Vehicle
  – System need high availability and to operate autonomously for long periods of time

Source of slide: NASA, "Overview of Intelligent Power Controller Development for Human Deep Space Exploration", IECEC 2014 Cleveland, Ohio

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

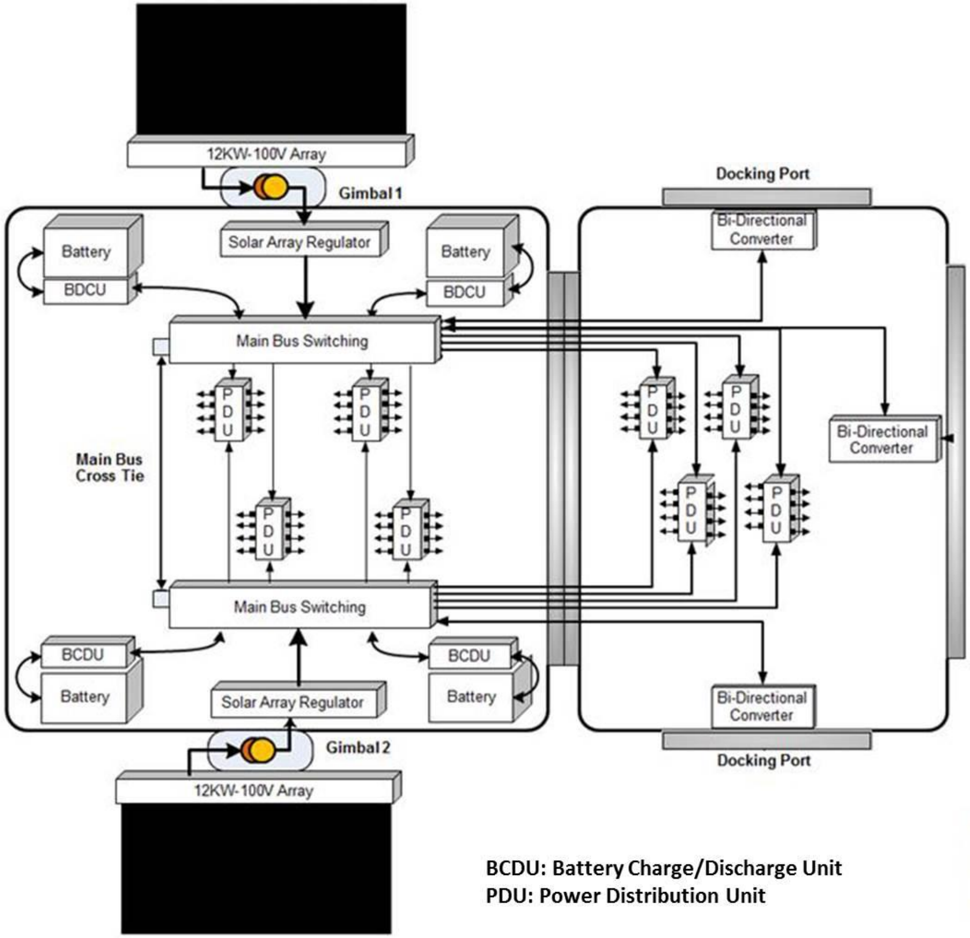
IEEE 300 Bus Model
HELM™ Sigma Curve



Spacecraft Power System Architecture

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

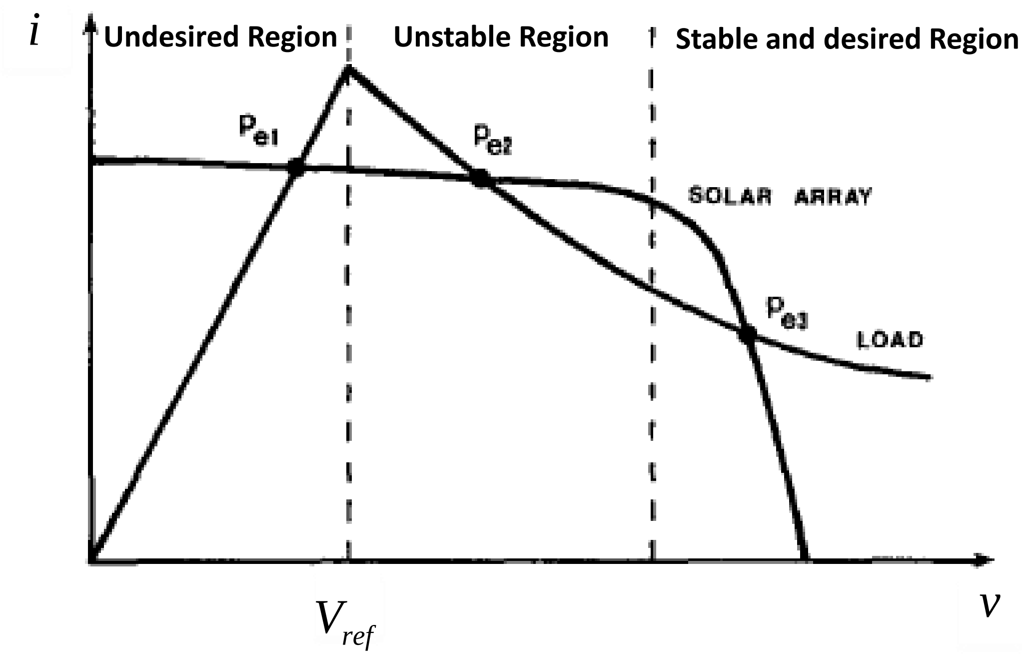
- Highly non-linear components



Source of picture : Soeder, James F., et al. "Overview of Intelligent Power Controller Development for Human Deep Space Exploration", 2014.

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:

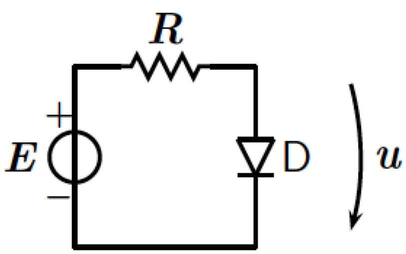
$$\frac{dx}{dt} = F(x, y, u, p)$$

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

Source : Cho, Bo H., Jae R. Lee, and Fred CY Lee. "Large-signal stability analysis of spacecraft power processing systems", Power Electronics, IEEE Transactions on 5, no. 1, pp. 110-116, 1990.

HELM™ Flow DC Adaptation: Diode Example

Diode Example



Diode: $i(u) = I_s(\exp(u/VT) - 1)$

$VT \approx 25$ mV, $I_s = 1$ nA

$E = 5$ V, $R = 10\,\Omega$

Solution: $u \approx 498.13$ mV

- Number of DC iterations depend on the initial guess

initial guess [V]	number of iterations
0.1	184
0.7	11
1.5	43
3.5	123

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

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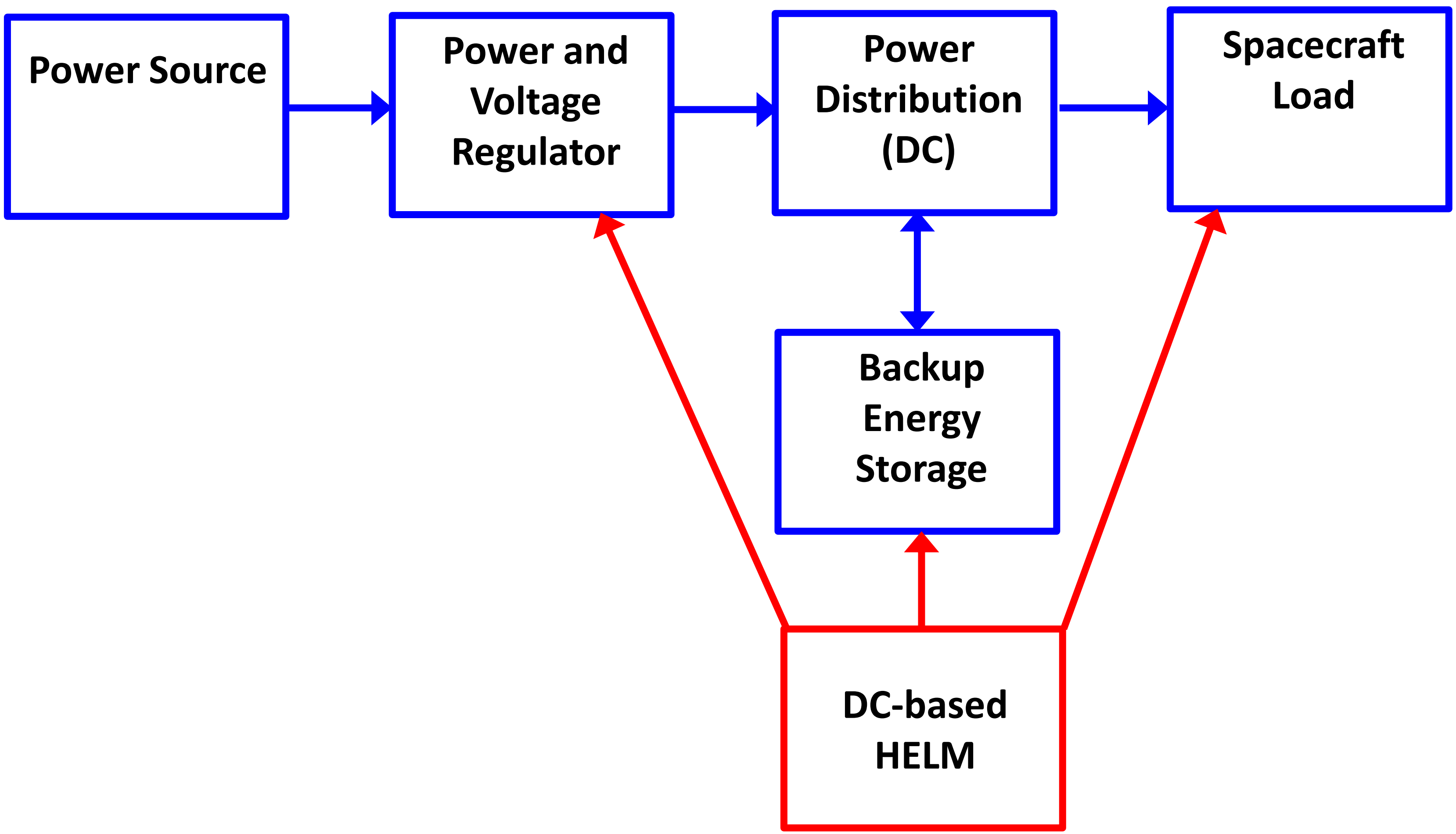
DC-based HELM for Intelligent Power Control



Terrestrial Microgrids

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

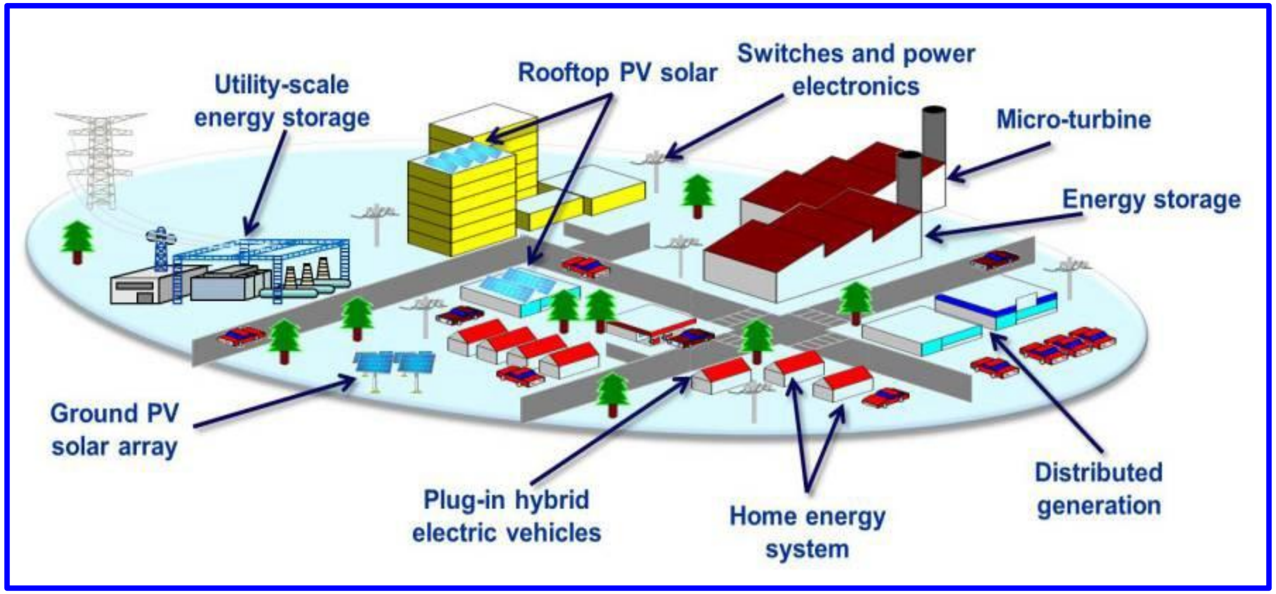


Figure 1. Schematic of microgrid

- Emerging Microgrids will require more robust software

Source of Picture: Soeder, James F., et al. "Application of Autonomous Spacecraft Power Control Technology to Terrestrial Microrgrids"; July 28 – 30, 2014, 12th International Energy Conversion Engineering Conference

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